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Book

Technology and the dynamics of specialization in open economies

Kieler Studien, No. 271

Provided in cooperation with:
Institut für Weltwirtschaft (IfW)

Suggested citation: Stolpe, Michael (1995) : Technology and the dynamics of specialization in open economies, Kieler Studien, No. 271, http://hdl.handle.net/10419/738

TECHNOLOGY AND THE DYNAMICS OF SPECIALIZATION IN OPEN ECONOMIES

Inaugural-Dissertation zur Erlangung des Grades eines
Doktors der Wirtschafts- und Sozialwissenschaften der
Wirtschafts- und Sozialwissenschaftlichen Fakultät
der Christian-Albrechts-Universität zu Kiel

vorgelegt von
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aus Kiel

Kiel 1995

Gedruckt mit Genehmigung der
Wirtschafts- und Sozialwissenschaftlichen Fakultät
der Christian-Albrechts-Universität zu Kiel

Dekan: Prof. Dr. Klaus-Rüdiger Veit
Referent: Prof. Dr. Horst Siebert
Korreferent: Prof. Dr. Klaus Brockhoff

Tag des Abschlusses der Arbeit: 18. April 1995
Tag der mündlichen Prüfung: 10. Juli 1995

Kieler Studien

Institut für Weltwirtschaft an der Universität Kiel

Herausgegeben von Horst Siebert

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Technology and the Dynamics of Specialization in Open Economies

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ISSN 0340-6989

Die Deutsche Bibliothek - CIP-Einheitsaufnahme

Stolpe, Michael:
Technology and the dynamics of specialization in open economies / Michael Stolpe. - Tübingen : Mohr, 1995
(Kieler Studien ; 271)
ISBN 3-16-146525-3
NE: GT

Schriftleitung: Harmen Lehment

Printed in Germany
ISSN 0340-6989

Preface

Economic news of recent years have been full of signs that a new division of business is emerging between entrepreneurs and politicians in some of the old industrialized countries: While entrepreneurs with proprietary rights over some technology continue to worry, as they have always done, about product sales and their share in particular markets, politicians increasingly seem to worry about their country's share of particular technologies. Indeed, it is now a widely held belief that there are certain technologies which hold the key to economic growth and prosperity for the country that masters them best. These technologies are generally thought to be distinguished by having the greatest potential for future innovations and the widest range of possible practical applications. Many of today's politicians seem to think that it is part of their job to identify these technologies and to make sure their home economy gets its fair share in each of them.

This theme was swiftly taken up by economic theorists who have since the mid-1980s devised various new approaches to modelling the notion that national leadership in high-technologies may result in a lasting lead of a country's productivity growth. These new approaches surely help to identify the theoretical conditions that would have to be met before targeted technology policies should be seriously considered in practice. Yet, empirical studies able to either substantiate or dismiss the theoretical possibilities for growth enhancing targeting of key technologies are so far largely lacking. It is for this reason that the present study *empirically* examines the impact of technology on the dynamics of technological and industrial specialization in OECD countries. It is hoped that the results of this empirical exploration will prove to be informative for politicians and economists alike.

This study would not have been doable without generous financial support granted by the Deutsche Forschungsgemeinschaft, which is greatly appreciated. I have further benefited from numerous discussions with fellow economists at the Kiel Institute of World Economics and at the University of Kiel's Institute for Research in Innovation Management. In particular, I would like to thank Prof. Dr. Horst Siebert, the Kiel Institute's President, Prof. Dr. Klaus Brockhoff, Director of the Institute for Research in Innovation Management, and Privatdozent Dr. habil. Karl-Heinz Paqué, head of the Kiel Institute's division for

research on economic growth, structural policy and the international division of labour. Computational assistance was provided by Dr. Deok Ryong Yoon. Thanks are also due to Frank-Joachim Ballke, Dietmar Gebert and Itta Schulte for their editorial work. — To my parents, I am grateful for giving me the right kind of attention and guidance to foster my natural curiosity in the earlier years of my life. Lastly, but by no means least, I would like to thank my beloved wife, Ute, who shared both the pain and the joy of writing this study.

Kiel, October 1995 Michael Stolpe

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A. Introduction

I. Aim and Scope of the Study

The dynamics of industrial specialization in open economies pose an unmet challenge for economic research. As proposals for targeted industrial and technology policies have come to the forefront of the public policy debate in recent years, the challenge to understand the forces behind economic and technological specialization is no longer of academic interest only. Yet, it remains primarily a challenge for the economic theorist and for the researcher in applied economics to provide a comprehensive assessment of old and new arguments for and against targeted policies, and to communicate the relevant results to the public.

Some recent theoretical models of endogenous economic growth and industrial specialization have attracted considerable attention for the support they appear to lend to selective industrial policies. In particular, the focus has been on government support to selected high-technology industries, whose growth is suspected of being constrained by insufficient market incentives due to strong external economies from research and development. The purpose of the research reported in this study is to explore various implications of these models, notably those that are essential to the argument for selectively targeted industrial and technology policies.

In essence, this study has two objectives, one empirical and one policy-oriented. Empirically, it is to critically examine the relevance of the hypothesis of path-dependence in the sectoral technological development of open economies — an hypothesis which has been derived from the supposedly localized nature of external economies from knowledge creation in recent models of endogenous technological change, specialization and growth. As to policy, the study seeks to identify the informational requirements that would have to be fulfilled to make targeted industrial and technology policies a recommendable course of government action in a concrete situation, if path-dependence was generally found to be empirically relevant.

The structure of the study is as follows. Chapter B will review some of the models of endogenous technological change in open economies which have been influential in the recent debate among economists about growth policies, and will discuss how these models might be adapted to serve as a framework for an empirical investigation of path-dependence in the dynamics of countries' specialization in technology-intensive industries. This review will focus on methodological issues and will point out the gaps in the existing empirical literature which the present study intends to close. The review will thus provide a case for the particular methodology chosen in the present study.

At the same time, the opening chapter will address a number of theoretical questions which have motivated the recent rise in economists' work on technology and growth: Why does growth of per capita income in today's advanced economies seem to depend so much on technological innovation? Since not any kind of innovation will do, since innovation per se — a mere change of what is — seems unlikely to be beneficial to growth, one is then led to ask how the right kinds of innovation are selected in growing economies. In particular, how does the market, which historically appears to have been the most successful selection device, actually select the innovations that turn out to be not merely profitable for private entrepreneurs at a particular place and time but also conducive for overall productivity growth in the long term? Can we trust that the market is an efficient selection process in the sense that it enables the economy to grow at the optimal rate given consumers' time preferences and attitudes towards risk?

A fundamental question — and one considered extensively by new growth theory — is the following one: What prevents the stream of innovations, which raise productivity, yet make each innovator a temporary monopolist, from running dry in the course of time? It seems doubtful that the answer to this can be fully understood looking at innovation as a purely microscopic phenomenon only, involving individual enterprises in isolation. Instead, it seems to be necessary to look as well at the macroscopic level of innovating economies, at the potentially complex interdependencies between all decentralized entrepreneurial activities which are probably exacerbated by the systemic nature of many modern technologies.

Put as a question for methodology: Does marginalism, one of the premises of neoclassical economics, still provide the adequate tools to analyze innovation, specialization and growth in today's world? Is there, perhaps, a need to supplement or replace marginalism by something else — in order to avoid the pitfalls of applying marginalism to optimization over non-convex sets? A related policy question being: Is a continually beneficial stream of technological innovations conceivable without some supplementary process of organizational and institutional innovations in the economy at large?

Chapter C will discuss how models of hysteresis in industrial specialization can be formalized in terms of mathematical probability theory, in a way which takes feedbacks from macropatterns to microdynamics properly into account. In particular, the discussion will ask how these models can be embedded in Markov processes. Computer simulations will be used to exhibit the likely long-term trends of specialization derived from selected model specifications. These should help to understand what conditions actually make path-dependence or hysteresis a likely feature in historical processes of specialization in technology-intensive economies.

Interpretation of the computer simulations will be based on the ensemble view, which will also serve as the guiding principle in the subsequent empirical investigation in Chapter E. The ensemble view is a simplified and restricted version of the ideal model in terms of Markov random fields which would take into account all important interdependencies between individual industries within and across countries as well as across time, yet presently remains analytically intractable. The ensemble view instead takes the simulated or observed sequences of individual industries' states of specialization in different countries as members of a statistical population, so that inferences can be drawn from the variation in the data.

Chapters D and E will report the results of several different approaches to examine the actual determinants and the actual dynamics of specialization in OECD countries. First, in Chapter D, conventional regressions will be discussed which attempt to identify the specific sets of determinants for particular industries' research and development activities to be relatively strongly or weakly represented in an economy. These exploratory regressions are intended to assess the empirical relevance of the notion of comparative advantage for the allocation of R&D activities across countries and across industries.

In Chapter E, the observed *dynamics* of technological and production specialization will be explored by means of nonparametric estimation of Markov chain transition probabilities. At issue is here persistence and the hypothesis of hysteresis in national patterns of industrial specialization, often claimed to be an implication of strong path-dependence in the evolution of high technologies specific to certain industries. A crude, preliminary attempt will be made to take changes in countries' relative factor endowments into account.

Chapter F will evaluate and discuss, on the background of the various empirical findings, the implications of new growth theory for industrial and technology policies in advanced open economies. This chapter will suggest the outlines of a unified interpretation of present knowledge in the field. Importantly, it will point out a number of crucial questions which would have to be answered before any targeted industrial and technology policies could be recommended for use in practice. Reasons will be given why many of these questions still cannot be satisfactorily answered given the analytical restrictions of the tools which are today available for theoretical and empirical research in economics. Chapter G concludes.

II. Preliminaries on Methodology and Terminology

It may be useful to emphasize at the outset that the empirical research reported in this study is exploratory in several directions which have hitherto received little attention in the literature. This work is based on particular choices of theoretical models and empirical methodology. It will become clear in the subsequent chapters why these choices were made. Some preliminary thoughts on their appropriateness, as well as some basic definitions, are offered in the remainder of this introduction.

Targeted *technology* policies can often be considered as targeted *industrial* policies in disguise. This correspondence in terms of the motivation to adopt such policies has a factual basis because industries are often defined by the typical technologies they use. A good example is telecommunications, but a counter-example is provided by hydraulics, a technology applied in many industries as different as aircraft, electric power generation and medical engineering. To be sure, technology policies targeted at key technologies, defined as those with immediate applications in virtually all industries, cannot be considered industrial policies; conversely, industrial policies not aimed at improving a particular industry's *technological* basis cannot count as technology policy. Finally, there is yet another class of technology policies which are not targeted, but aim at improving the creation and diffusion of new technologies in general.

The present study does not consider distributional objectives as a motivation for policy, but only the potential failure of markets to ensure an efficient allocation of resources. Inasmuch as industrial (or technology) policy pursues the goal of correcting or compensating for market failures, these are generally attributed to external effects or increasing returns to scale. External effects, broadly defined, arise when the activities of one economic agent have a positive or negative impact on the activities of others without the former having an incentive to include this in his decision calculus, because these effects are not at all, or not fully, compensated by counter-transactions. External effects thus may imply that the conditions for efficient production and consumption are not met in market equilibrium. Under the assumption of differentiability, these conditions require that the marginal rates of substitution between any two inputs be equal in all production (or consumption) activities and that the marginal rates of transformation between any two goods be equal to the marginal rates of substitution in using these goods. These conditions though may not be sufficient if there are non-convexities in an economy's production technology.

One case of non-convexities are increasing returns to scale, which a production process is said to exhibit when output can be increased over-proportionally by a simultaneous increase of all inputs at a constant ratio. Increasing returns to the scale of the individual firm represent a market failure insofar as they must eventually lead to a monopoly of the largest producer, who can produce at lower average costs than any of the competitors. The monopolist will then seek to maximize profits by setting prices above marginal costs, a situation which has long been known to be suboptimal from a social point of view (Marshall 1922). The reason is that this divergence of price from marginal costs violates the efficiency condition that marginal rates of transformation be equal to the marginal rates-of substitution. By lowering price a given monopolist would create a kind of external effect benefiting his customers who would then use greater quantities of the monopoly good at lower unit costs; but an optimizing monopolist would of course avert such a move in a static equilibrium.

Not every compensation for, or correction of, market failures can, however, be called industrial policy. The provision of public goods, for example of the (natural) monopoly product of national security, is normally not classified as industrial policy, although here surely is a case of market failure. The correction of, or compensation for, market failures can reasonably be called industrial policy only when the market failure affects the different industries in an economy to a differing degree and when the market failure therefore leads to an inefficient allocation of resources *across* the different industries. This is the case, e.g., when investments in research and development in one industry yield positive technological external effects for research in other industries, while the former industry does not benefit from equivalent reciprocal external effects itself. But inefficiency of resource allocation across industries might also be a problem because one industry suffers distortions in the form of monopolistic price setting while other industries operate under perfect competition.

Scitovsky (1954) suggested to distinguish between technological and pecuniary external effects. External effects which directly influence the level of production of the recipient firm or the level of utility of the recipient consumer are called technological; they are generally an indication of incomplete property rights. Siebert (1992a) points out that the analysis of technological externalities can usually be enriched by explicitly considering the technological system through which they are communicated. Pecuniary external effects on the other hand do not presuppose a technological system other than the market mechanism. They are indirectly propagated via a change in market prices, and influence the profit level of other firms. If they occur in a dynamic equilibrium, they can imply aggregate-level distortions which may be observationally similar to those of technological external effects.

While the introduction of a new good often comes with a negative *pecuniary* externality for the direct competitors, who lose sales or face lower prices, it may also give rise to positive *technological* external effects, when the invention reveals new technical possibilities which competitors can incorporate into the next generation of their own products without paying a fee to the original inventor. On the other hand, also pecuniary externalities may be positive, so for instance when they involve upstream or downstream linkages between vertically not integrated firms within an industry. After all, an innovator lowers the price of his new good from infinity to some finite value. Because the different external effects associated with innovation are partly positive and partly negative in their impact, it is generally difficult to evaluate whether the world is economically improved or made worse by the introduction of some particular new good or by an ongoing process of innovation in a particular technological direction.

The well-known criterion to compare allocative equilibria of production and consumption in terms of efficiency, due to Pareto (1919) who extended an idea previously used by Edgeworth ([1881] 1932) in the context of pure exchange economies, states that an allocation is optimal if it cannot be changed in favour of any one person or firm without lowering the well-being of at least one other economic agent. Welfare economics, which inquires into the conditions to ensure that resource allocation is efficient, i.e. Pareto-optimal, has in the past strictly distinguished between technological and pecuniary external effects in its use of comparative statics to analyze perfectly competitive markets: While technological external effects were accepted as a theoretical justification for correcting government intervention, pecuniary external effects were implicitly excluded from equilibrium by the assumption that all consumers and firms are price takers and that all profits are zero. Pecuniary effects were merely seen as an unavoidable part of the adjustment to a new Pareto-optimal allocation after an *exogenous* parameter or price change has destroyed a given equilibrium allocation.

That only technological externalities are considered a potential economic justification of government intervention is thus an implicit result of a traditional, *static* approach to the analysis of external effects in the context of general equilibrium on perfectly competitive markets for a given set of goods (Scitovsky 1954). New growth theory has recognized that perfect competition is rarely relevant in actual growing economies, and has reasserted the insight that a strict dichotomy between the welfare relevance of technological versus pecuniary external effects is often neither practical nor useful within a *dynamic* context (Krugman 1992: 425). Ongoing and endogenous, yet often intrinsically unpredictable parameter and price changes are, after all, the essence of economic growth, which is hardly conceivable without price setting by temporary monopolists and without pecuniary external effects occurring all the time. New growth theory has managed to include some of those endogenous parameter and price changes in its *dynamic* definition of equilibrium, and to model steady-state growth with pecuniary as well as technological external effects.

Where genuinely new goods and services enter the world, the allocation problem cannot be simply reduced to one of static equilibrium in perfect competition by devising a complete set of future markets, as in Arrow and Debreu (1954). Nor can institutions to internalize externalities, which may solve part of the incentive problem as envisaged by Coase (1960), always be relied on to emerge at the right place and time, because the irregular, unstable and unpredictable nature of innovations may imply that such institutions would have to change their rules continuously, and would have to deal with ever-changing groups of originators, beneficiaries and burden bearers. Software and genetic engineering, for example, have raised the issue of extending intellectual property rights to cover hitherto unpatentable technologies. Yet, where such institutions do emerge they may actually tend to increase the degree of monopoly in the economy, and may thus create additional distortions from optimality.

It is therefore a premise of much of new growth theory that neither pecuniary nor technological external effects from the creation of new technical knowledge should be *a priori* disregarded in assessing whether economic growth in a particular place and time is optimal, and in deciding what might need to be done in a given suboptimal situation to make growth more efficient. With respect to pecuniary externalities associated with indivisibilities (a case of local non-convexities) like bridges and other infrastructure services, a similar point was already noted by Dupuit ([1844] 1952), and has since been re-emphasized by Scitovsky (1954) and Romer (1994). Any economically useful piece of new technical knowledge can be analyzed as an extreme case of an indivisibility, namely one without a capacity constraint on the number of potential users, which really introduces a global non-convexity, i.e. increasing returns to scale (Romer 1990).

It is in this sense that the present study cannot be fully appreciated without acknowledging the coexistence of pecuniary and technological externalities. Both kinds of externalities may be the source of positive feedbacks and path-dependence in the dynamics of specialization in open economies. To examine these hypothetical macroscopic consequences of external effects from innovation and from the adoption of new technologies, the present study necessarily pursues a macroapproach based on aggregate observations for individual industries. But this is, of course, a level of aggregation at which the impacts of pecuniary and technological externalities on patterns of specialization are empirically indistinguishable. A proper distinction between these impacts could only be expected from a detailed and comprehensive examination at the level of individual firms of the origin, direction and transmission mechanisms of the different kinds of external effects.

As Chapter F will argue, a clear distinction between technological and pecuniary external effects from innovation would be a precondition for an efficient choice of targets and instruments in the implementation of a consistent set of industrial and technology policies in practice. The reason is that the diagnosis of *pecuniary* externalities may call for the use of instruments which would be ineffective or inefficient in the case of *technological* externalities, and vice versa. Hence, the difficulties of empirically discriminating between the different kinds of externalities in the context of technological innovation, which for lack of sufficiently disaggregated data and of appropriate methodology appear insurmountable for the time being, are closely related to, and indeed constitute an important part of, the information problem for any benevolent government, which was first spelled out by Hayek (1945). Ultimately, it is only by acknowledging the potential of pecuniary (as well as technological) external effects to cause deviations from Pareto optimality that the full extent of the information problem in the design of targeted industrial and technology policies can be appreciated.

> More can be less. Much of mathematical economics in the 1950s gained in elegance over poor old Pareto and Edward Chamberlain. But the fine garments sometimes achieved fit only by chopping off some real arms and legs. The theory of cones, polyhedra, and convex sets made possible "elementary" theorems and lemmas. But they seduced economists away from the phenomena of increasing returns to scale and non-convex technology that lie at the heart of oligopoly problems and many real-world maximising assignments. Easy victories over a science's wrong opponents are hollow victories — at least almost always.
> —Paul Samuelson (1983: xix)

B. The Theory of Endogenous Growth, Technological Change and Hysteresis in Open Economies

I. What Makes Growth an Endogenous Process?

The common fundamental point of many different approaches within new growth theory is that government policy can actually have a sustained influence on the long-term speed of economic growth in a country. This is the reason why new growth theory is also often referred to as a theory of *endogenous* growth, in contrast to the theory of *exogenous* long-term growth developed by Solow (1956, 1957), which has since become the orthodoxy. A central objective of new growth theory has been to explain how different policy measures affect the rate of long-term growth and the welfare of an economy.

In the model devised and popularized by Solow, which originally goes back to Tinbergen (1942) and later became the neoclassical paradigm of postwar reconstruction, the rate of growth depends only temporarily on the preferences of consumers, i.e. on people's propensity to save, and on economic policy measures. In the long term, it is solely the rate of technical progress, assumed to be exogenous, which determines the growth rate of productivity. Without exogenous technical progress the growth rate of output per employee would be zero in the long term. Full determination of long-term growth by exogenous productivity progress results from the underlying assumptions about the economy's production technology. In the Solow model, production technology is represented by a substitutional production function — for the sake of simplicity formalized as a Cobb-Douglas function[1] — with constant returns to scale, whose arguments are labour and capital. Since capital's partial elasticity of production[2] is taken to be smaller than one, the real rate of return on investment, and thus the percentage increase in the per capita capital stock which can be achieved with a constant rate of investment, necessarily shrinks in the course of the accumulation process. Hence, over time the private incentives to invest into the further accumulation of capital deteriorate, and the economy approaches, asymptotically, its long-term (steady-state) equilibrium in which neither the per capita capital stock nor per capita income grow any further.

To make this point more formally, as e.g. in Sala-i-Martin (1990a), assume that output in each period t is related to the aggregate inputs labour, L, and capital, K, via a simple Cobb-Douglas function, where α and β denote partial elasticities of production:

$$[1] \qquad Y_t = L_t^{\alpha} K_t^{\beta} \qquad \alpha, \beta \geq 0.$$

Capital is the factor which can be accumulated; aggregate net investment per period being denoted by $K' = dK/dt$. Labour, by contrast, cannot be accumulated, but is assumed to grow at the exogenous rate n. To simplify the analysis, one may initially dispense with setting up the problem in terms of a model of intertemporal utility maximization in the spirit of Ramsey (1928), and may instead follow Solow (1956) in assuming a constant rate of saving, s, and of capital depreciation, δ, so that net investment takes the following form in each period:

$$[2] \qquad K_t' = sL_t^{\alpha} K_t^{\beta} - \delta K_t .$$

This implies the accumulation equation of per capita capital, where k denotes the capital intensity, K/L :

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[1] In a Cobb-Douglas production function the individual inputs are linked in a multiplicative manner to determine the output. This production function is substitutional because the output can be kept constant when the amount of any one input is reduced by appropriately increasing the amounts of other inputs. Constant returns to scale mean that the output is increased proportionally to a simultaneous increase of all inputs in equal proportions. Technically speaking: A Cobb-Douglas production function has constant returns to scale when the sum of all partial production elasticities is one. For an explanation of the term 'partial production elasticities' see the next footnote. Constant returns to scale are generally formalized by linear-homogeneous functions of production.

[2] A partial production elasticity measures the percentage increase of output which results from a percentage increase in the amount of one individual production input. A partial production elasticity is — just like any elasticity — the ratio of two percentage values.

[3] $$k_t' = s k_t^{\beta} L_t^{\alpha+\beta-1} - (\delta+n) k_t \,.$$

The per capita capital stock, i.e. the capital intensity, thus grows at the rate:

[4] $$\gamma_k = \frac{k_t'}{k_t} = s k_t^{\beta-1} L_t^{\alpha+\beta-1} - (\delta+n) \,.$$

For the steady state, in which γ_k is constant by definition, the expression can be simplified by taking logarithms. Differentiation with respect to time then leads to the steady-state equation:

[5] $$(\beta-1)\gamma_k + n(\alpha+\beta-1) = 0 \,.$$

Assuming constant returns to scale, $\alpha+\beta=1$, the equation reduces to:

[6] $$(\beta-1)\gamma_k = 0 \,.$$

Clearly, the orthodox assumption of decreasing marginal returns to capital, i.e. $\beta<1$, implies that the steady-state growth rate γ_k equals zero. This is the crucial result of neoclassical growth theory as developed by Solow (1956, 1957), which can accommodate long-term growth of per capita income only with reference to exogenous technical progress, but which does not offer any real explanation itself.

This analysis makes clear that sustained growth is only possible when the average return on investment does not continuously decrease in the course of the accumulation process until it falls below a certain critical level which depends positively on the growth rate of the population and negatively on people's savings rate. Technically speaking, and assuming instead of a constant savings rate a representative consumer who maximizes a time-additive[3] utility function with a constant intertemporal elasticity of substitution[4], per capita income can

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[3] A utility function is time-additive if total utility realized over a period of time is just a weighted sum of the utility levels in each period. This means that the instantaneous utility a consumer realizes in a particular period only depends on the level of consumption in this period and not on the levels of consumption in any other period. Time-additivity is assumed merely for analytical tractability.

[4] The intertemporal elasticity of substitution is a measure of how 'substitutable' consumption tomorrow is for consumption today. It is defined as the percentage change in the ratio of consumption in one period over consumption in the next period due to a percentage change in the ratio of prices for consumption in each period. Changes in the relative prices of consumption in different periods may result from changes in the real rate of interest; when the rate of interest rises, the price of future consumption decreases, and vice versa. The larger this intertemporal elasticity of substitution, the larger the rate of growth for a given *positive* difference between the

only grow as long as the real rate of interest, i.e. the marginal product of capital net of the growth rate of employed labour (or population for convenience) is higher than the subjective rate of time preference for consumption.

This condition for endogenous growth can be formally interpreted as a characteristic of the production function which ensures that the marginal product of the accumulating factor *does not decrease in the long term.* This condition, however, cannot be fulfilled if an economy's production apparatus is appropriately described by a Cobb-Douglas function with physical capital and labour as the only inputs and with constant returns to scale. Nondecreasing marginal returns presuppose a partial elasticity of production for capital of at least one. So, if labour is taken into account as a nonaccumulating factor of production with a positive partial production elasticity, the sum of both partial production elasticities will necessarily be larger than one. This implies that the economy must have increasing returns to scale — a feature which can hardly be justified on economic grounds in a model which only takes into account pure labour and physical capital of uniform qualities.

One way out[5] of this difficulty of formally depicting economic production technology with the flexibility required for endogenous growth[6] is provided by the simple observation that *physical* capital is obviously not the only production factor whose accumulation can account for economic growth. In fact, variants of *human* capital appear to be much more important for processes of accumulation and growth in the long term, at least in the advanced industrialized economies. Starting from this observation, a central objective of new growth theory has been to explain why the average return on investment need not decrease in the

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marginal product of capital (net of population growth) and the rate of time preference (Blanchard and Fischer 1989: 43).

[5] Another way out would be to assume that *all* inputs are in fact variants of capital and can be accumulated, as in Rebelo (1991). The Rebelo model has the simple production function $Y = AK$ and always fulfills the general condition for endogenous steady-state growth, which requires constant returns to scale in all inputs that can be accumulated.

[6] Some theoreticians, like Scott (1989), reject any mathematical formalization of an economy's production function to explain long-term growth as entirely misleading. Scott instead sees growth as the aggregate manifestation of entrepreneurs' uncoordinated responses to temporary investment opportunities, of which a dynamic economy offers new ones at every point in time. Because these investment opportunities are largely created by previous investments, via learning and demand externalities of a primarily pecuniary kind, there is no reason, in Scott's theory, to believe that investment as such is subject to diminishing returns over time, or in the course of capital accumulation, as it would be under an intertemporally fixed substitutional production function. Scott only thinks it appropriate to assume the existence of decreasing marginal returns to investment at any given point in time, at which the set of investment opportunities is predetermined.

course of time when human capital in its different variants is taken into account as an accumulating factor of production.

The new literature on economic growth distinguishes between human capital as an endowment of individuals, i.e. the skills as well as technical and professional qualifications people have acquired, and knowledge capital, as the economically relevant part of technical knowledge is often termed. Knowledge capital is either currently used in production or is available for future use in the economy. A large part of technical knowledge is contained in product features, materials and design forms used in production, or is documented in patents, and can be used more or less freely by competitors or other unrelated firms in their own research and development work. Another part of knowledge capital, however, is at least temporarily specific to the firm where it is used. This seems to be so particularly in the case of process technologies and of technical innovations whose control requires extremely large initial investments or highly specialized complementary skills for the operators.

Presumably, a significant part of this knowledge capital which is not revealed by selling products in which it is incorporated is nevertheless not firm-specific since qualified employees may carry it to other firms when changing jobs, and in fact often do so with only a short delay after an innovation has taken place. This part of knowledge capital can, however, in many cases be considered region-specific or country-specific, because many labour markets are not integrated at all, or only poorly, at an interregional level, let alone internationally. The accumulation of technical knowledge in different firms can be connected via a number of channels other than geographical proximity, i.e. for example via common research programmes, institutes and conferences or via strategic alliances. In these cases one can talk of *network-specific* knowledge capital that need not be specific to a region or country.

The reason why proponents of new growth theory invoke knowledge capital as an explanation of how the drag placed on productivity growth by non-accumulating inputs may be overcome, lies in the special combination of economic features which distinguish knowledge capital from other inputs: non-rivalry and at least partial non-excludability in use. Rivalry means that one person can get full utility from a certain good only if he prevents other persons from using the good instead or simultaneously; excludability means that the owner of a good can *actually* prevent others from using it. Perfect rivalry and perfect excludability are features which define private goods, like food items, and most other tangibles. Perfect non-rivalry and perfect non-excludability, by contrast, define pure public goods, of which public safety is an example. Table 1 presents possible combinations of the two basic economic features of goods, gives examples, and indicates whether the respective case creates problems for allocational efficiency (according to economic theory). Furthermore, the table indicates whether these goods can serve as a building block for an explanation of endogenous growth if they are accumulated as inputs of production in the presence of other, non-accumulating inputs.

Table 1 — A Taxonomy of Capital Inputs and Growth Effects Implied by Ongoing Accumulation

Degree of excludability (partly a legal, partly a technological feature)	Degree of rivalry in use (a technological feature)		
	Full rivalry	Partial rivalry	No rivalry
Full excludability	*Private goods:* efficient market allocation, no long-term growth effects	*Club goods:* efficient market allocation, no long-term growth effects	*Secret technical information:* inefficient market allocation, no long-term growth effects
Partial non-excludability	*Common pool goods:* inefficient market allocation, no long-term growth effects		*Ideas, designs, software* (intellectual property which is revealed in tangible products and only partly protected): efficiency of market allocation doubtful, endogenous growth effects possible (Romer 1990; Grossman and Helpman 1991)
Full non-excludability	*The environment* or *randomly allocated goods:* inefficient market allocation, no long-term growth effects	*Public goods with crowding* (e.g. infrastructure): inefficient market allocation, endogenous growth effects possible (Barro and Sala-i-Martin 1992b)	*Pure public goods* (e.g. basic research results): inefficient market allocation, endogenous growth effects possible (Barro 1990; Romer 1986)

Non-rivalry implies increasing returns to scale, i.e. global non-convexities, and may indeed prevent the decline of the *physical* marginal product in the course of capital accumulation. But non-rivalry alone cannot prevent the decline of the marginal *value* product of capital accumulation, which would be the proximate cause of diminishing incentives to invest in new capital in models without positive externalities: The accumulation of non-rival inputs, from which other firms can be perfectly excluded, would create private monopolies whose growth would ultimately be constrained by declining schedules of demand. Endogenous growth is thus not feasible without at least partial non-excludability of the non-rival input whose accumulation drives growth. Positive *external* effects are therefore crucial in preventing the monopolization of production and knowledge creation in spite of increasing returns to scale from technical knowledge. External effects may achieve this by raising the marginal value product of other firms' activities, by thus reinforcing other firms' investment incentives, provided the positive external effects are of sufficient strength and sufficiently symmetric so that all firms get their turn to be beneficiaries.

There may be both legal and technological reasons that new technical knowledge is partly non-excludable. Patent protection is always limited in breadth and duration, and may not be fully enforceable even during the officially granted protection period. Innovative ideas are frequently copied or re-used in slightly altered form, and it is rarely possible to even keep track of all this. Often it is the mere information that someone has succeeded in achieving a certain invention that provides a valuable stimulus and research focus for competing firms that try to come up with a similar invention or directly seek to imitate a first mover.

In the following sections, several approaches of new growth theory, each of which is based on the accumulation of a different variant of human capital, are examined with respect to the implications they have for industrial policy, especially in open economies. In this context, the central role of human capital will become clear: much can be said for the hypothesis that human-capital accumulation holds the key to answering the question of why the return on investment, and thus the incentive for private capital accumulation, does not decrease, or at least need not decrease, over time. Diverse types of human capital have lent themselves to equally diverse approaches to modelling endogenous growth.

In the following discussion, the main interest will be whether, and to what extent, external effects in the allocation and accumulation of human capital play an essential part in these models, and what economic policy measures are suggested as appropriate to help the economy get on a Pareto-optimal growth path. In order to assess proposals for targeted industrial policy, it will be necessary to look at growth models with multiple sectors. In these, the primary concern will be what kind of market imperfections in the allocation and accumulation of human capital might prevent promising industries from developing, and from growing at a rate which would be optimal from a welfare-theoretic point of view.

II. Models of Endogenous Technological Change

1. Industry-Specific Dynamic Returns to Scale Based on Learning by Doing

The first model of Romer (1986) is generally regarded as the beginning of new growth theory. This model analyzes endogenous growth based on the assumption that private investments do not only yield a physical return but also a knowledge return which, in contrast to the physical return, cannot be privately appropriated (Romer 1986). In fact, an important feature of this model is that the knowledge return from private investment activities is available to all firms as an external learning effect, and increases the productivity of all future investments in the economy. This idea goes back to Arrow (1962) and is designated as 'learning by doing'. Already in his model, external learning effects are invoked to explain that private investment activity might not only augment a *physical* capital stock but also a stock of *knowledge* capital with features of a public input in private production.[7] However, Arrow's model cannot yet be deemed a theory of endogenous growth since the productivity gains due to external learning effects are too weak to admit of a self-sustaining growth process, which would have to be based on non-decreasing returns on investment over time.[8]

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[7] A public input in production is an example of a public good, defined by its constituent features of non-rivalry and non-excludability in use.

[8] Arrow (1962) assumes that each individual firm i produces according to $Y_i = K_i^{\beta} L_i^{1-\beta} \kappa^{\eta}$, where $\kappa(t) = \int_{-\infty}^{t} I(v)dv$ is an index of experience from cumulated past investments I of *all* firms in the economy. Holding κ fixed, the production function has constant returns to scale, but taking changes of κ into account it has increasing returns to scale. These changes in κ are, however, external to the individual firm's investment decision, which is therefore suboptimal. The model fails to generate endogenous growth, though, because, in order to preserve steady-state dynamics accessible to the analytical techniques then available for optimizing models, Arrow did not consider increasing returns of sufficient strength to overcome the drag placed on growth by the non-accumulating input, labour. Instead, he added *exogenous* population growth to explain why investment incentives would be main-

Romer (1986) is the first to assume that the partial production elasticities of private capital and of public knowledge capital add up to one. The incentives for private investment thus remain unchanged over time, and the economy grows in the long term at a steady-state rate which depends on the characteristics of technology and preference parameters of the representative consumer as well as on economic policies. In Romer's model the long-term rate of growth is larger, the more efficient the economy's technologies are on the one hand, and the lower the rate of time preference of the consumers and the lower the taxation of capital income are on the other.

The sum of the partial production elasticities of labour, private capital and public knowledge capital is actually larger than one in Romer's model, the production function hence assumes increasing returns to scale. Monopolistic tendencies are nevertheless excluded because, as in Arrow (1962), the presence of external effects makes sure that increasing returns to scale arise only at the level of the economy as a whole. Each individual firm still bases its investment decisions on the assumption of constant returns to scale and acts as a price taker in perfectly competitive markets. The presence of positive external learning effects from private investments implies that the rate of accumulation and growth is suboptimal. A subsidy for private investment therefore has the potential to improve the allocation in the model economy.

The formal description of Romer's model is again based on the Cobb-Douglas function, this time augmented by a third factor Z, which represents the total capital accumulated in the economy. The individual firm deals with:

$$[7] \qquad Y_i(t) = A\, L_i(t)^{1-\beta}\, K_i(t)^{\beta}\, Z(t)^{f} ,$$

where K_i denotes the private capital of the individual firm i, and f the partial production elasticity of the economy-wide capital stock Z, which captures the external returns to capital accumulation. These external returns are not taken into account by the individual firm, which simply takes Z to be exogenous and solves its (concave) intertemporal profit maximization problem in direct application of the standard Kuhn-Tucker theorem. In the aggregate of the economy there is, of course, no difference between the sum of all private capital and the economy's total capital stock. Aggregate output is thus determined by:

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tained over time. The growth rate of per capita income is in steady state proportional to the growth rate of population, and invariant with respect to policy. Another drawback of Arrow's model is the implausible implication that countries with a larger labour force are richer in steady state, which stems from the external effects being related to the aggregate capital stock, and not to the average, per capita capital stock.

$$[8] \qquad Y_t = A\,K_t^{\beta+f}\,L_t^{1-\beta}\,.$$

Romer (1986) shows that this model admits of positive steady-state growth without any exogenous driving force behind it, when the decreasing private returns to capital are augmented by external returns of appropriate strength, so that the total *social* returns to capital remain constant over time.[9]

To make the approach of Romer (1986) relevant for industrial policy, it has to be framed in a model with several sectors of which some show only weak or, perhaps, no external learning effects at all, while in other sectors learning effects contribute considerably to the dynamic performance of the returns to private investments over time. In this case, the government can use industrial policies to encourage private investment in the industries with the strongest external learning effects to achieve an efficient allocation of private investment. Lucas (1988: 27–31), shows this for a *closed* economy in a stylized model of multi-sectoral endogenous growth based on learning by doing.

To make this point, Lucas introduces a model stripped down to the essentials: two consumption goods, c_1 and c_2, and human capital, h_i, which is specialized in the production of either consumption good; and for simplicity there is no physical capital. Each good is produced according to

$$[9] \qquad c_i(t) = h_i(t)u_i(t)N(t), \qquad i = 1,2 \quad \wedge \quad u_i \geq 0 \quad \wedge \quad u_1 + u_2 = 1\,,$$

where u_i is the fraction of the constant labour force *N(t)* devoted to producing good *i*. The accumulation of specialized human capital is entirely due to learning by doing in the form of positive external effects:

$$[10] \qquad h_i(t) = h_i(t)\delta_i u_i(t)\,,$$

where the high-technology good, c_1, is assumed to be associated with higher learning rates, implying $\delta_1 > \delta_2$. Productivity and human capital accumulation in each industry depend on the respective average endowment with specialized human capital. Lucas suggests to interpret this formalization to stand for the continued introduction of new goods, in which human capital accumulated by learning on old goods is inherited by new goods, so that learning by doing may

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[9] He does not, however, explain what mechanism might ensure that the social production elasticity of capital actually equals one and remains at this value over time. In the case of $\beta + f > 1$, there also would be endogenous growth, albeit without a steady state; instead with growth rates increasing over time. Although some authors, Romer (1989) and Kremer (1993) in particular, have attempted to corroborate the idea of historically, i.e. over centuries, increasing rates of growth, it seems to be at odds with the experience of Western industrialized countries since World War II.

be bounded on each individual good, but need not be bounded for the industry as a whole.

As the model abstracts from all intertemporal decisions, only the current-period utility function of the representative consumer, assumed to have a constant elasticity of substitution[10] between the two goods, bears on the efficient allocation of the labour force across the two industries. Specifying the current-period utility function to be

$$[11] \qquad U(c_1, c_2) = \left(\alpha_1 c_1^{-\rho} + \alpha_2 c_2^{-\rho}\right)^{-1/\rho},$$

where $\alpha_i \geq 0$, $\alpha_1 + \alpha_2 = 1$, $\rho > -1$, and where $\sigma = 1/(1+\rho)$ is the elasticity of substitution, closes the model so that it can be solved. The first-order condition is:

$$[12] \qquad \frac{1}{q}\frac{dq}{dt} = (\delta_1 + \delta_2)\left[1 + (\alpha_2 / \alpha_1)^{\sigma} q^{1-\sigma}\right]^{-1} - \delta_2,$$

where q is the equilibrium price ratio in terms of good 1 as a numeraire. This condition determines the allocation of the labour force for each date t, since the initial endowments of human capital $h_1(0)$ and $h_2(0)$ dictate relative prices according to $q(t) = h_1(t)/h_2(t)$, which follows from utility and profit maximization.

Lucas then discusses three cases for different assumptions about the elasticity of substitution between the two goods. First, if these are good substitutes ($\sigma > 1$), the economy will even in autarky converge to complete specialization in one of the two goods, namely in the one favoured by the initial allocation of the labour force. Second, if $\sigma = 1$, the initial labour force allocation does not change over time, although relative prices may change, depending on the relative size of the preference and learning parameters α_i and δ_i. Third, if the goods are poor substitutes ($\sigma < 1$), the labour force allocation converges to a stable stationary point where the strength of the learning effects in the two industries is equalized ($\delta_1 u_1 = \delta_2 u_2$).

Because the learning effects take the form of externalities in the model, none of the equilibrium paths is efficient, unless (for $\sigma > 1$) initial conditions, by chance, select the path leading to complete specialization in the high-tech good, where learning effects are strongest. The model therefore calls for a subsidy to the high-tech industry, that is for an industrial policy to take advantage of that

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[10] The elasticity of substitution in consumption is defined as the percentage change in the quantity ratio of the two goods in consumption induced by a relative price change.

industry's higher growth potential, assuming that this industry can be identified ex ante.

Yet, of greater relevance for the industrial policy debate are inefficiencies which might be implied by multi-sectoral endogenous growth processes based on external learning effects in open economies.[11] In such models the assumption of external learning effects, which are constrained to benefit only firms in their country of origin, may give rise to a conflict over exports because under appropriate assumptions about preferences every country may want to specialize in producing the good with the greatest learning and productivity growth potential.

Lucas extends the above model by introducing free international trade in two goods among a continuum of small countries, so that the world market price ratio is the exogenous determinant of each country's domestic price ratio. At a given world market price ratio p countries either specialize in the production of good 1, if their ratio of specialized human capital endowments is $h_1/h_2 > p$, or they specialize in the production of good 2, if $h_1/h_2 < p$. The equilibrium world price ratio p is uniquely determined when all countries' consumers have the same homothetic preferences as above.[12] Since all countries are completely specialized, they will grow either slowly, if they are specialized in good 2 (with low learning rates) or they will grow fast, if they are specialized in good 1 (the high-tech good). In each country, only the type of human capital specialized on the good actually produced by the country is accumulated through learning by doing; initial comparative advantages are thus continuously reinforced.

But the endogenous changes in countries' relative human capital endowments will also change the equilibrium world price ratio p. Lucas points out that these endogenous price changes may cause some countries to lose their comparative advantage in the high-tech good, whose world market supplies grow faster and whose terms of trade therefore deteriorate. However, that marginal countries lose their comparative advantage in the high-tech good is a possibility only given if the elasticity of substitution between the two goods, σ, is sufficiently low. Even if that possibility is ruled out by assuming $\sigma \geq 1 - \delta_2/\delta_1$, there remain two qualitatively distinct cases: only for $\sigma > 1$ will countries specialized in the high-tech good enjoy faster real income growth, and Lucas thinks this to be the empirically more relevant case. But for $\sigma < 1$ the model

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[11] A detailed analysis of such processes can be found in Young (1991), who pays particular attention to the problem how an industry may overcome the bounds on learning by doing which is specific to individual goods, and how the industry as a whole may benefit and increase productivity as a continuous process.

[12] Preferences are called homothetic when changes in the size of the budget, over which a consumer has command, do not by themselves lead to changes in the relative shares of the budget spent on individual goods.

has the possibility that adverse terms-of-trade effects dominate the productivity gains of learning by doing in countries specialized in high-tech, which would cause these countries to experience slower real income growth than the countries specialized in low-tech production.

Although considerable external learning effects can never imply that some economies gradually lose their comparative advantage in all industries and finally remain without any foreign trade at all, Lucas (1988) has shown that certain model variants are at least not entirely implausible in which individual countries have the potential to succeed by means of targeted industrial policies in getting an artificial productivity advantage over competing countries in those industries which have the strongest external economies and whose growth prospects are particularly favourable. Some countries may thus be able to increase the rewards to their internationally immobile factors — albeit at the expense of other countries. Insofar as external learning effects are effective only in their respective country of origin, total factor productivity may differ from country to country, even in a direct comparison for the same industry, for the sole reason that countries have arrived at different levels of learning by doing. Consequently, the patterns of specialization of open economies linked by international trade cannot be fully explained with reference to the traditional theory of comparative advantages based on countries' relative endowments with elementary factors of production, which are exogenously provided by nature.[13]

Instead, the actual patterns of specialization may reflect historical, perhaps even arbitrary, leads and lags in the development of individual industries or sectors as well as advantages or disadvantages in market size which an economy has vis-à-vis its trade partners. Positive external learning effects tend to strengthen a given trade pattern and existing differentials in the productivity of immobile factors over time. Thus, even countries with identical elementary factor endowments may, over time, come to specialize in the production and export of completely different sets of products, and may thus realize rather distinct growth paths of income for their immobile factors.

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[13] Here, the 'traditional' theory of international trade refers to the exclusive thinking in terms of relative factor endowments, which is embodied in the Heckscher-Ohlin-Samuelson theory and its subsequent refinements. This theory admits of international differentials of the marginal productivities of individual factors of production in one and the same industry only insofar as equilibrium trade between countries with rather distinct factor endowments does not lead to the full equalization of factor prices. But the theory generally assumes equal *total* factor productivities for all countries. One should note that the earlier theory of trade associated with the name of David Ricardo did, in fact, recognize international productivity differentials of factors of production as a source of comparative advantage. These Ricardian productivity differentials are often interpreted as being due to technological differences between countries.

Of course, such a development cannot continue forever, a fact to which Krugman (1987) draws attention in the context of a two-country analysis with labour as the only internationally immobile factor. This model of dynamic comparative advantage due to learning by doing actually preceded, and inspired, the analysis of Lucas (1988) discussed above. Krugman's model is more primitive on the demand side where he does not specify a utility function, but simply assumes that of all income in each country a constant share s is spent on non-traded goods and an equal share, $(1-s)/n$, on each of n traded goods. The dynamics of specialization are thus entirely determined by countries' differential accumulation of learning effects in the production of each good. Learning experiences are different as long as cross-country spill-overs are less strong than those within countries. Since the model is Ricardian, with labour as the only factor that is mobile across industries in each country (but immobile across countries), each tradeable good is at any point in time produced by one country only. Both countries are always completely specialized in the subset of goods in which they hold a comparative productivity advantage, which can only arise from differential learning effects in the two countries.

Krugman's model has two equilibrium conditions: On the production side, equilibrium requires that the ratio of wage rates in the two countries equals the ratio of productivities in the marginal industry, which separates the industries for which either one or the other country has a clear comparative advantage. On the demand side, equilibrium requires, in the absence of any credit markets, that the balance of payments be in equilibrium, i.e. that the ratio of total wage incomes paid equals the ratio of the number of industries located in the two countries. Because comparative advantage is 'created' over time by the dynamics of learning, the model allows for the possibility that one country conquers a marginal industry located in the foreign country by protecting it temporarily from international trade until the home country has accumulated sufficient learning, which gives this country a permanent productivity advantage in the protected industry. Temporary protection can then shift to the new marginal industry, so that one country may, within limits, 'slice off' one industry after the other, provided the other country remains passive.

As a result of successful targeting, labour in one country may enjoy higher real wages for some time. But if the wage differential vis-à-vis the foreign country, which contests the 'marginal' industries with external learning effects, becomes 'too large', the home country will begin to lose its cost advantage from a productivity lead due to external learning. The country with the higher real wages will then begin to lose at least part of production in at least one of the 'marginal' industries which will shift abroad.

The industrial policy conclusion that Krugman (1987) draws from this two-country model with industry-specific dynamic external effects is of more general significance: in order to establish a permanent productivity advantage at home, the subsidies or trade policy measures a country seizes upon to encourage an industry with particularly strong external effects — bounded in their range to the country of origin — may need to be only temporary, provided of course that the foreign countries remain passive.[14] Yet, even if foreign countries do not react to unilateral industrial policy measures, these may nevertheless fail to bring about an increase in welfare in the country actively pursuing the industrial policy, since this country may suffer terms-of-trade losses as a result of export expansion in the targeted industries which might over-compensate any productivity gains. Only if terms-of-trade effects are relatively weak can overall welfare be expected to increase for a country initiating an active industrial policy.[15]

Recall that Lucas (1988) discusses these questions in the context of a two-goods model with many countries none of which is large enough to have a substantial influence on relative world market prices, in order to clarify the influence of the demand side on the development of country-specific patterns of production and export specialization in a growing world economy with dynamic external effects. The crucial parameter in this analysis is the elasticity of substitution in consumption on the world market. If this is low for the two products, the terms-of-trade changes resulting from an overproportional supply expansion of the high-tech product can be so strong that some countries despite being specialized in high-tech production and having accumulated external learning effects in this area, give up their specialization and transfer production to the traditional sector.

Even if such a restructuring of individual economies back to the traditional sector were not to be the outcome, an elasticity of substitution smaller than one[16] would imply that high-tech countries realize lower real income growth than other countries. Only if the elasticity of substitution is larger than one, i.e. if the model's two products are good substitutes in consumption, are initial

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[14] A further caveat Krugman (1987) notes is that the domestic market of a small country may not provide sufficient learning experience to overtake the foreign country in terms of productivity. Krugman speculates that the use of protection to shift comparative advantage may merely be an attractive choice for a country with a large labour force and low wages.

[15] The terms-of-trade losses as a consequence of export expansion may be weak when the demand for the exported goods on the world market is very price-elastic or when the country's exports only make up so small a part of the world market that they have no substantial influence on the price level anyway.

[16] In the case of an elasticity of substitution smaller than one, each good is used for special purposes and can thus only poorly be substituted for by any other good. Consequently, if one set of goods becomes more expensive, its share in total expenditure after adjustments to the new utility-maximizing consumption mix is larger than before the observed changes in relative prices took place.

patterns of specialization reinforced for all countries in the course of development, *and* do people in those countries which have specialized in the production and export of high-tech goods realize above-average real income growth.

It seems likely that for high-tech products the case of a relatively large elasticity of substitution vis-à-vis traditional goods is empirically more relevant besides being, naturally, more interesting for the discussion of industrial policies. In both the two-country model of Krugman (1987) and the multi-country model of Lucas (1988), certain industrial policy measures, aimed at creating a comparative advantage in the production of high-tech goods, may turn out to be advantageous for a country, even if these measures are applied only temporarily, provided the high-tech sector has an above-average growth potential in the world market.

One further insight from the analysis of these models is noteworthy: Stability of once established patterns of trade and specialization as well as of productivity growth differentials between countries over time can be expected despite (modest) changes in relative factor endowments only when the world market demand functions can be traced back to homothetic preferences, i.e. when the relative expenditure shares of the individual types of goods are not changed as a result of world-wide income growth alone. Empirical examinations since Engel (1895), however, have shown consistently that this condition does not hold for any type of goods in reality (Deaton and Muellbauer 1980). Different income elasticities of demand for different types of goods are, in fact, an important reason for the actually observed long-term changes in patterns of trade and specialization of open economies in a growing world economy.

Critiques of the learning by doing model point to the fact that all firms of one industry are assumed to benefit from the external learning effects automatically without any effort on their own part, even without wanting to, or without knowing about it. In reality, by contrast, many companies invest huge sums in research and development specifically directed at selected technological objectives. Models that do better justice to this reality facilitate a more detailed analysis of how and why different industrial policy instruments, such as for example subsidies for production or research and development, trade policy measures and the design of patent laws, are effective under certain circumstances. These models are discussed next.

2. Endogenous Technical Progress Based on a Process of Self-Sustaining Industrial Innovation

Explicit modelling of the contribution of private profit-seeking research and development investments to the accumulation of technical knowledge as the driving force of economic growth is the approach of the theory of endogenous technical change developed by Romer (1990), Aghion and Howitt (1992) and Grossman and Helpman (1991) — initially for the closed economy. Following Schumpeter's idea of economic development as a 'process of creative destruction' (Schumpeter 1942), technical progress in the form of product and process innovations is interpreted as the consequence of research and development undertaken by private firms with a view to maximizing their profits under certain constraints determined by the relative scarcities of resources and by a country's institutional framework, including the extent and enforceability of intellectual property rights. A long-term, self-sustaining process of growth is possible if the incentives for the accumulation of technical knowledge are large enough and do not weaken over time.

For this condition to be fulfilled in the models, it is assumed that the creation of new technical knowledge through private research and development yields positive external effects, because at least part of new technical knowledge is freely accessible to other firms and of use in their own respective innovative activities. If there were no external effects from new knowledge at all, the pioneers of any new technology would establish themselves as permanent monopolies which would be able to defend themselves without further research efforts. The private incentives for the creation of new knowledge would thus be lost and per capita income would sooner or later cease to grow.

Other modelling approaches, like those of Romer (1987) and of Barro and Sala-i-Martin (1992b), can do without the assumption of *technological* external effects, because they instead place positive *pecuniary* externalities at the centre of their analysis. In these models of monopolistic competition between manufacturers of investment goods, positive pecuniary externalities arise when a firm's demand for a larger diversity of specialized capital goods, which will increase its own productivity, leads to the innovation of more differentiated and specialized investment goods, which are then offered not only to the original customer firm but also to its competitors, who thus can raise their own productivity as well. Since a clear distinction is necessary in view of the rather different economic policy implications, the approaches of Romer (1987) as well as Barro and Sala-i-Martin (1992 b) are in this paper not subsumed under the models of endogenous technical progress, but are put in a class of their own: 'models of monopolistic competition and increasing specialization in capital goods'.

The models of *endogenous technical progress*, which are the focus of this subsection, differ from the models of 'learning by doing' at least in two respects. First, positive external effects do not arise from all investments but only from the invention and development of new products and services. Second, the technological external effects of new knowledge do not directly affect an economy's production function by directly increasing the productivity of elementary factors of production, but they only bring about a reduction in the costs of future R&D for all firms.

There are two basic approaches to modelling endogenous technological change, both of which are described in the seminal book of Grossman and Helpman (1991). One of these approaches interprets technological progress as an increase in the variety of goods which are consumed, or alternatively of goods which are used as intermediate inputs in final production for consumption. The other approach interprets technological progress as an ongoing process of increases in the quality of a fixed set of different goods, which are again used either as intermediates or for consumption.[17] Both approaches can explain endogenous steady-state growth provided the stock of technical knowledge can grow without bound. In both types of models, non-rivalry of knowledge implies that there are increasing physical returns to scale and that the marginal product of capital need not decline to zero. And partial non-excludability of knowledge makes sure that neither a technology leader in the case of quality ladders nor an established monopolist producer of a differentiated product in the case of expanding variety can hold on to his full market power without making further innovations. Partial non-excludability thus ensures that the private incentives to invest in the creation of new knowledge through R&D need not vanish over time.

In the model of rising product quality, it is obvious that utility-maximizing consumers, or profit-maximizing firms, will demand consumption goods, or capital inputs, of higher quality as they become available. To explain demand for ever more differentiated goods in the model of expanding product variety, Grossman and Helpman (1991) invoke the so-called love-of-variety function originally proposed by Dixit and Stiglitz (1977). This function with constant elasticity of substitution between input varieties can be interpreted either as an index of consumption or as an index of efficiency in final production, as proposed by Ethier (1982):

$$[13] \qquad D = \left[\int_0^n x(j)^\alpha \, dj\right]^{1/\alpha}, \qquad 0 < \alpha < 1,$$

where $x(j)$ denotes the quantity of variety j of n goods available at a particular point in time, either as capital inputs in final production or directly for consumption. The elasticity of substitution between any pair of goods is $1/(1-\alpha)$, which is larger than one given the restrictions imposed on α. The parameter α

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[17] The process of technological change described by the second approach is often referred to as a quality ladder.

can be interpreted as a measure of consumers' preference for variety, which for the admitted values is positive and increasing as α declines. Alternatively, if D is interpreted as an efficiency index in production, the function implies that total factor productivity is an increasing function of the total number n of different input varieties used and that the technology has constant returns to scale for a given number of input varieties.

To model economic growth, the love-of-variety function is built into a dynamic model of monopolistic competition among the suppliers of inputs or consumption goods along the lines first explored by Judd (1985). Each profit-maximizing firm attains some price-setting monopoly power by bringing a new variety of capital input, or consumption good, to market, but faces the economy-wide resource constraint set by a fixed supply of labour. When this constraint binds, the representative firm can increase the volume of manufacturing or the rate of innovation, but not both at the same time. Furthermore, individual profits are constrained by the capital market, where equilibrium requires that there are no profitable opportunities of arbitrage in ownership of the various firms, and by the product market, where new firms can freely enter and compete away all excess profits.

It follows that entrepreneurs invest in the development of new product varieties until the expected reward on each R&D effort, i.e. the present value of firms' profits, is competed down to the level of development costs, which are assumed to decline as the stock of available knowledge capital in the economy rises. Grossman and Helpman (1991) show that for a constant stock of knowledge capital both the flow of new goods and the total volume of manufacturing are bounded by the economy's resource constraint. The rate of innovation and the growth rate of real consumption, equal to the index D in equilibrium, converge to zero, because an increase in the total number of goods implies that for each one of them less and less labour is available for manufacturing. Eventually, R&D outlays, which are a fixed cost for each new good, can no longer be recovered through sales revenue unless labour is reallocated from the research sector to manufacturing, which slows the rate of innovation down.

Endogenous steady-state growth becomes feasible only when knowledge capital is assumed to be augmented by positive learning externalities from each innovation. It is necessary that knowledge capital, a public input into private R&D, accumulates over time, so that the productivity of private resources in R&D steadily increases, and the costs of innovation decline. Steady-state growth is then determined by two equations which represent labour market and capital market equilibrium (Helpman 1992: 93):

$$ag + X = L\,,$$

$$[14]\qquad \frac{(1-\alpha)X}{\alpha\, a} = \rho + g\left[1 + \frac{1-\alpha}{\alpha}(v-1)\right].$$

These steady-state conditions can be depicted graphically, as in Figure 1, whose axes are labelled g for the innovation rate and X for total manufacturing output. The first equation is represented by the downward sloping line *LL*: the economy's total labour has to be distributed between manufacturing and R&D laboratories at any point in time; raising the rate of innovation thus carries the opportunity cost of reducing manufacturing output. The second equation is represented by the upward sloping line *NN*, which Grossman and Helpman (1991) call the Schumpeter-line, because it highlights that innovation is driven by the profit motive. The 'Schumpeter-line' slopes upward because an increase in the rate of innovation raises the effective cost of capital to an entrepreneur by raising the real rate of interest and by accelerating depreciation of the firm's present value; higher costs of capital must be offset by a higher profit rate (i.e. a lower price-earnings ratio) which can be attained only through the expansion of manufacturing.

The two steady-state conditions can be solved to yield the explicit solution for the rate of innovation (Helpman 1992: 94):

$$[15]\qquad g = \frac{1}{\alpha + (1-\alpha)v}\left[(1-\alpha)\frac{L}{a} - \alpha\rho\right].$$

This solution makes clear that a positive rate of innovation cannot be taken for granted, it rather requires $L/a > \alpha\rho/(1-\alpha)$, i.e. that an economy's resource base (L/a) is *large* enough, that its degree of monopoly power $(1/\alpha)$ is *large* enough, and that the rate of time preference is *low* enough. If these conditions were not met, the *LL* line in Figure 1 would be closer to the origin and would not intersect the *NN* line in the first quadrant. Provided a positive rate of innovation obtains, its size is seen to be positively related to the economy's resource base, to its degree of monopoly power and to the intertemporal elasticity of substitution, but negatively related to the rate of time preference. The impact of changing these parameters on the economy's steady-state rate of innovation can be visualized in Figure 1, where the enlargement of the labour force (L) would be represented as an outward shift of the *LL* line, whereas an increase in the degree of monopoly power ($1/\alpha$), an increase in the intertemporal elasticity of substitution (v) and a reduction in the rate of time preference (ρ) would all be represented by a downward shift of the *NN* line.[18]

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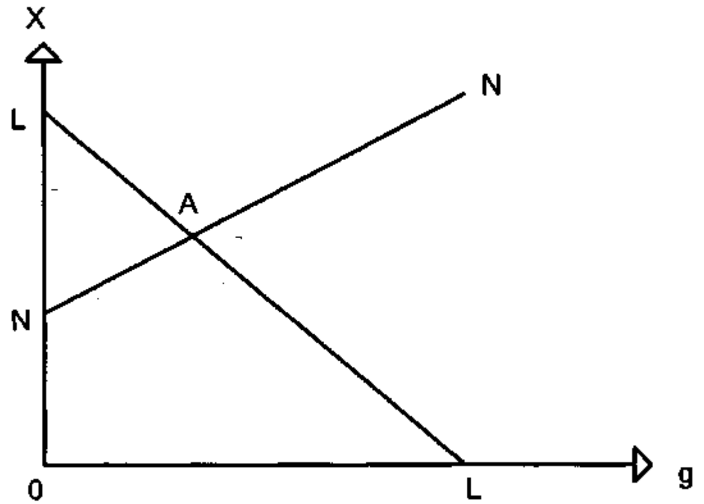
[18] Final output, which equals $Xn^{(1-\alpha)/\alpha}$, grows at the steady-state rate $g_D = g\,(1-\alpha)/\alpha$, which is always positively related to the rate of innovation, but

Figure 1 — Equilibrium Conditions in a Model of Endogenous Technological Progress



Note: X denotes manufacturing output, g the rate of innovation, LL the resource constraint, NN the capital market equilibrium; the steady-state equilibrium is at point A.

Source: Helpman (1992: 93).

Figure 1 can also be used to depict the steady-state equilibrium conditions in the model of quality ladders, whose reduced form in steady-state is very similar to the model of horizontal product differentiation. The rate of innovation in the quality ladder model is defined as the fraction of goods that are improved per unit of time. The resource constraint again implies a trade-off between the equilibrium rate of innovation and the volume of manufacturing, whereas capital market equilibrium again requires that a higher rate of innovation (implying higher R&D investments) be matched by a higher volume of output. And again, steady-state growth is feasible only when the cost of innovation is continually

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which may be lower or higher than the rate of innovation, depending on how large the elasticity of substitution between the differentiated goods actually is. A relatively small elasticity of substitution ($\alpha < 0.5$) would imply that the growth rate of final output is higher than the innovation rate, and vice versa. The reason seems to be that a very large preference for variety ($\alpha < 0.5$) places a higher premium on a large number of different goods per aggregate unit of consumption. Similar reasoning applies when the love-of-variety function is interpreted as explaining the productivity gains from using intermediates in final production.

reduced by knowledge spill-overs from current to future innovators (Grossman and Helpman 1991: Chapter 4).

The industrial policy analysis of the models must always keep four sources for a potential market failure in mind (cf. Grossman and Helpman 1991: 339): (i) Since the manufacturers of innovative products are in monopolistic competition or have transitory monopoly power, depending on model variants, they can keep prices above marginal costs of production. This distorts the allocation particularly in relation to 'traditional' industries, in which no significant innovation takes place and in which prices equal marginal costs.[19] (ii) Finite price elasticities of demand imply that most buyers' willingness to pay is higher than the market price. The introduction of a new good — be it for consumption or as an intermediate product — thus creates a buyer rent which is not taken into account by the manufacturer. (iii) At the same time, the introduction of a new good destroys part of the producer rent of other firms whose products lose market share or become completely obsolete. This again is left out of the innovator's decision calculus. (iv) Finally, also the positive technological externalities associated with the increase in generally available technical knowledge due to private innovations are not taken into account by the innovator.

The external effects of private research and development are on the one hand pecuniary or technological in nature, on the other hand positive or negative in their impact. Whether, on balance, the positive or the negative external effects are stronger, that is whether the private incentives are too small or too large, cannot be definitely decided on theoretical grounds alone. This follows from the distinct welfare implications of the two different prototype models of endogenous technical progress: the one which interprets the innovation process as a process of increasing horizontal product differentiation, and the other which sees it as a process of continuous vertical quality improvements with a stochastic success rate of research and development investments.[20]

For the model of product differentiation in consumer goods, Grossman and Helpman (1991: 82–83), can show that the increase in consumer rents and the loss in producer rents, which result from the introduction of a new product, are equal in size when the demand functions are derived from a representative consumer's utility function with constant elasticities of substitution (CES).[21]

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[19] But even if all industries innovate, the extent of monopoly power may vary between them. The volume of output will be too small in industries with particularly high deviations of price from marginal costs.

[20] This model originated in the work of Aghion and Howitt (1992).

[21] CES is the abbreviation for Constant Elasticity of Substitution. Consumers whose utility function possesses this characteristic respond to any change in the relative prices of two goods by always changing the quantities consumed in a certain proportion to the relative price change. In other words: the elasticity of substitution is

Hence, in this case, the desirability of an innovation depends only on the welfare effects of the increase in freely available technical knowledge and of a possible intersectoral distortion of relative prices. Considering the industry in which an innovation occurs in isolation, the incentives to innovate can thus be shown to be clearly too small in the case of horizontal product differentiation, assuming a CES utility function for the representative consumer. A subsidy for research and development seems reasonable.

In the model of rising product quality, however, the welfare analysis cannot be simplified by assuming a particular utility function. In this model, the incentives to innovate can be either too *small* or too *large*, even when disregarding intersectoral distortions. Whether the incentives are in fact too small or too large depends on how large the quality leap is which results from a certain volume of R&D investment. Grossman and Helpman (1991: 104–105) show that the market incentives are too large when the quality leap is very small *or* very large. If, on the other hand, it is of medium size, the market incentives to innovate are too small.[22] Economically, the possibility of excessive incentives for R&D arises because the individual firm does not take into account that successfully patenting a quality improvement for a particular product makes obsolete the competitors' R&D efforts aimed at improving the same type of product,[23] and shortens the life cycle of the previous product generation which is displaced by the innovation. In short, there is a 'business stealing' effect which places a burden on established firms (Aghion and Howitt 1992). For this reason, competition may turn into an inefficient patent race, in which each individual firm invests the more into its research and development for a particular product improvement, the greater the effort of its competitors. Provided the size

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independent of the consumer's income, the mix of goods consumed, and of relative prices before the price change.

[22] Formally, this contingency of the efficiency of the market incentives for research and development results from the fact that the present value of the loss in producer rents created by the introduction of a new product of higher quality is a linear function, while the present value of the increase in consumer rent (inclusive of the intertemporal transfer of knowledge) is a logarithmic function of the size of the quality leap (Grossman and Helpman 1991: 110–111). The quality leap λ is defined as the factor that measures how many times as many services the new generation of a product provides over the generation before it. The utility U of the representative consumer is in equilibrium affected by a marginal quality raising innovation according to: $dU(t)/dI = \log \lambda/\rho - \lambda/(L/a + \rho)$, where I is the number of quality improvements in a certain time interval, a a research input coefficient, L the labour force, and ρ the rate of time preference.

[23] By contrast, in the model of horizontal product differentiation, research and development investments can never become completely obsolete as a result of the development success of a competitor, because in these models each firm has a unique R&D objective and programme, so that there cannot be ex post obsolescence of research spending due to patent protection.

of the quality leaps is exogenously set, and cannot be changed by policy, the model of rising product quality calls for either a subsidy or a tax on R&D as a second-best industrial policy measure to influence the frequency of innovations in steady state.

However, when the size of the quality leaps is modelled as an endogenous parameter, it cannot be influenced by a tax or a subsidy, because in this case it depends on the characteristics of the research technology only. In the steady-state growth equilibrium of the model, the quality leaps are the smaller, the greater the elasticity of the resource requirement with respect to the size of any one quality leap (Grossman and Helpman 1991: 100).

The welfare analysis of Aghion and Howitt (1992: 342) reveals that the market forces on their own render the endogenous size of the quality leap too small.[24] In this case, patent legislation may be considered as a means to control the size of quality leaps. For example, patent law could fix a minimum novelty requirement for patent applications.[25]

III. Specialization and Growth in Open Economies

1. General Considerations and the Small-Country Model

Grossman and Helpman (1991) as well as Rivera-Batiz and Romer (1991a, 1991b) have elaborated and further developed the theory of endogenous technical progress to explain growth processes in open economies. In doing so, they built on the factor proportions theory of international trade originally developed by Heckscher (1919), Ohlin (1933) and Samuelson (1949). Comparative ad-

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[24] The reason seems to be that the private innovator, who neglects the displacement of the existing product vintage, maximizes the expected arrival rate of innovations times the quality leap λ, i.e. the factor by which product service is qualitatively improved, whereas the benevolent social planner would maximize the arrival rate multiplied by the net size $(\lambda - 1)$ of innovations. The innovator's revenue depends on customer's willingness to pay, and thus on the absolute quality of his new product, but social benefits accrue only from the quality gain relative to the established product generation.

[25] It is worth noting that the first-best policy to decentralize the choice of optimal innovation frequency by means of an R&D tax or subsidy presupposes that the problem of the optimal size of the quality leap has been solved. If this problem cannot be solved with the available instruments, the first-best choice of innovation frequency may no longer be appropriate, and a second-best rate of innovation should be implemented, which may be higher or lower than the first-best rate (Grossman and Helpman 1991: 109).

vantages, which determine the direction and size of international trade flows, are attributed to differences in countries' relative factor endowments, while the factor qualities are assumed equal across countries. In the new theory of *dynamic* comparative advantages, a country can change its relative factor endowments over time not only by investing in physical capital but also by accumulating human capital in the form of vocational or academic training.

A country which has above-average success in training qualified scientific personnel will, according to the theory, specialize in research and development and in the production and export of technology-intensive products in the long term.[26] If the external effects of knowledge creation, which continue to be a conditio sine qua non for positive steady-state growth, are internationally as effective as they are in their country of origin, differences in technological development between countries are ultimately irrelevant for resource allocation and trade flows; instead, these tend to reflect the relative endowments of a country with elementary factors of production, like land, labour, and human capital, especially in the form of scientific personnel.

This need not be so, however, if the external effects of new knowledge are only effective within their country of origin. In this case, as in the model of nationally bounded learning by doing, a country's development of trade, patterns of specialization, and rate of innovation and growth depend not only on resource endowments but also on historical leads or lags, which the country may have in individual industries with differing technological potential vis-à-vis its trade partners. Leads can then favour the accumulation of technical knowledge in certain fields, even though the country's true comparative advantages may not be in these fields.

If a country's government recognizes a certain industry as having a particularly promising potential, it may — under certain conditions — be successful in establishing a corresponding technological lead by adopting well-designed, strategically targeted industrial policies, at least within the framework of a consistent model of hysteresis[27] in trade and growth. With some luck, and

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[26] Grossman (1990a) takes this as an explanation for the spectacular growth and export performance of Japan after World War II.

[27] The term hysteresis is borrowed from physics, where it describes the phenomenon that temporary events can have permanent results. Hysteresis may be formally defined as a system's response to a transitory change in an exogenous or a control variable where one or several endogenous variables do not return to their initial value after the exogenous control variable has been switched back. In the theory of economic growth, hysteresis means that the growth path and long-term growth rate are not uniquely determined by the fundamental characteristics of an economy, but are also influenced by temporary historical events like, for example, temporary economic policy interventions. In this sense, dynamic processes in the economy are often said to be path-dependent. Strictly speaking, hysteresis makes sense only in a

at the expense of other countries, the intervening country may get onto a steeper path of innovation and growth. Although these industrial policy conclusions appear at first sight to be identical to those from multi-sectoral learning-by-doing models, the theory of endogenous technical progress in fact facilitates a much more detailed analysis of the comparative effectiveness of different industrial policy instruments than the theory of learning by doing.

A careful analysis of endogenous growth and specialization in open economies must distinguish a number of different cases: first, according to the traditional divide of trade theory between the small-country case and the case of two large countries; second, according to the degree of similarity of countries in terms of factor endowments; third, according to the intensity of competition between R&D and manufacturing for common resources; and fourth, according to the ease with which new technical knowledge and ideas flow across international borders relative to their mobility within countries.[28] These distinct cases cover much of the ground relevant to the analysis of the comparative merits and demerits of various industrial policy instruments that might be used in practice to influence a country's pattern of specialization and its rate of innovation and growth.

The small-country case is based on the assumption that world market prices and the world-wide rate of innovation and growth are all exogenous to the home country considered. This assumption is useful to study the impact of world market conditions on the incentives for innovation in the home country without worrying about any repercussions reallocations in the home country might have on resource allocation abroad.

Grossman and Helpman (1991: Chapter 6) have studied the equilibrium patterns of trade and growth in a small country which, initially in autarky, produces two tradeable consumption goods, using a non-tradeable intermediate product and either unskilled labour or human capital in the form of scientists and engineers as inputs. New intermediate inputs are continuously generated by an R&D sector using human capital of scientists and engineers as the only private input, yet with continuous reductions in the input requirement due to economy-wide knowledge spill-overs from other R&D laboratories (as described

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stochastic model of the process of equilibrium selection. Hysteresis presupposes random fluctuations and bifurcation, a point which will be discussed further in Section D.I below.

[28] Instead of treating the penetrability of international borders for knowledge as an exogenously fixed parameter, it could be analyzed as an endogenous or a policy variable. This would undermine some of the arguments in favour of targeted industrial and technology policies in open economies which rely on borders being barriers to communication. Ultimately, however, it remains an unresolved empirical question how far, and on what time scale, the transmission of knowledge and ideas across borders could actually be influenced by policies.

above). The R&D sector sells the intermediate inputs at monopoly prices to the two perfectly competitive consumption goods industries. To exhibit balanced steady-state growth, the model assumes that production of both consumption goods uses the intermediate inputs with the same intensity, for otherwise the relative size of the two industries would diverge until one of them vanishes in importance from the long-term equilibrium. Households maximize an intertemporal utility function, whose instantaneous utility is a non-decreasing, strictly quasi-concave, linear-homogeneous function of the two consumption goods.

The opening of international trade in consumption goods, but not in intermediate goods, changes the pattern of specialization and the rate of growth in this model. But exactly *how* international trade affects the home economy depends on how the pre-trade world market price ratio for the two consumption goods differs from the domestic price ratio in autarky equilibrium. The good which is relatively more expensive in the world market will become the export good of the small country, so that the corresponding industry expands, while the other industry shrinks as relatively cheap imports capture part of its domestic market. Factor price changes and resource reallocations ensue according to the Stolper-Samuelson theorem familiar from traditional trade theory: A rise in the relative price of the labour-intensive consumption good causes the relative reward to human capital to decline; but this reduces the cost of R&D so that the rate of innovation and growth increase. Conversely, a rise in the price of the human-capital-intensive consumption good raises the relative reward to human capital so that the cost of R&D increases, and the rate of innovation and growth declines; in this case the export sector expands at the expense of the R&D sector.

The analysis of the small economy would be more complicated if production of the two consumption goods used the non-traded intermediate goods with different intensities. In this case, expansion of one consumption good industry for export would not only affect the relative reward to human capital but also the price of intermediates. The profitability of R&D would therefore be increased twofold if international trade benefited an industry which makes intensive use of intermediates, but relatively little use of human capital; in this situation, the price of intermediates would be raised and the reward to human capital reduced so that innovation and growth would accelerate. On the other hand, the effects of international trade via the price of intermediates and via the rewards to human capital would tend to offset each other whenever the more human-capital-intensive industry makes more intensive use of intermediate inputs as well.

Further growth effects may be generated by the international integration of capital markets (Grossman and Helpman 1991: 162–165). After the external liberalization of a small country's domestic capital market, its interest rate will be fully determined by the prevailing world market rate of interest. The liberalization of capital flows will tend to accelerate growth only if the domestic interest rate has been higher than the world market rate prior to capital market integration. In the reverse case, when a small country has enjoyed a lower rate of interest, possibly due to a lower rate of time preference of domestic consumers, the liberalization of capital flows will raise the domestic rate of interest and will tend to reduce growth, because domestic investors will withdraw some of their funds from domestic R&D and will invest these in the international capital market instead.

A third mechanism by which the integration of a small economy into world markets may affect the domestic rate of innovation and growth is through international flows of technical knowledge. This mechanism would, according to the model, raise the productivity of human capital in the domestic R&D laboratories by making more technical knowledge available as a public R&D input. To analyze this possibility, Grossman and Helpman (1991: 165–170), assume that the size of such knowledge flows is directly, and proportionally, related to the size of international trade flows. They justify this assumption with the observation that technical knowledge is usually transmitted through personal contacts between individuals and that many such contacts are facilitated through trade in goods.

In such a model, the rate of innovation and growth in the small country is affected by the direct impact of international knowledge spill-overs on R&D productivity as well as by the indirect impact via the reallocation of human capital between the R&D sector and manufacturing. The overall impact of trade on growth therefore depends on prevailing circumstances, in particular on whether the small country would have a comparative advantage in human-capital-intensive manufacturing after the liberalization of trade. That the rate of innovation and growth would be lower without trade can unambiguously be said only for a country which imports human-capital-intensive goods in free-trade equilibrium; this country would in autarky withdraw human capital from the R&D sector to manufacture substitutes for the otherwise imported consumption goods.

This part of the analysis has assumed that the rate of innovation, expanding the variety of intermediate goods, equals the growth rate of the trade volume in the steady-state equilibrium. This, however, need not be the case. If the trade volume, instead, grows more slowly, the relative importance of international knowledge spill-overs will tend to decrease over time relative to knowledge spill-overs emanating from national R&D activities. Then, the international knowledge spill-overs will have no impact on the domestic rate of innovation and growth in the long term. On the other hand, if the trade volume grows faster than the number of intermediate inputs expands, the relative importance of international knowledge spill-overs may increase, and productivity in the domestic R&D laboratories might theoretically increase without bound. As the domestic rate of innovation and growth would accelerate, the small country would sooner or later begin to have an impact on patterns of specialization and growth abroad; the model of a small country would therefore cease to be applicable to such a situation of unbounded growth (Grossman and Helpman 1991: 169).

2. Two-Country Models of Endogenous Growth

The situation of a large country is better understood within a two-country trade model. Two-country models with endogenous growth are particularly useful for analyzing the distinct trade and growth implications of comparative advantages due to factor endowments versus economies of scale due to market integration. Moreover, compared with the small-country model, two-country models provide a more satisfactory and more policy-relevant analysis of the role of international knowledge spill-overs in endogenous specialization and growth. Related approaches, which nevertheless feature some important differences, have been pursued by Grossman and Helpman (1991) on the one hand and by Rivera-Batiz and Romer (1991a, 1991b) on the other.

Grossman and Helpman (1991: Chapter 7) seek to emphasize the implications of comparative advantages due to differential factor endowments, and therefore assume two manufacturing sectors with distinct input requirements as well as an R&D sector, which uses human capital to generate blueprints for new varieties of a high-technology good. In contrast to the small country case, the two consumer goods industries are now distinguished not only by the intensity with which they use the primary inputs unskilled labour and human capital (embodied in scientists and engineers) but also by the opportunities they afford for technological progress: One industry produces traditional goods using only unskilled labour and human capital according to a constant-returns-to-scale technology. The other industry also uses a constant-returns-to-scale technology to turn blueprints from the R&D sector into high-tech goods, which generate utility either according to the love-of-variety function of Dixit and Stiglitz (1977) or according to the quality ladder model.

It is initially assumed that due to communication problems the blueprints for new high-tech goods can be used only in their country of origin. It is further assumed that the three activities can be ranked according to the intensity with which they use human capital: This intensity is highest in R&D, still high in high-tech manufacturing and lowest in the traditional goods industry, which makes the most intensive use of unskilled labour. The analysis proceeds by applying the factor proportions theorem of comparative advantage due to Heckscher (1919) and Ohlin (1933) to the case of open economies in a dynamic setting. The result of this exercise is a dynamic theory of comparative advantages, which can explain the evolution of comparative advantages over time on the basis of country-specific technological developments. The new theory of dynamic comparative advantages thereby yields important *new* insights which could not be obtained from any static theory of international trade.

Grossman and Helpman (1991) can show, disregarding the theoretical possibility of factor intensity reversals, that the two-country model implies the equalization of factor prices if both trading economies are incompletely specialized in steady-state equilibrium. This implies further that both countries are active in all three activities, i.e. in R&D and both manufacturing industries. Since the private costs of doing R&D are the same in both countries, they will both generate blueprints for new high-tech goods at the same rate, but the country with the relatively greater endowment of human capital will at any point in time make a greater relative volume of high-tech goods because this country will devote relatively more human capital to R&D.

In the case of horizontal product differentiation, this pattern of specialization implies that the equilibrium entails interindustry trade in high-tech goods since preferences are such that households in both countries devote constant budget shares to each type of good. The more human-capital-rich country generates relatively more blueprints, has a relatively larger high-tech industry and thus is a net exporter of high-tech goods. Under the assumption of no international trade in financial assets, the more labour-intensive country must balance its trade deficit in high-tech goods by a corresponding surplus in the trade with traditional goods.[29] Although the rates of innovation are equal in the two countries, real rates of growth, a weighted average of sectoral rates of productivity growth in the two manufacturing industries, will be higher in the human-capital-rich country where a larger share of value added is generated in the high-tech industry. Nevertheless, both countries' real consumption possibilities grow at the same rate, because all consumers have access to the same set of goods, and long-term interest rates are equalized.

Such an equilibrium with full equalization of factor prices, however, is only feasible when countries' resource endowments do not differ too much. Other-

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[29] If there is international trade in financial assets, countries need to balance only the present value of their trade flows. It is then a possibility even in steady state that one country runs a deficit on trade account balanced by a surplus on service account. In accordance with the spirit of Heckscher-Ohlin theory, a country's trade deficit will be larger in the industry where this country has a comparative disadvantage due to its relative factor endowments (Grossman and Helpman 1991: 188).

wise, at least one of the two countries will lose at least one of the three activities in steady-sate equilibrium. The human-capital-rich country may become uncompetitive in the traditional industry, the labour-rich country in the R&D sector; or one country may even lose two activities which are not at the extreme end of the ranking in terms of factor intensity corresponding to the country's own ranking in terms of relative factor endowments. In such equilibria without factor price equalization, there may be incentives for innovators in the human-capital-rich country to locate part of the production of high-tech goods in the labour-intensive country. These incentives may result from cost considerations in the case where innovation expands the variety of horizontally differentiated products, or they may result from the quest to evade the higher competitive pressure which prevails in the market of the human-capital-rich country for innovations in the quality ladder case (Grossman and Helpman 1991: 192–196). In some of these cases, where there is an incentive to export or import R&D services, multinational companies may contribute to the equalization of factor prices by responding to these incentives. The human-capital-rich country may then have a permanent trade deficit balanced by a surplus in services.[30]

The upshot of the preceding two-country analysis is that a national advantage in R&D can only be due to differences in factor costs, which may ultimately be explained by different factor endowments of the two countries, provided that all knowledge spill-overs from innovative activities augment a stock of technical knowledge that is available world-wide as a public input for private R&D. By contrast, if technical knowledge diffuses only within its country of origin, patterns of specialization and the rates of innovation and growth in each country will depend not only on factor endowments but also on relative country size and on historical starting conditions, in particular on technological leads or lags which an individual country may possess. This implies that a country which has come to lag in technology will continue to do so and may experience a lower rate of innovation than the leading country; the steady-state equilibrium may well be characterized by concentration of all R&D in one country, and usually in that one which inherited a technological lead or a bigger R&D sector to begin with.[31]

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[30] As an alternative to direct foreign investments, international licences may be used to transfer new technology provided the licence contracts are internationally enforceable (Grossman and Helpman 1991: 200–204).

[31] Grossman and Helpman (1991: Chapter 8) restrict their analysis of national knowledge diffusion to the case where the two countries have identical factor endowments and differ only in size and in accumulated research experience. This case is useful to highlight the possibility of multiple steady-state equilibria and the role of history in determining outcomes, yet it neglects the *interaction* between comparative advantage and dynamic learning externalities bounded to their country of origin.

However, such a model with nationally bounded learning by doing from R&D entails the possibility that the government of a lagging country may alter the national pattern of specialization by subsidizing domestic R&D, which would put the domestic economy on a faster growth path. These models therefore formalize the theoretical possibility that subsidies, which may need to be applied only temporarily, can have *permanent* effects — a possibility which can be considered a case of policy hysteresis.

The economic reason that temporary R&D subsidies may turn a lagging country into a technology leader is that the future costs of doing R&D in this country will be reduced by the build-up of a sufficiently large national stock of technical knowledge. In this way, targeted industrial and technology policy may help a country to acquire a locational advantage for R&D even though relative factor endowments on their own would render R&D in this country more costly than abroad. As an important caveat, Grossman and Helpman (1991: 232) note that success in raising a country's rate of innovation and growth does not necessarily imply that such a policy also raises national welfare. Normally, they argue, national welfare will be reduced because a larger share of world-wide R&D is then done in the country which is less efficient in this activity, because the world-wide rate of growth may thus fall and because the intervening country has to bear the direct costs of the subsidy.

Nevertheless, there are circumstances in which national welfare may be raised by temporary R&D subsidies, strategically designed to push domestic R&D at the expense of foreign R&D. So in particular if factor prices do not equalize in free-trade equilibrium and if wages are higher in the country specializing in R&D, or if returns to domestic investments can be raised by subsidizing domestic R&D because capital is not fully mobile across national borders (Grossman and Helpman 1991: 233).

While this discussion of the two-country model has emphasized the role of international knowledge spill-overs in determining patterns of specialization and growth in models in which knowledge spill-overs from innovation are essential for endogenous steady-state growth, it is important to keep in mind that there are alternative specifications of endogenous growth which do not rely on positive *technological* externalities to sustain growth. Romer (1987) has shown in his model of monopolistic competition and increasing specialization in capital inputs that models of ongoing profit-driven innovation can in fact dispense with external learning by doing in private R&D. Rivera-Batiz and Romer (1991a) use a similar model to demonstrate that international economic integration can speed up growth in all countries even when neither R&D nor manufacturing benefit in any way from external knowledge spill-overs. In this model, called the lab equipment specification of R&D, both R&D and manufacturing share the same technology and use the same inputs, including endogenously created varieties of differentiated capital goods. International trade of these goods is then sufficient to generate welfare gains through faster growth because it permits a better exploitation of the increasing returns to scale which are associated with the fixed cost of designing a new capital good.

IV. The Role of Targeted Industrial and Technology Policies in the Models

While targeted industrial and technology policies should ideally aim at enhancing welfare world-wide, or at least the welfare in the country whose government takes the initiative to intervene, such policies are in practice often aimed at merely raising the rate of innovation and growth in a particular industry. It is clear from the preceding discussion of endogenous growth models that raising welfare and raising innovation and growth are in fact two distinct objectives, which may even be in conflict under actual circumstances.

With regard to welfare, it is important to acknowledge that models of endogenous technological change generally feature more than one distortion from efficient resource allocation. This is important because an efficient intervention requires at least as many instruments as there are policy targets, i.e. market failures, which has been known since Tinbergen (1956). For example, in each innovating industry, which generates productivity growth in final production by continuously introducing new intermediate goods, there is a *static* distortion due to monopoly pricing of the new capital inputs and a potential *dynamic* distortion due to the imbalance of customer surplus, profit destruction and intertemporal spill-over effects that emanate from each innovation.[32]

Open economies with nationally restricted spill-overs from R&D may have an additional source of inefficiency because the world's R&D activities may, for historical reasons, be concentrated in a country which does not have the most appropriate mix of factor endowments. While this would constitute an inefficiency from a world-wide point of view, it may well be in the partial interest of the country which benefits from being the preferred location for R&D. Conversely, a national government may be justified to view any outcome of hysteresis in the dynamics of specialization as suboptimal in which its own country has little or no R&D — even if that is in accordance with the home country being relatively poorly endowed with human capital. In a world without inter-

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[32] In addition, multi-sectoral economies typically have also intersectoral distortions because the degree of monopoly power may vary from industry to industry.

national policy coordination and without the possibility of sharing welfare gains among all countries, an individual country may indeed see a potential for intervention to increase national welfare at the expense of other countries if there are multiple equilibria with different welfare implications for different countries.

When a particular steady-state equilibrium has been recognized to be affected by more than one type of market failure, policy making needs to search for an at least equal number of policy instruments, and must solve the assignment problem how to allocate these instruments to the various market failures. This assignment involves both the selection of specific instruments for specific targets and the dosing of each instrument; it is usually an interdependent problem in the sense that additions of a new instrument or marginal adjustments of an already used instrument require re-adjustments of other instruments. In particular, the assignment may become a problem of the second best[33] if policy lacks an instrument that would be needed for a first-best solution, or if an essential instrument cannot be appropriately dosed.

In the model of horizontal product differentiation, it is clear that the dynamic inefficiency due to the intertemporal knowledge spill-over (assuming that consumer surplus generation and profit destruction of each innovation cancel each other out in equilibrium) can be appropriately addressed by a subsidy to R&D. The static inefficiency due to monopoly pricing of intermediates would require a second instrument, e.g. a subsidy to the purchasers of these intermediate inputs for final production, so that the user cost of intermediates are equated with the marginal cost of producing them (Grossman and Helpman 1991: 157–158).

But this assignment would often be too simple in the model of innovation which raises the quality of intermediates. As seen above, such a quality ladder may, in addition to instruments targeted at the frequency of innovation, require the fine tuning of parameters of patent protection, such as novelty requirements. This is because in quality ladders, deviations from dynamic optimality may take the form of too small a size of the equilibrium quality leap as well as the form of too high or too low a frequency of innovations. These two problems are ideally solved simultaneously by adopting two separate instruments, including appropriate novelty requirements for patent protection and either an R&D tax or an R&D subsidy. Given that the first-best solution to patent law may often not

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[33] The theory of the second best, first formalized by Lipsey and Lancaster (1956), states that one can often not argue that removing some distortions (which are in conflict with the marginal conditions of Pareto optimality) will move the economy closer to a Pareto-optimal allocation if other distortions are present. It follows that it may be inefficient to use policy rules derived from a hypothetical first-best solution if some distortions can in fact not be corrected with the instruments available.

be found in practice,[34] the choice of innovation frequency has to be reconsidered for the size of the quality leap as determined by the market. The second-best R&D tax or R&D subsidy will generally differ quantitatively and may even reverse the first-best policy choice qualitatively.

Grossman and Helpman (1991: 158–159), also discuss the case of endogenous innovation where the government cannot implement the first-best subsidy on the use of intermediate inputs in final production.[35] Their model of a small open economy has the feature that the first and second-best rates of innovations coincide in this situation. Then, the second-best R&D policy ought to encourage R&D if the market rate falls short of the first-best rate of innovation, and discourage R&D when the market rate exceeds the first-best rate, but the second-best R&D policy would need a different dosage than the first-best policy. This implies that the second-best R&D policy qualitatively remains a subsidy in the model of expanding variety, but that the second-best R&D policy in the quality ladder model may for some parameter values reverse a first-best tax on R&D into a subsidy.[36]

When the analysis of targeted industrial and technology policy turns to the two-country model, it has to cope with even more endogenous parameters, which can make the comparison between different assignments of instruments to specific distortions quite complicated. Part of these complications arise because the governments of similarly endowed countries may get into conflict over certain high-tech industries thought to have a supernormal growth potential. Interaction between these governments may then turn into a strategic game with uncertain outcome. Although such strategic interaction may be an important part of reality, it remains useful to analyze policy instruments initially as if strategic interaction was absent.

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[34] It would only be in a world where steady-state growth was a reality that one could hope to find the appropriate parameters for patent law. In the real world, by contrast, it is more than doubtful that the appropriate novelty for ever new and unexpected inventions could be determined *ex ante*.

[35] The reason for this inability may simply be that users cannot be identified empirically without excessive information cost.

[36] Recall that quality ladders in isolation may call either for a tax on R&D if the market rate of innovation is too high, or for a subsidy if the rate is too low, disregarding here the problem of optimal size of the quality leap of innovation. When subsidies are granted to the users of quality-improved intermediates, to alleviate the static distortion of monopoly pricing, this may operate like a subsidy for R&D at the same time. But this subsidy may be too large if the market rate of innovation is only slightly below the optimal rate, so that a tax on R&D is needed merely to correct the unwanted side effects of compensating for the static inefficiency of monopoly pricing.

Some of the most important policy instruments to consider are output subsidies, trade restrictions and R&D subsidies. The general equilibrium analysis of Grossman and Helpman (1991) reveals that subsidies for the output of a high-technology industry generally miss the aim of raising a country's rate of innovation and growth if expansion of production in the high-technology sector requires additional highly qualified engineering personnel, much of which would have to be removed from research and development. Consequently, while the innovation rate in the home country may decrease, once output subsidies take effect in such a model of resource competition between innovation and manufacturing, the rate of innovation may even increase abroad where a shrinking production sector releases scarce qualified personnel, which then becomes available for research. Similarly, the growth effect of tariffs, meant to protect high-technology industries, can also be counterproductive for the home country (Grossman and Helpman 1991: 275–276). The net growth effect here again depends on whether factor price changes due to the introduction of export subsidies or import tariffs tend to increase or decrease the cost of R&D in the home economy.

In two-country models, it can be shown that measures which raise the rewards to scarce human capital, embodied in scientific personnel and used intensively in research and development, tend to reduce R&D activities at home, but may encourage the opposite development abroad. It is for this reason that growth, let alone a country's welfare, may be harmed by targeted support for high-tech industries, which make more intensive use than traditional industries of the kind of human capital, i.e. scientists and engineers, that is also used intensively in R&D. The general equilibrium analysis of two-country models suggests that a country which imports more high-technology products than it exports may indeed reduce its own innovative activities by adopting trade policy measures for the protection of its own high-tech manufacturing, but may indirectly contribute to an increase in the world-wide rate of innovation while the same trade policy may lead to a reduction of the world-wide rate of innovation, if it is carried out by a net-exporter of technology-intensive products.

However, the world-wide rate of innovation and growth can be increased as a consequence of a country's protectionist measures only if the economies involved are sufficiently distinct in terms of their factor endowments, or else work with very different technologies, so that the introduction of trade barriers sets in motion a considerable intersectoral resource reallocation. Rivera-Batiz and Romer (1991b) show within a model similar to the Grossman-Helpman model that symmetrical trade restrictions between trading partners, symmetrically endowed with factors of production and technological potential (which may apply to the United States, Japan and the European Union), necessarily reduce the world-wide rate of innovation and growth.

Rivera-Batiz and Romer (1991b) develop a method of separately analyzing three different effects of trade restrictions on the world-wide rate of growth: they use the term *allocation effect* to describe the resource reallocation which results from the introduction of trade restrictions, in particular the reallocation of human capital embodied in scientists and engineers between research and development on the one hand and high-tech production on the other hand. They use the term *integration effect* to describe the reduced scope for exploiting increasing returns to scale, which are a consequence of positive external effects at the level of individual industries. Finally, they use the term *redundancy effect* to describe productivity losses in R&D, which are to be expected when the mutual fertilization of research efforts by ideas from different countries is diminished as a consequence of a reduced international exchange of goods and services. While the integration and redundancy effects of trade restrictions are always negative, the theory does not make a general prediction on the direction of the allocation effect. Rivera-Batiz and Romer (1991b) argue that the allocation effects of trade restrictions will be small in the case of trade partners which are similarly endowed with factors of production and whose production technologies are not very distinct from each other, and that therefore the allocation effect will almost always be dominated by the integration and redundancy effects.

Thus, the main reasons for adverse growth effects of trade barriers appear to be the reduced scope for exploiting increasing returns to scale in the application of new technical knowledge, which is non-rival, and in the waste of resources used in redundant research efforts: When trade is restricted some of the new capital inputs may be developed twice, once in each country, and each new good will generally find fewer buyers so that R&D is less profitable for private investors in fragmented markets.[37]

Finally, the most promising instrument of industrial policy intervention in open economies is the massive subsidization of research and development in the industry recognized as having the greatest productivity growth potential. Under the assumption that the diffusion of new technical knowledge is limited to its country of origin, and provided foreign countries do not react, the subsidization[38] of R&D need only be temporary to establish a *permanent* tech-

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[37] One must caution that these conclusion for the rate of innovation and growth may not necessarily be warranted in the case of quality ladders. While trade restrictions indeed reduce the size of monopoly rents that reward successful innovators, they also reduce competition which tends to reduce the monopolistic price mark-up for a given market size, offsetting the previous effect.

[38] The case for subsidies versus tariffs, given a certain level of support has been decided, was convincingly argued by Baldwin (1969). And this case is particularly strong with respect to R&D whenever there is an unambiguous presumption of underinvestment because of positive external effects, as in the prototype model of expanding variety.

nological lead for the home industry — a lead which may indeed accelerate the endogenous rate of innovation and productivity growth in the home economy.

Nevertheless, it remains questionable whether the intervening country is really helped by this policy, because research in the supported industry is now carried out to a larger extent in a country that is less efficient in this activity because of its relative factor endowments. The world-wide rate of innovation in this industry may thus fall. And the intervening country will in any case have to carry the direct cost of the subsidy, yet will never reap more than a fraction of any potential benefits (Grossman and Helpman 1991: 232). However, as noted above, there is a possibility for national welfare gains from temporary R&D subsidies if the free trade equilibrium does not imply the international equalization of factor prices *and* if the free trade wages are higher in the country in which research and development of the most promising industry is concentrated, *or* if financial capital is not completely mobile internationally. The reason for this possibility is that government support for R&D can in these cases raise wages or the returns to private R&D investments, respectively.

Thus, the theory of endogenous technical progress can help to justify targeted industrial policies only in those cases in which trade partners clearly differ with regard to factor endowments or industrial production technologies and in which positive external effects of R&D accrue overwhelmingly within their respective countries of origin, because the diffusion of new technical knowledge is nationally bounded.[39] In these well-defined cases, then, the most suitable measures are subsidies for R&D activities in the most promising growth industries. Strategic counter-measures of foreign countries can, however, undermine the intended positive growth effect or even reverse it.[40]

In view of this danger, two measures *outside* of industrial policies appear particularly advantageous in the light of the theory of endogenous technical progress: First, the liberalization of international capital movements gives private individuals the opportunity to invest their savings in whatever home or foreign company they expect to yield the highest returns in the future. Second, investments in education, which improve individual incentives for the accumulation of human capital and thus tend to increase a country's attractiveness

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[39] It may also suffice that there is a notable diffusion lag for technical information across international borders, perhaps due to language problems and due to the lower intensity of personal contacts.

[40] To avoid confusion on this point, notice that strategic interaction cannot by itself be a persuasive argument against selectively targeted industrial or strategic technology policies. For if it was, for the sake of consistency, one should also warn private firms in oligopolistic markets with strategic interaction never to take the initiative, but always to remain passive until there comes an opportunity to *react* to someone else's 'foolish' first move.

as a site for R&D activities by gradually changing its relative factor endowments, always strengthen economic growth in the long term (Grossman 1990a). Investments in education can also help to make the relative factor endowments of technologically lagging countries more similar to the world's technology leader. And this makes it more likely that steady-state equilibrium with free trade implies international factor price equalization, in which case the real *consumption possibilities* grow at the same long-term rate in all countries,[41] although the real growth rate of production may be higher in those countries that are more abundantly endowed with human capital and thus 'naturally' specialize more strongly in high-technology sectors.

V. Empirical Studies of the Returns to Innovation, Patterns of Specialization, and Economic Growth

To assess the reliability of industrial policy recommendations based on insights of new growth theory, it is important to check whether this theory stands up to a thorough empirical examination of its hypotheses. Since new growth theory is only a few years old, not too much empirical work has yet been done to test the relevant hypotheses; moreover, the methodology of some of the existing studies has been criticized. The efforts have mainly concentrated on three issues: (i) the *convergence* of the growth rates of different countries over time; (ii) the existence, direction and strength of external effects and knowledge *spill-overs* from R&D activities; and (iii) a possible acceleration of the *international diffusion of new technical knowledge* due to the greater speed of new communication technologies and due to the increasing significance of multi-national companies in international economic transactions.

1. Convergence

Many studies have attempted to test the hypothesis of the convergence of growth rates of different countries, which is derived from the neoclassical growth theory

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[41] This conclusion may rest on the assumption which Grossman and Helpman (1991) make about preferences, namely that constant budget shares are allocated to traditional and high-tech goods and that the elasticitiy of substitution between any pair of high-tech goods is always greater than one. These assumptions effectively exclude the possibility of immiserizing growth (cf. the discussion of the small-country model of Lucas (1988) in Section B.II.1).

of Solow (1956). In essence, it claims that countries with a relatively small per capita capital stock in some base year subsequently grow faster than countries which had a larger per capita capital stock in the base year. Many economists believe that data on such a convergence of international growth rates can help to discriminate empirically between the Solovian growth model and the competing models of the new growth theory, because many of these allegedly contradict the hypothesis of convergence and instead suggest the hypothesis of a random walk[42] or of divergence of per capita income of different countries.[43]

But a random walk is really an implication only of stochastic versions of linear models, e.g. the AK-model of Rebelo (1991), a point noted also by Romer (1989: 105). And some endogenous growth models can be formulated so as to accommodate periods of (incomplete) convergence that may lead to partial and not to full equalization of growth rates in initially unequally endowed countries (Jones and Manuelli 1990); other endogenous growth models have multiple equilibria and may thus imply *local* convergence.[44]

While these caveats should caution the claim that empirical convergence studies are testing new versus old growth theory, there are also a number of conceptual traps in interpreting them as an application of old Solovian growth theory. For example, a careful empirical examination of the convergence question requires that the hypothesis must not be formulated in terms of *absolute* convergence, but in terms of *conditional* convergence, taking into account the supposedly exogenous determinants of the different long-term relative per capita income positions of different countries.

Some of the more careful empirical examinations, such as those Barro and Sala-i-Martin (1992a) carried out for Europe and the United States and Mankiw et al. (1992) for a larger group of countries, which take into account a country's

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[42] A time series of data is described as a random walk when, given the current observation, values of this series realized in the past do not help to predict future realizations. A typical example is $y_t = y_{t-1} + \varepsilon_t$ where ε_t is assumed to be a zero-mean stationary process. Because the coefficient on y_{t-1} equals one, empirical tests of the random walk hypothesis are commonly called unit root tests.

[43] For a critical discussion see Amable et al. (1994). They argue that unit roots in discrete processes and hysteresis are two distinct phenomena. Whereas unit roots point to a continuum of equilibria, implying permanence of exogenous shocks, hysteresis is strongly related to bifurcations. Bifurcations, however, occur when there is local instability only at certain critical values of the control parameter, but robustness of the model for values far from the critical ones. Hysteresis thus typically implies the shifting of mean values in an otherwise fairly stationary process, permanence only of exogenous shocks which lead to fluctuations around the control parameter's critical value. Compare for the more detailed discussion of this issue in Section E.I.1.

[44] The hypothesis of local convergence is supported by recent empirical studies of Ben-David (1994) and Durlauf and Johnson (1992).

investment quota as the crucial determinant of its long-term per capita income, cannot reject the hypothesis of *conditional* convergence. With reference to an 'augmented' Solow model, these studies claim to explain about 80 per cent of the observed international variation in per capita income.

These studies estimate not only the contribution of physical capital accumulation but also the contribution of the accumulation of human capital to the observed growth in labour productivity, and thus refer to an 'augmented' Solow-model. The results suggest that human capital accumulated in schools and in vocational training is at least as important for growth as the accumulation of physical capital. Both forms of capital together have an estimated partial elasticity of production of 66 up to 80 per cent, which is indeed considerable, yet still clearly below one, the value assumed by new growth theory for the sum of the partial production elasticities of all accumulating factors.[45]

Once more, however, the new growth theory cannot thus be considered rejected because as a test of old versus new growth theory the convergence regressions suffer from a number of conceptual and methodological shortcomings: *First*, the regression equation is derived from a linear approximation around the steady state, whereas the dynamics far from the steady state may be non-linear even in simple growth models. *Second*, collapsing the growth dynamics over several decades into a cross-section of countries may be grossly misleading if the observation period is marked by structural breaks, like the oil shock of the 1970s. Such structural breaks may indeed put the notion of timeless steady states seriously in doubt.

Third, conditioning on country characteristics can conceal that countries may actually be moving towards different, and possibly diverging, steady states. *Fourth*, the existence of transitory adjustment processes to a long-term growth path, which would be consistent with a hypothesis of temporary but ultimately incomplete convergence of international per capita income, is in fact compatible with some models of the new growth theory. It may even be compatible with multi-sectoral models in which the condition for endogenous growth — non-decreasing average returns to investment — is fulfilled only in some of the industries of an economy (Rebelo 1991; Mulligan and Sala-i-Martin 1993).

Notwithstanding these potential fallacies, attempts have been made to apply the methodology of convergence regression at the level of individual industries. Dollar and Wolff (1993: Chapter 4) have used regression analysis to test for total factor productivity convergence at the level of twelve manufacturing in-

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[45] Levine and Renelt (1992) give an excellent overview of empirical cross-country growth studies.

dustries in thirteen OECD countries[46] for the period 1963–1983. They find what they call the catch-up hypothesis confirmed: Their results indicate a highly significant *inverse* relation between the rate of total factor productivity convergence and the corresponding initial level of total factor productivity for data disaggregated by industry and country — relative to the United States. They also use the regression to test, as a second hypothesis, the embodiment or vintage effect, which would imply positive interactions between capital accumulation and technological advance in an industry located in a particular country, but find evidence for this only for the years prior to 1973.[47]

This analysis of total factor productivity convergence is part of Dollar and Wolff's more general quest for the sources of aggregate labour productivity convergence among the advanced industrialized countries. They argue that international trade has played a crucial role in the convergence process, having been accompanied by increasing specialization rather than by a trend towards greater similarity in trade patterns since the mid-1970s. But this increasing specialization has apparently not been of the mercantilist kind where some countries succeed at the expense of others in moving their employment mix towards the industries with the highest value added per employee. Instead, different countries seem to have chosen different industries for their main investment in new technology. Dollar and Wolff (1993) take this as the main explanation why labour and total factor productivity have continued to converge in the aggregate after 1973, although their convergence within individual industries seems to have slowed down, and even to have ceased in the case of total factor productivity.

These findings underscore the need for the kind of disaggregated empirical work to be reported in the subsequent chapters of the present study. Noteworthy is in particular that dispersion among countries of labour and total factor pro-

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[46] The industries are: basic metals, metal products, chemicals, minerals, machinery, transport equipment, electricals, food (including beverages and tobacco), textiles (including clothing, footwear and leather goods), paper and printing, rubber and plastics, wood products, other manufacturing. The countries are: Australia, Belgium, Canada, Denmark, Finland, France, West Germany, Italy, Japan, the Netherlands, Norway, Sweden and the United Kingdom. Dollar and Wolff (1993) have run their regression twice, on two different data sets. One of these, from the OECD, covers the period 1970–1985, but excludes transport equipment as well as rubber and plastics. The other data set, compiled by Dollar and Wolff from various sources, covers the period 1963–1983, but excludes the Scandinavian countries, Belgium and Australia.

[47] The absence of a positive correlation after the mid-1970s, however, is not surprising given that the measure of total factor productivity, which Dollar and Wolff (1993) have computed for individual industries, shows convergence to the United States reference level primarily up to the mid-1970s, and little or no convergence since then. But convergence in capital intensity (per worker) seems to have continued.

ductivity measures is generally greater within industries than in the aggregate. Dollar and Wolff (1993: 63) point out that this finding is difficult to reconcile with the traditional neoclassical trade theory of Heckscher, Ohlin and Samuelson. As Deardorff (1984) has shown, labour productivity differences at the industry level are implied by Heckscher-Ohlin trade theory only if there is *no* factor price equalization in equilibrium. But in this case, a relatively capital-rich country should have a *higher* capital-labour ratio and a *higher* labour productivity in *every* industry; and vice versa for a relatively labour-rich country.

Dollar and Wolff seem to think that since general technological capabilities have converged, as a result of international technology diffusion, individual countries have begun to develop idiosyncratic technological leads in different industries — in line with the new theories of endogenous technological innovation, economies of scale and learning by doing in R&D. They also suggest that these emerging technology leads and lags at the industry level are now a more important explanation of comparative advantage among industrialized countries than differences in the cost of labour or capital.[48]

2. R&D Spill-Overs

A number of recent studies have looked for detailed empirical evidence of static and dynamic external effects. In this context, the major questions are whether the external effects are specific to individual industries or equally effective across all industries, whether they are limited in range to their respective region or nation of origin, or whether they are equally effective across national borders, and finally, whether they are sufficiently strong to justify the assumption of increasing returns to scale at the aggregate level of entire industries or even economies.

A good example is the recent study by Irwin and Klenow (1994) who find on the basis of quarterly firm level data from the semiconductor industry (dynamic random access memory semiconductors, to be precise) for the period 1974–1992 that there have been significant learning rates, but relatively small intergenerational spill-overs, and importantly, that learning spill-overs seem to have benefited firms in other countries just as much as firms in the country of spill-

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[48] In fact, Dollar and Wolff (1993: Chapter 3) report strong convergence of real wages for individual industries as well as for total manufacturing among the sample countries and some convergence of profit rates within industries among countries. They conclude (Dollar and Wolff 1993: 134) that unit cost differences between countries were mainly due to real wage differences in the 1960s, but mainly due to intercountry variation in total factor productivity in the early 1980s.

over origin. In particular, they find that learning rates average 20 per cent and accrue overwhelmingly to the own firm.[49]

Another interesting piece of work, concerned with interindustry spill-overs rather than one industry in isolation, is offered by Glaeser et al. (1992), who examine the sectoral employment growth in American cities, which differ in the degree of structural diversification, over the period from 1956 to 1987. Their findings suggest that employment growth tends to be larger in cities with a strongly diversified economic structure than in cities whose economic structure is dominated by one particular industry. Glaeser et al. (1992) conclude that knowledge spill-overs within any particular industry, as assumed in models of sectoral learning by doing and in some models of sectoral endogenous technical progress, are apparently less important for growth than intersectoral knowledge spill-overs.

Further results reported by Caballero and Lyons (1992) seem to confirm the hypothesis of positive *intersectoral* external effects. These findings point to increasing social returns to scale for total manufacturing in the U.S. and selected European countries, while measuring constant returns to scale at the statistical level of individual industries within the manufacturing sector. For example, they estimate for West Germany that productivity in any industry whose own inputs are held constant increases on average by approximately two and a half per cent when all other manufacturing industries increase their output by ten per cent. Their examination of input-output relationships between different industries, assumed to be the transmission paths for the intersectoral spill-over effects, suggests that most of the external effects relevant in the long term are of the pecuniary type and can be traced to increasing specialization and quality improvements in intermediate products and capital inputs rather than to the accumulation of physical capital or of human capital, as assumed in the theories of learning by doing and endogenous technical progress.

It is, however, doubtful that Caballero and Lyons (1992) do justice to the problem of knowledge spill-overs in the form of technological external effects from private R&D when they regard the intersectoral input-output relationships as the relevant transmission path, and simply compute intersectoral coefficients of correlation in the time series of sectoral value added. In order to trace knowledge spill-overs from R&D, it may be unavoidable to start from observations of inputs or outputs of research and development themselves.

Studies which estimate the impact of research and development expenditure (or of patent applications as an output indicator) outside a particular industry on the productivity in this industry have modelled the transmission paths in differ-

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[49] The authors also note that the learning rates of Japanese firms are not significantly faster or slower than those of non-Japanese firms.

ent ways. Many have not relied on input-output relations but instead, for example, on the particular sequences of first applications of individual innovations in different industries on the utilization frequency of patented technology in different industries or on the official classification of patents to different fields of technology corresponding to different industries (Mohnen 1990). Generally, these examinations appear to support the view that the degree to which productivity in a particular industry benefits from knowledge spill-overs originating outside the industry depends a lot on which industry is considered. Griliches (1992) reports from a number of independent studies by other authors who have estimated social returns to investments with intersectoral spill-overs of between 10 and 80 per cent. The main sources of intersectoral spill-over effects have been found in chemistry, mechanical engineering, electronics and in the development of scientific instruments (Mohnen 1990).

Yet, even these studies of intersectoral spill-overs presumably do not distinguish in a reliable way between technological and pecuniary external effects of research and development. Moreover, they might ignore part of the technological effects because they inevitably base their distinction of individual industries on a particular level of aggregation, and thus must exclude spill-overs that are effective at lower or higher aggregation levels. In most cases, these studies do not take into account the fact that spill-overs often have their impact only after some time lag. Finally, they cannot capture that share of the pecuniary external effects which accrues to consumers or to some of the commercial buyers in the form of additional consumer rents due to quality improvements and due to the introduction of entirely new products. The studies therefore fail to deliver full estimates of the entire social returns to research and development.

In spite of these shortcomings, a fairly robust finding seems to be that intersectoral spill-overs are incomplete, partly due to time lags. The time series regularly show a strong positive correlation between the productivity growth of an individual firm, or an individual industry, and its respective own research and development investments. Lichtenberg (1993) shows that also the productivity growth of a number of industrialized countries is significantly positively correlated with the corresponding private research and development expenditures of these countries. Under the assumption that research and development expenditures are not themselves influenced by productivity, the hypothesis that technological external effects from research and development are not at all inhibited by international borders therefore has to be rejected. Thus, an assumption, which is crucial for the validity of hysteretic models of endogenous technical progress appears to be confirmed empirically.

From this alone, however, can by no means be concluded that targeted government support for industrial research and development is advisable. At this point, instead, the question arises of how high the social marginal product of government funded research capital actually is. In his recent study, Lichtenberg (1993) estimates the social marginal product to be not significantly different from zero; in some of his regressions it is even negative. Moreover, Lichtenberg's results cannot lend support to a regime of selectively targeted industrial policies, discriminating between industries, because his study does not measure sectoral differences in the international effectiveness of spill-over effects at all; the data used by Lichtenberg (1993) are far too aggregated.

Furthermore, his model does not specify the hypothetical transmission path of external effects in any detail. But the hypothesis that the intensity of trade relations between countries is a determinant of the magnitude of international spill-overs from R&D finds some support in a recent empirical study by Coe and Helpman (1993), who use trade-weighted foreign R&D capital stocks, in addition to national R&D capital stocks, to explain variations in the total factor productivity growth of 21 OECD countries and Israel during the 1970s and 1980s.

For an assessment of the actual prospects of successfully promoting economic growth by subsidizing selected areas of research and development, one should also consider the results from a number of interesting case studies which attempt to measure the social returns to selected individual technological innovations, whose application takes place in a clearly delimited area and is thus easy to oversee for the purpose of data collection. For example, Trajtenberg (1990a) examines the social returns in the form of consumer rents that can be traced back to the continual quality improvements in computer tomographs since their introduction in 1972. The social returns were apparently extremely high at the start of product development. For innovations up until 1977, Trajtenberg (1990a) estimates the social returns to be eighty times the sums invested in research and development; for innovations between 1978 and 1982, however, they are less than one and a half times the corresponding amount.

This result suggests the conclusion that at the beginning of product development government aid might have been sensible, but later, when the technology was already established, it might have been ineffective or even damaging. This example illustrates the often underestimated industrial policy information problem governments face: As soon as they recognize a promising new technology, the time of high social returns has probably passed. Moreover, results from case studies are generally suspected of painting a far too rosy picture of the social returns to research and development, because they tend to focus on successful innovations and to neglect unsuccessful research efforts.

Future empirical research on the existence and nature of external effects in industrialized economies promises to help discriminate between different approaches within the new growth theory. Nevertheless, it remains doubtful that present methods of empirical research will suffice to make reliable and detailed recommendations for targeted industrial policy, which would fit particular circumstances in the near future and which would be based on an undisputed body of knowledge about economic growth in the real world.

3. The International Diffusion of New Technical Knowledge and the Role of Multinational Companies

The third empirical issue relevant to assessing industrial policy proposals comes down to the question what impact the ongoing improvements of communication and information storage technologies will have on the rate of diffusion and speed of transfer of new knowledge and thus on the strength and range of technological externalities.[50] In this context, it is also of interest whether the increasing importance of multinational companies and their strategic alliances has led to a greater acceleration of the *international* diffusion than of the *national* diffusion of knowledge (Chesnais 1988).

The convergence of national and international knowledge diffusion and transfer processes would tend to make country-specific technological accumulation processes, which do not reflect the true comparative advantages on the basis of relative factor endowments, impossible to sustain. Such a convergence would thus tend to make industrial policy measures to establish national technological leadership in promising industries ineffective. Some authors, however, express concern that the international transfer of technology in all its various forms could in the future be dominated even more than today by multinational companies and that some kind of technological dualization of markets could occur, excluding local firms from the latest developments in the field of high technologies (Chesnais 1988).

The empirical evidence shows that the measurable share of international technology transfer, i.e. the trade with patents, licences and technical knowhow, has been dominated by multinational companies for years, apparently with an upward trend (Vickery 1986). At the same time, an increasing internationalization of the R&D activities of multinational enterprises is observed (Mansfield et al. 1979; Wortmann 1990). Part of this trend is not only the increasing number of strategic alliances between different multinational companies but also their setting up of own R&D laboratories abroad, which seem to follow the setting up of foreign production locations with some time lag (Vickery 1986).

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[50] See Tassey (1992) and the various contributions in Casson (1991a) for related work on these questions.

Beneficiaries of these investments seem to be primarily countries which already have established a strong technological base in the corresponding industry. This is confirmed by the long-term trend towards the international agglomeration of research and development activities observed by Cantwell (1991). Taken together, the observed trends appear to confirm the hypothesis, especially for research-intensive industries, that multinational companies do contribute to an accelerated international transfer of knowledge. However, there do not appear to exist any thorough empirical studies on the related question of whether positive technological spill-over effects for local firms in the various host countries of the multinational companies have increased or decreased over time. Thus, the fear of a coming technological dualization between multinational and local companies is presently still unfounded.

> Like a river which digs its own bed deeper, a pattern of specialization, once established, will induce relative productivity changes which strengthen the forces preserving that pattern. ... but eventually the larger forces of tectonics will bury that history.
> — Paul Krugman (1987: 47, 54)

C. Modelling the Complex Stochastic Dynamics of Innovation and Specialization in Open Economies

I. The Stochastic Nature of Innovation, External Effects and Hysteresis

Although people know from experience that a stream of technological innovations will be part of economic life in the future, no single innovation can normally be predicted with respect to the place and time of its occurrence, nor with respect to the actual features of any new product or production process. If all this could be predicted in advance, one would already know enough to make the innovation today. The randomness of technological change is both an empirical fact and a logical consequence of invention and innovation coming as discrete events.[51] But an important question remains: Is the stochastic nature of innovation really an objective reality or merely a reflection of subjective ex ante ignorance about the precise laws of some deterministic dynamic which might underlie technological change?

1. Objective Randomness and Emergence in the Sciences

If the randomness of technological change was merely subjective, then no genuine newness could ever come into this world; everything would rather be predetermined. Thus, one may argue that genuine innovation as an individual event would be inconceivable if it did not contain a fundamental random element. In particular, the irreversible character of the creation of new knowledge could not be reconciled with a deterministic view of innovation. After the event, it is never possible to return the world to its initial state, as it would be in

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[51] It is only after quantum mechanics introduced an irreducible random element into physics that one can no longer maintain that nature does not make jumps.

a deterministic world. Even if one took away all the blueprints, designs and products that embody a particular invention, many people would still know how to make the product anew. Although some parts of knowledge may indeed be forgotten if they are not kept in constant use, it is hardly conceivable that an economy could be returned to its initial state and thereby be deprived of all technical knowledge that has been accumulated in the course of its development. The growth and development of innovating economies takes place in irreversible historical time, as opposed to the reversible analytical time of neoclassical growth theory.[52]

Yet, even assuming innovation to be partly random still leaves the question open whether this randomness also matters in the aggregate: Are we justified to invoke the law of large numbers and to regard the aggregate sequence of individual innovations as a deterministic and predictable stream of variety increases and productivity advances merely veiled by random measurement errors? Or does the stochastic nature of innovation itself have implications for the direction of technological specialization and the rate of productivity growth in the economy at large, and thus ultimately for economic policy?

In the past, economists have been reluctant to acknowledge the possibility of truly new things and new ideas coming into existence, let alone the consequences of innovation being fundamentally stochastic. An important reason for ignoring newness, it is argued by Romer (1994), has been the inability, only recently overcome, of dealing with non-convexities in mathematical models of general equilibrium in economic systems. In the past, only interior equilibria on convex sets could be handled with the formal apparatus of general equilibrium analysis. But, as Romer points out, an interior equilibrium is incompatible with innovation. The fact that there are continual technological innovations implies that the economy is always near or on the boundary of goods space.

Moreover, the introduction of any new good must be associated with a fixed cost, for else there would be no reason why the good was not already available in the market. Fixed costs, however, are incompatible with perfect competition. They require some form of monopolistic competition which economists have learned only recently to model within a consistent general equilibrium framework. And the existence of fixed costs raises the question why the effort to bring some particular new good to market seems to become profitable at a particular place and time, and not before or elsewhere. In other words: what is it that moves an economy out of an established equilibrium and puts it on the path to a new equilibrium allocation which includes some particular new good?

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[52] Time is reversible in neoclassical growth theory because the models suggest that simply by destroying the capital stock of an economy the process of accumulation would start all over again and would be repeated in identical fashion.

This involves the question how new goods are actually selected from the wealth of inventions possible at any given time, from the many more innovations conceivable than are on firms' drawing boards and from the many more designs on firms' drawing boards than will eventually be brought to market.[53] Is this selection entirely arbitrary, do all small perturbations accumulate to large effects, as Romer (1994) seems to imply? Or does the ongoing selection of new goods obey certain regular patterns with regard to the direction and frequency of innovations? Does perhaps some kind of self-organized criticality play an important role?

A first selection takes place in the inventor's brain. Unfortunately, individual creativity is still little understood. One can only guess what kind of mental processes liberate the inventor's brain from the constraints of an ingrained set of beliefs and prejudices about the world and enable him to perceive new technical combinations for given ends or new uses for existing technologies.[54] Anecdotal evidence suggests that people who are social or intellectual outsiders, for one reason or another, are more likely to generate new ideas which lead to useful inventions.[55] In brief, eccentric brains seem to possess a comparative, and often

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[53] Romer (1994) presents a combinatorial calculation which demonstrates that, of the set of all possible computer programmes which would fit — one at a time — on a low capacity floppy disk, only a very tiny fraction could be stored simultaneously in this world, even if every elementary particle in the universe was used to code a different bit of information.

[54] One such guess is discussed by Siebert (1969) who distinguishes between the acquisition of new technical knowledge through processes of unanticipated learning and through intentional search behaviour. He contrasts a Markov learning model with a mathematical model of optimal search intensity. Both of these models are stochastic and may imply path-dependence, as they rely on positive feedbacks. Moreover, as Siebert (1969: 528) points out, the presence of external effects from one learning experience or search effort to another may imply that a whole economy need not be constrained by decreasing marginal returns even if these would be relevant to each individual effort of searching for new technical knowledge in isolation. At the same time, Siebert (1969: 535) recognizes that the path-dependent nature of learning and searching for new knowledge may provide an argument for infant industry protection.

[55] For example, think of Leonardo da Vinci, an illegitimate child, Thomas Alva Edison, who developed serious hearing problems as a young boy and was labelled a misfit in elementary school, Rudolf Diesel, a German born in Paris and at the age of twelve deported to England (following the outbreak of the Franco-Prussian war), or Werner (von) Siemens, who was pushed into inventing by financial need after the death of his parents made him at the age of 24 responsible for the upbringing of nine younger siblings. Apart from unusual individual circumstances, unusual *social* conditions may favour the clustering of inventive activities in certain, relatively brief historical periods. Mokyr (1991) notes that technologically creative societies have been historical exceptions rather than the rule. He points out that for certain limited periods of time some societies (e.g. the United States and Germany in the late 19th century) have been able to generate such enormous bursts of technical

even absolute, advantage for invention. This would be consistent with the (phenomenological) theory of emergence in the natural world, the theory of 'dissipative structures', of which perceptions, thoughts and ideas may well be important examples.[56]

This theory claims that any new, and self-stabilizing, structure involves the breaking of natural symmetries and can emerge only far from a system's equilibrium, in the sense of maximum entropy as defined by thermodynamics.[57] Since the pioneering paper of Prigogine (1969), the theory has been used in a variety of contexts to explain the emergence of physical, chemical and biological structures out of the utter chaos which is supposed to have dominated the universe at the beginning. It had long been recognized by scientists that the observed degree of order and complexity, manifesting itself most remarkably in human life on earth, cannot easily be reconciled with the second law of thermodynamics, according to which the entropy of any closed system increases irreversibly until equilibrium is reached. Nor could the irreversible increase in entropy be easily reconciled with the deterministic laws of classical dynamics, derived by Newton to describe mechanical systems, which can be shown to be fully reversible.

The physicists Paul and Tatjana Ehrenfest (1907), however, showed that entropy could be understood within a simple model of a *stochastic* process. Thermodynamic equilibrium has since then been viewed as a statistical concept describing the macroscopic state which is most likely to be observed in a closed system in the long term. In the Ehrenfest model, there are two balls of different colour which are initially distributed in an arbitrary fashion between two urns. Someone makes a random selection of balls from the urns at regular intervals, one ball at a time, and these balls are moved from one urn to the other.

For this experiment, reported by Eigen (1989), it can be shown theoretically that in the long term, regardless of the initial distribution of balls, convergence of the relative distribution of the two types of balls in each urn to the relative

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creativity and innovation that it would be difficult to consider these as mere random fluctuations in the frequency of individual geniuses.

[56] Compare for the views of Haken and Haken-Krell (1992) who attribute all qualities and achievements of the human brain to the emergence of 'dissipative structure'. A similar hypothesis has been held by Gestalt theory which claims that creative thinking involves more than mere cognitive associations. By contrast, the neurologist Eccles (1977) seems to see an independent spirit in control of the material brain.

[57] Entropy is defined as the amount of randomness in the macroscopic state of a closed system. This randomness of a macroscopic state (e.g. the density distribution of a system's elements in space) is the greater, the more combinations of different allocations of the microscopic elements of the system represent this particular macroscopic state.

distribution in the totality of balls is to be expected, because there are clearly more allocations of individual balls across the two urns that represent this macroscopic 'equilibrium' distribution than there are allocations that would represent any other particular distribution. This equilibrium, which corresponds to a state of maximum entropy, is thus without any meaning at the level of a system's individual elements. If each individual element was thought to move on a deterministic trajectory, the system as a whole would eventually return to any macroscopic state, given enough time even to the most improbable ones. The system would thus be fluctuating around the most likely macroscopic state, and any observed increase in entropy would not really constitute an irreversible process but only part of a fluctuation with an extremely low frequency.

In recent research, however, it has been argued that true irreversibility is not only possible, but indeed inevitable in complex systems in which entropy is linked to a gradual loss of information about the system's initial conditions. This argument builds on the concept of information introduced by Shannon (1948) to develop a microscopic theory of irreversibility. Since the work of Lorenz (1963) and Prigogine (1969, 1979), partly following Poincaré (1893), scientists have learned that the deterministic trajectories of the microscopic elements in a system of sufficient complexity can easily turn out to be chaotic. Prigogine and Stengers (1984) argue that, because the chaotic trajectories of any two points in phase space, which may be arbitrarily close together initially, will diverge at an exponential rate and because, according to quantum mechanics, an infinitely precise localization is never feasible, the microscopic dynamics of such a system are to be considered intrinsically random and unstable. In contrast to classical dynamics, the system therefore does not retain the information about initial conditions, to which the system will thus never return. Prigogine and Stengers (1984) conclude that sufficiently complex systems necessarily exhibit irreversible dynamics in unidirectional, historical time.

The simple model proposed by P. and T. Ehrenfest can be adapted to illustrate irreversibility due to the loss of initial information. Suppose that the two urns are each filled with the same number of balls of each of the two colours. Again, balls are randomly selected from the two urns at regular intervals, but now the selected ball is left in its urn and an additional ball of the same colour is taken from an external reservoir and put in the other urn to replace a ball of the other colour in that urn. Although there is no a priori preference for either of the two colours, and there may thus be fluctuations around the initial distribution of the two types of balls in the urns, eventually one of the two colours will come to dominate both urns, and the other colour will 'die out'. The reason, of course, is that the colour which has already gained a greater share of the total number of balls is with increasing probability selected again and augmented even further.

In this model, it is a priori *certain* that the symmetry of the initial distribution will sooner or later be broken irreversibly. But it is *uncertain* when this will happen, and importantly, which colour will survive. There is thus a bifurcation point, before which the long-term development is fundamentally unpredictable and after which it is fully deterministic. Moreover, the model implies that information about the initial distribution will be lost so that the system can never return to its initial state. This model illustrates that there are potentially useful insights about the dynamics of complex systems which can only be gained from probabilistic models implying irreversibility and unidirectional time, as opposed to the reversible time of classical dynamics.

2. Emergence in Economics

It is from probabilistic models of open systems with irreversibility that the hypothesis of intrinsically unstable equilibria in innovating economies can be derived, provided these economies are sufficiently complex to render elementary dynamics at the microscopic level chaotic, and thus intrinsically random. Much anecdotal evidence in support of this hypothesis has recently been provided by the technological revolution that led to the birth of the personal computer (PC) industry.

When the first PCs came to market, many experts of computer technology held that these small and fragile machines would never be able to compete with the much more powerful mainframe computers, at least not outside of narrow niche markets. What these experts failed to foresee was the enormous attraction the PC has since generated for complementary innovations and quality improvements in the areas of software, printers, communication and interface technologies as well as in the PC's core technologies, its processing and memory chips. A rapidly growing market made product differentiation profitable, especially in software and printing technology, which in turn generated significant pecuniary externalities, by making every PC potentially more productive. Moreover, the demand for compatibility generated strong network externalities in favour of PC adoption.

After only a few years, PC technology began to close the productivity gap vis-à-vis mainframes so dramatically that the PC was able to gain market share even in large scale business and sophisticated scientific applications, areas which had been considered the reserve of mainframe computers. There are a number of identifiable historical events which shaped the course of technological development in the PC industry. One of these stochastic events was IBM's decision in the early 1980s to launch its own range of PCs with the operating system and processing chip — two of the PC's key components —

bought from external sources, yet without securing exclusive rights to use these inputs and their specific quality and compatibility standards. Many think this to have been the decisive event that unleashed an exploding PC components industry.[58]

The example of the PC demonstrates that some of the potentially important consequences of the fact that innovation is an intrinsically unstable stochastic process may arise at the macroscopic level of technological and economic development, from the systemic interaction of individual innovations. These macroscopic effects, in turn, may feed back onto the microscopic level by changing the relevant supply and demand conditions and thus the economic landscape in which entrepreneurs search for profitable innovation opportunities. The market selection among competing innovations, superimposed on the temporally preceding selection procedures in the brains of the inventors and in the R&D departments of innovating firms, is thus a non-trivial stochastic process with no obvious implication of optimality. In a sense, the path taken by the market process may come to 'enslave'[59] individual innovation behaviour by making certain technological choices more attractive to the individual innovator who operates within a highly interdependent technological and economic environment. Because the economy is a complex evolving system according to this view, both chance and necessity, i.e. random events and positive feedbacks, are thought to determine the course of development, which thus cannot be understood with reference to a microeconomic theory of individual innovations alone.

That neoclassical theory has so far largely ignored these issues may have been due to a lack of appropriate analytical tools to study the interaction of stochastic processes in open systems and the implications of this interaction for resource allocation in dynamic economies. By now, however, the natural sciences have developed several complementary methodologies to formalize explanations of how today's apparent order in the natural world may have emerged out of the utter chaos supposed to have dominated the universe at its beginning. Ebeling and Feistel (1994) distinguish five complementary ways of modelling self-organizing processes:

(i) Kinetic models can be used to describe the observed sequence of relevant events, either verbally or by graphical representation.

(ii) Thermodynamic models are used to analyze diffusion processes with the implication of a monotonically increasing entropy in closed systems. Georgescu-

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[58] It remains to be seen whether a similarly productivity-enhancing *software* components industry would emerge if software firms were helped, or forced, to agree and implement compatible software standards, so that users could assemble different firms' components to meet their specific needs in the best possible way.

[59] To use a terminology suggested by Haken (1983).

Roegen (1971) has used this modelling approach for the flows of matter and energy into and out of the open system that an economy constitutes within its natural environment. A continuous export of entropy out of the economic system is seen to be a precondition for its ongoing, self-organized evolution.

(iii) Models of deterministic dynamics, represented by differential equations, are used to analyze the often non-linear dynamics of certain key variables *which* characterize a system's behaviour over time. Haken (1983) has called such variables the order parameters of a system. An example would be the share of a certain technology in a particular product market, say, the share of Betamax in the market for video cassette recorders (VCRs).

(iv) Stochastic dynamics are used to model the evolution of probability distributions for the order parameters of Markov processes.[60] The evolution of probability distributions is calculated either on the basis of the so-called Master equation (in the case of discrete states) or on the basis of the so-called Fokker-Planck equation (in the case of continuous states). These equations give a complete account of discrete or continuous changes in the probability distribution of a vector of random variables on a discrete or continuous state space, respectively, over time. Because this method clearly reveals the stochastic nature of newly emerging structures, it is often more appropriate, yet also more difficult, than the use of deterministic differential equation.

(v) Statistical physics, finally, attempts to formulate probabilistic models for the microscopic states of a system, building on the sophisticated statistical methodology developed by Boltzmann (1872a, 1872b) and Gibbs (1960). This methodology, however, is too complicated and too demanding of detailed, often unavailable, information about a system's elements to be used widely in the analysis of self-organization even in the natural sciences, let alone in the social sciences.

It is a question of current research in economics whether some of these methods can usefully be transferred to explain how today's complex economies, with their distinct patterns of agglomerations, and how today's sophisticated technologies of an increasingly systemic nature have evolved from primitive tools and rudimentary trading relationships at the beginning of human civilization. Arthur (1990) and Krugman (1994) have used some of these tools to model the emergence of spatial agglomerations of economic activity; Scheinkman and Woodford (1994) as well as Hall (1991) have sought to explain

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[60] Markov processes are stochastic processes in which the probabilities of transition from the present state to other states at some future date are independent of the states realized in the past; the transition probabilities are contingent only on the present state. For further discussions and for applications of Markov processes see Section C.II and Chapter E.

the emergence of business cycles with reference to non-linearities, local interaction and a stochastic economic environment. Silverberg et al. (1988) present a model of self-organization in the diffusion of innovations with transitions between different technological trajectories, which is capable of accounting for the often observed S-shaped form of the technology diffusion curve. Dosi and Kaniovski (1994) assess how useful it might be to apply the method of generalized urn schemes, of the kind first introduced by P. and T. Ehrenfest (1907), in the analysis of technological and economic dynamics.

This line of research recognizes that for many purposes the deterministic dynamics of neoclassical growth theory may well be a misleading and not just a poor approximation of economic development in reality. These deterministic dynamics, in the case of intertemporal utility maximization formalized in terms of Hamiltonian functions, are directly transferred from the Newtonian theory of dynamics in closed mechanical systems.[61] These systems typically possess one global equilibrium to which the system inevitably converges. Once the laws of motion and the initial conditions are known, the dynamics are fully predictable and, what is more, reversible.

This criticism also applies to Romer's (1990) deterministic model of endogenous technological change and similar models within the new growth theory. Although these models assume positive external effects, and thus do feature more than one steady-state growth equilibrium, they admit only the suboptimal equilibrium to be within the reach of market forces on their own. Unless the government intervenes, there is no source of random fluctuations to endogenize the selection of an alternative self-reinforcing equilibrium as a feasible outcome of the market process. The mechanical determinism of these models is as well mirrored by their completely symmetric treatment of all newly introduced varieties of capital inputs, which drive productivity.

In reality, by contrast, innovations usually seem to imply the breaking of symmetries, in the technological, sectoral and geographical dimension. A particular technical solution often gains market share at the expense of competing approaches, as in the case of PCs versus mainframe computers, electric engines versus internal combustion technology, Diesel engines versus steam power on ships, the supersonic aircraft versus wide-bodied passenger aircraft, etc. Moreover, history has seen many unexpected path-breaking technological break-

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[61] Samuelson (1983), one of the pioneers of formal dynamics in economics, is quite explicit on this in the introduction to the enlarged edition of his *Foundations of Economic Analysis*.

through inventions that provided focal points around which subsequent complementary innovations have tended to cluster (Sahal 1985; Perez 1985).[62]

Nor does the other prototype model of endogenous technological change, the one due to Aghion and Howitt (1992) and based on a Poisson process of randomly distributed quality increments for a well-defined product line, do full justice to the essentially stochastic nature of innovation. Obviously, this model cannot capture symmetry breakings in the heterogeneity of emerging technologies, because it is restricted to one technological dimension only. But Aghion and Saint-Paul (1991) have shown how Markovian fluctuations can be introduced into a vertical model of productivity growth, and have analyzed how long-term growth changes in response to changes in the amplitude or frequency of fluctuations. Cheng and Dinopoulos (1991) have used a similar model to analyze how the interaction between stochastically distributed technological breakthroughs and quality improvements may generate endogenous growth with fluctuations. These Schumpeterian models of growth thus have the potential to explain an asymmetrical distribution of economic activity over time.

A further source of randomness which may affect technological change at the level of industries and entire economies are pecuniary and technological external effects: Their relative magnitudes and ranges across industries and regions are, at least to some extent, specific to each individual innovation, for they depend on the kind of complementary technologies and institutions that may facilitate their diffusion as well as on the particular sets of complementary and substitutional goods and services already in existence at the particular point in time of an innovation's occurrence.[63] Moreover, the dynamic effects of network externalities, provided they are significant, depend on the particular path taken by the stochastic adoption process.

What is then the most fundamental reason why neoclassical deterministic dynamics are likely to be misleading in the study of innovating economies? If it is to be summarized in one word, it should be *irreversibility*; breaking the time

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[62] Rosenberg (1994) has emphasized that the emergence of technological guideposts, focusing devices or paradigms can best be understood with reference to a path-dependent process, in which randomness plays a crucial role.

[63] Sometimes it may not even be clear in advance whether a new piece of technical knowledge will diffuse primarily as a technological external effect or as a kind of pecuniary external effect. For example, a firm may have developed a new specialized machine tool for in-house use and may have decided to keep it secret to hold on to its productivity advantage vis-à-vis competitors. In this case, a competitor's learning about the new machine tool would be considered a technological external effect. Or the firm may come to think that it would be cheaper to buy the machine tool from a specialist supplier to whom it may therefore license the innovation, granting the right to cover fix costs from sales to competitors. In this case, competitors would benefit from pecuniary external effects.

symmetry, implied by deterministic dynamics, is one of the characteristic features of innovation and technological change. To be sure, the creation of new technical knowledge, which seems to be a driving force of economic growth, is an irreversible process. But this requires to adopt a probabilistic, instead of a deterministic model of dynamics. In particular, any empirical test of hysteresis, a phenomenon related to irreversibility, must be based on a probabilistic methodology that encompasses hysteresis, rather than on a deterministic model that would exclude hysteresis *a priori*.

Much of the empirical work reported below is concerned with the question whether it matters for aggregate industrial dynamics that innovation is a fundamentally stochastic phenomenon from a microeconomic point of view. The following two subsections will discuss some of the mathematical tools which can be used in modelling the complex dynamics in economies characterized by stochastic technological innovation and change. This discussion, accompanied by illustrative computer simulations, will prepare the ground for the subsequent empirical work by illustrating how certain features of stochastic processes generate characteristic patterns in the data.

II. The Master Equation Approach to Specialization in Small Open Economies

The transitional dynamics of multisectoral growth and specialization are already quite difficult to analyze in the context of deterministic models. A recent paper of Mulligan and Sala-i-Martin (1993) demonstrates that new analytical techniques are needed to understand other than the most basic versions of such models. Yet, even more involved is the formal analysis of multisectoral growth and specialization in essentially stochastic models. Durlauf (1993) provides a fairly general example of a multisectoral stochastic model, which yields non-ergodic growth.[64] This model is appropriately formalized in terms of random fields methodology, a new branch of probability theory which deals with stochastic processes in more than one dimension. Multi-dimensionality of the stochastic analysis is essential to multisectoral models of economic growth, where interaction between individual elements of the system may take place across industries as well as across time.

The aim of this section is more modest. The following discussion of stochastic models of specialization in open economies will be restricted to the case

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[64] For a definition of non-ergodicity, see Section E.I.

of two sectors. This can be modelled as a one-dimensional stochastic process in time, because under the assumption of full employment the relative shares of the two sectors in the total resources of the model economy require one state variable only. The simplest way to illustrate some of the basic implications of *national* external effects for the dynamics of specialization is within a stylized model of a small open Ricardian economy with labour as the only factor of production, where a comparative advantage is due to higher labour productivity in one of the two sectors and where increasing returns to scale take the form of a positive externality for all firms in the respective sector. Reallocation of labour between sectors can be characterized as a stochastic recontracting process on perfectly competitive labour markets (Arthur 1988).

Suppose two new technologies are being introduced, replacing an older technology used in the small open economy, which has been completely specialized in that one old technology, as is typical for Ricardian economies with only one factor of production. Subsequently the one industry of that economy separates into two, with each branch specializing in the production of only one of the two new differentiated products, which are assumed to sell both at the same constant price in world markets. Each entrepreneur makes an initial random choice for one of the two technologies. But workers, who make only individual and uncoordinated decisions, frequently change jobs and decide anew with which technology to work. Let p_{AB} denote the probability of transitions from technology A to technology B, and p_{BA} the probability of transitions from technology B to technology A.

Assume initially workers are on average indifferent between the two technologies, so that in each event of a job change both technologies are chosen with probability $p_{AB} = p_{BA} = 1/2$. The result of workers' never-ending recontracting is that the share of workers in each of the two technologies moves up and down in the form of a Markov random walk[65] with reflecting barriers. Reflecting barriers are, of course, the direct consequence of the limited size of the economy's labour force: when all workers are in one sector, intersectoral transitions can only be in one direction, namely from the full sector into the abandoned sector. Four different cases illustrate how comparative advantages and increasing returns to scale in the form of positive external effects may shape the dynamics of such a stochastic process:

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[65] A Markov random walk is a well-known type of a stochastic process in discrete (event or historical) time in which the probabilities of transition of the state variable (here the share of workers in technology A) from any present state to any other state are not only independent of the past (which defines a general Markov process) but also independent of the present state. When the Markov random walk takes place over a discrete state space, as it does here, it is also called a Markov chain.

(i) Identical productivities. First, assume labour productivity to be exogenous and the same in both constant-returns-to-scale technologies. Assuming that job switches occur strictly sequentially, one at a time, and that workers' individual transition rates are homogeneous, the probability $P(n,t+1)$ of having a certain number n of workers involved with technology A at time $t+1$, which stands here for event time rather than historical time, is defined as:

$$[16] \quad \begin{aligned} P(n,t+1) &= P(n,t)\left(1-p_{AB}(n)-p_{BA}(n)\right) \\ &\quad + P(n-1,t)p_{BA}(n-1)+P(n+1,t)p_{AB}(n+1) \\ &= 0.5\,P(n+1,t)+0.5\,P(n-1,t). \end{aligned}$$

The evolution of this probability is described by the Master equation of motion[66] taking into account the lower boundary at $\underline{n}=0$ and the upper boundary at $\bar{n}=100$, set by the fixed size of the small country's labour force:

$$[17] \quad \begin{aligned} \frac{dP(n,t)}{dt} &= P(n+1,t)p_{AB}(n+1)-P(n,t)p_{AB}(n)+P(n-1,t)p_{BA}(n-1) \\ &\quad - P(n,t)p_{BA}(n) \\ &= 0.5\,P(n+1,t)-0.5\,P(n,t)+0.5\,P(n-1,t)-0.5\,P(n,t) \\ &\qquad\qquad \forall \quad \underline{n}<n<\bar{n} \end{aligned}$$

$$\frac{dP(\underline{n},t)}{dt} = 0.5\,P(\underline{n}+1,t)-0.5\,P(\underline{n},t)$$

$$\frac{dP(\bar{n},t)}{dt} = 0.5\,P(\bar{n}-1,t)-0.5\,P(\bar{n},t).$$

Approximating the state variable n to a continuous variable would lead to the one-dimensional Fokker-Planck diffusion equation, used extensively in the natural sciences. Both of these equations have the property of finally developing into a long-run stationary probability distribution, irrespective of the initial allocation of workers across industries (Weidlich and Haag 1983: 9). This distribution can be calculated by setting the Master equation equal to zero and solving for $\tilde{P}(n)$, given the transition probabilities. The Markov random walk

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[66] The basic assumptions that justify the use of the Master equation to account for changes in the common probability distribution of a vector of random variables, defined on a discrete state space over time, are that workers' transition rates are homogeneous, depend on the current state of the economy, but not on its history, and that there is only one event at any one time. For further details see Woeckener (1992).

with reflecting barriers, considered here, will result in equal stationary probability of all possible allocations of workers, whatever the initial choices of entrepreneurs. This is easily seen to be the only feasible solution to the stationary Master equation:

$$[18] \quad \frac{d\tilde{P}(n,t)}{dt}=0 \quad \Rightarrow \quad \tilde{P}(n+1)+\tilde{P}(n-1)=2\tilde{P}(n) \quad \forall \quad \underline{n}<n<\bar{n}$$

with the boundary conditions

$$0.5\,\tilde{P}(\underline{n}+1)-0.5\,\tilde{P}(\underline{n})=0=0.5\,\tilde{P}(\bar{n}-1)-0.5\,\tilde{P}(\bar{n})$$

subject to the normalization condition $\sum_n \tilde{P}(n)=1$.

(ii) Comparative advantage. If workers are more productive in technology B, giving the country a comparative advantage in that industry, so that sector B's firms therefore pay higher wages, this can be modelled by making the probability of transitions from A to B higher than that of transitions from B to A. As a result, the long-run stationary probability distribution of the share of workers in technology A will be highly skewed towards a *low* long-run share of workers in technology A. Assuming $p_{AB}=0.6$ and $p_{BA}=0.4$, the Master equation reads:

$$[19] \quad \frac{dP(n,t)}{dt}=0.6P(n+1,t)-0.6P(n,t)+0.4P(n-1,t)-0.4P(n,t)$$

$$\forall \quad \underline{n}<n<\bar{n}$$

and at the boundaries

$$\frac{dP(\underline{n},t)}{dt}=0.6P(\underline{n}+1,t)-0.4P(\underline{n},t)$$

$$\frac{dP(\bar{n},t)}{dt}=0.4P(\bar{n}+1,t)-0.6P(\bar{n},t).$$

Setting these equations equal to zero, one can recursively express the stationary probabilities of all states in terms of the stationary probability of one of the boundary states, so for instance in terms of the lower boundary $\underline{n}$ according to:

$$[20] \quad \tilde{P}(n)=\tilde{P}(\underline{n})\prod_{v=\underline{n}}^{n}\frac{p_{BA}(v-1)}{p_{AB}(v)}.$$

In the simple case considered here, where transition probabilities are equal for all states, this formula simplifies to:

$$[21] \quad \tilde{P}(n) = \tilde{P}(\underline{n})\ (p_{BA}/p_{AB})^n ,$$

which can be solved explicitly using $\sum_n \tilde{P}(n) = 1$. The stationary probability is distributed according to an exponentially decreasing function of *n*. A few selected values are $\tilde{P}(0) = 1/3$, $\tilde{P}(5) = 0.0439$ and $\tilde{P}(10) = 0.0058$, while $\tilde{P}(100)$ is virtually, yet not quite equal to zero.

(iii) Increasing returns to scale. What cases (*i*) and (*ii*) have in common is that the transition probabilities are equal for all states. Thus, there is no real need to evaluate the process in terms of the Master equation to understand the main trend of convergence to the long-run stationary distribution. A standard analysis in terms of mean values of the stochastic Markov process would suffice. Mean value analysis, however, ceases to be sufficient when increasing returns to scale in the form of positive external effects are introduced into the model. Firms are unable to internalize the externality, thus remain in perfect competition with each other and pay wages equal to average productivity in their industry. Average productivity and wages in each industry are then a positive function of industry size, so that the probability of choosing a job in a particular industry positively depends on the number of workers already involved with the corresponding technology. This clearly is a case of positive feedback.

To illustrate the case of positive externalities in both technologies, assume that the ($N = 100$) workers in a small open economy have the following probabilities of transition:

$$[22] \quad p_{AB}(n) = \begin{cases} 0 \quad \forall \quad n > 75 \\ 1.5 - 2n/N \quad \forall \quad 25 \le n \le 75 \\ 1 \quad \forall \quad n < 25 \end{cases}$$

$$p_{BA}(n) = \begin{cases} 1 \quad \forall \quad n > 75 \\ -0.5 + 2n/N \quad \forall \quad 25 \le n \le 75 \\ 0 \quad \forall \quad n < 25 \end{cases}$$

From the Master equation follows that the stationary probabilities must obey:

$$[23] \quad (1.5 - 2n/N)\tilde{P}(n+1) + (-0.5 + 2n/N)\tilde{P}(n-1) = \tilde{P}(n)$$

with the boundary conditions

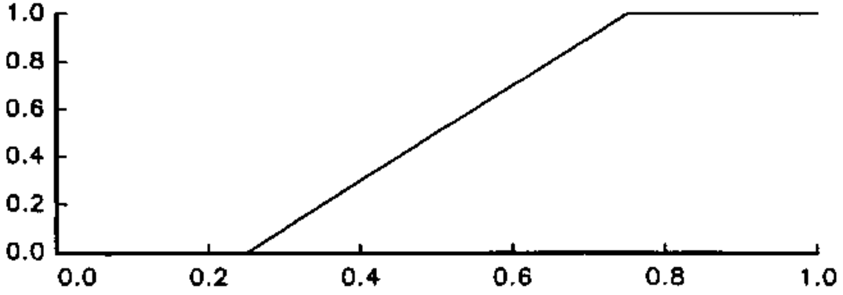
$$\tilde{P}(\underline{n}+1) = 0\tilde{P}(\underline{n})$$
$$\tilde{P}(\bar{n}-1) = 0\tilde{P}(\bar{n}).$$

Assuming that there are positive probabilities for both $\underline{n}$ and $\bar{n}$ being greater than zero, it is straightforward to argue recursively that all other states of incomplete specialization must have zero probability: The only feasible long-term stationary distributions are those where all states, except the two end states of complete specialization, have zero probability. Since the system is entirely symmetrical when it starts from $n = 50$, there is no reason to believe that the stationary probabilities are anything but

$$\tilde{P}(\underline{n}) = \tilde{P}(\bar{n}) = 0.5\,.$$

Technically speaking, there are absorbing barriers at $n = 25$ and at $n = 75$ due to the force of the increasing returns, assumed to be of equal strength in both technologies. Once the process of specialization has moved beyond one of these absorbing barriers, it is impossible that whatever technology is then dominant fails to attract all workers in the small economy. This can be recognized in the graphical representation of the switching function $p(n)$ on the domain of n, depicted in Figure 2. Probability piles up in the end states because there is zero probability of exit from either of these.

Figure 2 — Workers' Switching Function in a Small Open Economy: The Case of Absorbing Barriers due to Strong Positive Externalities in Both Technologies



Note: The horizontal axis shows the share of workers in technology A, the vertical axis the probability of the next switch being from B to A.

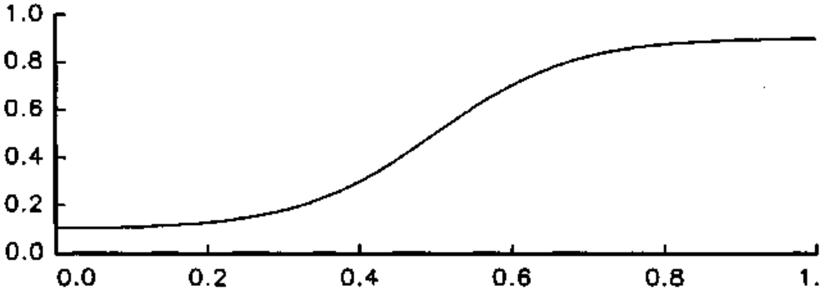
If, however, the strength of the increasing returns in the form of positive external effects was not so rapidly increasing, there would not have to be absorbing barriers. Consider, as an example, the Markov process with transition probabilities

$$[24] \quad \begin{aligned} p_{BA}(n) &= 0.1 + 0.8 / (1 + 20e^{2.5-11(n/N)}) \\ p_{AB}(n) &= 0.9 - 0.8 / (1 + 20e^{2.5-11(n/N)}). \end{aligned}$$

The switching function is depicted in Figure 3. This function has a positive probability of exit from every state. While there is again a pile-up of probability at the end states, the economy will never be irreversibly locked into any of these, it will rather from time to time make sojourns in both states of complete specialization. One can therefore aptly speak of punctuated equilibria. A snapshot of the evolving probability distribution after 100 switches is given in Figure 4, which graphs a non-parametric density estimate based on data from a computer simulation.

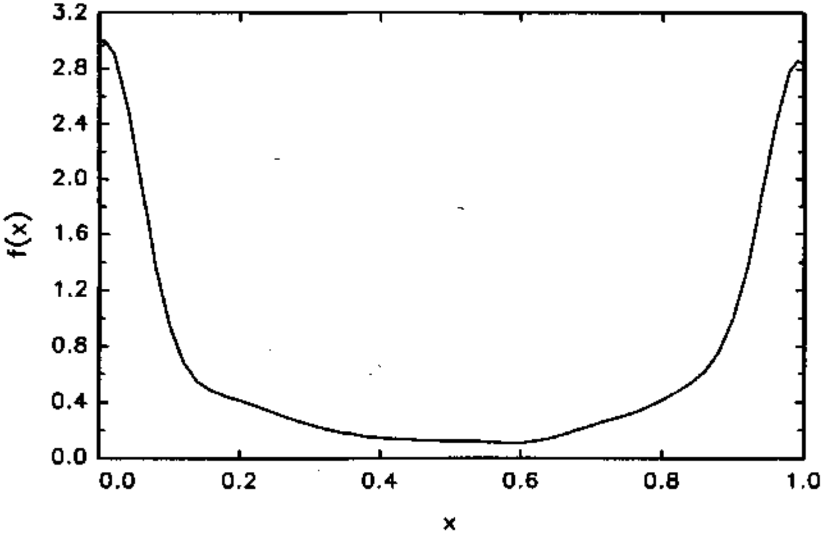
The existence of punctuated equilibria need not, however, imply that the end states have the highest probability in the long term. The likeliest states may well be ones where the economy is incompletely specialized. As an example, Figure 5 has the switching function for a process where the probability of switching to technology A first increases, as A wins the larger share of the economy's resources, but then decreases, as the economy gets too congested with firms using technology A. An economic reason for such a phenomenon might be that workers are not all homogeneous and that some workers do not have the

Figure 3 — Workers' Switching Function in a Small Open Economy: The Case of Bounded Positive Externalities in Both Technologies



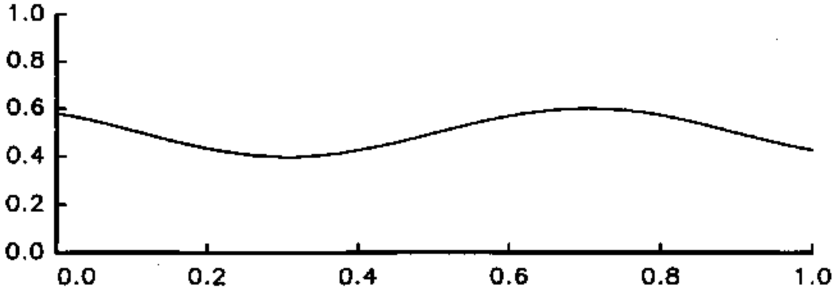
Note: The horizontal axis depicts the shares of workers in technology A, the vertical axis the probabilities of the next switch being from B to A.

Figure 4 — The Probability Distribution of Workers' Shares in Technology *A* in a Small Open Economy: The Case of Bounded Positive Externalities in Both Technologies after 100 Switches



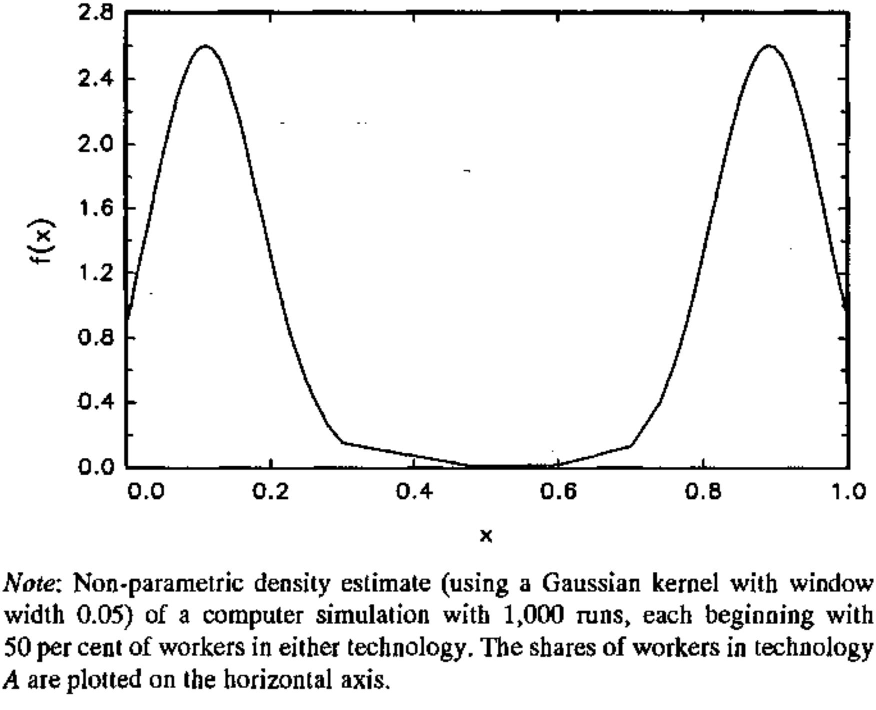
Note: Non-parametric density estimate (using a Gaussian kernel with window width 0.05) of a computer simulation with 1,000 runs, each beginning with 50 per cent of workers in either technology. The shares of workers in technology *A* are plotted on the horizontal axis.

Figure 5 — Workers' Switching Function in a Small Open Economy: The Case of Bounded Positive Externalities and Congestion in Both Technologies



Note: The horizontal axis depicts the shares of workers in technology *A*, the vertical axis the probabilities of the next switch being from *B* to *A*.

Figure 6 — The Probability Distribution of Workers' Shares in Technology A in a Small Open Economy: The Case of Bounded Positive Externalities and Congestion in Both Technologies after 500 Switches



Note: Non-parametric density estimate (using a Gaussian kernel with window width 0.05) of a computer simulation with 1,000 runs, each beginning with 50 per cent of workers in either technology. The shares of workers in technology A are plotted on the horizontal axis.

appropriate skills to work with technology A. The probability of further job switches from B to A would therefore decline, once all workers with flexible skills are already employed with technology A. The same would hold for technology B if there was congestion, too. A snapshot, again based on computer simulation, of the probability distribution after 500 switches is given in Figure 6; notice that the two modi of the distribution are not at the extremes of complete specialization in either technology.

(iv) Increasing returns versus comparative advantage. As a final case, consider a small open economy with increasing returns in the form of positive externalities in technology A and a comparative advantage in technology B. In particular, assume transition probabilities are

[25] $p_{BA}(n) = 1/3 + n^2/2N^2$

$$p_{AB}(n) = 2/3 - n^2/2N^2\,.$$

The Master equation reads

$$[26] \quad \frac{dP(n,t)}{dt} = \left(1/3 + \frac{n^2}{2N^2}\right)P(n+1,t) - \left(1/3 + \frac{n^2}{2N^2}\right)P(n,t) + \left(2/3 - \frac{n^2}{2N^2}\right)P(n-1,t) - \left(2/3 - \frac{n^2}{2N^2}\right)P(n,t)\,.$$

Again, the long-run stationary probabilities of all states can be expressed in terms of the probability of the lower end state according to:

$$[27] \quad \tilde{P}(n) = \tilde{P}(\underline{n}) \prod_{\nu=\underline{n}}^{n} \frac{p_{BA}(\nu-1)}{p_{AB}(\nu)} = \tilde{P}(\underline{n}) \prod_{\nu=\underline{n}}^{n} \frac{2N^2+3n^2}{4N^2-3n^2}$$

subject to the normalization condition $\sum_n \bar{P}(n) = 1$. The solution is an extreme form of a bimodal distribution, where the modi are at the end states of complete specialization. Their stationary probabilities are

$$\bar{P}(0) = 0.1087 \text{ and } \bar{P}(100) = 0.6209\,,$$

while the stationary probabilities of almost all states in between are virtually, yet not quite equal to zero. Thus, the economy is almost certain to develop a very high degree of specialization in either technology, and much more likely to be specialized in technology A, where it exploits increasing returns to scale, than in technology B, where it has a comparative advantage. Yet in either case, the economy may still have transitions from complete specialization in one technology to complete specialization in the other, even if that would be an extremely rare event.[67]

The characteristic feature of this kind of recontracting process with punctuated equilibria is that the likely allocation of labour may depend for a long time on the initial (perhaps arbitrary) share of workers in technology A. If that share was small, the positive external effects would be weak and wages lower than in industry B so that workers would be more likely to move there. If the initial share of A exceeded a critical level, the positive external effects would already be sufficiently strong to entice more workers into technology A, re-

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[67] If the time horizon is extended to infinity, such radical transitions will certainly happen at some points in time. Recall that one may therefore aptly speak of *punctuated equilibria*.

inforcing its productivity and wage lead. Because the economy remains almost completely specialized in one technology for long periods of time, the dynamics of specialization may now look to a temporary observer like a Markov chain with absorbing barriers. But, of course, unless complete specialization in one technology is fully absorbing, there always remains the possibility of a transition to the other extreme, however unlikely it may be.

The assumption made about the evolution of transition probabilities in cases (*iii*) and (*iv*) prevent these processes from being adequately understood by making reference to the theory of ordinary stochastic processes. A fundamental characteristic of these cases is the asymmetric frequency distribution of fluctuations around the global mean of the state variable before and after the point of bifurcation. These fluctuations happen frequently before, and only rarely after this point. For the time-dependent as well as for the stationary solution of these processes, use of the Master equation in discrete (event) time is therefore indispensable.

Similar stochastic processes with hysteresis can as well arise in open economy models other than the simple Ricardian one, although in more complex models of the Heckscher-Ohlin variety rarely with the result of (almost) complete specialization. In any case, to rationalize the hypothesis of technological accumulation, based on historical leads and lags, in economic terms, the assumptions of the standard neoclassical model of perfectly competitive markets and constant returns to scale production technologies have to be altered in some way that would affect identical countries asymmetrically. As an important example, Grossman and Helpman (1991) derive a hysteretic variant of their model of dynamic comparative advantages by simply assuming that knowledge spill-overs from R&D are only national in reach. The unintended by-product of private R&D investments then contributes to the national stock of public technical knowledge, thereby enhancing productivity in the R&D of national firms relative to foreign competitors in the same sector.[68]

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[68] But other explanations for hysteresis might also be relevant. So for instance the network externalities stemming from large distribution and service networks in international markets (Katz and Shapiro 1985).

III. The Approach of Generalized Urn Schemes to Specialization in a Two-Country Model

While the small country case, in which the process of specialization is bounded by the scarcity of factors of production, can be suitably modelled as a re-contracting process, using the Master equation approach, this does not hold for the case of a large open economy. In this case, the resources of the large country are less likely to place the binding constraint on the growth of any individual specialized industry whose share in the total economy remains small. Instead, the process of a country's specialization in an emerging industry, whose speed and sustainability largely depend on the elasticity of effective demand, is likely to be bounded by the limited size of world markets for the specialized good. It is for this reason that a modelling approach within the framework of generalized urn schemes seems more appropriate.[69]

The difference between this and the Master equation approach is simple, yet important: While the Master equation models transitions which remain of constant magnitude relative to market size, generalized urn schemes have transitions which shrink monotonically in proportion to market size. As a consequence, systems described by the Master equation have convergence in distribution, while generalized urn schemes exhibit the stronger form of convergence to one of possibly several stable fixed points of the process.

1. Bounded Learning by Doing

Suppose there are two large open economies each of which has a perfectly competitive machine tool industry. These competing industries begin at about the same time with the introduction of some newly invented product where productivity is subject to positive external effects from learning by doing. Assume that both countries have the same potential of learning by doing and that prices equal marginal costs in each industry, but that marginal costs decline as learning by doing accumulates. Although the production function may be identical in the two countries, marginal costs may differ at any given point in time due to differential learning experiences. The potential customers, distributed uniformly on a straight line between the two countries, are highly price sensitive and take transport costs into account, which are a linear function of distance from the respective producer.

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[69] Applications of such schemes to economic allocation processes are described in Arthur (1988), and more extensively in Dosi and Kaniovski (1994).

What determines the shape of this allocation process is the sequence of customers' orders which arrive at random from the different locations between the two countries, where the producers are located. At any point in time, the next purchase will pick the offer from country *A* if the excess transport costs of this offer (versus country *B*'s offer) are lower than the excess price of country *B*'s offer over country A's offer, and vice versa. Assume that purchases are strictly sequential, i.e. never simultaneous.

As in the dynamics of specialization in a small country, there may be situations where the allocation process leads to an equal share of the market between the two countries' industries and others where the process leads to a monopoly of one country. However, because in general the probability that the next customer will buy from a particular country does not only depend on the current share of that country in the world market but also on the current total size of the expanding world market for the newly introduced good, these allocation processes do not have the property that probabilities of transitions are only dependent on the current relative market shares of the countries. Because the transition probabilities, instead, also depend on the absolute numbers of adoptions from each country, these processes are more difficult to analyze formally than the recontracting processes examined above.

Nevertheless, Arthur et al. (1983), Arthur and Ermoliev (1986) and Arthur (1989) have been able to establish a number of general theorems, which cover a large number of cases. These theorems assert that the possibility of monopoly of one country's industry depends on the shape of the relevant adoption function which maps vectors of adoption shares of the two countries' products x onto the space of probabilities p, with which the products will be adopted when the next customer makes his choice. In this representation there may be certain stable attractors, or fixed points, to one of which market shares and choice probabilities would converge. The main theorems are as follows (Arthur 1989: 125):

THEOREM 1: *"An adoption process is non-ergodic and non-predictable if and only if its adoption function* **p** *possesses multiple stable fixed points." Non-ergodicity means here that the process converges to one of several asymptotic adoption shares.*

THEOREM 2: *"An adoption process converges with probability one to the dominance of a single supply country if and only if its adoption function* **p** *possesses stable fixed points only where* **x** *is a unit vector."*

THEOREM 3: *In a general model, where the next customer's payoff to buying from country A, after country A's industry has already produced and sold* α *units, is given by* $\pi(\alpha) = u(A) + g(\alpha)$*, an additive function of random transport costs* $u(A)$ *and the product price* $g(\alpha)$*, the possibility of country monopoly depends on the shape of the monotonically increasing price-saving function*

$g(\alpha)$. Where this function increases without upper bound, the process has stable limit points only at simplex vertices, with probability one. Where this function is bounded, because the potential for price saving becomes exhausted, the monopoly of a single country may not occur.

To prove these theorems is not easy when p is a function of shares as well as market size, which grows over time. Since this is the case here, one first has to show that the adoption function converges to a limiting function p. In the present example of bounded learning by doing the limiting function is one where both countries' goods are chosen with probability 1/2. This is because the productivity lead a country may have gained through faster learning by doing will inevitably be eroded, when the learning in the leading country levels off and the other country catches up. Hence the limiting function has only one stable fixed point, namely at equal market shares for both countries; and a stable asymmetric adoption pattern (a permanent bifurcation in terms of market shares) could only occur if the market was saturated before the upper bound of learning by doing was reached in both countries. So, unless the system has a mechanism to exit one country, if it does not sell a certain minimum share of products over a specified period of time, the termination of the adoption process, i.e. the collapse of the market, appears to be the only mechanism capable to prevent convergence to equal world market shares of the two countries.[70]

The evolution of the probability distribution of a country's market share can be illustrated be means of computer simulations for particular cases. Suppose that the probability that the next purchase will be from country A is a function of the number of previous sales from country A as well as of the number of previous sales from the competing country B:

$$[28] \qquad P(\alpha,t)=\frac{1}{2}\left[\left(1+100e^{(12-\alpha)/4}\right)^{-1}-\left(1+100e^{(12+\alpha-t)/4}\right)^{-1}+1\right],$$

where α is the number of previous purchases from country A, t is the total number of previous purchases from both countries, the current size of the world market. For various given values of t, this adoption function is represented in Figure 7. These graphs clearly show that the market share a country must have to raise the likelihood (above the even odds) of winning the next purchase is larger, the larger the total market has already grown.

Computer simulations, selected results of which are displayed in Figure 8, reveal that the probability distribution of adoption shares of the two countries does not converge *monotonically* to its long-term equilibrium: It begins as an

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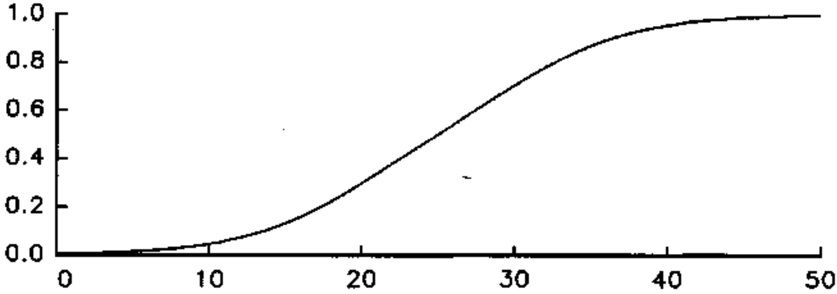
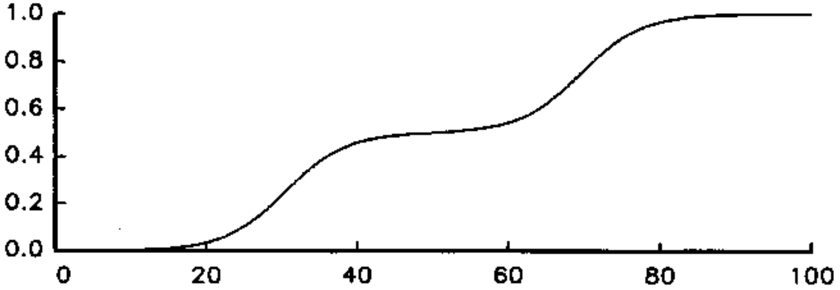
[70] As an aside, the situation of market collapse would, in fact, be quite relevant in the case of product cycles.

Figure 7 — The Adoption Function for Two Large Countries' Products in the World Market: The Case of Bounded Learning by Doing

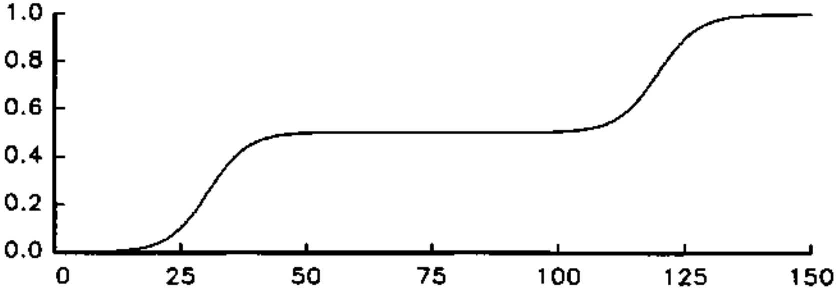
Panel a: total market size $t = 50$



Panel b: total market size $t = 100$

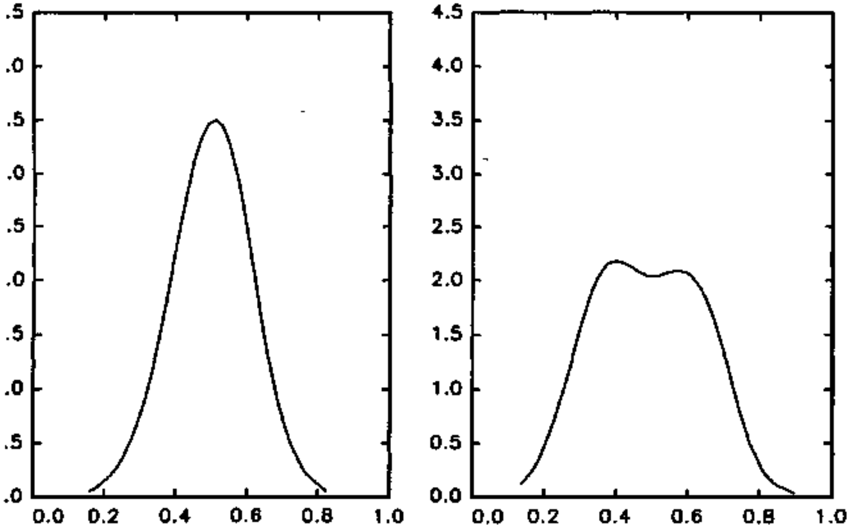


Panel c: total market size $t = 150$



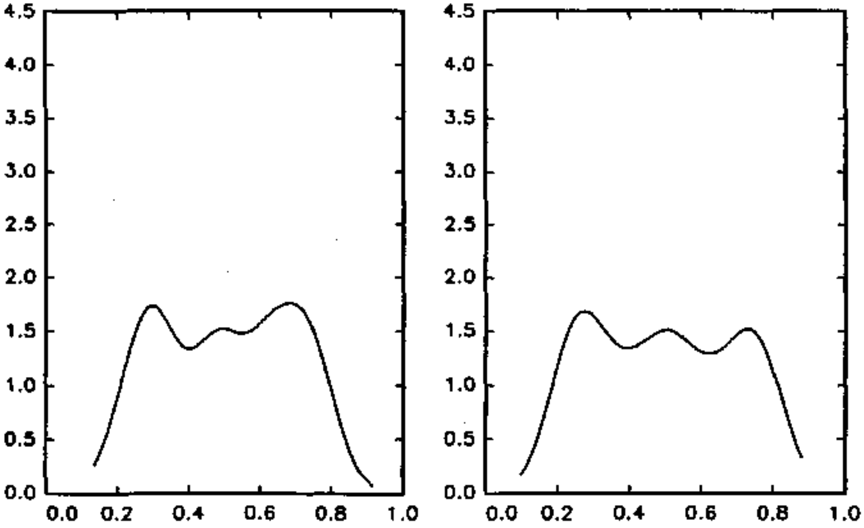
Note: The vertical axis plots the probability that the next adoption will benefit exporters in country *A* as a function of the number of previous adoptions of products from that country; this number is plotted on the horizontal axis.

Figure 8 — Evolution of the Probability Distribution for Adoption Shares of Two Large Countries' Products in the World Market: The Case of Bounded Learning by Doing



After 50 adoptions

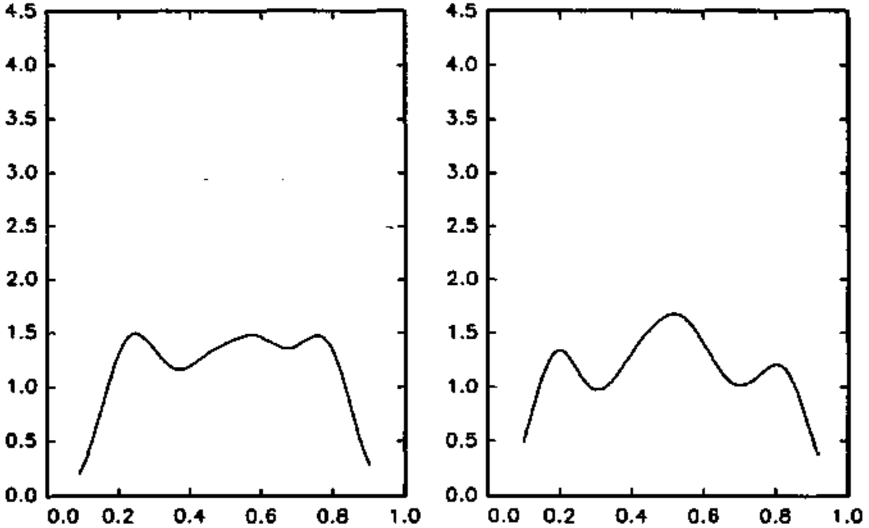
After 65 adoptions



After 80 adoptions

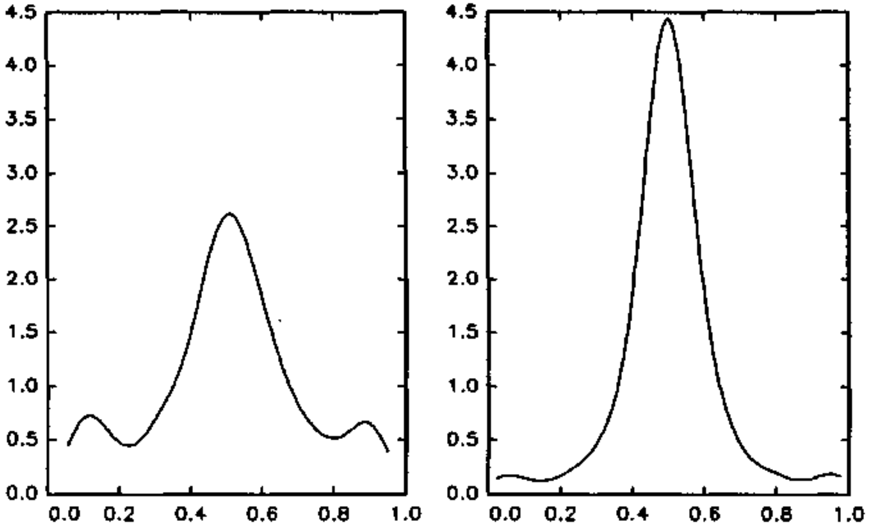
After 90 adoptions

Figure 8 continued



After 100 adoptions

After 120 adoptions



After 200 adoptions

After 500 adoptions

Note: The graphs are non-parametric density estimates (using a Gaussian kernel with window width 0.05) of computer simulations with at least 1,000 runs each. The horizontal axis stands for adoption shares of products from country *A*.

unimodal symmetrical distribution, evolves into a bimodal distribution after about 60 adoptions, and then into a trimodal distribution after about 90 adoptions. The third, central modus subsequently continues to grow, to attract a larger and larger share of the distribution's total probability mass, while the two marginal modi move towards the end states of the allocation domain, and shrink into insignificance. Finally, the distribution regains a unimodal shape, and then goes on to converge in probability to the point where all probability mass is concentrated at the state of equal market shares for both countries' industries.

In reality, of course, this process would in many cases be truncated, because markets for any particular good rarely grow without bound. But then, if the market collapses at a time when the probability distribution has reached its bimodal or trimodal stage, one country's industry may indeed have come to dominate the market at the other country's expense in an actual realization of the adoption process. This temporary asymmetry of adoption realizations would be due to the more rapid learning by doing which the winning country's industry would have accidentally been able to exploit, benefiting from a comparatively larger share of the early adoptions (by lead customers).

On the other hand, the market might not collapse, but might stabilize at a certain size despite saturation if there is demand for product replacements. The continuing process could then be modelled as a recontracting process, in which positive feedback and path-dependence may or may not be important. A reason for continued positive externalities in product adoption might be conformity effects as in the case of fashionable product design, or quality improvements incorporating learning-by-using feedbacks from customers. The country which has won the larger share at the time of market emergence may thus be able to hold on to self-sustaining market dominance even as market growth levels off. Endogenous quality improvements have, at least theoretically, the potential of providing unbounded reinforcement in the adoption process.

2. Unbounded Positive Feedbacks

Unbounded positive feedbacks, which can help to sustain productivity gains from bounded learning by doing in a particular country, may as well originate from the production side. For example, a country could raise the quality of its products by introducing more differentiated and specialized non-traded inputs,[71] which would become a profitable activity as the volume of production in

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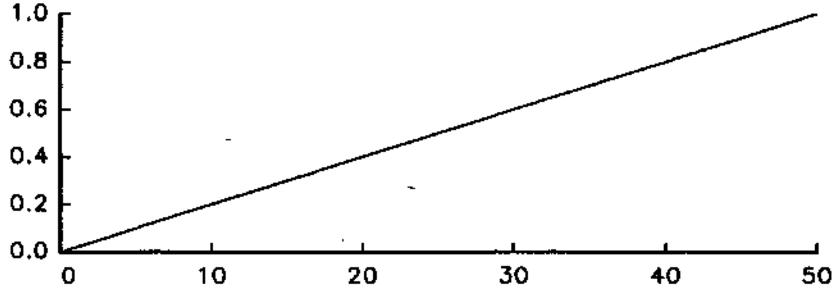
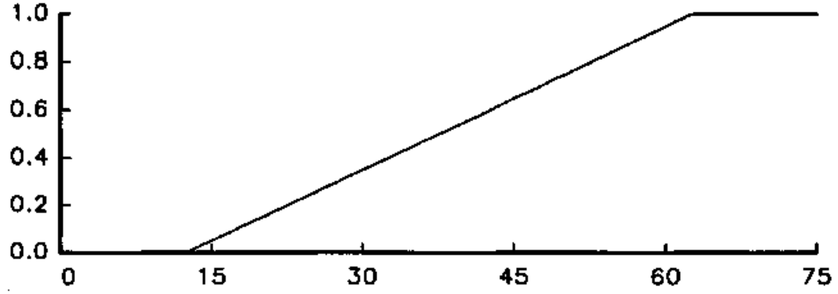
[71] This would not only hold in the case of strictly non-traded inputs, but also when inputs are costly to trade, for example, because they require extensive specialized service facilities or other fixed set-up costs.

Figure 9 — The Adoption Function for Two Large Countries' Products in the World Market: The Case of Unbounded Learning by Doing

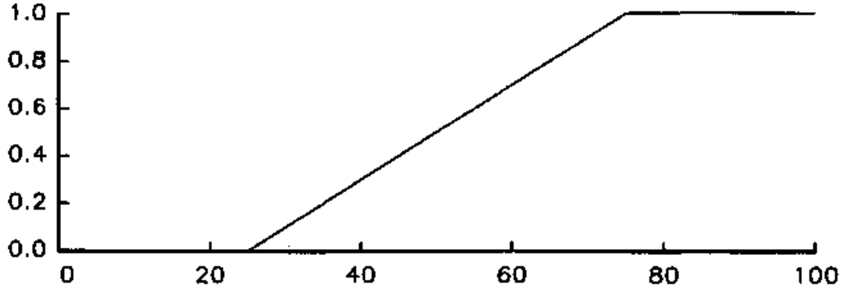
Panel a: total market size $t = 50$



Panel b: total market size $t = 75$



Panel c: total market size $t = 100$



Note: The vertical axis plots the probability that the next adoption will benefit exporters in country *A* as a function of the number of previous adoptions of products from that country; this number is plotted on the horizontal axis.

the country grows. Such a process would be akin to endogenous growth due to monopolistic competition and increasing specialization in capital goods, as modelled by Romer (1987) as well as by Barro and Sala-i-Martin (1992b). Another way to sustain productivity gains from bounded learning by doing might be to transfer these gains, at least partly, to other product lines, or to the next generation of products, a possibility examined in recent theoretical work by Stokey (1988) and Young (1991).

The case of unbounded positive feedbacks is relatively simple to analyze with reference to an adoption function, like that depicted in Figure 9, which converges to a function with stable fixed points at the end states of monopoly of either country. This is confirmed by computer simulations, in which the probability of purchase from country A is assumed to evolve according to (where α is again the number of previous purchases from country A, and t the total number of purchases from both countries):

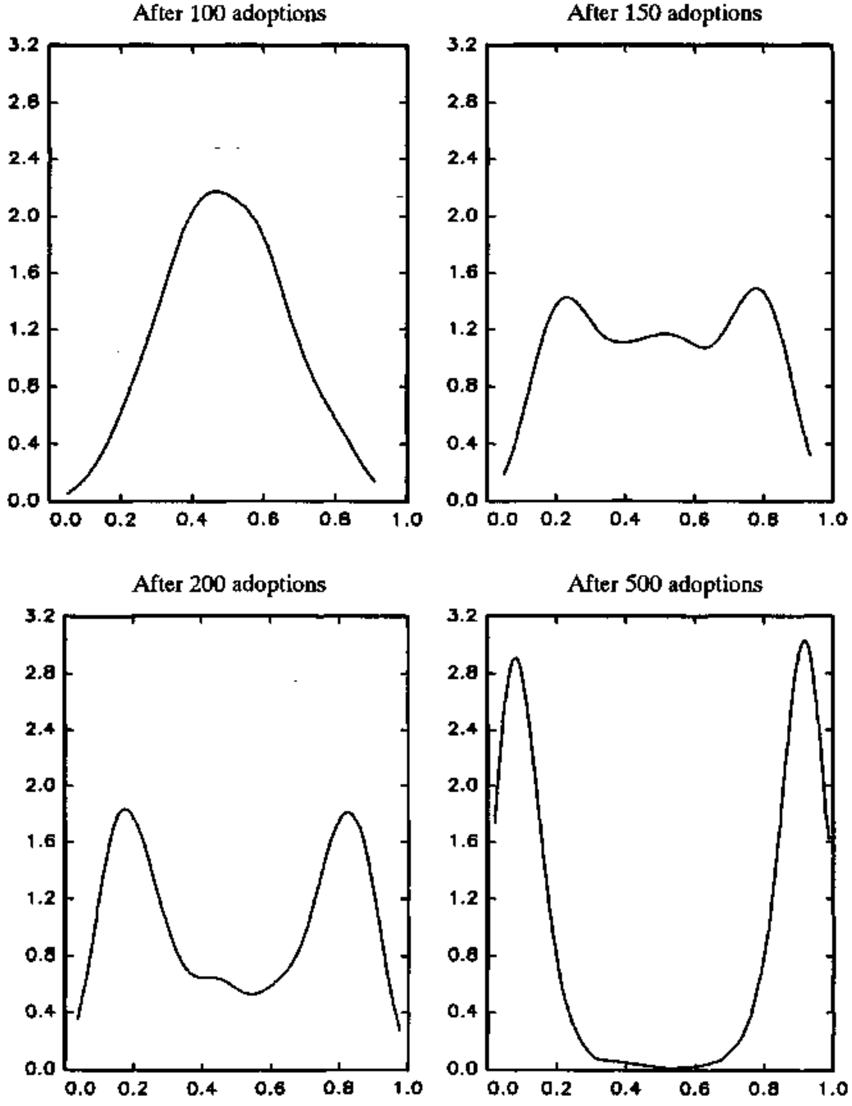
$$[29] \qquad p(\alpha,t)=\begin{cases} 1 \quad \text{if} \quad \alpha \geq t/2+25 \\ 1/2(0.02(\alpha)-0.02(t-\alpha)+1) \quad \text{if} \quad t/2-25<\alpha<t/2+25 \\ 0 \quad \text{if} \quad \alpha \leq t/2-25. \end{cases}$$

Figure 10 reveals that the evolution of the probability distribution of adoption shares has basically three stages: it is first unimodal, then trimodal, and finally bimodal. In the final stage, the two modi grow relative to the rest of the distribution, and move towards the end states on the domain. It is interesting to note that the trend towards the concentration of an entire industry in one country, which results from unbounded learning by doing in large countries, may render the observable dynamics of increasing industrial specialization in that country quite similar to the situation in a small country, where positive externalities may lead to the absorption of all resources in one industry.

As a caveat, these results suggest that unless learning by doing is unbounded, for one reason or another, the assumption of stationary transition probabilities, which is important in the subsequent empirical work, may be a less defensible assumption in the case of large countries than in small countries.

To summarize, the benchmark model of dynamic comparative advantage assumes both that the privately appropriable part of R&D output is internationally tradeable and that knowledge spill-overs are not impeded by international borders. Then, disregarding other institutional factors, the international allocation of R&D activities is — at least in principle — not tied to the location of the *users* of R&D output. Moreover, in the absence of adjustment and transaction costs, patterns of specialization in technology as well as in actual production would be quite mobile over time and independent of each other as they respond to changes in the relative factor endowments of countries. Since the comparative

Figure 10 — The Evolution of the Probability Distribution for Adoption Shares of Two Large Countries' Products in the World Market: The Case of Unbounded Learning by Doing



After 100 adoptions

After 150 adoptions

After 200 adoptions

After 500 adoptions

Note: The graphs are non-parametric density estimates (using a Gaussian kernel with window width 0.05) of computer simulations with at least 1,000 runs each. The horizontal axis stands for adoption shares of products from country *A*.

advantages for production and for R&D in an industry would be distinct and might be located in different countries, not even the specialization patterns of those technologies which are confined to single industries would need to evolve along the same trends as the corresponding industries.

By contrast, the case for historical events as the determinants of sectoral patterns of technological specialization, based on the theory of technological accumulation, would imply that patterns of specialization in technology as well as in production are much less mobile, especially when a country's industrial structure is already heavily skewed towards certain industries.[72] If knowledge spill-overs from R&D were only national in reach, hysteresis could be decisive in the sense that temporary events, like price shocks or industrial and technology policies, can have lasting effects on a country's pattern of technological specialization and trade. Such lasting effects might be recognizable through high persistence of specialization patterns in production and technology despite changes in the relative factor abundance of countries. Persistence would be expected to be particularly pronounced in technological specialization where the positive external effects in the form of knowledge spill-overs from R&D would have their most direct and strongest impact. But in general, a close relationship would be expected between the dynamics of countries' specialization in certain technologies and in the production in those industries whose products make intensive use of these technologies.

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[72] Although related, the theory of technological accumulation is not simply a revamping of earlier technology gap theories. Whereas the latter assumed a single country to be the technological leader in all sectors, and all other countries more or less behind, technological accumulation theory allows for the possibility that technological leads are spread across different countries rather than being all concentrated in one.

> ... the effect of the *division of labour*, both in mechanical and in mental operations, is, that it enables us to purchase and apply to each process precisely the quantity of skill and knowledge which is required for it: we avoid employing any part of the time of a man who can get eight or ten shillings a day by his skill in tempering needles, in turning a wheel, which can be done for sixpence a day; and we equally avoid the loss arising from the employment of an accomplished mathematician in performing the lowest processes of arithmetic.
> — Charles Babbage (1835: 201)

D. Comparative Advantage for Research and Development across Industries in OECD Countries

I. The Hypothesis of Comparative Advantage for Research and Development

Is the notion of comparative advantage relevant for the allocation of R&D activities across countries and across industries? This question, although of great importance for the desirability and design of industrial and technology policies, seems to have received little attention in the scholarly literature so far. As a general theoretical explanation for specialization in production and trade, the concept of comparative advantage is sometimes used as a catch-all for a variety of sources like different productivity levels due to different technologies (the case of Ricardo 1817), differences in factor endowments (the basis of Heckscher-Ohlin theory), or even differences in organizational conventions between countries as recently suggested by Aoki (1993).[73] To better understand the pros and cons of selective industrial and technology policies, it will be important to empirically discriminate between the different potential sources of comparative advantage. The present chapter explores whether factor proportions are empirically relevant as a potential source of comparative advantage in R&D activities.

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[73] Aoki (1993) argues that comparative advantage for innovative activities in different kinds of technological environments can arise endogenously as differentiated modes (i.e. organizational conventions) of information processing in firms and R&D laboratories emerge from the evolutionary interaction of managers within their respective systems. In his analysis the relative magnitudes of systemic risk at the macrolevel and of idiosyncratic risk at the microlevel of a given technological environment determine which mode of information processing is more efficient.

Recent advances in the theory of economic growth, surveyed in Chapter B, have emphasized the importance of the creation and adoption of new technical knowledge in determining the distribution of industrial production across interdependent economies and in raising productivity. Knowledge capital created by industrial research and development and the capacity to absorb and apply new technical knowledge in the production sphere are thought to be additional factors in determining countries' production specialization across industries. This thinking rests on the assumption that industries can be distinguished by the intensity with which they rely on innovation and on the adoption of new technology. Only if industries can be consistently classified into high-, medium- and low-technology industries, can countries' differential innovative abilities constitute an important source of comparative advantage for high-tech versus low-tech industries.[74] This kind of comparative advantage is a central theme of much recent theoretical work on endogenous technological change in open economies, like that of Grossman and Helpman (1991), but also of earlier empirical work on the technology factor in international trade, like that of Dosi et al. (1990).

A considerable part of R&D outputs probably is industry-specific. So, too, are some of the inputs, like highly specialized scientists, at least in the short run. But apart from this, R&D may be industry-specific in the deeper sense that it is not an economically homogeneous activity across industries in which any kind of R&D output can be generated efficiently by much the same combination of inputs: teams of scientists, engineers and technical support staff in equal proportions and all equipped with a capital stock of approximately equal value per employee, consisting of laboratories with all the necessary instrumentation. Instead, R&D activities in different industries seem to have different relative resource requirements. Consequently, not only the overall level of R&D activities in any particular country, but also the relative distribution of a country's R&D activities across different industries may reflect comparative advantages distinct from those for the production of tangibles in the corresponding industries.[75]

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[74] A widely used measure is R&D intensity, defined as the ratio of business enterprise R&D expenditure either to sales or to value added. On this criterion aerospace (aircrafts), computers, electronics, pharmaceuticals (drugs and medicines), professional instruments and electrical machinery are usually classified as high-technology industries. See, for instance, OECD (1992a: 125).

[75] In an early empirical analysis of factor endowments and international innovation patterns Davidson (1979) concludes that countries tend to concentrate their innovative activities in those industries whose production uses intensively their most expensive factors. This, he argues, might lead to trade patterns conflicting with Heckscher-Ohlin theory. But he does not consider the possibility — to be examined here — that differential factor costs in the R&D of different industries can also be

Of course, the possibility that comparative advantages for production and for R&D in one and the same industry are economically and geographically distinct can only arise if the output of R&D is internationally tradeable, at least to some extent. If it were not, then patterns of specialization in R&D would be fully determined by countries' patterns of specialization in the production of tangibles, thus ultimately by the comparative advantages for producing the different manufacturing products. But in reality, the generation and application of new technical knowledge need not always happen in the same place. Within firms, R&D is often concentrated in centralized laboratories, whereas the application of new technical knowledge takes place in all plants wherever they may be located. The pervasive activities of multinational enterprises — the prototype of a capitalist institution geared towards the transfer of technology across national borders — testify that profitable opportunities for international trade in technical knowledge exist and are indeed exploited, although perhaps not fully. Moreover, there is evidence of a considerable and increasing international trade in patents and licences for new technology even between unrelated firms in the OECD countries (Vickery 1986).

This raises the question whether one can empirically identify the sources of comparative advantage for the R&D activities in individual industries that are distinct from the country-specific determinants of the related manufacturing activities. Looking at individual industries, what actually determines the allocation of their R&D activities across countries? To the extent that part of the industry-specific technical knowledge is not tradeable, or tradeable only at very high transaction costs, R&D activities should be geographically tied to industrial production. But to the extent that tradeable technical knowledge is generated, other factors may become important codeterminants of the international allocation of industry-specific R&D activities.

Countries with above-average endowments of university-educated scientists and engineers, for instance, might have a comparative advantage in those R&D activities which require the most intensive use of scientists and engineers and relatively little use of technical and other supportive staff.[76] These countries

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an important influence. To measure patterns of innovations in eight selected industries he relies on a (University of Sussex) data base of product and process innovations that certain 'knowledgeable sources' (technology experts) deemed to be of commercial and technical significance.

[76] In the medium term, scientists and engineers — at least the majority of them — can be viewed to be sufficiently mobile across technical fields so as not to be constrained to work in only one particular industry. For example, aircraft engineers can do useful work also in other transport engineering, the knowledge of pharmacists can be of use in general chemical or food research, and electrical engineers can apply their skills just as well to computers or electrical machinery as to radio, television and communications equipment. Also relevant in the medium term is the

would then have a greater share of their total manufacturing R&D devoted to the most human-capital-intensive R&D activities. Analogously, countries with a relatively low percentage of university-educated engineers in the labour force might specialize in R&D activities which are comparatively less demanding of human capital, but more labour-intensive. Of course, if other factors were important codeterminants of comparative advantage in R&D, these would make things more complicated. Nevertheless, any relevant factor which is and remains characteristic of countries in the long run, could — at least in principle — be identified in empirical cross-country studies. The preceding is taken to be the factor endowments hypothesis of R&D in the present study.

The alternative hypothesis would be that patterns of specialization in R&D are not directly determined by relative factor endowments, but instead are the outcome of a unique historical process. Economic historians like Rosenberg (1994), Arthur (1989) and David (1988a, 1988b) have argued that such processes are path-dependent, so that future patterns of specialization in R&D would remain unpredictable even if the likely future movements of all relevant factor endowments were known.

Any empirical study of these issues will have to cope with several theoretical and methodological difficulties, including the question of exogeneity of factor endowments with respect to specialization patterns, the Heckscher-Ohlin assumptions of complete immobility of the relevant factors across borders and perfect mobility of factors within countries, and the difficulties of measuring human capital endowments of countries and human capital requirements of production.

The present value of the human capital endowments of the richest OECD countries may well have surpassed the present value of their respective endowments of physical capital. But much of this immense stock of human capital is unusable in R&D. To measure the relevant portion of human capital in a pragmatic way, this study simply takes the full-time equivalents of R&D scientists and engineers employed in a country, as defined in the 'Frascati Manual' of the OECD (1981).[77]

It is a basic assumption of this study that many scientists and engineers are not so specialized that they can be employed only in the R&D of one particular industry. At the same time, it is assumed that scientists and engineers do not

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mobility of students of science and engineering. Cohorts of students often concentrate their studies on those fields which are expected to offer the broadest choice of job openings and the highest salaries.

[77] These are 'scientists or engineers engaged in the conception or creation of new knowledge, products, processes, methods and systems, including managers and administrators engaged in the planning and management of the scientific and technical aspects of research work' (OECD 1981: 67).

migrate in large numbers across international borders in search of higher income opportunities. Although there is some evidence that scientists and engineers are more mobile within the English-speaking industrial countries than across countries with different languages, it remains realistic to assume that for most countries people's cultural and social ties tend to be quite effective breaks on the mobility of human capital.[78] The assumption of no international mobility of human capital may therefore be a good approximation for the purposes of this study.

Section D.II presents a preliminary exploration of some of the relevant data on R&D activities in OECD countries which bear on the questions discussed here. Section D.III, then, goes on to examine the relevant hypotheses more carefully within the framework of regression analyses. Section D.IV presents tests for the impact of human capital endowments on countries' specialization in the R&D of individual industries, and draws preliminary conclusions from this particular empirical approach.

II. The Distribution of R&D Activities across Industries in OECD Countries

The present study looks at fourteen OECD member countries for which more or less comparable data on R&D activities is available for the period from 1970 to 1989, albeit with quite a few deplorable data gaps.[79] These countries are Australia (AUS), Belgium (BEL), Canada (CAN), Denmark (DK), Finland (FIN), France (FRA), West Germany (DEU), Italy (ITA), Japan (JAP), the Netherlands (NL), Norway (NOR), Sweden (SWE), the United Kingdom (UK) and the United States (US). Combined they generated roughly 90 per cent of total OECD exports throughout the period considered here. Panel a of Figure A1 in Appendix III shows countries' relative endowments with R&D scientists and engineers.

Four subgroups of countries can be distinguished for the 1970s, with the United States and Japan being the countries relatively (as well as absolutely)

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[78] It is noteworthy that recent empirical research of Feldstein and Horioka (1980) as well as Sinn (1992) suggests that even the international mobility of financial capital remains much lower than was once thought by many advocates of free exchange rates and of the abolishment of capital controls.

[79] The descriptive statistics of this section refer to data averaged over two ten-year intervals, the 1970s and the 1980s, so that data gaps are hidden. See Appendix I for a list of variables and observations included in this study.

best endowed with R&D scientists and engineers, West Germany, the United Kingdom and Australia being almost at a par in the second group, Sweden, Norway, the Netherlands, France and Canada forming the third group, and Finland, Belgium, Denmark and Italy having the smallest share of R&D scientists and engineers in their respective total labour forces. Japan, after overtaking the United States in the late 1970s, has improved its lead in the 1980s. For the other countries, the figures for decades' average endowments with R&D scientists and engineers indicate that Sweden and Norway have overtaken both Australia and the United Kingdom, thus moving from sixth and seventh place, respectively, to fourth and fifth place right behind West Germany. Australia has also been overtaken by France and finds itself at about the same level as Canada which has meanwhile surpassed the Netherlands. Among the laggards, Belgium seems to have had the biggest relative improvement, overtaking Finland and almost catching up to the level of the neighbouring Netherlands.

Panel b of Figure A1 shows the average years of schooling of the adult population in 1975 and 1985. Comparing this graph with the previous one suggests that having a high level of formal schooling in the average may provide a fertile breeding ground for scientists and engineers, but that schooling alone is apparently not the whole story in explaining why some countries carry out relatively more industrial R&D than others. In fact, there may be a size effect: the three countries best endowed with R&D scientists and engineers, the United States, Japan and West Germany, are also the three biggest in the group.[80] On the other hand, the economies of France and Italy, also rather big, appear to be constrained by their comparatively low levels of educational achievements in the adult population average.[81] Among the well-educated Scandinavian countries and Canada, only Sweden and Norway seem to have translated this advantage into a relative endowment with R&D scientists and engineers comparable to that of the leading big countries.

Hence, this first look reveals something for everybody: For superficial support of the factor proportions version of comparative advantage one might point to the United States and Italy, whose ranking in terms of average schooling coincides with that in terms of R&D scientist and engineers endowment *and*

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[80] A size effect may stem from economies of scale associated with the application of new knowledge in production and from positive externalities in the form of knowledge spill-overs as emphasized by Romer (1990), or from other kinds of complementarities, like world class technical universities, public research institutions and technology transfer centres, which are sometimes subsumed under the term 'technology infrastructure'. See Tassey (1992).

[81] A scarce supply of skilled scientists and engineers can become a binding constraint for an economy already at relatively low levels of innovative activity because these are the people which are also needed in the planning and supervision of much of modern manufacturing.

which are two countries that are generally considered a technological leader and a technological laggard, respectively.[82] Those who believe in economies of scale and agglomeration in the creation and application of new knowledge can point to the fact that the three recognized technology leaders, the United States, Japan and West Germany, are not only relatively best endowed with R&D scientists and engineers, but are also the three biggest economies. Those who believe in country idiosyncrasies and path-dependency can point to the diverse Scandinavian experiences where Sweden seems to have caught up to the global R&D leaders, whereas Finland and Denmark, although equally well educated, keep on lagging in terms of their relative endowments with R&D scientists and engineers, which may be indicative of their intensity of engaging in innovative activities.

Clearly, the data, summarily described above, are too highly aggregated and too small in number to really test any of the competing hypotheses mentioned, but they do indicate that the resource which probably has the greatest importance for the allocation of R&D activities — human capital embodied in R&D scientists and engineers — is distributed rather unevenly across countries. This picture already emerges from a small sample of some of the richest OECD countries which are, at the same time, quite similar in so many other respects.

More pertinent information can be extracted from detailed data on the resources devoted to R&D activities in individual industries. Table A1 in Appendix III lists average R&D intensities, defined here as the percentage of current R&D expenditure to value added, in 17 manufacturing industries and 14 countries in the 1970s (panel a) and in the 1980s (panel b). Tables A2 and A3 list the corresponding rankings across countries and across industries, respectively. Table A2 indicates that those countries with a higher ranking in terms of total manufacturing R&D intensity tend to have a higher ranking in individual industries as well. In the 1970s as well as in the 1980s, the US had the highest ranking in terms of total manufacturing R&D intensity and Australia the lowest of all sample countries. Most of the other countries (with intermediate rankings) also kept their relative position over time. Among the few countries which did change their ranking slightly are West Germany, moving from fifth to fourth place, and Japan, moving from seventh to sixth place. For some countries, the rankings in terms of total manufacturing R&D intensity largely coincide with their rankings in terms of relative endowments of R&D scientists and engineers, but notably for Australia, Japan, the Netherlands and Sweden they do not. Japan

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[82] It is clear that a more rigorous statement on comparative advantages would have to relate relative prices to relative factor endowments, rather than relative factor endowments to market outcomes in terms of countries' relative technological strength.

ranks much lower in terms of R&D intensity than in terms of relative endowment with R&D scientists and engineers, the other three countries much higher.

Perhaps more revealing are the rankings of R&D intensity across industries in Table A3: those industries with a higher (lower) ranking in terms of overall R&D intensity for all countries combined tend to have a higher (lower) ranking also in individual countries. This pattern seems to be remarkably stable for most industries. Exceptions are shipbuilding and aircraft which have a very high ranking in some countries and a very low ranking in others. Shipbuilding is the second most R&D-intensive industry in Japan, but among the least R&D-intensive industries in Australia, Finland, France and Norway. Aircraft is the most R&D-intensive industry in France, West Germany, the US and others, but among the least R&D-intensive industries in Finland and Japan. These discrepancies suggest that shipbuilding and aircraft may be industries in which R&D activities are highly concentrated on a world-wide scale and that the technologically lagging countries in these fields compete either with older technology or with technology licensed from the small group of technological leaders. But in general, R&D intensity appears to be a property of industries which is preserved across countries.

This overall picture is supported by the correlations between countries' R&D intensities across industries (Table 2) and between industries' R&D intensities across countries (Table 3). In the 1970s as well as in the 1980s, correlations of R&D intensities across industries are remarkably high. For each country, the correlations with overall R&D intensities, computed for all countries combined, are actually positive and mostly close to unity. Only West Germany's R&D intensities in the 1970s are negatively correlated with more than two other countries. The correlations in Table 2 thus support the view that industries are universally distinguishable by the relative intensity with which R&D activities are pursued. Incidentally, industries with the highest relative R&D intensity as defined here, such as aircraft; radio, television and communication equipment; computers; and drugs and medicines, are among those classified as high-technology industries by the OECD (1992a: 125), on the basis of ratios between R&D expenditure and production in the three periods 1972–1974, 1979–1981 and 1987–1989. Also the industries with the lowest relative R&D intensity in Table A1, such as food, beverages, tobacco; fabricated metals; iron and steel; and non-metallic mineral products, are consistently classified as low technology by the OECD.

Looking at correlations between the R&D intensities of industries across countries (Table 3), a similar picture emerges.[83] Except for non-ferrous metals

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[83] That the correlations in Table 3 appear weaker than those in Table 2 may be partly due to the fact that there are fewer countries than industries in the sample.

Table 2 — Bivariate Correlations between Countries' R&D Intensities across Industries in the 1970s and 1980s[a]

	Australia	Belgium	Canada	Denmark	Finland	France	West Germany	Italy	Japan	Norway	Sweden	United Kingdom	United States	All countries
Australia	1.00	0.78	0.51	0.58	0.40	0.28	–0.22	0.65	0.18	0.71	0.11	0.23	0.21	0.15
Belgium	(0.86)	1.00	0.90	0.92	0.83	0.93	0.84	0.92	0.95	0.94	0.90	0.96	0.77	0.90
Canada	(0.80)	(0.92)	1.00	0.69	0.46	0.92	0.99	0.83	0.37	0.91	0.23	0.92	0.87	0.90
Denmark	(0.84)	(0.84)	(0.75)	1.00	0.93	0.80	0.29	0.83	0.11	0.87	0.87	0.77	0.57	0.60
Finland	(0.72)	(0.71)	(0.55)	(0.80)	1.00	0.22	–0.12	0.80	0.16	0.83	0.71	0.38	0.57	0.40
France	(0.49)	(0.98)	(0.82)	(0.71)	(0.45)	1.00	0.99	0.63	–0.09	0.91	0.47	0.96	0.81	0.90
West Germany	(0.19)	(0.94)	(0.65)	(0.63)	(0.10)	(0.89)	1.00	0.68	–0.17	0.47	0.29	0.99	0.96	0.97
Italy	(0.63)	(0.97)	(0.93)	(0.83)	(0.38)	(0.93)	(0.84)	1.00	0.16	0.90	0.49	0.67	0.70	0.63
Japan	(0.68)	(0.75)	(0.46)	(0.68)	(0.70)	(0.20)	(–0.06)	(0.18)	1.00	0.25	0.35	–0.11	0.03	0.07
Norway	(0.89)	(0.65)	(0.73)	(0.94)	(0.86)	(0.41)	(0.12)	(0.50)	(0.70)	1.00	0.63	0.92	0.75	0.81
Sweden	(0.20)	(0.96)	(0.45)	(0.36)	(0.12)	(0.26)	(0.27)	(0.33)	(–0.00)	(0.19)	1.00	0.47	0.29	0.40
United Kingdom	(0.75)	(0.96)	(0.95)	(0.78)	(0.47)	(0.89)	(0.77)	(0.96)	(0.28)	(0.60)	(0.61)	1.00	0.91	0.95
United States	(0.50)	(0.64)	(0.87)	(0.87)	(0.28)	(0.87)	(0.87)	(0.92)	(0.18)	(0.44)	(0.31)	(0.86)	1.00	0.96
All countries	(0.38)	(0.82)	(0.80)	(0.88)	(0.25)	(0.90)	(0.94)	(0.91)	(0.11)	(0.34)	(0.29)	(0.83)	(0.98)	1.00

[a] The results for the 1980s are given in parentheses.

in the 1970s, all correlations of individual industries with the total manufacturing R&D intensities of countries are positive. Also, most bivariate correlations between individual industries are positive. The only industry which stands out in both periods as an exception is radio, television and communication equipment where countries' R&D intensities are negatively correlated with most other industries. Apparently, the countries making a particularly strong R&D effort in this industry — relative to their value added in this industry — are not the countries most specialized in R&D generally. On the whole, however, the correlations in Tables 2 and 3 suggest that the R&D intensity of country-indexed industries, that is to say the ratio of R&D activities to value added in an industry as observed in a particular country, depends largely on two things: which industry one is talking about and whether the country, where the activities are located, has a comparative advantage in doing R&D.

The high aggregate R&D intensity of some countries does not seem to be merely a statistical artefact concealing totally random patterns in individual industries. Instead, countries that specialize in innovative activity — doing R&D with a comparatively higher intensity relative to their other economic activities in manufacturing — tend to do so throughout all industries. This supports the

Table 3 — Bivariate Correlations between Countries' R&D Intensities across Countries in the 1970s and 1980s

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
Food, beverages, tobacco (1)	1.00	–0.10	0.58	–0.13	0.53	0.87	0.25	0.56	0.61	0.55	0.55	–0.56	0.37	0.01	–0.25	0.49	0.45	0.39
Chemicals, excl. drugs and medicines (2)	(0.13)	1.00	0.21	–0.01	0.42	0.03	–0.07	0.18	0.45	0.50	0.57	0.38	0.27	0.38	0.85	0.11	–0.22	0.55
Drugs and medicines (3)	(0.34)	(0.41)	1.00	–0.09	0.28	0.78	0.48	0.55	0.79	0.33	0.01	–0.31	–0.05	–0.01	0.55	–0.31	0.37	0.31
Rubber and plastics (4)	(0.39)	(0.33)	(0.25)	1.00	0.24	–0.32	0.16	–0.04	–0.05	0.61	0.60	0.55	–0.26	0.70	0.18	0.02	0.28	0.47
Non-metallic mineral products (5)	(0.68)	(0.39)	(0.03)	(0.68)	1.00	0.57	0.20	0.70	0.47	0.67	0.68	–0.14	0.55	0.52	0.11	0.56	0.45	0.50
Iron and steel (6)	(0.63)	(0.23)	(0.73)	(0.12)	(0.27)	1.00	0.30	0.71	0.66	0.20	0.24	–0.70	0.17	–0.43	–0.22	0.21	0.32	0.23
Non-ferrous metals (7)	(0.62)	(–0.10)	(0.10)	(0.48)	(0.52)	(0.12)	1.00	0.19	0.27	0.38	0.06	–0.23	–0.09	0.46	–0.05	–0,09	0.40	–0.00
Fabricated metal products (8)	(0.31)	(0.63)	(0.53)	(0.39)	(0.61)	(0.48)	(0.22)	1.00	0.70	0.37	0.56	–0.17	0.13	–0.21	–0.08	0.25	0.34	0.27
Machinery, not elsewhere classified (9)	(0.44)	(0.58)	(0.54)	(0.36)	(0.39)	(0.54)	(0.20)	(0.92)	1.00	0.67	0.74	–0.33	0.17	0.19	0.71	0.15	0.35	0.52
Office and computing machinery (10)	(0.30)	(0.20)	(0.35)	(–0.23)	(0.09)	(0.43)	(–0.20)	(0.25)	(0.01)	1.00	0.90	0.31	0.54	0.82	0.47	0.59	0.89	0.75
Electrical machinery, excluding radio, TV and communication equip. (11)	(0.68)	(0.67)	(0.61)	(0.28)	(0.51)	(0.78)	(0.26)	(0.89)	(0.82)	(0.40)	1.00	0.46	0.33	0.71	0.53	0.36	0.58	0.87
Radio, TV and communication equip. (12)	(–0.50)	(0.15)	(–0.33)	(0.08)	(–0.17)	(–0.75)	(0.03)	(–0.32)	(–0.43)	(–0.05)	(–0.45)	1.00	–0.23	0.34	0.93	–0.23	–0.11	0.25
Shipbuilding and repair (13)	(0.55)	(0.19)	(–0.15)	(0.30)	(0.82)	(0.32)	(0.32)	(0.38)	(0.15)	(0.15)	(0.43)	(–0.32)	1.00	0.27	–0.16	0.88	0.12	0.25
Motor vehicles (14)	(0.79)	(0.39)	(0.60)	(0.55)	(0.49)	(0.63)	(0.26)	(0.51)	(0.47)	(0.48)	(0.66)	(–0.41)	(0.34)	1.00	0.42	0.27	0.60	0.81
Aircraft (15)	(–0.15)	(0.59)	(0.19)	(0.34)	(0.05)	(–0.18)	(–0.41)	(0.20)	(0.22)	(0.07)	(0.10)	(0.24)	(–0.09)	(0.44)	1.00	–0.25	–0.17	0.61
Other transport equipment (16)	(0.56)	(0.31)	(0.73)	(0.06)	(0.08)	(0.93)	(–0.04)	(0.47)	(0.52)	(0.55)	(0.76)	(–0.74)	(0.13)	(0.79)	(0.06)	1.00	0.15	0.23
Professional goods (scientific instruments) (17)	(0.39)	(–0.32)	(0.05)	(0.21)	(0.34)	(0.14)	(0.49)	(0.11)	(0.15)	(0.34)	(0.11)	(–0.00)	(0.19)	(0.11)	(–0.28)	(–0.03)	1.00	0.33
All industries (18)	(0.50)	(0.71)	(0.44)	(0.55)	(0.51)	(0.37)	(0.05)	(0.44)	(0.49)	(0.43)	(0.65)	(0.01)	(0.38)	(0.84)	(0.64)	(0.49)	(0.14)	1.00

[a] The results for the 1980s are given in parentheses.

view that a comparative advantage in R&D is indeed a country characteristic which some of them have and others do not.

But not all R&D activities are of the same kind — another fact which can be exploited in assessing and testing the impact of factor endowments on the allocation of R&D activities across countries. Hence, if countries' unequal relative endowments with R&D scientists and engineers are suspected to be a source of comparative advantage for R&D, this may be relevant not only for the aggregate level of R&D compared with all other economic activity, but also for countries' differential emphasis on R&D in different industries, provided that industries' R&D can actually be distinguished by their intensity of using different factors of production.

Focusing on human capital intensity, the ratios of R&D scientists and engineers to other R&D personnel observed in different industries and countries are given in Table A4. These ratios can be considered a first, rough indicator of human capital intensity of R&D activities.[84] Rankings across countries are shown in Table A5, rankings across industries in Table A6. These rankings do mostly not coincide with those in terms of R&D intensity shown in Tables A3 and A4. For example, Australia and Japan whose ranking in terms of R&D intensity is low and roughly average, respectively, have the highest rankings in terms of R&D scientists and engineers per other R&D personnel in both periods. Sweden, on the other hand, ranks high in terms of R&D intensity but roughly average in terms of human capital intensity in R&D. Similarly, industries' rankings in terms of R&D intensity and human capital intensity in R&D differ markedly.[85] Aircraft, for instance, the highest ranking industry in

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[84] Worries that this indicator might be misleading in the presence of important other factors — physical capital for instance — may actually be unwarranted. Brockhoff (1988) finds in regression analyses that the number of persons employed in R&D can in fact serve as a rather good indicator of real R&D expenditure. These regressions lend some support to one of the crucial assumptions of this study — that non-human factors are of minor importance in R&D. Only on the basis of this assumption, as well as on the assumption of no factor intensity reversals, can industries' R&D activities be completely and transitively ordered according to their human capital intensity alone, and the 'chain of comparative advantage' can be invoked. Each country will tend to export R&D services from the segment of industries, in which this country has a comparative advantage due to its relative endowment with human capital, and import R&D services of other industries.

[85] This is hardly surprising given the complex causality for industries' R&D intensity discussed in the theoretical and empirical literature on industrial organization and R&D. The main causal factors considered in this literature are expected market size, technological opportunities stemming from favourable supply side conditions, and the degree of appropriability of quasi-rents on innovations, which depends partly on the system of intellectual property rights and the market structure of a given industry. For a theoretical review and an empirical exploration into the determinants of R&D intensity, see Pakes and Schankerman (1984).

Table 4 — Bivariate Correlations between Countries' Average Ratios of R&D Scientists and Engineers to Other R&D Personnel across Industries in the 1970s and 1980s[a]

	Australia	Belgium	Canada	Denmark	Finland	France	West Germany	Italy	Japan	Norway	Sweden	United Kingdom	All countries
Australia	1.00	0.43	0.14	0.38	–0.25	0.20	–0.20	0.61	0.32	–0.17	0.24	0.13	0.25
Belgium	...	1.00	–0.03	0.23	0.83	0.71	0.70	0.31	0.20	0.60	–0.12	0.52	0.32
Canada	(0.50)	...	1.00	0.37	0.24	0.24	–0.25	–0.19	–0.18	0.32	0.37	–0.01	–0.08
Denmark	(0.49)	...	(0.25)	1.00	0.23	0.28	–0.09	0.47	–0.50	0.60	0.57	–0.06	–0.27
Finland	...	...	...	...	1.00	0.92	0.82	0.18	–0.00	0.83	–0.16	0.40	0.30
France	(0.45)	...	(0.69)	(0.33)	...	1.00	0.67	0.38	0.08	0.84	–0.29	0.43	0.51
West Germany	(0.09)	...	(0.52)	(–0.10)	...	(0.82)	1.00	0.21	0.50	0.81	0.05	0.22	0.23
Italy	(0.78)	...	(0.58)	(0.63)	...	(0.83)	(0.65)	1.00	0.27	0.21	–0.24	0.11	0.42
Japan	(0.02)	...	(–0.14)	(–0.17)	...	(0.18)	(0.47)	(0.08)	1.00	0.12	–0.15	–0.28	–0.06
Norway	...	...	...	...	...	...	...	...	...	1.00	0.22	0.25	0.34
Sweden	(0.26)	...	(–0.03)	(0.56)	...	(–0.17)	(–0.19)	(0.02)	(0.00)	...	1.00	–0.20	–0.18
United Kingdom	(0.21)	...	(0.49)	(–0.52)	...	(0.56)	(0.72)	(0.54)	(0.26)	...	(–0.28)	1.00	0.41
All countries	(0.39)	...	(0.39)	(0.19)	...	(0.65)	(0.72)	(0.62)	(0.67)	...	(–0.02)	(0.74)	1.00

[a] Results for the 1980s are given in parentheses.

terms of R&D intensity in both periods ranks only sixteen in terms of human capital intensity in R&D. Food, beverages and tobacco, on the other hand, with the lowest ranking in terms of R&D intensity, has an average ranking in terms of human capital intensity in R&D. There is some correspondence, however, in the case of the metal industries, which have low rankings both in terms of R&D intensity and in terms of human capital intensity in R&D, as well as in the microelectronics industries, namely office machines and computers, electrical machinery and radio, television, communication equipment, which have high rankings on both indicators.

Table 4 gives the coefficients of bivariate correlations between countries' human capital intensity in R&D across industries as well as of the correlations of each country's human capital intensity in R&D with all countries' combined human capital intensity of R&D across industries. After eliminating — for lack of sufficient data — the Netherlands as well as the United States, the remaining countries have mostly positive correlations with the overall ratios and directly with the other countries in the sample. In the 1970s, though, Canada, Denmark, Japan and Sweden have negative correlations with the overall ratios, whereas in the 1980s only Sweden displays a slightly negative correlation coefficient with the overall ratios. Assuming industry-specific R&D production functions being identical across countries, several potential explanations for the high percentage of negative correlations remain: there might be factor intensity reversals, increasing returns due to economies of agglomeration in R&D,[86] or important additional R&D production factors other than R&D personnel and scientists and engineers.

A more uniform picture emerges from the table of correlations for human capital intensities in R&D between industries and across countries (Table 5). All correlations of individual industries with the overall ratios are highly positive in both the 1970s and the 1980s. Negative correlations between individual industries are rare. Most industries' ratios of R&D scientists and engineers to other R&D personnel and the countries' ratios in total manufacturing are also positively correlated with the relative R&D scientists and engineers endowments of countries. All this is consistent with the prediction of factors proportions theory of international trade that countries, while specializing in the production of those goods which make relatively intensive use of the abundant factor, also tend to use the abundant factor more intensively whenever smoothly convex production technologies permit factor substitution as a response to changing relative factor scarcities. But there are puzzles left, namely the negative correlations of the relative R&D scientists and engineers endowments with the ratios of R&D scientists and engineers to other R&D personnel in the iron and steel, office and computing machinery and shipbuilding industries in the 1970s as well as with the iron and steel and the office and computing machinery industries in the 1980s.

The factor proportions theory of international trade considers three basic (non-exclusive) possibilities for an open economy to respond to changes in the factor endowments relative to the trading partners which may be relevant for the allocation of resources in R&D activities: above average endowments of scarce human capital in the form of R&D scientists and engineers can be allocated, first, so as to generally increase the human capital intensity of all R&D activities, second, to increase the R&D intensity equally in all industries, or third, to shift the pattern of specialization to those activities for which factor endowment relations constitute a source of a comparative advantage.

To sum up, the data on some of the relevant factor endowments, on R&D intensities and on relative input requirements in R&D suggest that countries actually make use of the first two possibilities mentioned, namely to increase the human capital intensity in all R&D activities and to increase the R&D intensity in all industries. For a preliminary examination of the third possibility, charts of R&D intensities in each country, relative to the respective industry's overall R&D intensity across all countries, are presented in Figure A2 and charts of normalized R&D intensities in each industry, i.e. R&D intensities relative to the

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[86] For an empirical test of tendencies towards the international agglomeration of R&D see Cantwell (1991).

Table 5 — Bivariate Correlations between Industries' Average Ratios of R&D Scientists and Engineers to Other R&D Personnel across Countries in the 1970s and 1980s[a]

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
Food, beverages, tobacco (1)	1.00	0.82	0.45	0.50	0.61	0.57	0.60	0.72	0.72	0.09	0.66	0.72	0.29	–0.07	0.49	0.86	0.51	0.67
Chemicals, excl. drugs and medicines (2)	(0.91)	1.00	0.62	0.77	0.61	0.48	0.84	0.60	0.59	–0.28	0.53	0.73	0.02	0.01	0.54	0.68	0.55	0.68
Drugs and medicines (3)	(0.73)	(0.78)	1.00	0.79	0.69	0.53	0.52	0.73	0.71	0.30	0.38	0.74	0.41	0.71	0.43	0.38	0.67	0.74
Rubber and plastics (4)	(0.87)	(0.80)	(0.78)	1.00	0.72	0.36	0.75	0.72	0.66	0.12	0.53	0.84	0.21	0.28	0.60	0.61	0.72	0.77
Non-metallic mineral products (5)	(0.62)	(0.86)	(0.47)	(0.71)	1.00	0.74	0.47	0.73	0.65	0.81	0.49	0.76	0.71	0.33	0.30	0.51	0.53	0.72
Iron and steel (6)	(0.49)	(0.62)	(0.23)	(0.51)	(0.71)	1.00	0.18	0.73	0.58	0.55	0.30	0.68	0.72	0.25	0.19	0.58	0.38	0.68
Non-ferrous metals (7)	(0.84)	(0.73)	(0.46)	(0.74)	(0.85)	(0.62)	1.00	0.47	0.55	–0.56	0.71	0.67	–0.28	0.34	0.59	0.45	0.56	0.52
Fabricated metal products (8)	(0.75)	(0.63)	(0.46)	(0.85)	(0.68)	(0.41)	(0.53)	1.00	0.91	0.37	0.71	0.93	0.59	0.46	0.63	0.65	0.87	0.88
Machinery, not elsewhere classified (9)	(0.72)	(0.57)	(0.40)	(0.78)	(0.70)	(0.16)	(0.55)	(0.91)	1.00	0.21	0.87	0.93	0.45	0.40	0.77	0.74	0.91	0.90
Office and computing machinery (10)	(0.05)	(0.07)	(–0.55)	(–0.24)	(0.11)	(0.20)	(0.15)	(0.05)	(0.25)	1.00	–0.05	0.22	0.97	0.58	0.04	0.02	–0.06	0.33
Electrical machinery, excl. radio, TV and communication equip. (11)	(0.60)	(0.40)	(0.30)	(0.72)	(0.56)	(0.05)	(0.45)	(0.87)	(0.97)	(0.16)	1.00	0.79	0.20	0.40	0.74	0.86	0.84	0.74
Radio, TV and communication equip. (12)	(0.66)	(0.59)	(0.33)	(0.77)	(0.70)	(0.51)	(0.48)	(0.85)	(0.86)	(0.38)	(0.80)	1.00	0.51	0.34	0.67	0.94	0.91	0.97
Shipbuilding and repair (13)	(0.73)	(0.63)	(0.30)	(0.71)	(0.75)	(0.43)	(0.64)	(0.87)	(0.93)	(0.35)	(0.89)	(0.89)	1.00	0.55	0.25	0.43	0.26	0.59
Motor vehicles (14)	(0.54)	(0.50)	(0.17)	(0.71)	(0.56)	(0.90)	(0.56)	(0.69)	(0.50)	(0.08)	(0.52)	(0.80)	(0.59)	1.00	0.50	0.16	0.52	0.46
Aircraft (15)	(0.66)	(0.57)	(0.60)	(0.82)	(0.56)	(0.11)	(0.56)	(0.82)	(0.87)	(0.04)	(0.86)	(0.84)	(0.70)	(0.56)	1.00	0.75	0.75	0.71
Other transport equipment (16)	(0.66)	(0.56)	(0.34)	(0.75)	(0.63)	(0.32)	(0.46)	(0.94)	(0.97)	(0.24)	(0.97)	(0.88)	(0.86)	(0.70)	(0.92)	1.00	0.79	0.87
Professional goods (scientific instruments) (17)	(0.90)	(0.78)	(0.34)	(0.70)	(0.77)	(0.57)	(0.81)	(0.70)	(0.76)	(0.55)	(0.63)	(0.76)	(0.80)	(0.59)	(0.65)	(0.70)	1.00	0.90
All industries (18)	(0.86)	(0.81)	(0.55)	(0.88)	(0.69)	(0.67)	(0.69)	(0.89)	(0.84)	(0.30)	(0.74)	(0.93)	(0.89)	(0.81)	(0.78)	(0.86)	(0.88)	1.00
Countries' endowment with R&D scientists and engineers	0.08 (0.44)	0.21 (0.20)	0.26 (0.33)	0.46 (0.64)	0.12 (0.24)	–0.14 (–0.19)	0.44 (0.08)	0.45 (0.77)	0.55 (0.81)	–0.30 (–0.15)	0.75 (0.89)	0.58 (0.71)	–0.10 (0.66)	0.58 (0.43)	0.62 (0.69)	0.67 (0.84)	0.73 (0.37)	0.56 (0.59)

[a] The results for the 1980s are given in parentheses.

respective country's total manufacturing R&D intensity, in Figure A3. These charts are designed to make visible any simple patterns of R&D specialization across industries — if there are any — which conform to the factor proportions version of comparative advantage. In fact, the charts provide a rough illustration of how countries' strengths in R&D across industries are distributed over the space of human capital intensities in R&D (Figure A2), and of how the relative degree of R&D specialization in a particular industry is distributed across countries that are ranked according to their relative endowment with R&D scientists and engineers (Figure A3).

Remember that, in Figure A2, a clear-cut pattern can be expected only for those countries which rank either very high or very low in terms of their relative endowments with R&D scientists and engineers. A case in point is the United States which had the highest ranking in the 1970s. As expected the US economy invested relatively more in R&D for industries which make relatively intensive use of R&D scientists and engineers, the exceptions being the high R&D specialization in motor vehicles and rubber and plastics.[87] By contrast, France as a country with a relatively small endowment of R&D scientists and engineers seems to have invested more in R&D for industries whose R&D makes relatively little use of R&D scientists and engineers, with radio, television and communication equipment industry being the exception here. Unfortunately, no fitting patterns can be recognized for any of the other countries.

A glance at the normalized R&D intensities in each industry (across countries) in Figure A3 reveals patterns confirming expectations only in the cases of drugs and medicines, rubber and plastics and electrical machinery. The latter industry is the industry with the highest ranking in terms of human capital intensity in R&D in the 1970s as well as in the 1980s. Ignoring Finland and Norway, there is indeed the expected positive relationship between countries' relative endowments with R&D scientists and engineers and countries' R&D intensity in the electrical machinery industry relative to their total manufacturing R&D intensity in the 1970s. In the 1980s, however, this relationship seems to have broken down. In the case of rubber and plastics, one of those industries making the least intensive use of scientists and engineers in their R&D activities, a negative relationship is expected and more or less confirmed by the data.[88] The drugs and medicines industry also shows a negative relationship,

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[87] A possible explanation for these exceptions is that both the motor vehicles and the rubber and plastics industries are classified as scale-intensive by the OECD (1992a: 152). The United States, being the biggest economy of all, should naturally have a locational advantage for these industries.

[88] The appearance of two subgroups of observations in the case of rubber and plastics suggests that there may be another important explanatory variable in the relationship discussed here.

which is not inconsistent with this industry's fairly low ranking in terms of human capital intensity in R&D. Unfortunately, negative relationships are also recognizable in the radio, television and communication equipment and professional instruments industries, two industries with high rankings in terms of human capital intensity in R&D. These observations are at odds with the factor proportions hypothesis to explain countries' patterns of specialization in industrial R&D.

The next section will examine these issues more systematically within the framework of regression analyses which will allow the inclusion of other explanatory variables, such as country size and time trends to capture secular changes in countries' industrial structure.

III. Testing for the Determinants of Human Capital Intensity in the R&D of Individual Industries

The previous section reported bivariate correlations between averages of the ratios of R&D scientists and engineers over other R&D personnel in different countries and in different industries for the 1970s and the 1980s which support the assumption that country-indexed industries can be economically identified by the intensity with which human capital is used in the pertinent R&D activities. To provide a sharper test of this assumption, which is essential for the relevance of comparative advantages based on factor proportions, an analysis of variance has been carried out using yearly data on employment of scientists and engineers as well as of university graduates in R&D activities.[89] Separate regressions of the following type have been run first for each country across industries, and secondly, for each industry across countries indexed by *i*:

[30] $\ln(h) = \mu + \delta_i + \gamma_t + \beta \ln(t) + \varepsilon_{it}$,

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[89] Full-time equivalents of university graduates employed in R&D are a measure of human capital which better captures the relative frequency of formal academic qualifications among R&D personnel. Unfortunately, there are many large gaps in the data, and for several countries the data on university graduates in R&D are entirely missing. Data on research scientists and engineers are not, however, to be seen as a poor substitute, but may after all be the more appropriate data: R&D scientists and engineers are the people who actually create new knowledge and most of them presumably hold university degrees or have other advanced technical qualifications.

where h is either the ratio of R&D scientists and engineers to other R&D personnel or the ratio of university graduates to other R&D personnel, δ denotes country dummies in the industry regressions and industry dummies in the country regressions, γ time dummies controlling for seven three-year periods between 1969 and 1989, t a linear time trend and ε the residuals.[90] On the basis of the residuals from the full model, from the model with dummies for time effects only and from the model with country or industry effects only, F-tests are carried out to test for the joint significance of the respectively omitted dummy variables in each case. The results of the regressions for each country and industry, for which sufficient data have been available, are reported in Tables 6 and 7.

Table 6 — ANOVA Results with Test Statistics for Industry and Time Effects in Each Country

	R^2	RSS-FM	RSS-T-O	RSS-IN-O	TEST-IN	IN-DOF-N	IN-DOF-D	TEST-T	T-DOF-N	T-DOF-D
	a. Results for the ratio of R&D scientists and engineers to other R&D personnel									
Australia	0.43	11.75	18.34	13.33	2.06	15	55	1.85	4	55
Belgium	0.46	10.73	19.87	10.77	3.41	15	60	0.12	2	60
Canada	0.65	9.37	23.93	9.93	28.56	13	239	2.39	6	239
Denmark	0.82	5.64	27.69	6.87	36.08	9	83	3.03	6	83
Finland	0.74	8.45	28.21	8.73	10.75	15	69	0.75	3	69
France	0.95	2.80	46.39	2.97	201.37	16	207	2.11	6	207
West Germany	0.70	8.15	25.79	9.08	16.66	16	123	2.34	6	123
Italy	0.61	24.82	61.58	25.40	20.64	16	223	0.86	6	223
Japan	0.83	10.54	40.76	12.03	51.60	16	288	6.79	6	288
Netherlands	0.77	0.73	3.10	0.78	12.97	3	12	0.29	3	12
Norway	0.74	3.00	10.86	3.14	12.06	15	69	1.08	3	69
Sweden	0.57	14.45	27.68	17.86	4.70	15	77	4.55	4	77
United Kingdom	0.74	3.97	8.44	4.18	6.45	15	86	0.76	6	86
	b. Results for the ratio of university graduates to other R&D personnel									
Belgium	0.56	28.03	46.09	31.46	6.24	16	155	3.16	6	155
Denmark	0.89	1.68	15.68	1.82	33.30	9	36	1.02	3	36
Finland	0.81	4.08	20.92	4.30	14.15	14	48	0.87	3	48
West Germany	0.89	2.96	24.16	3.02	27.31	16	61	0.43	3	61
Italy	0.82	7.74	40.98	7.88	42.96	15	150	0.90	3	150
Netherlands	0.83	1.20	4.94	1.43	50.72	3	49	1.52	6	49
Norway	0.65	20.60	51.51	25.81	16.03	16	171	7.20	6	171
Sweden	0.79	9.00	30.81	9.09	19.89	14	115	0.19	6	115

Note: RSS denotes the residual sum of squares; FM refers to the full model, T-O to the model with time effects only, and IN-O to the model with industry effects only. TEST-IN denotes the F-test statistic for industry effects, TEST-T that for time effects; DOF-N and DOF-D denote the degrees of freedom for numerator and denominator, respectively.

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[90] In equation [30], the coefficients for the dummies, which are 0, 1-variables depending on the category to which an observation belongs, are not explicitly written just as they are customarily not written for the constant term μ, which captures the sample mean.

Table 7 — ANOVA Results with Test Statistics for Country and Time Effects in Each Industry

	R^2	RSS-FM	RSS-T-O	RSS-C-O	TEST-C	C-DOF-N	C-DOF-D	TEST-T	T-DOF-N	T-DOF-D
	a. Results for the ratio of R&D scientists and engineers to other R&D personnel									
Food, beverages, tobacco	0.85	4.89	32.59	4.96	55.65	12	118	0.25	6	118
Chemicals, excl. drugs and medicines	0.92	3.48	39.80	3.72	108.17	11	114	1.32	6	114
Drugs and medicines	0.89	2.83	25.01	2.89	66.75	12	102	0.39	6	102
Rubber and plastics	0.84	11.52	69.11	12.30	48.74	12	117	1.33	6	117
Non-metallic mineral products	0.77	6.69	26.94	7.21	29.02	12	115	1.49	6	115
Iron and steel	0.81	4.06	20.28	4.61	38.40	10	96	2.20	6	96
Non-ferrous metals	0.59	14.97	34.14	16.31	12.17	10	95	1.42	6	95
Fabricated metal products	0.82	7.06	35.03	7.88	37.61	10	95	1.83	6	95
Machinery, not elsewhere classified	0.88	5.74	43.41	6.19	67.44	11	113	1.49	6	113
Office and computing machinery	0.83	2.56	6.39	2.73	9.56	8	51	0.58	6	51
Electrical machinery, excl. radio, TV and communication equip.	0.88	5.79	38.96	6.39	45.86	11	88	1.53	6	88
Radio, TV and communication equip.	0.92	4.00	38.36	4.36	68.75	11	88	1.33	6	88
Shipbuilding and repair	0.58	9.64	22.40	10.54	8.52	9	58	0.90	6	58
Motor vehicles	0.78	5.46	20.08	6.28	20.39	8	61	1.51	6	61
Aircraft	0.78	7.08	25.71	8.23	24.33	8	74	2.01	6	74
Other transport equipment	0.84	10.47	61.56	11.44	39.04	9	72	1.12	6	72
Professional goods (scientific instruments)	0.80	8.19	30.51	8.37	26.28	11	106	0.39	6	106
Manufacturing total	0.97	0.96	23.93	1.04	244.85	12	123	1.61	6	123
All sectors of an economy	0.97	0.95	22.76	1.02	250.11	12	131	1.53	6	131
Subtotal chemical group	0.96	1.50	28.16	1.64	170.22	11	105	1.64	6	105
Subtotal electrical group	0.93	3.11	35.14	3.20	110.30	11	118	0.56	6	118
	b. Results for the ratio of university graduates to other R&D personnel									
Food, beverages, tobacco	0.79	3.17	12.99	3.44	27.89	8	72	1.03	6	72
Chemicals, excl. drugs and medicines	0.90	1.10	8.96	1.38	50.12	7	49	2.09	6	49
Drugs and medicines	0.96	0.52	10.72	0.60	104.36	8	43	1.02	6	43
Rubber and plastics	0.84	6.11	34.68	6.69	40.35	8	69	1.09	6	69
Non-metallic mineral products	0.72	4.44	14.71	4.90	19.95	8	69	1.19	6	69
Iron and steel	0.81	2.48	10.57	3.25	26.11	6	48	2.49	6	48
Non-ferrous metals	0.77	2.68	9.95	3.71	18.04	3	20	1.28	6	20
Fabricated metal products	0.68	3.52	9.97	4.04	13.72	6	45	1.11	6	45
Machinery, not elsewhere classified	0.87	2.34	13.79	2.50	35.62	7	51	0.57	6	51
Office and computing machinery	0.81	4.55	19.81	6.84	12.88	6	23	3.88	3	23
Electrical machinery, excl. radio, TV and communication equip.	0.82	1.63	3.84	2.18	6.22	7	32	1.81	6	32
Radio, TV and communication equip.	0.85	2.47	5.60	3.31	5.78	7	32	1.81	6	32

Table 7 continued

	R^2	RSS-FM	RSS-T-O	RSS-C-O	TEST-C	C-DOF-N	C-DOF-D	TEST-T	T-DOF-N	T-DOF-D
Shipbuilding and repair	0.32	7.71	9.83	8.27	1.92	6	42	0.51	6	42
Motor vehicles	0.83	5.16	23.15	7.66	20.19	5	29	2.33	6	29
Aircraft	0.69	3.24	5.14	6.52	2.45	5	21	3.53	6	21
Other transport equipment	0.70	7.10	19.40	8.74	11.83	6	41	1.58	6	41
Professional goods (scientific instruments)	0.76	4.12	9.50	4.50	9.14	7	49	0.76	6	49
Manufacturing total	0.93	1.09	10.05	1.25	74.27	8	72	1.81	6	72
All sectors of an economy	0.95	0.93	13.94	1.12	127.79	8	73	2.57	6	73
Subtotal chemical group	0.96	0.85	14.44	0.98	143.63	8	72	1.83	6	72
Subtotal electrical group	0.86	2.22	7.99	2.41	19.26	7	52	0.72	6	52

Note: RSS denotes the residual sum of squares; FM refers to the full model, T-O to the model with time effects only, and C-O to the model with country effects only. TEST-C denotes the F-test statistic for country effects, TEST-T that for time effects; DOF-N and DOF-D denote the degrees of freedom for numerator and denominator, respectively.

Table 6, panel a, has the results for thirteen country regressions in which the dependent variable is the log of the ratio of R&D scientists and engineers to other R&D personnel. The test statistics for industry effects are larger than the critical value at the 95 per cent level of significance for all thirteen countries; in fact, the test statistics are even larger than the critical value at the 99 per cent level of significance for all countries except for Australia. Time effects not captured by the linear time trend, on the other hand, are insignificant at the 99 per cent level except for Japan and Sweden. In other cases than these, time effects are significant at the 95 per cent level in Canada, Denmark, France, West Germany, but only just.

Table 6, panel b, displays the results from country regressions using the ratio of university graduates to other R&D personnel as the dependent variable. Again, all industry effects are highly significant, but time effects are significant only for Belgium and Sweden.

Table 7, panel a, shows the results from industry regressions using the ratio of R&D scientists and engineers to other R&D personnel as the dependent variable. Country effects are highly significant even at the 99 per cent level for all industries, but time effects are insignificant even at the 95 per cent level except, perhaps, for iron and steel in which case the test statistic just equals the critical value.

Table 7, panel b, displays the results from industry regressions using the ratio of university graduates to other R&D personnel as the dependent variable. Here, all country effects are significant except those for the shipbuilding industry. Time effects, on the other hand, are insignificant for almost all industries. They are significant at the 95 per cent level only for iron and steel, office and computing machinery and the aircraft industries.

Taken together, these results support the assumption that the intensity of using human capital in R&D is a characteristic feature of industries, when holding the country fixed, and of countries, when holding the industry fixed. On the background of this confirmed assumption, it makes sense to pose the question to what extent countries' choices to devote resources to the R&D of particular industries depend on countries' production specialization in these same industries, and to what extent they depend on whether countries are abundantly or poorly endowed with scientists and engineers.

IV. Testing for the Impact of Human Capital Endowments on Countries' Specialization in the R&D of Individual Industries

To test for the impact of sectoral specialization in value added and of the endowment with R&D scientists and engineers on the sectoral specialization in R&D, regressions have been run for each industry separately, which have the following form:

$$[31]\qquad \ln(shrdp_{t-1}) = \beta_0 + \beta_1 \ln(shva_t) + \beta_2 \ln(rdse_t / rgdp_t) + \beta_3 \ln(rgdp_t) + \beta_4 \ln(t) + \varepsilon_t .$$

In these regressions the dependent variable is the (lagged[91]) share of an industry in the corresponding country's total R&D personnel in manufacturing.[92] Independent variables are the corresponding share of the industry in total manufacturing value added (*shva*), the total R&D endowment of the country, scaled

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[91] A one-year lag in variables averaged over five-year intervals means that relationships are assumed to be close to contemporaneous. Longer lags might be justified if one were to estimate the effects of R&D on productivity or on other variables of the tangible side of the economy. Yet even for this case, empirical studies, like that of Griliches and Lichtenberg (1984), tend to find only shortly lagged and contemporaneous correlations between R&D expenditures and productivity growth. In the present context, one-year lags are taken into account only to acknowledge that R&D activities logically precede the other economic activities with which they are economically connected.

[92] Expressing the variables as shares is done to avoid regressing country size on country size and to alleviate the heteroscedasticity problem. This same purpose is pursued when scaling countries' R&D endowments on countries' real GDP.

on the country's real GDP (*rdse/rgdp*), real GDP (*rgdp*) as a scale variable,[93] and time (*t*).[94] The data are entered as averages over five year periods from 1970 to 1974, 1975 to 1979, 1980 to 1984 and 1985 to 1989 in the case of the independent variables, and of the periods from 1969 to 1973, 1974 to 1978, 1979 to 1983 and 1984 to 1988 in the case of the dependent variables. The intertemporal averaging is done to reduce random noise and serial correlation as well as to alleviate the problem of data gaps of which there are more for some countries than for others.[95] For all industries, separate regressions for two subperiods, the 1970s and the 1980s, as well as a regression over the entire twenty-year period have been run, and conventional Chow tests carried out to test for structural stability over time. According to these tests, the hypothesis of structural stability cannot be rejected for any of the industries at the 95 per cent level of significance. Results of the regressions over the full period are reported in Table 8.

Some of the estimates of coefficients that capture the impact of value added and countries' endowments with R&D scientists and engineers may be difficult to interpret due to multi-collinearity,[96] but in general they are suggestive of how industries differ with respect to the determinants of countries' specialization in R&D. Four cases can be distinguished: (*i*) industries in which both value added specialization and endowments with R&D scientists and engineers have a positive impact on specialization in R&D; (*ii*) industries in which countries' endowments with R&D scientists and engineers are insignificant but a positive impact of value added is highly significant, in other words: industries in which R&D activities are closely tied to production; (*iii*) industries in which endowments with R&D scientists and engineers are highly significant, but value added specialization insignificant, i.e. industries which may be distinguished by the greater international mobility of their R&D output; (*iv*) industries in which neither endowments with R&D scientists and engineers nor specialization in value added seems to be an important (positive) determinant in R&D allocation, e.g. industries in which historical and path-dependent processes of allocating R&D activities dominate.

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[93] Included in the regression to capture scale effects which might be of particular importance for the allocation of R&D in some industries.

[94] Included in the regression to capture the effects of long-run structural change, which might cause some industries to become generally more R&D intensive and others to become less so over time.

[95] Aggregation over five-year time intervals reduces the danger of giving some countries much more weight than others simply because their statistical offices have worked on a more regular basis.

[96] Coefficients of bivariate correlations between the independent and dependent variables are reported for each industry in Table A7.

Table 8 — Determinants of Sectoral R&D Specialization: Results from Multiple Regressions

Model	*Constant*	*Value added*	*R&D-S&E endowm.*	*RGDP*	*Time*	R²	RSS	DOF	F-VR	F-RT	F-ST
Food, beverages, tobacco (7th in 1970s, 7th in 1980s)											
Full model	–364.92	1.11	0.18	–0.24	49.13	0.37	15.37	46	5.47	5.24	0.81
	(253.24)	(0.34)	(0.16)	(0.08)	(33.56)				[2, 46]	[2, 46]	[5, 41]
Without *Time*	5.73	1.10	0.11	–0.20		0.34	16.09	47			
	(2.90)	(0.34)	(0.15)	(0.07)							
Chemicals, excl. drugs (13th in 1970s, 12th in 1980s)											
Full model	411.94	1.63	0.03	0.04	–54.03	0.79	2.45	41	62.62	6.46	1.04
	(114.01)	(0.15)	(0.06)	(0.03)	(15.11)				[2, 41]	[2, 41]	[5, 36]
Without *RGDP*	364.90	1.68	0.03		–47.67	0.78	2.52	42			
	(105.45)	(0.14)	(0.06)		(13.93)						
Drugs and medicines (10th in 1970s, 9th in 1980s)											
Full model	238.52	0.94	–0.35	–0.24	–31.15	0.67	3.10	38	36.77	15.11	0.23
	(141.03)	(0.12)	(0.07)	(0.05)	(18.63)				[2, 38]	[2, 38]	[5, 33]
Without *Time*	2.77	0.88	–0.31	–0.25		0.64	3.33	39			
	(1.77)	(0.11)	(0.07)	(0.05)							
Rubber and plastics (14th in 1970s, 10th in 1980s)											
Full model	135.99	0.64	–0.23	0.07	–18.86	0.17	14.16	46	2.13	0.35	0.35
	(243.03)	(0.40)	(0.14)	(0.09)	(32.21)				[2, 46]	[2, 46]	[5, 41]
Without *RGDP* and *Time*	–4.79	0.80	–0.22			0.16	14.37	48			
	(2.14)	(0.31)	(0.13)								
Non-metallic mineral products (12th in 1970s, 13th in 1980s)											
Full model	228.27	–0.26	–0.06	–0.08	–30.58	0.05	22.62	46	0.12	1.06	0.13
	(332.61)	(0.54)	(0.19)	(0.09)	(44.21)				[2, 46]	[2, 46]	[5, 41]
Iron and steel (15th in 1970s, 11th in 1980s)											
Full model	–646.03	1.47	–0.04	–0.45	86.70	0.57	8.98	37	12.49	18.35	0.66
	(287.55)	(0.30)	(0.13)	(0.08)	(38.15)				[2, 37]	[2, 37]	[5, 32]
Non-ferrous metals (11th in 1970s, 11th in 1980s)											
Full model	542.62	0.79	–0.34	–0.19	–71.66	0.63	10.96	37	22.58	7.95	0.44
	(266.67)	(0.13)	(0.14)	(0.08)	(35.31)				[2, 37]	[2, 37]	[5, 32]
Fabricated metal products (6th in 1970s, 8th in 1980s)											
Full model	–411.88	0.02	–0.09	–0.30	54.61	0.38	7.87	35	0.29	10.22	0.55
	(244.75)	(0.40)	(0.12)	(0.07)	(32.43)				[2, 35]	[2, 35]	[5, 30]
Without *Value added* and *R&D-S&E endowment*	–475.72			–0.30	63.20	0.36	8.01	37			
	(223.96)			(0.06)	(29.60)						
Machinery, not elsewhere classified (8th in 1970s, 6th in 1980s)											
Full model	–464.70	0.56	0.15	–0.25	62.24	0.54	5.80	36	4.53	9.07	0.12
	(204.39)	(0.27)	(0.12)	(0.06)	(27.09)				[2, 36]	[2, 36]	[5, 31]

Table 8 continued

Model	*Constant*	*Value added*	*R&D-S&E endowm.*	*RGDP*	*Time*	R^2	RSS	DOF	F-VR	F-RT	F-ST
Office and computing machinery (3rd in 1970s, 2nd in 1980s)											
Full model	–838.71	0.16	–0.10	–0.05	110.16	0.60	1.79	20	0.46	9.89	2.06
	(199.32)	(0.19)	(0.12)	(0.07)	(26.29)				[2, 20]	[2, 20]	[5, 15]
Without *RGDP*	–865.81	0.08	–0.07		113.55	0.59	1.84	21			
	(193.97)	(0.15)	(0.11)		(25.63)						
Electrical machinery, excl. radio, TV and communication equip. (1st in 1970s, 1st in 1980s)											
Full model	–195.38	0.42	0.04	–0.19	26.33	0.27	4.22	30	1.08	4.84	0.33
	(202.37)	(0.35)	(0.11)	(0.06)	(26.81)				[2, 30]	[2, 30]	[5, 25]
Without *Time*	3.36	0.39	0.01	–0.17		0.24	4.36	31			
	(2.24)	(0.35)	(0.11)	(0.06)							
Radio, TV and communication equip. (4th in 1970s, 4th in 1980s)											
Full model	–28.69	0.09	0.25	0.19	3.45	0.28	8.02	30	2.19	2.04	0.66
	(305.99)	(0.35)	(0.24)	(0.09)	(40.51)				[2, 30]	[2, 30]	[5, 25]
Without *Time*	–2.63	0.10	0.24	0.19		0.28	8.02	31			
	(2.60)	(0.31)	(0.21)	(0.09)							
Shipbuilding and repair (5th in 1970s, 3rd in 1980s)											
Full model	–1205.36	0.79	0.88	–0.14	160.85	0.76	9.60	22	10.91	3.99	1.20
	(430.58)	(0.27)	(0.30)	(0.19)	(57.17)				[2, 22]	[2, 22]	[5, 17]
Without *RGDP*	–1095.89	0.96	0.86		145.99	0.76	9.85	23			
	(401.25)	(0.14)	(0.30)		(53.12)						
Motor vehicles (17th in 1970s, 17th in 1980s)											
Full model	102.52	1.32	–0.33	–0.09	–13.69	0.88	1.73	20	45.42	0.78	1.43
	(190.10)	(0.14)	(0.11)	(0.09)	(25.20)				[2, 20]	[2, 20]	[5.15]
Without *RGDP* and *Time*	–3.24	1.23	–0.28			0.87	1.87	22			
	(1.48)	(0.10)	(0.09)								
Aircraft (16th in 1970s, 16th in 1980s)											
Full model	2629.53	1.72	–0.72	0.36	–348.55	0.78	19.69	19	29.23	6.39	1.61
	(770.92)	(0.24)	(0.42)	(0.32)	(102.58)				[2, 19]	[2, 19]	[5, 14]
Without *RGDP*	2120.66	1.77	–0.61		–279.99	0.77	21.00	20			
	(628.13)	(0.24)	(0.41)		(83.02)						
Other transport equipment (9th in 1970s, 14th in 1980s)											
Full model	–1494.60	2.12	1.88	–0.02	201.61	0.53	35.52	25	9.33	2.14	1.27
	(755.49)	(0.52)	(0.50)	(0.21)	(100.12)				[2, 25]	[2, 25]	[5, 20]
Without *RGDP*	–1474.02	2.15	1.90		198.88	0.53	35.54	26			
	(711.73)	(0.42)	(0.46)		(94.32)						
Professional goods (scientific instruments) (2nd in 1970s, 5th in 1980s)											
Full model	126.14	0.73	–0.33	–0.24	–16.54	0.28	16.94	36	6.92	2.64	0.76
	(346.11)	(0.22)	(0.18)	(0.12)	(45.89)				[2, 36]	[2, 36]	[5, 31]
Without *Time*	1.38	0.73	–0.30	–0.25		0.28	17.00	37			
	(4.12)	(0.21)	(0.16)	(0.11)							

Note: The regressions are based on data pooled over fourteen OECD countries and four five-year periods from 1970 to 1989 for the independent variables, and from 1969 to 1988 for the dependent variable. Missing data imply a badly reduced sample for some industries. For data availability see the data appendix. Behind the industry names there are

Continued on next page

Table 8 continued

the industries' rankings in terms of their average ratios of R&D scientists and engineers to other R&D personnel in the 1970s and 1980s, taken from the last column of Table A4.

All variables are in natural logarithms. The dependent variable is the industry's share of countries' total R&D personnel employed in manufacturing. Independent variables are the industry's share in total value added of the countries' manufacturing sector, the countries' endowment with R&D scientists and engineers relative to the labour force, the countries' real GDP in 1985 US$ at purchasing power parities, and the calendar time, i.e. the year of observation. Data have been averaged for each of the four five-year intervals before taking logarithms. Figures in parentheses below the coefficients are standard errors.

F-VR denotes the F-test statistics for the joint significance of Value added and R&D-S&E endowment. F-RT denotes the F-test statistics for the joint significance of RGDP and Time. F-ST denotes the F-test statistics for structural stability of the full model across the two subperiods, the 1970s and the 1980s. Figures in brackets show the degrees of freedom for the numerator and denominator, respectively.

(i) R&D specialization driven by value added and endowments. Empirically, industries of type 1 turn out to be drugs and medicines, non-ferrous metals, shipbuilding, motor vehicle and other transport equipment industries.[97] Of these, only shipbuilding and other transport equipment show a significant positive impact of the country's relative endowment with R&D scientists and engineers on the R&D specialization in the industry. This is consistent with shipbuilding's high ranking in terms of human capital intensity in R&D, but inconsistent with the fairly low ranking of other transport equipment. The case of Sweden appears to be the outlier which disturbs the picture. However, since other transport equipment is an industry formed as a statistical residual, not much weight should be given to the results in this case.

Strength in R&D for drugs and medicines, non-ferrous metals and motor vehicles, by contrast, seems to be associated with below-average relative endowments with R&D scientists and engineers. And these industries have relatively low average ratios of R&D scientists and engineers to other R&D personnel, ranking ten, eleven and seventeen among the seventeen industries included in the sample. This is consistent with the factor proportions hypothesis of trade and specialization. In the case of drugs and medicines and non-ferrous metals, it is the significant negative effect of size (measured by real GDP) that is striking, in the case of shipbuilding, it is the significant positive time effect. In the case of other transport equipment, the coefficient on value added, which is much greater than unity in absolute size, may be interpreted as pointing to positive scale effects from the production side, perhaps in the form of cumulative learning effects.

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[97] Interpretations have to be treated with caution, not least because the sample size is small. Moreover, in shipbuilding the case of Japan may dominate the impact of all other countries, while in the case of other transport equipment Sweden may be an outlier.

(*ii*) *R&D tied to production.* Industries of type 2, where R&D is closely tied to production and where countries' relative endowments with R&D scientists and engineers have no significant effect, are food, beverages and tobacco, chemicals, rubber and plastics, iron and steel, machinery nec, aircraft and professional instruments. Apart form the significant positive effect of the share in value added, the food, beverages and tobacco and professional instruments industries have a negative size effect, the chemical and aircraft industries a negative time effect, and the iron and steel and the machinery industries a negative size effect but a positive time effect. In the chemical industry's case, the finding of a close tie between value added and R&D specialization may at first sight seem to be in contrast to Klodt (1987: 65–66), who reports a negative, albeit insignificant, coefficient of correlation between the share of chemical industry R&D in a country's total industrial R&D and an indicator of 'revealed comparative advantage' based on export and import data for the chemical industry. But Klodt's regression is based on a more aggregated data set and subsumes under chemicals petroleum refineries as well as petroleum and coal products, both of which are excluded from the data on chemicals in the present study.

(*iii*) *R&D specialization independent of value added specialization.* None of the industries falls into the third group. Those industries in which the industry's share in total manufacturing value added does not help to explain the industry's share in R&D employment are either cases for which the regression is clearly misspecified, as for non-metallic mineral products, or industries in which neither specialization in value added nor endowments with R&D scientists and engineers are a significant determinant, that is to say type 4 industries.

(*iv*) *R&D specialization apparently determined by unique historical events.* To this group belong fabricated metals, office and computing machinery, electrical machinery as well as radio, television and communication equipment. Of these, office and computing machinery seems to have a positive time effect, electrical machinery a negative size effect, radio, television and communication equipment a positive size effect and fabricated metal products a negative size and a positive time effect.

In this group of industries, which comprises the entire microelectronics complex, specialization in R&D does not seem to be associated with patterns of strengths and weaknesses in production, nor with relative endowments of R&D scientists and engineers. These industries thus seem to offer broad scope for historical explanations for the observed patterns and dynamics of specialization in R&D activities. But such historical explanations cannot always be reduced to first-mover advantages and relative country size. For example, in the case of the electrical machinery industry, the present findings suggest that the *large* technology pioneers in this field at the turn of the century, i.e. the United States and Germany, far from being able to monopolize R&D activities, may actually have lost out compared with the increasing relative strength of pertinent R&D specialization of *smaller* countries.

To sum up, the results of multiple regression analyses reported here do not appear to be inconsistent with the factor proportions hypothesis of specialization in R&D for those industries in which countries' endowments with R&D scientists and engineers do have a significant effect. However, for most industries they do not. Among these, there is a group of industries in which R&D activities appear to be closely tied to production. Several of this group are well-established, some even traditional industries: chemical, machinery nec, aircraft and professional instruments, are all among the higher ranking industries in terms of R&D intensity, but they are nevertheless industries which have in recent years relied more on gradual technological development than on revolutionary technological breakthroughs. By contrast, in the entire microelectronics group — which has probably experienced the fastest and most radical technological change of all industries in the twenty years from 1970 to 1989 — specialization in R&D does not appear to be associated with specialization in production, nor with countries' relative endowments with R&D scientists and engineers.[98] Instead, a significant part of the variation in countries' share of their total R&D personnel allocated to these industries appears to be associated with structural change over time in the case of office and computing machinery, an industry which enjoyed spectacular growth in the 1970s and 1980s, and with country size in the case of electrical machinery and radio, television and communication equipment.

An obvious drawback of the regression analysis reported here is that it uses pooled cross-section and time series data. Although the latter has been averaged over four five-year intervals, there is no assurance that observations from one country on any particular variable are independent in the time dimension. The effects discussed here stem primarily from variation in the cross-country dimension, which consists of no more than fourteen cases. Hence, the information contained in each country's time series is not exploited efficiently. There may well be better ways of simultaneously exploiting the information from cross-section and time series data to answer the questions posed. For example, it might be more appropriate to estimate separate cross-country equations for each subperiod by using the technique of seemingly unrelated regressions. In such a model one could constrain the parameters of interest to be the same for all periods, so as to use the information from the whole sample efficiently.

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[98] Incidentally, this also seems to hold for the fabricated metal products industry, certainly for the greater part a rather traditional industry.

Another drawback of the regression analysis in this chapter, however, would not be solved by adopting the seemingly unrelated regression technique: Since estimation would essentially concentrate on cross-section variation, any important dynamic effects on which the data might contain interesting information would continue to be ignored. To resolve this problem, new co-integration techniques for panel data, like those recently developed by Quah (1994) and Levin and Lin (1992, 1993), promise to capture some of the dynamic effects which lead to countries' patterns of technological specialization by exploiting all the available information about how the variation in the relevant variables over a cross section of countries changes over time.

Applying these new techniques will be a task for future research. The present study, however, takes a different path, and uses a more direct methodology to analyze the empirical dynamics of technological as well as industrial specialization, which is the subject of Chapter E.

> It must be emphasised that the economies of large-scale production and the different equipment of factors are not independent "causes" of trade; on the contrary their effects are intermingled in several ways.
> — Bertil Ohlin (1933: 107)

E. Technology and Empirical Dynamics of Specialization in Open Economies

I. Statistical Inference for Stochastic Processes and the Hypothesis of Hysteresis

For the purposes of this study, a stochastic process can be defined as a time-ordered sequence of random variables, realizations of which are observed at various times *t*. These realizations are also called states, and the set of all feasible realizations is termed the state space of the process; it is in this study the real line ***R***. A more general definition of stochastic processes might allow for multi-dimensional random 'variables', i.e. random vectors, or even for concepts other than random variables to quantify events on a sample space.

A rigorous treatment of stochastic processes with applications to economics is provided by Stokey and Lucas (1989). According to their general definition (Stokey and Lucas 1989: 223) a stochastic process on some fixed probability space[99] (Ω, Γ, P) is an increasing sequence of σ-algebras $\Gamma_1 \subseteq \Gamma_2 \subseteq \Gamma_3 \subseteq ... \subseteq \Gamma$, a measurable space $(Z, \mathfrak{Z})$, and a sequence of functions $\sigma_t : \Omega \rightarrow Z$, $t = 1, 2, \ldots$, such that each σ_t is Γ_t-measurable. Then, in the case where $Z = \boldsymbol{R}$, i.e. the real line, the σ_t are simply random variables for each t on the probability space (Ω, Γ, P); and a sample path of the process is a sequence of real numbers $\{\sigma_t(\omega)\}_{t=1}^{\infty}$ for each fixed event $\omega \in \Omega$. The minimum σ-algebra that can be applied on the real line is called a Borel algebra; and any of its subsets are referred to as Borel sets.

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[99] A probability space consists of a sample space Ω, i.e. the set of all possible outcomes of a random experiment, a σ-algebra Γ, i.e. an appropriate mathematical structure to handle events on an infinite and uncountable sample space, and a probability measure *P*, i.e. a set function with Γ as its domain and the closed interval [0, 1] on the real line as its range.

Economic time series often contain observations at regular time intervals so that it is usually convenient to formulate the stochastic process, assumed to have generated the data in terms of random variables, in discrete time. All empirical work reported in the present section is based on such processes in discrete time. The primary task for statistical inference is to uncover the structure of dependency between the various random variables which constitute a particular process and whose realizations are observed at different points in time. From the dependency structure, it may then be possible to make inferences about the long-term asymptotic behaviour of the process, which may for example display hysteresis or other characteristics.

Inference on the dependency structure, however, is made difficult by the fact that non-experimental data normally reveal only a single realization of the sequence of random variables, each of which may well have a different distribution (Spanos 1986: Chapter 8). To draw any inferences in such a situation requires that some *a priori* restrictions on the process be imposed so that some more specific probability model can be constructed. The purpose of such restrictions is to reduce the dimensionality of the time-ordered random variables' joint distribution, and thus to reduce the number of unknown parameters whose values have to be estimated from the data of a single realization.

1. The Inappropriateness of Stationarity Assumptions

The justification for imposing specific restrictions should ideally be derived from some a priori knowledge, say, in the form of economic theory. For example, the assumption that the individual random variables of a stochastic process are normally distributed is usually justified with reference to the frequency of experimental data sets, which can be approximated by the normal distribution. The assumption of stationarity, i.e. roughly speaking the tendency of a time series to stay within certain bounds around a constant mean, is usually justified by postulating that the series represents a (stable) long-term equilibrium. A restriction on the structure of serial correlations between different time-indexed random variables is often derived from some theoretical assumption about the formation of expectations by economic agents, e.g. adaptive or rational expectations.

The a priori restrictions that econometric analysis imposes on a stochastic process are generally of two kinds (Spanos 1986: 137–144): *(i)* restrictions on the *time-heterogeneity* of the process, and *(ii)* restrictions on the *memory* of the process. Restrictions on the time-heterogeneity are usually designed to impose some degree of stationarity on the process so that the impossible task of estimating an entirely different distribution function for each point of observation is avoided. There are several different definitions of stationarity which are more or less amenable to tests in actual data. Strict stationarity requires that the joint distribution function for any number of consecutive time periods of a process remains unchanged when it is shifted in time by an arbitrary value τ, implying that the individual random variables are *identically* distributed.

In practice, though, this would be impossible to verify from the data of a single sample path. A weaker form of stationarity, which is testable, is defined in terms of the first two moments of the joint distribution and requires that the mean $E[X(t)] = \mu$ and the variance $E[\{X[t]\}^2]$ of the stochastic process $X(t)$ be constant and independent of time t, and that the autocovariance $v(t_1,t_2) = E[\{X(0)\}\{X(t_2 - t_1)\}] - \mu_1^2$ depends on the time distance $|t_2 - t_1|$, but not on the dates t_1 or t_2.[100]

Spanos (1986: 137) points out that stationary processes with considerable time-homogeneity are appropriate for modelling phenomena close to their (globally stable) steady-state equilibrium, which random fluctuations continually perturb, but never irreversibly or for long periods of time destabilize. It is therefore clear that processes with *hysteresis* do not belong to the class of stochastic processes which are stationary: The discussion in Chapter C showed that hysteresis implies *bifurcations*, i.e. the breaking of time symmetry in the distribution of the time-indexed random variables of the process. The assumption of stationarity, by contrast, would impose time symmetry and would thus exclude hysteresis *a priori*.

It follows that an operational probability model to examine the hypothesis of hysteresis without bias must allow for at least some degree of time-heterogeneity, i.e. non-stationarity. Current econometric practice usually associates non-stationarity with a limiting case of stochastic processes, which has in recent years caught a great deal of attention by researchers of macroeconomic series — namely autoregressive processes with a unit root. These are best described as non-stationary time series which are stationary in first differences. For example, consider $y_t = y_{t-1} + \varepsilon_t$ where ε_t is a zero-mean stationary process. If ε_t is normally distributed with $E[\varepsilon_t^2] = \sigma^2$, y_t follows a random walk. In this special case, the shape of the random variables' distribution is maintained over time, but the variance grows linearly with time, i.e. $E[\{X(t)\}^2] = t \cdot \sigma^2$, which

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[100] Since the normal distribution is fully characterized by its first two moments, weak stationarity implies strict stationarity if the random variables are known to be normally distributed.

means in practice that the variance grows with the sample size (Hansen 1991: 345).

Since the non-stationarity of unit-root processes manifests itself merely in the variance being a linear function of time, it is clear that this limiting case is not far enough away from stationarity to accommodate hysteresis. Recall from the computer simulations in Chapter C that hysteresis implies that the shape of the distribution, not only its variance, changes over time. An appropriate probability model therefore has to allow for a more general kind of time-heterogeneity than random-walk processes do.

Random walks nevertheless have one important feature which may innocuously carry over to an appropriate probability model of hysteresis, and that is the nature of the restriction imposed on the *memory* of the process. This restriction takes the form of the so-called Markov property, which simply says that the future realizations of the process are independent of the past when the present realization is known. This property is, strictly speaking, a restriction on the *conditional* memory of the process, but not directly on the memory of the process itself. For this reason, the Markov property is compatible with both *ergodicity* and *non-ergodicity*, and may consequently encompass both the absence and the presence of path-dependence (or state-dependence), of which hysteresis is an example.

Ergodicity is a *weak* form of temporal independence, which nevertheless directly restricts the memory of a stochastic process. Ergodicity means that the conditional probability measures of a stochastic process are consistent with only one joint time-invariant probability measure, which is thus necessarily independent of the state initially realized. Non-ergodicity, by contrast, means that there may be multiple time-invariant probability measures for the joint distribution; and this may imply a 'long', i.e. an unrestricted memory. In other words, initial conditions or the history of a particular sample path matter even in the long term.

Spanos (1986: 143) argues that memory restrictions are necessary for inference because they enable the econometrician to 'model the temporal dependence of a stochastic process using a finite set of parameters in the form of temporal moments or some parametric process'. Obviously, as long as there are only finite data sets, no more than a finite number of parameters can be estimated. But, even appropriate memory restrictions on their own may be insufficient to estimate a stochastic process on the basis of a single sample path, because this path may bypass parts of the state space under the hypothesis of hysteresis.[101]

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[101] The time series of such a sample path would be considered as 'degenerate'.

Both implications of hysteresis, the *a priori* unspecified form of time-heterogeneity in the distribution and the non-ergodicity in the temporal dependence structure, seem to render classical statistical-inference techniques incapable of properly testing the hysteresis-hypothesis. These techniques are, after all, based on specific assumptions about the nature of the underlying distribution.[102] Classical tests generally require that the type of the distribution is known and that it is of a sort whose exact shape can be described by a small set of parameters. But in view of possible hysteresis in the data, the unknown distribution of the random variables must be allowed to evolve over time, which can hardly be compatible with any standard distribution; no particular assumption about the type of the underlying distribution or its parametric description can hence be appropriate as an a priori restriction.

It follows that one may need to adopt non-parametric methods as well as use data from more than one realization if non-ergodicity is presumed to hold for a stochastic process. Before turning to the details of methodology and application of non-parametric estimation of Markov processes from several parallel realizations, it may be useful to clarify the general structure of Markov processes more formally, and to discuss how ergodicity and non-ergodicity would manifest themselves in a finite number of observations.

2. Non-Ergodicity in Markov Processes

To gain a better understanding of Markov processes, think of a stochastic process in general as a sequence of transition functions; for each of which an associated operator T^* maps the space of probability measures λ on the measurable space $(Z, \mathfrak{J})$ into itself. Stokey and Lucas (1989: 213) suggest to interpret $(T^*\lambda)(A)$ as the probability that a state in set A will be realized after the transition if the preceding state is drawn according to the probability measure λ. In general, the transition functions of a stochastic process can have arbitrary arguments. It is therefore a special case when they have the current realization of the process as their only argument. This special case defines a first-order[103] Markov process, for which the conditional probability of the event $\{\omega \in \Omega : [\sigma_{t+1}(\omega), \ldots, \sigma_{t+n}(\omega)] \in C\}$, given the event $\{\omega \in \Omega : \sigma_\tau(\omega) = a_\tau,$

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[102] Compare for the introductory chapter in Gibbons and Chakraborti (1992).

[103] In higher-order Markov processes, the transition function would have as its arguments realizations of some finite number of periods into the past. But the assumption of a *first-order* Markov process does usually not constitute a serious restriction because, as Stokey and Lucas (1989: Section 8.4) show, second- or higher-order Markov processes can be written as a first-order process after suitably redefining the state space.

$\tau = t-s,\dots,t-1,t\}$ has occurred, can be written as (Stokey and Lucas 1989: 223):

$$[32] \quad P_{t+1,\dots,t+n}\left(C \middle| a_{t-s},\dots,a_{t-1},a_t\right) = P_{t+1,\dots,t+n}\left(C \middle| a_t\right),$$
$$t = 2,3,\dots; \quad n = 1,2,\dots; \quad s = 1,2,\dots,t-1; \quad C \in \Im^n.$$

If these conditional probabilities are independent of time t for all $a \in Z$ and $C \in \Im$, the Markov process is said to have stationary transitions. It is important to keep in mind that this does not necessarily imply a stationary stochastic process as defined above; in fact, the stationarity of a Markov process does not depend in any way on whether the process has stationary transitions. Stationarity instead requires that the sequence of probability measures λ_t converges, in some sense, to an invariant probability measure λ^*. Stokey and Lucas (1989: 317) define an invariant probability measure to be a fixed point of the operator T^*, so that $\lambda^* = T^*\lambda^*$. This is equivalent to saying that λ^* is the probability measure over the state s_{t+1} in period t+1 if it is the probability measure over the state s_t in period t.

There are different classes of Markov processes depending on whether they are defined on a continuous or on a denumerable state space. The following discussion is primarily concerned with *finite-state* Markov processes, which are defined on a denumerable space with a finite number of states. Such processes are also called (finite) Markov *chains*. They illustrate many of the typical long-run behaviour patterns of general Markov processes, and are an important tool in the empirical implementation below.

Suppose (as in Stokey and Lucas 1989: 320) that a suitable probability measure for the finite state space $S = \{s_1,\dots,s_l\}$ is given by a vector p in the l-dimensional unit simplex:

$$\Delta^l = \{p \in R^l : p \geq 0 \; and \; \textstyle\sum_{i=1}^{l} p_i = 1\}.$$

A transition function P can then be represented by an $l \times l$ matrix $\Pi = [\pi_{ij}]$, with elements $\pi_{ij} = P(s_i, \{s_j\})$. The ith row of this Markov transition matrix gives the probability distribution over the post-transition states conditional upon the ante-transition state being s_i. If $p \in \Delta^l$ denotes the probability distribution over the state in period t, then the probability distribution in period t+1 can be determined by matrix multiplication as $\hat{p} = p\Pi$. By inductive iteration, Π^n defines n-step transitions, and the behaviour of the sequence $\{\Pi^n\}_{n=0}^{\infty}$ reveals the long-term behaviour of the Markov chain.

Stokey and Lucas (1989: Chapter 11) illustrate all feasible types of long-term (limiting) behaviour by means of five typical examples of Markov matrices: (*i*) Their first example illustrates the case where the entire state space forms an *ergodic* set, denoted E and defined by the condition that $p(s_i, E) = 1$, for $s_i \in E$, and that no non-empty subset of E is itself ergodic. Ergodicity of a Markov chain thus implies that it is 'irreducible' because each state is accessible from all others, even if not necessarily by one-step transitions. *(ii)* The second example concerns the case where part of the state space is *transient*, which means that there is a positive probability of leaving and never returning to these transient states. These are therefore not part of any ergodic set that may exist. *(iii)* The third case illustrates the possibility of *cyclically moving subsets*, where the entire state space may be one ergodic set,[104] but where the sequence of transition matrices Π does not converge to a time-invariant distribution in each of its rows. *(iv)* Next, there is the possibility of two (or more) ergodic subsets, where the system may converge to two (or more) *different* invariant distributions depending on the system's initial state, or on the particular sample path realized. In this case, the Markov chain as a whole is said to be *non-ergodic*; and the different invariant distributions might correspond to different steady-state equilibria in a related deterministic model. *(v)* Finally, there can be mixtures of the aforementioned cases, e.g. the state space may consist of transient states and more than one ergodic set.

Stokey and Lucas (1989: 326–328) then show that in all five cases the sequence of *averages* $\{A^{(n)}\} = \{(1/n)\sum_{k=0}^{n-1}\Pi^k\}$ necessarily converges, as $n \to \infty$, to a limiting Markov matrix Q, whose rows are *invariant* distributions with respect to time. Thus, one can be sure that there always exist time-invariant distributions of the long-run average probabilities over all states of a finite Markov chain (with stationary transitions) and that these invariant distributions are given for each initial state s_i by the corresponding row of Q. In Sections E.II and E.III this kind of convergence will be invoked to draw inferences on ergodicity versus non-ergodicity in empirically estimated transition matrices.

To summarize, if one wishes to examine the hypothesis of hysteresis without inappropriate restrictions one may want to use a Markov process as an operational probability model. Yet, in order to draw inferences on Markov processes without any prior information about the transition functions one needs to assume stationary transition probabilities or get data on more than one sample path. However, if some states are transient or if the state space contains more than one ergodic set, as under the hypothesis of hysteresis, the assumption of stationary transitions may not suffice to estimate *all* transition probabilities from a single realization of the process. It is for this reason that the present study adopts the ensemble view, which assumes that the specialization dynamics of

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[104] Some authors exclude cyclically moving subsets from the definition of ergodicity. See, for example, Osaki (1992: 119).

different countries are each an independent realization of the same underlying Markov process.[105] According to the ensemble view, one may be able to estimate transition probabilities for all states even if an individual country's specialization path gets locked into one of the extreme states at an early date within the observation period.

This approach, admittedly, ignores potential cross-section interdependencies between different countries' specialization experiences. A probability model that explicitly accounts for the relevant cross-section correlations would have to be formulated as a stochastic process made up of random functions of several variables. These functions would have as their values elements ψ_a of some configuration space Ψ, where $a \in A$ is a set of multiple indexes, one for each dimension of potential interdependencies. In such a formulation, any element ψ_a would assign values from the state space S to a particular site a of A. A stochastic process of this kind is known as a random field in probability theory.[106]

For an application of random fields to the problem of industrial specialization dynamics in open economies, it would be useful to restrict the index set to an integer lattice and to let one index count time periods, a second index stand for countries' positions in geographical space, and a third index for countries' positions in some abstract space of technological similarity, for example. In this sense, there may be neighbour relations in more than one dimension. The relevant dimensions to consider in empirical work would have to be determined by theory. For example, as pointed out in Chapter B, the theory of endogenous technological change in open economies assumes that knowledge spill-overs from R&D accompany *trade relations*; and this hypothesis finds empirical support in Coe and Helpman (1993). Knowledge spill-overs may indeed be one of the most important kinds of interdependencies in economics, on which random fields analyses might shed new light in the future.

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[105] Recall that a similar interpretation was given for the analysis (in terms of Master equations) and for the computer simulations used in Chapter C to determine the long-run stationary distributions of a specialization indicator in two-sector models of small and large open economies. This analysis, too, relied on the ensemble view, i.e. on a statistical population of stochastic specialization processes, but in that case all starting from identical exogenous conditions. Unfortunately, it is not possible to control all the exogenous conditions for actual observations of countries' specialization patterns, data on which are used in the empirical analyses below, but Section E.III will make an attempt at including conditioning information about countries' factor endowments.

[106] For a formal introduction to this part of probability theory see Griffeath (1976). A more applied introduction is provided by Kindermann and Snell (1980). Applications so far have been primarily in statistical physics, going back to the pioneering work of Ernst Ising in the 1920s on ferromagnetic materials. Recall from Section C.2 that statistical physics is used to analyze the microscopic events in self-organizing processes.

To turn a random fields model of these issues into an operational probability model, one would restrict the conditional probabilities for ψ_a to depend only on elements which are within some fixed distance D, analogously to memory restrictions in ordinary stochastic processes. Indeed, for $D=1$, the Markov property, one would obtain a (symmetric) *Markov* random field.[107] As Durlauf (1993) points out such multi-dimensional stochastic processes may exhibit richer, and for many economic applications more interesting, forms of non-ergodicity than one-dimensional Markov processes do even if these are vector-valued. In particular, random fields may have multiple joint invariant probability measures which are consistent with non-degenerate time series (that is without excluding certain states from being realized).

The econometric analysis of random fields is still to be developed and will not be pursued much further in this study.[108] To make the available data on patterns of industrial specialization in OECD countries accessible to empirical analysis, the present study implicitly assumes that cross-section correlations are of little importance and concentrates on the dependency structure in the time dimension of the process. The data from different countries are essentially treated as independent observations. This simplifying assumption permits estimation of transition probabilities without explicitly modelling interdependencies between countries. But Section E.III will make an attempt to account for some of the cross-sectional variation by including countries' factor endowments as exogenous variables.

II. Estimating Markov Transition Probabilities for the Specialization Dynamics in OECD Countries

1. Autoregressions and Stochastic Kernels

The stylized model of the stochastic recontracting process and dynamic specialization in the small open Ricardian economy, which was analyzed in Section C.II, lends itself naturally to an empirical examination. The focus of this will be on questions like: What are the actual dynamics of specialization in technology and industrial production of open economies? Are these dynamics

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[107] Asymmetry, for instance in the time dimension, could be introduced by defining conditional probabilities that depend only on neighbouring states in one direction.

[108] The general theory of estimation in random fields without imposing a priori restrictions on the distribution is treated in Ramm (1990).

quite similar or rather different from one industry to another? Is there any evidence for hysteresis in terms of high persistence of above-average or below-average specialization in either technology, production or both?

Research on these questions should be seen as complementary to recent econometric attempts at diagnosing the international range of positive external effects from R&D more directly. Recall from Section B.V that a number of empirical studies, surveyed in Griliches (1992), have estimated social rates of return to R&D investments well above the private rates of return. These studies leave little doubt that intra- and intersectoral knowledge spill-overs from R&D are pervasive, yet incomplete and often effective only after some time lag. The time series regularly show a strong positive correlation between the productivity growth of a firm or an industry and its own R&D investment.

Lichtenberg (1993) extends this line of research and finds that in a number of industrial economies also the *national* productivity growth is significantly and positively correlated with the respective own R&D expenditure of these countries. Under the assumption that R&D expenditures are themselves exogenous with respect to productivity, this result leads to a rejection of the hypothesis that knowledge spill-overs from R&D are not at all reduced or slowed down at international borders. Coe and Helpman (1993) find empirical support for the assumption that international spill-overs from R&D depend mainly on the intensity of bilateral trade relations and that notably small countries with open markets derive considerable productivity gains from foreign R&D advances.

Despite these findings, it would seem premature to regard the hypothesis of hysteresis in the dynamics of specialization in open economies as confirmed. Sceptics would rightly point out that, although positive externalities may have some influence in the direction of idiosyncratic patterns of specialization, other factors like foreign direct investment and the associated technology transfers might prevent it. A theory of leapfrogging, like that of Brezis et al. (1993), would even argue that it is precisely the temporary exploitation of positive external effects and hysteresis in one country which gives other countries a better starting position in the next round of innovations and productivity advances, because after a change of technological trajectory the old externalities are quickly devalued and new innovators are more likely to look for low-wage labour rather than for a location in a high-wage country with a fading technology.

Ignoring the possibility of repeated switches among technological trajectories, the stylized model of Section C.II defined the state variable of the recontracting process as the share of workers in industry A. Specialization of the small two-sector Ricardian economy was unambiguously measured by the share of industry A in the total labour force. But how can sectoral specialization in industrial production be measured in a multi-country, multi-factor world? To obtain a measure which is comparable across countries and across industries, it is suggested to compute — for each industry in each country — an indicator on the basis of value added (VAI), namely the contribution of an industry to gross domestic product:

$$[33] \qquad VAIi,j = (V_{i,j} / \sum_i V_{i,j}) / (\sum_j V_{i,j} / \sum_i \sum_j V_{i,j}),$$

where $V_{i,j}$ stands for value added in country i and industry j, $\sum_i V_{i,j}$ for total value added in industry j over all countries, $\sum_j V_{i,j}$ for total value added in country i, and $\sum_i \sum_j V_{i,j}$ for total value added in all countries and all industries.[109] This indicator of specialization measures how many times greater or smaller the ratio of a country's value added to the world's value added is in a specific industry as compared with all of manufacturing. In a sense, the indicator compares the relative weight of a certain industry in individual countries with the relative weight of this industry in total world manufacturing. A logarithmic transformation renders the indicator unbounded on both sides, symmetric around zero — the point of no specialization — and relatively sensitive to small deviations from zero as they are typical for large countries (Grupp and Legler 1989). Nevertheless, large countries show much less specialization and dynamic variation of this indicator, basically for two reasons: one is the effect of regional evening out, and the other is large countries' effect on the normalizing quantity since they themselves make a considerable part of total value added in the world.

The indicator of industrial specialization largely suppresses information about the absolute scale of an industry, of a manufacturing sector, or of a country. The effects of some of these and other scale variables (e.g. human capital endowments and intraindustry trade) on rates of growth have been examined in cross-country regressions by Backus et al. (1992), who find positive correlations for the manufacturing sector, but little or no effect elsewhere. Instead of scale, the specialization indicator adopted here rather measures the relative impor-

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[109] This formula is closely related to the production intensity index (PII) suggested by Bowen (1983) as a comparative measure of trade specialization for each industry j within each country i:

$$PII_{i,j} = (T_{i,j} Y_w) / (Y_i Q_{w,j}) + 1 = Q_{i,j} / [(Y_i / Y_w) / Q_w],$$

where net trade $T_{i,j}$ is equivalent to domestic production $Q_{i,j}$ minus domestic consumption $C_{i,j}$, and Y_i and Y_w are gross national and gross world product, respectively. These kinds of pragmatic specialization indicators have their roots in the work of Liesner (1958) and Balassa (1965).

tance of an industry within a given manufacturing sector. This may be important to keep in mind when confronting the results of the present study with those of other empirical research on related issues.

Discussing the determinants of specialization in terms of comparative advantage versus hysteresis due to technological accumulation, it is natural to focus on the specialization in those tradeables for which the hypotheses are primarily formulated, namely manufactures. The limited availability of reliable data on value added by industry, which is taken from the 1992 version of the OECD STAN database, has made it necessary to restrict the scope of this study to only twelve countries — Australia, Canada, Finland, France, West Germany, Italy, Japan, the Netherlands, Norway, Sweden, the United Kingdom and the United States — and to the nineteen-year period from 1970 through 1988.

Unfortunately, the sample limitation implies that the specialization indicator could not be computed relative to world value added but only relative to total value added in the twelve sample countries. This would not matter much if the sectoral composition of value added in all countries excluded from the sample was on average the same as that of the countries included. In reality, however, the sectoral composition of value added in the remaining, mostly less developed countries is likely to be quite different. The absolute values of the specialization indicator as they have been computed for the sample countries are therefore misleading as measures for specialization relative to the world.[110] But, in the present context, the absolute values are of little interest compared with the *dynamics* of the relative specialization positions of specific industries in the various countries.

Thus the fact that not all countries of the world are included in the sample may matter far less than the small number of observations at the level of individual industries, which is a direct consequence of the small sample size of only twelve countries. In any case, one might argue that the twelve countries considered are responsible for most of the dynamics in specialization, since they command a dominant share in world trade, especially in manufactures: about 85 per cent of OECD exports and roughly two thirds of world exports in terms of

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[110] Although the omission of other countries may affect not only the absolute levels of the specialization indicator but also the relative position of industries in an individual country, the omission would not affect the relative ranking of countries in individual industries. In any case, the observed relative dynamics in industrial specialization *between* the twelve countries are unlikely to be affected in a fundamental way by the omission of other, mostly developing countries which are of lesser importance in world trade. The dynamics of specialization captured by the indicator are also unlikely to be disturbed by country-specific measurement problems. Inflating figures on value added for an entire country or for a particular industry need not significantly alter the dynamics of specialization unless the figures are treated inconsistently over time, say by being first understated and later overstated.

value. The twelve countries also have a dominant share in the world's value added in manufacturing as well as in the resources used intensively in manufacturing — especially in technology and R&D inputs, i.e. primarily human capital, which are thought responsible for hysteresis.

To measure technological specialization, one should ideally use a direct measure of the creation of new technical knowledge, essentially the output of R&D efforts, whose international mobility is crucial for the hypotheses considered here. Direct measurement of intangible R&D output, especially of the part which spills over as a technological externality, is of course infeasible. In view of these difficulties, Soete (1981) suggests as a proxy the index of revealed technological advantage (RTA) which is based on patent count data. This index is defined as the ratio of a country's share of sectoral patenting to the country's overall share of patenting in a particular foreign country. This gives some reassurance that patents granted are of similar 'quality' in terms of novelty, since novelty requirements are routinely checked during the nationally standardized approval procedure.

Usually the foreign country is chosen to be the United States — the country which has the largest and most important market for technology and, therefore, is most likely to stand high on the patent application agenda of every commercially minded inventor in any country. Moreover, the US Patent and Trademark Office publishes patent count data which are aggregated according to the US Standard Industrial Classification and are thus particularly suitable for economic analysis (see the Appendix for details). The RTA index defines the technological activities of a country as more specialized in those areas where this country gets a larger share of US patents than in the average of all sectors.[111] In its formal structure, this index is analogous to the indicator of industry specialization in terms of value added introduced above, so the RTA is:

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[111] While the RTA index obviously neglects potentially large differences in the economic value of patents (and may thus not be an all too reliable measure), it does have some important advantages, especially over R&D indicators based on input data. In contrast to these, the RTA index values are more readily comparable across countries and sectors and over time. The index automatically corrects for common industry trends across countries, such as industry-specific propensities to patent, and for common economy-wide trends across industries, such as the documented decline in the ratio of the number of patented innovations to the number of scientists end engineers involved in R&D since 1960 (Evenson 1991). A problem, however, remains with domestic US patents because individual US inventors are known to file relatively more patent applications in certain fields of technology than in others, while filing very few foreign patent applications at all. Many of the domestic applications of individual inventors cannot be counted as technical advances comparable to patents originating from corporate research laboratories. Therefore, US patents held by individuals have here been deducted before computing the technology specialization indicator in order to avoid biasing figures for the United States towards those sectors in which leisure inventors were most active.

$$[34] \quad RTA_{i,j} = (G_{i,j} / \sum_i G_{i,j}) / (\sum_j G_{i,j} / \sum_i \sum_j G_{i,j}),$$

where $G_{i,j}$ stands for the number of US patents, by date of application, which are of practical use mainly in industry j and granted to inventors resident in country i.

A general model of the stochastic process of the evolving cross-section distributions of measures of specialization is given by the stochastic difference equation (Quah 1993a: 13; Stokey and Lucas 1989: 234–237):

$$[35] \quad \lambda_t \; = \; T^*(\lambda_{t-1}, u_t),$$

where T^* is an operator which maps the probability measures λ in period t–1, together with a disturbance u, into probability measures in period t. Ignoring the disturbance u leaves a difference equation in probability measures, a model of the law of motion in industrial specialization, which can be used, by iteration, to predict future cross-section distributions:

$$[36] \quad \lambda_{t+s} \; = \; (T^{*} * T^{*} * \cdots * T^{*})(\lambda_t) \; = \; (T^*)^s \lambda_t \, .$$

Taking this iteration to the limit as $s \rightarrow \infty$, gives a characterization of the likely long-run distribution of the cross-country, cross-industry specialization indicator. Analogously to the conclusions from the small open Ricardian economy, hysteresis would imply that the probability measure $\{\lambda_{t+s} : s > 0\}$ tends towards a bimodal distribution in the long run, with very little or virtually no measurable mobility of individual industries between the two modes. The alternative hypothesis would be that the future degree of specialization of a certain industry in a particular country is only temporarily dependent on that industry's starting position, but entirely independent of it in the long run, provided there is either virtual equality of relative factor endowments across countries or enough *mobility* in relative factor endowments to undermine established comparative advantages over time. The probability measure would then tend towards a uniform distribution in the long run.

As Quah (1993b) points out, such a model of dynamically evolving distributions is like an autoregression, except that its values are distributions rather than scalars or vectors of numbers.[112] But one should emphasize that simple *parametric* autoregressions fail to be informative on the hypothesis of hysteresis

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[112] Recall from Section E.I that the model of evolving distributions is designed to avoid stationarity assumptions which would exclude hysteresis *a priori*.

which is here appropriately formalized in terms of a probability model of evolving cross-section distributions. In particular, an estimated slope coefficient smaller than one, obtained from regressing an indicator of specialization on its lagged values, cannot be taken as evidence that past specialization in a certain sector would give this sector a disadvantage for future growth. A linear regression of the logarithmic industry specialization indicator in 1988 on a constant and the industry specialization indicator in 1970 (lagged 18 years) yields an estimated slope coefficient of 0.70, a t-value of 20.2 and an adjusted R^2 of 0.67, which seems to imply that past specialization does *not* give countries much of an advantage in particular sectors for the future. Instead, the sectoral strengths of countries seem to erode over time; measured specialization seems to converge to neutrality.

Similarly, a regression of the technology specialization indicator in 1989 on a constant and the technology specialization indicator in 1972 (lagged 17 years) gives a slope estimate of 0.49, which suggests there was even less long-term influence of past specialization in technology. But this interpretation is merely an example of the so-called Galton's regression fallacy, which often arises when the dependent variable y and the independent variable x have a bivariate normal distribution and are measured as deviations from their means, which is true for the specialization indicators used here. The conditional distribution of the dependent variable y is then also normal around the mean m, according to: $E(Y|X=x)=m(y)+\rho\sigma(y)/\sigma(x)(x-m(x))$. If the variances of the two marginal distributions $\sigma^2(.)$ are very similar, the regression coefficient *must* be smaller than unity because the correlation coefficient ρ always is. This does not reveal any useful information about the relationship between the two variables (Maddala 1992: 104–106).

Moreover, taking the negative slope estimates from above at face value would imply that the distributions of the specialization indicators must converge to a single point at the mean. But as can be seen from comparing non-parametric density estimates for selected years (Figures 11 and 12),[113] the distributions of the specialization indicators do not collapse. Instead, excess kurtosis, made visible in Figure 12 by graphing — in addition to the density estimates — the normal density for the sample mean and sample variance of the technology specialization indicator, seems to be decreasing over time, and that for both the technology and the industry specialization indicator. These kinds of methodo-

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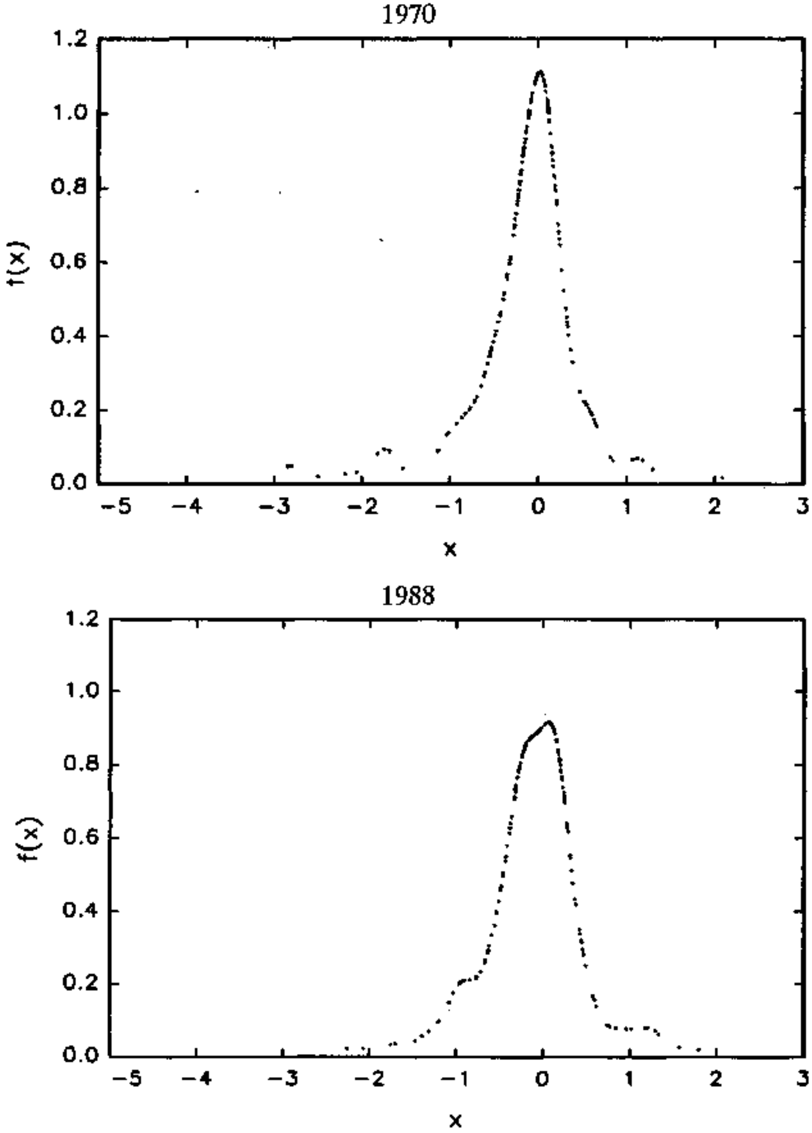
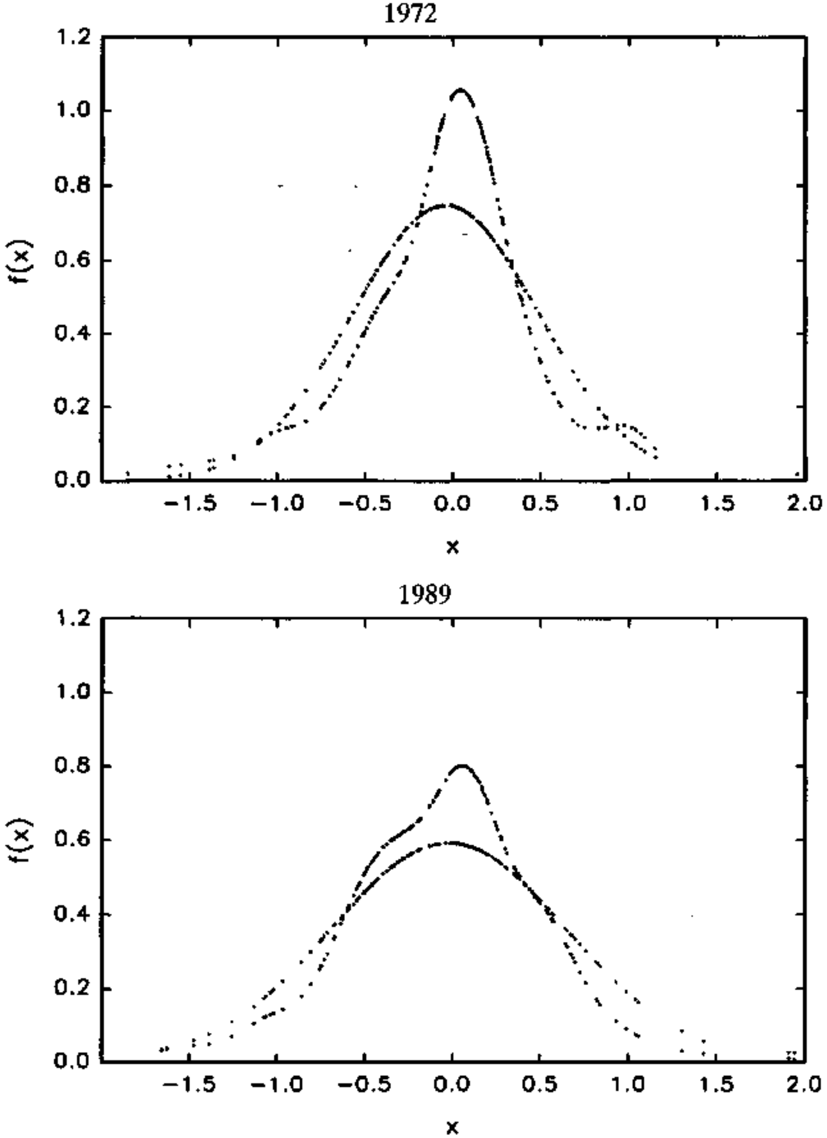
[113] The density estimates in Figures 11 and 12 are based on the Gaussian kernel with window width selected automatically as suggested in Silverman (1986: 45–48).

Figure 11 — Non-Parametric Density Estimates for the Industry Specialization Indicator for 1970 and 1988



Note: Only points supported by sample data are shown, so as to indicate the differential reliability of the estimate on various subsections of the domain.

Figure 12 — Non-Parametric Density Estimates for the Technology Specialization Indicator for 1972 and 1989


1972

1989

Note: The more regular shaped (flatter) lines graph the corresponding normal densities for the sample means and variances.

logical problems, associated with 'Galton's fallacy', also beset the (growth) convergence regressions discussed in Section B.V above.

A better way of estimating a model of evolving cross-section distributions in terms of probability measures, recently used by Quah (1993a) in a different context, is to specify the operator T^* as a stochastic kernel,[114] which maps the product of the real line with its Borel sets to the unit interval, and to estimate this by appropriately rescaling a non-parametric density estimate of transitions, to obtain a conditional probability for each fixed neighbourhood in the continuous state space of degrees of industrial specialization. Loosely speaking, this method makes a (two-dimensional) non-parametric density estimate of the transition function implied by the underlying stochastic difference equation. While a proper judgement on the hypothesis of hysteresis will have to take into account the actual movements in relative factor endowments, unconditional estimation may already give valuable insights into the nature of specialization dynamics. Indeed, the unconditional dynamics should be looked at first, because conditioning brings in methodological problems of its own; e.g. the exogeneity of changes in relative factor endowments may be in doubt.

Figure 13 graphs stochastic kernel estimates[115] of one-year and five-year transitions in the industry specialization indicator. Figure 14 does the same for the corresponding technology specialization transitions. These graphs make clear that there is high persistence in specialization in the short run — probability mass is concentrated on and closely around the 45°-diagonal. But there seems to be considerably less persistence over longer time horizons, particularly in the case of technological specialization: probability mass leaks out and flows away from the diagonal, and apparently more so at the ends of extreme specialization.[116] Comparing the lower panel in Figure 13 and 14 suggests that over a five-year period there is less persistence in technology than in industry speciali-

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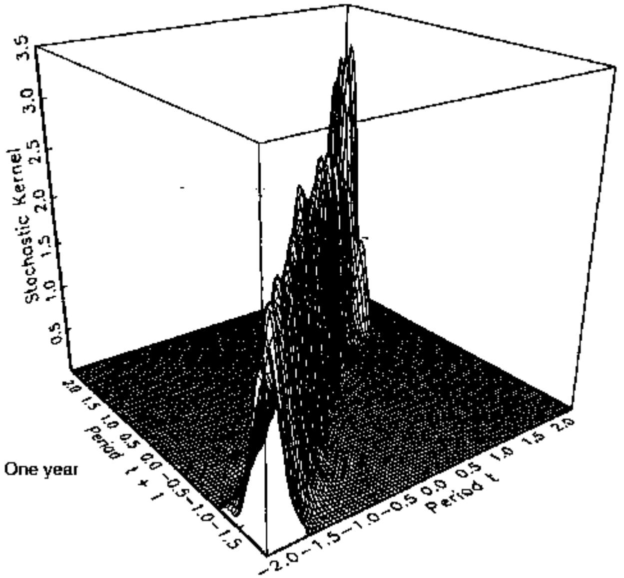
[114] The difference equation in probability measures then becomes, for all H on the real line, $\lambda_t(H) = \int M(x,H)\, \lambda_{t-1}(dx)$, where $M : R \times \mathfrak{R} \rightarrow [0,1]$ denotes the stochastic kernel, x the specialization indicator at time $t-1$, and H the expected specialization indicator at t; recall that λ is a suitably defined probability measure.

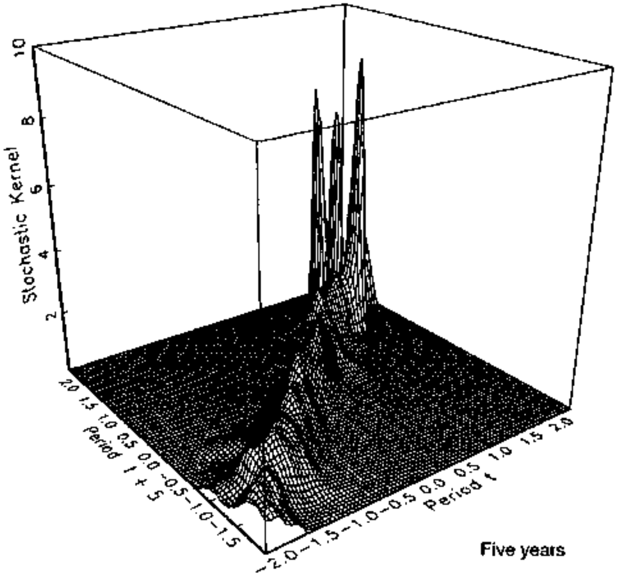
[115] Using the squared Epanechnikov kernel, as described in Silverman (1986: Chapter 4).

[116] In the lower panel of Figure 13, the spikes at the positive end of specialization are merely a consequence of outliers in non-parametric density estimation and should not distract from the more relevant other parts of the picture. Such outliers are more frequent for small countries where manufacturing is more likely to be dominated by one particular industry, which then causes the 'value added indicator' of specialization to take on an unusually high value. A usually law value would indicate that an industry is almost non-existent in a country; for example, many countries have no real aircraft industry.

Figure 13 — Stochastic Kernel Estimate for Industry Specialization Transitions after One Year and Five Years

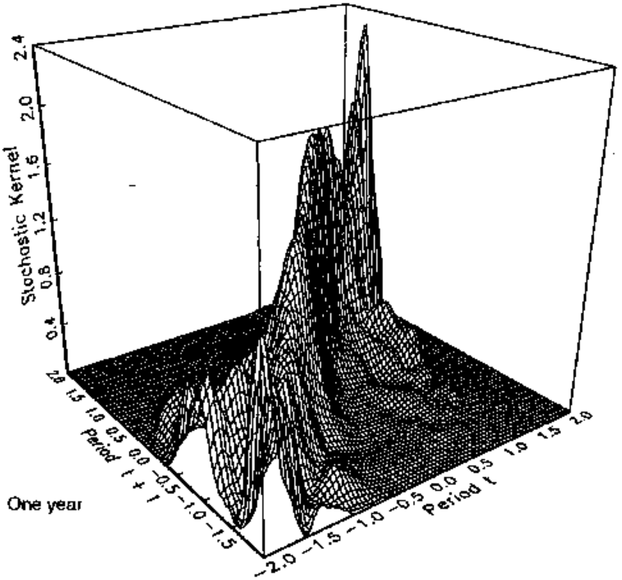


One year

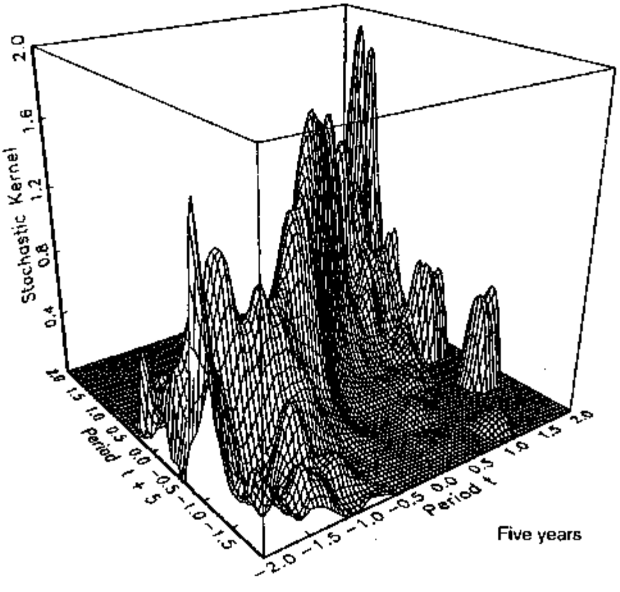


Five years

Figure 14 — Stochastic Kernel Estimate for Technology Specialization Transitions after One Year and Five Years



One year



Five years

zation measured in terms of value added — just the contrary of what would presumably be needed to establish causality from hysteresis in technological development to hysteresis in industrial specialization patterns.

2. Finite Markov Chains

Although the graphic results of the preceding subsection give a rather suggestive visual picture of the overall dynamics in sectoral specialization, as documented in the data, they do not allow to draw proper statistical inferences, nor to calculate the expected long-run stationary distributions, should they exist. But these kinds of inferences would be essential for a sound judgement on the hypothesis of hysteresis.

Therefore, an alternative approach to estimation may be preferable, in which the operator *T** is approximated by a finite Markov chain transition matrix for a discretized state space. An empirical estimate of the transition matrix can give useful information on the intradistributional mobility of individual industries between different degrees of specialization over time, and can be used to calculate long-run stationary distributions of the specialization indicator — provided they exist — according to the Chapman-Kolmogorov equation:

$$[37] \qquad \Pi^s = \Pi^r \cdot \Pi^{s-r} \qquad \text{with the time period index } s \longrightarrow \infty,$$

where Π denotes the transition probability matrix; its rows contain the conditional probabilities that a transition beginning in a certain discrete state (row *i*) will end after one step (in event time) or one period (in historical time) at a certain state (column *j*). Π^r consequently has the probabilities of moving from initial states to intermediate states after *r* steps or periods of time.

To discretize the continuous state space of the logarithmic specialization indicator, six states are defined — somewhat arbitrarily — by setting upper boundaries at $\mu - sd$, $\mu - sd/3$, μ, $\mu + sd/3$, $\mu + sd$, and at ∞, where μ stands for the sample mean and *sd* for the standard deviation of the indicator realizations over all years from 1970 to 1988. The corresponding 6 × 6 Markov chain transition matrix is estimated by maximizing the log-likelihood function

$$[38] \qquad \log L = \log p_i(1970) + \sum_{i,j} h_{ij} \log p_{ij}$$

with respect to p_{ij} and subject to the restriction $\sum_j p_{ij} = 1$,

where $p_i(1970)$ are the initial probabilities of having a realization of the specialization indicator in state *i*, p_{ij} are the probabilities of having a realization in state *j* after a specified transition period, conditional upon a prior realization in state i, and h_{ij} are the observed frequencies of transitions from state i to state j in that period. Ignoring any information about transition probabilities which may be contained in the initial probability distribution,[117] and assuming the transition probabilities to be invariant with respect to time as well as across industries and countries, the Maximum Likelihood estimator can be readily computed as:

$$[39] \qquad \hat{p}_{ij} = h_{ij}/h_i, \text{ where } h_i = \textstyle\sum_j h_{ij}.$$

This estimator can be shown to be consistent and to have an asymptotic normal distribution (Basawa and Prakasa Rao 1980: 54–57).

Table 9 presents estimates of first-order, time-stationary transition probabilities over periods of one, five and ten years for the entire data set of industry specialization in terms of value added, including all twelve countries and the seventeen industries described in the appendix. The first panel gives the one-step annual transition matrix, whose (i, j) entry is the conditional probability that the degree of specialization of a certain industry in a certain country has transited from state i to state j after one year. The first column gives the total number of observed transitions from all starting states i, which are arranged in increasing order of indicator values. Entries on the main diagonal are the probabilities that the degree of specialization of an industry observed in a certain interval of the state space will *not* have moved out of that interval after one year. Entries to the right of the main diagonal give the probabilities that an industry increases its relative weight in a certain country compared with that industry's weight in the world, whereas entries to the left of the main diagonal are the probabilities for an industry to lose ground in a certain country, relative to the overall share of this industry in the world.[118]

The first panel shows high persistence at the extremes, with diagonal entries of 89 per cent at the low and 90 per cent at the high end of specialization states. Entries in the middle of the diagonal are much lower, indicating substantial mobility of industries in those countries in which they have a relative weight similar to the world average. In rows 2 and 3, the sum of entries to the right of the main diagonal is greater than the sum of entries to the left, which indicates

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[117] This is warranted for large h but may be problematic in other cases. If the total number of observed transitions were small, due to a short observation period, one would have to decide how much weight the initial distribution of the specialization indicator should be given in making inferences about transition probabilities and about the long-term probability distribution.

[118] Entries are rounded to two decimal places; non-entries indicate that both decimal places are zero after rounding.

Table 9 — Six-State Markov Chain Estimates for the Industry Spezialization Indicator, 1970–1988

Observations	Transition end state (upper boundary)					
	$\mu - sd$	$\mu - sd/3$	μ	$\mu + sd/3$	$\mu + sd$	$> \mu + sd$
	First-order, time-stationary estimates of the one-year transition probabilities					
441	0.89	0.11				
497	0.08	0.78	0.12	0.01		
493		0.11	0.64	0.23	0.02	
643		0.02	0.18	0.63	0.17	
1151				0.10	0.86	0.03
321					0.10	0.90
Stationary distribution	0.116	0.142	0.143	0.185	0.323	0.093
Sample distr.	0.124	0.140	0.139	0.181	0.325	0.090
	First-order, time-stationary estimates of the five-year transition probabilities					
340	0.78	0.19	0.03			
385	0.17	0.6	0.14	0.07	0.02	
381		0.15	0.46	0.24	0.15	
518		0.05	0.23	0.47	0.24	
886			0.04	0.15	0.76	0.05
248					0.17	0.82
Stationary distribution	0.113	0.135	0.139	0.172	0.337	0.103
Sample distr.	0.123	0.139	0.138	0.188	0.321	0.099
	First-order, time-stationary estimates of the ten-year transition probabilities					
212	0.77	0.17	0.03		0.02	
257	0.21	0.49	0.15	0.10	0.06	
234	0.04	0.18	0.37	0.25	0.16	
342		0.09	0.25	0.35	0.31	0.01
572		0.01	0.07	0.15	0.69	0.08
156		0.01	0.03	0.02	0.17	0.77
Stationary distribution	0.149	0.134	0.138	0.152	0.315	0.113
Sample distr.	0.119	0.145	0.132	0.193	0.323	0.088
	One-year transitions, iterated ten times					
	0.44	0.29	0.13	0.08	0.05	
	0.24	0.27	0.18	0.16	0.14	0.01
	0.09	0.17	0.19	0.22	0.28	0.04
	0.05	0.12	0.17	0.23	0.37	0.06
	0.02	0.06	0.12	0.21	0.47	0.11
		0.02	0.05	0.12	0.40	0.40

that below-average specialization is more likely to be followed by an increase than by a decline. In rows 4 and 5, the reverse is true for above-average specialization. These estimates thus do not indicate perfect persistence, but considerable inertia in patterns of specialization. Not surprisingly then, the long-run stationary distribution — computed according to the Chapman-Kolmogorov equation and reported in the first panel along with the sample distribution — is ergodic[119] and does not show any concentration of probability mass at the extreme ends of specialization.

The second and third panels give estimates of five- and ten-year transition matrices, respectively. The entries on the main diagonal are here much lower, indicating much less persistence over longer periods of time. Qualitatively, however, the overall picture remains basically unchanged from the one-year transitions. The only interesting difference is in the third panel where the stationary distribution computed from the ten-year transition matrix does seem to show slightly higher concentration of probability at the extremes than the sample distribution. But this may merely indicate a mild general trend towards increasing specialization rather than high persistence, because the off-diagonal entries in the ten-year transition matrix again show convergence of countries' shares in industries' value added to the world average.

To illustrate consistency of short-run and long-run estimates, the one-year transition matrix has been iterated ten times, the result of which is reported in the fourth panel. Since the entries on the main diagonal are much smaller than the corresponding entries in the directly estimated ten-year transition matrix, this comparison suggests that persistence may actually be higher than estimated by first-order Markov chain models. As a caveat, one should note that part of the higher mobility in technology may be due to measurement problems: Because the patent count data are integer-constrained, small countries with often very few patents per year in some industries will show spuriously high mobility, so for instance when a year with two recorded patents, assigned for a small country to a particular industry, is followed by a year with only one patented application from the same country in that particular industry.

An overall similar picture emerges from estimates of six-state Markov chain transition matrices for the RTA index of technological specialization, reported in Table 10. The major difference to the results for industry specialization in terms of value added seems to be that almost all entries on the main diagonal (in all panels) are much smaller than the corresponding entries in Table 9. There appears to be considerably less persistence in technological specialization than in production, which casts doubt on the hypothesized causality from technological externalities in the form of knowledge spill-overs from R&D to hysteresis in production. The high mobility in technological specialization is underlined by the speedy convergence of the iterated one-year transition matrix to its stationary distribution, which seems to be almost completed after only ten iterations (last panel in Table 10).

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[119] Recall that a Markov chain is ergodic if it is irreducible, positively recurrent and, according to some authors, aperiodic.

Table 10 — Six-State Markov Chain Estimates for the Technology Specialization Indicator, 1972–1989

Observations	Transition end state (upper boundary)					
	$\mu - sd$	$\mu - sd/3$	μ	$\mu + sd/3$	$\mu + sd$	$> \mu + sd$
	First-order, time-stationary estimates of the one-year transition probabilities					
424	0.54	0.25	0.08	0.04	0.06	0.03
661	0.17	0.50	0.16	0.08	0.06	0.02
631	0.04	0.21	0.44	0.19	0.90	0.02
777	0.02	0.06	0.17	0.56	0.16	0.02
892	0.03	0.05	0.06	0.13	0.63	0.09
355	0.04	0.02	0.05	0.05	0.21	0.64
Stationary distribution	0.116	0.181	0.163	0.201	0.236	0.102
Sample distr.	0.113	0.177	0.169	0.208	0.239	0.095
	First-order, time-stationary estimates of the five-year transition probabilities					
315	0.51	0.25	0.07	0.04	0.08	0.03
501	0.18	0.48	0.18	0.07	0.07	0.02
487	0.06	0.22	0.38	0.22	0.09	0.03
590	0.03	0.08	0.18	0.50	0.18	0.02
692	0.03	0.06	0.08	0.15	0.56	0.12
275	0.05	0.03	0.04	0.06	0.23	0.59
Stationary distribution	0.125	0.191	0.164	0.192	0.222	0.105
Sample distr.	0.110	0.175	0.170	0.206	0.242	0.096
	First-order, time-stationary estimates of the ten-year transition probabilities					
200	0.45	0.24	0.09	0.07	0.07	0.07
294	0.21	0.43	0.13	0.10	0.08	0.03
296	0.07	0.26	0.31	0.24	0.08	0.02
366	0.05	0.11	0.18	0.42	0.20	0.08
444	0.02	0.08	0.11	0.17	0.48	0.14
160	0.03	0.06	0.09	0.04	0.26	0.52
Stationary distribution	0.132	0.205	0.156	0.189	0.206	0.112
Sample distr.	0.114	0.167	0.168	0.208	0.252	0.090
	One-year transitions, iterated ten times					
	0.12	0.18	0.16	0.19	0.23	0.10
	0.12	0.19	0.16	0.19	0.23	0.09
	0.12	0.18	0.16	0.20	0.23	0.09
	0.11	0.18	0.16	0.20	0.24	0.10
	0.11	0.18	0.16	0.20	0.24	0.10
	0.11	0.17	0.16	0.21	0.25	0.11

Although these estimation results on the overall dynamics of specialization in value added and technology do not seem to support the hypothesis of hysteresis, the picture may be different at the level of individual industries. After all, the claim of hysteresis is made mostly in view of those industries which make intensive use of technological innovation and which are therefore rightly classified as high-technology industries. Separate estimates of five-year transition matrices for a number of industries, selected for the high technology content of their typical products, are presented in Table A8, both for the industry and the technology specialization indicators.

Empirical research on positive external effects from innovation at the industry level has repeatedly found evidence for their existence in parts of the chemical industry, in pharmaceuticals, machinery, microelectronics and in the professional instruments industry (Mohnen 1990). Particular attention will therefore be paid to the specialization dynamics in these and the closely related industries of the sample.[120] In the *chemical (CHEM)* industry (excluding drugs and medicines), persistence in terms of entries on the main diagonal appears to be even lower than in the five-year transition matrix for all industries, except at the extreme end of above-average specialization, where the estimated probability of remaining in the highest state is 94 per cent. The off-diagonal entries suggest that the degree of specialization tends to converge towards the average whenever a national chemical industry is over- or underrepresented in its home country compared with the share of chemicals in total world manufacturing.

In the *technological* specialization indicator of the chemical industry, on the other hand, persistence on the main diagonal is higher for almost all states than in the five-year technology transition matrix for all industries. Moreover, the entries in the second, third and fourth row suggest that transitions may often be away from the average share of chemical patenting in total patents granted in all fields of technology. However, the bulk of observations, entries in row five, do not show divergence from the mean. And overall, the *chemical* industry technology transition matrix does not look very different from the transition matrix of specialization in terms of value added.

For the industry specialization indicator in the *drug and medicine (DRUG)* industry, generally less persistence is estimated on the main diagonal than in the chemical industry and in all industries together. This holds, too, for the technology specialization indicator, except for the middle states. Moreover, only the third row of the technology transition matrix suggests slightly higher probability of the indicator moving away from the mean. In the five-year transition matrix for the *rubber and plastics (RAP)* industry, by contrast, persistence appears to be high at the extreme ends of industrial specialization, with a tendency in the second, third and fourth row to move further away from the mean. The technology transition probabilities appear to be more in line with those of all industries, except for the fourth row, where a trend away from the mean is estimated.

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[120] See the data appendix for a listing of all sample industries and their ISIC codes.

In the *office and computing machinery (COMP)* industry, generally less persistence is observable — in both value added and technology (except for the high end of technology transitions) — than in all industries together, and no tendency of divergence can be detected. Also the *electrical machinery (ELMA)* industry seems to have generally lower persistence than the specialization indicators for all industries. But divergence is observed in the second and to some extent in the fifth row of the value added transition matrix as well as in the fourth row of the technology transition matrix. The transition matrix estimated for value added in the *motor vehicle (MOTV)* industry is rather irregular and difficult to interpret — due to the unfortunate clustering of most observations in the fifth interval of the discretizing grid. The technology transition matrix is characterized by low persistence in the middle states and high persistence at the ends; but only the third row has an entry that signals a trend away from the mean.

High persistence at the end states is again characteristic for the estimated technology transitions in *shipbuilding (SHIP)*, but the transition matrix in terms of value added is quite similar to that of all industries together. Finally, both the *aircraft (AIRC)* industry and the *professional instruments (PROF)* industry have very high persistence at the extremes in their value added specialization indicator, but much less so in their technology specialization indicator.

Except for the value added specialization indicator in the *motor vehicle (MOTV)* industry and for the technology indicator in the *radio, television and communication equipment (RTVC)* industry[121], the estimated transition dynamics of industrial and technological specialization in individual industries are all ergodic with unique stationary distributions. But only for industry and technology transitions in the *drug and medicine (DRUG)* industry and for technology transitions in the *aircraft, electrical machinery* and, arguably, *non-metallic mineral products* industry do the stationary distributions resemble the corresponding sample distribution, as would be expected in the *absence* of any path-dependence or hysteresis. On the other hand, only the stationary distributions for technology in the *motor vehicle* and *professional goods* industries and for value added in the *non-metallic mineral products* industry turn out really bimodal, as would be expected in the case of hysteresis. Most stationary distributions rather have a concentration of probability mass in the middle states (*CHEM, COMP, ELMA* value added and *AIRC* technology) or at one end only

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[121] The *motor vehicle (MOTV)* industry indicator and the *radio, TV and communication equipment (RTVC)* technology indicator transitions matrices are divided in two ergodic sets. In the case of *RTVC* technology, the highest state appears to be absorbing, no transitions out of this state are observed. In the case of *MOTV* value added, one ergodic set is comprised of the two lowest states, the other of the remaining four states.

(*RTVC* and *PROF* value added, *CHEM* and *COMP* technology and both indicators for *FOOD, RAP, IRON, NFM, FABM, MACH* and SHIP).

On the whole, these observations, however, should neither be taken as final evidence for nor against high persistence pointing to hysteresis. Instead, they may be an unfortunate consequence of including countries of vastly different sizes in one and the same transition matrix. When the largest or a few of the largest economies increase their share in total value added in a certain industry, then more of the smaller economies must be losing shares in this industry. Consequently, the Maximum Likelihood estimator assigns a larger weight to the more frequently observed losses of the more numerous smaller economies than to the corresponding gains of one or very few big economies. A stationary distribution with a concentration at one end may thus often reflect a monotone trend in the specialization dynamics in the largest economy in the sample, the United States.[122]

One way of dealing with the inconvenience caused by the great disparity in the sizes of countries in the sample is to estimate transition matrices for *fractile* Markov chains as proposed by Geweke et al. (1986) and recently applied by Quah (1993c) in another context. Instead of using an arbitrary grid to discretize the continuous state space of the specialization indicators, one can fix a set of increasing, non-redundant probabilities, equally spaced on the open unit interval, say $P = \{1/6, 1/3, 1/2, 2/3, 5/6, 1\}$, and let this determine for each period t a corresponding set of quantiles.[123] The sequence of quantile sets $\{Q(t)\text{: integer } t\}$ then parametrizes movements in the entire distribution, while the estimated fractile transition probability matrix — named so by Quah (1993c) —parametrizes intradistribution mobility.

The simple Maximum Likelihood estimator is again based on the assumption of invariance of the transition probabilities with respect to time and the relevant cross-section dimension — countries, industries or both. If the estimated fractile matrix is ergodic, its stationary distribution will be uniform relative to the

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[122] Similarly, a stationary distribution with a concentration in the middle may lend spurious support to the hypothesis of convergence in specialization indicators. In fact, it may indicate that the two largest economies, the United States and Japan, have monotonically moved in opposite directions away from the middle states, pulling many of the smaller, perhaps initially more specialized economies inwards from the end states. In theory, the move of two dominating economies in opposite directions may even be the consequence of hysteresis when one of them is winning a path-dependent technological race in a certain industry where positive externalities have a strong impact on productivity.

[123] Experimenting with different ways of discretizing the state space is generally recommended as a test for robustness of Markov chain estimates, regardless of any specific problems like varying country sizes. Arbitrary and inappropriate discretization without considering alternatives often is a source of spurious results.

quantiles Q (Quah 1993c: 15). Estimates of intradistribution mobility will here be less disturbed by a trend movement of a large country since the fractile method basically implies a redefinition of the grid discretizing the state space in each period of time. In order to relate the stationary distribution to the original state space one would have to consider — in addition to intradistribution mobility — movements in the entire distribution as estimated in the sequence of quantile sets $\{Q(t)\text{: integer } t\}$.[124]

In the present context, it will suffice to examine whether the interquantile range increases, decreases or remains constant over time. This can be done by running a simple linear regression of the interquantile range on time and testing for significance of the slope coefficient. Within this approach, a significant positive time trend in the interquantile range combined with high persistence in terms of large entries on the main diagonal — especially at the ends — of the estimated fractile matrix would point to hysteresis, whereas a negative or no time trend in the interquantile range and low persistence in the transitions matrix would appear to contradict the hypothesis of hysteresis.

Estimates of the ten-year *fractile* Markov chains for specialization in value added and technology taking all industries together (reported in Table 11) reveal almost the same degree of persistence on the main diagonal as observed in the previously reported non-fractile Markov chain estimates. Again, persistence appears to be lower in technology than in value added. But for both, a positive time trend in the interquantile range, albeit a mild one, is found to be significant at the 5 per cent level.

Looking at fractile Markov chain transition estimates for individual industries (Table A9) generally confirms the picture that has emerged from the estimates of non-fractile Markov chain transitions. However, more persistence at the end states of specialization is observed in the *chemical*, *electrical machinery* and *professional instruments* industry, while the *radio, television and communication equipment* industry divides into two ergodic sets of three states each. But in the *machinery* industry as well as the *office and computing equipment* industry persistence at the end states appears less pronounced when estimating fractile Markov chains. In the fractile estimates of five-year *technology* transition matrices for individual industries, more persistence at the ends is noticeable in the *drug and medicine* and *electrical machinery* industries, less persistence in the *radio, TV and communication equipment* and *motor vehicle* industries.

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[124] But any attempt at forecasting the stationary distribution of individual industries' specialization on the corresponding original state space may bear the danger of reintroducing the stated problems associated with vastly differing country sizes.

Table 11 — Fractile Markov Chain Estimates for the Specialization Indicators

(First-order, time-stationary estimates of the ten-year transition probabilities)

	Transition end state (quantile)					
Observations	1/6	1/3	1/2	2/3	5/6	1
	Industry specialization in value added, 1970–1988[a]					
288	0.73	0.19	0.06	0.01	0.01	
297	0.23	0.38	0.23	0.10	0.07	
297	0.02	0.29	0.35	0.23	0.08	0.02
297	0.01	0.10	0.23	0.37	0.22	0.06
297		0.03	0.09	0.26	0.48	0.13
297		0.02	0.04	0.02	0.14	0.78
	Technology specialization, 1972–1989[b]					
264	0.50	0.20	0.10	0.06	0.06	0.06
272	0.24	0.36	0.17	0.11	0.08	0.04
272	0.12	0.19	0.31	0.25	0.08	0.05
272	0.05	0.11	0.19	0.33	0.23	0.08
272	0.04	0.08	0.14	0.19	0.31	0.25
272	0.04	0.06	0.08	0.06	0.25	0.51

[a] A regression of the interquantile range on time (in years) yields a slope coefficient of 0.005 with a t-value of 2.31 and an adjusted R^2 of 0.194. — [b] A regression of the interquantile range on time (in years) yields a slope coefficient of 0.006 with a t-value of 2.43 and an adjusted R^2 of 0.224.

But only for the technology transitions in *shipbuilding*, *machinery* and the *professional instruments* industries are positive time trends in the interquantile range detected which are significant at the 5 per cent level. Of these three industries, the *machinery* industry also has a significant positive time trend in the interquantile range of its industry specialization indicator in terms of value added, whereas the corresponding interquantile range for the *professional instruments* industry is significantly negative, and that of *shipbuilding* not significantly different from zero. The evidence of high persistence in the estimated fractile transition matrices of specialization in terms of value added is again undermined by a negative time trend in the interquantile range in the case of the *chemical*, *electrical machinery*, *motor vehicle* and *aircraft* industries.

Where a *positive* time trend coincides with high persistence at the end states of value added specialization — as in the *rubber and plastics*, *non-metallic mineral products* and *non-ferrous metals* industries — this can still not justify a hysteretic explanation based on knowledge externalities, because no time trend and low persistence are observed in the corresponding *technology* specialization indicators. It appears that the estimated fractile transition matrices for both technology and value added specialization are jointly supportive of the hypothesis of hysteresis only in the case of the *machinery* industry.

III. The Impact of Changes in Factor Endowments

Although the preceding discussion has described the observable dynamics of technological and industrial specialization for twelve OECD countries in some detail, this is still a long way from giving *conclusive* evidence on hysteresis. Apart from methodological questions such as robustness of the non-parametric estimates, the main shortcoming of the preceding analysis is its lack of accounting for relative factor endowments in the sample countries and changes thereof during the sample period. If factor endowments have any impact at all on the international allocation of sectoral economic activities, they might — in the case of monotonic time trends in the dynamic comparative advantages of countries — even be responsible for patterns of specialization dynamics which point to a bimodal stationary distribution, just like hysteresis would.[125] It is surely important to account for the influence of changes in the relative factor supplies of countries when analyzing the dynamics of specialization with a view to testing hysteresis, although this will — admittedly — be a very difficult task.

A first attempt is made by simply regressing the familiar value added indicator of an industry's specialization in the sample countries on conceptually similar indicators of countries' relative factor endowments, and by subsequently estimating fractile Markov chain transition matrices on the residuals. Provided all relevant endowments are appropriately considered, this procedure eliminates that part of the specialization dynamics which can be accounted for by the dynamics of comparative advantages. The residual dynamics would then lend support to the hypothesis of hysteresis, if they showed high persistence at the end states of specialization and a positive time trend in the interquantile range. They would, on the other hand, cast doubt on hysteresis if there was low persistence or a negative time trend in the interquantile range.

The factor endowments considered here for each of the twelve countries are: physical capital, R&D capital, the number of R&D scientists and engineers in the business enterprise sector, the labour force, and the years of schooling in the labour force. While R&D capital, using cumulative R&D expenditures as a proxy for the national stock of technical knowledge, and physical capital are both stocks from which input services flow, the other three factors are more direct measures of input flows, although years of schooling and the number of R&D scientists and engineers stand for facets of human capital in labour services.[126]

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[125] This can already be seen from the stylized Ricardian model with stochastic recontracting discussed in Section C.II.

[126] For sources and methods see Appendix II.

On theoretical grounds one might argue that these factor endowments should not be given equal weight as conditioning factors for sectoral specialization, because they are likely to possess quite different degrees of international mobility. Only fully immobile factor endowments should ideally be treated as country-specific characteristics, but this issue seems to be of lesser importance here, and is therefore neglected. To avoid implicitly regressing on country size, yearly factor supplies have been normalized dividing each country's share in the total supply of all twelve countries by the country's share in the sum of the gross domestic products of all twelve countries. As with the industry specialization indicators, a logarithmic transformation is made to obtain more symmetrically distributed variables.

The separate regressions of each industry's indicator of specialization in value added on the indicators of relative factor endowments have been done by ordinary least squares, pooling time series across countries. By design, no attempt has been made to correct the estimation for the substantial autocorrelation (over time) which is evident in the residuals. After all, it is precisely the structure of this autocorrelation which is subsequently to be analyzed in terms of fractile Markov chain transition probabilities. A general tendency of divergence in the autocorrelated residuals away from their theoretical mean of zero could be interpreted as evidence in support of hysteresis, whereas substantial non-monotonic mobility of the residuals, or even convergence to the mean, would lend support to the alternative hypothesis of dynamic comparative advantages as an adequate explanation of industrial specialization dynamics. Notice that neither divergence nor convergence in the residuals is predisposed by the chosen regression method. But the assumption of *exogeneity* of factor endowments with respect to industrial specialization patterns is fundamental to the interpretations advanced. This assumption may, of course, be open to question.

Results of the regressions are reported in Table 12. Note that the estimated parameters should not be interpreted as revealing any specific economic causality — for several reasons. First, there is substantial collinearity between the factor endowment indicators. Some bivariate correlations between the exogenous variables are higher than bivariate correlations with the dependent variable in many of these regressions; the variance inflation factors, i.e. the diagonal elements of the inverse of the correlation matrix, are all around two in magnitude.[127] Second, the regressions are, by ordinary standards, misspecified since the hypothesis of no country-fixed effects, which is implicit in using only one common intercept for each industry regression, is clearly rejected at any

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[127] This indicates that all variances of the estimated coefficients are about twice as large as they would be if there was no correlation between the respective regressor and the other independent variables.

Table 12 — Regressions of Specialization in Value Added on Relative Factor Endowments[a]

Industry	*Constant*	*Capital*	*R&D capital*	*R&D scientists & engineers*	*Labour*	*Schooling*	Adjusted R^2
Food, beverages, tobacco	0.06	0.16	–0.05	–0.04	–0.41	0.07	0.16
		(1.82)	(–2.29)	(–0.89)	(–4.07)	(1.04)	
Chemicals, excl. drugs	0.01	0.59	0.38	–0.22	–0.39	–0.01	0.43
		(4.79)	(11.53)	(–3.06)	(–2.78)	(–0.12)	
Drugs and medicines	–0.13	–1.71	–0.19	0.65	1.63	–1.16	0.54
		(–11.42)	(–4.67)	(7.48)	(9.52)	(–9.36)	
Rubber and plastics	–0.03	–0.36	–0.10	0.43	0.31	–0.75	0.47
		(–4.99)	(–5.20)	(10.18)	(3.69)	(–12.43)	
Non-metallic mineral products	–0.09	–0.25	–0.17	–0.05	0.92	–0.65	0.64
		(–4.02)	(–9.91)	(–1.53)	(12.88)	(–12.53)	
Iron and steel	–0.10	–0.18	–0.22	0.71	0.23	–0.50	0.41
		(–1.69)	(–7.88)	(11.58)	(1.93)	(–5.68)	
Non-ferrous metals	0.12	0.46	–0.35	0.80	–2.42	0.30	0.39
		(1.98)	(–5.59)	(5.95)	(–9.04)	(1.56)	
Fabricated metal products	–0.02	–0.21	–0.04	–0.06	–0.15	–0.15	0.26
		(–3.15)	(–2.15)	(–1.46)	(–1.99)	(–2.71)	
Machinery, not elsewhere classified	–0.05	–0.04	0.19	–0.05	0.92	0.23	0.44
		(–0.36)	(5.96)	(–0.74)	(6.82)	(1.93)	
Office and computing machinery	–0.15	–0.84	–0.16	1.44	–0.99	–1.07	0.37
		(–2.81)	(–1.99)	(8.47)	(–2.96)	(–3.65)	
Electrical machinery, excl. radio, TV and communication equip.	–0.24	–0.69	–0.36	0.51	2.06	–1.03	0.33
		(–2.93)	(–5.84)	(3.78)	(7.85)	(–4.51)	
Radio, TV and communication equip.	0.11	0.87	0.66	0.49	–1.34	–0.14	0.72
		(5.36)	(15.56)	(5.30)	(–7.42)	(–0.92)	
Motor vehicles	–0.07	–2.64	–0.45	1.09	1.29	–1.91	0.47
		(–10.29)	(–6.49)	(7.36)	(4.38)	(–8.97)	
Shipbuilding and repair	0.06	2.07	0.36	–0.60	–0.40	2.13	0.39
		(6.55)	(4.22)	(–3.29)	(–1.11)	(8.16)	
Aircraft	–0.27	–2.58	0.30	–0.79	–1.27	0.14	0.73
		(–10.24)	(4.30)	(–5.60)	(–4.48)	(0.71)	
Professional goods (scientific instruments)	–0.29	–1.21	0.07	0.27	0.55	–0.89	0.30
		(–4.68)	(0.97)	(1.86)	(1.93)	(–4.27)	

[a] Annual data for the period 1970–1988 and for twelve countries (eleven countries for MACH, COMP, ELMA, RTVC, AIRC and PROF). t-values in parentheses. — For further explanations see Section E.III in the main text.

conventional level of significance.[128] And third, the estimation of pooled data by simple ordinary least squares ignores that in reality adjustment costs are

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[128] Similarly, the hypothesis of structural stability across time is rejected at the 1 per cent level of significance in the case of *RAP, IRON, NFM, MACH, COMP, ELMA, RTVC* and at the 5 per cent level of significance in the case of *CHEM, SCG, MOTV, SHIP* and *AIRC*. These inferences are based on a general Wald test for the joint significance of an intercept and slope dummies for the subperiod 1980 through 1988. In the case of the *PROF* industry, slope dummies for the specified subperiod are significant at the 5 per cent level for the schooling and the R&D scientists and engineers endowment indicators.

likely to have an important impact on the relationship between changing relative factor endowments and the industrial specialization in open economies.

Nevertheless, the residuals from these 'naive' regressions may be of use in Markov chain analysis where they are simply taken to be that part of the specialization dynamics which is *statistically* unexplained by movements in countries' relative factor endowments. The regressions are merely used to filter out those components of the industry specialization dynamics which are *not* orthogonal to relative factor endowments. It would therefore be misleading to include dummies to capture country-fixed effects in these regressions and thus to avoid what is, from a statistical point of view, a misspecification. Although such dummies would surely account for much of the variation in the specialization indicators and greatly improve the fit of the regressions reported in Table 12, they would spoil those characteristics in the residuals which bear on the hypothesis of hysteresis. After all, it is precisely the persistence of country specific effects in the residuals' autocorrelation structures which is to be analyzed in terms of fractile Markov chains.

A glance at Table 12 suggests that, in some industries — notably in food, beverages and tobacco and in fabricated metal products — factor endowments do not account well for the variation in measured specialization. In most other regressions, however, there are acceptable coefficients of determination, adjusted for degrees of freedom. Thus, the residuals from these regressions are likely to have dynamics quite distinct from those of the unconditioned indicators of industrial specialization in the sample countries.

Estimation of a six-state, five-year *fractile* Markov chain transition matrix on the residuals from all industries together reveals clearly less persistence on the main diagonal than in the corresponding *unconditioned* fractile transition matrix.[129] Moreover, there is no significant time trend. This evidence against hysteresis is in fact confirmed by most fractile transition probability estimates for individual industries' residuals: less persistence than in the unconditional specialization dynamics is observed in the residuals from the *drug and medicine*, *professional instruments*, *aircraft*, *shipbuilding*, *rubber and plastics*, *electrical machinery*, *office and computing machinery* as well as from the *radio, TV, communication equipment* industries. The latter industry's residuals also lose their previously striking division of the five-year fractile transition matrix into two ergodic sets.

Furthermore, testifying against the case of hysteresis are the significant negative time trends in the interquantile range — mostly higher in absolute terms than in the unconditioned dynamics — which are estimated for several

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[129] See Table 13 for the estimated overall residual transition probabilities and for separate estimates of selected industries' residual transition matrices.

Table 13 — Fractile Markov Chain Estimates for the Industry Residual Specialization Indicator, 1970–1988

1. First-order, time-stationary estimates of the five-year transition probabilities

Transition end state (quantile)					
1/6	1/3	1/2	2/3	5/6	1
All industries					
0.57	0.2	0.1	0.06	0.05	0.02
0.21	0.34	0.23	0.1	0.07	0.03
0.09	0.23	0.32	0.21	0.11	0.04
0.06	0.13	0.19	0.31	0.24	0.08
0.04	0.08	0.14	0.21	0.33	0.2
0.02	0.03	0.03	0.09	0.2	0.63
Chemicals, excl. drugs					
0.93	0.04	0.04			
0.07	0.29	0.29	0.21	0.11	0.04
	0.29	0.32	0.18	0.11	0.11
	0.25	0.14	0.29	0.29	0.04
	0.07	0.18	0.18	0.39	0.18
	0.07	0.04	0.14	0.11	0.64
Drugs and medicine					
0.46	0.18	0.21	0.11	0.04	
0.29	0.36	0.04	0.18	0.04	0.11
0.11	0.18	0.21	0.11	0.25	0.14
0.07	0.11	0.29	0.14	0.18	0.21
0.07	0.14	0.11	0.05	0.32	0.11
	0.04	0.14	0.21	0.18	0.43
Rubber and plastics					
0.46	0.14	0.11	0.21	0.07	
0.18	0.25	0.29	0.11	0.04	0.14
0.14	0.21	0.18	0.11	0.14	0.21
0.07	0.18	0.14	0.18	0.21	0.21
0.04	0.11	0.11	0.18	0.32	0.25
0.11	0.11	0.18	0.21	0.21	0.18
Machinery, not elsewhere classified					
0.57	0.43				
0.21	0.11	0.36	0.11	0.18	0.04
	0.36	0.29	0.29	0.04	0.04
	0.25	0.25	0.28	0.14	0.07
	0.07	0.11	0.25	0.36	0.21
			0.07	0.29	0.64

Table 13 continued

Transition end state (quantile)					
1/6	1/3	1/2	2/3	5/6	1
Office and computing machinery					
0.36	0.43	0.07	0.14		
0.07	0.39	0.07	0.29	0.14	0.04
0.14	0.18	0.25	0.18	0.25	
0.04	0.14	0.46	0.21	0.04	0.11
0.07	0.07	0.14	0.21	0.21	0.29
		0.04	0.04	0.36	0.57
Electrical machinery, excl. radio, TV and communication equip.					
0.14	0.21	0.36		0.21	0.07
0.25	0.39	0.21	0.11		0.04
0.11	0.09	0.21	0.18	0.18	0.04
0.04	0.04	0.14	0.32	0.35	0.11
	0.11	0.25	0.21	0.18	0.25
0.04	0.07		0.18	0.18	0.54
Radio, TV and communication equip.					
0.21	0.43	0.21	0.14		
0.29	0.43	0.18	0.07	0.04	
0.11	0.21	0.18	0.19	0.21	
	0.11	0.25	0.25	0.36	0.04
	0.04	0.14	0.25	0.29	0.29
		0.14	0.07	0.11	0.67
Motor vehicles					
0.79	0.11	0.11			
0.11	0.46	0.39	0.04		
0.04	0.32	0.04	0.14	0.14	
0.04	0.11	0.07	0.36	0.29	0.14
0.04		0.07	0.39	0.39	0.11
			0.07	0.18	0.75
Shipbuilding					
0.61	0.07	0.18	0.11	0.04	
0.18	0.36	0.25	0.11	0.11	
0.14	0.29	0.21	0.29	0.07	
0.04	0.21	0.14	0.25	0.32	0.04
0.04	0.07	0.21	0.18	0.43	0.07
			0.07	0.04	0.89
Aircraft					
0.43	0.14	0.21	0.21		
0.11	0.21	0.5	0.11	0.07	

Table 13 contiuned

Transition end state (quantile)					
1/6	1/3	1/2	2/3	5/6	1
0.14	0.57	0.11	0.18		
0.04	0.07	0.29	0.32	0.14	0.14
	0.07		0.18	0.43	0.32
			0.11	0.36	0.54
Professional goods (scientific instruments)					
0.71	0.29				
0.07	0.50	0.36	0.04	0.04	
0.07	0.32	0.36	0.21	0.04	
		0.21	0.64	0.14	
		0.04	0.07	0.54	0.36
	0.04	0.04	0.04	0.25	0.64

2. Regressions of Interquantile Range in Residuals on Time

	Coefficient	t-value	Adj. R^2
All industries	0.00	–0.72	–0.028
Chemicals, excl. drugs	0.00	–0.75	–0.025
Drugs and medicine	–0.02	–7.65	0.762
Rubber and plastics	0.01	3.18	0.336
Machinery, not elsewhere classified	0.01	3.21	0.340
Office and computing machinery	–0.11	–6.36	0.687
Electrical machinery, excl. radio, TV and communication equip.	–0.07	–1.77	0.106
Radio, TV and communication equip.	–0.01	–1.52	0.068
Motor vehicles	–0.01	–0.06	–0.059
Shipbuilding	0.01	0.84	–0.017
Aircraft	–0.04	–5.35	0.600
Professional goods (scientific instruments)	–0.02	–2.11	0.161

industries. But a significant positive time trend in the interquantile range remains in the *machinery* as well as in the *rubber and plastics* industries. Nevertheless, hysteresis on the basis of knowledge spill-overs is most unlikely in the case of the *rubber and plastics* industry— not only because the residual dynamics show so little persistence, but also because low persistence is as well characteristic for the technology dynamics, be they estimated in terms of fractile or non-fractile five-year Markov chains transitions (reported in Section E.II.2 above). In the case of the *machinery* industry the degree of persistence in technology and in the residual dynamics is quite similar to that of all industries together — no special case here either. So it seems that the hypothesis of hysteresis in industrial specialization, based on positive knowledge spill-overs from R&D, finds little convincing support in the available data, once they are subjected to a close and careful examination.

To sum up, this chapter has reported new evidence, using an approximation in terms of finite Markov chains, to assess the empirical dynamics of specialization in advanced open economies — with an eye on the controversial hypothesis of hysteresis, allegedly caused by path-dependence and national idiosyncracies in sectoral technological accumulation. The evidence from the nonparametric estimates of Markov chain transition probabilities presented here does not point to hysteresis in the dynamics of industrial specialization, although there may be considerable inertia in some industries.

The basic finding of no real hysteresis appears to be fairly robust since it is confirmed both when considering all industries together and when scrutinizing individual industries separately. Conditioning on five factor endowments, assumed to be of particular relevance in technological development and modern manufacturing, has not overturned the findings. On the contrary, conditioning — although done here in a crude, preliminary fashion — has strengthened the case for dynamic comparative advantages (the alternative hypothesis) as an adequate explanation of observable specialization dynamics.

As a caveat, one should note that these conclusions are arrived at without having considered the possibility that the observed specialization dynamics have in part been shaped by specific industrial policies, which governments of individual countries may have undertaken in the past. Moreover, the conclusions drawn from the residual dynamics hinge on the exogeneity of changes in factor supplies, including physical and R&D capital, with respect to changing patterns of specialization. This exogeneity is likely to be disputed by advocates of path-dependence in technological change and industrial specialization dynamics.

A number of other important problems also remain unresolved in this study. One of these is how to take the great variation in the size of national economies properly into account. This problem might be alleviated if a larger cross section of countries became available, in which the specialization dynamics of more countries of similar size could be compared with each other. Another possibility to come to terms with size might be to apply the methodology explored here to regional data sets, where hysteresis would again be a serious hypothesis to confront, and where the largest region might not be as dominant as the United

States are in the world economy. Alternatively, instead of trying to avoid the statistical problems stemming from vastly differing country sizes, one could address the issue more directly; an important question would be whether hysteresis might become effective only when a certain industry, or the pertinent R&D activities of a country, had passed a certain threshold in terms of absolute size.

Another important question relates to the level of industry aggregation used in this study. The hypothesis of hysteresis based on path-dependence in technological dynamics may actually be more relevant at lower levels of sectoral aggregation. Besides, potentially interesting information may surface from technology measures other than patent count data. Quantitative information on R&D inputs, for instance, may reveal how intensively the R&D activities in different industries make use of scarce factors, like specialized human capital. Finally, the incorporation of conditioning information needs to be improved upon, and more powerful methods of statistical inference need to be devised and applied in future work on this subject.

> In the model, "picking winners" is easy. If only it were so in reality!
> — Robert E. Lucas, Jr. (1988: 31)

F. Implications for Industrial and Technology Policies

The theory of endogenous technological change, which was discussed in Chapters B and C, states conditions, i.e. the national diffusion of knowledge spillovers from R&D among others, under which certain targeted industrial and technology policies have the potential to raise national welfare. The empirical findings reported in Chapters D and E, however, raise doubts whether in the 1970s and 1980s the theoretical conditions were met in OECD countries for which data on sectoral R&D activities and patterns of industrial and technological specialization have been available. Chapter D showed that the notion of comparative advantage goes a long way towards explaining actual patterns of specialization in countries' R&D activities. And the work reported in Chapter E did not find much evidence of hysteresis in patterns of industrial and technological specialization.

I. Human Capital, Path-Dependence and the Historical Nature of Economic Development in Geographical and Technological Space

1. Positive Feedbacks in Human Capital Accumulation

In the present chapter, these empirical findings are taken to be merely preliminary results, not giving a final verdict on recent theories of endogenous technical change and path-dependent economic development. The discussion will adopt the perspective of an economic consultant to a benevolent government which considers embarking on a regime of targeted industrial and technology policies despite the uncertainty about the validity of economic rationalizations of such policies. Such a discussion seems important in view of the possibility that, despite the predominantly negative findings of the present study, hysteresis in specialization dynamics may still hold on a lower level of aggregation.

What are the deliberations a responsible economic consultant should make and present to his benevolent government? The answer has to be that, before recommending any targeted policies for practical implementation, the applied economist must first test the empirical implications of the theory in general, so as to verify its validity, and second check whether all the particular conditions for a welfare-improving potential of certain kinds of policy interventions, which the theory identifies, are fulfilled in a given historical situation.

This twofold test would be a formidable task even if a theory of endogenous technological change were to be considered in isolation, as the only relevant hypothesis. But an additional, major difficulty lies in the need to discriminate both between the various particular versions of the theory of endogenous technological change, on the one hand, and between these theories and other theories of human capital accumulation and growth, on the other hand. The problem is that some of the latter have empirical implications similar to those of some of the former theories. Observational equivalence, however, does not necessarily imply that the industrial policy implications are equal, too. It is for this reason that the present chapter discusses some other new (and not so new) theories of growth, which contend hypotheses that are partly complementary and partly alternatives to the theory of endogenous technical change.

This is not to deny that recent strides in the microeconomic modelling of the private incentives to invest in research and development, from which the theory of endogenous technical change derives the determinants of innovation and growth, have contributed considerably to a better understanding of growth in industrialized economies. In particular, the models of horizontal product differentiation are able to formally describe the increasing differentiation and specialization of technical knowledge as an important source of progress in productivity, and to make it accessible to general equilibrium analysis.

Variety must have value: what else could explain the enormous complexity of modern economies? The models, in particular the 'love-of-variety' function of Dixit and Stiglitz (1977), formalize the economy's production apparatus with a flexibility that does better justice to real-life arrangements, characterized by never-ending adjustments and rearrangements through investments, than does the Cobb-Douglas production function on its own, or its direct theoretical generalizations which are rooted in static analysis. It is, of course, characteristic for the change in the production apparatus of a growing economy that relative scarcities of goods and factors change all the time and that production processes used are constantly being replaced — and not merely by other technically efficient processes previously known but often by entirely new processes. These are sometimes discovered accidentally, but for the larger part they are found by carefully planned, profit-seeking research and development efforts. However, the accumulation of technical knowledge alone can hardly be the complete answer to the perennial question what causes growth. One hint at the complexity of these causes is the observation that new knowledge can often generate productivity gains only when it is efficiently put to use by specialists.

To be sure, Grossman and Helpman (1991) seem to recognize this, as they differentiate between unskilled labour and scientifically or technically trained specialists, and in Chapter 5 of their book endogenize the supply of human capital (which individuals offer in the labour market) by explicitly modelling the incentives for the young to undergo specialized academic or vocational training. The models of endogenous technological change generally emphasize the scarcity of individual human capital as a crucial bottleneck for long-term growth. But in their dichotomy of skilled versus unskilled workers, which are assumed to substitute (albeit imperfectly) in production, the authors neglect any direct, threshold complementarity between skilled specialists and specialized technical knowledge, which is frequently observed in reality. Yet, it is explicit consideration of the increasing differentiation and specialization of individual human capital which reveals important new insights into the potential growth effects of industrial policies; and some of these are overlooked in the theory of endogenous technical change.

A certain restrictiveness of the models of endogenous technical progress results, for example, from the models' implication that the exogenous size of the labour force sets an upper limit for the accumulation of individual human capital in each country. Indeed, the capacity of each individual brain may be limited, but this does not necessarily restrict the capacity of a whole people when the accumulation of individual human capital is a process of increasing differentiation and specialization of individual skills and qualifications. Already Adam Smith ([1776] 1994) recognized the productivity gains that a team of complementary specialists could realize in comparison to the same number of 'jacks of all trades', but he assumed that the scope for specialization was limited by the size of the respective market. Many economists have accepted this idea and have viewed the observed secular increase in specialization since the industrial revolution as a consequence of falling transport costs, facilitating the spatial expansion of local markets.

Becker and Murphy (1992), by contrast, develop a theory of endogenous growth in which the specialization of individual human capital is not constrained by the limitations of local markets, but rather by costs of coordination without which cooperation between different specialists would be all but impossible. These coordination costs consist of communication costs, an increased probability of error in sequential and complementary work processes, and of efficiency losses, which are due to free-rider behaviour and blackmail attempts in teams as well as due to the unavoidable debates and vote-taking to unify different individual goals into a common group goal.

In Becker and Murphy's model, the costs of coordinating a team, which can be achieved either hierarchically within an organization or decentrally via markets, increase overproportionally when the size of the team grows. At the same time, the productivity of the individual team member increases because in larger teams it is profitable to invest in a deepening of human capital facilitating an even stronger specialization of the individual. The limit of an efficient team expansion is reached when the marginal productivity gain just equals the additional coordination cost per team member. This limit is approached more rapidly, the higher the coordination costs and the steeper their increase in the course of team expansion. The coordination of specialized human capital and of other production factors is probably the most important task of entrepreneurs. A large part of the decentral information needed for this job is in market economies transferred via prices which indicate the scarcity of specialized resources and the relative importance and urgency of tasks (Hayek 1945).

An increase in (private) technical knowledge, on which specialists can rely in their work, raises both their average productivity and the marginal product of team expansion, which in turn creates further incentives to expand the division of labour, the specialization of individuals, and to deepen the individuals' human capital. Although Becker and Murphy (1992) assume that the returns to training any one individual decrease, they do manage to model a process of endogenous growth because each expansion of the division of labour due to an increase of average productivity raises the private marginal product of additional knowledge; the private incentives for human capital accumulation are hence maintained. The division of labour and the accumulation of human capital as a private endowment of individuals are linked by mutual causality without any involvement of technological external effects.

Given the absence of any market failure, the growth rate of the model economy is efficient. Nevertheless, economic policy measures can have an influence on the growth rate by altering the level of coordination costs and thus the incentives to acquire specialized skills and knowledge. The coordination costs are lower in economies with a stable market-based system and with a government guaranteeing free price formation, so that the advantages of an increasing division of labour can be used optimally even in anonymous teams. Consequently as far as industrial policy measures bring about price distortions in product and factor markets — especially in the case of output subsidies and artificial trade barriers, but possibly also in the case of R&D subsidies — they put a constraint on growth in the long term, regardless of any short-term merits they may have.

This model of endogenous growth based on an increasing division of labour assumes that the individual's comparative advantages in performing certain kinds of work are not bestowed upon him by nature, but rather that people are born without any bias to develop special skills and that they acquire their particular comparative advantages by undergoing specialized education and training. Although in reality specific talents for particular types of jobs may indeed be rare, great differences in people's general talents are observable. Each general talent for learning and creative problem solving can become productive in a variety of areas. Since the leading positions in the management of an economy and its government are (and should be) mostly occupied by highly talented people, their choice of career can be extremely important for an economy. This is so especially because the kind of leadership exerted can cause considerable positive or negative external effects; and thus the private incentives for a highly talented person to choose a particular career may differ from the social incentives. Murphy et al. (1991) develop an endogenous growth model in which the consequences of the individual career choices of an economy's most talented young people for the long-term rate of growth can be analyzed.

The starting point of this analysis is the observation that the most talented individuals are attracted to occupations which exhibit increasing returns to ability. Such occupations are found in industries which have a large market, whose technology is characterized by only weakly decreasing returns to scale, and in which the 'compensation contract' guarantees the private appropriation of a large share of the total social returns to an individual's talent in his occupation. Thus, for example, inventive and entrepreneurial activity is more attractive for highly talented individuals, the lower and flatter the shape of the marginal cost curve for manufacturing and sales, the better the patent protection and the more favourable the opportunities for price discrimination so as to appropriate part of the consumer rent generated by product innovation or some other entrepreneurial move.[130] On the other hand, leading positions in the government bureaucracy or in the legal profession, say, that of lawyer specializing in civil law cases, can also be attractive for highly talented individuals.

But while inventive and entrepreneurial activity contributes to technical progress and productivity growth, i.e. generates positive external effects, lawyers and government bureaucrats draw their incomes primarily from the redistribution and partial acquisition of other people's income and wealth. They thus generate negative external effects because they reduce the amount of resources available for productive use and, by imposing an implicit or explicit tax, weaken the incentives to undertake inventive and entrepreneurial activity. When the attractiveness of leading positions in the redistribution sector exceeds that of

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[130] The breadth and length of patent protection and the opportunities for price discrimination — for example by regional segmentation of the market — are typical determinants of the share of the social returns to innovation which are privately appropriable by the inventor. Further determinants are, among other things, the extent of legal regulations pertaining to licence contracts, the extent and reliability of intellectual property rights and the rate of income taxation.

entrepreneurial activities, many of the most talented young individuals will choose careers in the redistribution sector and will thus come to waste a great deal of talent in an economic 'zero-sum game'. Consequently, fewer talented individuals will find their way into inventive and entrepreneurial activities so that the rate of technical progress and economic growth will be lastingly reduced.

In their model-based analysis, Murphy et al. (1991) show how the individual choices for a career in redistribution versus a career in entrepreneurship, made by the most talented young people, can reinforce themselves over time. When the talent of the best inventors and entrepreneurs in an industry increases, technical progress in this industry will accelerate. Provided the industry faces elastic demand, it will expand more rapidly and thereby become more attractive for additional talent. On the other hand, positive feedback can also result from the decisions of highly talented individuals to choose leading positions in the redistribution sector. Since these talents are lost for inventive activities, and even help to further raise the tax burden on entrepreneurial activities, technical progress and growth will be reduced. Slow growth, in turn, reduces the opportunities and profits of entrepreneurial activity, since innovative products generally have an income elasticity of demand greater than one.

Murphy et al. (1991) conclude that rent-seeking[131] occupations in the redistribution sector are particularly attractive for talent in wealthy, but slowly growing economies in which government consumption and transfer payments claim a large share of national income. The attractiveness of entrepreneurial activities, by contrast, depends on the size of markets for goods and services, the quality of the infrastructure, as well as on free access to capital markets, freedom of contract and the security of private property, inclusive of patent protection.

Viewed from this perspective, there are at least three reasons why targeted industrial policies may constrain or reduce economic growth. First, they directly increase employment in the redistribution sector because industrial policy programmes have to be administered by the government bureaucracy and taken into consideration by private business in their own administration. Qualified human

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[131] In the political economy literature, 'rent seeking' refers to entrepreneurial activity which is not directed at the expansion of production, but rather at the exploitation of opportunities for income and wealth redistribution, created by policies which restrict the elasticity of supply or demand functions artificially and which favour insiders at the expense of outsiders. Rents are really income that is received by the owner of a naturally fixed production factor, e.g. land. Since in the model of Murphy et al. (1991) the quantitative allocation of talent to different sectors of the economy is not exogenously given, but depends on the quality of the respectively most talented individual in a sector, the incomes of the highly talented are more correctly to be termed as quasi rents, instead of simply rents.

capital is thus tied up and distracted from innovative and productivity-enhancing activities. Second, any industrial policy, even when initially intended for a limited time only, raises expectations that it will be continued, further developed and eventually complemented or replaced by new programmes. Industrial policies thus create incentives for private firms to invest resources in lobbying for direct influence on the future design of industrial policy. This lobbying — a socially unproductive activity — is yet another distraction for scarce individual human capital, away from more productive activities. Third, if the industrial policy measures fail to generate an immediate and substantial growth stimulus, the relative income positions of lawyers and bureaucrats are raised both in the private and the public sector so that, from the perspective of highly talented young people, legal studies tend to become a more attractive choice than engineering or scientific training.

Widespread concern about the negative impact of government regulations and of an expanding bureaucracy on economic growth has been voiced for many years in the United States, especially in view of the financial incentives that this trend has created to seek a career as a lawyer. And Murphy et al. (1991) do find in regression analyses some empirical support for the hypothesis that countries with a large share of students in engineering studies subsequently attain higher growth rates, and countries with a large share of their students in legal studies lower growth rates, than the average of all countries observed.

2. Positive Feedbacks in Spatial Agglomeration

As shown in Chapter B, productivity gains from using ever more specialized and differentiated inputs, technological external effects of new knowledge and those pecuniary external effects on the supply or demand side of firms, which are characteristic for dynamic imperfect competition in the presence of increasing returns to scale, are essential elements in various modelling approaches within new growth theory. These elements have important implications not only for the temporal, but also for the spatial development of economic activity. This is evidenced by the general geographical concentration of economic activity as well as by the differences in growth rates between different regions and countries that are linked by trade in goods and movements of factors such as labour and capital. Efficient agglomerations can, says an implicit hypothesis of new growth theory, contribute to the acceleration of long-term growth by strengthening the effectiveness of positive pecuniary and technological external effects in industries with returns to investment that do not decrease over time.

But just as endogenous technological progress need not be based on positive technological external effects (though it may be), so are spatial agglomerations not necessarily based on positive technological external effects. Here again, competing explanations have implications which are partly observationally equivalent.[132] One explanation which does not necessarily rely on technological externalities, and which is emphasized by Krugman (1991), begins with the recognition that the individual industrial firm has to bear a fixed cost for each production site it uses, and will thus generally want to concentrate its production at as few sites as possible, indeed whenever possible at just one. Whichever site the firm prefers depends, on the one hand, on the spatial allocation pattern of demand, on the other hand, on supply conditions which are often influenced by other firms of the same industry; so for example when several firms move their production to one and the same site.

Thus, of interest here are not those industries which are tied to the location of mineral deposits or other immobile factors; in a sense this can even be said of agriculture which depends on the quality of soil. For those other industries, which can be defined as 'footloose', technological externalities may, but need not be important determinants of spatial concentration. Whichever determinants are decisive in a particular case, depends on a number of circumstances: the prevailing level of transport costs; the strength and range of external learning effects or, respectively, the speed of new knowledge diffusion; the strength of returns to scale internal to the firm; the prevailing market structures in the relevant goods and labour markets; the degree of specialization of workers for their respective industry; and the share of specialized capital and service inputs in a particular industry's gross production.

In any case, the determinants of economic concentration are linked to what are essential modelling assumptions in new growth theory. In the models of learning by doing and of endogenous technical progress, the possibility of self-sustaining long-term growth depends on the existence of sufficiently strong positive external effects from private investments, especially from those in research and development. If such external learning exists, it seems reasonable to suppose that its impact is greatest at the site of origin, in the source city or in the surrounding region of a firm, and that the impact decreases with increasing distance, particularly when language and cultural barriers are crossed. The individual firm is then attracted to locate in the vicinity of other firms of the same industry by the prospect of benefitting from technological externalities where they are strongest.

However, even if external learning effects do not play any role at all, it can still be advantageous for a firm to establish itself in the vicinity of similar firms. One reason is the greater availability of specialized inputs and services at that

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[132] This is important to keep in mind when the discussion turns to the problem of how to design efficient policies in Sections F.II and F.III.

location. In the models of Romer (1990) and Grossman and Helpman (1991), productivity gains due to increased use of specialized and differentiated inputs serve as an explanation why the average physical return on investment does not decrease in the course of the accumulation process. Although in these particular models of endogenous technical change, technological external effects in the form of knowledge spill-overs are essential, the assumption of non-decreasing marginal returns does not generally presuppose the existence of technological external effects when productivity growth is caused by an ongoing process of introducing new varieties of capital goods and service inputs.

Recall that Romer (1987) and Barro and Sala-i-Martin (1992b) have in fact shown that a positive long-term rate of growth can also be explained as an endogenous phenomenon within models in which the users of specialized and differentiated capital goods and input services benefit from purely pecuniary external effects, associated with the sharing of common sources for the supply of specialized and ever more refined capital and service inputs by a group of user firms from one and the same industry. The suppliers of these inputs have to bear a fixed cost for research and development whenever introducing a new variant. The suppliers thus work under conditions of increasing returns to scale and will — in the absence of price discrimination — pass on at least part of their fix cost digression in the form of price reductions to all user firms whenever a new customer, or the expanding business of an existing customer, creates additional demand. In these models of monopolistic competition and increasing specialization in the capital goods sector, the monopoly power of individual firms is constrained, and prevented from becoming permanent,[133] not by technological but by pecuniary external effects.

At the same time, these pecuniary externalities are a major force that encourages the spatial agglomeration of an industry: The productivity advantages of using differentiated and specialized inputs are better exploited in a geographically concentrated industry whenever increasing returns to scale and the costs of transporting industry-specific inputs play a non-negligible role in firms' location decisions. This has been well known since the 19th century; Alfred Marshall (1922) devoted the entire chapter ten in book four of his *Principles of Economics* to this problem. Krugman (1991) has taken up this theme and examines the spatial implications of economic development with the aid of modern analytical tools.

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[133] Recall from Section A.II that monopoly power which can be permanently secured without further effort to invent and develop new goods would eventually destroy all incentives for private investments in new knowledge; economic growth would thus peter out.

In today's industrialized economies, labour and human capital represent particularly important specialized and differentiated inputs. Recall from the previous subsection that this observation motivated Becker and Murphy (1992) to focus on the costs of coordinating individual human capital as a determinant of endogenous long-term growth. The more specific to individual industries workers' skills are — and they often seem to be quite specific in reality —, the more advantageous becomes the geographically concentrated allocation of production in these industries. Each individual worker has to bear the cost of his training, and therefore — in a sense — faces increasing returns to the quality scale of his qualification. As long as the industry, for which someone is specialized, grows and there is strong demand for his particular skills, all is fine. But if demand unexpectedly shifts to other qualifications, the individual worker, who may then have a shorter span of his working life left, will shy away from incurring the additional fixed cost of retraining for another industry, even if that might earn him higher periodic income. The individual worker will therefore prefer to be in a location where competing firms of 'his' industry offer alternatives without retraining should 'his' particular firm reduce employment for internal reasons.

This consideration is important because the labour demand schedules of the various firms in an industry fluctuate in uncertain and unpredictable ways over time; in general, the fluctuations in the amount of labour demanded by individual firms are incompletely correlated. If the individual firm (as argued above) wants to avoid spreading its production activities over several locations, so as to better exploit increasing returns to scale, then it is advantageous for all participants, workers as well as firms, and thus economically efficient to concentrate the entire industry at one site. The advantage for workers is, in the case of inflexible wages, that the probability of unemployment is reduced, and in the case of flexible wages that the amplitude of wage fluctuations due to firm-specific shocks is reduced. In both cases do firms, concentrated in one location, benefit from a greater flexibility (in the average) of adjusting their employment to firm-specific shocks (Krugman 1991: 38–41).

In addition, the tendency of an industry to form local clusters can also be explained by the fact that an individual firm located separately from its competitors would have the position of a local monopsony in the labour market and — by restricting activity — could push wages below labour's marginal product. Since the degree of monopsony power of the individual firm depends negatively on how many other firms it competes with in its local labour market, workers usually prefer to offer their services at the location with the greatest number of firms of one and the same industry. Hence, at this location each individual firm can find more workers willing to work at some fixed rate of pay, and consequently each firm can make larger profits there than in any location with a lower number of firms from the industry. — As it is advantageous for both firms and workers to migrate to the location with the highest density of firms in the industry, eventually the entire industry will end up in just one location. The quest for allocational efficiency in the labour market seems to be an important force behind agglomeration at the industry level (Krugman 1991: 45–49).

While these effects can explain the geographical concentration of individual industries, agglomerations at the aggregate level of an economy appear to be primarily related to the interaction of strong firm-specific returns to scale, low transport costs and a large share of footloose production, i.e. production not tied to the location of mineral deposits. Strong firm-specific returns to scale imply that it may be advantageous for a firm to concentrate all of its production at one location even when it will thereby incur considerable transport costs when delivering to geographically distant markets. As transport costs fall, it becomes advantageous even for firms with less strong internal returns to scale to concentrate all of their production at one site. By choosing a particular location, firms generate a positive pecuniary externality, mostly due to the additional demand of the firm's workers for other industries' goods and services.

To be sure, this mobile demand is irrelevant for the location of industries which are geographically tied to certain places, for instance because of mineral deposits. However, what can be said is this: the larger an economy's share of geographically mobile production, the lower the relative significance of the share of demand generated by geographically immobile industries, and consequently, the greater the influence of the demand externalities from mobile production on spatial patterns of allocating mobile production (Krugman 1991: Chapter 1). Demand externalities are often reinforced by locational advantages resulting from dense traffic and communication networks. The densest infrastructure naturally develops in the region with the largest concentration of economic activity, because in this region the cost of a given infrastructure — due to indivisibilities in infrastructure investments — makes up a lower share of value added than in other regions; and indivisibilities of infrastructure investments prevent networks from being adjusted continuously in proportion to a rising level of economic activity.

Although demand and infrastructure externalities, both in a sense examples of 'network externalities', help to explain why there are agglomerations of economic activity at the aggregate level, these explanations do not account for how the geographic patterns of agglomerations evolve within a given economic space. In what regions the forces of localization become so strong that these regions turn into gravitation centres of economic activity, is often decided either by historical accidents or by developments set in motion by the power of self-fulfilling collective expectations. Krugman (1991: 11–14), discusses the example of agglomeration in the American industry belt which emerged in the north-eastern United States and in the southern part of Canada in the last century. This agglomeration, he argues, represents just one of several paths of development possible at the time. Correspondingly, the observed agglomeration of industrial activities in the Ruhr area and in the Rhine-Main area of Germany can be interpreted as just one of several patterns that were possible ex ante.

Spatial allocation patterns develop and reinforce themselves as a result of decentral, but interdependent decisions of market participants in the course of a path-dependent allocation process with stochastic elements (see for the analysis Chapter C). Stochastic elements come into play, for example, when individual firms which are important first-movers make erroneous location decisions which may then reinforce themselves as suppliers and competitors follow. Stochastic allocation processes of this kind generally have multiple, irreversible long-term equilibria which can differ considerably in terms of efficiency. That the result of decentral decisions under these conditions is a Pareto-optimal allocation in the long term is put into doubt by careful analysis: there is very little a priori reason to expect a bias towards a Pareto-optimal allocation (Arthur 1988; David 1988a; David 1988b). Even rational expectations would not prevent a possible lock-in into an inefficient long-term allocation, as Arthur (1989) shows. On the contrary, rational expectations may actually worsen the fundamental market instability and accelerate the process of lock-in.

Moreover, the optimality of path-dependent processes can normally not even ex post be verified because a welfare-economic comparison would require complete knowledge of the alternative development paths, which were excluded from becoming reality. In any case, in planning industrial policy interventions one has to take into account that these may influence not only the temporal but also the spatial allocation of resources, provided they have any effect at all. Industrial policy is therefore, in its motivation as well as in its effect, often intertwined with regional policy.

Agglomeration hypotheses have in recent years been put forward not only to explain the differences in development between regions, but also to explain agglomerations across industries or technologies, as well as temporal fluctuations in economic activity (Hall 1991). The latter is of obvious interest to growth theory since economic cycles are empirically inseparably connected with the temporal development of economic activity. The interpretation of economic cycles as agglomeration phenomena assumes that it is advantageous for the individual firm to synchronize its activities with the general economic cycle, either for reasons internal to the firm, e.g. increasing returns to variable factors of production, or for the presence of positive external effects, e.g. the higher probability of success in many kinds of market searches during a boom relative to a recession.

Similar reasoning is sometimes put forward to explain technological development as a sequence of agglomerations. Search under extreme uncertainty, the need to synchronise new technologies with existing technologies so as to exploit complementarities, and increasing returns to R&D investments are features of technological development which seem to favour agglomerations along certain technological paths, or 'innovation avenues' (Sahal 1985). And so are the many specialized capital inputs and the high degree of specialization of the scientists and engineers needed to push the frontier of knowledge back in certain delimited areas of technology. Hence, the advantages of locally concentrated labour markets, pointed out by Krugman (1991), seem to be just as relevant to agglomeration in some abstract technology space. In addition, true technological externalities in the form of knowledge spill-overs from R&D may reinforce path-dependence in technological development if they benefit primarily those who work on related research programmes. Any such agglomerations in technology would likely affect the dynamics of industrial structure, since many industries are defined around (and their productivity is driven by) the typical technologies they use.

But agglomerations in technological space or across industries can also be explained in a rather different way, namely in terms of the agglomeration of a country's individual human capital, particularly its entrepreneurial and inventive talent, in certain industries (or technologies). This explanation has been formalized by Murphy et al. (1991) who show that sectoral rates of growth may differ from industry to industry, and can deviate from the Pareto-optimal growth rates, for the sole reason that entrepreneurial and inventive talents are attracted to cluster together in certain industries. This model assumes that highly talented persons leaving school rarely ask themselves what their comparative advantages are — which are anyway in most cases only weakly formed at that point in time — but rather look for careers in which private returns increase overproportionally to talent. Although the choices of school leavers for a particular career may not be strictly irreversible, they certainly have weight for the individual's future because of the high fixed cost incurred in the course of specialized study and training.

In Section F.I.1, the negative effects on growth were discussed which — under these assumptions — may result from the allocation of individual human capital when highly talented persons of a country can earn the highest private returns on their talents in redistributive occupations, for example as a civil lawyer or a government bureaucrat, and not in economically more productive, i.e. knowledge-creating, inventive and entrepreneurial occupations. Yet even ignoring redistributive activities for the moment, the allocation of the highly talented to the various productive sectors of an economy need not be efficient. In an efficient allocation, the best talents would be close to equally distributed across all industries so that productivity growth in all industries is as large as possible (Murphy et al. 1991: 511). In the equilibrium of the model, by contrast, the entire group of the very best of the talented comes together in one and the same industry, in which the quasi rents[134] on extraordinary talent are particularly high.

The reason is the model's assumption that the most talented person alone determines productivity progress in her industry, yet due to technological and pecuniary external effects can appropriate only a fraction of the social returns generated by her activities. Thus, the industry, which is led by the most talented entrepreneur of all, will attract many other entrepreneurially particularly talented persons who can here earn extremely high private returns in the form of quasi rents on their talent, mainly by technological imitation and by quickly filling some of the many market gaps and niches, of which new ones emerge in a dynamic industry all the time. Thus, for the other industries of the economy only the less highly talented persons remain as inventors and entrepreneurs, so that productivity progress is slower there than it could be, while leaving productivity progress in the industry preferred by the performance elite unchanged. A clear case of Pareto suboptimality.

While the social returns which the most talented entrepreneur in an industry generates depend on the size of the market and on the scale characteristics of the industry's production and sales technology, her private share of the social returns is mainly determined by the type of compensation contract offered in the industry. The compensation contract reflects, among other things, the potential for price discrimination to capture a share of consumer rents and the scope of protection for intellectual property. Inefficiently slow growth can therefore become a problem even in industries which have a large market with great opportunities for growth, and which have production and sales technologies with scarcely decreasing returns to scale, if these industries are stuck with a poor compensation contract relative to other industries, and thus attract clearly less inventive and entrepreneurial talent than would be desirable for the economy as a whole.

At least in theory, then, certain interventions targeted at improving the compensation contract in a 'neglected' industry might appear as potentially welfare improving industrial policies. The long-term productivity growth could under certain circumstances be considerably increased in this industry — possibly, however, at the expense of other industries, which might lose not only rent-

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[134] Recall that the term 'quasi rents' describes income that the owner of a production factor receives whose supply, due to legal regulations or other artificial market entrance barriers, is less than fully elastic during a particular time. Rents, in contrast, are income from production factors whose amount is naturally, and often permanently, fixed.

seeking human capital to the promoted industry, but also their performance elite, which has determined their speed of innovation and productivity progress. Apart from unlikely coincidences, the new equilibrium would, following the logic of the model, again be economically inefficient; and this holds independently of whether the rate of productivity growth aggregated across all industries, i.e. the weighted average of the different sectoral growth rates, has in the end increased, remained the same or even decreased as a result of targeted intervention.

Even more complexity is introduced into the model if the sectoral allocation of the highly talented is assumed to be a stochastic process in time, analogously to the spatial allocation of economic activities. The motivation for a stochastic model might be, for example, that the highly talented are individuals with idiosyncratic, yet stochastically distributed, preferences on top of their desire to maximize life-time income. In this kind of stochastic model, the economy-wide growth effects of some specific industrial policy intervention would be virtually impossible to predict even if the model was a precise and accurate description of an economy's past and present.

To mention a final instance of a theory which seems to be at least in part observationally equivalent, there is the claim of Milgrom et al. (1991) to explain persistent patterns of endogenous structural change in a growing economy without relying on increasing returns to scale at the level of individual activities. Remember that both the theory of endogenous technical progress and the theory of 'monopolistic competition among the suppliers of specialized and differentiated capital inputs' invoke increasing returns to the scale of firms' output to explain why the physical return to investment need not decline in the course of capital accumulation. These theories differ in their assumption about the relevance of technological external effects. In the model of Milgrom et al. (1991), by contrast, innovation merely results in falling marginal costs, which induces both increasing usage of these products as inputs and more investments in the development of complementary technologies. Instead of assuming increasing returns to scale for individual activities and temporary monopoly power for innovators, the momentum of technological change and economic development is maintained entirely by positive feedbacks among certain mutually complementary core activities and practices in the economy. Learning in one industry is assumed to benefit from high activity levels and learning in related industries. The formal analysis of these complementarities relies on lattice-theoretic methods which can handle non-convexities without reference to differentiable production function, and thus without specifying scale characteristics at the outset.[135]

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[135] For details of the mathematical model see Milgrom and Roberts (1990).

II. The Merits and Demerits of Targeted Industrial and Technology Policy in the Light of New Growth Theory

Since new growth theory has generated quite a number of candidate explanations for the determinants of long-term economic growth, it is hardly surprising that no simple, clear-cut and uniform conclusions for industrial policy have so far emerged. Hence, the presently available results will have to be used within a contingency approach in assessing and designing the particular industrial policies under consideration to remedy a given situation. Every theoretical analysis makes certain assumptions about the properties of the technology of production in the analyzed economy, about the industrial organization, the mobility of resources, the accessibility of technical knowledge to scientists and engineers inside and outside of established firms, about the direction and strength of external effects, as well as about many other things. For the purpose of policy consulting it will hence be essential to choose, or devise, models appropriate for the particular industrial policy problem at hand, and to test their assumptions in a careful empirical study of the particular circumstances from which the problem is thought to have arisen.

The critical analysis of some of the fundamental approaches to new growth theory helps to identify a number of conditions necessary for the mere possibility that targeted industrial policies may succeed in raising the rate of long-term economic growth. However, this kind of 'success' and its necessary conditions do not imply that a particular set of industrial policies will be judged beneficial from a welfare-theoretic point of view. For a complete welfare assessment, one would have to compare the expected present value of the possibly accelerated rate of growth with the direct financial costs and the indirect burden of raising the means through (inevitably) distortionary taxation; and in most cases, one would also have to take distributional implications of the planned industrial policies into consideration.

In the following, only steady-state comparisons of an economy's dynamics before and after intervention will be considered, which is in the spirit of most new growth theories' reliance on steady-state constructions (without paying much attention to transitional dynamics). Abstracting, for the moment, from the enormous informational requirements in any actual industrial policy planning — which are the subject of the next subsection — one can isolate, as a first step, the merely technical conditions to justify targeted industrial policy interventions under the assumption of complete information and perfect foresight. These necessary conditions help to define, as a second step, the informational requirements for making sure a programme of industrial and technological targeting is planned and executed in such a way that it will have the intended effects.

Among the merely technical conditions are, primarily, certain requirements for the economic apparatus of production. Provided the hypothesis of non-decreasing returns to investment in the course of capital accumulation holds, it will be necessary to check that the incentives for investment are distorted across sectors, i.e. that they are suboptimal either in certain industries only, or suboptimal to varying degrees if suboptimal in all industries. By contrast, if the incentives for investment were equally suboptimal in all industries, this would not constitute a case for targeted industrial policies, but rather for a general policy of supporting investment, for example by lowering the rate of taxing income or capital income, or by subsidizing private investments in general. Should not the incentives for investment in general, but only those for investment in research and development be deemed suboptimal, then again support policies which affect all industries equally would be called for. One example would be preferential depreciation allowances for research and development investments.

Many countries in fact do grant preferential tax treatment of R&D investment, because their corporate tax laws prohibit entering own inventions on the asset side of corporate balance sheets and prescribe treating personnel costs as current expenditure. This is an implicit discrimination in favour of R&D and against investments in physical capital because the latter always have to be entered on the asset side which implies that no part of the costs, not even personnel expenditure in the case of in-house production of physical investment goods, can effectively be written down within the first year. From an economic point of view, this side effect of precautionary tax laws implies distortions not only in favour of R&D in general, but also in the direction of too much use of personnel and too little use of machinery and equipment in R&D laboratories, as well as distortions across industries since the input ratios of personnel to physical capital in private R&D actually differ significantly from one industry to another (see Sections II and III in Chapter D).

But there are other, more important reasons why the investment incentives may deviate to varying degrees from the optimal incentives in the various industries of an economy. For one, positive external effects in the form of knowledge spill-overs from research and development may vary in strength. It is often presumed, for example, that knowledge spill-overs are particularly strong in the computer, scientific instruments, chemicals and machinery industries. Another reason might be that an industry supplies key technologies whose adoption generates positive pecuniary external effects in other industries, apart from any direct knowledge spill-overs, without the 'key industry' benefitting from any reciprocal external effects. On the other hand, the investment incentives may deviate because of particularly strong pecuniary or technological external effects within an industry. This could be related to a particular type of industrial organization or market structure, say, the degree of monopoly power in the industry.

In the case of horizontal product differentiation, the loss of competing firms' producer rents caused by an innovation is the larger, the smaller the number of substitutes in the market (Grossman and Helpman 1991: 83).[136] Moreover, the partial elasticities of production as well as the elasticities of substitution among industry-specific, differentiated capital and service inputs normally differ from industry to industry. So do the productivity gains which the typical firm of an industry can reap as a pecuniary external effect after an increase in the variety of specialized capital or service inputs, even if this variety increase is comparable in magnitude across industries. This again lets the private investment incentives deviate from the respective social incentives to a degree which varies across industries.

Thus, the mere identification of industries for which evidence of market failure due to technological or pecuniary externalities can be produced is insufficient to justify the adoption of targeted industrial policies. It is rather necessary to check whether the private investment incentives deviate in some industries more from their respective social optimum than in others. In a closed economy, then, the technical requirements of the production side for industrial policies targeted at the industries found to be constrained by suboptimal private investment incentives are fulfilled. In open economies, by contrast, the prospects of targeted industrial policies to attain their objectives depend also on the extent to which the external effects, to be internalized, are limited in range to the home economy; they might, for example, diffuse to competing economies only slowly, or considerably reduced in strength.[137]

In the case of technological external effects in the form of knowledge spillovers, these might be constrained in range by the lower intensity of international communications compared to intranational communications, for instance, due to natural language and cultural barriers, or due to intentional

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[136] Whether this loss is 'compensated' for the economy as a whole by an equal gain in consumer rent in the model, depends on the specification of the representative consumer's preferences. Recall from Chapter B that full compensation occurs in the special case of a CES utility function, as Grossman and Helpman (1991) have shown.

[137] In his pioneering empirical study of knowledge leakage from 100 American industrial firms, Mansfield (1985) finds that information concerning development decisions, including the detailed nature and operation of new products and processes, is in the hands of rivals within 12 to 18 months, on average. While he can find only minor interindustry differences in the rate of knowledge diffusion, Mansfield (1985: 223) notes that the technologies transferred by US-based multinational firms to their overseas subsidiaries seem to leak out to non-US firms more slowly than to rival US-firms (Mansfield et al. 1982: 38–40).

secrecy towards strangers. In the case of pecuniary external effects, limited spatial range might be partly due to the fact that some of the specialized and differentiated capital goods and services are not easily tradeable across regions or countries; think of technology transfer centres or custom-built equipment requiring a great deal of after-sales service. It was pointed out in Section E.I that targeted policies may, in the case of purely national external effects from knowledge creation, raise national welfare at the expense of other countries. In the case of international external effects, by contrast, targeting by one country on its own may be ineffective or suboptimal, and may even lower national welfare in the country which carries the direct costs while reaping only a small fraction of the benefits; this case might instead call for an internationally coordinated response to market failure in knowledge creation.

However, even in this extended form applicable to open economies the necessary conditions for an economy's production apparatus capture only part of the technical requirements for approving targeted industrial policy interventions. As further necessary conditions, certain requirements on the structural development of demand as well as on the system of incentives for the economy's most valuable talents have to be fulfilled. As a general rule, there must be a high world market elasticity of demand for the products of any industry considered as an industrial policy target. The expansion of exports of a selected industry can be beneficial for an economy as a whole only if this does not result in too large a fall in world market prices, i.e. if the price elasticity of demand for these exports is larger than one. In the case of homothetic preferences, this presupposes a high elasticity of substitution in consumption between the goods concerned and the bundle of other tradeables.

In the case of non-homothetic preferences, which is likely to be more relevant in practice, the price elasticity of demand for a particular good additionally depends on the income elasticity of demand. The price elasticity of demand then tends to be larger for those goods whose budget share increases with increasing income, i.e. whose income elasticity is larger than one. Thus, in the case of non-homothetic preferences the possibility of immiserizing growth is not necessarily due to a low elasticity of substitution in consumption between the goods of the expanding industry and those of other industries. In fact, immiserizing growth can also occur under the condition of a high elasticity of substitution if the expanding industry supplies goods whose income elasticity of demand lies considerably below one.[138] For this reason, economic growth may slow down in an economy where industrial policy is targeted at an industry whose growth prospects are limited not merely by some kind of market failure, but ultimately by a low income elasticity of demand.

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[138] See the theoretical discussion in Section B.II.1.

In the incentive system for the allocation of talent, targeted industrial policy intervention must not distort sectoral compensation contracts in such a way that part of the particularly talented human capital is enticed away from its present occupations to other activities yielding a comparatively lower social return, be these other activities inside or outside the industry of present occupation. Targeted industrial policy might cause such a distortion in a number of ways: First, as seen in Section E.I.1, industrial policy generally increases employment in the redistribution bureaucracy. Second, it rewards the 'directly unproductive activity' of lobbying on the part of private firms. And third, it raises the attractiveness of legal studies and lawyer careers as compared to science and engineering studies and R&D careers, thus placing a drag on innovation sooner or later to be felt throughout the economy.

Furthermore, targeted industrial policies may, by unilaterally improving the compensation contract in a particular industry, attract not only some of those talented individuals who have hitherto earned quasi rents on their talents in other industries, but also some of the talents who have actually driven innovation and productivity in some of the other industries. These talents may well have generated higher social returns in their former occupations than they might be able, or have opportunity, to generate in the targeted industry, to which these talents are drawn. Thus, not only the migration of talent from innovative and productive activities to the 'zero-sum game' of economic redistribution may have negative growth effects, but also the reallocation of inventive and entrepreneurial talent from one productive industry to another, when the kinds of innovation prevailing in the latter industry generate lower social returns than those in the former.

Finally, one always has to consider price distortions, which inevitably result from raising the financial means for targeted subsidies. Price distortions will tend to make the coordination of specialized human capital more costly, lower the private incentives to invest in human capital, slow down the process of increasing the division of labour and, ultimately, retard economic growth. These indirect negative effects may, on balance, have more weight than any intended, more directly felt, positive growth effects of targeted subsidies.

III. The Informational Requirements for Implementing a Consistent Set of Targeted Industrial and Technology Policies

1. The Information Problem in the Closed Economy

The last section discussed necessary conditions to be met for giving targeted industrial or technology policies any chance at all of raising an economy's rate of growth. Knowledge of these conditions helps to formulate the informational requirements of planning and executing targeted industrial and technology policies in practice. The necessary conditions alone, however, are by no means sufficient to define the informational requirements fully. After all, industrial policy would hardly want to undertake any kind of intervention, but rather a carefully designed one targeted at the root of the market failure actually diagnosed. Moreover, the intervention is to make efficient use of the available instruments of industrial and technology policy.

Thus, the information demand of the industrial policy maker must not only be concerned with the question of whether there is a case for industrial policy *per se*, but also with the more involved operational questions: Of what kind is the observed case of market failure? What theoretical model matches this case best? What particular industrial policy instruments would likely lead to what kinds of result, including the type and magnitude of social costs? — Especially the choice of an appropriate instrument often requires very detailed knowledge of the actual situation, since the industrial policy implications of some new growth models are quite sensitive to changes in parameter values or model structure. Furthermore, the informational problem is in practice complicated by the fact that it never suffices to look merely at the situation in one industry in isolation. Instead, the analysis of the particular situation at which industrial policies are to be targeted always has to be comparative with respect to the situations in all other industries, and has to consider the major interindustry linkages and feedback relationships.

Initially, the problem of information will be discussed in the context of models that yield industrial policy implications on the basis of pecuniary external effects only. This discussion will show that these models do not contain any parameters which could serve as a reliable empirical base for the design of industrial policy programmes to work over longer periods of time. Recall that in the growth models of 'monopolistic competition and increasing specialization of capital inputs', developed by Romer (1987) and Barro and Sala-i-Martin (1992b) for a closed economy, the producers of capital goods set prices above marginal costs, by a factor which depends on the partial elasticity of final production with respect to employing specialized capital inputs. This monopoly pricing distorts the decentralized decisions about the number of capital input varieties in use relative to the amounts employed of each one of them (Romer 1987: 58–59).

There are two opposite effects to consider: On the one hand, each individual producer of a unique capital good faces a downward-sloping schedule of demand, so that the quantities supplied of each capital input are inefficiently low, whereas the variety on offer is inefficiently large. On the other hand, the introduction of a new capital input variety generates a pecuniary external effect accruing to the users of the capital input, a kind of 'consumer rent', for which the innovator is not compensated, so that the variety offered is too small and the quantities supplied of each individual capital good are to large. Which of these opposing effects dominates depends on the technology in which the capital inputs are used. In the special case of a Cobb-Douglas technology, the two opposing effects just cancel each other. Even in this case, however, does the monopoly pricing of capital goods imply that the private returns to investment are smaller than the social returns, so that the process of economic accumulation is too slow from a welfare point of view.

In order to raise the private returns to investment in this model, one may want to use general investment subsidies, i.e. subsidies for the purchase of specialized capital inputs, or subsidies for capital income (Barro and Sala-i-Martin 1992b: 654). Both policies have the potential to attain a first-best solution, but require knowledge of the partial production elasticity of using the specialized capital inputs in order to determine the appropriate level of subsidization. Direct subsidies for research and development in the capital goods industry, by contrast, turn out to be inappropriate measures, although these would also raise the private returns to investment. But at the same time, these subsidies would distort the decentral choices regarding the optimal ratio of variety to the average quantity of specialized capital inputs in the direction of too large a variety (Barro and Sala-i-Martin 1992b: 655).

These industrial policy conclusions, however, are not shared by those models of endogenous technological change which assign an important role not only to pecuniary external effects but also to technological external effects in the form of knowledge spill-overs from research and development, while maintaining to explain productivity gains with an increasing differentiation and specialization of capital inputs (Romer 1990; Grossman and Helpman 1991). In these models, subsidies for research and development turn out to be advantageous, whereas output subsidies fail to be effective when production and R&D compete for the same resources, e.g. scientifically trained specialists, and thus operate under a common resource constraint. In addition to R&D subsidies, investment subsidies may be called for if monopoly pricing is more pronounced in the innovative industry (under consideration) than in the other sectors of the economy, for instance, because the other sectors are without monopolistic competition among the producers of investment goods or because productivity there may not be driven by endogenous technical progress.

Thus, the important operational question of how to select and combine the appropriate industrial policy instruments is difficult to address even with reference to the simplest model of industrial innovation based on increasing specialization and differentiation of capital inputs: Should preference be given to R&D subsidies or to subsidies for the acquisition of capital inputs? Or perhaps to a combination of the two? The answer seems to depend on whether the alleged inefficiency in the sectoral process of accumulation is primarily due to pecuniary or essentially due to technological external effects. As seen in Section B.V, this question cannot even in the context of narrowly focused case studies be answered satisfactorily using the empirical methodology available today. Yet, still more difficult would be an empirical study of the intersectoral interdependencies and a comparison of the type and magnitude of external effects across industries.

Faced with these difficulties, many economists have chosen a pragmatic line and have excluded pecuniary external effects altogether from their industrial policy analysis. They have instead focused their analysis fully on the implications of technological external effects, which supposedly do not leave a grey area of uncertainty about how to use welfare theory to assess proposals for targeted industrial policies in practice. In addition, some of these economists even ignore the unresolved empirical problems of measuring technological external effects. This light-minded approach will, if adopted provisionally despite being hardly tenable by scientific standards, soon hit on further difficulties that are immanent to the models and put in doubt whether there is any practical payoff, in terms of insight, from exclusively focusing on technological external effects.

These doubts arise because the presence of positive technological external effects in models of endogenous technological change does not necessarily imply that the market incentives for research and development are suboptimal. Grossman and Helpman (1991) show this to be the case in the model of expanding product variety only under the assumption that the representative consumer maximizes a CES utility function, that is a homothetic utility function whose empirical validity can be considered refuted (see, e.g. Hunter and Markusen 1988).

Yet, even if a CES utility function was taken to be a valid description, the incentives for research and development need not necessarily be 'too small', if endogenous technological change is based on continual improvements of quality instead of horizontal product differentiation. Recall from Section B.II.2 that in the model of quality ladders the incentives to innovate turn out 'too large' if the size of the respective quality leap is either 'too small' or 'too large'. The model then calls for the taxation, instead of the subsidization, of research and development (see for the theoretical discussion Section B.IV). On the other hand, the quality leaps turn out 'too small' in the model if their size is endogenously determined by market forces. In this case, a change in patent law, with respect to novelty requirements, might be helpful. Yet, how the various parameters of patent law will influence the innovation behaviour of actual firms in reality is an underresearched question, on which not even theoretical work has seriously begun to emerge. Moreover, it is often difficult to measure 'novelty' in practice.[139]

The choice of appropriate instruments to support the process of industrial innovation in a selected industry inevitably raises the question whether this particular process is better described by the model of horizontal product differentiation or by the model of quality ladders. In reality of course, this analytical distinction, along the dichotomous lines of stylized models, may not easily be made even for individual cases of innovation, let alone for a continual sequence of innovations over longer periods of time. After all, the combination of both quality improvements and continual product differentiation is characteristic of endogenous technical progress in reality. In parts of an industry, technical progress may at least temporarily correspond to the model of quality ladders, so for example in the development of memory chips or microprocessors in the computer industry. In this industry as a whole, however, the trend towards increasing variety can hardly be overlooked: some of the pertinent catchwords are desktop, laptop and notebook computers, networking, CD-ROM, multimedia, etc. Similarly, in the motor industry, to mention the example of a mature industry, the trend towards increasing variety is all too visible, but there still are important quality improvements from time to time, e.g. safety systems.[140]

Presumably, the character of the innovation process in any particular industry depends partly on the state of pertinent patent law. While patent law may therefore provide a starting point for targeted industrial policy intervention, new growth theory has so far to say very little about the relevant causality in any

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[139] For a discussion of novelty measurement problems in the case of computer software see Brockhoff and Zanger (1993).

[140] An example for displacement in car technology is the driver protection system developed by 'Audi' (the luxury division of Volkswagen) that was supposed to automatically pull the steering column away from the driver in case of a collision; this system was only a very short time in the market when it was displaced by airbag technology.

detail. Nor is much relevant insight to be gained from the sparse economic analyses of patent protection, or from the recent literature of patent races (see, e.g. Judd 1985 or Dasgupta and Stiglitz 1980). It is not clear, for example, whether a strengthening of patent protection — say, the prolongation of its duration or the widening of the breadth of protection — would support or inhibit the diffusion of knowledge spill-overs from innovation. Rivera-Batiz and Xie (1992) argue that, as a result of stronger patent protection, firms would be more willing to apply for patent protection and, thus, to make their findings of new technical knowledge public, instead of keeping them secret. Scotchmer (1991), however, objects that other firms are excluded from freely using any new knowledge for the specified period of protection, which diminishes the profitability of investing in complementary, and further on going research and development in the area. A reduction of knowledge spill-overs would raise the costs of research and development (because the individual firm would derive reduced benefits from the research activities of other firms) but might strengthen the direct rewards for private research and development (Ordover 1991).

There appear to be few agreed general predictions about the consequences of reorganizing patent laws for the rate of innovation of private firms. Nevertheless, it seems safe to suppose that increasing the breadth of patent protection would imply a more intense competition among private firms for certain exclusive patent rights, which are anticipated to return particularly high value to their owners by covering numerous subsequent applications, although they might be based on relatively small technical advances themselves. The process of innovation would thus tend to lose the character of product differentiation and would instead assume more of the character of quality ladders.[141] Then, in the context of quality ladders, the question of appropriate novelty requirements for patent law would become increasingly important.

The discussion of these selected issues has highlighted that the information problem is already rather confounded in the case of a closed economy. The detailed planning of targeted industrial and technology policies appears to be a virtually impossible task. Yet, many more complications arise in open economies, some of which will be discussed next.

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[141] Compare this with the welfare analysis of the optimal breadth of patent protection in a model of product differentiation given by Klemperer (1990). In Klemperer's analysis, the particular assumptions made about the substitutability of product features in consumption are important determinants of whether narrowly defined patent protection with a long duration or broadly defined protection with a short duration is more efficient.

2. The Information Problem in Open Economies

Initially, one needs to assess how similar or how different the relative factor endowments are for the relevant trading partners, that is for the countries which compete over export market shares in high-technology industries. The analysis of Rivera-Batiz and Romer (1991a, 1991b) suggests that symmetrical trade barriers will inevitably reduce growth if the trade partners are very similarly endowed with factors of production. In the case of considerable differences in relative factor endowments, the consequences of trade barriers for growth cannot generally be predicted. While it is true that the individual innovating firm can usually earn higher temporary monopoly profits in larger, integrated markets, there also is more competition from foreign firms, which tends to reduce monopoly rents, ceteris paribus.

For an assessment of the prospects of enhancing growth by subsidizing, temporarily, research and development in selected industries it is important to know whether positive external effects, such as knowledge spill-overs or learning-by-doing, which might cause path-dependent developments, are really more strongly, or much sooner, effective within their country of origin. This is a rather difficult empirical question, on which no satisfactory way of answering it for whatever circumstances may be at hand has yet been found (see the empirical studies surveyed in Section B.V).

In addition, whether temporary targeted R&D subsidies are a good choice for a country to win a permanent technological lead in a selected industry also depends on the degree of international inequality of factor rewards that would prevail in the free-trade equilibrium. Recall from Section B.III.2 that targeted subsidies only merit consideration if the free-trade equilibrium does not imply full equalization of factor prices, and if real wages are higher in the country in which most of the R&D of the selected industry is concentrated, or else, if capital is not fully mobile across countries and the real rate of interest is higher in the country in which most of the R&D of the selected industry is concentrated. Both conditions will be difficult to verify empirically, not least because international quality differences of labour as well as country-specific market risks for foreign investments cannot be measured accurately and reliably.

Some economists have argued that the increasing internationalization of the R&D activities of multinational companies, and the ongoing improvements of information storage and communication technologies, will lead to an increase of international knowledge transfers (see, e.g. Vernon 1982 and Vickery 1986). Moreover, it has been argued that the speed of international knowledge diffusion will come to match the speed of national knowledge diffusion in the future (see the evidence reported in Section B.V). This argument is supported by the observation that over the past few decades the cost of international communication (as well as of international transport) has already fallen more rapidly than the cost of communication (and transport) within countries.

But, as Krugman (1991) points out, a fall in the cost of communication must often be interpreted as a simultaneous decline in the cost of transporting the specialized and differentiated inputs as well as the outputs of information-intensive industries. Thus, the fall in communication costs might lead to an increased spatial concentration of these industries, because cheaper access to a geographically dispersed customer base would permit better exploitation of scale economies in information processing.[142] In this case, the intensity (and speed) of knowledge transfers, including those in the form of true technological externalities, might increase within the individual national research and development centres, or networks, relative to the intensity (and speed) of international knowledge transfers. Nevertheless, multinational companies could keep their role as international arbitrageurs of new knowledge.[143] The improvement of communication technologies, however, makes it likely that small firms will increasingly participate in the international exchange of knowledge.

On a related issue, the analysis of Becker and Murphy (1992), reviewed in Section F.I.1, suggests that the costs of coordinating specialized human capital is an important determinant of the rate of economic growth. This insight bears on the design of industrial and technology policy. It raises the question how much individual industrial policy instruments would affect the costs of coordination, for example by introducing price distortions. For a small country, which has no impact on world market price ratios, the introduction of tariffs and non-tariff trade barriers presumably distorts prices in the home markets more than the introduction of subsidies for certain R&D activities would. But subsidies have to be financed from tax revenue; since truly neutral taxes are not available in reality, the appropriation of revenue for government subsidies will inevitably create price distortions which should not be overlooked in assessing the relative merits of subsidies versus tariffs.

In view of the danger that industrial policies may distort the private incentives for talent to choose a career in the directly productive sectors of the economy versus the redistribution sector, one should ask how large the government share in national income already is, how common industrial policy inter-

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[142] By contrast, if the costs of transporting specialized inputs declined more rapidly than those of transporting the output of an industry, this would increase the spatial range of the pecuniary external effects, generated by the variety of specialized inputs readily available in a particular location. The result could then be a *lower* spatial concentration of this particular industry because the distance to sales markets would now have more weight in the individual firm's location decision.

[143] Cf. Aoki (1993) who sees this as a major source of benefits from integrating diversely specialized national economies.

ventions are in the economy, how strong the influence of industry lobbies is on the design and execution of economic policies, and whether additional price distortions and quantity restrictions would be introduced by a particular newly proposed industrial or technology policy initiative. Unfortunately, the theory of positive feedbacks in the allocation of talent does not give any hints what thresholds might have to be observed, where crossing any such threshold might trigger an accelerating shift of talent towards redistribution and might ultimately lead to a dramatic decline in the economy's growth performance. In view of this paucity of theory, it is hardly surprising that empirical research has not generated much insight into these issues either.

3. Information Problems Immanent to the Models

Part of the information needed to formulate a programme of targeted industrial policies relates to the question whether it makes sense to view an entire economy as being identifiable by a single production function, without taking into account, for example, the geographical dimension at all. Most models of economic growth implicitly ignore this question. But, once the process of economic growth is found to be characterized by agglomeration of economic activity in the aggregate, or at the level of individual industries, this raises additional questions about efficiency and distribution in whatever dimension the agglomeration takes place. These questions are inevitably excluded from any analysis based on a single production function.

A basic policy question, however, which should not be excluded, is whether industrial policies are intended to support existing patterns of agglomeration, or rather aim at inducing a regional restructuring of the economy. In order to assess the prospects of success in either case, it would be important to know whether past trends of agglomeration can confidently be extrapolated into the future, or whether new trends should be expected to emerge, for example, towards a more even spatial distribution of economic activity. Here, crucial parameters are likely to be the future costs of transport and communication. Indeed, one can argue that the advantages of agglomeration at the industry level, due to productivity gains from specialized and differentiated capital and service inputs, diminish when the costs of transporting these inputs decline more rapidly than those for the final products of an industry, and that the advantages of spatial concentration normally become greater for an industry when the transport costs for inputs and outputs fall at an equal rate (Krugman 1991: 50–52). But in general, the impact of declining transport costs on patterns of agglomeration cannot be easily predicted: while the disadvantage, due to transport costs, of producing at the periphery for the centre is reduced, the potential for exploiting economies of scale is increased, which primarily benefits the producers at the centre from where delivery to a larger area becomes profitable.

Equally important, and just as difficult, is the question what makes the pattern of economic agglomeration established in a certain country or region efficient. The theory of economic agglomeration suggests that there are generally several ex ante feasible patterns of agglomeration, both for individual industries and for the entire economy, which might be centred around different locations. Which of these patterns ultimately emerges, is often decided by accidental historical events. Historical events which take place early in the process of location formation may, however, trigger patterns of regional allocation and agglomeration which turn out to be inefficient in the long term. Yet, even in these cases it may be advantageous for the individual firm, and the individual worker, to locate in whatever centres emerge, because only there will it be possible to reap the full benefits of positive external effects emanating from the contemporaneous economic activities of other firms and individuals. The possible long-term inefficiency of an emerging pattern of agglomeration, to which the individual's location decision contributes, does not enter the individual's decision calculus provided he has a sufficiently high rate of time preference. Thus, even rational expectations based on perfect information cannot deter the individual from joining an inefficient pattern of agglomeration if he cannot coordinate his decision with those of other firms and workers. In reality, of course, perfect information about all feasible future development paths does not prevail, because the set of feasible paths depends partly on non-predictable parameters, like future transport costs.

What makes these kinds of forecasting problems, due to economic complexity and fundamental indeterminacy of non-stationary stochastic processes, especially serious for the design of industrial and technology policy is that multiple equilibria seem to be by no means characteristic of spatial agglomerations only. They rather seem to be a common feature of many models within new growth theory which are of interest in the analysis and design of industrial policies. This holds for models of hysteresis in open economies, either based on learning by doing or on endogenous technical progress with nationally or regionally bounded external effects, for models of the evolution of technology along certain ex ante unpredictable trajectories,[144] as well as for models of the sectoral allocation of personal human capital (Murphy et al. 1991) (see the theoretical analysis in Chapter C).

In the design of industrial and technology policies it is important to be aware that models of path-dependent allocation processes do not impart any way to

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[144] Cf. Rosenberg (1994) for the perspective of an economic historian on this hypothesis.

predict which equilibrium of an assumed multiplicity of long-term equilibria will be selected by market forces. But if targeted industrial policy intervention shall be used to influence the final outcome, the prospects of success will depend crucially on the timing of intervention. Intervention will only be promising as long as no 'irreversible' move[145] towards one particular equilibrium has occurred, i.e. as long as the 'window of opportunity' has not been closed (Perez and Soete 1988). Once an irreversible move has occurred, the attempt to change the allocation towards a pattern belatedly recognized as more efficient in the long term could be so costly that the benefits do not justify an intervention.

Thus, an efficient use of industrial policy instruments requires careful timing. However, not all is lost when some particular opportunity is missed. In fact, industries undergoing rapid technological change will all the time open, and close, 'windows' of ever new opportunities. Hence, any economy of sufficient complexity will inevitably experience structural change and from time to time give birth to entirely new industries, and thus have numerous opportunities to embark on a new path of innovation and learning. In times of rapid change, established patterns of allocation will sooner or later be destroyed and resources set free, so that they can be redirected to new uses at comparatively low cost.[146] The observance of 'historical opportunities' thus may appear as an important condition for the cost-effective design of targeted industrial policies, but it represents neither a necessary nor a sufficient condition for attaining the goal of raising the rate of long-term economic growth. The timely recognition of historical cross-roads, which may open up new opportunities to influence the technological, spatial and structural development of an economy, is part of the informational requirements for industrial policy. In practice though, historical opportunities are mostly missed, because they can normally be recognized only ex post, when it is already too late to exploit them for policy purposes.[147]

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[145] This irreversibility refers to the influence of market participants' individual allocation decisions as well as to accidental events. Hence, it does not exclude that government action, making a sufficiently great effort, may still overturn an 'irreversible' allocation pattern under particular circumstances. In any case, a belated intervention would normally not be justified in terms of benefits and costs.

[146] In the context of open economies, this suggests a theory of leapfrogging, like that recently formalized by Brezis et al. (1993). An especially pronounced specialization of a whole country in a particular area of high-technology, perhaps pushed by industrial policy to exploit technological hysteresis, will eventually reach its limits whenever the country's supply of appropriately trained scientists and engineers is less than perfectly elastic. From that point on, other countries would have opportunity to catch up in the same area of high-technology even without adopting targeted industrial policies themselves.

[147] As an example consider the erroneous decision of IBM not to prepare its marketing organization full speed for the age of Personal Computers in the 1980s, and to keep largely unchanged the scale of producing and marketing mainframe machines. Or

For the informational requirements of industrial policy is further important that stochastic processes of resource allocation seem to play a crucial role also when one of several competing technologies is selected for adoption by market participants, and in the selection of technological paradigms in the market place of ideas.[148] In these cases, it is practically impossible to predict the course of technological change in the future. It thus becomes futile to extrapolate past trends of technological change into the future, a practice which has hitherto formed the informational basis for many industrial and technology policy programmes. Nobody can really predict over longer periods of time in which areas there will be technological breakthroughs, in which direction technological change will speed up or slow down, where new 'key' technologies will generate particularly strong external effects, and whether these will, in a shrinking world, be communicated on a regional, national or even on a world-wide scale.

It may indeed appear as if many small, and some not so small, historical events determine the course of technological development, of spatial allocation, of the sectoral specialization in open economies as well as of the sectoral allocation of talent in the real world. And in some sense, these developments are, of course, nothing else but the succession of historical events that occur more or less at random. Yet, this view may just as well be a delusion about what really drives economic development. Krugman (1991) discusses the possibility that collective expectations, instead of historical events, determine the selection from multiple long-term equilibria, when there is decentralized, yet through positive feedbacks interdependent decision making in a market economy. This possibility has great relevance to the design of targeted industrial and technology policy, for basically two reasons: First, the impact of expectations can undermine attempts to influence the outcome of allocation processes by manipulating the

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think of the disastrous decision of the Polaroid company to develop a Polaroid home-movie camera, with the ability of delivering instant pictures, at a time when the technology of video cameras was already knocking at the door.

[148] To illustrate such cases, Arthur (1988) models competition, leading to 'technological exclusion', of the video systems Betamax versus VHS within the framework of a path-dependent stochastic allocation process. David and Bunn (1990) similarly interpret the competition of alternative technological paradigms within the electrical industry, namely the choice for alternating versus direct current in long-distance transmission at the turn of the century. In the same vein, he discusses the selection of designs for nuclear power stations after World War II. Today, there may again be a comparable situation in consumer electronics where Philips and Sony have prepared their incompatible technologies of 'Digital Compact Cassette' and 'Minidisc', respectively, to succeed the popular Compact Disc (CD) for music recordings. To mention one more example, the technologies proposed for the electric motoring of cars could soon enter into fierce competition, which might finally lead to the exclusive adoption of one of these technologies, because here again the rapid provision of complementary infrastructure, specific to a particular technology, could be crucial.

initial conditions originally set by history. Second, a cost-effective industrial policy may take the form of directly influencing the expectations of market participants, as far as this is at all feasible. Collective expectations might move markets and become self-fulfilling prophecies.

Krugman (1991: 31), derives three conditions for collective expectations to play a decisive role, in the sense of self-fulfilling prophecies, in the selection of long-term equilibria in stochastic allocation processes: (i) The speed with which resources can be reallocated must be high relative to the rate of time preference, with which future income-differentials are discounted, so that the potential future benefits of the best long-term allocation outweigh the benefits of whatever allocation may be initially realized. In other words the cost of reallocating resources and the real rate of interest must be low. (ii) There must be increasing returns to scale of sufficient strength, which operate at the level of individual industries, or of the entire economy, and make one allocation better in the long term, so that a redirection of resources to this allocation lets incomes rise rapidly. (iii) The initial historical situation must not already be irreversibly 'locked' into an inferior pattern of allocation.

Under these conditions industrial policy might achieve cost-effective results if it succeeds in directing the expectations of the numerous decentral decision takers towards a self-fulfilling prophecy. Whether this strategy can succeed probably does not only depend on economic context conditions, but also on sociological and cultural factors. Japan and France, for example, have traditionally placed more emphasis on central government control and guidance, and people there may thus be more prepared to believe visions announced by the government, and to act accordingly, than in, say, individualistic Britain or the United States. There is anecdotal evidence that informal guidance has played a more important role in Japan's industrial policy, attempting to influence the coordination of industrial planning among the large firms, than direct subsidies or trade policies have done. In Germany, by contrast, the government has, probably for good, lost much of its past credibility in this respect, through the experience of Nazi-rule.[149] Studies in economic history suggest that more pronounced industrial policy intervention was common in the Kaiserreich and in the Weimar Republic than in the Federal Republic of Germany.[150] To assess the

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[149] Hitler's government used industrial and technological targeting mainly to pursue its ambitious military objectives. A prominent example is the founding of 'Volkswagen' as a state enterprise in 1938, which soon began to produce tanks for the military.

[150] But even in those former periods has German industry probably benefited more from public efforts in education, e.g. the promotion and partial funding of technical universities, and in infrastructure, e.g. the building of a dense nation-wide railway system, than from targeted interventions. — An interesting example for the benefits

prospects of success in any modern country today, it would be important to establish whether the cultural preconditions for influencing collective expectations through government initiative are at all fulfilled, apart from looking at the economic parameters which may or may not give self-fulfilling prophecies a chance. There are reasons to suppose that neither of these conditions are met in Germany today, nor in many of the other leading industrialized countries.[151]

Nevertheless, innovation avenues, technological guideposts, focusing devices or paradigms may actually continue to hold sway in technological development. In this context, it is an interesting question to what extent technological paradigms are necessarily spontaneous, emergent phenomena which would ultimately elude any steering attempt by central government. The answer is likely to be yes. However, assuming for the moment that the formation of technological paradigms could be manipulated by government and could be used as a focusing device for private R&D investments, one may want to ask whether a strong influence of technological paradigms would actually help, or rather hinder, the course of technological change to move in a desirable direction and at an appropriate speed. Put differently: Is there a need for more concentration on selected technological paradigms to help focus scarce resources into private R&D on certain promising technologies, or is there already too much concentration of R&D on too few paradigms?

The recent theory of endogenous technical change provides an analytical framework which may help to answer this difficult question. As stated in Section B.II.2, this theory has developed two prototype models of endogenous innovation in growing economies, namely the model of increasing variety in horizontally differentiated goods and the model of quality ladders with the displacement of previous generations of (lower quality) goods. Remember that the

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of self-fulfilling prophecies is provided by the success of the German apprenticeship system. Both sides, the trainees as well as the training firms, reap part of the benefits and seem to be fully aware of these. By contrast, in Britain and in the United States most firms seem to stick to the expectation, based on individual rationality, that teaching and training young workers more than absolutely necessary for a particular job cannot be profitable, because the fully trained workers would be enticed away by other, free-riding firms. It is hardly conceivable that these entrenched attitudes and expectations, or the corresponding elements in the national economic system, could be easily changed, let alone quickly.

[151] The way in which the technology policies of the United States, Japan, France, the United Kingdom and West Germany have been formed by the respective historical experiences of these countries is vividly described by Nelson (1984). Ergas (1986) develops, for the same group of countries, a useful typology of technology policy regimes and institutions. He goes on to discuss a number of interesting hypotheses about the origins of country-specific patterns of industrial innovation. He distinguishes between countries which tend to support the general diffusion of new knowledge and those which tend to promote and pursue ambitious technological 'missions' in certain prestigious fields of technology.

possibility of too intensive competition for innovation is, on theoretical grounds, more likely to be relevant in the model of quality ladders. The promotion of technological paradigms, in turn, is likely to concentrate the R&D focus of private firms even further on a small number of quality ladders — and quite possibly to do so at the expense of enhancing variety. This danger may well be exacerbated when certain technological paradigms become national priorities in a world-wide contest for technological superiority among countries.

For example, consider the recent race between the United States, Japan and the European Union to develop a universal technical standard for high-definition television (HDTV) to be introduced into networks world-wide. It seems likely that the advantages of compatibility in a world-wide network render the establishment of a single standard efficient; and it is at least possible that this may be the only outcome that can prevail in the long term. Then, if this standard is proprietary, two of today's three contenders in HDTV development will see much of their current R&D efforts become obsolete at some point in the future. An incentive problem arises because the system which wins the race to technical maturity and market introduction may subsequently have the greatest probability of becoming the world-wide standard and of returning export revenue to its inventor country. It is therefore individually rational for each contender to raise the stakes of his R&D investment whenever any of his competitors does so, in order to reach the market sooner.

This situation is comparable to that of a group of fishermen who compete for private gain over a limited number of fish in a public pond. The private incentives are set inefficiently, so that over-fishing will be the likely outcome.[152] However, while the problem of over-fishing can easily be solved by creating private property rights for the fish in the pond, this solution is not available in the case of patent races. Private property cannot be defined for non-existing knowledge. Patents are only allocated after new technical knowledge has been found. Technology policy thus faces some hard questions when it comes to justifying the promotion of specific technological paradigms, especially when these are already in vogue in other countries.

To summarize this description of the informational problems in the design of targeted industrial or technology policy programmes a questionnaire is offered which may serve as a rough guide to some of the most important factual questions, suggested by new growth theory, that would have to be answered in a given historical situation:

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[152] See the thorough analysis of the implications for innovations by Dasgupta and Stiglitz (1980).

What kind of market failure lies behind the perceived industrial or technological development problem? Is there evidence of positive technological external effects? How large is their spatial range: regional, national or international?

What would be the most direct way to correct the market failure? Is this feasible?

Is the industry's market small or large, shrinking or growing?

What is the objective with respect to technology: support for a newly emerging technology or improvement of a mature one?

How large are the supply and demand elasticities for the typical products of the industry under consideration? How large is the world market share of home country exports from this industry?

Is the labour market of the industry integrated with the labour markets of other industries, across regions, and across countries?

Is the personal human capital mobile across industries and across countries?

Is the supply of appropriately trained human capital for the industry elastic or rather inelastic?

Are the rewards for the immobile factors of production higher or lower than in other industries at home or abroad, which are comparable in terms of quality demands?

How does the industry compare in terms of productivity across industries and across countries?

Will the proposed industrial policy measures tend to support or hinder the further specialization and differentiation of personal human capital in the industry, or in the economy as a whole?

Are the country's capital markets internally efficient, and is the external exchange of capital liberalized?

Is the technical knowledge, which is relevant to the industry, internationally as mobile as within countries?

How does the technological standard of the industry compare across countries? Is the home industry more of a technology laggard, or rather a technology leader in the industry?

Is the economy's rate of growth reasonably high or disappointingly low, if compared with similarly endowed economies?

Is the government share in GDP high or low?

Are industrial policy interventions the exception or the rule? Have they so far been mostly temporary in effect so far, or have they already become permanent features of the national economic system?

How common are government regulations of prices and quantities? Are more price distortions to be expected as a result of the proposed measures?

How strong is the influence of industry lobbies?

Is the same industry protected by industrial policies abroad? Is the related technology already heavily subsidized abroad, and thus not at risk of being undersupplied in world markets?
Are strategic counter-measures to be expected in response to any home country initiatives?

IV. Some Questions for Future Research

Some questions for further research were already suggested at various points in the text, in particular at the end of the empirical Chapters D and E. One of these questions concerns the level of aggregation at which path-dependence may be a relevant feature of specialization dynamics. The theory does not make a precise prediction, but it seems likely that path-dependence is more important at lower levels of aggregation than that considered here (for reasons of data availability). Future applications of the empirical methodology explored in Chapter E should therefore use data at lower levels of aggregation over subindustries, say, at the five-digit ISIC level. In similar vein, many of the large countries treated here as uniform entities may in fact be heterogeneous enough to make the use of regionally disaggregated data advisable; after all, the localized nature of externalities might imply that California and New York or Hamburg and Munich have different specialization dynamics due to hysteresis, which could not be detected using national data.

Neighbouring relations between economic activities, however, need not be defined by geographical proximity, given the modern means of telecommunication and cheap transport. Instead, they might be defined by the intensity of input-output-linkages, or by the extent to which different economic activities share similar base technologies or similarly trained specialists. Recall from Section B.V that empirical spill-over studies have already used specifications which attempt to take account of neighbouring relations in dimensions other than geographical space. Provided that enough disaggregated data can be made available, such an attempt could also enrich the methodology of Markov chain analysis explored in Chapter E.

Moreover, Markov chain analysis could be extended in other ways to test specific hypotheses. For example, if several subgroups of regions could be formed, according to some criterion of similarity within groups and differences between groups, it might be feasible to estimate separate Markov transition matrices for selected industries in each subgroup and to test for homogeneity versus heterogeneity across these estimates. This might give more insight into regional or national idiosyncracies that potentially affect the specialization dynamics in industries or technologies.

A further extension of the empirical research would ask whether a long-term equilibrium relationship can be detected between industry- and country-indexed technology input and value added output indicators. To simultaneously exploit variation in the data across time and across countries (or regions), the new methodology of cointegration in random fields, developed by Levin and Lin (1992, 1993) as well as by Quah (1994), might be appropriate to investigate this question.

An important question for theory might be whether the concept of a production function can survive as a workhorse in the analysis of specialization in open economies, given the apparent speed of technological change and the growing influence of various kinds of external effects, including knowledge spill-overs from R&D. Instead of maintaining rigid production functions at the centre of analysis, the learning spill-over effects and the multi-dimensional channels for technology transfers between decentralized economic activities might be analyzed more directly, say, in terms of neural networks in which the intensity of specific linkages and information exchange relations would be modelled to grow or decline endogenously in the course of economic development.

It may turn out, for example, that the concept of a production function need not be abandoned altogether, but that it should be used in a more flexible way to understand what appears to be the emergence of an information-intensive economy. One issue, for sure, would have to be resolved within the framework of production functions, namely the question under what conditions technical progress tends to take the form of increasing variety, as suggested by the Dixit-Stiglitz function, or the form of quality ladders, as suggested by Aghion and Howitt (1992). Will it be possible to formulate a consistent general theory of institutional factors that favour the one or the other of these prototypes of technical change?

In this context, theory should also ask whether the value of variety necessarily increases in the course of economic development, or whether decreases in the value of variety might also be compatible with economic growth — at least temporarily. Furthermore, economic theory might attempt to prepare the ground for a quantitative assessment of the value which certain types (or degrees) of diversification in regional (or national) economic structure, or technology portfolios for that matter, might have in terms of the prospects they give for future productivity growth. A related policy question would be what a benevolent government could do to enhance the variety of technological knowledge available in a given region or country, if that was found to be a bottleneck to innovation and growth.

Last, but not least, a highly topical question concerns the formulation of technology policies in the European Union. Since EU member states have developed different, partly incompatible regimes of technology policy in the past, the question arises what course a common European technology policy will (or should) take in the future. Will the emerging European regime of technology policy follow the French model of promoting specific and ambitious technological missions, often involving technologies of a very large scale, or will it rather follow the German and Scandinavian line of supporting the diffusion of new technologies in general, for instance by funding and promoting decentralized technology transfer centres? Will it be at all necessary to choose between these two models at the European level? Or would the continued coexistence of different national technology policies still be a feasible alternative in the common market? And would that be desirable?

G. Concluding Remarks: Has the Design of Targeted Policies Got Any Easier?

This study has sought empirical evidence on the hypothesis that the dynamics of technological and industrial specialization in open economies are characterized by path-dependence or hysteresis. This hypothesis has often been interpreted to imply that a benevolent government can — under certain well-defined circumstances — use targeted industrial and technology policies to steer an economy's evolving pattern of specialization onto a superior course, resulting in faster overall productivity growth. Although this study has not been able to either verify or reject this claim with finality, it has put forward new empirical evidence which is predominantly negative on hysteresis.

Furthermore, the study has surveyed the informational requirements that would have to be fulfilled to recommend any targeted industrial and technology policies in an actual historical situation, in which hysteresis is thought to be relevant for an economy's evolution of specialization. This synthesis has suggested that the information problems remain insurmountable for the time being. The study therefore closes on a sceptical note about the prospects of targeting being beneficial in today's highly diversified industrial economies. The basic message for policy is that it has not got any easier to design and implement targeted policies which would enhance productivity and welfare in open economies. On the contrary, the study has pointed out a number of major difficulties, which would inevitably get in the way of targeting and which cannot presently be resolved, given the limitations of available data and empirical methodology in economic research.

It would be easy to dismiss any proposal for targeted industrial and technology policies by making a preconceived philosophical choice of treating free markets as an end in themselves, instead of as a means to an end. This study, by contrast, has implicitly treated the market mechanism of resource allocation merely as a means, which will never cease to be subject to comparative evaluation vis-à-vis alternative means, including targeted interventions in market-based economies. In this view, the choice of a benevolent government for or against targeted policies should be based on empirical research, and should be re-evaluated whenever important new empirical evidence challenges the wisdom of policies adopted in the past.

The demise of communism has made it fashionable today to call for more entrepreneurial decision making at lower levels of economic organization. But an important question raised in parts of new growth theory asks whether some entrepreneurial decisions rather should be made at higher levels of organization than most firms have traditionally operated, if technological change is of an essentially systemic nature. Indeed, one may wonder: Is it not part of healthy locational competition when a local or national government makes an entrepreneurial move to attract or to keep research and development on promising technologies in its domain? To answer this, it would not suffice to say that strategic action cannot do any good because it would evoke strategic counteraction by foreign governments. A compelling answer will have to be based on a more sophisticated analysis — one based on rigorous theory and thorough empirical testing.

Such a more sophisticated analysis has in recent years been attempted in parts of new growth theory, where models of endogenous technological change suggest that positive external effects from private R&D may be a *sine qua non* for sustaining long-run economic growth. These models, which were reviewed in Chapter B, interpret product and process innovations as the result of purposeful R&D investments made by private profit-seeking enterprises. Sustained growth of per capita productivity is feasible whenever the private incentives to accumulate technical knowledge are strong enough and do not weaken over time. The models meet this condition by postulating that the creation of knowledge through private R&D yields positive external effects: part of the new knowledge adds to the public stock of technical knowledge and is accessible to all firms doing R&D themselves. Without these positive externalities, which have the effect of reducing every firm's costs of future R&D, the pioneers of a new technology would be in a position to establish a permanent monopoly that could be defended virtually without further R&D effort.

Using this theory to understand trade, growth and specialization in open economies, it is necessary to make some assumptions about the cross-border mobility of R&D output. One important assumption concerns the privately appropriable part of R&D output. This may be either internationally tradeable, like most other private inputs in production, or may be largely excluded from international trade, since it is often complementary to specific knowledge and skills, available only in the firm or country that has done the R&D. The assumption of international mobility of R&D output is supported by the observation of many instances of technological imitation and of a widespread, and increasing, commercial trade in patents and licences. On the other hand, the assumption of limited international mobility of R&D output is supported by the fact that the recipients of international technology transfers often cannot use the acquired technology straight away, but rather have to invest in complementary knowledge and skills and to literally re-search the acquired knowledge to understand its tacit components. Hence, it is not surprising that a large, and apparently increasing, share of international technology transfers takes place within multinational companies, which are generally in a better position to move not just pure technical knowledge but also complementary human capital resources across borders.

To what extent the privately appropriable part of R&D output, itself an input in other production, is internationally tradeable has interesting implications for resource allocation and patterns of specialization within a theory of dynamic comparative advantage. By extending the international division of labour, trade in new technical knowledge — either through trade in patents and licences or through technology transfers within multinational companies — can lead to a more efficient use of resources in knowledge creation and so raise the rate of innovation and growth in the world economy. The crucial assumption, however, which distinguishes the theory of dynamic comparative advantage from the hysteretic theory of national technological accumulation, is that the speed, strength and scope, with which the positive external effects of knowledge creation through R&D spill over to other firms, are not reduced by international borders, nor by geographical or cultural distance between industry locations.

Chapter D explored the empirical relevance of the concept of comparative advantage and of the factor proportions theory of international trade and specialization for the distribution of R&D activities across seventeen industries in fourteen OECD member countries over the period from 1970 to 1989. This chapter first discussed bivariate correlations between countries' R&D intensities across industries and industries' R&D intensities across countries which confirm that the average R&D intensity is a characteristic feature of individual industries as well as of individual countries. Using the analysis of variance technique, the chapter then showed that the type of industry and the country of its location are significant determinants of the observed human capital intensity in R&D, measured here either by the ratio of university graduates in R&D to other R&D personnel or by the ratio of R&D scientists and engineers to other R&D personnel.

Chapter D, finally, reported multiple regression analysis to examine — separately for each industry in the sample — the impact of a country's human capital endowment, production specialization, size and time on the degree to which the country specializes in a particular industry's R&D activities. While the results of these regressions are generally not inconsistent with the factor proportions theory, they do reveal strikingly distinct patterns of R&D specialization for computers, electrical machinery and radio, television and communication equipment, the industries most closely connected to the fast changing microelectronic technologies.

Chapter E looked at the empirical evolution of specialization in OECD countries over time. According to the hypothesis of dynamic comparative advantage, patterns of specialization in technology as well as in actual production should — in the absence of adjustment and transaction costs — be quite mobile over time and independent of each other as they respond to changes in the relative factor endowments of countries. Since the comparative advantages for production and for R&D in an industry would be distinct and might be located in different countries, not even the specialization patterns of those technologies which are confined to single industries would need to evolve along the same trends as the corresponding industries.

By contrast, the case for historical events and path-dependence as the determinant of sectoral patterns of technological specialization would imply that patterns of specialization in technology as well as in production are much less mobile, especially when a country's industrial structure is already heavily skewed towards certain industries. If knowledge spill-overs from R&D diffused faster within countries than across international boundaries, hysteresis could be decisive in the sense that temporary events, like price shocks or industrial and technology policies, can have lasting effects on a country's pattern of technological specialization and trade. Such lasting effects might be recognizable through high persistence of specialization patterns in production and technology despite changes in the relative factor abundance of countries. Persistence would be expected to be particularly pronounced in technological specialization where the positive external effects in the form of knowledge spill-overs from R&D would have their most direct and strongest impact. But in general, a close relationship would be expected between the dynamics of countries' specialization in certain technologies and in the production in those industries whose products make intensive use of these technologies.

An important practical question in this research was: How can sectoral specialization in industrial production be measured in a multi-country, multi-factor world? To obtain a measure which is comparable across countries and across industries it was suggested to compare the relative weight of a certain industry in individual countries with the relative weight of this industry in total world manufacturing. This indicator of specialization measures how many times greater or smaller the ratio of a country's value added to the world's value added is in a specific industry as compared with all of manufacturing. Discussing the determinants of specialization in terms of comparative advantage versus hysteresis due to technological accumulation, it is natural to focus on the specialization in those tradeables for which the hypotheses are primarily formulated, namely manufactures. The limited availability of reliable data on value added by industry, which was taken from the 1992 version of the OECD STAN database, made it necessary to restrict the scope of the study to only 12 countries — Australia, Canada, Finland, France, West Germany, Italy, Japan, the Netherlands, Norway, Sweden, the United Kingdom and the United States — and to the 19 year period from 1970 through 1988.

For each year and for each industry in all sample countries, the indicator of industry specialization and a conceptually similar indicator of technological specialization were computed. These transformed data were then used to study the evolution of their cross-section distribution — across industries, across countries, or both. Since the time-series and cross-section dimensions of these data are of similar magnitude — a structure known in probability theory as a random field — conventional methods of either panel or pooled regressions would not have been appropriate. These methods simply control for variation in one dimension to estimate correlations in the other. An appropriate model instead had to take both dimensions into account simultaneously. That is to say, the model had to specify a stochastic process of the evolution of cross-section distributions, which could be estimated so that the mobility of the specialization indicator over time could be examined on the basis of the estimates. Such modelling might take several forms. One approach chosen for estimation was in terms of an approximation by a finite Markov chain for a discretized state space. This assumes that the underlying stochastic process has the Markov property that future patterns of specialization only depend on the present pattern and not on the past.

The chosen discretizing grid has six states. The estimated transition matrix therefore gives probabilities for each of these six states of specialization that an industry will have moved there after one period of time, conditional on the industry's initial state of specialization. An empirical estimate of such a transition matrix can give useful information on the intra-distributional mobility of individual industries between different degrees of specialization over time, and can also be used to calculate long-run stationary distributions of the specialization indicator — provided they exist — by matrix multiplication according to the Chapman-Kolmogorov equation.

A bimodal long-run stationary distribution, where the probability of an industry being either very strong or very weak in its country of location is much higher than it being close to the mean of specialization, combined with high persistence in terms of large entries on the main diagonal — especially at the ends — of the estimated transition matrix would point to hysteresis, whereas low persistence in the transitions matrix combined with a uniform or unimodal long-run stationary distribution of the specialization indicator would appear to contradict the hypothesis of hysteresis.

The main shortcoming of this analysis summarized so far is its lack of accounting for relative factor endowments in the sample countries and changes thereof during the sample period. If factor endowments had any impact at all on the international allocation of sectoral economic activities, they might — in the case of monotonic time trends in the underlying dynamic comparative advantages of countries — even be responsible for patterns of specialization dynamics which point to a bimodal stationary distribution, just like hysteresis would. It is therefore important to control for the influence of changes in the relative factor supplies of countries when analyzing the dynamics of specialization with a view to testing hysteresis, although this is — admittedly — a very difficult task.

A first attempt was made by simply regressing the familiar value added indicator of an industry's specialization in the sample countries on conceptually similar indicators of countries' relative factor endowments, and by subsequently estimating Markov chain transition matrices on the residuals. Provided all relevant endowments are appropriately considered, this procedure eliminates that part of the specialization dynamics which can be 'accounted for' by the dynamics of comparative advantages.

The factor endowments considered for each of the twelve countries were: Physical capital, R & D capital, the number of R & D scientists and engineers in the business enterprise sector, the labour force, and the years of schooling in the labour force. A general tendency of divergence in the autocorrelated residuals away from their theoretical mean of zero could be interpreted as evidence in support of hysteresis, whereas substantial non-monotonic mobility of the residuals, or even convergence to the mean, would lend support to the alternative hypothesis of dynamic comparative advantages as an adequate explanation of industrial specialization dynamics.

The evidence — in brief — from 12 OECD member countries' time series of value added in 17 manufacturing industries and from corresponding patent count data does not support the hypothesis of hysteresis based on nationally restricted knowledge spill-overs from industrial research and development activities. On the contrary, there seems to be generally lower persistence in patterns of technological specialization than in the corresponding production specialization. Moreover, high persistence in some parts of manufacturing mostly disappears when taking into account changes in countries' relative factor endowments, which form the basis of dynamic comparative advantages. These findings cast doubt on the popular belief that a government can — by making cleverly designed and appropriately timed industrial policy interventions — secure a permanently larger share of certain industries for the national economy which are supposed to lock in first-mover advantages in terms of particularly high rates of technological innovation and productivity growth.

Chapter F then turned to a discussion of the information problem any benevolent government would face that did not take the empirical results of the preceding chapters as the final verdict on the merits and demerits of targeted industrial and technology policies in practice. The main conclusion from this analysis is the recognition that most methods so far used to measure the strength and range of positive external effects from new knowledge (or newly introduced products) are too crude, and therefore fail, to distinguish properly between different kinds of external effects, which may have quite different theoretical implications for industrial and technology policy. Here, empirical research inevitably faces serious identification problems, say, when technological externalities are hardly distinguishable from pecuniary externalities in high-technology markets.

For example, while the introduction of a new computer software often comes with a negative pecuniary externality for the direct competitors, it may also give rise to a positive technological external effect, when the new software reveals new technical possibilities which the competitors can freely incorporate in the next generation of their own products. On the other hand, also pecuniary externalities can be positive, so for instance, when the increase in demand for specialized software programming tools due to the expansion of a particular consumer software company induces a differentiation of the pertinent supply, which in turn benefits other software companies as well as the originally expanding one.

Much of the existing literature on industrial and technology policy, being focused on comparing the strength of positive external effects from investments in different industries so as to identify the most promising industries for targeted subsidies, has neglected the equally important question how a reliable distinction can be made between the relative strength and direction of different kinds of pecuniary and technological externalities. This distinction would be important for an efficient choice of policy instruments because direct R&D subsidies would be wasteful if the relevant positive externalities were primarily of the pecuniary kind and linked to the intensity of interfirm transactions, while subsidies targeted at specific types of transactions — say, by subsidizing the acquisition and installation of certain types of machinery — would be wasteful in the case of true technological knowledge spill-over effects.

Whatever microeconomic nature of the external effects from knowledge creation is dominant in reality, the new theory of endogenous technological change seems right in emphasizing the importance of external learning by doing from private R&D. But, as the models typically exhibit multiple equilibria with the implication of different self-reinforcing patterns of specialization in open economies, they have fuelled worries about national lock-out from promising technologies which are apparently unwarranted in the case of industrialized countries, as the empirical results of the present study indicate.

The theory of endogenous technological change and learning by doing, which is to some extent localized, might still be compatible with these findings, though. Yet, to prevent once-established patterns of specialization from persisting through time may even under the hypothesis of localized learning not actually require strategically targeted industrial and technology policies in open economies when these have a rather diverse industrial structure to begin with. In such a situation, it may suffice that the economy is fully integrated into the international division of labour and occasionally affected by terms-of-trade shocks of sufficient magnitude to cause substantial sectoral reallocations of resources despite some degree of path-dependence, or hysteresis. Workers and entrepreneurs thus pulled into new activities by unexpectedly changing comparative advantage would be given a new start at learning on a different path. The examples of Finland and Ireland in the 1970s and 1980s have shown that even small countries and latecomers are not generally prevented from substantially improving their export base in high-technologies (OECD 1994b: 19).

Appendix

I. Sources and Methods for Chapter D

The data set covers the fourteen following countries: Australia (AUS), Belgium (BEL), Canada (CAN), Denmark (DK), Finland (FIN), France (FRA), West Germany (DEU), Italy (ITA), Japan (JAP), the Netherlands (NL), Norway (NOR), Sweden (SWE), the United Kingdom (UK) and the United States (US), and the twenty-year period from 1970 through 1989 — as far as possible. Data gaps are mentioned in the descriptions of the variables below.

The table below comprises all industries, their ISIC codes,[153] and the corresponding abbreviations used in the tables of Chapter D.

Industries Included in the Analysis of Chapter D

	ISIC-Code	Abbreviation
Food, beverages, tobacco	31	FOOD
Chemicals, excl. drugs	351 & 352 (excl. 3522)	CHEM
Drugs and medicines	3522	DRUG
Rubber and plastics	355 & 356	RAP
Non-metallic mineral products (stone, clay, glass)	36	SCG
Iron and steel	371	IRON
Non-ferrous metals	372	NFM
Fabricated metal products	381	FABM
Machinery, not elsewhere classified, excl. office and computing machinery	382 (excl. 3825)	MACH
Office and computing machinery	3825	COMP
Electrical Machinery, excluding RTVC	383 (excl. 3832)	ELMA
Radio, TV and communication equip.	3832	RTVC
Shipbuilding and repair	3841	SHIP
Motor vehicles	3843	MOTV
Aircraft	3845	AIRC
Other transport equipment	3842, 3844, 3849	OTRA
Professional goods (scientific instruments)	385	PROF
Subtotal electrical group	383	ET
Subtotal chemical group	351, 352, 353, 354	CT

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[153] International Standard Industrial Classification (see United Nations 1968).

Data on average years of schooling in the adult population are from Barro and Lee (1993: 26–29 [Table A.2]). Adults are defined as people older than 25 years of age. For Figure A1, panel b, only the data referring to the years 1975 and 1985 have been taken; they are used as an approximation of the averages for the respective decades. The data source provides these data only at five-year intervals. See Barro and Lee (1993) for their method of estimation.

Data on value added by industry are from the *OECD STAN Database for Industrial Analysis* (OECD 1992a; OECD 1994a). These yearly data are estimated by the OECD, instead of being a mere compilation of OECD member countries' official data. The estimates are geared towards compatibility with national accounts and towards international comparability. Data for the following cases are missing in the data source (partly because some of the industries have not existed in some of the countries for all or part of the time): in Belgium for MACH, COMP, ELMA, RTVC, SHIP, MOTV, AIRC and OTRA throughout, in Canada for PROF throughout, in Denmark for MACH and COMP from 1970 to 1979 and for MOTV and OTRA throughout, in Finland for AIRC and OTRA from 1970 to 1979, in Italy for CHEM, DRUG, MACH, COMP, SHIP, MOTV, AIRC and OTRA in 1988 and from 1989 as well as for ELMA and RTVC in 1989, in the Netherlands for MACH and COMP in 1989, and in the United States for AIRC and OTRA in 1970 and from 1971. Value added for the total manufacturing sector is used as a scale variable. This is done because the manufacturing sector is largely identical with the tradeable sector, the sector for which the question of international specialization is relevant.

All other data are from the *OECD Science and Technology Statistics* on magnetic tape (OECD 1992b). Here is a list of the other variables and missing data:

Data on Total Intramural Business Expenditures on R&D by Industry are from group 25 of the *OECD Science and Technology Statistics.* Data for the following cases are missing in the data source (partly because some of the industries have not existed in some of the countries for all or part of the time): in Australia for all industries in 1970, 1972, 1974, 1975, 1977, 1979, 1980, 1982, 1983, 1985, 1987, 1989, and for CHEM and DRUG in 1971, RAP, FABM and SCG in 1973, COMP in 1971, 1973, 1988, AIRC in 1971, 1973, 1981, 1988, for IRON, NFM, MACH, ELMA, RTVC, SHIP, MOTV, OTRA and PROF in 1971 and 1973; in Belgium for all industries in 1970, 1972, 1974, 1976, 1978, 1980, 1982, 1984, 1989, and for COMP from 1970 to 1980; in Canada for all industries in 1970, for MACH, COMP, ELMA and RTVC in 1971, and for SHIP, MOTV and OTRA throughout; in Denmark for all industries in 1971, 1972, 1974, 1976, 1978, 1980, 1982, 1984, 1986, for FABM and COMP from 1970 to 1978, and for IRON, NFM, MOTV and AIRC throughout; in Finland for all industries in 1970, 1972, 1974, 1976, 1978, 1980, 1982, 1984, 1986, 1988, for CHEM, DRUG, ELMA, RTVC, SHIP and OTRA from 1985 to 1989, for COMP from 1970 to 1978 and from 1985 to 1989, for AIRC in 1971 and from 1985 to 1989, and for MOTV throughout; in France for ELMA and RTVC from 1970 to 1973; in West Germany for all industries in 1970, 1972, 1974, 1976, 1978, 1980, 1982, 1984, 1986, 1988, for OTRA in 1973, and for DRUG, COMP, ELMA and RTVC throughout; in Italy for AIRC from 1970 to 1974 and from 1976 to 1977, and for FABM, COMP, SHIP, MOTV and OTRA from 1970 to 1977; in Japan for SHIP and AIRC from 1970 to 1978, and for COMP throughout; in the Netherlands for DRUG from 1970 to 1972 and for FOOD, CHEM, IRON, NFM, FABM, MACH, COMP, ELMA, RTVC, SHIP, MOTV, AIRC, OTRA and PROF throughout; in Norway for all industries in 1973, 1976, 1978, 1980, 1986, 1988, for DRUG and OTRA from 1970 to 1971, for NFM from 1973 to 1976, for ELMA, RTVC and SHIP from 1970 to 1971 and from 1973 to 1976, for MOTV from 1970 to 1978, and for AIRC from 1970 to 1988; in Sweden for all industries in 1970, 1972, 1974, 1976, 1978, 1980, 1982, 1984, 1986, 1988, for FABM in 1971, for COMP, ELMA and MOTV from 1970 to 1982, and for AIRC from 1970 to 1982 and from 1984 to 1989; in the UK for all industries in 1970, 1971, 1973, 1974, 1976, 1977, 1979, 1980, 1982, 1984, and for OTRA from 1973 to 1989; in the US for CHEM, DRUG and MACH from 1981 to 1985, for FOOD from 1981 to 1986 and from 1988 to 1989, for RAP from 1981 to 1989, for SCG from 1981 to 1985 and from 1988 to 1989, for IRON from 1981 to 1987 and in 1989, for NFM from 1981 to 1983 and in 1987 and 1989, for COMP from 1970 to 1971 and from 1981 to 1989, for ELMA and RTVC from 1981 to 1986, for MOTV from 1970 to 1971 and from 1986 to 1989, for OTRA from 1970 to 1971 and from 1981 to 1989, and for SHIP throughout.

Data on Total R&D Personnel by Industry are from group 29 of the *OECD Science and Technology Statistics*. Data for the following cases are missing in the data source (partly because some of the industries have not existed in some of the countries for all or part of the time): in Australia for all industries from 1969 to 1975, in 1977, 1979, 1980, 1982, 1983, 1985, 1987, 1989, for RAP, ELMA, RTVC and OTRA in 1978, for IRON in 1978, 1984, 1986, for NFM in 1984, 1986, for SHIP and AIRC from 1976 to 1984, and for COMP throughout; in Belgium for all industries in 1970, 1972, 1974, 1976, 1978, 1980, 1982, 1984, 1988, 1989, for OTRA in 1971, and for COMP from 1969 to 1980; in Canada for all industries in 1970, 1989, for COMP, ELMA and RTVC in 1969, 1971, and for SHIP, MOTV and OTRA throughout; in Denmark for all industries in 1969, 1971, 1972, 1974, 1976, 1978, 1980, 1982, 1984, 1986, 1988, and for IRON, NFM, FABM, SHIP, MOTV, AIRC throughout; in Finland for all industries in 1970, 1972, 1974, 1976, 1978, 1980, 1982, 1984, 1986, 1988, for CHEM, DRUG, ELMA, RTVC, SHIP and OTRA from 1985 to 1989, for AIRC in 1969, 1971 and from 1985 to 1989, for COMP from 1969 to 1977 and 1985 to 1987, and for MOTV throughout; in France for all industries in 1969 and 1984, for SCG in 1976, 1978, for IRON from 1970 to 1974 and in 1976, 1978, 1980, for NFM from 1970 to 1974 and in 1976, 1978, for FABM, ELMA, RTVC from 1970 to 1974, for SHIP in 1976, 1978, 1980, for OTRA from 1970 to 1973 and in 1976, 1978, and for PROF from 1970 to 1979; in West Germany for all industries in 1970, 1972, 1974, 1976, 1978, 1980, 1982, 1984, 1986, 1988, for DRUG, COMP, ELMA and RTVC from 1969 to 1987; in Italy for all industries in 1970, 1972, 1974, 1978, for AIRC from 1969 to 1973 and in 1977, for SHIP and MOTV from 1969 to 1977, for FABM and OTRA from 1969 to 1981; in Japan for all industries in 1982, for COMP from 1986 to 1989, for SHIP and AIRC from 1969 to 1978; in the Netherlands for DRUG from 1969 to 1986, and for CHEM, IRON, NFM, FABM, MACH, COMP, ELMA, RTVC, SHIP, MOTV, AIRC, OTRA and PROF throughout; in Norway for all industries in 1973, 1976, 1978, 1980, 1986, 1988, for PROF and MACH in 1969, for DRUG, SHIP, OTRA from 1969 to 1971, for NFM in 1969, 1974, 1975, for COMP and MOTV from 1969 to 1977, for ELMA and RTVC from 1969 to 1971 and from 1974 to 1975, and for AIRC from 1969 to 1987; in Sweden for all industries in 1970, 1972, 1974, 1976, 1978, 1980, 1982, 1984, 1986, 1988, for NFM in 1969, 1971, for COMP, ELMA, RTVC and MOTV from 1969 to 1981, and for AIRC throughout; in the UK for all industries in 1970, 1971, 1973, 1974, 1976, 1977, 1979, 1980, 1982, 1983, 1984, 1986, 1987, 1988, and for OTRA throughout; in the US for all industries in all years. The total R&D personnel for each country's total manufacturing sector is used as a scale variable. This is done because the manufacturing sector is largely identical with the tradeable sector, the sector for which the question of international specialization is relevant.

Data on R&D Scientists and Engineers by Industry are from group 26 of the *OECD Science and Technology Statistics* (1992b). Data for the following cases[154] are missing in the data source (partly because some of the industries have not existed in some of the countries for all or part of the time): in Australia for all industries from 1969 to 1975 and in 1977, 1979, 1980, 1982, 1983, 1985, 1987, 1989, for RAP, ELMA, RTVC and MOTV in 1978, for IRON in 1978, 1984, 1986, for NFM in 1984, 1986, for SHIP and AIRC from 1976 to 1984, for OTRA in 1978 and 1984, and for COMP throughout; in Belgium for all industries in 1970, 1972, 1974, 1976 and from 1978 to 1989, for OTRA in 1971, and for COMP throughout; in Canada for all industries in 1970, 1989, for

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[154] Missing cases refer to the ratios of R&D scientists and engineers to total R&D personnel, as used in this study.

COMP, ELMA, RTVC from 1969 to 1971, and for SHIP, MOTV and OTRA throughout; in Denmark for all industries in 1969, 1971, 1972, 1974, 1976, 1978, 1980, 1982, 1984, 1986, 1988, for IRON, NFM, FABM, MOTV and AIRC throughout; in Finland for all industries in 1970, 1972, 1974, 1976, 1978 and from 1980 to 1989, for COMP from 1969 to 1977, for AIRC from 1969 to 1971, and for MOTV throughout; in France for all industries in 1970 and 1984, for CHEM, DRUG, MACH, COMP, MOTV from 1969 to 1973, for RAP, FABM, ELMA and RTV from 1969 to 1974, for SCG, NFM and OTRA from 1969 to 1974 and in-1976, 1978, for IRON and SHIP from 1969 to 1974 and in 1976, 1978, 1980, and for PROF from 1969 to 1979; in West Germany for all industries in 1970, 1972, 1974, 1976, 1978, 1980, 1982, 1984, 1986, 1988, for DRUG, COMP, ELMA, RTVC from 1969 to 1987, in Italy for all industries in 1970, 1972, 1974, 1978, for IRON in 1984, 1986, for FABM and OTRA from 1969 to 1981, for COMP, SHIP and MOTV from 1969 to 1977, for AIRC from 1969 to 1973 and in 1977; in Japan for all industries in 1982, for COMP from 1981 to 1989, for SHIP and AIRC from 1969 to 1977; in the Netherlands for all industries from 1969 to 1978 and in 1980, 1982, 1984, 1986, 1988, for DRUG from 1969 to 1985, and for CHEM, IRON, NFM, FABM, MACH, COMP, ELMA, RTVC, SHIP, MOTV, AIRC, OTRA and PROF throughout; in Norway for all industries in 1973, 1976, 1978 and from 1980 to 1989, for DRUG, SHIP and OTRA from 1969 to 1971, for NFM in 1969, 1974, 1975, for MACH in 1969, for COMP and MOTV from 1969 to 1977, for ELMA and RTVC from 1969 to 1971 and from 1974 to 1975, for PROF in 1969, 1971, and for AIRC throughout; in Sweden for all industries in 1970, 1972, 1974, 1976, 1978, 1980, 1982 and from 1984 to 1989, for NFM in 1969, 1971, for COMP, ELMA, RTVC and MOTV from 1969 to 1981, for AIRC throughout; in the UK for all industries in 1970, 1971, 1973, 1974, 1976, 1977, 1979, 1980, 1982, 1983, 1984, 1986, 1987, 1988, for SCG in 1969, for SHIP in 1985, 1989, for OTRA throughout; in the US for all industries in all years.

The source for *Countries' Endowments with R&D Scientists and Engineers* (all fields of science) is group 15 of the *OECD Science and Technology Statistics* (1992b). Missing data have been filled in from linear trend regressions in the case of Canada (1970, 1972–1976), the Netherlands (1970, 1972, 1974, 1976, 1978, 1980, 1982, 1984, 1986, 1988), Norway (1971, 1973, 1976, 1986, 1988) and Sweden (1970, 1972, 1976, 1978, 1980, 1982, 1984, 1986, 1988), by interpolation in the case of Australia (1970–1972, 1974, 1975, 1977, 1980, 1982, 1983, 1989), West Germany (1976, 1978, 1980, 1982, 1984, 1986, 1988) and France (1978, 1980). For Belgium (1970–1979) and Finland (1970, 1972–1982, 1984–1989), data on university graduates of science and engineering studies employed in R&D have been used, filling in missing data with fitted values from a linear trend regression.[155] In the case of the United Kingdom (1970–1984, 1989), a trend has been extracted from figures on R&D scientists and engineers employed by industry as well as by governments, published by the National Science Board (1991: 301) of the United States in its annual *Science and Engineering Indicators*.[156]

Data on University Graduates in R&D by Industry are from group 30 of the *OECD Science and Technology Statistics* (1992b). Data for the following cases[157] are missing in the data source (partly because some of the industries have not existed in some of the countries for all or part of the time): in Australia for all industries in all years; in Belgium for all industries in 1970, 1972, 1974, 1976, 1978, 1980, 1982, 1984, 1988, 1989, for OTRA in 1971, and for COMP from 1969 to 1979 and in 1983; in Canada for all industries in all years; in Denmark for all industries in 1969, 1971, 1972, 1974, 1976, 1978 and from 1980 to 1989, for IRON, NFM, FABM, MOTV and AIRC throughout; in Finland for all industries from 1969 to 1978 and in 1980, 1982, 1984, 1986, 1988, for CHEM, DRUG, ELMA, RTVC, SHIP, AIRC, OTRA from 1985 to 1989, for COMP from 1985 to 1987, and for NFM and MOTV throughout; in France for all industries in all years, except for NFM, in which case biannual data from 1979 to 1989 are available; in West Germany for all industries from 1969 to 1978 and in 1980, 1982, 1984, 1986, 1988, for DRUG, COMP, ELMA and RTVC from 1979 to 1987; in Italy for all industries from 1969 to 1978, for FABM and OTRA from 1969 to 1981, and for NFM throughout; in Japan for all industries in all years; in the Netherlands for RAP and SCG from 1970 to 1972, for CHEM, IRON, NFM, FABM, MACH, COMP, ELMA, RTVC, SHIP, MOTV, AIRC, OTRA and PROF throughout; in Norway for all industries in 1973, 1976, 1978, 1980, 1986, 1988, for DRUG, SHIP and OTRA from 1969 to 1971, for NFM from 1969 to 1975, for MACH in 1969, for COMP and MOTV from 1969 to 1977, for ELMA and RTVC from 1969 to 1971 and from 1974 to 1975, for AIRC from 1969 to 1987; in Sweden for all industries in 1970, 1972, 1974, 1976, 1978, 1980, 1982, 1984, 1986, 1988, for NFM from 1969 to 1979 and from 1983 to 1989, for COMP, ELMA, RTVC and MOTV from 1969 to 1981, and for AIRC throughout; in the UK for all industries from 1969 to 1980

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[155] For Finland, the regression with logarithmic data (from seven observations) has yielded a slope coefficient of 278.28 (50.80), a constant of –543,851 (878.98) and an R^2 of 0.86 (standard errors in parentheses).

[156] The estimated trend regression with logarithmic data (from eleven observations) has a slope coefficient of 2365,138 (192.75), a constant of –4,594,550 (4,620.77) and an R^2 of 0.94 (standard errors in parentheses).

[157] Missing cases refer to the ratios of university graduates to total R&D personnel.

and from 1982 to 1989, for NFM and OTRA throughout; in the US for all industries in all years.

Data on countries' labour forces, nominal gross domestic products (GDP), purchasing power parities and GDP price indices are from the economic indicator series — group 94 — of the *OECD Science and Technology Statistics* (1992b).

II. Sources and Methods for Chapter E

Data on sectoral value added for the industry specialization indicator has been taken from the 1992 version of the *OECD STAN Database for Industrial Analysis*, an estimated database, not composed of OECD member countries' official data, but geared towards compatibility with national accounts and towards international comparability. This database covers the twelve countries Australia, Canada, Finland, France, West Germany, Italy, Japan, the Netherlands, Norway, Sweden, the United Kingdom and the United States for the years 1970–1988 (U.S. Patent and Trademark Office 1991). For these countries, data on patents granted by the US patent office, by date of application, is available from the Office of Technology Assessment and Forecasting at the US Department of Commerce, for the years 1972–1989. The data used are reclassified according to the US Standard Industrial Classification (SIC) according to a concordance between the US Patent Classification System (USPCS) and 55 product fields based on the SIC. The data are so-called fractional counts, which eliminate multiple counting by dividing each patent count by the number of product fields to which it is assigned and adding the resulting fraction to each assigned product field.

Time series on countries' relative factor endowments have been obtained from various sources: Capital stocks are computed, for the beginning of each period, on the basis of annual investment data in Summers and Heston (1991), using the perpetual inventory method, assuming a rate of depreciation of 13.3 per cent as would be implied by an average asset life of 15 years. R&D capital stocks are taken from Coe and Helpman (1993), who have used R&D expenditure data from the *OECD's Main Science and Technology Indicators*. Their computations are again based on a perpetual inventory model, with the assumption of a 5 per cent rate of depreciation or obsolescence. For further details see the appendix in Coe and Helpman (1993). Data on the size of labour forces and on national employment of research scientists and engineers (in the business enterprise sector) are taken from the *OECD Science and Technology*

Statistics (1992b). Missing figures for research scientists and engineers have been filled in from linear trend regressions in the case of Canada, the Netherlands, Norway and Sweden, by interpolation in the case of Australia, Germany and France. For Finland, a trend regression on university graduates of science and engineering studies in the business enterprise sector has been used. In the case of the United Kingdom, a trend has been extracted from figures on scientists and engineers employed by industry as well as by government, published by the National Science Board (1991: 301) in its annual *Science and Engineering Indicators*. Figures on years of schooling in the labour force are based on linear trend regressions for the five-yearly data on average years of schooling attained by adults over 25 years of age, which have recently been compiled by Barro and Lee (1993).

To normalize relative factor endowments, the different shares of each country in the total factor endowments of all twelve countries have been divided by the country's share in the sum of all countries' gross domestic product (GDP). A logarithmic transformation has then been made to assure symmetry of the factor endowment indicators. GDP figures are from the chain index series of per capita GDP in constant dollars at 1985 international prices in Summers and Heston (1991). Purchasing power parities are from the *OECD Science and Technology Statistics* (1992b).

The table below lists the seventeen industries included in the study and indicates how patent data, based on the concordance between the US patent classes and product fields of the US standard industrial classification, have been assigned to the International Standard Industrial Classification of the United Nations (ISIC), on which the OECD STAN data on industries' value added is based. An adjustment to the source data has been made when patent count data for a small country was zero in a particular industry for one or several consecutive years. In these cases, the sum of patented applications recorded for the preceding and subsequent year has been evenly distributed across the years. The purpose of this is to avoid realizations at minus infinity in the logarithmic transformation of the technology specialization indicator.

Missing values for the Netherlands' value added in NFM in 1988 and for Italy's value added in the DRUG, COMP, SHIP and AIRC industries in 1988 have been added from extrapolations by the author. In a number of cases, time series of individual industries' value added are not reported at all in the 1992 OECD STAN database. These cases are therefore omitted from the analysis: MACH, COMP, ELMA and RTVC in France, AIRC in the Netherlands, OTRA in the United Kingdom and PROF in Canada.

Industries Included in the Analysis of Chapter E

ISIC-Code	Industry	US-SIC	OTAF sequence number	Abbreviation
31	Food, beverages, tobacco	20	*1*	FOOD
351 & 352 (excl. 3522)	Chemicals, excl. drugs	281, 282, 284, 285, 286, 287, 289	*4*	CHEM
3522	Drugs and medicines	283	*14*	DRUG
355 & 356	Rubber and plastics	30	*16*	RAP
36	Non-metallic mineral products (stone, clay, glass)	32	*17*	SCG
371	Iron and steel (ferrous metals)	331, 332, 3398	*19*	IRON
372	Non-ferrous metals	333, 334, 335, 336, 3399	*20*	NFM
381	Fabricated metal products	341, 342, 343, 344, 345, 3466, 3469, 347, 3493–9	*21*	FABM
382 (excl. 3825)	Machinery, not elsewhere classified, excl. office and computing machinery	348–3492, 351–356, 358–3594, 3599, 3631–33	*22 minus 27*	MACH
3825	Office and computing machinery	3571, 3572, 3575, 3577–3579	*27*	COMP
383 (excl. 3832)	Electrical Machinery, excl. RTVC	3612–3, 362, 364, 369	*34*	ELMA
3832	Radio, TV and communication equip.	3651–2, 3661, 3663, 3669, 3671–2, 3674–9, 3844–5	*41*	RTVC
3841	Shipbuilding and repair	373	*49*	SHIP
3843	Motor vehicles	371	*46*	MOTV
3845	Aircraft	372, 376	*47, 54*	AIRC
3842, 3844, 3849	Other transport equipment	74–5, 379	*48 minus 49*	OTRA
385	Professional goods (scientific instruments)	38, except 384	*55*	PROF

III. Figures and Tables

Table A1 —Average R&D Intensities of Industries in Various Countries in the 1970s and the 1980s[a]

	Australia	Belgium	Canada	Denmark	Finland	France	West Germany	Italy	Japan	Netherlands	Norway	Sweden	United Kingdom	United States	All countries
Panel a: average R&D intensities for the 1970s															
Food, beverages, tobacco	0.50	0.54	0.57	0.75	0.72	0.38	0.22	0.10	1.05	...	0.90	1.87	0.93	0.81	0.68
Chemicals, excl. drugs and medicines	2.31	10.40	2.80	4.65	2.83	5.57	13.21	2.47	6.86	...	4.65	4.36	9.90	6.85	6.78
Drugs and medicines	3.34	18.40	7.44	22.11	14.39	16.97	...	9.79	8.74	24.55	18.76	27.94	14.42	11.06	11.00
Rubber and plastics	0.85	1.42	0.87	1.25	2.73	4.12	1.30	2.18	1.61	1.20	1.69	1.38	1.59	4.16	2.91
Non-metallic mineral products	0.62	2.82	0.40	1.24	1.00	1.52	0.62	0.08	1.98	0.43	0.79	2.12	1.52	1.88	1.40
Iron and steel	1.42	2.81	0.83	...	1.82	0.74	0.88	0.31	1.89	...	2.27	5.81	2.25	1.05	1.24
Non-ferrous metals	0.50	3.59	3.73	...	6.84	3.41	2.86	1.85	2.41	...	2.36	4.26	2.60	2.35	2.52
Fabricated metal products	0.62	1.94	0.44	0.55	0.81	0.65	0.40	0.21	0.90	...	1.70	1.58	0.72	1.00	0.87
Machinery, not elsewhere classified	0.85	...	1.19	...	2.88	1.62	5.22	0.60	2.89	...	4.81	6.31	2.35	3.73	3.12
Office and computing machinery	2.06	...	10.82	...	28.36	11.12	...	11.93	...	...	16.96	...	21.06	39.40	27.12
Electrical machinery, excl. radio, TV and communication equip.	2.25	...	2.81	2.30	6.20	4.05	...	0.76	7.23	...	6.80	...	6.20	15.83	9.86
Radio, TV and communication equip.	10.70	...	15.66	11.26	10.65	21.11	...	12.10	10.12	...	18.30	1.36	17.35	19.79	16.44
Shipbuilding and repair	0.11	...	...	3.32	0.62	0.54	2.14	0.87	10.58	...	1.74	2.59	2.84	...	1.92
Motor vehicles	1.73	...	...	...	...	6.17	6.70	5.85	6.28	...	1.74	...	5.18	11.16	8.08
Aircraft	0.12	...	18.04	...	1.47	44.68	95.53	6.36	0.84	...	...	...	41.69	44.01	46.17
Other transport equipment	0.51	...	...	0.94	1.73	1.12	1.61	1.26	27.42	...	3.26	...	0.01	6.31	11.15
Professional goods (scientific instruments)	4.06	7.55	...	11.42	9.13	4.16	2.29	3.46	6.02	...	6.21	8.57	4.00	11.97	8.68
Total manufacturing	1.16	3.08	1.81	2.17	1.86	3.61	3.74	1.36	3.25	4.25	2.36	4.50	4.49	6.42	4.55

Table A1 continued

	Australia	Belgium	Canada	Denmark	Finland	France	West Germany	Italy	Japan	Netherlands	Norway	Sweden	United Kingdom	United States	All countries
	Panel b: average R&D intensities for the 1980s														
Food, beverages, tobacco	0.55	0.68	0.67	1.19	1.44	0.60	0.55	0.18	1.60	...	0.36	1.78	0.77	1.18	0.92
Chemicals, excl. drugs and medicines	2.29	10.83	3.06	3.93	3.48	7.84	13.81	3.67	9.23	...	4.61	9.46	14.46	8.11	8.64
Drugs and medicines	6.27	23.10	7.82	21.89	18.68	23.51	17.81	14.46	12.07	27.07	19.66	33.52	20.53	14.64	15.01
Rubber and plastics	0.54	3.15	0.86	1.49	4.10	4.51	2.89	1.83	3.29	1.54	1.71	2.70	1.57	4.43	2.98
Non-metallic mineral products	0.64	2.90	0.55	1.81	2.21	1.49	1.67	0.13	4.14	0.51	0.82	1.84	1.14	3.12	2.06
Iron and steel	1.82	3.28	0.79	...	2.17	2.06	1.49	1.05	3.44	...	2.80	8.09	1.93	1.17	2.49
Non-ferrous metals	0.79	3.46	3.43	...	9.32	3.00	1.64	1.21	6.07	...	3.18	3.01	3.07	3.01	3.59
Fabricated metal products	0.51	2.46	0.64	1.05	1.24	0.78	1.73	0.59	1.46	...	1.31	1.67	1.17	1.23	1.18
Machinery, not elsewhere classified	1.91	...	1.63	3.18	5.49	2.59	9.03	1.12	4.56	...	4.60	7.85	3.51	3.81	4.00
Office and computing machinery	13.99	...	22.58	24.81	9.59	11.57	11.06	19.41	...	...	27.54	32.90	30.39	29.74	18.50
Electrical machinery, excl. radio, TV and communication equip.	2.85	...	3.15	5.12	7.02	3.81	9.23	2.92	10.03	...	5.97	14.07	8.96	6.00	7.08
Radio, TV and communication equip.	13.33	...	28.08	13.17	19.63	27.55	18.21	19.20	15.73	...	24.06	1.00	33.44	26.03	20.31
Shipbuilding and repair	0.45	...	...	3.13	1.74	1.33	2.53	3.01	14.78	...	1.18	5.22	0.46		8.08
Motor vehicles	3.94	...	...	...	...	9.15	8.68	6.49	9.40	...	2.99	20.44	8.44	15.63	10.49
Aircraft	1.16	...	21.48	...	1.43	36.30	55.25	27.11	0.77	...	1.24	24.65	32.71	51.29	46.00
Other transport equipment	1.24	...	...	2.36	3.79	3.49	4.68	1.90	4.85	...	1.71	61.73	...	6.62	4.89
Professional goods (scientific instruments)	4.38	5.80	...	14.55	15.95	4.92	3.35	0.80	12.51	...	23.47	10.02	3.81	18.20	12.95
Total manufacturing	1.53	4.65	3.00	3.37	3.34	5.26	5.80	2.18	5.50	5.74	3.01	7.76	6.43	9.03	6.52

[a] Current R&D spending as a percentage of value added.

Source: For details on definitions of industries and on data sources for this table and the following ones in Chapter D see Appendix I.

Table A2 —Rankings of Average R&D Intensities across Countries in the 1970s and the 1980s[a]

	Australia	Belgium	Canada	Denmark	Finland	France	West Germany	Italy	Japan	Netherlands	Norway	Sweden	United Kingdom	United States
Food, beverages, tobacco	10(11)	9 (7)	8 (8)	6 (4)	7 (3)	11 (9)	12(10)	13(13)	2 (2)		4(12)	1 (1)	3 (6)	5 (5)
Chemicals, excl. drugs and medicines	13(13)	2 (3)	11(12)	8 (9)	10(11)	6 (7)	1 (2)	12(10)	4 (5)		7 (8)	9 (4)	3 (1)	5 (6)
Drugs and medicines	13(14)	5 (4)	12(13)	3 (5)	8 (8)	6 (3)	(9)	10(11)	11(12)	2 (2)	4 (7)	1 (1)	7 (6)	9(10)
Rubber and plastics	14(14)	8 (5)	13(13)	11(12)	3 (3)	2 (1)	10 (6)	4 (8)	6 (4)	12(11)	5 (9)	9 (7)	7(10)	1 (2)
Non-metallic mineral products	10(11)	1 (3)	13(12)	7 (6)	8 (4)	5 (8)	11 (7)	14(14)	3 (1)	12(13)	9(10)	2 (5)	6 (9)	4 (2)
Iron and steel	7 (8)	2 (3)	10(12)		6 (5)	11 (6)	9 (9)	12(11)	5 (2)		3 (4)	1 (1)	4 (7)	8(10)
Non-ferrous metals	12(12)	4 (3)	3 (4)		1 (1)	5 (9)	6(10)	11(11)	8 (2)		9 (5)	2 (8)	7 (6)	10 (7)
Fabricated metal products	9(13)	1 (1)	11(11)	10 (9)	6 (6)	8(10)	12 (2)	13(12)	5 (4)		2 (5)	3 (3)	7 (8)	4 (7)
Machinery, not elsewhere classified	10(10)		9(11)	(8)	6 (3)	8 (9)	2 (1)	11(12)	5 (5)		3 (4)	1 (2)	7 (7)	4 (6)
Office and computing machinery	8 (8)		7 (6)	(5)	2(11)	6 (9)	(10)	5 (7)			4 (4)	(1)	3 (2)	1 (3)
Electrical machinery, excl. radio, TV and communication equip.	9(12)		7(10)	8 (8)	4 (5)	6 (9)	(3)	10(11)	2 (2)		3 (7)	(1)	5 (4)	1 (6)
Radio, TV and communication equip.	8(10)		5 (2)	7(11)	9 (6)	1 (3)	(8)	6 (7)	10 (9)		3 (5)	11(12)	4 (1)	2 (4)
Shipbuilding and repair	10(10)			2 (3)	8 (6)	9 (7)	5 (5)	7 (4)	1 (1)		6 (8)	4 (2)	3 (9)	
Motor vehicles	8 (8)					4 (4)	2 (5)	5 (7)	3 (3)		7 (9)	(1)	6 (6)	1 (2)
Aircraft	9(10)		5 (7)		7 (8)	2 (3)	1 (1)	6 (5)	8(11)		(9)	(6)	4 (4)	3 (2)
Other transport equipment	9(10)			8 (7)	4 (5)	7 (6)	5 (4)	6 (8)	1 (3)		3 (9)	(1)	10	2 (2)
Professional goods (scientific instruments)	9 (9)	5 (7)		2 (4)	3 (3)	8 (8)	12(11)	11(12)	7 (5)		6 (1)	4 (6)	10(10)	1 (2)
Total manufacturing	14(14)	8 (8)	12(12)	10 (9)	11(10)	6 (7)	5 (4)	13(13)	7 (6)	4 (5)	9(11)	2 (2)	3 (3)	1 (1)

[a] The rankings for the 1980s are given in parentheses.

Table A3 —Rankings of Average R&D Intensities across Industries in the 1970s and the 1980s[a]

	Australia	Belgium	Canada	Denmark	Finland	France	West Germany	Italy	Japan	Netherlands	Norway	Sweden	United Kingdom	United States	All countries
Food, beverages, tobacco	15 (14)	9 (9)	11 (11)	10 (12)	15 (14)	17 (17)	13 (17)	16 (16)	14 (14)		15 (17)	9 (15)	15 (15)	16 (15)	17 (17)
Chemicals, excl. drugs and medicines	4 (7)	2 (2)	7 (7)	4 (6)	8 (10)	6 (6)	2 (4)	7 (6)	6 (7)		7 (6)	5 (8)	5 (5)	8 (7)	9 (7)
Drugs and medicines	3 (3)	1 (1)	4 (4)	1 (2)	2 (2)	3 (3)	(3)	3 (4)	4 (4)	1 (1)	1 (4)	1 (2)	4 (4)	7 (6)	5 (4)
Rubber and plastics	9 (15)	8 (6)	9 (9)	7 (11)	9 (8)	8 (8)	9 (11)	8 (10)	13 (13)	2 (2)	14 (11)	11 (13)	13 (12)	10 (10)	11 (13)
Non-metallic mineral products	12 (13)	5 (7)	13 (13)	8 (10)	13 (11)	12 (14)	11 (14)	17 (17)	11 (11)	3 (3)	16 (16)	8 (14)	14 (14)	13 (12)	14 (15)
Iron and steel	8 (9)	6 (5)	10 (10)		10 (12)	14 (13)	10 (16)	14 (13)	12 (12)		10 (10)	4 (9)	12 (11)	14 (16)	15 (14)
Non-ferrous metals	14 (12)	4 (4)	5 (5)		5 (5)	10 (11)	5 (15)	9 (11)	10 (8)		9 (8)	6 (12)	10 (10)	12 (13)	12 (12)
Fabricated metal products	11 (16)	7 (8)	12 (12)	11 (13)	14 (16)	15 (16)	12 (13)	15 (15)	15 (15)		13 (13)	10 (16)	16 (13)	15 (14)	16 (16)
Machinery, not elsewhere classified	10 (8)		8 (8)	(7)	7 (7)	11 (12)	4 (7)	13 (12)	9 (10)		6 (7)	3 (10)	11 (9)	11 (11)	10 (11)
Office and computing machinery	6 (1)		3 (2)	(1)	1 (4)	4 (4)	(5)	2 (2)			3 (1)	(3)	2 (3)	2 (2)	2 (3)
Electrical machinery, excl. radio, TV and communication equip.	5 (6)		6 (6)	6 (5)	6 (6)	9 (9)	(6)	12 (8)	5 (5)		4 (5)	(6)	6 (6)	4 (9)	(9)
Radio, TV and communication equip.	1 (2)		2 (1)	3 (4)	3 (1)	2 (2)	(2)	1 (3)	3 (1)		2 (2)	12 (17)	3 (1)	3 (3)	3 (2)
Shipbuilding and repair	17 (17)			5 (8)	16 (13)	16 (15)	7 (12)	11 (7)	2 (2)		12 (15)	7 (11)	9 (16)		13 (8)
Motor vehicles	7 (5)					5 (5)	3 (8)	5 (5)	7 (6)		11 (9)	(5)	7 (7)	6 (5)	8 (6)
Aircraft	16 (11)		1 (3)		12 (15)	1 (1)	1 (1)	4 (1)	16 (16)		(14)	(4)	1 (2)	1 (1)	1 (1)
Other transport equipment	13 (10)			9 (9)	11 (9)	13 (10)	8 (9)	10 (9)	1 (9)		8 (12)	(1)	17	9 (8)	4 (10)
Professional goods (scientific instruments)	2 (4)	3 (3)		2 (3)	4 (3)	7 (7)	6 (10)	6 (14)	8 (3)		5 (3)	2 (7)	8 (8)	5 (4)	7 (5)

[a] The rankings for the 1980s are given in parentheses.

Table A4 —Average Ratios of R&D Scientists and Engineers to Other R&D Personnel in the 1970s and the 1980s

	Australia	Belgium	Canada	Denmark	Finland	France	West Germany	Italy	Japan	Netherlands	Norway	Sweden	United Kingdom	All countries
Panel a: average ratios for the 1970s														
Food, beverages, tobacco	1.19	0.25	0.73	0.44	0.86	0.37	0.38	1.40	0.99	0.37	0.58	0.76	0.42	0.77
Chemicals, excl. drugs and medicines	1.19	0.17	0.87	0.47	0.47	0.27	0.24	0.87	0.84	...	0.40	0.87	0.53	0.57
Drugs and medicines	0.81	0.25	1.26	0.52	0.93	0.37	...	0.63	0.89	...	0.91	1.07	0.52	0.72
Rubber and plastics	1.01	0.21	0.97	0.18	0.64	0.13	0.41	0.27	0.89	0.29	0.33	1.10	0.50	0.56
Non-metallic mineral products	0.94	0.22	0.69	0.37	1.21	0.28	0.47	0.66	0.67	0.57	0.57	0.97	0.67	0.61
Iron and steel	0.63	0.24	0.81	...	0.98	0.31	0.36	0.77	0.57	...	0.50	0.45	0.74	0.54
Non-ferrous metals	0.86	0.24	0.58	...	0.27	0.23	0.37	0.65	0.83	...	0.52	0.98	0.62	0.65
Fabricated metal products	0.60	0.18	0.88	...	0.97	0.38	0.45	...	1.01	...	0.42	0.76	0.59	0.79
Machinery, not elsewhere classified	0.63	0.13	0.75	0.16	0.82	0.23	0.57	0.76	1.13	...	0.54	0.65	0.42	0.76
Office and computing machinery	...	...	0.91	...	3.39	0.88	...	0.79	0.92	...	1.32	...	0.62	0.83
Electrical machinery, excl. radio, TV and communication equipment	0.67	0.22	0.38	0.22	0.63	0.29	...	0.73	1.18	...	0.51	...	0.57	0.93
Radio, TV and communication equip.	0.91	0.15	0.91	0.20	0.89	0.46	...	0.72	1.07	...	0.50	...	0.62	0.82
Shipbuilding and repair	...	0.56	...	...	2.92	0.64	0.95	0.85	1.16	...	0.89	0.61	0.71	0.81
Motor vehicles	0.21	0.09	...	...	...	0.18	0.28	0.14	0.38	...	0.52	...	0.36	0.32
Aircraft	...	0.24	0.71	...	0.89	0.31	0.68	0.81	2.78	...	...	...	0.40	0.38
Other transport equipment	1.00	0.24	...	0.10	0.65	0.30	0.20	...	0.99	...	0.31	0.22	...	0.73
Professional goods (scientific instruments)	0.70	0.28	0.83	0.24	0.73	...	0.45	0.54	1.16	...	0.64	0.71	0.59	0.84
All industries	0.75	0.18	0.73	0.29	0.74	0.32	0.45	0.49	0.87	0.40	0.49	0.49	0.50	0.60

Table A4 continued

	Australia	Belgium	Canada	Denmark	Finland	France	West Germany	Italy	Japan	Netherlands	Norway	Sweden	United Kingdom	All countries
	Panel b: average ratios for the 1980s													
Food, beverages, tobacco	1.33	...	0.84	0.50	...	0.45	0.34	0.92	1.34	0.39	...	0.82	0.64	0.95
Chemicals, excl. drugs and medicines	1.22	...	1.19	0.52	...	0.34	0.28	0.95	1.19	...	...	0.82	0.61	0.75
Drugs and medicines	1.01	...	1.15	0.56	...	0.45	0.37	0.79	1.16	0.36	...	1.46	0.67	0.83
Rubber and plastics	1.05	...	0.82	0.23	...	0.17	0.32	0.61	1.48	0.39	...	0.95	0.89	0.78
Non-metallic mineral products	0.76	...	0.81	0.38	...	0.34	0.34	0.86	0.94	0.88	...	0.67	0.77	0.75
Iron and steel	1.08	...	1.02	...	...	0.38	0.40	...	0.70	...	...	0.47	1.13	0.71
Non-ferrous metals	1.05	...	0.58	...	...	0.33	0.41	1.07	1.02	...	...	0.70	0.82	0.76
Fabricated metal products	0.82	...	0.79	...	...	0.41	0.27	0.41	1.62	...	...	0.51	0.77	0.89
Machinery, not elsewhere classified	0.73	...	0.73	0.32	...	0.49	0.59	0.79	1.70	...	...	0.55	0.68	1.02
Office and computing machinery	...	...	1.51	...	...	1.35	1.55	1.85	1.44	...	...	0.39	1.20	1.44
Electrical machinery, excl. radio, TV and communication equip.	0.86	...	0.72	0.46	...	0.43	1.01	0.85	2.96	...	...	0.71	1.00	1.61
Radio, TV and communication equip.	1.27	...	1.33	0.31	...	0.60	1.11	0.92	1.84	...	...	0.65	1.19	1.29
Shipbuilding and repair	0.97	...	...	...	...	0.61	0.72	0.95	1.46	...	...	0.67	0.91	1.29
Motor vehicles	0.60	...	...	...	...	0.20	0.35	0.27	0.59	...	...	0.27	0.64	0.42
Aircraft	0.86	...	0.70	...	...	0.40	0.71	0.72	1.66	...	...	...	0.69	0.53
Other transport equipment	0.55	...	...	0.16	...	0.34	0.40	0.43	1.82	...	...	0.23	...	0.72
Professional goods (scientific instruments)	1.68	...	0.99	0.46	...	0.58	0.52	1.31	1.69	...	...	0.42	0.82	1.24
All industries	1.00	...	0.96	0.38	...	0.43	0.52	0.74	1.26	0.49	...	0.52	0.83	0.85

Table A5—Rankings of the Average Ratios of R&D Scientists and Engineers to Other R&D Personnel across Countries in the 1970s and the 1980s[a]

	Australia	Belgium	Canada	Denmark	Finland	France	West Germany	Italy	Japan	Netherlands	Norway	Sweden	United Kingdom
Food, beverages, tobacco	2 (2)	13	6 (4)	8 (7)	4	11 (8)	10 (10)	1 (3)	3 (1)	12 (9)	7	5 (5)	9 (6)
Chemicals, excl. drugs and medicines	1 (1)	12	3 (3)	8 (7)	7	10 (8)	11 (9)	4 (4)	5 (2)		9	2 (5)	6 (6)
Drugs and medicines	6 (4)	11	1 (3)	9 (7)	3	10 (8)	(9)	7 (5)	5 (2)	(10)	4	2 (1)	8 (6)
Rubber and plastics	2 (2)	11	3 (5)	12 (9)	5	13 (10)	7 (8)	10 (6)	4 (1)	9 (7)	8	1 (3)	6 (4)
Non-metallic mineral products	3 (6)	13	4 (4)	11 (8)	1	12 (9)	10 (10)	7 (3)	5 (1)	9 (2)	8	2 (7)	6 (5)
Iron and steel	5 (2)	11	2 (3)		1	10 (7)	9 (6)	3	6 (4)		7	8 (5)	4 (1)
Non-ferrous metals	2 (2)	10	6 (6)		9	11 (8)	8 (7)	4 (1)	3 (3)		7	1 (5)	5 (4)
Fabricated metal products	5 (2)	10	3 (3)		2	9 (7)	7 (8)	(6)	1 (1)		8	4 (5)	6 (4)
Machinery, not elsewhere classified	6 (3)	12	4 (4)	11 (9)	2	10 (8)	7 (6)	3 (2)	1 (1)		8	5 (7)	9 (5)
Office and computing machinery			4 (3)		1	5 (5)	(2)	6 (1)	3 (4)		2	(7)	7 (6)
Electrical machinery, excl. radio, TV and communication equip.	3 (4)	10	7 (6)	9 (8)	4	8 (9)	(2)	2 (5)	1 (1)		6	(7)	5 (3)
Radio, TV and communication equip.	2 (3)	10	3 (2)	9 (9)	4	8 (8)	(5)	5 (6)	1 (1)		7	(7)	6 (4)
Shipbuilding and repair	(2)	9			1	7 (7)	3 (5)	5 (3)	2 (1)		4	8 (6)	6 (4)
Motor vehicles	5 (2)	8				6 (7)	4 (4)	7 (5)	2 (3)		1	(6)	3 (1)
Aircraft	(2)	8	4 (5)		2	7 (7)	5 (4)	3 (3)	1 (1)				6 (6)
Other transport equipment	1 (2)	6		9 (7)	3	5 (5)	8 (4)	(3)	2 (1)		4	7 (6)	
Professional goods (scientific instruments)	5 (2)	10	2 (4)	11 (8)	3	(6)	9 (7)	8 (3)	1 (1)		6	4 (9)	7 (5)
All industries	2 (2)	13	4 (3)	12 (10)	3	11 (9)	9 (6)	8 (5)	1 (1)	10 (8)	7	6 (7)	5 (4)

[a] The results for the 1980s are given in parentheses.

Table A6 —Rankings of the Average Ratios of R&D Scientists and Engineers to Other R&D Personnel across Industries in the 1970s and the 1980s[a]

	Australia	Belgium	Canada	Denmark	Finland	France	West Germany	Italy	Japan	Netherlands	Norway	Sweden	United Kingdom	All countries
Food, beverages, tobacco	2 (2)	4	10 (7)	3 (3)	9	5 (7)	8 (13)	1 (7)	8 (11)	2 (3)	5	6 (4)	14 (14)	7 (7)
Chemicals, excl. drugs and medicines	1 (4)	13	6 (3)	2 (2)	15	12 (14)	12 (16)	2 (5)	13 (12)		14	5 (3)	10 (16)	13 (12)
Drugs and medicines	8 (8)	3	1 (4)	1 (1)	6	6 (6)	(11)	12 (10)	12 (13)	(4)	2	2 (1)	11 (13)	10 (9)
Rubber and plastics	3 (6)	11	2 (8)	8 (9)	13	16 (17)	7 (15)	14 (13)	11 (8)	3 (2)	15	1 (2)	12 (6)	14 (10)
Non-metallic mineral products	5 (13)	9	12 (9)	4 (6)	3	11 (12)	4 (14)	10 (8)	15 (15)	1 (1)	6	4 (8)	3 (10)	12 (13)
Iron and steel	12 (5)	7	8 (5)		4	7 (11)	10 (10)	6	16 (16)		11	11 (12)	1 (3)	15 (15)
Non-ferrous metals	7 (7)	5	13 (14)		16	14 (15)	9 (8)	11 (3)	14 (14)		8	3 (6)	6 (8)	11 (11)
Fabricated metal products	13 (12)	12	5 (10)		5	4 (9)	5 (17)	(15)	7 (7)		13	7 (11)	8 (9)	6 (8)
Machinery, not elsewhere classified	11 (14)	15	9 (11)	9 (7)	10	13 (5)	3 (6)	7 (11)	5 (4)		7	9 (10)	13 (12)	8 (6)
Office and computing machinery			3 (1)		1	1 (1)	(1)	5 (1)	10 (10)		1	(14)	5 (1)	3 (2)
Electrical machinery, excl. radio, TV and communication equip.	10 (11)	10	14 (12)	6 (5)	14	10 (8)	(3)	8 (9)	2 (1)		10	(5)	9 (4)	1 (1)
Radio, TV and communication equip.	6 (3)	14	4 (2)	7 (8)	7	3 (3)	(2)	9 (6)	6 (2)		12	(9)	4 (2)	4 (4)
Shipbuilding and repair	(9)	1			2	2 (2)	1 (4)	3 (4)	4 (9)		3	10 (7)	2 (5)	5 (3)
Motor vehicles	14 (15)	16				15 (16)	11 (12)	15 (16)	17 (17)		9	(15)	16 (15)	17 (17)
Aircraft	(10)	6	11 (13)		8	8 (10)	2 (5)	4 (12)	1 (6)				15 (11)	16 (16)
Other transport equipment	4 (16)	8		10 (10)	12	9 (13)	13 (9)	(14)	9 (3)		16	12 (16)		9 (14)
Professional goods (scientific instruments)	9 (1)	2	7 (6)	5 (4)	11	(4)	6 (7)	13 (2)	3 (5)		4	8 (13)	7 (7)	2 (5)

[a] The results for the 1980s are given in parentheses.

Table A7 —Bivariate Correlations between the Independent and Dependent Variables

	R&D-S&E	*RGDP*	*Time*	*R&D-Pers*
		Food, beverages, tobacco		
Value added	–0.42	–0.14	0.06	0.44
R&D-S&E		–0.14	–0.37	–0.04
RGDP			0.40	–0.43
Time				0.00
		Chemicals, excl. drugs		
Value added	–0.30	0.37	0.18	0.84
R&D-S&E		–0.14	–0.35	–0.14
RGDP			0.42	0.29
Time				–0.11
		Drugs and medicines		
Value added	0.01	0.64	0.42	0.55
R&D-S&E		–0.16	–0.33	–0.32
RGDP			0.41	0.04
Time				0.15
		Rubber and plastics		
Value added	0.12	0.61	0.16	0.32
R&D-S&E		–0.14	–0.37	–0.20
RGDP			0.40	0.31
Time				0.10
		Non-metallic mineral products		
Value added	–0.30	0.06	–0.20	–0.04
R&D-S&E		–0.14	–0.37	0.04
RGDP			0.40	–0.19
Time				–0.15
		Iron and steel		
Value added	0.16	0.16	–0.45	0.38
R&D-S&E		–0.20	–0.37	0.10
RGDP			0.41	–0.53
Time				–0.27
		Non-ferrous metals		
Value added	–0.13	–0.16	0.05	0.68
R&D-S&E		–0.20	–0.37	–0.20
RGDP			0.41	–0.41
Time				–0.22

Table A7 continued

	R&D-S&E	*RGDP*	*Time*	*R&D-Pers*
Fabricated metal products				
Value added	0.05	0.06	–0.08	–0.06
R&D-S&E		–0.20	–0.40	–0.09
RGDP			0.43	–0.54
Time				0.02
Machinery, not elsewhere classified				
Value added	0.35	–0.39	–0.03	0.55
R&D-S&E		–0.20	–0.44	0.24
RGDP			0.34	–0.59
Time				0.04
Office and computing machinery				
Value added	0.40	0.54	0.12	0.13
R&D-S&E		0.01	–0.38	–0.34
RGDP			0.05	0.00
Time				0.76
Electrical machinery, excl. radio, TV and communication equip.				
Value added	0.33	0.42	0.01	–0.01
R&D-S&E		–0.13	–0.32	0.16
RGDP			0.40	–0.45
Time				–0.08
Radio, TV and communication equip.				
Value added	0.63	0.42	0.19	0.43
R&D-S&E		–0.13	–0.32	0.27
RGDP			0.40	0.42
Time				0.11
Shipbuilding and repair				
Value added	0.38	–0.87	–0.35	0.80
R&D-S&E		–0.37	–0.49	0.49
RGDP			0.46	–0.69
Time				–0.12
Motor vehicles				
Value added	0.02	0.66	–0.12	0.90
R&D-S&E		–0.16	–0.44	–0.21
RGDP			0.12	0.57
Time				–0.05

Table A7 continued

	R&D-S&E	*RGDP*	*Time*	*R&D-Pers*
		Aircraft		
Value added	–0.13	0.17	0.07	0.80
R&D-S&E		–0.03	–0.34	–0.15
RGDP			0.56	0.02
Time				–0.27
		Other transport equipment		
Value added	–0.51	–0.47	–0.00	0.47
R&D-S&E		–0.14	–0.44	0.17
RGDP			0.41	–0.38
Time				–0.00
		Professional goods (scientific instruments)		
Value added	0.03	0.64	0.22	0.35
R&D-S&E		–0.07	–0.38	–0.21
RGDP			0.42	0.00
Time				0.02

Note: Value added denotes the industry's shares of countries' total manufacturing value added, *R&D-S&E* the countries' endowment with R&D scientists and engineers relative to the labour force, *RGDP* the countries' real GDP at purchasing power parities, *Time* the calendar time in years, and *R&D-Pers*, the dependent, industry's shares of countries' total R&D personnel in manufacturing.

Table A8 —Six-State Markov Chain Estimates for the Industry and Technology Specialization Indicators of Individual Industries

(First-order, time-stationary estimates of the five-year transition probabilities)

Observations	Transition end state (upper boundary)					
	$\mu - sd$	$\mu - sd/3$	μ	$\mu + sd/3$	$\mu + sd$	$> \mu + sd$
			FOOD: industry specialization			
35	0.51	0.31	0.09	0.06		0.03
35	0.23	0.54	0.17		0.03	0.03
17		0.59	0.18	0.18		0.06
40	0.05	0.08	0.07	0.55	0.20	0.05
13	0.23	0.08	0.08	0.23	0.31	0.12
28					0.04	0.96
Station. distr.	0.126	0.193	0.065	0.072	0.059	0.484
Sample distr.	0.208	0.208	0.101	0.238	0.077	0.166
			FOOD: technology specialization			
35	0.43	0.26	0.06	0.11	0.11	0.03
25	0.28	0.28	0.12	0.04	0.20	0.08
19	0.16	0.11	0.32	0.16	0.16	0.11
30	0.13	0.13	0.10	0.33	0.30	
39	0.08	0.08	0.03	0.18	0.39	0.26
21	0.10		0.05	0.05	0.24	0.57
Station. distr.	0.189	0.132	0.083	0.142	0.248	0.206
Sample distr.	0.207	0.148	0.112	0.178	0.231	0.124
			CHEM: industry specialization			
30	0.67	0.17	0.17			
26	0.04	0.58	0.31	0.07		
33		0.27	0.54	0.15	0.03	
14		0.14	0.36	0.28	0.21	
48		0.04	0.06	0.06	0.77	0.06
17					0.05	0.94
Station. distr.	0.027	0.237	0.272	0.099	0.177	0.188
Sample distr.	0.178	0.154	0.196	0.083	0.285	0.101
			CHEM: technology specialization			
32	0.72	0.16	0.06	0.03	0.03	
22	0.27	0.59	0.05	0.09		
10	0.30	0.10	0.40		0.20	
19	0.05	0.16	0.16	0.26	0.37	
68	0.02	0.03	0.02	0.12	0.71	0.12

Table A8 continued

Observations	Transition end state (upper boundary)					
	$\mu - sd$	$\mu - sd/3$	μ	$\mu + sd/3$	$\mu + sd$	$> \mu + sd$
18					0.39	0.61
Station. distr.	0.279	0.177	0.071	0.082	0.301	0.091
Sample distr.	0.189	0.13	0.059	0.112	0.402	0.107
	DRUG: industry specialization					
27	0.63	0.11	0.15	0.07	0.04	
17	0.12	0.53	0.24		0.12	
24	0.04	0.29	0.29	0.08	0.29	
10		0.20	0.40		0.30	0.10
70			0.07	0.07	0.80	0.06
20					0.50	0.50
Station. distr.	0.055	0.123	0.139	0.055	0.554	0.074
Sample distr.	0.161	0.101	0.142	0.059	0.416	0.119
	DRUG: technology specialization					
14	0.14	0.29	0.14	0.29	0.07	0.07
36	0.14	0.53	0.16	0.14		0.03
39	0.03	0.33	0.41	0.18	0.03	0.03
33	0.09	0.16	0.28	0.42	0.06	
38	0.03	0.03	0.05	0.21	0.53	0.16
9		0.11			0.67	0.22
Station. distr.	0.082	0.296	0.22	0.226	0.125	0.051
Sample distr.	0.083	0.213	0.231	0.195	0.225	0.053
	RAP: industry specialization					
18	1.00					
16	0.56	0.19	0.13		0.13	
27	0.19	0.31	0.11	0.07	0.33	
24		0.13	0.13	0.33	0.42	
60		0.08	0.13	0.17	0.53	0.08
23				0.04	0.35	0.61
Station. distr.	1					
Sample distr.	0.107	0.095	0.161	0.143	0.357	0.137
	RAP: technology specialization					
20	0.50	0.25	0.10	0.05	0.05	0.05
21	0.29	0.10	0.29	0.05	0.24	0.05
18	0.06	0.28	0.17	0.28	0.22	
16	0.13	0.13	0.06	0.13	0.50	0.06
84	0.04	0.06	0.11	0.08	0.69	0.02
10	0.20			0.10	0.50	0.20

Table A8 continued

Observations	Transition end state (upper boundary)					
	$\mu - sd$	$\mu - sd/3$	μ	$\mu + sd/3$	$\mu + sd$	$> \mu + sd$
Station. distr.	0.16	0.127	0.127	0.103	0.444	0.039
Sample distr.	0.118	0.124	0.107	0.095	0.497	0.059
			SCG: industry specialization			
23	0.78	0.17	0.04			
40	0.25	0.47	0.12	0.07	0.05	0.03
39	0.03	0.36	0.41	0.15	0.05	
24		0.08	0.29	0.33	0.29	
22			0.09	0.23	0.36	0.32
20					0.20	0.80
Station. distr.	0.207	0.167	0.122	0.098	0.149	0.257
Sample distr.	0.137	0.238	0.232	0.143	0.131	0.119
			SCG: technology specialization			
24	0.25	0.21	0.08	0.13	0.17	0.17
22	0.36	0.05	0.14	0.18	0.27	
25	0.04	0.08	0.24	0.48	0.16	
41	0.49	0.12	0.20	0.39	0.20	0.05
40	0.03	0.20	0.05	0.20	0.43	0.10
17	0.06	0.12	0.06		0.47	0.29
Station. distr.	0.106	0.137	0.128	0.258	0.287	0.084
Sample distr.	0.142	0.13	0.148	0.243	0.237	0.101
			IRON: industry specialization			
28	0.46	0.32	0.14		0.07	
38	0.07	0.39	0.28	0.08	0.16	
30	0.07	0.27	0.30	0.07	0.30	
10	0.20	0.50	0.10		0.20	
38		0.18	0.18	0.13	0.32	0.18
24					0.17	0.83
Station. distr.	0.078	0.233	0.177	0.059	0.215	0.237
Sample distr.	0.167	0.226	0.178	0.059	0.226	0.142
			IRON: technology specialization			
17	0.47	0.18	0.18	0.18		
39	0.03	0.46	0.28	0.05	0.10	0.08
29	0.17	0.31	0.17	0.14	0.14	0.07
28	0.11	0.18	0.39	0.07	0.25	
23	0.12	0.15	0.21	0.15	0.24	0.12
23	0.09	0.04	0.09	0.09	0.26	0.43
Station. distr.	0.101	0.231	0.172	0.166	0.195	0.136
Sample distr.	0.157	0.266	0.224	0.111	0.146	0.095

Table A8 continued

Observations	Transition end state (upper boundary)					
	$\mu - sd$	$\mu - sd/3$	μ	$\mu + sd/3$	$\mu + sd$	$> \mu + sd$
	NFM: industry specialization					
28	0.46	0.32	0.14		0.07	
38	0.07	0.39	0.28	0.08	0.16	
30	0.07	0.27	0.30	0.07	0.30	
10	0.20	0.50	0.10		0.20	
38		0.18	0.18	0.13	0.32	0.18
24					0.17	0.83
Station. distr.	0.078	0.233	0.177	0.059	0.215	0.237
Sample distr.	0.167	0.226	0.178	0.059	0.226	0.142
	NFM: technology specialization					
18	0.67	0.17	0.06	0.06	0.06	
44	0.14	0.50	0.18	0.05	0.14	
19	0.05	0.16	0.53	0.16	0.11	
30	0.03	0.10	0.17	0.47	0.13	0.10
36		0.14	0.14	0.17	0.36	0.19
22	0.05	0.09	0.05	0.18	0.32	0.32
Station. distr.	0.15	0.214	0.218	0.176	0.168	0.074
Sample distr.	0.107	0.26	0.112	0.176	0.213	0.13
	FABM: industry specialization					
32	0.63	0.31	0.06			
33	0.15	0.57	0.24	0.03		
11	0.27	0.18	0.18	0.27	0.09	
15		0.07	0.07	0.34	0.47	0.07
55		0.02		0.07	0.64	0.27
22					0.41	0.59
Station. distr.	0.066	0.094	0.039	0.067	0.434	0.300
Sample distr.	0.191	0.196	0.065	0.089	0.327	0.131
	FABM: technology specialization					
25	0.64	0.20	0.08		0.04	0.04
41	0.17	0.39	0.27	0.15	0.02	
29	0.07	0.14	0.66	0.10		0.03
10			0.30	0.20	0.10	0.40
36	0.03	0.03	0.03	0.03	0.64	0.25
28	0.04	0.04	0.04	0.07	0.21	0.61
Station. distr.	0.141	0.122	0.237	0.08	0.185	0.235
Sample distr.	0.148	0.242	0.172	0.059	0.213	0.166
	COMP: industry specialization					
21	0.48	0.48	0.05			

Table A8 continued

Observations	Transition end state (upper boundary)					
	$\mu - sd$	$\mu - sd/3$	μ	$\mu + sd/3$	$\mu + sd$	$> \mu + sd$
31	0.06	0.65	0.16	0.03	0.1	
13	0.08	0.31		0.23	0.38	
6		0.33	0.17	0.17	0.33	
58		0.09	0.12	0.09	0.55	0.16
25					0.40	0.60
Station. distr.	0.054	0.313	0.105	0.075	0.326	0.127
Sample distr.	0.136	0.201	0.084	0.039	0.377	0.162
	COMP: technology specialization					
19	0.42	0.42			0.16	
25	0.32	0.32	0.24	0.20		
20	0.10	0.25	0.25	0.20	0.20	
14	0.14	0.29	0.21	0.14	0.21	
70	0.06	0.09	0.16	0.09	0.57	0.04
21	0.05				0.29	0.67
Station. distr.	0.223	0.266	0.16	0.097	0.225	0.029
Sample distr.	0.112	0.148	0.118	0.828	0.414	0.124
	MACH: industry specialization					
43	0.84	0.07	0.05	0.05		
8	0.25		0.13	0.38	0.25	
10		0.10		0.80	0.10	
33		0.06	0.09	0.30	0.55	
45			0.02	0.16	0.58	0.24
15					0.20	0.80
Station. distr.	0.016	0.010	0.021	0.115	0.378	0.416
Sample distr.	0.279	0.052	0.065	0.214	0.292	0.097
	MACH: technology specialization					
22	0.55	0.32	0.09	0.45		
55	0.15	0.67	0.15	0.02	0.02	
18	0.11	0.39	0.17	0.17	0.11	0.06
30	0.03	0.10	0.10	0.43		
18				0.06	0.39	0.56
26			0.04	0.04	0.19	0.73
Station. distr.	0.083	0.188	0.07	0.078	0.169	0.412
Sample distr.	0.13	0.325	0.107	0.178	0.107	0.154
	ELMA: industry specialization					
13	0.54	0.46				
15	0.47	0.47		0.07		
23		0.13	0.35	0.30	0.22	

Table A8 continued

Observations	Transition end state (upper boundary)					
	μ − sd	*μ − sd/3*	*μ*	*μ + sd/3*	*μ + sd*	*> μ + sd*
37		0.11	0.22	0.54	0.14	
59		0.03	0.07	0.03	0.69	0.17
7					0.86	0.14
Station. distr.	0.331	0.328	0.048	0.092	0.168	0.033
Sample distr.	0.084	0.097	0.149	0.240	0.383	0.045
	ELMA: technology specialization					
22	0.36	0.23	0.05	0.09	0.18	0.09
14	0.14	0.36	0.29	0.07	0.07	0.07
20		0.35	0.20	0.15	0.30	
30	0.03	0.10	0.03	0.43	0.33	0.07
73	0.03	0.05	0.04	0.10	0.67	0.14
10	0.30	0.00	0.20		0.30	0.20
Station. distr.	0.084	0.17	0.152	0.144	0.437	0.044
Sample distr.	0.13	0.083	0.118	0.178	0.432	0.059
	RTVC: industry specialization					
25	0.84	0.16				
33	0.39	0.48	0.12			
13		0.77	0.15		0.08	
1					1.00	
61				0.11	0.70	0.18
21					0.19	0.81
Station. distr.				0.056	0.485	0.459
Sample distr.	0.162	0.214	0.084	0.006	0.396	0.136
	RTVC: technology specialization					
29	0.62	0.24	0.10	0.03		
25	0.24	0.52	0.20	0.04		
24		0.38	0.38	0.17	0.08	
10	0.40	0.10	0.30	0.00	0.20	
55	0.02		0.04	0.04	0.91	
26						1.00
Station. distr.	0.238	0.262	0.166	0.057	0.277	
Sample distr.	0.172	0.148	0.142	0.059	0.325	0.154
	MOTV: industry specialiation					
36	0.86	0.14				
6	0.50	0.50				
1					1.00	
6				0.50	0.50	
113			0.03	0.12	0.79	0.07
6					0.33	0.66

Table A8 continued

Observations	Transition end state (upper boundary)					
	$\mu - sd$	$\mu - sd/3$	μ	$\mu + sd/3$	$\mu + sd$	$> \mu + sd$
	0.783	0.217				
Station. distr.			0.018	0.170	0.685	0.127
Sample distr.	0.214	0.036	0.006	0.036	0.673	0.036
	MOTV: technology specialization					
23	0.61	0.26	0.04		0.09	
25	0.24	0.44	0.12	0.04	0.16	
14	0.07	0.57	0.14	0.07	0.14	
18		0.28	0.22	0.16	0.28	0.06
71	0.01	0.07	0.07	0.20	0.18	0.17
18		0.06	0.06		0.17	0.72
Station. distr.	0.187	0.264	0.094	0.074	0.227	0.153
Sample distr.	0.136	0.148	0.083	0.107	0.42	0.107
	AIRC: industry specialization					
29	0.86	0.14				
25	0.04	0.44	0.52			
20		0.20	0.65		0.15	
1			1.00			
47		0.02	0.06	0.02	0.77	0.13
32					0.19	0.81
Station. distr.	0.032	0.111	0.252	0.008	0.355	0.242
Sample distr.	0.188	0.162	0.130	0.006	0.305	0.208
	AIRC: technology specialization					
29	0.52	0.21	0.10	0.07	0.03	0.07
18	0.22	0.22	0.22	0.22	0.11	
21	0.19	0.14	0.24	0.19	0.24	
22	0.09	0.09	0.23	0.41	0.18	
58	0.02	0.03	0.07	0.16	0.53	0.19
21	0.05				0.67	0.29
Station. distr.	0.157	0.102	0.135	0.185	0.321	0.100
Sample distr.	0.172	0.107	0.124	0.130	0.343	0.124
	SHIP: industry specialization					
32	0.56	0.44				
54	0.16	0.64	0.2			
12		0.25	0.17	0.50	0.08	
24		0.83	0.25	0.42	0.25	
24		0.04	0.08	0.29	0.17	0.42
31					0.19	0.81

Table A8 continued

Observations	Transition end state (upper boundary)					
	$\mu - sd$	$\mu - sd/3$	μ	$\mu + sd/3$	$\mu + sd$	$> \mu + sd$
Station. distr.	0.087	0.244	0.120	0.164	0.122	0.263
Sample distr.	0.190	0.268	0.071	0.143	0.143	0.185
	SHIP: technology specialization					
19	0.37	0.47		0.05	0.11	
51	0.25	0.45	0.16	0.06	0.08	
31	0.06	0.19	0.39	0.06	0.19	0.10
13	0.08	0.08	0.23	0.31	0.23	0.08
30			0.27	0.10	0.33	0.30
25	0.04	0.04	0.04	0.08	0.16	0.64
Station. distr.	0.125	0.2	0.18	0.095	0.181	0.219
Sample distr.	0.112	0.302	0.183	0.077	0.178	0.148
	PROF: industry specialization					
19	0.79	0.05	0.16			
36	0.08	0.61	0.19	0.03	0.08	
23	0.09	0.09	0.35	0.09	0.39	
5		0.20	0.40	0.20		
42	0.05	0.05	0.17	0.05	0.60	0.1
29					0.03	0.97
Station. distr.	0.116	0.076	0.112	0.025	0.178	0.492
Sample distr.	0.123	0.234	0.149	0.032	0.272	0.188
	PROF: technology specialization					
19	0.42	0.32	0.05	0.05	0.11	0.05
32	0.31	0.25	0.28		0.16	
28	0.07	0.32	0.07	0.04	0.50	
8			0.50	0.13	0.38	
61	0.03	0.07	0.16	0.05	0.66	0.03
21	0.10				0.19	0.71
Station. distr.	0.144	0.163	0.154	0.039	0.425	0.075
Sample distr.	0.112	0.189	0.166	0.047	0.361	0.124

Note: For the abbreviations of the industries' names see Appendix II.

Table A9 —Fractile Markov Chain Estimates for the Specialization Indicators of Individual Industries

1. First-order, time-stationary estimates of the five-year transition probabilities

Transition end state (quantile)					
1/6	1/3	1/2	2/3	5/6	1
CHEM: value added specialization					
0.82		0.14	0.03		
0.11	0.53	0.25	0.11		
0.04	0.28	0.39	0.25	0.04	
0.04	0.14	0.18	0.43	0.21	
	0.04	0.04	0.18	0.75	
					1
CHEM: technology specialization					
0.62	0.23	0.11	0.04		
0.27	0.46	0.27			
0.12	0.23	0.35	0.31		
	0.08	0.27	0.42	0.15	0.08
			0.19	0.35	0.46
			0.03	0.33	0.64
DRUG: value added specialization					
0.64	0.28	0.07			
0.32	0.46	0.07	0.11	0.04	
0.04	0.21	0.46	0.11	0.11	0.07
	0.04	0.21	0.25	0.25	0.25
		0.17	0.42	0.28	0.11
			0.11	0.32	0.57
DRUG: technology specialization					
0.27	0.08	0.31	0.19	0.12	0.04
0.35	0.42	0.12	0.04	0.04	0.04
0.12	0.27	0.15	0.23	0.19	0.04
0.11	0.15	0.35	0.12	0.27	
0.12	0.08	0.08	0.35	0.15	0.23
0.02			0.05	0.15	0.77
RAP: value added specialization					
0.75	0.21				0.03
0.17	0.43	0.11	0.18	0.07	0.04
0.04	0.18	0.43	0.25	0.04	0.07
0.04	0.15	0.28	0.17	0.25	0.11
	0.04	0.14	0.35	0.32	0.14
		0.04	0.04	0.32	0.61
RAP: technology specialization					
0.35	0.31	0.19	0.04		0.12
0.27	0.38	0.04	0.19	0.08	0.04

Table A9 continued

Transition end state (quantile)					
1/6	1/3	1/2	2/3	5/6	1
0.15	0.12	0.31	0.12	0.15	0.15
	0.08	0.23	0.19	0.23	0.27
0.08		0.08	0.19	0.35	0.31
0.10	0.08	0.10	0.18	0.13	0.41
SCG: value added specialization					
0.61	0.28	0.04	0.04	0.04	
0.28	0.28	0.21	0.17		0.04
0.04	0.32	0.42	0.11	0.11	
0.04	0.11	0.21	0.35	0.28	
0.04		0.11	0.32	0.39	0.14
				0.18	0.82
SCG: technology specialization					
0.27	0.19	0.08	0.15	0.12	0.19
0.31	0.27	0.08	0.12	0.12	0.12
0.23	0.12	0.19	0.15	0.23	0.08
0.04	0.04	0.35	0.15	0.19	0.23
0.08	0.15	0.12	0.23	0.08	0.35
0.05	0.15	0.13	0.13	0.18	0.36
IRON: value added specialization					
0.71	0.14	0.11	0.04		
0.07	0.28	0.21	0.35	0.07	
0.07	0.36	0.25	0.25	0.07	
	0.17	0.25	0.18	0.39	
0.14	0.03	0.18	0.18	0.18	0.28
				0.28	0.71
IRON: technology specialization					
0.35	0.23	0.08	0.12	0.12	0.12
0.08	0.31	0.38	0.12	0.08	0.04
0.15	0.12	0.27	0.15	0.19	0.12
0.08	0.15	0.04	0.27	0.19	0.27
0.12	0.12	0.08	0.12	0.31	0.27
0.15	0.05	0.10	0.15	0.08	0.46
NFM: value added specialization					
0.93	0.07				
0.07	0.64	0.17	0.11		
	0.21	0.39	0.25	0.14	
	0.07	0.28	0.5	0.14	
		0.14	0.14	0.64	0.07
				0.07	0.92

Table A9 continued

Transition end state (quantile)					
1/6	1/3	1/2	2/3	5/6	1
		NFM: technology specialization			
0.46	0.27	0.04	0.12	0.04	0.08
0.27	0.27	0.27	0.04	0.15	
0.08	0.15	0.38	0.19	0.08	0.12
0.04	0.12	0.12	0.35	0.23	0.15
0.04	0.12	0.12	0.15	0.23	0.35
0.08	0.05	0.05	0.10	0.18	0.54
		FABM: value added specialization			
0.61	0.32	0.07			
0.32	0.46	0.21			
0.07	0.17	0.57	0.14	0.04	
	0.03	0.11	0.57	0.17	0.11
			0.17	0.46	0.35
		0.04	0.11	0.32	0.54
		FABM: technology specialization			
0.62	0.15	0.15		0.04	0.04
0.19	0.38	0.19	0.15	0.04	0.04
0.08	0.31	0.35	0.27		
0.04	0.04	0.27	0.31	0.23	0.12
0.04	0.04		0.15	0.38	0.38
0.03	0.05	0.03	0.08	0.21	0.32
		MACH: value added specialization			
0.5	0.42	0.07			
0.21	0.67	0.11			
0.04	0.11	0.21	0.5	0.11	0.04
		0.46	0.39	0.11	0.04
		0.14	0.11	0.43	0.32
		0.03		0.36	0.61
		MACH: technology specialization			
0.62	0.15	0.15		0.04	0.04
0.19	0.38	0.19	0.15	0.04	0.04
0.08	0.31	0.35	0.27		
0.04	0.04	0.27	0.31	0.23	0.12
0.04	0.04		0.15	0.38	0.38
0.03	0.05	0.03	0.08	0.21	0.32
		COMP: value added specialization			
0.36	0.57	0.07			
0.07	0.46	0.43	0.04		
0.18	0.18	0.21	0.39		0.04

Table A9 continued

Transition end state (quantile)					
1/6	1/3	1/2	2/3	5/6	1
0.07	0.04	0.25	0.46	0.14	0.04
	0.04		0.07	0.54	0.41
		0.07	0.04	0.32	0.57
COMP: technology specialization					
0.46	0.35	0.08	0.04		0.08
0.27	0.23	0.23	0.15	0.08	0.04
0.08	0.23	0.15	0.38	0.08	0.08
0.08	0.12	0.27	0.19	0.23	0.12
0.08	0.04	0.12	0.08	0.38	0.31
0.03	0.03	0.10	0.10	0.15	0.59
ELMA: value added specialization					
0.64	0.28		0.07		
0.17	0.39	0.25	0.18		
	0.39	0.53	0.07		
	0.07	0.21	0.67	0.03	
			0.03	0.89	0.07
				0.07	0.92
ELMA: technology specialization					
0.50	0.04	0.15	0.12	0.04	0.15
0.15	0.38	0.23	0.08		0.15
0.15	0.08	0.31	0.08	0.15	0.23
0.04	0.08	0.19	0.31	0.27	0.12
0.04	0.15	0.04	0.27	0.15	0.35
0.08	0.18	0.05	0.10	0.26	0.33
RTVC: value added specialization					
0.29	0.71				
0.36	0.61	0.04			
	0.04	0.96			
			0.82	0.14	0.04
			0.14	0.61	0.25
			0.04	0.25	0.71
RTVC: technology specialization					
0.50	0.04	0.15	0.12	0.04	0.15
0.15	0.38	0.23	0.08		0.15
0.15	0.08	0.31	0.08	0.15	0.23
0.04	0.08	0.19	0.31	0.27	0.12
0.04	0.15	0.04	0.27	0.15	0.35
0.08	0.18	0.05	0.10	0.26	0.33

Table A9 continued

Transition end state (quantile)					
1/6	1/3	1/2	2/3	5/6	1
MOTV: value added specialization					
1					
	0.75	0.07	0.11	0.04	0.04
	0.18	0.5	0.21	0.04	0.07
	0.07	0.28	0.21	0.21	0.21
		0.07	0.36	0.39	0.18
		0.07	0.11	0.32	0.5
MOTV: technology specialization					
0.50	0.31	0.08	0.04	0.04	0.04
0.31	0.42	0.15	0.04	0.04	0.04
0.04	0.12	0.42	0.19	0.12	0.12
0.04	0.08	0.12	0.31	0.27	0.19
	0.08	0.12	0.35	0.19	0.27
0.08		0.08	0.05	0.23	0.56
SHIP: value added specialization					
0.71	0.28				
0.17	0.46	0.32	0.04		
0.11	0.21	0.46	0.11	0.11	0
		0.14	0.61	0.25	
	0.04	0.07	0.25	0.43	0.21
				0.21	0.79
SHIP: technology specialization					
0.38	0.42	0.08	0.04		0.08
0.38	0.31	0.23	0.04	0.04	
0.08	0.19	0.23	0.19	0.23	0.08
0.15	0.04	0.23	0.23	0.19	0.15
		0.15	0.27	0.15	0.42
	0.03	0.05	0.15	0.25	0.51
AIRC: value added specialization					
0.86	0.14				
0.07	0.68	0.25			
	0.25	0.71	0.04		
		0.04	0.68	0.28	
			0.28	0.61	0.11
				0.11	0.89
AIRC: technology specialization					
0.46	0.31	0.12			0.12
0.31	0.27	0.27	0.08	0.04	0.04
0.15	0.19	0.27	0.23	0.15	

Table A9 continued

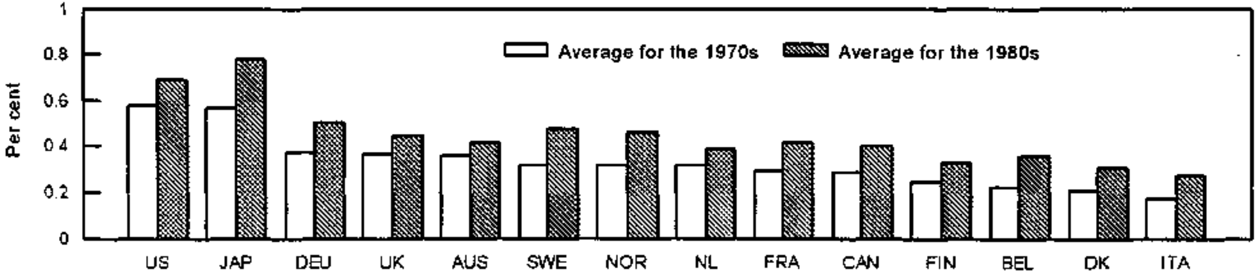
Transition end state (quantile)					
1/6	1/3	1/2	2/3	5/6	1
	0.15	0.23	0.46	0.08	0.08
0.04	0.08	0.08	0.12	0.41	0.38
0.03		0.03	0.08	0.28	0.59
		PROF: value added specialization			
1.00					
	0.50	0.43	0.07		
	0.28	0.32	–0.36	0.04	
	0.21	0.07	0.43	0.28	
		0.18	0.14	0.68	
					1.00
		PROF: technology specialization			
0.62	0.12	0.08	0.08	0.04	0.08
0.23	0.38	0.27	0.08	0.04	
0.08	0.19	0.23	0.23	0.15	0.19
0.04	0.08	0.27	0.31	0.08	0.23
	0.19	0.11	0.15	0.46	0.08
0.03	0.03	0.03	0.10	0.15	0.67

2. Regressions of Interquantile Range in Industry Specialization on Time and Technology

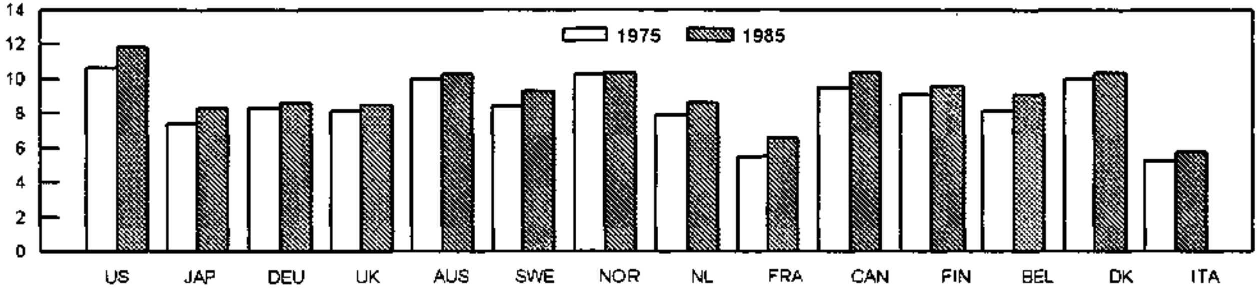
	Industry specialization			Technology specialization		
	coefficient	t-value	adj.R^2	coefficient	t-value	adj. R^2
All industries	0.00	2.31	0.194	0.01	2.43	0.224
CHEM	–0.02	–6.75	0.710	0.01	0.65	0.035
DRUG	–0.02	–1.64	0.085	–0.01	–0.43	–0.05
RAP	0.02	8.73	0.807	–0.02	–0.36	–0.054
SCG	0.01	3.19	0.337	–0.01	–1.25	0.033
IRON	–0.00	–0.84	–0.016	0.00	0.23	–0.059
NFM	0.02	2.28	0.190	–0.00	–0.11	–0.062
FABM	0.00	2.09	0.158	0.01	1.83	0.122
MACH	0.02	5.85	0.649	0.02	5.36	0.620
COMP	–0.12	–8.04	0.779	0.02	1.26	0.034
ELMA	–0.06	–1.61	0.081	–0.01	–1.76	0.111
RTVC	0.01	1.63	0.085	–0.01	–0.57	–0.041
MOTV	–0.01	–2.31	0.195	–0.01	–0.61	–0.039
SHIP	0.01	0.32	0.052	0.04	3.09	0.336
AIRC	–0.01	–1.68	0.091	–0.02	–1.27	0.035
PROF	–0.02	–2.43	0.215	0.01	2.75	0.278

Figure A1 — OECD Countries' Endowment with Human Capital

Panel a: Countries' Relative Endowments with R&D Scientists and Engineers[a]



Panel b: Average Years of Schooling in the Adult Population[b]

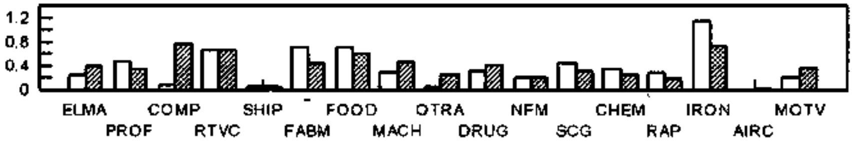


[a]Percentage shares of employed R&D scientists and engineers in total labour force. Averages for all countries combined: 0.45 per cent in the 1970s and 0.58 per cent in the 1980s. Data Source: OECD (1992 b), partly based on own estimates. — [b]Adult population comprises people older than 25 years. Data Source: Barro and Lee (1993).

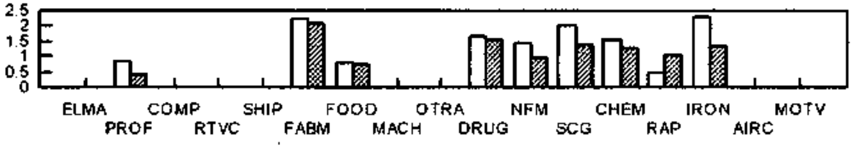
Figure A2 — R&D Intensities for Major Industries[a] Relative to the Industry Average over All Countries in the 1970s and the 1980s

☐ 1970s ▨ 1980s

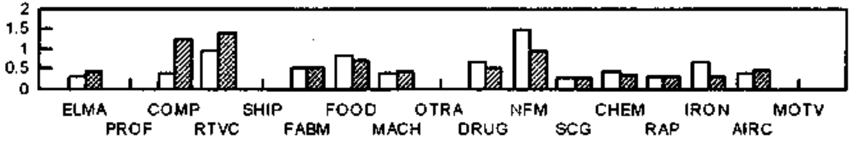
Australia (5th in 1970s, 8th in 1980s)



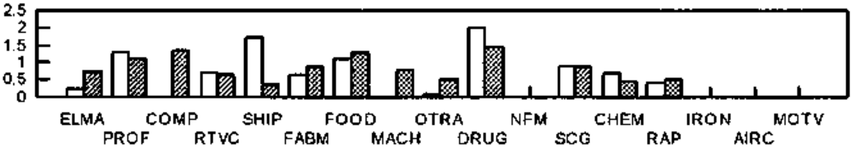
Belgium (12th in 1970s, 8th in 1980s)



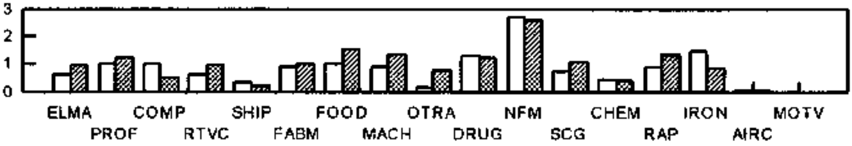
Canada (10th in 1970s, 9th in 1980s)



Denmark (13th in 1970s, 13th in 1980s)



Finland (11th in 1970s, 12th in 1980s)



France (9th in 1970s, 7th in 1980s)

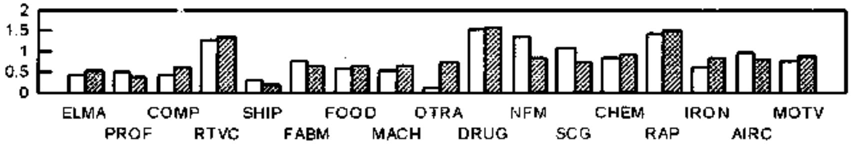
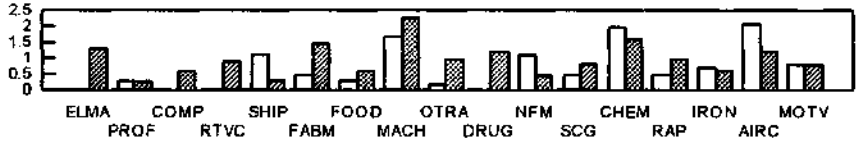
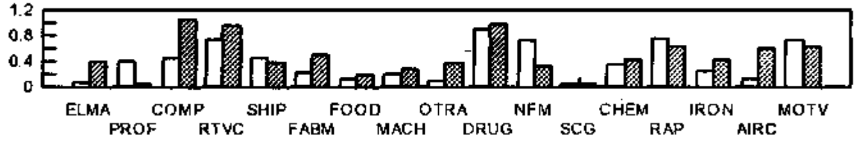


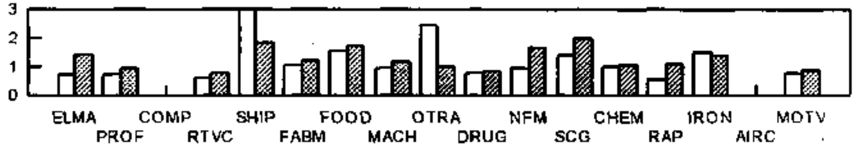
Figure A2 continued



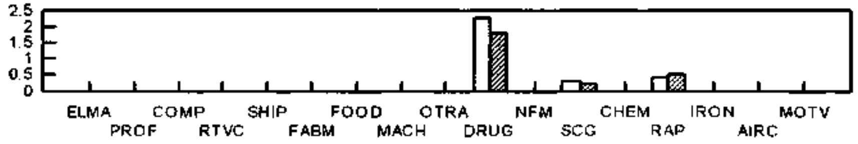
West Germany (3rd in 1970s, 3rd in 1980s)



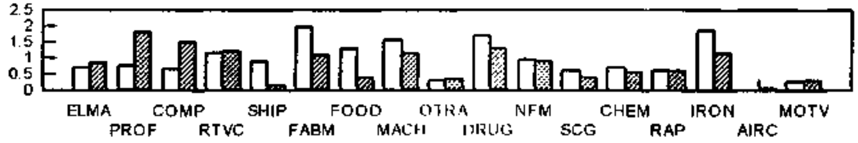
Italy (14th in 1970s, 14th in 1980s)



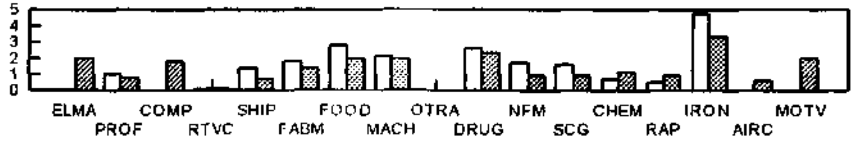
Japan (2nd in 1970s, 1st in 1980s) — 5.5 for SHIP in 1970s



The Netherlands (8th in 1970s, 10th in 1980s)



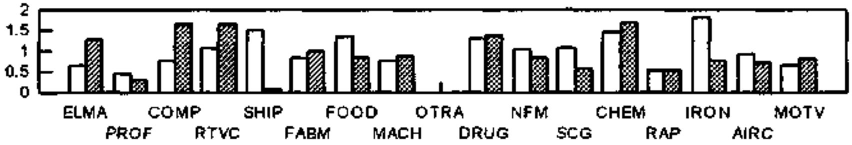
Norway (7th in 1970s, 5th in 1980s)



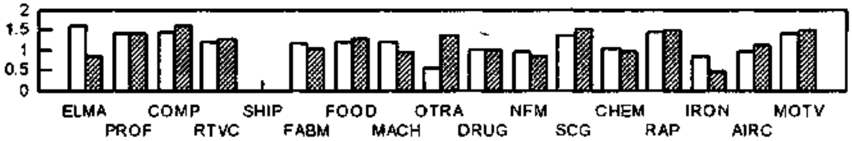
Sweden (6th in 1970s, 4th in 1980s)

Figure A2 continued

United Kingdom (4th in 1970s, 6th in 1980s)

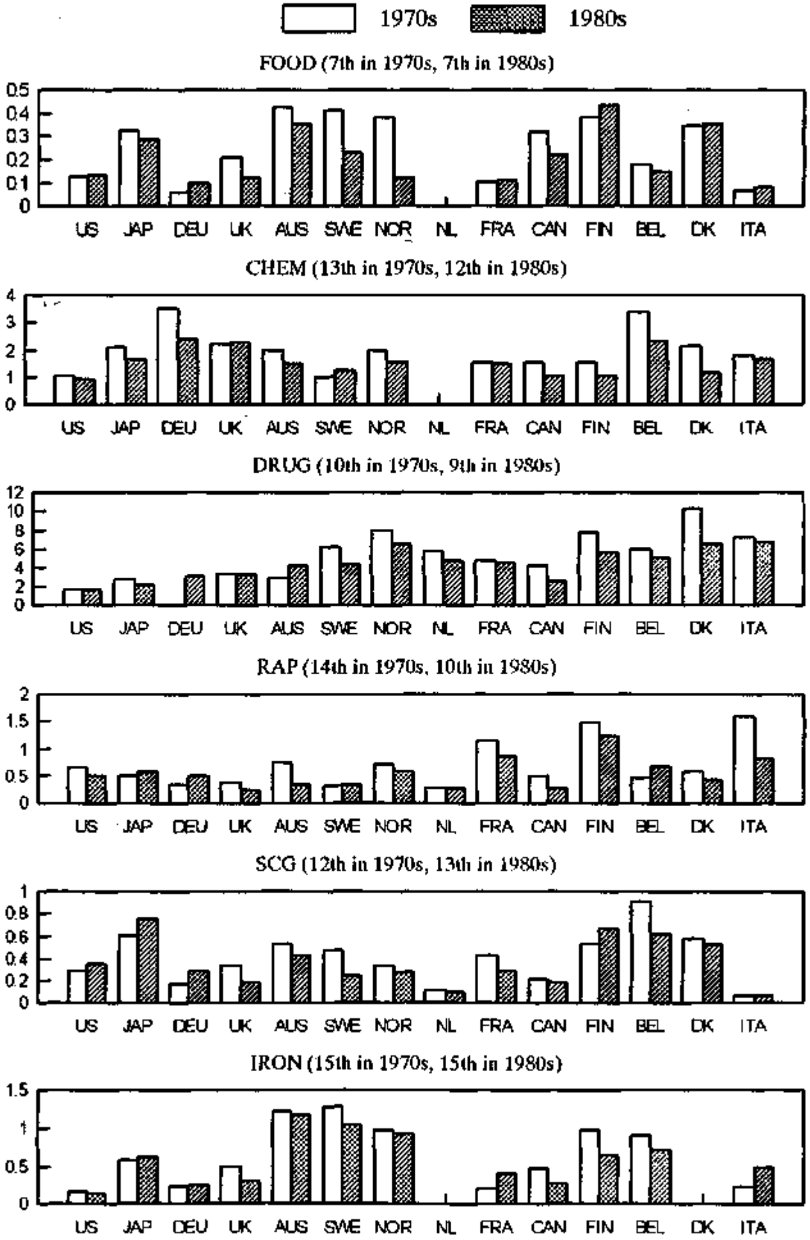


United States (1st in 1970s, 2nd in 1980s)



[a] On the horizontal axis, industries are ranked by their average ratios of R&D scientists and engineers to other R&D personnel in the 1970s. After countries' names, the rankings of countries by their overall relative endowments with R&D scientists and engineers in the 1970s and 1980s are given in parentheses. — For abbreviations of industries' names see Appendix I.

Figure A3 — R&D Intensities for OECD Countries[a] Relative to the Country Average over All Industries in the 1970s and the 1980s



FOOD (7th in 1970s, 7th in 1980s)

CHEM (13th in 1970s, 12th in 1980s)

DRUG (10th in 1970s, 9th in 1980s)

RAP (14th in 1970s, 10th in 1980s)

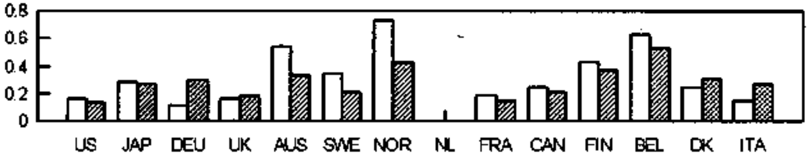
SCG (12th in 1970s, 13th in 1980s)

IRON (15th in 1970s, 15th in 1980s)

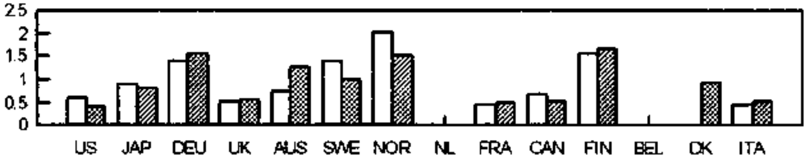
Figure A3 continued

NFM (11th in 1970s, 11th in 1980s)

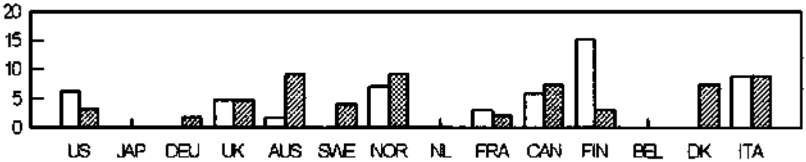
FABM (6th in 1970s, 8th in 1980s)



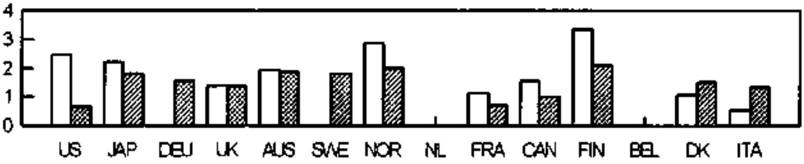
MACH (8th in 1970s, 6th in 1980s)



COMP (3th in 1970s, 2nd in 1980s)



ELMA (1st in 1970s, 1st in 1980s)



RTVC (4th in 1970s, 4th in 1980s)

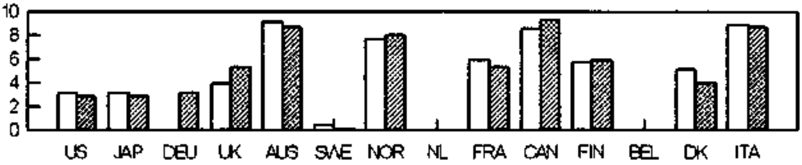
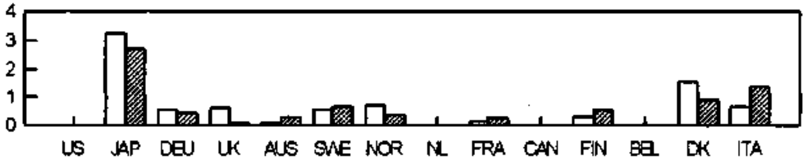
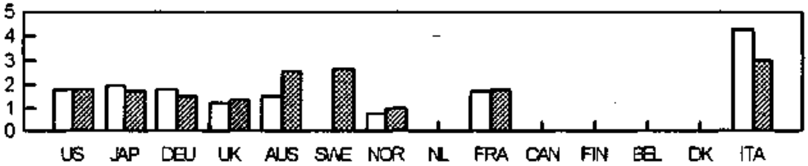
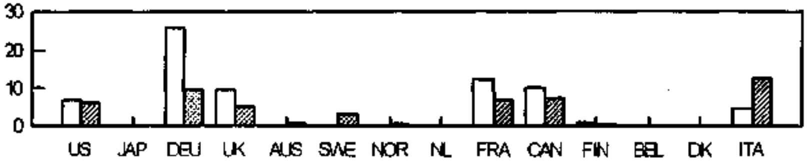
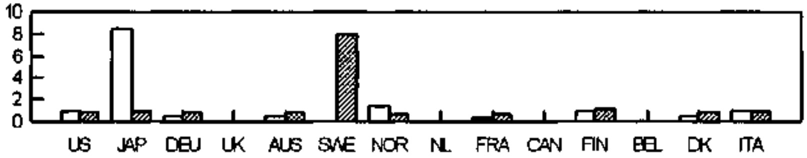


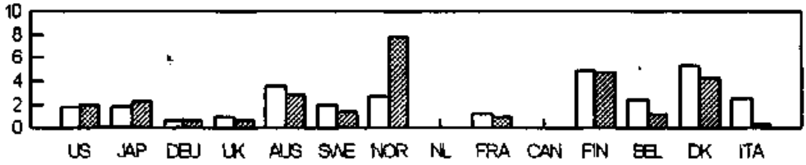
Figure A3 continued


SHIP (5th in 1970s, 3rd in 1980s)


MOTV (17th in 1970s, 17th in 1980s)


AIRC (16th in 1970s, 16th in 1980s)


OTRA (9th in 1970s, 14th in 1980s)


PROF (2nd in 1970s, 5th in 1980s)

[a] On the horizontal axis, countries are ranked by their relative endowments with R&D scientists and engineers in the 1970s. After the industries' names, the rankings of industries by their average ratios of R&D scientists and engineers to other R&D personnel in the 1970s and 1980s are given in parentheses. — For abbreviations of industries' names see Appendix I.

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