C. Disco, A. Rip and B. van der Meulen

Technical innovation and the universities: divisions of labour in cosmopolitan technical regimes

Introduction

Is the increasing intimacy of university–industry relations, and university involvement in business and government sponsored programmes of technological innovation a sign of complicity or enlightenment? Are the universities selling their birthright, or are they finally becoming socially responsible? Such questions are hotly debated, but often with a focus on institutional roles and the value of the academic ethos, with attendant neglect of what one could call the *epistemology* of university–industry relations.

The linkage of university education and research in technical disciplines with the affairs of government and industry are by no means an historical novelty. It is necessary to place this issue in historical perspective to see what is structural in such collaborations and interactions, and what is ad hoc, contingent. On the institutional side, Etzkowitz has proposed thinking of two major shifts in university–society relations: a first academic revolution (at the end of the 19th century, when research entered the [American] universities) and a second academic revolution, at the end of the 20th century (Etzkowitz, 1990). The latter entails a new phase in the role of the university, with societal (including economic) responsibilities in addition to education and research. Etzkowitz's proposal is useful in understanding what is happening, but it remains somewhat simplistic, among other things because it is limited to the institutional aspects. The basic question we want to address in this paper is: what makes a role for the university in technological

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development *at all* possible? This is an epistemological question (in the broad sense, taking into account the social nature of knowledge acquisition and validation), and it is immediately followed by a historical and sociological question: how did this role evolve over time, and what does the present situation look like from this perspective? Is it a continuation of patterns established earlier on, or indeed some sort of revolutionary development (and if so of what kind)?

Universities, after they took up training of students in technical and scientific fields, i.e. by the late 19th century in most western countries, played an important role in the supply of trained manpower and, in some domains, also in the supply of research results. But what did the training and the research consist of, and why was that relevant for ongoing technical developments on the shop floor elsewhere, not based in universities, and often not even immediately linked to universities? The core of technical development is design work, which as such is always local. But it can be shown that in most cases these local design activities at different places and different times add up to aggregate technical development in a more or less common direction, thus implying some sort of division of design labour. Insofar as this division of labour has included a theoretical component (as it has since the mid-19th century) it has thus also presupposed some shared cognitive-technical infrastructure which is both sufficiently concrete to guide local design work and sufficiently general to allow universities to contribute in their own way.

In this article we attempt to show, conceptually and historically, that such shared cognitive-technical infrastructures indeed exist, and that they allow a division of labour through which universities can participate in technological innovation. Such cognitive-technical infrastructures are emergent phenomena, shaped by the social, institutional and political situation in which they emerge, and they evolve through time, again for social, institutional and political reasons, as well as because of scientific and technical advances. The two basic cognitive-technical infrastructures that we shall discuss, design hierarchies and technical models, pervade design work, technical development and the technical and engineering sciences. In fact, the emergence of the technical sciences, as well as their present situation inside and outside the universities, can be understood with the help of the conceptual and historical analysis that we offer in this article.

Local and cosmopolitan technological regimes

Polytechnics and universities can in principle only get incorporated into design work when the latter ceases to be purely a matter of local trial-and-error. The concept of "local technological regimes" refers in an absolute sense to a situation in which design heuristics and production processes are entirely self-contained within local contexts (pre-eminently firms), such that outside sources of expertise and materials are not required for regular production or even innovation.[1] At best, however, such self-containment is relative. Even in rather traditional craft settings, both technical knowledge and raw materials ultimately come from outside the firm. The most "local" situation imaginable is probably one in which a large degree of vertical integration (e.g. a furniture factory attached to a lumber mill which also did its own logging) was coupled to significant and proprietary local technical advances. But again, even here the bulk of the technical knowledge and production equipment would be such as were available in any number of similar industrial settings. In practice localism is always limited by the relative standardization of craft or professional training, by the concentration of sources of supply of raw materials and tools, and by such processes of technological diffusion as inevitably befall really good ideas like gunpowder, stirrups, anchor and balance escapements or the magnetic compass.

This does not invalidate the concept of "local technological regimes". Although the hermetically isolated firm cannot serve as a serious referent, "localism" is still useful for denoting a particular pattern of the distribution of knowledge and tools within an industrial sector as a whole. In this sense, "localism" refers to the siting of all relevant knowledge and tools *within* the firms in a given industrial sector. Hence, although exchanges of materials and information among the firms in a given sector (and with customers and suppliers outside the sector) are inevitable, there are no (or very few) exchanges with other *kinds* of institutions (like universities, or government agencies and/or laboratories). Moreover, the exchanges that do take place tend to be *unmediated*, i.e. to involve direct exchanges of personnel, information, raw materials, or components between firms rather than exchanges via intermediary bodies like regulatory agencies or professional societies. What "localism" boils down to in this "collective" sense, therefore, is that there is no institutional position external to the firms themselves which is seen by firms as relevant or useful to improving the quality of their production processes or design efforts or which, alternatively, is able to impose itself as an authoritative arbiter of the way firms shape their technologies.[2]

While even in this latter sense "localism" is never total, the weaker conception undoubtedly applies to most pre-19th-century industrial sectors. What happened during the 19th century, we contend, was that a process of "cosmopolitanization" set in, visible in the increasing articulation of information exchange among organizations and in the emergence of new interstitial institutions dedicated to the accumulation and processing of technical information. In fact, we argue that ultimately, in most sectors, technical design became dispersed in the form of an interorganizational *division of design labour*. While this process is far too variable and complex to describe in any kind of detail here, a number of aspects may be noted in passing. The "prime mover" of the process was unquestionably the British-based iron and steam revolution which spread to the European continent and the USA in the form of radically new kinds of industrial capital goods and raw materials and not, incidentally, in the form of expert practitioners and much written and oral information (Landes, 1969). While the sheer increase in interfirm exchanges which this entailed does not in itself threaten "localism" as we have defined it, the pressures on firms to appropriate and implement the new technologies encouraged much more extensive interdependencies which in turn cleared the ground for a "cosmopolitan" restructuring of a number of key industrial sectors.[3] One manifestation was the rapidly increasing number of design handbooks being published by individual engineers and scientists, or by institutional suppliers of equipment (Kroes, 1990). This meant that the more generalizable aspects of technical knowledge became relatively emancipated from local contexts and assumed a "universalist", cosmopolitan character. Another central factor was the gradual intrusion of governments into industrial regulation (pioneered in England in the 1820s with the Factory Acts) and into the construction and management of infrastructural systems (adumbrated everywhere in aspects of military engineering, but given its first civilian embodiment in France as early as 1716 with the formation of the *Corps des Ponts et Chaussées*). This meant, in the first place, that regulatory government agencies began to immerse themselves in the technical details of, e.g., steam boilers, truss bridges, or factory buildings in order to establish standards and regulations for industrial producers and users. But it also meant that a new type of civilian government agency began to function as planning, design and contracting organizations, inviting tenders from private firms on the basis of specifications which were as a rule quite detailed. It goes without saying that these "system tending" agencies, politically mandated with specific technical responsibilities and enjoying concomitant if not always sufficient budgets, cultivated their own notions of "adequate technological practice" and acted in many respects as "cosmopolitan" tutors to the "localist" contractors who assumed the burdens of actual construction.[4] Finally, though this enumeration is by no means exhaustive, one can point to the promulgation of standard classifications of raw materials by large-scale industrial or governmental consumers. The military, of course, already had an ancient reputation on this score, but during the 19th century large private consumers, starting with the railroads, also found it essential to purchase their iron and steel track on the basis of quality classifications which could be backed up with non-contestable physical and chemical analyses (Misa, forthcoming). With respect to the iron and steel producers, the railroads thus assumed a typically "cosmopolitan" position, mobilizing universalistic criteria to influence local design heuristics, including the design of production processes. The elaboration of similar supplier–consumer relations in other industrial sectors generalized this phenomenon throughout the industrial economy.

Design hierarchies and technical models

The gradual emergence of "cosmopolitan divisions of design labour" did not take place in an organizational or epistemological vacuum, but emerged as a by-product of a double process of rationalization: the economic rationalization of production processes and the cognitive rationalization of design heuristics. These two substrates of cosmopolitanization can be explicated around the concepts of, respectively, "design hierarchies" and "technical models".

"Design hierarchies" refer to the constraints imposed on design strategies by the hierarchical structure of artifacts themselves.[5] The basic idea is that in order to introduce innovations into a complexly hierarchical artifact like, say, an automobile, one is forced to design in a hierarchical fashion as well.[6] At the very least, this means that one is forced to confront the problem of functional compatibilities among discrete structural levels such as, e.g., overall configuration, subsystems and components. It also suggests the hierarchization of design *strategy*, proceeding from some overall concept and then working through an implied design agenda to "work up" subsystems and components into compatible configurations and functionalities.

In this limited sense, i.e. as it pertains specifically to *design*, hierarchy does not necessarily imply the abrogation of "technological localism" in either the strong or weak sense. The hierarchical structure of many artifacts not only enforces a hierarchy of design but also of *production*. Diego Rivera's well-known murals of Ford's River Rouge Plant graphically display what this is about: we see the transformation of iron ore into various components like engine blocks, pistons, crankshafts and their aggregation into working sub-assemblies (engines) and we see these in turn incorporated along with tyres, windshields, paint, etc. into finished automobiles. Although Ford was in fact a notorious vertical integrator, we can easily imagine that the engines (or the pistons, crankshafts, windshields, etc.) might just as well have been supplied by another manufacturer – given appropriate agreements on measurements and accurate standards. In other words, what the hierarchy of production makes possible is the organizational dispersion of production and ultimately also the organizational dispersion of design.

More or less ramified networks of industrial supplier–customer relationships have been with us for a very long time, most ubiquitously with regard to commercial divisions of labour around the extraction and/or cultivation of raw materials on the one hand and their processing into useful artifacts on the other. Since the industrial revolution, which brought us both intensively mechanized production processes and the possibility of manufacturing to close and standardized tolerances (i.e. interchangeable parts), two additional patterns of interfirm buying and selling gradually became prevalent. In the first place, manufacturing firms – under perennial pressure to maintain up-to-date and efficient production facilities – increasingly turned to ever more specialized capital goods manufacturers for the necessary processing machinery. In the second place, manufacturers of end-products increasingly began to farm out the production of components and sub-assemblies to specialized firms. The economic rationale for this interfirm division of manufacturing labour parallels, mutatis mutandis, Adam Smith's apologetics for the division of labour within individual manufacturies: specialization, standardization, repetition and what these make possible, namely, the increase of skill and knowledge and the increased possibility for the specific mechanization of discrete steps of the production process; in short, increased productivity and lower costs per unit product.

The point we would like to make about the increasingly dispersed production of both process equipment and components is that it necessarily entails the cosmopolitanization of technical regimes. This comes about because dispersed production implies the need to transmit local technical information beyond the boundaries of the individual firm and because such transmission eventuates in the accumulation of such local information at specific organizational sites in what gradually becomes an interorganizational *system* of design and production. Initially, one would imagine that both process equipment and components were ordered from more or less specialized producers on a one-time basis and according to customized and detailed specifications. In this phase, production is dispersed but the design process is not; for example, a manufacturer of linen also designs the power looms he wants to use. Clearly this is an unstable phase because expertise on loom building tends to accumulate at the loom manufactury and not at the textile plant; the former is not only intimately acquainted with the actual making of looms but also – as a recipient of detailed specifications and accounts of practical experiences – with the various local demands made on looms throughout the textile industry. As a repository of specialized knowledge and skills relating to looms, the loom manufacturer is in an increasingly favourable position to provide valuable technical and commercial advice to the textile plant, to become, in effect, co-designer of textile processing equipment. Ultimately, as larger markets begin to solidify, the loom manufacturer's positional advantage can provide him with a virtual design monopoly; thenceforth industrial customers may purchase looms *prêt à porter* from trade catalogues. Similar dispersion of production and design – and concomitant transfers and concentration of technical knowledge and experience – occurred in respect of suppliers of components and sub-assemblies. In the course of the 19th century we see increasing numbers of trade catalogues advertising standard products like fasteners, steam engines, or machine tools. Other things being equal, the dispersion of design – implying the relative technological autonomy of suppliers – will likely occur more rapidly for more generic types of capital good or component. That is, the greater the number of customers that can in principle be served by the same design, the more economic incentives will encourage interorganizational dispersion of production and design and hence the cosmopolitanization of the associated technical regime.

However, the progressive ramification of supplier-customer relations is not the only institutional substrate of the cosmopolitan division of design labour. An additional basis can be found in the very epistemology of the design process itself. In a recent paper, one of us (Rip, 1991) has argued that design can be understood as a search process guided by heuristics, i.e. intersubjectively sanctioned rules of procedure which promise to "deliver the goods". This can be studied on a purely cognitive and psychological level, but even then it is clear that a sociological analysis is necessary for a comprehensive understanding (cf. Gorman and Carlsson, 1990). An example of a (potentially) broader analysis is the introduction of "evaluative dimensions" derived from organizational strategies and professional disciplinary cultures.[7] We think that a more adequate understanding of design as heuristically guided action is served by bringing the notion of "technical model" to bear, in the sense of a reasoned (though not necessarily fully articulated) conceptual representation of a species of artifact. Technical models start out being socially embedded in local design practices, eventually become embedded in technical communities, and (after a time) are formalized in engineering curricula.

A technical model is a mental or symbolic representation of a family of artifacts, such that the latter becomes comprehensible as a system of interrelated and mutually constraining sub-elements. This definition suggests two principal features of a technical model, namely, first that it is always a *conceptual abstraction* from a certain range of concrete artifacts and, second, that it *reveals the hidden or non-evident structure/functionality* of such a class of artifacts. Practical technical models can, and most obviously do, vary considerably in their degree of abstraction and in what they reveal of hidden properties. Nonetheless, technical models are invariably the result of mental labour by designers (or others) aimed at facilitating the inference of aggregate artifact behaviours from specific element parameters and the overall configuration of elements. Technical models thus "map" the possible variability of element states – constrained by, among other things, the mutual dependencies obtaining by virtue of the fact that the combination of elements must under all conditions constitute a functional artifact – onto ranges of artifact "outputs". As such, they are a crucial step in transforming socially or economically defined "reverse salients" into technologically tractable "critical problems" (cf. Hughes, 1983). Technical models serve in the actual design process to allow designers to "manipulate" artifacts in a kind of virtual cognitive space characterized by idealization, abstraction, relative simplicity and efficiency. The "material embodiments" of technical models include mental images, technical drawings, systems of mathematical equations, physical models, or computer simulations. A familiar and almost minimalist example is Ohm's Law, at least insofar as it is used to describe electrical circuits for the purpose of designing or modifying them according to specific design criteria, e.g. to specify the value of resistance necessary to achieve some specific voltage drop across two points in an electrical circuit. Another example is provided in Figure 1, which shows a deficient configuration of steel rods in a reinforced concrete construction (which in fact had collapsed in a fire after 5 years of service).[8] It should be noted in passing that a given species of artifact may be modelled in any number of different ways, depending on the specific behaviours which are of interest, i.e. the specific "evaluative criteria" at issue. Thus, for example, ships' hulls may be modelled for their hydrodynamic, their aesthetic, or their mechanical properties; electrical power plants may be modelled as self-contained thermodynamic systems or as self-regulating components in a larger system of variable demand power loads. It should also be obvious that modelling can, and routinely does, pertain to any level of the "technical hierarchy" which may be embodied in a given artifact. A bicycle, for example, may be conceived and modelled as a system of structural stresses, but in attempting to improve its aggregate resistance to vibration fatigue one may be forced to redesign – and consequently also to model – wheels or bearing assemblies as distinct and autonomous artifacts.

The above should not be taken to imply that we consider rational engineering design to be impossible without fully articulated technical models, or, for that matter, that we consider technical models themselves to be unproblematic artifacts. On the first point, postulating the ubiquity of technical models in engineering design does not rule out their assuming the form of tacit, intuitive and

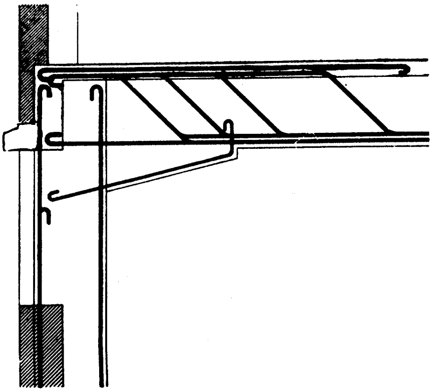

FIGURE 1
Reinforcement configuration in reinforced concrete beam and column joint of collapsed building (1930)

highly personal representations, particularly in unexplored technical domains where inspired invention is the order of the day.[9] Again, however, psychological explanation alone will be insufficient, if only because of the irreducibly social character of basic perceptual and cognitive categories. The necessity of appealing to a sociological level of analysis holds a fortiori for more "public" cosmopolitan technical modelling repertoires such as are employed by design engineers working in mature technologies. Here, technical models take the form of stabilized and objectively available cognitive and practical design heuristics, complete with standardized symbol systems and application protocols. In such cases, technical models are the shared cultural property of what Constant (1980, 1987) has termed "technological communities" and often already incorporated into engineering curricula and hence into the professional engineering habitus. The subjective element here tends to be limited to decision making about how to apply or adapt existing cosmopolitan technical models to the solution of local design problems, e.g. how to adapt accepted standard practices for modelling ships' hulls to the design of *this particular* ship's hull (which has to achieve particular performance levels on a stipulated – if ultimately negotiable – set of evaluative criteria).

It is clear, however, that the sociology of technical modelling is not exhausted in the study of what might be called "immanent modelling", i.e. the application of normalized cosmopolitan technical models to particular local design problems. In many cases, the solution of local difficulties demands either the production or the modification of existing technical models. Thus, for example, meeting more stringent evaluative criteria may require increased precision in the prediction of aggregate functioning from specified component parameters or it may require incorporation of new variable elements, the influence of which could be regarded simply as "noise" in the previous, less stringent, design situation. For example, in the design of current high-performance ships' propellers, the problem of cavitation has taken on new salience as a source of potentially destructive vibration, rather than as a mere limit to efficiency. Levels of cavitation which could previously be regarded as tolerable "noise" must now be designed away. In order to do this, profound analysis of the aetiology of cavitation has had to be carried out, i.e. cavitation has had to be modelled as a specific product of the movement of skewed blades through water. In any case, local requirements often indicate the necessity for purposive work on technical models themselves, a kind of activity in which the focus of attention is no longer the artifact to be designed, but rather the conceptual framework by which the design process is to be steered. We propose to call the labour of producing and modifying technical models "meta-design". The notion of "meta-design", we contend, is an essential but neglected aspect of technological development, and in fact the aspect that allows technical sciences to emerge and take on a life of their own.

The kinds of questions to be addressed here concern the relationship between instances of local "immanent modelling" (and local excursions into "meta-design") and a cosmopolitan process of "meta-design", i.e. the genesis, modification and stabilization of shared inter-organizational technical modelling repertoires. This process entails at least the achievement of consensus among local designers on efficient nomenclatures and symbolizations and may include broad agreement on the relative salience of particular relationships and the values of parameters in technical models of particular types of artifacts.

The above suggests both a certain "heuristic layering" in the structure of technical models as well as a corresponding "temporal sequencing" in their development. In early design processes within unfamiliar domains, we may expect intuitive, "private", mental technical models to predominate. Although there is no doubt a link to existing cosmopolitan cognitive representations, this is seldom explicit; as a consequence "meta-design" does not yet appear as a distinct activity. Typically, however, perceived shortcomings in intuitive technical models caused by the pursuit of more ambitious artifact performances or the imposition of new "evaluative dimensions" may well force the intuitive inventor (or organization) to problematize the "private" tacit technical model. This may lead both to local excursions into "meta-design", sometimes involving very basic scientific research coupled with the importation of professional researchers, as well as to efforts to learn from the experiences of others, including appropriation of published findings and other forms of information exchange with technological competitors. Within particularly large and wealthy organizations such "meta-design" may even become a differentiated activity, either on an ad hoc basis to solve emergent design problems and to appropriate new technologies (e.g. in the form of incidental experimentation within such organizations as army artillery corps, railways, national public works agencies) or more structurally as evidenced in the emergence of state and corporate research laboratories around the turn of the century. As these developed, "meta-design" experienced a certain emancipation from immanent design concerns as it became increasingly good corporate policy to try to model "technically promising" phenomena despite the absence (as yet) of any immediate design relevance.

Nowadays, powerful technical models are deeply anchored in basic science almost from the first, in the sense that design-relevant representations of artifacts draw heavily on scientific theories about phenomena which are embodied in the artifacts. Examples which come readily to mind are nuclear fission (and fusion), micro-electronics, biotechnology, or lasers. Hence, complex R&D systems and specific design processes are today more or less epistemologically seamless – if still organizationally distributed – wholes; in fact, entire classes of artifacts seem to have emerged out of basic scientific investigations, rather than the rote design processes specific to artifactual design itself. Note that this does not mean that the reputational communities of science simply produce artifacts in the sense that we hold cosmopolitan design networks to do. What "science" produces are "promising phenomena" which may be incorporated into practical artifacts through a complex process of translation and specification, primarily entailing the transformation of cognitively oriented scientific theory and laboratory set-ups into practically oriented technical models and prototypes.[10]

In the classic configuration of the 19th and early 20th centuries, however, technical models generally started out as local ad hoc constructions, and only later tended to become stabilized within the cosmopolitan culture as standard generators of design heuristics. The construction and optimization of technical models, i.e. "meta-design", only gradually became a distinct type of activity within the overall process of engineering design, i.e. only gradually became the province of research specialists within a cosmopolitan division of technological labour. But whether basic scientific investigations are involved or not, the general point is that this is where (and how) interorganizational couplings around collective design problems, and sometimes even couplings with "relevant social groups" take place (cf. Bijker and Pinch, 1987). Cosmopolitan stabilization of technical modelling repertoires, as the institutionalization of standard heuristics and functionalities, has become the rule. Although technical models are regularly applied, modified and even constructed within the confines of single organizations for the purpose of forcing specific breakthroughs in local design bottlenecks or for mastering "promising" technical effects, the thesis of "cosmopolitan design networks" stipulates that portions of this design labour occur in *other* organizations or in emergent interorganizational settings.[11]

It is relatively easy to point to clear-cut instances of technical modelling and to describe its role in technological innovation. The way we are generalizing the notion here, however, implies that we want to use it as an organizing resource, rather than simply as a label for a particular phenomenon. Such usage creates a certain *explanatory* perspective on technological development, because it helps us to understand how various types of inter-organizational linkages develop and stabilize. Particular divisions of cosmopolitan design labour turn out to be possible in technological development precisely because the epistemic articulation of technical models comes to be seen as a useful activity at some point in the development of specific technologies. We do not want to imply that our approach provides an overarching scheme or model which is capable of specifying all divisions of labour and allocating all inter-organizational linkages in some a priori fashion. Actors create all sorts of interdependencies through the interlocking of their strategies. Our argument is that some patterns of interlocking can stabilize (and expand) because they build on what turns out to be a division of labour around the construction or deployment of a technical model or associated technical hierarchies, i.e. in terms of a cognitive infrastructure that is itself only a product of the same development.

While the concept of "design hierarchies" can explain a good deal of the complex informational networking that takes place among manufacturing firms, the notion of "technical modelling" and the more general point about different levels of "theoreticity" in technical knowledge allows us to go further. In particular, it equips us for analysing the emergence of technical sciences, and the division of labour between technical innovation and university research which becomes visible towards the end of the 19th century. It is to this historical delineation that we now turn.

The historical emergence of "cosmopolitan technical regimes"

The precise configurations of organizational actors in divisions of design labour are technically, nationally and historically contingent. Nonetheless, at least in the nations of the European continent, a general pattern crystallized during the 19th century which, grosso modo, is still present today. In these nations, state agencies with mandated technological commitments, including branches of the military and public works agencies, had begun to incorporate "scientific insights" into their practices by as early as the mid-18th century. The practical efficacy and prestigious standing of such expertise stimulated the founding of engineering schools in order to supply the state with appropriately schooled personnel. Staff and administrators of such schools, in turn, rapidly established a significant relationship to design processes by first echoing the legitimacy and necessity of abstract, theoretical and therefore generalizable styles of technical modelling and subsequently assuming some of the burden of the associated labour of "meta-design". In some fields classical universities were also assuming a similar role, e.g. in medicine, a theme on which they would continue to embroider as the 19th century mellowed into the *Belle Epoque*, e.g. organic chemistry in relation to industrial synthesis.

The "polytechnic movement" became visible as early as the 18th century. The French *Ecole Polytechnique* (1794) and the two

Ecoles d'Application which preceded it, the *Ecole des Ponts et Chaussees* (1747) and the *Ecole des Mines* (1783) – the latter inspired on the Freiburg *Bergakademie*, founded in 1765 – set a typically "modern" and scientific standard in non-military engineering education which was widely copied throughout continental Europe in the ensuing century.[12] If professional engineering associations functioned as interorganizational fora for critical deliberations on "meta-designing", the primary actors responsible for the *production* of candidate technical models themselves turned out to be the faculty of these new polytechnics. These, as noted, had had precursors in the early university medical schools as well as in military engineering and artillery schools. Teaching staff at such institutions shared the fact of their mandate to train experts capable of producing "state of the art" designs and therapies in their particular practical domains. This meant that in designing curricula they could not make do with inculcating rote solutions to invariant problems but were compelled to impart more general representations which could guide optimal design strategies in a variety of local settings, i.e. to teach technical models and modelling rather than rote techniques. These specifically didactic responsibilities clearly acted as a spur to faculty to produce (or at least explicate and codify) generic technical models, which willy-nilly also entailed research to establish the salient relationships and parameters.

In addition, engineering professors traditionally felt (and may still feel) forced to "academize" technologies as part of an ongoing collective status struggle with the classical universities. This entailed orienting their research not only to the specific design needs of technologically committed organizations but also to participation as scholars in emerging disciplinary fields (i.e. to profiling themselves as professors of engineering *science*). Hence, while aspects of their research were still disseminated within "private" networking arrangements like advisorships, patents, or participation in state and professional committees for standardization of technologies or for threshing out major design challenges, from about the 1860s onward more and more of it began to hew to the reputational logic of public science, in the form of lectures before professional associations, monographs (including textbooks), and articles in the growing number of engineering journals (which almost invariably began as proceedings or at least official organs of the engineering associations) (Ziman, 1968).

Continental engineering associations began to emerge after the mid-19th century in close association with the polytechnics; some of them in fact began their careers as little more than tacit alumni associations. Their self-proclaimed aims in all cases were twofold: (1) to provide a forum for critical deliberations on local technical experience and (2) to improve the social status and prospects of professional engineers. These associations, whatever their particular disciplinary and organizational constituencies, thus simultaneously pursued both "technical closure" and "social closure", i.e. the stabilization and optimization of technologies and their appropriation as the exclusive possession of more or less well-defined communities of professional practitioners.[13] Around mid-century, these two aims can be seen to converge at a specific point: namely the demonstrable linkage of practical design processes with socially prestigious scientific theory and mathematics.[14] This meant that as engineering schools and employers of engineers proliferated, the professional associations became increasingly important as central fora for the reflexive examination and optimization of cosmopolitan technical models, i.e. for the collation of local efforts at design and "meta-design". Unanimity and uniformity of design protocols (and especially of technical models) was a central value for the newly self-conscious engineering professions.[15] In the first place, their demonstrative commitment to critical scientific scrutiny legitimated their claim to unique expertise in the optimization of design practices. Insofar as the ideology of science stipulated monolithic truth, such claims would have been impossible to maintain were the profession to have countenanced a persisting multiplicity of competing and contradictory technical models. In the second place, uniformity of technical models, insofar as it also entailed the standardization of symbolic representations and algorithms, facilitated communication among professional engineers (e.g. electrical circuit diagrams or stress calculations for bridges produced in one location could be routinely "read" and criticized by professional colleagues elsewhere). As uniformity in technical modelling thus cemented professional solidarities, it also set up significant symbolic and linguistic barriers against competition from non-professional practitioners.

In sum, by the 1860s we can begin to discern well-articulated cosmopolitan design (and meta-design) networks, embedded in large state agencies, a few of the larger enterprises, the engineering schools and professional associations. The key protagonists of cosmopolitanization at this point seem to have been the faculty and graduates of the polytechnics, formally organized within engineering associations in which state agencies and large industries were also represented via engineer employees. By that time, not only were the polytechnics turning out graduates trained to apply newly stabilized cosmopolitan technical models to idiosyncratic local situations but their faculty were also beginning to produce highly theoretical technical models for didactic purposes and for practical application. Even at this early stage, however, the engineering faculty did not utterly monopolize this position in the division of design labour: engineers associated with the various technical corps within the military and the large state infrastructural agencies, which were part and parcel of 19th-century state formation in Europe, also continued the originary French tradition of civil service contributions to the cosmopolitan fund of technical models.

Although it is safe to say that the engineering associations were the most important clearing house for critical deliberations on technical models and hence the prime sites for their consensual stabilization, 19th-century cosmopolitan design networks were also held together in large part by personal links between engineering faculty and counterparts in the practical field; in fact, engineering professors were typically recruited from among leading practitioners. As such they quite naturally imported a concern with major "reverse salients" into the quasi-academic setting of the polytechnics. Being, however, institutionally isolated from the specific local design imperatives of state agencies or private enterprises and seeing the education of engineers as their major task, they were both enabled and compelled to focus on the more basic and generalizable aspects of the design process, including codification and standardization but emphatically also the formulation of general technical models.[16]

This emergent process can be charted for different technical disciplines and domains. It should be stressed that the phases in the process of cosmopolitanization — particularly the point at which "meta-designing" begins to be practised in academic settings — are not fixed in historical time, but correlate with domain-specific technology dynamics; i.e. "cosmopolitanization" occurs in different technical domains at very different points in time. Nonetheless, both the academic motive and the institutional framework for design "cosmopolitanization" is given with 19th-century educational modernization and the rising status of science as a legitimate academic pursuit. From that point on, the division of design labour and the emergence of cosmopolitan design networks becomes a more or less standard milepost in the development of new technical domains. Synthetic organic chemistry goes through this phase — and in a number of steps — in the last half of the 19th century (van den Belt et al., 1984; van den Belt and Rip, 1987) A latter-day replay occurs in the 1970s and 1980s with "synthon" theory (Warren, 1982). Mechanical engineering exhibited a very early example of abstracted modelling with Sadi Carnot's thermodynamics of steam engines, published in the 1820s. This was followed a few years later by a specifically design-oriented modelling effort by François Guyonneau, le Comte de Pambour.[17] Later German efforts to compose a general theory of machines tended to be more "encyclopaedic" and taxonomic than analytical in nature, but nonetheless represented further efforts to introduce technical models into the teaching (if not immediately the practice) of mechanical engineering.[18] Chemical technology offers clear examples with the emergence of "unit operations" in the first decades of the century and the ensuing efforts to introduce chemical technology/chemical engineering into the universities, especially in relation to the petroleum industry (cf. Guédon, 1979; Guédon, 1980; Buchholz, 1979). In the field of civil engineering, academic involvement in the mathematical modelling of reinforced concrete construction from the late 1890s on, became a logical extension of traditional professorial involvements in the theory of applied mechanics and elasticity in general (cf. Disco, 1990).[19] Presumably because of the already well-established networks within civil engineering and intensive state inspection of building practices, formal technical modelling and the crystallization of cosmopolitan design networks proceeded apace in this domain. In radio engineering, on the other hand, the utter novelty of the technology implied a diffuse and uncertain theoretical base and the consequent dominance of practice over theory.[20] Classical biotechnology was an extremely late bloomer, showing cosmopolitanization only as late as the 1940s and 1950s and, from about 1960 onwards, attempts at academization, e.g. the founding of university departments, the publication of handbooks and the founding of scholarly journals (cf. Rip and van der Es, 1980). There are other examples of late (and sometimes negligible) entrance into academic settings, e.g. polymer science and engineering, heterogeneous catalysis (pioneered by the oil companies and some big chemical concerns) and atomic energy engineering.[21] An exposition of the dynamics behind these later developments logically follows on a discussion of the changes since the interbellum, and particularly around the Second World War.

The universities and cosmopolitan technical regimes

Having outlined the emergence of cosmopolitan design networks on the European continent in the 19th century, it is now relevant to consider what perils and attractions these emergent networks held for the traditional universities (and, for that matter, for the rapidly academizing polytechnics as well). Early efforts to introduce what had become known as "engineering sciences" into the universities were difficult and tension-ridden because both parties were potentially compromised by such a marriage. The engineering sciences would have been forced to adopt the trappings of public science even while their practices – probably more so than with existing academic sciences – tended to be replete with private interactions and in many cases dependent on utter secrecy. From the point of view of the universities, sheltering engineering sciences and thus endowing them with academic status implied a further threat to their traditional legitimacy as centres of universal, disinterested and militantly impractical knowledge (an ideological stance which of course the incorporation of the natural sciences was already corroding) (cf. Disco, 1990; Lundgreen, 1990; Manegold, 1978; Ringer, 1979). The upshot was that for the 19th century the classical universities could be described for the most part as non-participants in divisions of design labour.[22] Indeed, until after 1900, with the notable exception of the USA, the universities eschewed participation in cosmopolitan design networks in a largely successful effort to avoid being perceived as centres of "applied science" research.[23]

Maintaining the high ground of pure public scholarship was made easier – in fact almost statutorily imperative – for the universities in continental settings because the polytechnics (acquiring formal academic status, i.e. the *Ius Promovendi*, in Germany, Austria and Holland around the turn of the century) had effectively monopolized engineering science in most fields. Hence, the electrical and electronic revolutions, despite their historical roots in academic physics and chemistry, did not become an occasion for university-based applied science on the continent because of the institutionalization of electrical engineering at the technical schools (and, parenthetically, the rapid privatization of research in state and corporate R&D labs). Until after the turn of the century, academic geology anxiously kept its distance from polytechnic-based mining engineering, concentrating on mineralogical classifications and the aetiology of formations rather than on technical models of geological strata directly relevant to the discovery and extraction of ore deposits.[24] A somewhat different relationship prevailed between university chemistry and the "chemical technology" which had emerged within the polytechnics as a pendant to various process industries.[25] It should be stressed that this academic distance from emergent cosmopolitan design networks was typical of the European continent and that other developmental patterns prevailed elsewhere. In Britain and especially the USA, where engineering schools were often tacked on to universities and where universities in any case had long experience in interfacing with practical fields (e.g. agriculture, industry and mining) academic research developed an "applied" orientation early on in the game.

The period between the two World Wars also witnessed the definitive breakthrough of industrial research laboratories (state laboratories had a longer tradition inasmuch as they were originally related to standard-setting and other regulatory tasks (Lundgreen 1986; Lundgreen et al., 1986). This implied that the engineering schools were gradually forced to relinquish their acquired monopolies on "meta-designing". More formally, the epistemological hierarchy of technical modelling began to lose its correlation with the institutional loci of, respectively, industrial production and engineering education; i.e. whereas hitherto highly generalized technical models tended to be produced by polytechnic faculty, sometimes inspired by the more contextual ad hoc technical models used in industrial design offices, it was increasingly the case that theoretically sophisticated "meta-designing" was being carried out within industry itself – either in close association with design facilities or within specialized R&D units. Such local excursions into meta-design incidentally provided ideas for numerous new artifacts and processes. For example, the Philips Corporation's facile entry into radio vacuum tube design and production after the First World War appears to have been a direct consequence of the in-house production of technical models related to the design of medical

X-ray tubes during the First World War. These developments, which tendentially began to divorce the production of theoretically sophisticated technical models from specific types of sites in the institutional division of design labour, adumbrated the new configurations in cosmopolitan design networks which would emerge after the Second World War. In these configurations, the universities (both technical and classical, insofar as the latter had begun to host "applied sciences") would cease to play the role of *sole* "custodians of meta-designing" and become integrated into cosmopolitan design networks in a much more piecemeal and fragmented fashion, even if their contributions continued to emphasize generic and abstract aspects of technology rather than contextualized design proposals.

As the loci of theoreticity and meta-design began to be organizationally dispersed, the second substrate we have identified for the division of the design labour, i.e. "design hierarchies", began to become increasingly salient. A possible categorization of such a hierarchy might be:

- *components* (e.g. materials, nuts and bolts, resistors and condensers, radio vacuum tubes) that do not "perform" by themselves, but have to be assembled to do their job;
- *devices* (e.g. a pump, a switching circuit, a sensor) that are assembled sufficiently to show their primary effect;
- *functional artifacts* (e.g. a machine, a bridge, a radio), that work by themselves;
- *systems* (a plant, an electricity network, radio broadcasting plus receivers plus organizations to produce radio programmes) that fulfil a sociotechnical function.

These levels merge into each other (a radio vacuum tube can also be seen as a device), but the point is that a hierarchy exists, and that design work can take place at different levels. At first (analytically, but often also historically), design takes place at the level of artifacts or systems, and components and devices are made for that purpose, or, where necessary, drawn from suppliers. Development work and design are frequently performed by suppliers, but will depend on specifications provided by the customer.[26] Network relationships develop, but these are concerned primarily with production and sales, not with a division of labour in design work. In principle, design cosmopolitanization can occur when suppliers begin to service several customers and can optimize their products according to generalized specifications. Technical and other sciences can be mobilized, but for specific purposes; for example, as Cooray (1985) has shown in the case of the synthetic rubber industry, petrochemical suppliers produce chemicals as building blocks for synthetic rubber products that other firms make, and do chemistry research which draws on general chemistry, rather than developing specialized research programmes (as they do for their own process technology, cf. the example of heterogeneous catalysis mentioned earlier).

Another route for technical innovation implicit in the technical design hierarchy is that components or rough versions of devices are discovered, and possibilities for using them in artifacts or systems are explored. The zipper is an interesting example of a device that has set into motion a whole series of innovations in clothing and coverings. It is also important as an example because it does not derive from scientific research at all. The use of X-rays in medical apparatus is an intermediate case: the phenomenon was discovered in a scientific laboratory, and in the course of basic scientific research, but it might also have occurred elsewhere (say, in a photographer's studio), and the design work did not draw on scientific insights (and could not do so, because there was no systematic knowledge of X-rays in the beginning).[27] By now, there are also many cases where (basic or strategic) science is working toward innovative components or devices systematically, for example in polymer science and solid-state science (new materials) and in micro-mechanics (sensors and actuators) and mechatronics (robotics). It is clear from the latter examples that technical-scientific fields have emerged that are partly institutionalized within technical and classical universities, which thus come to play a recognized "cosmopolitan" role in technical innovation on this basis.

Before this could happen, however, it was necessary that generalized design supply, the supply of components and devices, became an innovative activity, and recognized as something intrinsically worth pursuing. The rise of the industrial laboratory in the interbellum, discussed previously in relation to meta-designing, was also a consequence of the interest in research into components and devices in general, the Philips Corporation's Applied Physics Laboratory (*Natuurkundig Laboratorium*) again being a clear example. Subsequently, efforts during the Second World War provided a further push in this direction, when scientific knowledge and scientific manpower were mobilized on a large scale, and whole new areas of research were created in which much fundamental work occurred, but within an overall framework defined as component or device research. Polymer science, radar and other electronics areas, and atomic energy research, are well-known examples, where there had been specialized activities before the war, while full-fledged specialties existed after the war.

The universities were able to relate to the new situation through individual contacts and specific research projects, and participated in this new version of the cosmopolitan design network but now, as it were, "on call", instead of on their own terms by virtue of their monopoly of a specific institutional position in a well-defined functional division of labour. They were now included or excluded according to circumstances. In principle, they were in a position to pursue innovation at the level of components and devices, and in fact the technical sciences and parts of academic chemistry and physics did exhibit such activities. To the extent this occurred, however, there was no longer an exclusive focus on design at the abstract level of the technical models (i.e. "meta-design") but rather a focus on designing bits and pieces of the conceptual and artifactual "tools" that practitioners (e.g. industrial researchers and designers) needed in their quotidian work.[28] In the event, however, practitioners put little or no pressure on universities to produce such work, perhaps because there were other sources in the continuing expansion of industrial research laboratories and the new wave of government laboratories focusing on technical innovation rather than standard-setting and regulation. New academic specialties could and did emerge, however, and the training of technical specialists was increasingly seen as the primary mission of the universities (as the pressure — but only by the 1960s — for chairs in polymer science and heterogeneous catalysis shows). A role in cosmopolitan design networks became a salient issue again by the late 1970s and 1980s, but only because the nature of the cosmopolitan design networks was again changing, and becoming strategic.

After 1945, the different, nationally specific institutionalizations of the division of labour in engineering design, and thus the role of universities, converged as the patterns of organization of R&D in general became more uniform in all the western industrialized countries.[29] One aspect is particularly important for our argument: the way the research council system (in the USA: the National Science

Foundation) came to play a central role in academic research, with its peer-reviewed allocation of research funds putting a premium on reputation, specifically reputation in one's own discipline. This is a major factor in the persistent relative autonomy of academic research settings after the Second World War, where research agendas are set on the basis of promising avenues of research (i.e. promising in the sense of producing reputational capital for the researchers in the disciplinary field rather than on relevance to the solution of design problems in dispersed local design settings). This, incidentally, is a second reason why the academic educational and research system has become ever more loosely coupled to extant cosmopolitan design networks (i.e. apart from the rise of industrial and state labs). In any case, a very visible consequence has been that the contribution of the applied and technical sciences to the cosmopolitan design networks has become less coordinated; there has certainly been scarce evidence of direct or even indirect control of academic research agendas by technologically committed firms or state agencies.[30]

In the 1950s and 1960s, there was little concern about a possible gap with practice (and perhaps little reason to be concerned). During the 1970s, however, it seems to have become a universally recognized problem. It was felt that the "fit" between academic engineering and applied science on the one hand and organization-based design problems on the other was leaving much to be desired. Given the traditional structure of evaluation and financing of academic applied science – of which the research autonomy of scholars remained the ridgepole – there were also few points of leverage for outside organizations to influence patterns of academic research and networking so as to increase responsiveness to their local design needs. In the Netherlands this became recognized as a problem even with "applied research" at the technical universities and the state-sponsored central applied science research facility (TNO) *in spite* of their traditional proclivities and even mandates to network with technologically committed organizations. This lack of effective feedback from local design settings to the sites of abstract "meta-design" and "generalized design-supply" research became both a policy concern and a concern of many of the actors themselves, and has led to all sorts of local and national remedial activity.

The current state of cosmopolitan technical regimes and the role of universities

From the early 1980s on, three strands were being woven into the fabric of cosmopolitan design networks. First, the meta-design role of the technical sciences in academic settings has remained important, and links up with increasingly sophisticated mathematical modelling approaches. Second, the design supply role has become more important, and has extended to more sciences. One element of the recent programmes to promote strategic or innovation-oriented science is in fact no more than the mobilization of academic sciences for design supply. Programmes aimed at developing new materials (polymers, membranes, ceramics) are good examples. Third, innovation competition between firms and the strategic positioning of states and "blocks" of states (e.g. in the TRIAD) has added a new element to technical innovation: the primary aim is no longer an actual innovative outcome, but rather the coverage of a potentially important area of innovation. One indicator of this new orientation is that firms are prepared to spend (a lot of) money on the support of academic research in order to have a "window on science". The coupling with local design problems is becoming remote, even within firms themselves. Thus, there is now an expanded range of opportunities for academic science to link up with innovation interests. Science has become a strategic resource.

It is not immediately clear what the new cosmopolitan design network structure implies for the role of universities and the position of the technical sciences. What is clear is that the strategic alliances among firms now also include governments, professional engineering societies and universities.[31] It is also evident that future promises and expectations are becoming more important, sometimes more so than actual innovation.[32] Clearly, technical sciences and computer sciences are now in a position to play cognitively novel roles. What kind of institutional roles correspond to this, and what this implies for a division of design labour and the role of universities is less clear. Universities may well be becoming less unique and certainly less "ivory towerish" than they have ever been since the Second World War.

Nonetheless, academic engineering scientists have tended to persist in their efforts to become part of the established academic reputation and reward system. This creates tensions in some fields because traditional design-relevant research results may not always be visible in the usual academic productivity evaluations based on outputs of scientific articles. But this is seen to be temporary, and a problem only for building engineering, maritime engineering, and some parts of civil and mechanical engineering. It is expected that these fields will overcome their difficulties and become well integrated into the scientific publication system in another fifteen years or so. As one university researcher explained when asked about the conflict between design-based and "academic" technical sciences:

> . . . science hasn't penetrated very far in a number of technological fields. And at the moment the kinds of things you're raising are applicable there. Because if you look at design in, for example, airplanes then it's much less in evidence. Because designing an airplane also demands mastery of mathematics and mechanics. So people who design airplanes quite often have doctorates and publish articles. It mostly concerns sciences where technology is present but where the scientifically quantifiable element is rather limited. And I think that at present that pertains only to architecture, nautical engineering, and small pieces of traditional civil engineering (roads and hydraulic works) and mechanical engineering. But that's getting smaller and smaller. So I think it will end up disappearing altogether. In other words that it's a problem that won't exist any more in 10 to 15 years. And it's still an issue now because with promotions to associate professorships and professorial appointments or with the quantification of research program outputs a lot of engineering science departments plead this phenomenon as an excuse, in order to — if not exactly justify — then at least to explain their shortcomings or inadequate production and to say that it's also necessary to look at other things. (university researcher, mechanical engineering; van der Meulen, 1991)[33]

One should, however, be wary of taking such statements at face value. While they may be correct in the sense that publication outlets will be created in due course, this need not imply that technical-scientific work will de facto be limited to publishable research. In fact, one may well expect a renewed importance of links with practice, and of work that is produced for audiences other than the readership of scientific journals. Not only for strategic reasons, but also because much of the testing of the tools developed is done by using the tools for real design prototyping.

> Proof is not only mathematical or physical proof. The proof of a theory is also quite often that it works well under certain conditions. That is, showing examples. (university researcher, electrical engineering; van der Meulen, 1991)

Thus, this work will be done in addition to, rather than instead of, publishable academic work.

One incentive for academic technical scientists to remain within (or re-enter) cosmopolitan design networks comes from within the university system itself, in particular from the pursuit of "societal relevance" and alternative funding sources by university and departmental boards (Webster and Etzkowitz, 1990). Recently in the Netherlands, but also elsewhere, the continuing fiscal crisis of the state has given teeth to policy measures aimed at a better articulation of interorganizational relations and structures (innovation programmes, university-industry links) which can usefully be seen as part of cosmopolitan design networks. Budget cutbacks have indicated a zero-growth future for the universities — at least insofar as primary state financing itself is concerned. However, this financial regime is refracted through the structures of competitive relations among administrative units at all levels of the academic system. The basic constraint is that expansion at any level (departments, universities, disciplines) now depends in large part on the exploitation of "external" sources of funding by the lowest level working units within the universities. These relatively small semi-autonomous research and teaching units are accordingly under increasing pressure to perform as "cognitive entrepreneurs" within their specific scientific-technical domains. Increasing portions of their time and energy are now devoted to tapping sources of external funding (which incomes are in turn "taxed" by their departments and universities). These "tertiary" contracts with state or corporate clients are in fact beginning to overshadow traditional "secondary" funding via the research councils and foundations. This provides a strong motivation to link up with cosmopolitan design networks, but for different reasons than when the polytechnics and universities first ventured into actual "engineering-science" research. Then, it was to maintain a kind of cognitive dominance over technical practice; now, it is to get access to resources.

Tightly bound up with acquiring financial resources, yet a distinct problem, is acquiring informational resources. Given the division of design labour, the utility and hence the "exchange value" of each actor's contribution will depend to a large extent on information about what the others are doing and what they might need (and hence be willing to pay for). This becomes an especially critical problem for university research groups under pressure to produce academically countable results; the necessary concentration on *graue Theorie* entails a danger of estranging them from practical needs to such an extent that they are no longer able to produce *directly* marketable knowledge, yet they can't afford to abandon academic legitimations either:

> What's in it for the research unit is that . . . you (retain) feeling with practice. If you're preoccupied only with fundamental work and model systems then you run a chance of becoming a little isolated from what's happening in the practical world, in industry and such. And those are often counterparts. People who want to know things, that you talk to, where the students also finally end up. So when you look at research in our group then our own research is reasonably fundamental research on model systems and in this area we proceed independently on a scientific basis. In addition we have projects with a strong relation to practice. We find such a mix agreeable. Not just this kind of project, because then you're only applying knowledge and not learning anything new and not only fundamental projects because that's too isolated. For us, these kinds of projects are a nice combination with our own research. (university researcher, applied physics; van der Meulen, 1991)

Hence, both financial and cognitive logic compels university research groups to start building alternative technological networks, including ad hoc contractual relations with firms and state agencies looking for fundamental design support. Such initiatives are echoed and facilitated at all levels of the academic system, e.g. by the establishment of mediating nexuses like "transfer points" within the technical universities. Functionally, the new networks serve to integrate academic engineering science more intimately into the cosmopolitan R&D and design system because they are now subject to contractual stipulations with regard to budgets and specified outputs. For the universities this implies an unprecedented measure of external non-academic steering of research agendas.

Correspondingly, technically committed firms and state agencies, having become paying customers, rather than mere abstract beneficiaries, of university research, are now able to specify the latter's goals in line with their own specific design problems.[34] At the same time, their role as paying customers is predicated on their being able to define the research questions to be set, i.e. they have to work at technical modelling and design supply themselves in order to get something useful out of the universities. In other words, the very fact that firms and government agencies can profit from the fruits of university research presupposes that university research becomes defined as an extension of what already occurs (to some extent) within the firm or agency. This means that questions nowadays tend to get posed not in the language of the market, but in the language of technological science itself. All things being equal, this makes it easier for engineering academics to pursue both scientific reputation and practical design relevance. This is corroborated by a university researcher in chemical engineering participating in the Coatings Research Stimulation Project funded and coordinated by the Dutch government:

> I think that for a research project you have to pose (scientific) goals. Now that's not really strange because the big companies that work on the problem apply the same reasoning for themselves. And indeed, when we work for them they say, "give us background, design, give us information that will allow us to manipulate our (coatings) systems. And don't go and paint planks yourselves." They have their own people to paint planks. They stimulated us within the framework of the Coatings Research Stimulation Project to look at fundamental phenomena, and not at other things. (van der Meulen, 1991)[35]

This trend toward university-state-industry cooperation has been with us for some time now and has generated enthusiasm, as well as concern about shifts, possibly for the worse, in academic science. This also holds, mutatis mutandis, for emergent forms of cosmopolitanization in which the state acts as a collective proxy "steering agent" for national programmes of technology development. Here, although the intent is to stimulate design-relevant "technical modelling" and "design supply" research (in high-tech as well as more traditional areas) there are not always direct networking links to the end-users. Major R&D programmes of European countries and the European Community are aimed at stimulating such "strategic science" and, increasingly, in close collaboration with industrial firms (e.g. JESSI, BRITE, ESPRIT, EUREKA). The involvement of academic researchers in these programmes, not only as performers of research, but also as advisers and reviewers, creates a social carrier for a new reward and reputation structure, in which it becomes *bon ton* to participate in at least one European programme.

Participation in these emergent, contractually mediated cosmopolitan design networks raises (at least initially) identity, legitimation and allocation problems for the academic research units because it tendentially divorces the acquisition of growth resources from the acquisition of scholarly prestige and in fact subjects academic scientists to different evaluative regimes at the same time. While this is not entirely novel, insofar as both regimes have been present all along, the new situation demands the establishment of new working relationships. One way in which this problem manifests itself is as follows: as part of recent state efforts to rationalize research financing, research units (certainly including those at technical universities) have been confronted with systems of evaluation and concomitant reward structures, based on traditional "public science" criteria like volume of publications and international prestige. However, as actors in cosmopolitan R&D and design networks they are also being de facto rewarded on the basis of their ability to produce customer utilities. The more rational or gratifying it becomes for research units to pursue growth and "societal relevance" rather than scholarly prestige (a preference which has a chance of *once again* becoming the modal orientation of research units at least at technical universities) the more they will struggle to get scholarly evaluation criteria supplemented by criteria which reward participation in entrepreneurial rather than academic networks. Insofar as this succeeds (which will tend again to place the "exchange value" of publications on a par with private reports, advisorships, proto-designs and consultations) the university as a whole tends to become a functional link in cosmopolitan networks of technology development and hence to acquire a secondary research dynamic oriented to the new reward and reputation systems. Think in this connection of the rapid rise of quasi-academic R&D and consultancy firms (in the wake of the Route 128 phenomenon) in high-tech areas, but also in environment and in social science and policy analysis. If one confronts technical scientists in universities with this point, they tend to argue that scientific criteria must be, and in fact are, dominant, even though they confess that ultimately scientific and industrial criteria are inextricably intertwined:

> I think that that duality is clearly understood. That scientifically important aspects are treated and that at the same time people have the feeling that there are possibilities for application. . . . I've also spoken about this research (at a number of universities, BvdM) and they say, "gee, that's great that you've got this under control." Core-shell structures with anorganic particles. You can graft iso-groups onto it, pharmaceuticals, magnetic particles, you can do this with it and you can do that with it. In these settings they are, chemically speaking, very pleased with the idea that you can control these kinds of morphologies. I've also been to a firm . . . and they have a monstrously huge research lab, and yes there of course they're busy with applying core-shell structures to photocopying materials. And there they find the applications very important as well. (university researcher, chemical engineering; van der Meulen, 1991)

Another commentator, a university-based electrical engineer, testifies to the tacit importance of practical utility even in explicitly scientific evaluations:

> Practical applications are mentioned in the publications, but papers are reviewed chiefly on scientific grounds. But what has to be realized in addition is that each field has its own kind of discipline in the sense that certain theories are judged more favorably the more their practical usefulness becomes evident. Our field is not a theoretical field. It's a real applied science and the applicability of the results is something that willy-nilly plays a part in the evaluation of a theory. (van der Meulen, 1991)

Hence, in suitable contexts, university researchers can also emphasize the importance of participation in the strategic cosmopolitan design network. As long as this brings resources that can also be put to use for academic purposes, they do not see a problem. So a possible conflict is overcome by "double accounting", i.e. doing work that is relevant in more than one setting.

Summary and conclusions

Central to our argument has been the complementarity of local and cosmopolitan technological regimes. While actual production is almost always already embedded in supplier–customer relationships and *filières*, the knowledge, skills and artifacts that go into the design of new products and production processes may seem to depend only on the capacity of the local situation. But the quality and scope of the knowledge and skills is non-local in origin, and is maintained (and often certified) in interaction with professional colleagues elsewhere. The artifacts built reflect widespread views on what is a good ship's hull, a good reinforced concrete viaduct, or a good radio.

Historians of technology have always reconstructed what we here call "cosmopolitan technological regimes". But they have not generally understood the presuppositions underlying their compilation of locally specific data, documents and technical configurations into one homogeneous story. There must be some active sharing, some coordination and some standardization of knowledge, skills and artifacts. And since the overall body of knowledge, skills and state-of-the-art artifacts increases, based on local activities, there must be some division of labour. It takes a sociologist (actually, three) to pick up this point.

Thus, our first conclusion is that cosmopolitan technological regimes exist, and orient action and practice in different local situations. Given the existence of cosmopolitan technological regimes, and their orienting function when they are sufficiently shared, different kinds of actors can mutually adjust their roles. This will not happen without struggle, of course. One example is how the struggle of the engineers to be accepted in the academic system reinforced the tendencies to mathematization (cf. Layton on engineering theories, 1990) and to scientification, which existed already.

What sorts of things turn out to be the components of cosmopolitan technological regimes, especially those which are relevant to a possible institutional division of labour? One important component is the design hierachy, a concept that is a generalization of the well-known distinction between "system" and "components". The layered, hierarchical nature of design, from materials and components, to devices, artifacts and systems (even socio-technical systems), allows independent work to be done on part of the design, which can be optimized in its own terms and hence profit from novel inputs from other domains. New materials and components can be explored and developed further, without being bound to the specific requirements of a given system and its functionalities.

The other important component is the technical model, the generalized, often abstract representation of a kind of artifact, with its relevant configuration and related functionality. Immanent modelling, i.e. thinking in terms of a technical model during local design work, is ubiquitous, part of the skill of the technologist, and allows continuity and cumulation of work over time. When the configuration and functionality, say, of a ship's hull, is modelled in general, one can engage in, as it were, virtual manipulation of parameters and features of the model, independently of specific local design work. This is still technological work, and we have called it meta-design, to emphasize that one can contribute to technical development without producing *specific* practical outputs, artifacts or systems that work.

Both design hierarchy and technical model are epistemic categories. In each particular instance, a design hierarchy and a technical model is socially, institutionally and politically embedded, and in fact shaped by such factors. In Kim Clark's use of the concept of "design hierachy", it is out there, in the automobile firms. Our concept is epistemic, because we ask how it is at all possible that such concrete, socially located design hierarchies appear. Having accepted the epistemic nature of design hierachies, one can understand how they provide a cognitive-technical infrastructure, which is available to others and can be used for their purpose.

These considerations lead to our second main conclusion: in the dynamics of technical development itself, cognitive infrastructure appears, which has slots that can be filled by work which is distant from the site of actual design work and technical innovation. One can now trace the emergence of cognitive infrastructure, together with the development of technical and engineering sciences, and the role of universities in the overall division of labour in technical development. These are, as it were, three corners of a triangle. An important point emerging from our analysis is that the university is not essential for the development of technical and engineering sciences. The side of the triangle connecting cognitive infrastructure and the emergence of technical and engineering sciences is sufficient to describe the rise of, e.g., polymer science, heterogeneous catalysis and atomic energy engineering. Thus, when universities are involved, they must play a particular role. We have identified two main roles: (1) meta-design work, the production and improvement of technical models, in order to improve engineering instruction (and perhaps also to contribute to technical development directly); note that this role is historically possible because of the social infrastructure of the engineering profession; (2) the identification of physical effects, materials and components, and the exploration of possible applications.

Historically, we have shown that the universities (or at least the polytechnical schools) were, for a time, the main location for meta-designing. But with the rise of industrial research laboratories in the interbellum (with precursors in earlier periods) the meta-design role became much less exclusive, and the exploration of new materials and components was taken up in earnest in industrial research. After the Second World War, government research institutes added their bit, and universities were involved in an ad hoc and piecemeal fashion.

Sociologically, one can understand these changes as the effect of expansion, institutionalization and rationalization of technical development. Design hierarchies became more finely articulated, tasks for "suppliers" could be set more easily, and university research could be mobilized for specific jobs, rather than being focused on the comprehensive role of technical model creation and perfection. While technical and engineering sciences within the universities continued to emphasize professional training for a long time, the autonomization of university research, because of the rise of the research council system and other forms of reward and incentives to mimic basic sciences, reinforced the trend to be separated from local technical regimes, remaining on call, but not necessarily identifying with their problems.

Our third main conclusion thus pertains to the effects of the secular expansion and differentiation of technical development and its division of labour. The slots in the cognitive infrastructure were increasingly filled by meta-design and design-supply work performed by organizations other than universities, and universities were left, as it were, to find their own niches (which they did).

By the 1970s, two changes were under way. Because of the new political context, social relevance and industrial linkages were deemed important for the universities while, at the same time, the technical and engineering sciences were becoming strategic. The universities had to reposition themselves yet again, and this created all sorts of institutional adaptations (and concerns). These issues have often been foregrounded, as we noted in the introduction. But one should look at the epistemic level as well. Again, technical design work can be done at the meta-level, but now because of possibilities inherent in the strategic exploration of simulation models, identification of opportunities for innovation, and other aspects of the "strategic turn" that we began to identify in the last section. It is too early to reach any definite conclusions about this transformation. Our claim, however, is that there is a new cognitive infrastructure in the making, and that a new role for the universities is possible if they take up this challenge. Work done in the US Engineering Research Centers and in the European R&D Programmes at the Community level, is illustrative of the kinds of opportunities now emerging, and the divisions of labour apparent there adumbrate the new interorganizational division of labour of which the universities can be an integral part.

Cornelis Disco is Assistant Professor in the Department of Philosophy of Science and Technology of the University of Twente. He is engaged in a research project on "Influencing Technological Design Regimes". His thesis *Made in Delft: Professional Engineering in the Netherlands, 1880*-1940 was published in 1990 (University of Amsterdam).

Arie Rip is Professor in the Department of Philosophy of Science and Technology of the University of Twente and head of the research programme on "Dynamics and social shaping of development of technology". Recent publications not mentioned in this article: *The Research System in Transition*, S.E. Couzens, P. Healey, A. Rip and J. Ziman (eds) (1990) and "The Danger Culture of Industrial Society", in R.E. Kasperson and P.J.M. Stallen (eds) *Communicating Risk to the Public*, pp. 345-65 (1991).

Barend van der Meulen is Research Assistant in the same department and is writing his PhD thesis on evaluation and control of science. He has co-authored one article: "Has the Study of Philosophy at Dutch Universities Changed under Economic and Social Pressure" (with L. Leydesdorff), *Science, Technology and Human Values* 16 (1991): 288-321.

Authors' address: Vakgroep FWT; TW-RC 310; Postbus 217,7500 AE Enschede, Nederland.

Notes

1. To simplify the exposition we will write as if technical designing gets done only in private industrial firms and bracket other important settings like state agencies or even university researchers and research groups. In terms of budgets and personnel, for all but a few sectors, this is hardly a misrepresentation of the actual state of affairs, irrespective of the particular divisions of design labour prevailing at any historical juncture.

2. During the 18th century "industrial tourists" began to corrode the strictures of technical localism. Descriptions of typical industrial processes, such as appeared for example in Diderot and d'Alembert's famous *Encyclopédie*, not only acquainted general enlightened readers with "states of the art" in various industrial sectors, but also demonstrated to industrialists the importance of what was happening elsewhere. This established the paradigm for technical cosmopolitanization (in the tradition of important precursors like Agricola's *De Re Metallica*) inasmuch as a non-producing (and even non-designing) centre accumulated information on numerous more or less idiosyncratic local practices, abstracted a kind of idealized standard practice, and disseminated the transformed practice back to the local settings as an ideal example.

3. In fact, British technological hegemony in the areas of iron and steam had already produced a kind of "quasi-cosmopolitanization" in the technological peripheries. Inasmuch as the new technologies had been brought to maturity entirely within Britain (i.e. without significant involvement by non-British firms) they impinged on the various peripheral industrial communities as external, i.e. "cosmopolitan" technologies. That is, not having arisen out of existing "local technological regimes" in the peripheries, the new intertwined technologies of iron and steam implied the existence of a compelling third-party technological authority (i.e. the British capital goods industry) whose "universalist" accomplishments and edicts had willy-nilly to be absorbed into the technological practices of firms throughout the contemporary technologically developing countries.

4. In the case of innovative technologies the direction of tutelage could run the other way. In such cases firms often monopolized crucial know-how garnered in the course of experimentation and practical trials. An example is the case of reinforced concrete construction around the turn of the century, the practical (and even to a large extent theoretical) mastery of which was the prerogative of private contractors. Government agencies desiring to apply (or regulate the application of) the new technology to, e.g. bridges, locks, piers or buildings, had to learn to work with the new material by carefully observing the design and construction activities of private firms (cf. Disco, 1990).

5. The concept of "design hierarchies" is adapted from Clark (1985). Note however, that in contrast to Clark we attempt to work out an epistemic, rather than an institutional definition of design hierarchy.

6. Robert Pirsig (1974) not only explains the hierarchical functionality of motorcycles, but also relates this explicitly to the Kantian problem of conceptual order in the world. He also makes the valuable point that hierarchical heuristics are not only essential to intelligent innovation, but to intelligent maintenance and repair as well.

7. Hans Hutter, in his thesis on the development of fluorescent lighting and research in the Philips Corp. Research Laboratories (NatLab), introduced the notion of "evaluative dimension" in order to understand the directions of the research, and provided some insight into the question of how they related to organizational strategies and professional disciplinary cultures (cf. Hutter, 1988). Bijker, (forthcoming) also makes a similar point in his treatment of the controversies surrounding the development of fluorescent lighting in the USA.

8. The status of this particular technical model is ambiguous because it was unmasked, in terms of the cosmopolitan reinforced concrete regime of its time (1930), as portraying a distinctly inferior (though still partly functional) configuration of steel reinforcement in a reinforced concrete beam and column joint. In fact, insofar as it is a *normative* model, it is a model of evil rather than virtue, of how *not* to design this type of joint rather than how to design it. This shows that technical models can play many roles (among others, as diagnostic or evaluative tools in technology assessments). It also shows that the existence of empirically and theoretically justified technical models at the cosmopolitan level is no guarantee for their actual use in local practice; in fact in this case local practice produced its own deviant technical model and hence its own deviant and ultimately inferior constructions.

9. Examples include "inventors" like Thomas Edison (electrical equipment and power systems), Guglielmo Marconi (radio), and Francois Hennebique (reinforced concrete). On Edison cf. Hughes (1983), Gorman and Carlsson (1990); on Marconi, cf. Aitken (1976); on Hennebique, cf. Disco (1990).

10. Aitken (1978) discusses this problem in the field of early radio technology. Also pertinent is McMillan (1979) on the extensive development work required to transform high-density polythene from a laboratory phenomenon to a working artifact.

11. A clear-cut example is synthetic organic chemistry after 1880, especially in Germany. It may well be that the division of design labour only takes off in earnest when design work within industry itself becomes generalized through the establishment of a separate research laboratory. Evidence that this may indeed be the case can also be seen in Hans Hutter's (1988) observation that physics research in universities

relevant to fluorescent lighting commenced only after similar research in the Philips NatLab was taken up in earnest in the 1920s.

12. Starting with polytechnics at Prague (1805), Vienna (1815), and Karlsruhe (1833); but also with more heterogeneous schools like the *Berlin Gewerbsinstitut* (consolidated ca. 1810), the Parisian *Ecole Centrale* (1829) and the Dutch *Koninklijke Akademie* at Delft (1842). For histories of European engineering education see: Lundgreen (1990); Manegold (1978); Ringer (1979); Shinn (1980); Torstendahl (1985); Weiss (1982).

13. For instance, the circular sent around in 1847 to parties presumably interested in the formation of a Dutch engineering association proclaimed that, given the existence of such an organization, "the discoveries, the observations, the experiments, the inventions and the designs of engineers no longer need remain locked up in their studies; they can be more openly dealt with, evaluated, and estimated as to their worth, and the illuminating rays of art can be converged as in one focus" (cited in Lintsen, 1980: 97).

14. Such "mathematization" of design had already been prepared in France in the circles of the *Corps des Ponts et Chaussees* and among *Polytechniciens* in general, for example in the elaborate theory of suspension bridges published by Henri Claude Navier in 1823 (and which won him admission to the *Academie* in the following year) or the thermodynamic theory of steam engines published by Sadi Carnot in the 1820s. For Navier and the social origins of French theoretical mathematical modelling see Kranakis (1989).

15. In the Netherlands, for example, against the background of heated polemics about proper technical models and practices for the construction and evaluation of reinforced concrete constructions, the Royal Institute of Engineers appointed committees in 1906 and again in 1912 to draw up uniform codes. The committees were composed of engineers representing the major reinforced concrete contracting companies, the central state and several municipal public works agencies, the Army and the state railway company. Such examples could be multiplied at will, but are especially frequent in emergent technical domains where discursive closure on technical models and practices is strategically important for the establishment of professional hegemony.

16. A similar point can be made (and has been made) about the importance of teaching practices, and the teaching function in general, for the emergence of theory in science, e.g. by Peter Janich (1978), and is prefigured in the analysis of Medieval cathedral building by Böhme et al. (1978). Rip (1982) adds to this argument by looking at technical dynamics (i.e. control of conditions and effects) within science, and arguing that "Increasing restrictedness leads to empirical generalizations and conceptual distinctions, i.e. "bottom-up" theory formation" (p. 231). Generalization is important in science to spread one's knowledge claims more widely; this becomes important in technology as soon as technical sciences have created a domain for themselves, with colleague technical scientists rather than designers and practitioners as consumers. The point in the main text is then that generalization is already implied in the very establishment of polytechnics as teaching institutions *tout court*.

17. Pambour published his *Théorie de la machine à vapeur* in 1837. It was widely translated and in fact used to design practical steam engines by his contemporaries — in vivid contrast to Carnot (cf. Kroes, 1990).

18. A comprehensive theory of machines was developed by Redtenbacher and Grashof at the TU Karlsruhe, and by Franz Reuleaux during the 1860s and 1870s.

19. In fact the international cosmopolitan design network that emerged around reinforced concrete after 1890 was extremely heterogeneous in composition. At an international level it was embodied primarily in publications in national technical journals, in monographs, and unquestionably in visits and personal correspondence. Participants in what turned out to be a cosmopolitan technical modelling debate included prestigious professors of civil engineering, state public works engineers, officers of military engineering corps and engineers in the employ of major reinforced concrete contractors.

20. In radio engineering, technical models tended to be intuitive or at best highly speculative and, such as they were, to be generated mainly within firms manufacturing wireless equipment and within state agencies with mandates in this domain (Aitken, 1976, 1985). Only after radio technology began to stabilize in the mid-1920s did engineering schools become significant research sites for "meta-designing" (generally aimed at high-level theoretical models of waveforms, propagation, etc.) and did reasonably elaborated cosmopolitan design networks emerge (Disco, 1990).

21. See Freeman (1974) for the history of Catalytic Research Associates, a consortium of the big companies that developed catalytic cracking of oil in the 1930s and early 1940s. While the technical modelling of such technologies had gone a long way in industry, it was only in the 1960s that professors (at first, part-time) were appointed. This is probably related to a tradition of black boxing of the catalytic process (as a component or device, cf. discussion below) in chemical technology and process technology, and a renewed interest when research at the microscopic level became possible.

22. In the 18th and early 19th century, there was less reluctance in the classical universities to get involved in technology, as witness the fact that theology students were trained in agricultural techniques (so that they could also minister to the material wants of their parishioners). This can be related to the general Enlightenment ideology (cf. the *Encyclopédie*), and occurs at a time when the technology itself is not very articulated. So it is still a non-division of labour, but for other reasons.

23. Medicine might appear to be an exception but was, at the time, very little scientificized and instrumentalized, and insofar as it did work as a technology, could be ideologically papered over as really belonging to the realm of "ministering to the body". The situation in the US is complicated because the traditional universities were involved in a long struggle to emancipate themselves from an ideology of teaching and doing practical work, and did not want to fall under the newly created label of "applied science" (cf. Daniels, 1967), and attempted to imitate the German research university — while at the end of the century, land-grant colleges (including the University of California and other, by now well-known universities) could be established with tax relief, etc., provided they worked in the public interest.

24. In the Netherlands, at least, university geology began to proclaim its relevance for prospecting heuristics only after the state-owned East Indies Mining Agency began to expand after 1900 and to generate managerial and prospecting research positions attractive for academics. In 1912 and 1913, in the wake of a new expansion, a heated controversy broke out over the relative suitability of university geologists vs. mining engineers for these positions (cf. a series of articles and commentaries in the major Dutch engineering journal, *De Ingenieur*, 1912). Two things may be learned from this: first, "academic" air may become extremely rarefied in the face

of attractive research or employment opportunities in "applied" sectors, especially if the discipline in question is already low on the academic prestige hierarchy and is facing labour market or funding problems. Second, inasmuch as positions in "cosmopolitan design networks" are associated with legitimated access to particular kinds and amounts of resources, adjustments sought by interlopers always give rise to defensive moves and controversy before a new (and more complex) division of engineering labour is achieved.

25. Within chemistry, relations were more complicated: analytic chemistry and organic chemistry at the universities were also practice-oriented, and maintained an orientation to and interactions with government and industry. The professional associations, on the other hand, wanted to distance themselves from practice orientations, primarily because the label "chemist" also applied to low-status occupations. In the 1920s, when the pertinent distinctions seemed secure, much closer and more solidly institutionalized interaction with industry was realized. The technical universities, with their focus on chemical technology (i.e. technologies of processing chemicals on an industrial scale) were complementary, rather than competitive.

26. This by itself leads to one strand of technical innovation, and has become an important business strategy for firms like Philips, which glorify the relationship with the label "co-makership". Cf. also Pavitt's (1984) empirical analysis of patterns of innovation, leading to a classification of firms into four categories, one of which being "suppliers" (dominated by their customer) and thus often not much more than "jobbers".

27. There are many such intermediary cases, but they tend to be relabelled as fruits of science and hence illustrative of its cornucopian character. High-density, "regular" polythene is an example (cf. McMillan, 1979), penicillin another. Although Fleming is often seen as the innovator, his discovery was of a mould extract that killed certain bacteria, and could be used for taxonomic purposes. Antibiotic possibilities and large-scale production were taken up only later, by Florey and Chain. But "science takes credit for penicillin . . .", as Jerry Ravetz has put it (and his aphorism continues) " . . . while society takes the blame for the bomb".

28. Statements to this effect return in interviews with technical scientists (e.g. mechanical engineers working on fundamental issues in thermomechanics; van der Meulen, 1991).

29. The point has been recognized from time to time, for example by Rip (1979), but never properly analysed. An indicator of the convergence is the ease with which the OECD was able to set up science policy review activities in the early 1960s.

30. The situation is a bit more complicated, certainly in the Netherlands, where the research council system was extended only gradually to disciplines other than physics, with the technical sciences becoming integrated into the standing peer review panel system by the 1970s. Still, the technical universities, while maintaining their links with practice, were able to follow their own research agendas because of the continuing expansion in this branch of academia since the early 1950s. Their eventual integration into the research council system, and later into the conditionally financed research system in the universities modelled on peer review allocation, can be seen as a continuation of the trend. By that time, however, both the claims on technical sciences as well as the support structures for the universities were changing, and new strains developed.

31. John Hagedoorn (1989) has mapped strategic alliances, and is starting to publish analyses of his data. The role of engineering and universities is somewhat

neglected, although this could be an essential factor (e.g. as a locus for exchange of techno-economic intelligence; cf. Rip, 1991).

32. The innovation race in Very Large Scale Integrated circuits is a case in point. Not only is competition phrased in terms of "who will be the first to produce the next generation of chips", there is also a lot of work in computer aided design and testing of chips, and computer simulation of production technology possibilities. When the computer-generated designs of chips are tried out in the simulations of production technologies, the innovation competition could in principle be fought out completely within the computer. Cf. Rip (forthcoming) which refers to a report on "VLSI: Linking Design and Manufacturing", in *IEEE Spectrum* (Oct. 1988), 24–28. For a discussion of the role of expectations in setting the agenda in membrane R&D, see van Lente and Rip (1990).

33. The trend is not just academization of technical sciences. Because of the cosmopolitanization of design work, it becomes possible to have scientific journals publishing the generalized results. The pockets of traditional technical sciences that the interviewee identified are then exactly those where local design work is dominant, and it becomes a question of whether cosmopolitanization will be possible there or not.

34. They used to be much more concrete beneficiaries (especially in relation to the technical universities) but post-Second World War developments, and especially the dominance of the Helmholtz–Bush rationale for supporting science in general, redefined them as abstract beneficiaries.

35. It should be noted that this applies in general only to the largest firms, i.e. those capable of maintaining at least their own research facilities. Relations with smaller firms are much more difficult (and much less interesting) for university research groups to deal with. The respondent just cited continues: "And then of course you see the problem big as life. Because the participating coatings industry that doesn't, like AKZO and DSM (big multinationals, BvdM), possess their own research labs and that can't interpret the information, they say, 'What use are all those dissertations to us? I want to make a new coating next week.' But I'm sorry, that's a problem, but we have enough problems of our own, we tend to shy away from this area a little. I don't believe it's the task of the university to solve that problem" (van der Meulen, 1991).

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