Imperial College London
BUSINESS SCHOOL

Carol Corrado, Peter Goodridge, Jonathan Haskel

Constructing a price deflator for R&D: calculating the price of knowledge investments as a residual

Discussion paper 2011/07

November 2011

Constructing a Price Deflator for R&D: Calculating the Price of Knowledge Investments as a Residual*

Carol Corrado, The Conference Board and Georgetown Center for Business and Public Policy
Peter Goodridge, Imperial College Business School
Jonathan Haskel, Imperial College Business School and CEPR
August 30, 2011 (revised version)
July 3, 2010 (original version)

ABSTRACT

We model the production and use of knowledge investment and show how the model can be used to infer the unknown price of knowledge using two approaches. The first is often used by national accounting offices and is based on costs in the knowledge-producing sector. We show this implicitly assumes no market power and no productivity in the production of knowledge. We set out an alternative approach that focuses on the downstream knowledge-using sector, the final output sector. The science policy practice of using the GDP deflator is a simple variant of this approach, while the full approach allows market power and implies backing out the price of R&D from final output prices, factor costs, and TFP. We estimate a R&D price for the United Kingdom from 1985 to 2005 using the full approach. The index falls strongly relative to the GDP deflator suggesting conventionally-measured real R&D is substantially understated.

* The authors gratefully acknowledge support from NSF's SciSIP Grant 0830260 (Corrado) and the FP7 COINVEST Grant 217512 and UK NESTA innovation index project (Goodridge and Haskel). We thank Dennis Fixler, Shane Greenstein, and participants at the NBER/CRIW Summer 2010 workshop and 2010 CAED for comments. Errors are our own.

Corresponding author: carol.corrado@conference-board.org.

Constructing a Price Deflator for R&D: Calculating the Price of Knowledge Investments as a Residual

"The value of an idea lies in the using of it."
Thomas Alva Edison

International guidelines (SNA 2008) call for capitalizing R&D in national accounting systems, a welcome move, but one that raises vexing measurement issues. A major issue—perhaps *the* major issue at this point—is how to construct a price deflator for R&D. Currently there are quite a few candidates: (1) R&D often is equated with knowledge production, and an education deflator could be used. (2) Science policy analysts long have used the GDP deflator to deflate R&D, and national accountants could continue and enrich that practice. (3) National accountants could regard R&D as they regard other "hard to measure" outputs and use an input cost deflator, perhaps adjusted for productivity. (4) Finally, given the development of the R&D marketplace *via* the licensing of patents and the like, national accountants could obtain a price deflator by dividing revenue in the R&D marketplace by a quantity index of patents or scientists.

This paper sets out a framework that can be used to discuss and evaluate alternative price measures for knowledge investment; the framework is then used to construct a price index for private R&D in the United Kingdom from 1985 to 2005. The model and framework we develop is applicable to commercial knowledge investments more generally (i.e., investments in intangible assets as in Corrado, Hulten, and Sichel 2009, and Marrano, Haskel, and Wallis 2009, Haskel *et al.* 2009, Corrado and Hulten 2010, among others) and to measuring R&D price indexes for other countries.

The Edison quote above captures the basic notion behind the models and price estimates reported in this paper. We argue the four candidates can be reduced to two basic approaches: one we call the "upstream" approach in that it attempts to model and measure the knowledge production process itself, and the other we call the "downstream" approach that—in the spirit of the Edison quote—infers the price of knowledge investment from the fruits of the innovation process, total factor productivity (TFP).

Innovation arguably is a routine function within business these days (Baumol 2002). For some ongoing, existing firms, the business function devoted to innovation is explicit as the R&D or marketing or development department. In others, the function is less centralized or based on employee time, as in CEO Eric Schmidt's famous 80/20 rule at Google.[1] For entrepreneurial start-up businesses, almost by definition, high fractions of activity are devoted to innovation, broadly defined. Accordingly, we model aggregate business output as emanating from two sectors: one, the aggregate behavior of business functions devoted to innovation and R&D, and the other, an operations and/or producing sector consisting of all other business functions.[2]

In the first use of the model, we show how the price of the commercially-produced knowledge is related to measured output prices, factor costs, and productivity in the operations sector. We compare and contrast this "downstream" approach to the "upstream" approach typically favored by statistical agencies, and we relate both approaches to the endogenous growth model of Romer (1990) in which markups of self-produced knowledge capital play a critical role. After considering how key aspects of innovation types (e.g., breakthrough vs. incremental innovations) and imperfect competition (e.g., markups) impact the modeling and measurement of output prices for innovation, we conclude such prices are implicitly in measured downstream sector productivity, that is, the value of resources devoted to innovative activity can be inferred from their use in business operations.

Because productivity as conventionally measured includes a contribution from the innovation sector, the second use of our model frames how to tease this contribution out of standard productivity data. Of course, conventional wisdom is that *all* sustained increases in TFP are due to innovation because of spillover effects.[3] And even though data constrain us to concentrate on

[1] Known as the "Pareto principle" in management, this refers to Google's ITO (Innovation Time Out) policy that employees are encouraged to spend 80 percent of their time on core projects and 20 percent on "innovation" activities that pique their own interests.

[2] Business functions are entire classes of activity within a company. See Brown (2008) for further information on the use of business functions as a classification scheme for statistics on business activity.

[3] This view has its roots in the production function approach to R&D, in which *all* productivity growth is related to *all* expenditures on R&D (Griliches 1979, p. 93). Of course the view ignores the productivity-enhancing effects of public infrastructure, the climate for business formation, and the fact that R&D is not all there is to innovation, but nonetheless the view that TFP reflects the fruits of the business innovation process is acknowledged to be generally

estimating a price index for commercial R&D investments (rather than all investments in innovation), we still find that a substantial fraction of observed productivity change in the UK market sector emanates from its conduct of R&D. We obtain this result by exploiting the recursive nature of our model and the heterogeneity in R&D intensity by industry. The result impacts the estimated investment price index for UK R&D, the central estimate of which falls 7.5 percent per year from 1985 to 2005.

Our falling price index reflects both the success of industrial R&D (including spillovers) and the impact of innovations in the R&D process itself. Indeed, available evidence suggests technical progress in the "production of innovation" has been substantial. Consider how computer-enabled combinatorial chemistry has drastically lowered the costs of pharmaceutical experimentation, how computer-aided design has lowered product development times for items such as semiconductors, motor vehicles—even the British Museum's tessellated glass ceiling—and how the Internet has promoted academic collaboration and productivity (Adams, Black, Clemmons, and Stephan 2005; Ding, Levin, Stephan, and Winkler 2010) and made huge amounts of information available more or less for free.

Why is our finding of a falling price index for R&D of interest? Many advanced industrialized countries are concerned by the stagnation of their nation's R&D spending in relation to their GDP. But if the real price of R&D relative to GDP is falling, information in nominal terms is a misleading indicator. As we show below, with our new price index, the contribution of R&D capital deepening to the growth in output per hour in the UK remains substantial even though nominal R&D spending relative to GDP is flat/falling.

This paper proceeds as follows: In the next section, we set out the model and show how it can be used to infer the unknown price of commercial knowledge investments using two approaches. We then consider a host of theoretical and practical issues that confront the empirical application of each approach, and finally we turn to measurement and conclude.

---

more right than wrong. The view is an important element of the approach used to develop an innovation index for the UK (Haskel, et al. 2009).

1. Theoretical Framework

This section sets out a theoretical framework that can be used to discuss and evaluate alternative price measures for commercial knowledge investments such as R&D. We start with a very simple model to show the main arguments of our approach and how it compares with other methods. We then explore the robustness of the model and approach to relaxing certain assumptions.

1.1 The model

We posit a market economy with two sectors—knowledge-producing and knowledge-using—and three factors of production—labor, capital, and knowledge. The knowledge-producing (or upstream) sector generates new knowledge (N) using service flows from labor (L^N), capital (K^N), and a stock of existing knowledge, denoted R^N.

The stock of existing knowledge is superscripted by *N* because the knowledge used in the producing sector is assumed to be different from that in the using (or downstream) sector. Although we elaborate more fully on this assumption below, a simple way of thinking about the distinction is to suppose that the upstream sector uses "basic" or "unfinished" knowledge and transforms it into commercialised or "finished" knowledge. The finished knowledge is then employed in the production of goods and services by the downstream sector. We further assume that all basic knowledge is free, from universities say, and determined outside the model. In a subsequent section we relax some of these assumptions.

The production function for the upstream industry and corresponding accounting equation for factor payments is written as follows:

$$N_t = F^N(L_t^N, K_t^N, R_t^N, t); \quad P_t^N N_t = P_t^L L_t^N + P_t^K K_t^N \qquad (1)$$

where *N* is newly-produced appropriable knowledge and P^L and P^K are prices per unit of labor and capital input, respectively. There are no payments to R^N because its services are free. The downstream sector produces consumption and investment goods $(Y = C + I)$ by renting service flows of labor (L^Y), capital (K^Y), and a stock of finished commercial knowledge,

denoted R^Y. The stock of finished knowledge is the accumulated output of the upstream sector, which is assumed to grow with the production of *N via* the perpetual inventory model:

$$R_t = N_t + (1-\delta^R)R_{t-1} \tag{2}$$

The term δ^R is the rate of decay of appropriable revenues from the conduct of commercial knowledge production.[4]

The production function and flow equations in the downstream sector are

$$Y_t = F^Y(L_t^Y, K_t^Y, R_t^Y, t); \quad P_t^Y Y_t = P_t^L L_t^Y + P_t^K K_t^Y + P_t^R R_t^Y \tag{3}$$

where P^R is the price of renting a unit of the finished knowledge stock (e.g., a license fee for a patent or blueprint). The relationship between P^N, the price of a unit of newly-produced finished knowledge (an investment or asset price) and the price of renting a unit of the same knowledge is given by the user cost relation

$$P_t^R = P_t^N(\rho^N + \delta^R) \tag{4}$$

where ρ^N is the real rate of return in sector N and taxes are ignored. Recalling that sector Y includes the production of investment goods I, equations similar to (2) and (4) for tangible capital but expressed in terms of $K^Y, I, \rho^Y, \delta^K, P^K$ and P^I (instead of $R^Y, N, \rho^N, \delta^R, P^R$ and P^N) complete the model.

We are now in a position to understand two broad approaches, upstream and downstream, to modelling R&D prices. Log differentiation of the income flow equations and dropping time subscripts gives the following price duals:

$$\Delta \ln P^N = s_N^K \Delta \ln P^K + s_N^L \Delta \ln P^L - \Delta \ln TFP^N \tag{5}$$

$$\Delta \ln P^Y = s_Y^K \Delta \ln P^K + s_Y^L \Delta \ln P^L + s_Y^R \Delta \ln P^R - \Delta \ln TFP^Y \tag{6}$$

[4] This concept of depreciation was introduced and applied to private R&D by Pakes and Schankerman (1984).

The "s" terms are factor income shares for labor, capital, and knowledge calculated for each sector in the usual way from equations (1) and (3), respectively. The terms $\Delta \ln TFP^N$ and $\Delta \ln TFP^Y$ are the change in total factor productivity for each sector, i.e., the shift in each sector's production function. The interpretation of the sector productivities and their relationship to aggregate productivity for the economy as a whole is discussed in a subsequent section.

1.2 Upstream method: data from the R&D-performing sector

Consider equation (5). Most statistical agencies have survey data on the R&D business function of R&D-performing firms; thus, existing surveys give us information on the first two terms in equation (5). But equation (5) also shows that productivity *in* the R&D sector $\Delta \ln TFP^N$ is needed to estimate prices for R&D, and information on this quantity is very scant indeed.

Economists long have studied the impact of R&D *on* productivity, but quantitative studies of productivity *in* the R&D process itself are fairly rare. Studies of the impact of the Internet were mentioned previously. Agrawal and Gort (2001) show that product development times shortened steadily from 1887 to 1985, suggesting improvements in R&D productivity are somewhat of a norm. And Mokyr (2007, p. 1154) states "In the past, the practical difficulty of solving differential equations limited the application of theoretical models to engineering. A clever physicist, it has been said, is somebody who can rearrange the parameters of an insoluble equation so that it does not have to be solved. Computer simulation can evade that difficulty and help us see relations in the absence of exact closed-form solutions ... In recent years simulation models have been extended to include the effects of chemical compounds on human bodies. Combinatorial chemistry and molecular biology are both equally unimaginable without fast computers."

The upstream approach is the dominant approach used by statistical agencies.[5] In its most basic form, the method assumes, in (5), that $\Delta \ln TFP^N = 0$ and uses only share-weighted input costs to measure output price change. This variant has been used by both the UK Office of National Statistics (ONS) and US Bureau of Economic Analysis (BEA) to approach the measurement of

[5] In what follows, we review recent work in statistical agencies; for a review of the earlier literature on R&D deflators, see Cameron (1996). The very recent release of the US BEA/NSF Satellite Account on June 25 is not considered.

R&D prices, e.g. Galindo-Rueda (2007) and one of the approaches reported in Copeland, Medeiros and Robbins (2007).[6] A more refined variant, referred to in Fixler (2009) as scenario B, assumes a rate of TFP growth that is subtracted from share-weighted change in input costs, much as in equation (5). Finally, a related approach proposed by Copeland and Fixler (2009) is based on modeling the R&D services industry (US NAICS 5417, UK SIC 73.1); they suggest these "market-based" results can be used to proxy for all (i.e., in-house) private business R&D.[7]

The Copeland-Fixler price index increases a bit less than overall private R&D input costs and, taken literally, suggests $\Delta \ln TFP^N$ averaged 0.1 percentage point per year from 1987 to 2004. The plausibility of this result and interpretation is discussed below.[8] More fundamentally, the premise of the approach—using the R&D services industry to generate results for all private R&D—requires scrutiny. Some NAICS 5417 industry revenues are for contract research whose character may be inconsistent with the standard definition of R&D. And the establishment-based industry classification may place a nontrivial number of company-owned R&D laboratories in the R&D services industry, in which case industry "revenue" will not be entirely market-based.

Given the development of the R&D marketplace *via* the sales and licensing of patents, national accountants could strengthen the upstream approach by urging statisticians to collect data on unit sales and license fees for patent and other intellectual property rights (IPRs). But one must note that such observations could correspond to P^R, or to P^N, or to $(1-\delta^R)^{\mathrm{T}} P^N$ (the latter when data are for units of R of age T that obsolesce at the rate δ^R per period), suggesting just some

[6] Despite its drawbacks this approach has the advantage of consistency as it is widely used in recent efforts to produce R&D satellite accounts in other countries. The method also is used in areas where no market transaction data exist, such as measurement of own-account software investment in the UK, as well as much of government output and other hard-to-measure areas such as education services in many countries.

[7] The Copeland-Fixler approach is to back out price change from changes in the industry's sales (S) less changes in quantities of the industry's output. If one is willing to assume that the number of workers $(SCIENTISTS)$ and patents (Z) proxy for the quantity of R&D output in NAICS 5417, then their approach, expressed in our notation, is $\Delta \ln P^N = \Delta \ln S^{5417} - .5 * (\Delta \ln Z^{5417} + \Delta \ln SCIENTISTS^{5417})$.

[8] As practical matter we also note that the result partly rests on the assumption that output per worker is unchanged over time, an assumption that is difficult to accept for a technology-intensive activity such as R&D. To improve the validity of the Copeland-Fixler approach, it may be worthwhile adjusting the number of workers for changes in composition (or "quality") *via* marginal-product weighting.

hurdles to be crossed in working with data from the IPR marketplace. Indeed, existing revenue data for the R&D services industry are likely confounded by these same issues.

1.3 Downstream method: data from the R&D-using sector

An alternative approach is to consider the downstream or R&D-using sector. Manipulation of equation (6) shows that it can be re-written as:

$$\Delta \ln P^R = \left(\frac{\Delta \ln P^Y - s_Y^K \Delta \ln P^K - s_Y^L \Delta \ln P^L + \Delta \ln TFP^Y}{s_Y^R} \right) \qquad (7)$$

which says that the unknown $\Delta \ln P^R$ can be inferred from final-output price changes, net of changes in other input costs and offset by the sector's TFP. Because we have suppressed the dynamics that give rise to differences in the time paths of P^N and P^R, the unknown $\Delta \ln P^N$ will be equal to $\Delta \ln P^R$ given constancy of ρ^R and δ^R.

In practice, we have many R&D-using industries. If R&D were a homogeneous good, the price from any one of them will do or one might combine prices from a number of downstream industries together to give a "grand" index, $\Delta \ln P^{R^*}$, a weighted average of R&D rental prices across those industries

$$\Delta \ln P^{R^*} = \sum_{i=1}^{J} \omega_i \left(\frac{\Delta \ln P_i^Y - s_{iY}^K \Delta \ln P_i^K - s_{iY}^L \Delta \ln P_i^L + \Delta \ln TFP_i^Y}{s_{iY}^R} \right) \qquad (8)$$

where there are J R&D-using industries; each industry is indexed by i; and ω_i is a weight to be determined.

In its most general form, the downstream approach infers R&D prices from output prices (such as GDP prices) and is the most common approach used in analyzing R&D data for science policy analysis. It is a method that follows the Edison logic. Moreover, a specific approach in Copeland, Medeiros, and Robbins (2007) is an even closer cousin of equation (8) than the GDP deflator. This is the BEA price index for R&D used in their R&D satellite account; it is calculated as the weighted aggregate

$$\Delta \ln P^N = \sum \omega_i \Delta \ln P_i^Y \qquad (9)$$

across the most intensive R&D-using sectors with ω_j the j^{th} industry's share of total R&D investment. Equation (8) shows, however, that science-policy analysts and Copeland, Medeiros, and Robbins (2007) ignore the denominator and implicitly assume changes in the downstream sector's share-weighted factor prices and productivity net to zero.

The downstream approach requires information on the sector's productivity change, $\Delta \ln TFP^Y$. This will differ from the usual productivity measure because services from the stock of commercial knowledge are modelled as an input to the economy's core operations and attributed to the upstream sector. This service flow can be thought of as a Hicksian shift in the sector's standard labor/capital production function for the period during which each unit of knowledge remains commercially viable. While a host of factors determine the size of this effect (and some will be discussed in the next section), what matters in this model is that returns to appropriable inventive activity are allocated to the upstream sector.

In terms of the salient drivers established in the productivity literature, our model views the distinction between the sectoral productivities as follows: Upstream productivity includes the appropriated returns to R&D, spillovers from public R&D, and the efficacy of the overall R&D process, whereas downstream productivity includes spillovers from freely available commercial knowledge (i.e., diffusion), as well as phenomena we associate with operations efficiency (e.g., economies of scale and services delivery improvements, etc.) that are unrelated to R&D.

2. Theoretical issues

This paper uses the downstream method. The simple model of the previous section has been designed to set out the broad intuition of the approach and illustrate its relation to other recent work. To carry on with the application requires reviewing a number of practical theoretical issues to which we now turn.

2.1. Use of knowledge in each sector

How robust is our assumption that the N sector uses free "unfinished" or basic knowledge, R^N, and the Y sector rents "finished" knowledge, R^Y? A number of points are worth making. First,

of course, if the final-output sector also uses free unfinished knowledge (that is, in addition to renting of finished knowledge produced by the N sector), nothing changes. The contribution of the free part of knowledge to production in the downstream sector shows up in $\Delta \ln TFP^Y$.

Second, one might extend the model and assume that the N sector also uses "finished" knowledge, as an input for example into producing more finished knowledge. But then the problem arises of how to define the total stock of finished knowledge when both sectors draw from it. We cannot define each sector as renting from the entire pool of knowledge, because then we would implicitly be allowing the same knowledge to be "rented twice" which results in an overstatement. Although some studies suggest very large private returns to R&D, still others suggest little more than competitive returns when consideration also is given to measuring the rate of decline in the value of the underlying R&D asset, i.e., the rate of depreciation in (2).

We have already assumed that knowledge is partially nonrival. A useful direction at this point therefore is to think about how we pay, for example, for Microsoft Office and how we might distinguish between knowledge in "platforms" and in "versions," a form of the breakthrough versus incremental distinction in innovation analysis. Suppose the N sector uses a large quantity of resources to produce a knowledge *platform* from which it supplies *versions* to the Y sector every year (e.g., Microsoft creates Word and then leases Word 2003 version 1, version 2, etc. each year). In this case, the one-year leasing of a version does not generate any lasting asset held in the Y sector and so these payments are intermediates (just as payments by a cinema owner who rents a film to show for a month are treated as intermediates rather than rentals to the knowledge capital in the film industry).

But this does not necessarily mean that there is no stock of appropriable knowledge, or that there are just intermediate payments that net out. Rather we can think of the upstream sector as retaining ownership of the knowledge asset in its "inventory" or "product platform portfolio." As an asset, the platform both earns a return (say at the rate $\rho^R P^N$ per unit of R each period, equivalent to the value each unit adds to current production) *plus* it generates a flow of income via payments by the downstream sector for rentals of each version. If the version rentals are at the rate $\delta^R P^N$ per unit of R (that is less than the full rental value of the stock of R), then the

knowledge asset is not being "rented twice" and the aggregate payment to R remains as given by equation (4). This argument could be made more formal, but the logic is simple: The N sector must implicitly pay something (to itself) to rent the knowledge in its platform in order to have the resources to create version after version. Equivalently, the N sector cannot charge the full rental equivalence suggested by (4) for versions because the full knowledge capital inheres in the platform, and only partially in the versions.

2.2 Market power in the upstream sector

This issue was considered by Romer (1990), who assumed innovators practiced monopoly pricing. Our model is similar to his: he has three sectors. The ideas sector uses all knowledge in the economy freely as an input into ideas. Those ideas are then converted by the design sector into blueprints, knowledge which is appropriable and sold at a monopoly price to the production sector that uses blueprints as an intermediate good. Thus in our model it is the upstream, or innovation/R&D sector that can be thought of as the design sector who produces blueprints; in our language, they produce finished ideas that can be used in the output sector. Thus designs are rival and appropriable (at least for a time), and they are sold at the monopoly price to the production sector. Romer notes the "design" sector can of course be in-house.

Copeland and Fixler (2009) also state that uncertainty and market power are endemic in the research sector, by which they mean that although there is a correlation between the output and input prices of R&D, this relationship is highly non-linear and it is not possible to establish a linear approximation of R&D prices using input costs (see their Appendix B). As a concrete example, Copeland and Fixler follow Romer and model the innovator as a monopolistic competitor with respect to other innovators, which suggests the output price is above marginal production cost. In Romer the innovator's price is given by $P = \gamma MC$, where MC is the marginal cost of producing a new good and γ is the markup, a function of the good's price elasticity of demand (Romer 1990, un-numbered equations at the top of page S87).

Romer goes on to formulate the intertemporal zero-profit constraint, whose solution equates the instantaneous excess of revenue over marginal production cost as just sufficient to cover the interest cost of the innovation investment (equations 6 and 6', page S87). How does this result

relate to the framework in this paper? Let us follow Romer and assume that product market power is located in the upstream sector.[9] In other words, the downstream sector, which uses the innovation, is competitive while the upstream sector, which produces the innovation, is a (temporary) monopolist. Under these assumptions, in our model, downstream producers are price-takers for knowledge.

If downstream marginal production costs are expressed as competitive payments to the usual factors of production L^Y and K^Y, then final output prices are indeed marked up over such costs—but not necessarily because of imperfect competition. Denoting the competitive factor costs of core operations as $C^Y F^Y \ (= P^L L^Y + P^K K^Y)$ where C^Y is the weighted-average cost of the usual inputs per unit of final output, then the producer markup in our model is expressed as $P^Y = \gamma C^Y$, with the markup given by

$$\gamma = 1 \Big/ (1 - s_Y^R) \quad . \tag{10}$$

In this way, section 1's expressions for downstream factor payments (3) and price dual (6) still hold. We show this by moving from the producer markup relation given by (10) to the downstream factor payments identity as follows:

$$\begin{aligned} P^Y Y &= \gamma C^Y F^Y \\ &= C^Y F^Y + P^R R^Y \\ &= P^L L^Y + P^K K^Y + P^R R^Y \end{aligned} \quad . \tag{11}$$

This result establishes consistency of our framework with models of imperfect competition with producer markups and intertemporal zero profits, e.g., the equilibrium model of Rotemberg and Woodford (1995). Moreover, even if the knowledge price faced by the downstream sector is not the competitive price, as long as the downstream sector is a price-taker, the dual price equation for the downstream sector, which is what the downstream method relies upon, can still be written as equation (6).

[9] The same assumption is made in Aghion and Howitt (2007), among others.

If the price of knowledge faced by the downstream sector is not the competitive price due to imperfect competition in the upstream sector (*innovator* markups), the factor shares in *that* sector will be biased measures of output elasticities in which case measured $\Delta \ln TFP^N$ as conventionally calculated is a biased measure of "true" technical progress (e.g., see Hulten 2009). The implausibly small average annual percent change in R&D productivity implied by the Copeland-Fixler upstream approach as calculated (conventionally) and reported in section 1.2 of the paper is therefore theoretically invalid in the presence of innovator markups, as Copeland and Fixler themselves would and do argue. By contrast, as we show below, the downstream approach yields a measure of $\Delta \ln TFP^N$ even in the presence of innovator markups.

2.3 Market power in the downstream sector

Suppose there is market power in the *downstream* sector as well. Recalling that $\Delta \ln TFP^Y$ represents the contribution of knowledge that is freely available to all competitors, a shorthand for considering imperfect competition is to modify this term in equation (6). As written, changes in TFP pass through one-for-one to changes in output prices. If factor prices are exogenous, this is consistent with a competitive model of process innovations whereby any process innovator immediately lowers her output prices to undercut rivals, and the competitive equilibrium is that all such TFP changes are passed through 100 percent.

A simple way to represent imperfect competition in the downstream industry is to pre-multiply $\Delta \ln TFP^Y$ by $(1-\zeta)$, where $\zeta = 0$ is perfect competition (100% pass through) and $\zeta > 0$ indicates monopoly power. That is, we write:

$$\Delta \ln P^R = \left(\frac{\Delta \ln P^Y - s_Y^K \Delta \ln P^K - s_Y^L \Delta \ln P^L + (1-\zeta)\Delta \ln TFP^Y}{s_Y^R} \right) \tag{12}$$

to incorporate the impact of imperfect competition in the downstream industry. A monopolistic downstream industry with significant barriers to entry would have $\zeta = 1$ in which downstream R&D monopolist users appropriate all returns to process R&D (productivity gains) via pricing power.

In our discussion of equation (8) in section 1.3, we indicated that BEA has made use of a downstream method, but that an implicit assumption that factor costs and TFP net to zero was made via calculating an R&D price index as equation (9). Equation (12) suggests another way of thinking about the BEA index, namely, that the implicit netting may also reflect an implicit assumption about the degree of downstream monopoly power.

2.4 Product quality

Upstream production also leads to product-quality innovation in the downstream sector. If final output prices are not quality-adjusted, the true model written in terms of the quality adjusted-price, $\Delta \ln P^{Y^*}$, is as follows:

$$\Delta \ln P^R = \frac{1}{s_Y^R}(\Delta \ln P^Y - s_Y^K \Delta \ln P^K - s_Y^L \Delta \ln P^L + \Delta \ln TFP^{Y^*}) - \frac{1}{s_Y^R}(\Delta \ln P^Y - \Delta \ln P^{Y^*}) \quad (13)$$

where true productivity change $\Delta \ln TFP^{Y^*}$ has been calculated using quality-adjusted prices. Equation (13) suggests that if quality is improving, $\Delta \ln P^Y > \Delta \ln P^{Y^*}$ and a negative bias may be imparted to estimates of $\Delta \ln P^R$.

But the exact bias also depends the relationship between $\Delta \ln TFP^{Y^*}$ and $\Delta \ln TFP^Y$. In the Hulten (2009) steady-state quality ladder model,

$$\Delta \ln TFP^{Y^*} = \Delta \ln TFP^Y + (\Delta \ln P^Y - \Delta \ln P^{Y^*}) \ . \quad (14)$$

Equation (14) says that the measurement error from not quality-adjusting $\Delta \ln P^Y$ (and hence mis-measuring $\Delta \ln TFP^{Y^*}$) cancels out, rendering $\Delta \ln P^R$ an unbiased steady-state measure even with unobserved product quality improvement.

2.5 Sector productivities and markups in the steady state

The foregoing places imperfect competition in the upstream sector. We now explore the relationships among the sector productivities $\Delta \ln TFP^N$ and $\Delta \ln TFP^R$ and the relative value of resources devoted to innovation—the innovation intensity s_Y^N—in the presence of upstream markups.

Let the innovator markup over (competitive) upstream factor costs be given by $\mu \geq 1$. Continuing with the simplified notation of 2.2, the value of upstream output then becomes

$$P^N N = \mu C^N F^N \tag{15}$$

where $C^N F^N$ is the cost of the conduct of innovation/R&D in terms of the standard factors of production (labor and tangible capital) at competitive factor prices $(C^N F^N = P^L L^N + P^K K^N)$. Changes in the price and quantity elements of $C^N F^N$ refer to the per unit share-weighted input costs and share-weighted input quantities denoted as $\Delta \ln C^N$ and $\Delta \ln F^N$, respectively.[10]

Upstream productivity is then given by:

$$\Delta \ln TFP^N = \Delta \ln N - \mu \Delta \ln F^N \tag{16}$$

and downstream sector productivity is given by

$$\Delta \ln TFP^Y = \Delta \ln Y - (1 - s_Y^R)\Delta \ln F^Y - s_Y^R \Delta \ln R^Y \quad . \tag{17}$$

The upstream price dual now becomes

$$\Delta \ln P^N = \mu \Delta \ln C^N - TFP^N \tag{18}$$

whereas the downstream sector's factor payments and price dual remain as given in section 1.

How do innovator markups and sector productivities relate to (a) our previous discussion of the Romer model, (b) the literature on intangible capital that would include R&D co-investments in $P^N N$ and (c) actual measured productivity growth in an economy? First, equation (17) follows from our earlier argument that treating inputs to innovation as investment produces a Romer-style framework in which revenue from the production of final output must be sufficient to cover the "interest costs" of innovation. These costs subtract from productivity as per equation (17) because they are, in fact, forgone final output.

Second, theoretical models that incorporate markups usually follow Romer and impose intertemporal zero profits by setting the markup to one in steady-state equilibrium (e.g., Rotemberg and Woodford 1995). The structure of our model also is consistent with using the

[10] The similarly defined magnitudes for the final output sector and the total economy are $C^Y F^Y$, $\Delta \ln C^Y$, $\Delta \ln F^Y$ and CF, $\Delta \ln C$, $\Delta \ln F$, respectively, where $\Delta \ln F = (1 - s_Y^R)\Delta \ln F^Y + s_Y^R \Delta \ln F^N$, and so on.

parameter μ to incorporate the cost of commercializing R&D outcomes as a simple multiple of R&D (e.g., the intangible "complementary" capital in Basu *et al*. 2004), in which case temporal zero profits is imposed while μ is most assuredly not equal to one.[11]

Finally, following standard practice, measured productivity growth $\Delta \ln TFP^{measured}$ is given by the difference between the growth rate of final output, $\Delta \ln Y$, and the growth of measured share-weighted total factor inputs (that is, including the inputs used in the innovation sector), denoted as $\Delta \ln F^{measured}$. This quantity exceeds the competitive quantity $\Delta \ln F$ in the presence of innovator markups because some of the increment to revenue is used to cover markups. We denote the real value of this increment by Π, in which case the foregone growth in final output associated with markups on the conduct of R&D is written:

$$\begin{aligned} \Delta \ln TFP^{measured} &= \Delta \ln Y - \Delta \ln F^{measured} \\ &= \Delta \ln Y - \Delta \ln F - \Pi \end{aligned} \qquad (19)$$

Thus Π must be added to the change in (upstream) factor inputs valued at competitive factor prices to capture the full costs of the R&D "overhead" borne by the downstream sector.

Under steady-state conditions the growth rate of a capital stock is well approximated by the growth rate of real investment (Griliches 1980). Let *g* be such a growth rate for real R&D investment and its stock. As *g* approaches the real interest rate ρ^N, the investment share approaches the capital income share (Jorgenson 1966), i.e., we can write $s_Y^R = \tau s_Y^N$ where τ is a discrete-time version of the Griliches (1980) term that converts gross investment to income from accumulated net investments:

$$\tau = [(\rho^N + \delta^R)(1+g)] / (g + \delta^R) \qquad (20)$$

The term approaches one in the $\rho^N \cong g$ "maximal consumption" steady state.

[11] A rationale for this interpretation is that the R&D data only cover costs of pursuing new scientific and engineering knowledge, and a "successful" R&D outcome (a patent, say) does not necessarily imply immediate business viability, much less costless implementation. Many new product development costs are not captured in the available R&D data because they are associated with activities considered to lack sufficient experimentation to be classified as R&D but are nonetheless an inseparable aspect of the "value" of R&D.

Substituting τs_Y^N for s_Y^R and $\Delta \ln N$ for $\Delta \ln R^Y$ in equation (17) and then expanding the result using equations (16) and (19) yields the following:

$$\begin{aligned}\Delta \ln TFP^Y &= \Delta \ln Y - (1-\tau s_Y^N)\Delta \ln F^Y - \tau s_Y^N \Delta \ln N \\ &= \Delta \ln Y - (1-\tau s_Y^N)\Delta \ln F^Y - \tau s_Y^N \Delta \ln TFP^N - \tau s_Y^N \mu \Delta \ln F^N \\ &= \Delta \ln Y - \Delta \ln F - \tau s_Y^N \Delta \ln TFP^N - \tau s_Y^N (\mu - 1)\Delta \ln F^N \\ &= \Delta \ln TFP^{measured} - \tau s_Y^N \Delta \ln TFP^N\end{aligned} \tag{21}$$

where $\Pi = \tau s_Y^N (\mu - 1)\Delta \ln F^N$, which goes to zero as μ approaches one.

Rearranging terms in the last line of equation (21) yields

$$\Delta \ln TFP^{measured} = \Delta \ln TFP^Y + \tau s_Y^N \Delta \ln TFP^N \tag{22}$$

which depicts an economy's measured productivity growth as an (approximate) Domar-weighted average (Domar 1961; Hulten 1978) of the productivities in its innovation and final output sectors. The equation highlights our modelling of the knowledge *production process* (not just R&D spending) as an augmenter of final output productivity. Augmentation depends on R&D spending *and* the productivity or "success" of the R&D activity.

3. Measurement

Our approach is to formulate the empirical growth accounting counterpart to the theoretical model of the previous sections and then construct the terms on the right hand side of equation (8) to estimate price change for private R&D. For this we need estimates of input shares and final output productivity that account appropriately for the contribution of R&D to economic growth.

We cannot use the usual growth accounting terms because they are biased. We thus face three central measurement challenges: First, we need estimates of the unobserved final output productivity ($\Delta \ln TFP^Y$) i.e., productivity excluding the contribution of R&D. Second, we need values for the unobserved capital income share of innovation assets (s_Y^R). Third, we need a value for the unobserved innovator markup. These needs may be expressed in terms of available measurements and three parameters, θ, τ, and μ, as follows:

$$\begin{aligned} \Delta \ln TFP^{Y} &= \theta * \Delta \ln TFP^{measured} \\ s_Y^R &= \tau * s_Y^N \\ &= \tau * \mu * s_Y^{N\,measured} \end{aligned} \qquad (23)$$

where $s_Y^{N\ measured}$ is the R&D intensity calculated using the cost data available from R&D surveys.

We further note that values for the parameters τ and μ permit calculation of the producer markup of equation (10) as $\gamma = 1/(1-\tau * \mu * s_Y^{N\,measured})$.[12]

3.1 Obtaining values for θ, τ, and μ

Equation (22) suggests that the variation in *industry-level* measured TFP growth rates and R&D intensities can be exploited to decompose measured productivity for an economy into a contribution from its final output sector and a contribution from its innovation sector. In other words, assuming that downstream productivity does not vary with innovation intensity at the industry level, an industry dataset containing gross output-based TFP estimates for multiple industries and corresponding industry counterparts to $s_Y^{N\,measured}$ from R&D surveys can be used to run the following regression:

$$\Delta \ln TFP_{G,i,t}^{measured} = a \ + \ b \cdot s_{G,i,t}^{N\ \ measured} + e_{i,t} \quad . \qquad (24)$$

This regression determines a value for θ. Setting both τ and μ to one for the moment, the regression's estimated a is an estimate of $\Delta \ln TFP^{Y}$ and its estimated b is an estimate of $\Delta \ln TFP^{N}$. Of course, the effects discerned by this regression will be only those due to differences in resources allocated to R&D, on average, in the period of estimation. Consequently, the regression is best implemented as a long-run relationship, i.e., as a quest for underlying *trends* in the two unobservable sector productivities, $\overline{\Delta \ln TFP^{N}}$ and $\overline{\Delta \ln TFP^{Y}}$.

[12] Producer markups so defined are still related to the price elasticity of demand for the underlying goods as in Romer—indeed, our model connects expenditures on innovation to customer demand in this way. This is because when investments in innovation lead to products or brands with a high own-price elasticity of demand (think new Apple products vs. new brands of milk), "market power" and expenses devoted to developing and marketing new products become associated with one another and vice versa.

A number of implementation issues nonetheless remain. First, estimating $\overline{\Delta \ln TFP^{Y}}$ by a constant in a regression with data for multiple industries assumes that $\overline{\Delta \ln TFP^{Y}}$ is constant across industries (plus an error). Determining productivity differences across industries is problematic, of course—indeed, a topic afield from the central purpose of this paper. Accordingly, to pursue the upstream/downstream decomposition of productivity, we continue with the simple logic of equation (24), that downstream productivity trends are constant across industries.

Second, to capture long run relationships we might use data averaged over a long period but this gives us rather few observations. An alternative to gain more observations would be to break the data into productivity episodes that, presumably, are roughly equal in terms of productivity growth. There is of course a tension here, because the underlying relationships might be evolving over time, in which case additional controls will be needed to capture the appropriate trends.

Third, the analysis must confront the fact that the conduct of R&D is concentrated in a handful of industries, i.e., that measured R&D must be but one aspect of innovation's contribution to economic growth. Beyond the presence of R&D co-investments, in many advanced industrialized countries, large services industries (finance, distribution) contribute notably to economic growth but perform very little science-based R&D. Modeling all industries using equation (24) may therefore prove problematic. A related issue is that productivity growth for certain industries is poorly measured and including these observations may distort a regression's coefficient estimates.

Finally, we need values for τ and μ to implement the regression. We are willing to employ the "maximal consumption" (i.e., $\tau = 1$) steady state assumption because the UK and many other advanced industrialized economies generally have stable industry-level R&D intensities. But using the Romer zero intertemporal innovator profits (i.e., $\mu = 1$) assumption is problematic because single productivity episodes do not necessarily correspond to periods of zero innovator profits.

We therefore introduce a very practical reason for setting μ greater than one, namely, that the parameter places in-house R&D on the same footing with marketed R&D services. The costs of R&D exchanged between R&D establishments classified in a different industry than the parent/owner firm were in fact "marked up" in the US R&D satellite account for this reason (Moylan and Robbins 2007, p.52). A related strategy is to use μ as a R&D co-investment multiple (see earlier discussion and footnote 11).

Following Moylan/Robbins a markup margin can be obtained using the ratio of net operating surplus to gross output for the miscellaneous professional, scientific, and technical services industry; we estimate this ratio averages about .15 in the United States (implying an average innovator markup of 1.15). Hulten and Hao (2008) studied six multinational pharmaceutical firms and estimated that the "shadow" value of own-produced pharmaceutical R&D was 50 percent greater than its cost (i.e., the innovator markup was 1.5) in the year they studied (2006). They also estimated that the increment to organizational capital was 30 percent of the value of own-produced R&D (i.e., the R&D co-investment multiple is 1.3).

Although the Hulten/Hao results suggest that in some years some industries have large markups, we proceed by applying the same markup to all industries in all years. We therefore use 1.15 as our central estimate for μ—the value needed to put in-house R&D on the same footing with marketed R&D services—but examine results for higher values in light of Hulten/Hao.

3.2 A productivity decomposition for the UK

We constructed an industry dataset that integrates gross output-based TFP estimates with R&D performance statistics for 29 UK market sector industries from 1985 to 2005. The major data sources used were EUKLEMS (March 2008) and the ONS R&D survey (BERD). A few of the 29 industries are nonperformers according to BERD and certain others have very low R&D intensities (for further information see the appendix). Accordingly, summary statistics for entire market sector are shown on the first three lines of table 1, followed by statistics excluding the nonperformers, industries in the lowest R&D intensity quartile, and industries with problematic TFP estimates. (The lowest quartile R&D performers are industries with $s^N_{G,i} < .003$).

Line 1 of the table shows the aggregate productivity of the UK market sector, and line 2 reports a simple average of its constituent industry productivities. For all items, statistics for the entire period and for two sub-periods with 1995 as the break year are shown. As may be seen, both aggregate TFP growth and average industry TFP growth decelerates 0.2 percentage points between the two periods. When problematic industry TFP estimates and the lowest quartile of R&D performers are excluded, average industry productivity growth still decelerates (line 4).

Table 1. UK market sector productivity and R&D summary statistics

	1985 to 2005	1985 to 1995	1995 to 2005
All market sector industries:			
1. $\sum_{i=1,J} Domar_i * \Delta \ln TFP_{G,i}^{measured} * 100$ [1]	2.22	2.33	2.10
2. $(1/J)\sum_{i=1,J} \Delta \ln TFP_{G,i}^{measured} * 100$	1.05	1.17	.93
3. $(1/J)\sum_{i=1,J} s_{G,i}^{N} * 100$ [2]	1.60	1.69	1.53
Excl. lowest R&D quartile and industries with problematic TFP estimates:			
4. $(1/J)\sum_{i=1,J} \Delta \ln TFP_{G,i}^{measured} * 100$	1.25	1.39	1.06
5. $(1/J)\sum_{i=1,J} s_{G,i}^{N} * 100$ [2]	2.69	2.45	3.00
Memos:			
6. Nominal R&D spending	5.3	6.4	4.2
7. Real R&D spending (conventional)[3]	1.8	2.0	1.7
8. R&D spending/GVA ($s_Y^{N\ measured}$)[4]	1.93	2.05	1.82

Notes— TFP growth rates are estimated using the dual approach, and all growth rates are calculated using log differences. Aggregation in lines 1-3 is over 29 market sector industries excluding the R&D services industry, whose R&D is allocated to purchasing industries. For industries included in line 4 and 5, see the appendix.
1. The Domar weight is calculated as industry gross output relative to market sector value added.
2. Average R&D intensity of industries with μ=1.15.
3. Deflated using the GDP deflator.
4. GVA is for the market sector.

Line 3 summarizes the μ=1.15 R&D intensity of market sector industries. This statistic trails downward, as do the more familiar statistics, R&D relative to GDP or R&D relative to market

sector GVA (the memo item on line 8). When the lowest quartile of R&D performers and nonperformers are excluded, however, the average R&D intensity of industries trends up (line 5). Underlying the divergence is the fact that value added in major R&D-performing industries is falling as a share of total GDP. While this suggests conventional GDP-based science policy benchmarks for R&D are somewhat ill focused, more relevant to this study is the fact that the conventional *real* R&D spending measure—shown on line 7—grows rather slowly (under 2 percent per year).

To estimate equation (24) we use data in two cross-sections corresponding to the two sub-periods of table 1. The upper panel of figure 1 shows a scatter plot of the 58 μ=1.15 data points that we have available for estimating the regression coefficients. As may be seen, there are notable outliers, and a regression using all of these data points lacks robustness. Nonetheless, the figure confirms that the conduct of UK R&D is concentrated in a handful of industry sectors. It also suggests an underlying linear relationship between total factor productivity and R&D intensity.

The bottom panel of figure 1 shows a plot of the 34 data points that we have after excluding outliers and the bottom quartile of R&D performers. As may be seen the exclusion of the latter mainly reduces the mass (rather than the dispersion) of the data points at low R&D intensities while exclusion of the former appears to sharpen the underlying linear relationship. The bottom panel also distinguishes pre- and post-1995 data points and shows that the lower average industry productivity growth in the post-1995 period appears in industries with very high R&D shares.

Using the dataset plotted in the lower panel, we experimented with estimation technique (fixed versus random effects, OLS versus robust methods) and all methods yielded identical estimates of a and b. We also explored weighted LS (with Domar weights reflecting each industry's contribution to overall productivity) and found it lacked robustness. We then examined the sensitivity of the regression's estimates of θ on the value assumed for the innovator markup and tested whether the estimates were stable across sub-periods.

The central findings are set out in table 2. Estimation is by random effects with robust standard errors. Results are unweighted and relevant coefficients are estimated precisely. Column 1 and column 2 differ only according to the value for μ used to calculate the innovation intensity. As

may be seen, the value for μ affects the estimated coefficient on the innovation intensity (the estimate of upstream productivity) while the estimated constant term is unaffected. In fact, the column 2 coefficient on $s_{G,i}^{N}$ is 15 percent smaller than the column 1 coefficient because the observations used in the column 2 regression are precisely 15 percent larger by construction. This suggests that estimates of θ using the constant term from regressions such as equation (24) are unaffected by the assumption for the innovator markup (nor, by the same reasoning, the assumption for τ).

The basic point illustrated by columns 1 and 2 of table 2 then is that measured TFP change is an average of a contribution from very substantial productivity growth in the upstream R&D sector (the coefficient on $s_{G,i}^{N}$) and an order-of-magnitude slower growth in the downstream production sector (the coefficient on the constant term). Indeed, even though the share of resources devoted to R&D is relatively small in the UK (recall the value of $s_{Y}^{N\ measured}$ from table 1), the regressions suggest that the conduct of R&D has contributed substantially to UK productivity growth.

The estimates of θ shown in the table memos imply that the growth in UK R&D productivity accounted for 25 to 30 percent (1-θ) of average industry TFP growth for industries in the upper 3 quartiles of R&D performing industries. But columns 4 and 5 suggest that R&D productivity contributed much less in the second sub-period of our sample than in the first. The regressions with sub-period dummy variables detect a drop in the growth of R&D productivity, whereas estimated operational productivity grows at a constant 0.9 percent annual rate throughout (column 4).

In what follows, we examine R&D price change calculated using the estimates shown in both columns 2 and 4, and in the final analysis, we settle on using column 2's constant value for θ. We do this to keep the analysis simple and to present a transparent application of the downstream approach. We also believe additional research and more data points are needed to determine the presence (and size, if present) of a break in UK R&D productivity after 1995.

Table 2. Decomposition of UK productivity change, 1985 to 2005

	Estimation by Random Effects (Robust standard errors in parentheses)				
	Dependent variable: $\Delta \ln TFP_{G,i}^{measured}$				
	(1)	(2)	(3)	(4)	(5)
Independent variables	μ=1.00	μ=1.15	μ=1.15	μ=1.15	μ=1.15
Constant	.0091*** (.0017)	.0091*** (.0017)	.0107*** (.0019)	.0089*** (.0015)	.0080*** (.0019)
$s_{G,i}^{N}$	.1431*** (.0505)	.1244*** (.0439)	.1318*** (.0482)	.2258*** (.0482)	.2423*** (.0544)
1995-2005 dummy	--	--	-.0040* (.0023)	--	.0002 (.0030)
$s_{G,i}^{N}$ * 1995 – 2005 dummy	--	--	--	-.1852*** (.0541)	-.2222*** (.0771)
Memos:					
θ	.73	.73	.70	.71	.76
θ_1 (1985 - 1995)			.77	.63	.57
θ_2 (1995 - 2005)			.63	.83	.94

Note--Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

3.3 Calculating price indexes for R&D

With key parameters specified, we are very close to taking equation (8) to the data. We still need the weights ω_i to be applied to each industry's estimated price change in the overall price index for R&D—recall that they were left unspecified in section 2—and we need to develop an approach to computation. Dividing by very small industry-level $s^R_{G,i}$ terms as per equation (8) is generally not viable, and most integrated R&D/productivity datasets will have many such terms.

We proceed as follows: We first calculate the numerator of equation (8) for each industry as

$$\Delta \ln P^{GO}_{i,t} - (1-s^R_{G,i,t})\Delta \ln C^{measured}_{G,i,t} + \theta \Delta \ln TFP^{measured}_{G,i,t} \qquad (25)$$

where $\Delta \ln P^{GO}_{i,t}$ is the change in the downstream industry's final output price (its gross output price) and $\Delta \ln C^{measured}_{G,i,t}$ is the change in its share-weighted input costs (labor, capital, and materials).[13] Ignoring time subscripts, for each industry, equation (25) gives $s^R_{G,i,t}\Delta \ln P^R_i$, i.e., the contribution of the change in R&D asset rental prices to the change in industry *i*'s final output price. The overall contribution of the change knowledge asset prices to final output prices is obtained by aggregating these industry-level contributions using Domar weights.

We approximate Domar weights by the ratio of industry gross output (GO_j) to sector value added (GVA_s). The sum of the industry-level contributions is then given by:

$$s^R_Y \Delta \ln P^R = \sum_{i=1,J} \frac{GO_i}{GVA_S} s^R_{G,i} \Delta \ln P^R_i \qquad (26)$$

where s^R_Y is the aggregate knowledge capital income share. From (23) s^R_Y is given by—and calculated as:

$$s^R_Y = \tau P^N N / GVA_S \ . \qquad (27)$$

[13] The source for these items is the March 2008 version of the UK EUKLEMS dataset. We experimented with calculating $\Delta \ln C^Y_{G,i}$ directly by subtracting off R&D workers, materials, and capital inputs calculated using data from the BERD survey, but—lacking independent information on input prices--the approach did not yield measures that differed materially from using $(1-s^R_{G,i})\Delta \ln C^{measured}_{G,i}$.

The division of equation (26) by equation (27) yields an expression for aggregate R&D price change. The result also reveals three features of the downstream approach. The first concerns its computation. Namely, the change in the R&D asset price can be computed as follows:

$$\Delta \ln P^R = \sum_{i=1,J} \frac{GO_i}{\tau P^N N} s^R_{G,i} \Delta \ln P^R_i \qquad (28)$$

i.e., by weighting each industry's contribution by industry gross output relative to aggregate R&D capital income. This does not involve division by very small industry R&D intensities.

The second is that the final price index calculated on the basis of (28) does not depend on assumptions for τ. Substitution from (23) yields the equivalent expression,

$$\Delta \ln P^R = \sum_{i=1,J} \frac{GO_i}{P^N N} s^N_{G,i} \Delta \ln P^R_i \qquad (29)$$

which does not involve the parameter τ. Although this τ-independence result will not hold when industry-specific values for τ apply, it nonetheless suggests that pinning down τ is not a first order concern when using the downstream approach to construct a price index for R&D.

Finally, a third feature is that further simplification (substitution of $P^N N_i / GO_i$ for $s^N_{i,G}$) reveals that the implicit weight applied to each industry's R&D asset price is $P^N N_i / P^N N$, the industry's share of total R&D investment. Therefore, when equation (29) is used to calculate a price index for R&D, the result is formulaically equivalent to equation (8) where the ω_i weights are each industry's share of total private R&D. (This result supports BEA's choice of weights for its "output-based" R&D price index.)

The results of proceeding with the above computations are shown in table 3. The first two columns are benchmarks that correspond to two common national accounting practices. The first ascribes all productivity change to the downstream sector, or equivalently, it assumes R&D productivity shows no change. This produces the national accountants' "input-cost" price index, and as may be seen in column 1, it increases 4.0 percent per year. This is a faster rate of increase than the 3.5 percent per year change in the UK GDP price index.

Table 3. R&D price change according to assumptions for downstream productivity change ($\Delta \ln TFP^{Y}$).

	$\Delta \ln TFP^{Y} =$					
					Memos:	
Period	$\Delta \ln TFP^{meas.}$ $[\theta = 1]$	$\Delta \ln TFP^{N}$ $[\theta = 1/(1+s^{R}_{G,i})]$	Estimated $[\theta = \theta\,]$	Estimated $[\theta = \theta_1, \theta_2]$	Column (3) with $\mu = 1.3$	R&D weighted output price change
	(1)	(2)	(3)[1,2]	(4)[1,3]	(5)	(6)
1. 1985-1995	6.0	4.2	-9.2	-14.7	-8.4	3.6
2. 1995-2005	2.0	.8	-5.8	-3.0	-5.5	.7
3. 1985-2005	4.0	2.5	-7.5	-8.8	-7.0	2.1

Notes—Recall $\theta = \Delta \ln TFP^{Y} / \Delta \ln TFP^{measured}$ and $(1-\theta) = s^{R}_{Y} \Delta \ln TFP^{N} / \Delta \ln TFP^{measured}$ where $\Delta \ln TFP^{N}$ is upstream productivity change. Columns (1) through (4) use $\mu = 1.15$.

1. For industries with problematic TFP estimates as well as those in the lower R&D quartile, changes in operational and R&D productivity are assumed to be identical (i.e., that $\Delta \ln TFP^{N} = \Delta \ln TFP^{Y}$).
2. The estimated $\hat{\theta}$ is from column 2 of table 2.
3. The estimated θ_1, θ_2 are from column 4 of table 2.

The second column shows the result of assuming that the change in operational productivity and R&D productivity are identical, akin to national accountants substituting average measured productivity in market services for "hard-to-measure" or nonmarket services, such as R&D. This implies there are neither spillovers from public R&D nor private appropriated returns to investments in product and process innovation. In this scenario, the R&D price index increases 2-1/2 percent per year, less than the input-cost index and similar to the BEA-style R&D weighted output price index shown in column 6.

Columns 3 and 4 show the results of using estimated values for downstream vs. upstream productivity from the regressions the shown in columns 2 and 4 of table 2, respectively. As may be seen, the impact of attributing returns to the conduct of R&D is substantial. The price indexes in columns 3 and 4 fall 7.5 percent and 8.8 percent per year, respectively. The results for sub-periods are *very* sensitive to the shift in the value for theta, however, suggesting that the productivity decomposition parameter is of first order importance to determining the magnitude of R&D price change. By contrast, the results in column 5—where the innovator margin is doubled—suggest rather less sensitivity to this parameter.

In interpreting the estimates shown in columns 3 and 4, note that the *overall* assumed fraction of measured productivity growth attributed to the conduct of R&D reflects more than the assumption for θ that is applied to the upper three quartiles of R&D performing industries. The overall fraction also reflects the $\Delta \ln TFP^N = \Delta \ln TFP^Y$ assumption used for the lower quartile (and nonperformers and industries with problematic TFP measures). For example, when .73 is used to decompose productivity change for the major performers, the value for theta averaged over all industries, $\bar{\theta}$ (unweighted), is .84—implying that the conduct of R&D accounted for 16 percent (not 27 percent) of average industry TFP growth in the UK during the 1985 to 2005 period.

In keeping with our earlier caution against using the literal results of the break-adjusted productivity estimates, our preferred results from table 3 are those in column 3. The annual changes in this index are plotted in the upper panel of figure 2, along with components of its price dual (price change = cost change - productivity change), where cost change is the input cost of R&D and productivity is a residual including reductions due to innovator markups. The

resulting real growth rate of R&D spending is shown in the bottom panel of figure 2; it grows 15.6 percent per year in the first period, 9.9 percent in the second, and 12.7 percent per year overall.

The results shown in figure 2 are the central results of this paper. Their sensitivity to the decomposition parameter θ is illustrated in table 4. The table shows changes in the R&D price index ($\Delta \ln P^N$), the real growth of R&D ($\Delta \ln N$ or g), and the associated $\bar{\theta}$ for all industries according to a range of values for θ for industries with $s^R_{G,i} > .003$. All estimates in table 4 imply much faster growth of real R&D (line 3) than conventional estimates based on the GDP deflator (table 1, line 7).

Table 4. UK R&D price change for a range of values of θ, 1985-2005

1. θ if $s^R_{G,i} > .003$	.60	.70	.75	.80	.90
2. $\Delta \ln P^N$	-13.0	-8.8	-6.7	-4.6	-.4
3. $\Delta \ln N$ (or g)	18.3	14.1	12.0	9.9	5.6
4. $\bar{\theta}$, all industries	.76	.82	.85	.88	.94

Note—Figures are calculated assuming $\mu = 1.15$, $\tau = 1$. The variation in θ applies to productivity of major R&D performers only.

Applying the approximation, $g \cong \rho^N$, the table's values for real investment growth also are seen as suggestive of the range for the rates of return to R&D that inhere in our price estimates.[14] It is

[14] Indeed one might ask how the estimates in tables 3 and 4 relate to the literature on returns to R&D as most recently surveyed in Hall, Mairesse, and Mohen (2009), hereafter HMM. This literature runs a regression similar to ours. HMM point out that a regression for estimating the rate of return to R&D must use an "adjusted TFP" that has been calculated after subtracting R&D factor inputs. Productivity growth so calculated equals $s_Y^R \Delta lnR^Y$ in our notation, and regressing it on s_Y^N yields a coefficient that is related to the rate of return to R&D, namely, $g[(\rho^N+\delta^R)(1+g)]/(g+\delta^R)$. (Due to the presence of a discrete time term in (1+g), this is not quite what HMM obtain

difficult to say how our real investment growth rates line up with the results in the literature that estimates a rate of return to R&D because that literature is not at all definitive—indeed, it has produced results for the UK that range from 10 to 70 percent (Hall, Marisee, and Mohen 2009). From this perspective, the range of the estimates shown in table 4 is relatively narrow and our central estimate appears rather reasonable.

3.4 Implications

We now turn to gauging the importance of our new R&D price index. As depicted so far, the measured economy does not capitalize investments in innovation and track knowledge capital as a macroeconomic statistic. But when national accountants move to recognize R&D spending as investment, in our simple model (a closed economy, now with no intermediates) both aggregate final demand and aggregate industry value added will include the output of the innovation sector.

Under capitalization, real GDP (denoted by Q) is thus the sum of each sector's output $(Q = Y + N)$ [15] and aggregate productivity is given by

$$\Delta \ln TFP^Q = (1 - s_Q^N)\Delta \ln TFP^Y + s_Q^N \Delta \ln TFP^N \qquad (30)$$

where $s_Q^N = P^N N / (P^Y Y + P^N N)$. As may be seen, this differs only slightly from the expression derived for productivity growth without capitalization, equation (22).[16] The conceptual basis for the similarity in TFP growth before and after capitalization of R&D is, in fact, the premise of this paper—that the impact of the conduct of R&D on productivity is already in measured productivity. By contrast, the capitalization of R&D *does* produce visible changes in the growth of real output and output per hour because real GDP with our price index for R&D includes a component that is growing 12.7 percent per year.

These propositions are illustrated in table 5, which shows the growth in UK output per hour and TFP before and after capitalization of R&D. As may be seen little or no effect is discerned on

---

in equation (5) of their paper but our derivation is similar.) Substituting our expression for τ, the rate-of-return-approach regression is seen to yield a coefficient on s_Y^N that equals $g\tau$, which approaches ρ^N as τ approaches one.

[15] This of course is a simplified expression as summation in real terms does not hold under chain-weighting.

[16] The new trend in measured TFP change will be *slightly* lower than the rate prior to R&D capitalization because, arithmetically, the first term in equation (30) vs. equation (22) is smaller by $s^N{}_Q \Delta \ln TFP^Y$ (two small numbers multiplied by each other) and the second has a slightly smaller weight (i.e., $s^N{}_Q < s^N{}_Y$).

TFP growth (line 2b) whereas the growth of output per hour is noticeably affected (line 1b). Moreover, the bulk of the impact on output per hour stems from the R&D deflator (line 1c), not from the addition of new nominal investment to GDP. Finally, as shown on line 3, with our downstream deflator, estimated real stocks of R&D assets grow rapidly, especially from 1985 to 1995.[17] All told, stocks grow at a rapid clip, and R&D capital deepening (line 3a) contributes .25 percentage points to the growth in UK market sector output per hour.

Table 5. Growth in output per hour, TFP, and R&D stocks, UK market sector

	1985 to 2005	1985 to 1995	1995 to 2005
1. Output per hour, R&D capitalized	2.9	3.0	2.8
1a Without R&D capitalization	2.7	2.7	2.6
1b *Difference due to capitalization*[1]	*.22*	*.30*	*.14*
1c *Contribution of deflator*	*.16*	*.21*	*.12*
2. TFP, R&D capitalized	2.2	2.2	2.1
2a Without R&D capitalization	2.2	2.3	2.1
2b *Difference due to capitalization*[2]	*-.05*	*-.06*	*-.05*
3. Real stocks of R&D assets	12.7	14.2	11.1
3a *Contrib. of R&D capital deepening*[3]	*.25*	*.33*	*.17*

Note—Growth rates are annualized and calculated using log differences. Italicized entries are percentage points.
1. Line 1 less line 1a.
2. Line 2 less line 2a.
3. Contribution to the growth in output per hour, line 1.

4. Conclusion

This paper showed that aggregate business output may be modeled as emanating from two sectors: one, the aggregate behavior of business functions devoted to innovation and R&D, and the other, an operations and/or producing sector consisting of all other business functions. The model is very simple, assuming only the following: the innovation sector is entirely upstream of the operations sector; the operations (or "downstream") sector produces all final output and is a

[17] The stocks are calculated using a depreciation rate of 15 percent (the rate used by the US BEA) and an initial value as in Griliches (1980). See also equation (3) in Sliker (2007, p. 3).

price-taker for inputs; and the aggregate value of final output equals the sum of all factor payments by business.

The recursive nature of the model's price-dual relationships was used to show how the price of commercially-produced knowledge is related to innovator market power and downstream output prices, factor costs, and productivity. We related this "downstream" approach to measuring R&D price change to other methods under consideration for calculating an investment price index for R&D in national accounts and found that these methods tend to embody unrealistically weak assumptions for R&D productivity (or implausibly strong innovator market power).

The model, its parameterization via productivity decomposition, and use of price-dual solutions have ample precedence in the literature: The model is related both to Romer (1990) and the intangible capital literature (e.g., Corrado, Hulten, and Sichel 2009); the productivity decomposition is related to the literature on estimating returns to R&D (e.g., Griliches 1980, Mansfield 1980, and Schankerman 1981); and price-dual growth accounting relationships were exploited for productivity analysis by Oliner and Sichel (2000), among others.

When our downstream approach is applied to the UK data, we found that UK R&D investment prices fell 7.5 percent per year from 1985 to 2005, and that R&D capital deepening contributed notably to the growth in output per hour. The precise fall in a R&D price index obtained using the downstream approach depends on a decomposition of measured productivity between a contribution from R&D and from all other factors, but our central finding of falling R&D prices is robust relative to all that we know from the empirical R&D literature (spillovers, above average rates of return, etc.)—and stands in stark contrast to the assumption of rising R&D prices in all other work on the topic.

References

Adams, J., Black, G,. Clemons, J.R., Stephan, P., (2005, "Scientific Teams and Institutional Collaborations: Evidence from US universities, 1981-99", Research Policy, 24, pp. 259-285.

Agarwal, Rajshree and Michael Gort (2001). "First-Mover Advantage and the Speed of Competitive Entry, 1887-1986." *Journal of Law and Economics* 44:1 (April), 161-177.

Aghion, Philippe and Peter Howitt (2007). "Capital, Innovation, and Growth Accounting." *Oxford Review of Economic Policy*, vol. 23:1, 79–93.

Basu, Susanto, John Fernald, Nicholas Oulton, and Sally Srinivasan (2004). "The Case of the Missing Productivity Growth: Or, Does Information Technology Explain Why Productivity Accelerated in the United States but Not the United Kingdom?" *NBER Macroeconomics Annual 2003,* M. Gertler and K. Rogoff, eds., Cambridge, MA: The MIT Press, 2004.

Baumol, William J. (2002). *The Free-Market Innovation Machine.* Princeton, New Jersey: Princeton University Press.

Brown, Sharon P. (2008). "Business Processes and Business Functions: a new way of looking at employment." *Monthly Labor Review*, vol. 131:12 (December), 51-70.

Byrne, David M. and Carol A. Corrado (2011). "Prices for Communications Equipment: Rewriting the Sixty-year Record." Revised version of paper originally prepared for the CRIW workshop at the 2007 NBER Summer Institute (July).

Cameron, Gavin (1996). "On the Measurement of R&D—Divisia Price Indices for UK Business Enterprise R&D." *Research Evaluation* 6:3 (December), 215-19.

Copeland, Adam M., Gabriel W. Medeiros, and Carol A. Robbins (2007). "Estimating Prices for R&D Investment in the 2007 R&D Satellite Account." BEA paper (November).

Copeland, Adam and Dennis Fixler (2009). "Measuring the Price of Research and Development Output." BEA working paper WP2009-2 (February).

Corrado, Carol, Charles Hulten, and Daniel Sichel (2005). "Measuring Capital and Technology: An Expanded Framework." *In Measuring Capital in the New Economy*, C. Corrado, J. Haltiwanger, and D. Sichel, eds., Studies in Income and Wealth, Vol. 65, 11-14. Chicago: The University of Chicago Press, 2005, 11-41.

Corrado, Carol, Charles Hulten and Daniel Sichel (2009): Intangible Capital and US Economic Growth. *The Review of Income and Wealth*, vol. 55 (3), 661-685.

Corrado, Carol and Charles Hulten (2010). "How Do You Measure a 'Technological Revolution'?" *American Economic Review* 100:5 (May), 99-104.

Corrado, Carol A. (2011). "Communication Capital, Metcalfe's Law, and U.S. Productivity Growth (March). The Conference Board Economics Program Working Paper (11-01).

Ding, W, Levin, S, Stephan, P., and Winkler, A., (2010), "The Impact of IT on Academic Scientist's Productivity and Collaboration Patterns", Management Science, pp.1-23.

Domar, Evsey D. (1961). "On the Measurement of Technological Change." *Economic Journal* 71: 709-29.

Doms, Mark and Christopher Forman (2005). "Prices for Local Area Network Equipment." *Information Economics and Policy* vol. 17 (July), 365-388.

Doms, Mark (2005). "Communications Equipment: What has Happened to Prices?" In *Measuring Capital in the New Economy* C. Corrado, J. Haltiwanger, and D. Sichel, eds., 323-362. Chicago: The University of Chicago Press.

Dougherty, Sean M., Robert Inklaar, Robert H. McGuckin and Bart van Ark (2007), "International Comparisons of R&D Expenditures: Does an R&D PPP Make a Difference?" In Hard-to-Measure Goods and Services: Essays in Honor of Zvi Griliches, E. R. Berndt, C. M. Hulten, eds., 291-322. Chicago: University of Chicago Press.

Fixler, Dennis (2009). "Accounting for R&D in the National Accounts." paper presented at the ASSA meetings, San Francisco, California (January 4).

Galindo-Rueda, F. (2007). "Developing an R&D Satellite Account for the UK: A Preliminary Analysis." *Economic & Labour Market Review*, vol. 1:12, 18-29.

Griliches, Zvi (1979). "Issues in Assessing the Contribution of Research and Development to Productivity Growth." *Bell Journal of Economics*, vol. 10:1 (Spring), 92-116.

Griliches, Zvi (1980). "Returns to Research and Development Expenditures in the Private Sector." In *New Developments in Productivity Measurement*, John W. Kendrick and Beatrice Vaccara, eds., Studies in Income and Wealth, Vol. 44, 419-54. Chicago: University of Chicago Press.

Hall, Bronwyn H., Mairesse, Jacques, Mohnen, Pierre, (2009), "Measuring the Returns to R&D", National Bureau of Economic Research Working Paper Series, No. 15622 (December).

Haskel, Jonathan, Tony Clayton, Peter Goodridge, Annarosa Pesole, David Barnett, Graeme Chamberlin, Richard Jones, Khalid Khan and Alex Turvey (2009). *Innovation, Knowledge Spending and Productivity Growth in the UK*, NESTA Index Report (November).

Hulten, Charles R. (1978). "Growth Accounting with Intermediate Inputs." *Review of Economic Studies* 45 (October): 511-518.

Hulten, Charles R. and Janet X. Hao (2008). "What is a Company Really Worth? Intangible Capital and the 'Market to Book Value' Puzzle" NBER working paper No. 14548 (December).

Hulten, Charles R. (2009). "Growth Accounting." NBER working paper No. 15341 (September).

Jorgenson, Dale W. (1966). "The Embodiment Hypothesis." *Journal of Political Economy*: 74 (February), 1-17.

Jorgenson, Dale W. and Zvi Griliches (1967). "The Explanation of Productivity Change," *Review of Economic Studies*, Vol. 34 (July), 349-83.

Mansfield, Edwin (1980). "Basic Research and Productivity Increase in Manufacturing." *American Economic Review* 70:5 (December), 863-73.

Marrano, Mauro Giorgio, Jonathan Haskel and Gavin Wallis (2009): What happened to the knowledge economy? ICT, intangible investment and Britain's productivity record revisited. *The Review of Income and Wealth*, vol. 55 (3), 686-716.

Mead, Charles Ian (2007). "R&D Depreciation Rates in the 2007 R&D Satellite Account." BEA BEA/NSF 2007 R&D Satellite Account Background Paper (November).

Mokyr, Joel, 2005. "Long-Term Economic Growth and the History of Technology," Handbook of Economic Growth, in: Philippe Aghion & Steven Durlauf (ed.), Handbook of Economic Growth, edition 1, volume 1, chapter 17, pages 1113-1180 Elsevier.

Moylan, Carol and Carol Robbins (2007). "Research and Development Satellite Account Update" *Survey of Current Business* 87 (October): 49–92

Oliner, Stephen D. and Daniel E. Sichel (2000). "The Resurgence of Growth in the Late 1990s: Is Information Technology the Story?" *Journal of Economic Perspectives* 14, Fall: 3-22.

Pakes, Ariel, and Mark Schankerman (1984). "The Rate of Obsolescence of Patents, Research Gestation Lags, and the Private Rate of Return to Research Resources." In *R&D, Patents, and Productivity*, ed. Zvi Griliches, 73–88. Chicago: University of Chicago Press.

Romer, Paul M. (1990). "Endogenous Technological Change." *Journal of Political Economy*, Vol. 98:5 (October), Part 2: S71-S102.

Rotemberg, Julio J. and Michael Woodford (1995). "Dynamic General Equilibrium Models with Imperfectly Competitive Product Markets." In *Frontiers of Business Cycle Research*, Thomas F. Cooley, ed., 243-293. Princeton: Princeton University Press.

Schankerman, Mark (1981). "The Effects of Double-counting and Expensing on the Measured Returns to R&D." *Review of Economics and Statistics* 63:1097-1125.

Sliker, Brian (2007). "R&D Capital Stocks and Net Rates of Return" R&D Satellite Account Background Paper (December).

System of National Accounts 2008. European Commission, International Monetary Fund, OECD, United Nations, World Bank.

Figure 1
UK Industry Productivity and R&D Intensity

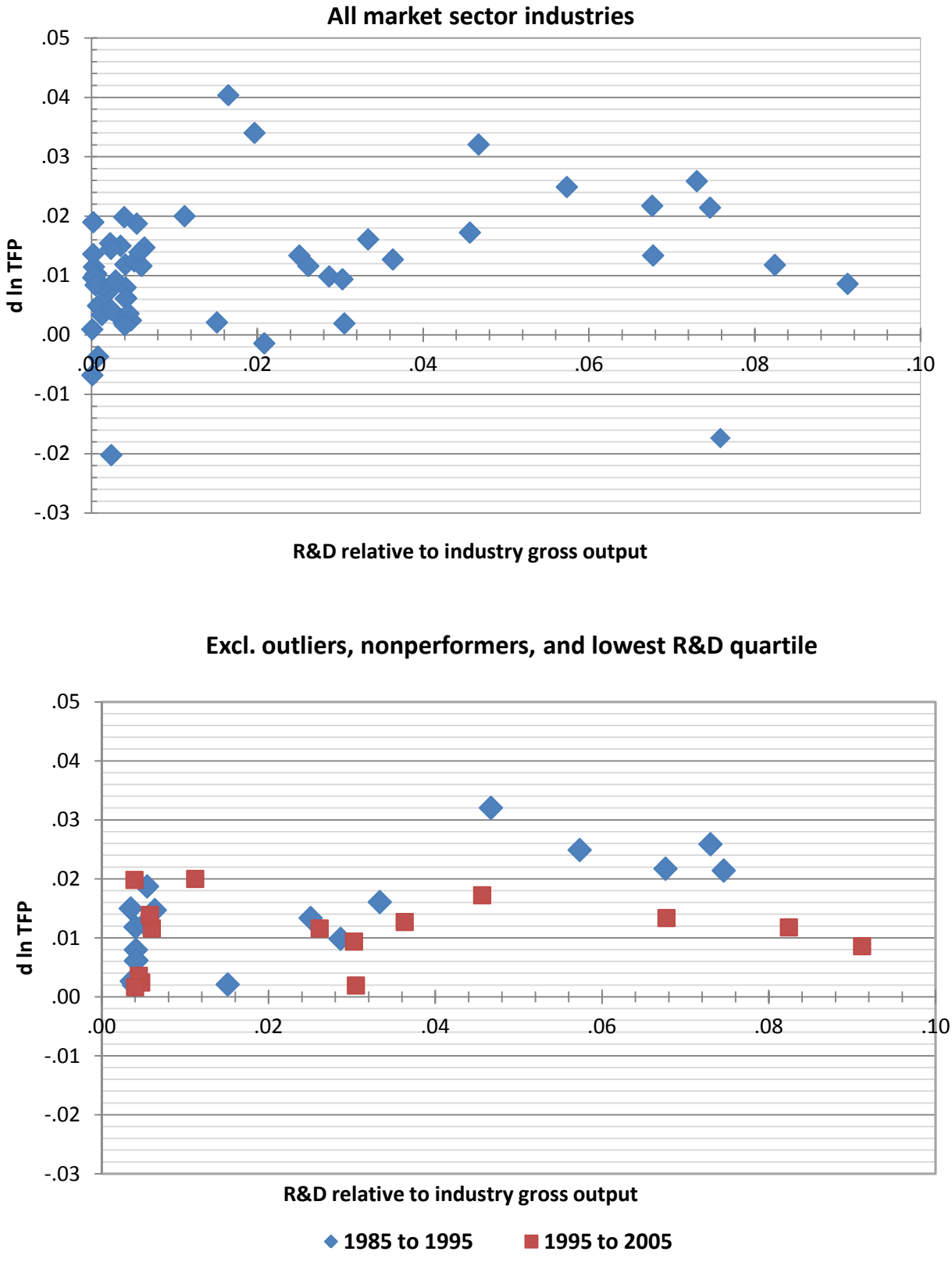
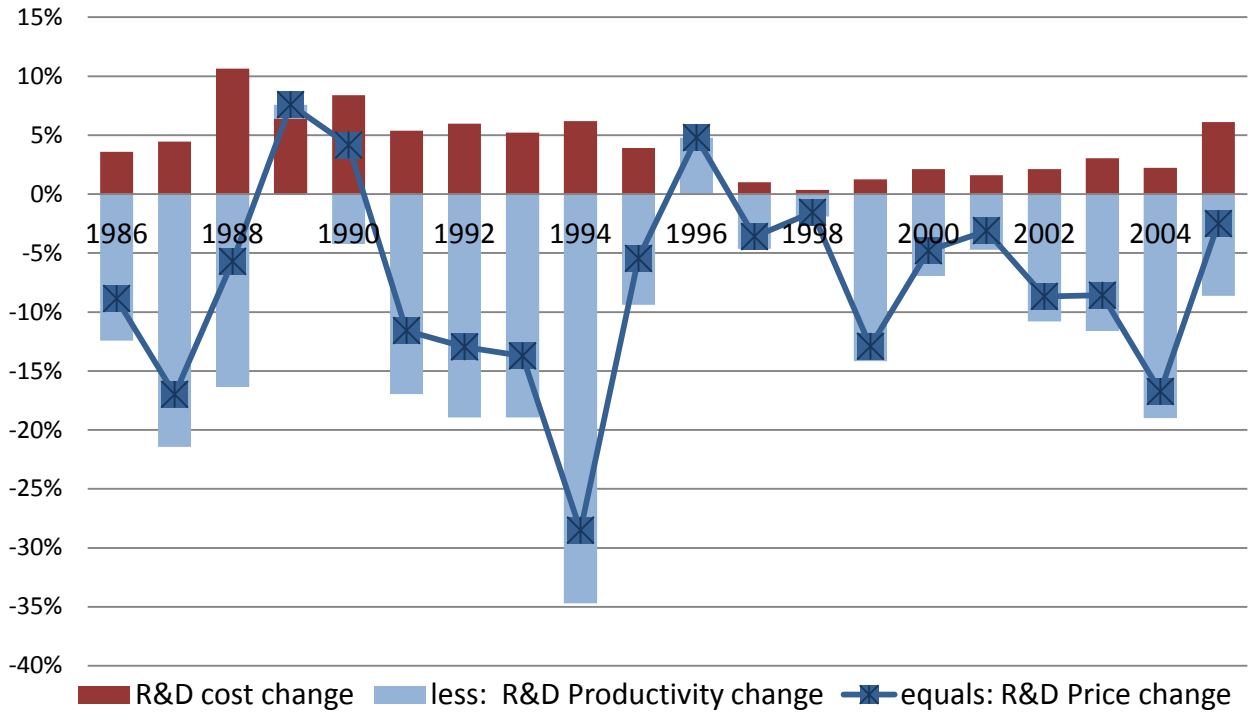
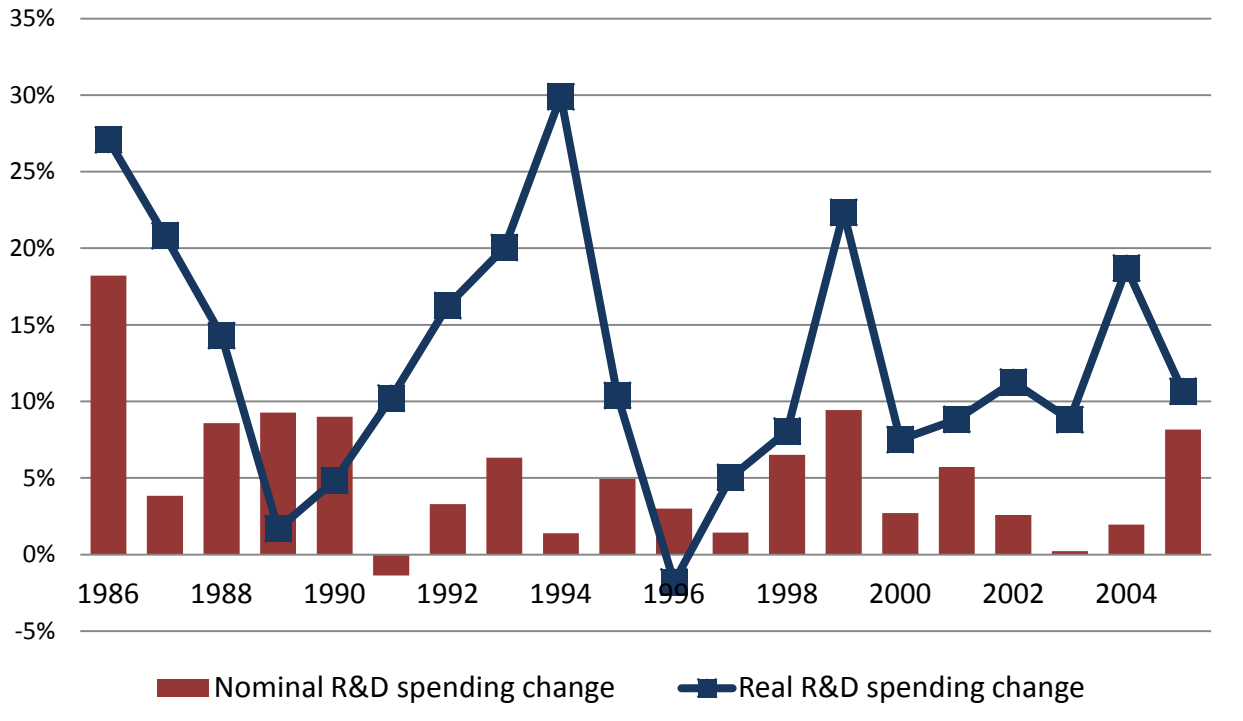


Figure 2
R&D Price Index and Real R&D Spending (percent change)





APPENDIX

R&D and TFP industry-level data

We have four industry-level data sources. First, we have the UK R&D spending data from BERD, which surveys own-account R&D spending by firms and reports R&D for 32 product groups that generally correspond to industry groups.[1] Second, we have the UK EUKLEMS March 2008 dataset covering the period through 2005, the latest data as of this writing. This dataset reports capital input and gross output-based TFP estimates for 26 market sector industries along with prices and quantities of output and labor and material input for 72 industries.[2] Third, we have capital services data from the UK ONS at a more disaggregate level than available from EUKLEMS (e.g., motor vehicles and other transport, rather than total transport equipment). We use these capital services estimates along with the other information from EUKLEMS to calculate TFPs for 5 additional industries. Fourth, we have the UK supply-use (IO) tables, for more than 100 industries from 1992 to 2006.

After merging the BERD data with the EUKLEMS, ONS and IO data and aggregating certain industries, we have a data set for 29 market industries from 1985 to 2005. The industries are listed in table A1. Note that, due to disclosure issues, we do not have separate capital stocks for pharmaceuticals—the largest R&D performer in the UK—and therefore are forced to work with the aggregate chemicals sector. The list shown in table A1 also excludes the R&D services industry because its R&D is allocated to using industries based on input-output relationships.

The lower quartile bound

The allocation of R&D conducted in the R&D services industry to using industries causes three industries that do not conduct scientific R&D according to BERD to show non-zero R&D intensities, albeit very small ones. These industries are financial services, hotels and restaurants, and other social, community and personal services. Then we calculate the cutoff point used to

[1] Because individual companies can perform R&D for a range of products, the correspondence must be regarded as an approximation, however.

[2] The market sector in EUKLEMS is NACE sectors A-Kpt plus O and P. We exclude P (private households) and work with NACE sectors A-Kpt plus O. Kpt is sector K excluding industry 70 (real estate).

determine the lower quartile of R&D performers, intensities for these nonperformers are excluded from the calculation.

The cutoff point we use is .003 (of gross output), and it is calculated as the lower quartile bound using the 1985-2005 average $(\mu = 1.15,\ \tau = 1.0)$ value for $s^{R}_{G,i}$ for the 26 R&D-performing industries shown in table A1, i.e., all industries except financial services, hotels and restaurants, and other social, community and personal services. Another way of thinking about this cutoff is that the lower 1/3 percentile of the industries shown in table A1 is dropped; the two approaches yield the same results.

Observations in the productivity regression

To determine the observations used in the productivity decomposition regression, we first exclude the nonperformers and the lower quartile of R&D performers. Then we test for outliers.

We apply the cutoff to each sub-period separately; this procedure leaves us with 38 observations. We note that two industries that make the cutoff on the basis of averages for the whole period do *not* make the cutoff in the second sub-period (utilities and miscellaneous business services). Also, two industries that fail to make the cutoff on the basis of averages for the whole period *do* make the cutoff in the first period (mining and other manufacturing). Thus after applying the cutoff, our observations consist of 21 observations on the first period and 17 on the second.

Of these 38 observations, the negative observations for computer and software services in the pre-1995 period and petroleum refining in the post-1995 period are detected as outliers and excluded from the regression analysis. The observations for the post and telecommunications industry also are excluded. Research has shown that quality change in the capital equipment used in this industry is substantially understated (Doms and Forman 2005, Doms 2005, Byrne and Corrado 2011), and we believe the industry's TFP estimates are overstated. For the U.S. broadcasting and telecommunications industry (NAICS 513), the overstatement of TFP growth due to mis-measured capital is estimated to be about 50 percent of the change based on published data (Corrado 2011). This type of measurement problem is not covered by the analysis in section 2.4 and, accordingly, the observations are dropped for our regression analysis. All told, the regressions use 34 observations.

Table A1. R&D Intensities by industry, 1985-2005 average

		(1)	(2)	(3)	(4)	(5)	(6)
					Memos:		
Number	Name	NACE code	R&D Intensity	Col (2) with mu=1.15	in upper 2/3 percentile of R&D intensities (> .003)	included in regression (first period, second period, both)	Source for capital services estimates
1	Agriculture	A,B	0.0044	0.0051	*	both	EUKLEMS
2	Extractive industries (mining)	C	0.0025	0.0029		first	EUKLEMS
3	Food, beverage, and tobacco products	15, 16	0.0039	0.0045	*	both	EUKLEMS
4	Textiles, clothing and leather products	17-19	0.0018	0.0021			EUKLEMS
5	Pulp & paper, printing; wood products	20-22	0.0011	0.0013			EUKLEMS
6	Refined petroleum and related produc	23	0.0156	0.0180	*	first	EUKLEMS
7	Chemicals and chemical products	24	0.0721	0.0829	*	both	EUKLEMS
8	Rubber and plastics	25	0.0043	0.0050	*	both	EUKLEMS
9	Nonmetallic mineral products	26	0.0053	0.0061	*	both	EUKLEMS
10	Basic metals	27	0.0035	0.0041	*	both	ONS
11	Fabricated metals	28	0.0035	0.0040	*	both	ONS
12	Machinery and equip.	29	0.0238	0.0274	*	both	EUKLEMS
13	Computers and office machinery	30	0.0158	0.0181	*	both	ONS
14	Electrical machinery and apparatus	31	0.0407	0.0468	*	both	ONS
15	Communications equipment	32	0.0589	0.0677	*	both	ONS
16	Instruments	33	0.0401	0.0462	*	both	ONS
17	Motor vehicles and parts	34	0.0278	0.0319	*	both	ONS
18	Other transport equipment	35	0.0676	0.0777	*	both	ONS
19	Other manufacturing	36-37	0.0026	0.0030		first	EUKLEMS
20	Utilities	E	0.0035	0.0040	*	first	EUKLEMS
21	Construction	F	0.0003	0.0003			EUKLEMS
22	Wholesale and retail trade	G	0.0002	0.0003			EUKLEMS
23	Hotels and restaurants	H	0.0001	0.0001			EUKLEMS
24	Transportion and storage services	60-63	0.0004	0.0005			EUKLEMS
25	Telecommunications and postal servic	64	0.0157	0.0181	*		EUKLEMS
26	Financial services	J	0.0002	0.0002			EUKLEMS
27	Misc Bus Services	Kpt	0.0027	0.0031	*	first	ONS
28	Computer and software services	72	0.0461	0.0531	*	second	ONS
29	Social, community, and personal srvs.	O	0.0007	0.0008			EUKLEMS

Note--R&D intensity is relative to industry gross output. R&D performed in the R&D services industry is allocated to using industries.

This paper has been produced by the Healthcare Management Group
at Imperial College Business School

ISSN: 1744-6783

Imperial College Business School
Tanaka Building
South Kensington Campus
London SW7 2AZ
United Kingdom

T: +44 (0)20 7589 5111
F: +44 (0)20 7594 9184

www.imperial.ac.uk/business-school