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

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PRELIMINARY AND NOT FOR QUOTATION

ABSTRACT

We introduce a model of the production and use of knowledge investments and show how it can be used to infer the unknown price of knowledge using two approaches. The first focuses on the knowledge-producing sector, where for R&D a variety of methods have recently been offered by national accounting offices. Uncertainty and market power are endemic in knowledge production (Romer 1990), however, rendering measurement of the process problematic. A second approach focuses on the downstream knowledge-using sector. The science policy practice of using the GDP deflator is a simple variant of this approach, but we show that in its fullness the approach implies backing out the price of R&D from final output prices, factor costs, and the sector's TFP. The theoretical validity of the approach rests on the downstream sector being a price-taker, not on the price of R&D being a competitive price. As a result, we believe the downstream approach is more tractable than the upstream approach, and we use the former to estimate a R&D price index for the United Kingdom from 1981 to 2005.

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"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 1981 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—indeed, the authors plan an application to U.S. R&D in the near future.

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). This is the approach we prefer, develop, and apply in this paper.

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) that builds in markups of self-produced knowledge capital, much as in Hulten (2010). 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

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[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, which we find falls about 2.5 percent per year from 1981 to 2005. Although our results at this point are still preliminary, the checks and tests that we have conducted to date suggest that our finding of a falling price index is very robust.

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. The second part of the paper develops a R&D price index for UK economy. We describe how the U.K's R&D survey data (BERD) are merged with EUKLEMS and IO data at the industry level and how we obtain measures for the upstream and downstream sectors in our model. We then explain how measured TFP can be allocated between operational and appropriable innovative activity, which enables us to calculate the final price index. A final section concludes.

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—a knowledge-producing and knowledge-using sector—and three factors of production—labor, capital, and knowledge. The knowledge-

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).

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 producing 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:

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

where N is newly-produced appropriable knowledge and prices P^L and P^K are for 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, or R&D, in the market sector.[4]

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

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 same 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) close 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:

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

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

The terms s_K, s_L and s_R 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 total factor productivity for each sector, i.e., the shift in each sector's production function. The interpretation of the sectoral 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.[5] The historical evolution of industrial R&D, from its conduct in large, centralized corporate labs to the more decentralized, collaborative and systemic arrangements of today suggests the elusive nature of the topic. Yet unsurprising themes emerge in case studies of the topic, namely, that information and communication technologies (ICTs) and outsourcing have led to increased productivity in R&D processes much as they have in core business processes.[6]

The upstream approach is the dominant approach used by statistical agencies.[7] In its most basic form, the method assumes $\Delta \ln TFP^N = 0$ and uses share-weighted input costs to measure output price change. This variant has been used by both the UK ONS and U.S. BEA to approach the measurement of R&D prices, e.g. Galindo-Rueda (2007) and one of the approaches reported in Copeland, Medeiros and Robbins (2007).[8] 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 (4). 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);

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[5] Exceptions include Furman *et al.* (2004) and McKinsey and Co. (2001; chapter on semiconductor sector).

[6] For example, by the late 1980s, computer-enabled combinatorial chemistry was drastically lowering the costs of experimentation in pharmaceutical laboratories; later in the 1990s, computerization and specialized software enabled shorter design and testing times for products as diverse as semiconductors and motor vehicles; and outsourcing of clinical drug trials beginning in the 2000s has also led to lower costs.

[7] 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 U.S. BEA/NSF Satellite Account on June 25 is not considered.

[8] 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.

they suggest these “market-based” results can be used to proxy for all (i.e., in-house) private business R&D.[9]

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.[10] More fundamentally, we believe the premise of the approach requires more scrutiny, namely, that the results are based on market revenues from the conduct of R&D. Some NAICS 5417 industry revenues are for contract research whose character may be inconsistent with the standard definition of R&D. Moreover, the establishment-based industry classification likely places a nontrivial number of company-owned R&D laboratories in the R&D services industry, in which case industry “revenue” is surely not entirely market-based.

Given the development of the R&D marketplace *via* the licensing of patents, national accountants could urge statisticians to collect data on unit lease and license fees for patent and other intellectual property rights (IPRs) and thereby strengthen the upstream approach. But such observations could correspond to P^R, or to P^N, or more likely to $(1-\delta_R)^{\mathrm{T}} P^N$ if data were for units of R of age T that obsolesce at the rate δ_R per period, suggesting some hurdles that need to be crossed in working with data from the IPR marketplace (a “lemons” problem?). Indeed, it is possible that the existing revenue data on the R&D services industry is confounded by such issues. For these and the reasons previously given, there indeed are many challenges in working with data from the R&D-performing sector.

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[9] 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 $\Delta \ln P^N = \Delta \ln S^{5417} - .5 * (\Delta \ln Z^{5417} + \Delta \ln SCIENTISTS^{5417})$.

[10] A 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.

1.3 Downstream Approach: 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:

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

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. (And equation (4) suggests the unknown $\Delta \ln P^N$ is proportional to $\Delta \ln P^R$ assuming constancy of other rental price determinants over time.)

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

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

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. Moreover, a specific approach in Copeland, Medeiros, and Robbins (2007) is a close cousin of equation (8) in that a price index for R&D is calculated as the weighted aggregate

$$\Delta \ln P^N = \sum \omega_j \Delta \ln P_j^Y \tag{9}$$

across the most intensive R&D-using sectors with ω_j the j^{th} industry's share of total R&D investment. Equation (8) also shows that science-policy analysts and Copeland, Medeiros, and

Robbins (2007) implicitly assume that share-weighted factor prices and sectoral productivity net to zero and ignore the denominator.

The downstream approach also requires information on the sector's productivity change. As such, the relationship of the sectoral productivities to the service flow from R^Y that enters the final-output production function (3) deserves a few words at this point. Services from the stock of commercial knowledge are modelled as inputs to the economy's core operations. The inputs can be thought of as a Hicksian shift in the sector's standard production function for the commercial lifetime of the knowledge. 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 the effect captures the commercial success of inventive activity. Thus, while $\Delta \ln TFP^Y$ will capture the contribution of knowledge that is freely available to all competitors in the economy (as well as absorb many phenomena associated with productivity and efficiency, e.g., economies of scale and adjustment costs), $\Delta \ln TFP^Y$ will *not* reflect returns to appropriable inventive activity. Those returns will be in $\Delta \ln TFP^N$.

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 the 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 its TFP.

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 seems like 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 equation (2) (e.g., Pakes and Schankerman 1984).

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 then 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 ρP^N per unit of R per 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 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.[11] In other words, the downstream sector, which uses the innovation, is competitive while the upstream sector, which produces the innovation, is a

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

(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. Denoting operation/production costs as CF^Y, then the producer markup relationship in our model is $P^Y = \gamma CF^Y$, with the markup given by

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

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

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

This result establishes consistency of our framework with models of imperfect competition with producer markups and intertemporal zero profits, i.e., 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).

If the price of knowledge faced by the downstream sector is not the competitive price due to imperfect competition in the upstream sector, 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 $\Delta \ln TFP^N$ implied by the 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 shall show, the downstream approach yields an implicit 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 the $\Delta \ln TFP^Y$ term in equation (6). As written, changes in TFP pass through one-for-one to changes in output prices. If all factor prices are exogenous, then 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 should 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 on $\Delta \ln P^R$ 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 also appropriate 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 this index, namely, that the implicit netting may also concern an assumption about the degree of downstream monopoly power.

2.4 Product quality

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

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

where the true productivity change denoted as $\Delta \ln TFP^{Y*}$ 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

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

in which case 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 Productivity and innovator markups

Although expressions for the change in the downstream sector's rental price are robust in the presence of *producer* markups, the relative value of the economy's resources devoted to innovation/R&D ($P^N N$ relative to $P^Y Y$, denoted below as s_N^Y) and the relative performance of sectoral productivities TFP^N and TFP^Y are sensitive to the presence (and size) of *innovator* markups. We now explore the steady state relationships among s_N^Y, the sectoral productivities TFP^N and TFP^Y, and measured TFP for the market economy as a whole in the presence of innovator markups.

Let CF^N be the cost of the conduct of innovation/R&D in terms of the standard factors of production (labor and capital) at competitive factor prices, that is, $CF^N = P^L L^N + P^K K^N$.

Furthermore, let $\Delta \ln F^N$ and $\Delta \ln C^N$ denote the change in its quantity and price elements such that $\Delta CF^N = \Delta C^N + \Delta F^N$, and let CF^Y, CF, $\Delta \ln F^Y$, $\Delta \ln F$, $\Delta \ln C^Y$ and $\Delta \ln C$ be the similarly-defined costs, quantity and price changes for the final-output sector and total production in the economy, respectively. Finally, let the innovator markup over costs be given by $\mu \geq 1$.

In the presence of innovator markups, the value of upstream output is given by

$$P^N N = \mu CF^N, \tag{15}$$

and instead of equation (5), the relationship $\Delta \ln P^N = \mu \Delta \ln C^N - TFP^N$ applies. The sector's productivity is expressed as:

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

The corresponding downstream expressions for factor payments and change in knowledge output price are as in section 1,[12] and the expression for downstream sector productivity is given by

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

If innovation/R&D investments are both expensed *and* not recognized as output (i.e., innovation as costless "inspiration"), measured productivity is given by the difference between the growth rate of final output and of share-weighted measured factor inputs $\Delta \ln F^{measured}$:

$$\begin{aligned} \Delta \ln TFP^{measured} &= \Delta \ln Y - \Delta \ln F^{measured} \\ &= \Delta \ln Y - \Delta \ln F - \Pi \end{aligned} \tag{18}$$

Innovator markups and returns to knowledge capital are absorbed in measured returns to ordinary capital when capital income is determined residually (as in Jorgenson and Griliches 1967). Therefore, the second line of equation (18) expresses measured TFP growth in terms of the change in factor inputs at competitive prices and a term Π that reflects the real cost of innovator mark ups borne by the downstream sector (in terms of foregone final output)

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[12] In the simplified notation of this section, these are $P^Y Y = CF^Y + P^R R$ and $\Delta \ln P^Y = (1 - s_R^Y) \Delta \ln C^Y + s_R^Y \Delta \ln P^R$, respectively.

Under steady-state conditions the growth rate of a stock g is well approximated by the growth rate of real investment (Griliches 1980) and s_N^Y approximates s_R^Y as g approaches ρ_N. Making these substitutions in equation (17) and then expanding it using equations (16) and (18) yields the following:

$$\begin{aligned}\Delta \ln TFP^Y &= \Delta \ln Y - (1-s_N^Y)\Delta \ln F^Y - s_N^Y \Delta \ln N \\ &= \Delta \ln Y - (1-s_N^Y)\Delta \ln F^Y - s_N^Y \Delta \ln TFP^N - s_N^Y \mu \Delta \ln F^N \\ &= \Delta \ln Y - \Delta \ln F - s_N^Y \Delta \ln TFP^N - s_N^Y(\mu - 1)\Delta \ln F^N \\ &= \Delta \ln TFP^{measured} - s_N^Y \Delta \ln TFP^N\end{aligned} \tag{19}$$

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

Rearranging the terms in the last line of equation (19) gives

$$\Delta \ln TFP^{measured} = \Delta \ln TFP^Y + s_N^Y \Delta \ln TFP^N \tag{20}$$

which says an economy's measured steady-state productivity growth is a Domar-weighted average (Domar 1961; Hulten 1978) of the productivities in its innovation and final output sectors. Equation (20) also suggests that the return to innovation/R&D spending is related both to the value of the resources devoted to the function (s_N^Y) and to the efficacy of those resources in final use, that is, the increase in downstream competitive advantage as summarized by the term $s_N \Delta \ln TFP^N$.[13]

As depicted so far, the measured economy does not recognize investments in innovation as knowledge capital. If national accountants move to recognize innovation/R&D spending as investment, in this simple model (a closed economy, now with no intermediates, but with innovator markups) both final demand and final output would be represented as the sum of the

[13] As an aside, we note that a feature of this model is its link to customer demand (via producer markups and demand elasticities) This link is useful for thinking about the resources devoted to inventive activity in a fashion parallel to Hausman's approach to the new goods problem in price measurement (see Hausman 2003 for summary review). If investments in innovation lead to products or brands that have relatively high own price elasticities of demand (think new Apple products vs. new brands of milk), then market power and innovator markups might be expected to be associated with high shares of expenses devoted to developing and marketing new products. A general equilibrium examination of the determinants of the amount of resources invested in innovation and the size of the relative sectoral productivities and markups, however, is outside the scope of this paper.

output of the two sectors $Q = Y + N$; measured factor inputs would include R^Y, as in the model of section 1; and aggregate productivity would be given by

$$\Delta \ln TFP^Q = (1 - s_N^Q)\Delta \ln TFP^Y + s_N^Q \Delta \ln TFP^N \quad . \tag{21}$$

where $s_N^Q = P^N N / (P^Y Y + P^N N)$. To measure this productivity in the usual way we of course need a real measure of N which requires a price index. Before we turn to that task, we conclude this section by summarizing in table 1 how our model and approach views the sectoral productivities in equations (20) and (21) when the N sector is identified as the R&D process in private business.

3. Measurement

We turn now to measurement, where our goal is to construct the terms on the right hand side of equation (8) and use them to estimate price change for R&D as private business investment.

Our approach is to formulate the empirical growth accounting counterpart to the theoretical model of the previous sections and use it to obtain R&D investment prices as a "residual." We highlight the residual nature of our approach to lay bare certain assumptions. In the usual economic growth accounting application, as highlighted in Hulten (2010), both productivity change and a rate of return are obtained as residuals (Jorgenson and Griliches 1967). But one need not necessarily proceed that way; for example, Basu, Fernald, and Shapiro (2001) examine the cyclicality of productivity *cum* markup by using an *ex ante* rate of interest and calculating variable markups residually, and Corrado (2010) calculates a variable capacity utilization for the telecommunications industry in the same manner.

As our quest is a "residual" estimate of R&D prices, we must proceed in different manner., To use our model to solve for the R&D price, as shall become clear, we need the relative sectoral productivities, a rate of return for inventive activity, and the innovator markup. Our strategy will be to (1) tie steady-state values of *both* the relative productivities *and* rate of return to R&D to an estimated form of equation (20), and (2) assume a degree of imperfect competition for the innovator markup μ as it pertains to R&D *per se*. This strategy leaves us the freedom to calculate productivity $\Delta \ln TFP^{Qmeasured}$ in the usual ("residual" way) which guarantees that

equation (21), which follows from our model, will inhere in conventionally-calculated estimates of multifactor productivity when R&D is treated as an asset in national accounts.

Let us first explain why the innovator markup as it pertains to R&D cannot be pinned down (in the sense of "backing it out" of the data). To jump ahead just a bit, the implied average value of the equation (10) producer markup in the system we shall describe shortly is 1.02 (for the UK market sector), within, but only barely, the range of 1 to 1.4 explored by Rotemberg and Woodford (1995) following a thorough review of the micro-empirical literature (pertaining to the United States). The small value of the implied UK producer markup is a direct consequence of its small R&D share, however. Were the share to be four to five times as high, the implied producer markup *cum* zero intertemporal innovator profits would be 1.1, etc. Therefore an implication of our model is that estimates of innovator markups (or other "inefficiency" wedges, for that matter) cannot be obtained without a more or less complete accounting of the resources business devotes to innovation.

The way in which equation (20) is implemented and used to determine sectoral productivities is best understood after introducing our dataset.

3.1 Industry data sets

Equation (8) is expressed in terms of R&D-performing industries, and we therefore rely on the available industry data for the R&D-performing sector of the UK economy.

We have three distinct data sets. First, we have the UK R&D spending data from BERD, which surveys own-account R&D spending by firms and is reported for 32 market sector industries. Second, we have the UK EUKLEMS March 2008 dataset covering the period through 2005, the latest data as of this writing to report capital input and gross output-based TFP estimates for 23 industries, along with prices and quantities of output and labor and material input for 72 industries. Third, we have the UK supply-use (IO) tables, for more than 100 industries from 1992 to 2006. We use the latter source to allocate sales of the R&D services industry to other (i.e., downstream) industries.

After merging the BERD data with the EUKLEMS and IO data and aggregating certain industries, we have a 19 industry data set from 1981 to 2005.[14] This list of R&D performing industries excludes the R&D services industry (because its sales are allocated to using industries) and, as a consequence, two other industries, one of which is software. In terms of availability of TFP estimates, the three are part of a larger industry aggregate in UK EUKLEMS (business services including leasing of equipment), and an appropriate TFP measure for business services excluding R&D services is not available. Because these R&D-performing industries are excluded from our analysis, when working with the R&D data from BERD, we exclude the amounts of R&D that are reported for them.[15]

In what follows, we superscript measured data with KLEMS, BERD and IO respectively. Thus KLEMS refers to all R&D using industries except the R&D services industry. BERD refers to R&D spending on own-account for all but the R&D services industry. And IO denotes data on purchased R&D from the R&D services industry by R&D-using industries.

Finally, although the theory in sections 1 and 2 ignored intermediate inputs for simplicity, when working at the industry level, we need to model and account for all inputs and output, and thus we work with gross output.

We now go through measuring equation (8) term by term.

3.2 Input shares

We wish here to measure the share of knowledge payments in downstream gross output. To accomplish this, we proceed in three steps.

3.2.1 Upstream gross output and value added

It will turn out that to calculate downstream gross output and value added, we need upstream gross output and value added and hence we deal with that first.

[14] As is typical with data on R&D, the UK data are categorized according to product groups, which we assigned to corresponding industries out of necessity, Because individual businesses can perform R&D for a range of product group, the correspondence must be regarded as an approximation. Aggregation of the data to the level of availability of EUKLEMS TFP estimates, however, somewhat diminishes this concern.

[15] R&D spending by the UK software and other business services industry was 7 percent of all R&D performed during our sample period. To achieve comprehensive coverage of R&D, we plan to work around the restricted availability of TFP for components of business services in a revision to this paper.

Consider our model where knowledge is free for the upstream sector. In taking the model to the data, note that the upstream sector consists of (a) in-house R&D performed by industries outside of the R&D services industry and (b) the portion of the R&D services industry that sells its services to the downstream sector.

Consider first the in-house operations of industries outside the R&D services industry. Because these in-house operations do not result in recorded sales, we have to infer their value from the costs of such operations. Costs are the sum of in-house payments for upstream materials, labor and capital. From BERD, we have upstream wage and materials payments, which we can use directly. BERD also collects upstream investment data, but we need to convert these data into rental equivalents. We do this in the standard way, namely by generating a real capital stock from the real investment payments via a perpetual inventory model and obtaining rental payments from the standard relation between asset and rental prices.[16]

The following points are worth noting. First, officially reported R&D expenditure is constructed the sum of labor, capital expenditures, and material payments. Second, as part of intermediate payments in the data, there are also payments for licenses of patents and the like, that is, the "rental" of R&D by one knowledge-producing firm from another. In the UK data these turn out to be very small and so we ignore them. Third, because we assume imperfect competition in the upstream knowledge-producing sector, the revenue from production will exceed costs by the value of a markup. The theoretical $P^N N$ for in-house production can be written

$$P^N N \text{ on own account } \equiv P^N N^{BERD} = \mu\left(P^L L^{BERD} + P^K K^{BERD} + P^M M^{BERD}\right) \quad (22)$$

where, as before, $\mu \geq 1$ is a markup over costs.

The second element of $P^N N$ is purchased R&D services by downstream sector industries, which are reported in IO tables by purchasing industry. The value of such purchases is assumed to

[16] An important complication is a lack of investment data by industry prior to 1992 although data for total investment are available. To circumvent this problem, the aggregate investment data were distributed to the industry level (I) based on R&D spending (Y) and the I/Y average for 1993 to 1996.

incorporate a markup over the cost of conducting R&D, if there is one, by the R&D services industry.

Thus we can write the value of new knowledge created in the upstream sector as the sum of that created own account and that purchased directly from the R&D services industry:

$$P^N N \equiv \mu\left(P^L L^{BERD} + P^K K^{BERD} + P^M M^{BERD}\right) + P^N N^{IO} \tag{23}$$

3.2.2 Downstream gross output and value added and their constituents

The main industry data available to us are EUKLEMS industry data on industry sales, materials, wage, and capital payments, with capital payments determined as a residual (namely the value of sales less materials less wages). Since much R&D is carried out in-house, we have to adjust the KLEMS industry data to correspond to that in our theory.

We wish to measure gross output of the downstream sector as the sum of payments to the downstream factors employed: materials, labor, tangible capital, and knowledge capital, and thus we write

$$P^G G^Y = P^M M^Y + P^L L^Y + P^K K^Y + P^R R^Y \tag{24}$$

where G with the price P^G. Let us review how this theoretical sector corresponds to the data term by term.

Starting with gross output, we may write $P^G G^{KLEMS}$ on the left hand side of equation (24) because measured gross output is actual sales in the downstream sector. Turning to the right hand side, we write measured material purchases, PM^{KLEMS} as

$$P^M M^{KLEMS} = P^M M^Y + P^M M^{BERD} + P^N N^{IO} \tag{25}$$

which says that the measured materials bill in the EUKLEMS industry is the sum of materials in the downstream industry, materials used in the in-house R&D sector (that is, own account R&D production carried out by KLEMS industries) and R&D services purchased from the R&D industry.

Turning to the next term in equation (24), we have, from EUKLEMS, wage bill data for the downstream industry. But again, due to the presence of R&D workers, this needs to be written as

$$P^L L^{KLEMS} = P^L L^Y + P^L L^{BERD} \tag{26}$$

to correspond to the model where payments to workers in the N sector (L^N) are known from BERD data and hence are labeled as such In addition, we know from BERD the number of workers in so we can write the correspondence of theoretical and measured employment as

$$L^{KLEMS} = L^Y + L^{BERD} \quad . \tag{27}$$

We come now to the last two terms, $P^K K^Y$ and $P^R R^Y$. The problem is that we have no independent measure of the returns to ordinary capital because in the KLEMS data it is derived residually, (i.e. $P^K K^{KLEMS} \equiv P^G G^{KLEMS} - P^M M^{KLEMS} - P^L L^{KLEMS}$). So without an independent measure of $P^K K^Y$ we cannot separate this from $P^R R^Y$ in $P^K K^{KLEMS}$.

Thus to proceed we need to make some assumptions. Consider first the own-account services, the total output of which is denoted above as $P^N N^{BERD}$. If we use the user-cost relation (equation (4)), multiplying and dividing by N^{BERD} gives

$$P_t^R R^{Y,OA} = P_t^N N^{BERD} (\rho_t + \delta_R) \frac{R^{Y,OA}}{N^{BERD}} \tag{28}$$

Dividing the perpetual inventory equation (1) by R^Y and re-arranging and substituting the results for the expression for $R^{Y,OA} / Y$ gives

$$\begin{aligned} P^R R^{Y,OA} &= \frac{P^N N^{BERD} (\rho + \delta_R)(1 + \Delta R^{Y,OA} / R^{Y,OA})}{\left(\Delta R^{Y,OA} / R^{Y,OA} + \delta_R\right)} \\ &= \tau\left(P^N N^{BERD}\right), \qquad where\ \tau = \frac{(\rho + \delta_R)(1 + \Delta R^{Y,OA} / R^{Y,OA})}{\left(\Delta R^{Y,OA} / R^{Y,OA} + \delta_R\right)} \end{aligned} \tag{29}$$

This gives an expression for $P^R R^{Y,OA}$ if we assume τ.

Besides these self-produced R&D services, we also have R&D services directly purchased from the R&D industry. In terms of the downstream sector, there are two ways to regard them. One is that they are payments for one-period renting of R&D services. The other is that they are payments for enduring use of the R&D asset, in which case they have to be converted into the equivalent one-period rental payments. If we assume the latter,[17] then we have

$$\begin{aligned} P^R R^Y &= \tau\left(P^N N^{BERD} + P^N N^{IO}\right) \\ &= \tau\left(\mu\left(P^L L^{BERD} + P^K K^{BERD} + P^M M^{BERD}\right) + P^N N^{IO}\right) \end{aligned} \tag{30}$$

Looking at (29), to derive τ we proceed as follows. First, we set δ_R to the industry-specific depreciation rates used by the U.S. BEA (Mead 2007). Second, $\Delta R/R$ is unobservable since to derive it depends on the unknown price of knowledge that we are trying to estimate. In principle therefore, we should be able to write down a (non-linear) simultaneous system and solve it. For the moment, we set $\Delta R/R = 0.05$. This is the average rate of growth of nominal R&D spending in the UK economy from 1981 to 2005. We shall also experiment below with $\Delta R/R = 0.03$ and $\Delta R/R = 0.07$. Thus we have three different estimates of τ, each using industry-specific δ_R, but differing according to whether $\Delta R/R = 0.05$, our central estimate, or $\Delta R/R = 0.03$ and $\Delta R/R = 0.07$.[18] Finally, we set ρ to .04, which with geometric growth, yields $\tau \approx 1$ for the central estimate.

As for μ in (30), we experiment with $\mu=1$, a zero innovator excess profits estimate, and $\mu=1.25$ and $\mu=1.5$.

Thus we can construct the relevant shares of factor payments in $P^G G^Y$ as follows

---

[17] To be valid this assumption requires revenues in the R&D industry to be largely made up of payments for a long-lasting right, rather than payments for intermediate services. It also requires these rights to be mainly paid as a one-off or a lump sum, rather than as annual payments. If we look at revenues of the R&D industry itself, from the IO tables, they are hugely greater than R&D costs from the BERD. See our discussion on page 7 of section 1.2.

[18] We plan to extend this analysis to include industry-specific assumptions for the growth rate of R. In that way, we can determine consistency of final prices for R&D with the implicit capital gains term, industry by industry. Our experimentation to date suggests that, while the introduction of industry-specific growth rates of R adds a good dose of realism, the impact on the resulting aggregate price index is very small.

$$
\begin{aligned}
s_{Y,G}^{M} &= \frac{P^M M^Y}{P^G G^Y} = \frac{P^M M^{KLEMS} - P^M M^{BERD} - P^N N^{IO}}{P^G G^{KLEMS}} \\
s_{Y,G}^{L} &= \frac{P^L L^Y}{P^G G^Y} = \frac{P^L L^{KLEMS} - P^L L^{BERD}}{P^G G^{KLEMS}} \\
s_{Y,G}^{R} &= \frac{P_t^R R^Y}{P^G G^Y} = \tau \frac{\left(\mu P_t^N N^{BERD} + P_t^N N^{IO}\right)}{P^G G^{KLEMS}} \\
s_{Y,G}^{K} &= 1 - s_{Y,G}^{M} - s_{Y,G}^{L} - s_{Y,G}^{R}
\end{aligned}
\tag{31}
$$

And the corresponding prices that we use for M, K and L are as follows[19]

$$
\begin{aligned}
\Delta \ln P^G &= \Delta \ln P^{G,KLEMS} \\
\Delta \ln P^M &= \Delta \ln P^{M,KLEMS} \\
\Delta \ln P^L &= \Delta \ln \left(\frac{P^L L^{KLEMS} - P^L L^{BERD}}{L^{KLEMS} - L^{BERD}} \right) \\
\Delta \ln P^K &= \Delta \ln \left(\frac{P^K K^{KLEMS} - P^L K^{BERD}}{K^{KLEMS} - K^{BERD}} \right)
\end{aligned}
$$

3.2.3 Weights for price indexes

We note the foregoing also provides the information needed to obtain industry shares of total R&D and thus aggregate prices indexes for P^N and P^R from industry-level estimates of price change. We compute three sets of weights,

$$\omega_J^{BERD} = \frac{P^N N_J^{BERD}}{\sum_{i=1}^{H} P^N N_J^{BERD}}$$

$$\omega_J^{P^N} = \frac{P^N N_J}{\sum_{i=1}^{H} P^N N_J}$$

$$\omega_J^{P^R} = \frac{P^R R_J}{\sum_{i=1}^{H} P^R R_J}$$

[19] Note that the indexes for capital and materials do not adhere strictly to our model, as they are not built from subindexes for the two sectors for each industry. For this reason, as well as good housekeeping, we conducted identity checks to determine whether our sectoral splits preserved the original EUKLEMS price dual for each industry and found that they did.

The first set of weights shows relative industry R&D costs according to BERD; the second after adjusting each industry by its purchased services; and the third is each industry's share in total R&D rental-equivalence payments, or R&D capital income.

The second set of weights is used to obtain P^N and the third set is used to obtain P^R.

3.3 Shares and weights for R&D-performing industries

Before delving into our results we report our results for shares and weights for the 19 UK R&D-performing industries in our sample. Figure 1 shows mean values for the ratios s^{BERD}, s_N^Y, and s_R^Y calculating as described above assuming $\mu = 1$, $\tau =$ central estimate, for each industry in our dataset. Figure 2 shows the ω's calculated using the same assumptions.

As may be seen in figure 1, the ratios derived using our estimates of R&D capital income are slightly higher than those based on the cost of investment, and that there is a good bit of variation across industries according to resources devoted to R&D. While some of these differences reflect the heterogeneity in materials- and own-use intensity by industry, figure 2 confirms that the conduct of UK R&D is indeed concentrated in a handful of industry sectors, much as in the United States and elsewhere.

3.4 Sectoral productivities

We cannot use the KLEMS gross output TFPG to measure TFPG in the downstream industry because it hasn't been constructed with knowledge as an asset. This omission renders the *level of TFP* too high, since it misses out the contribution of an asset. But the effect on the *growth rate of TFP* is not a priori obvious because that depends upon the relative growth of the excluded asset, and in the UK, for example, (measured) nominal R&D spending has been falling or flat for much of the 1990s. We are nonetheless stuck in a circular loop because we need to know the productivity of R&D to calculate its price and we need the real stock of R&D to calculate its productivity. Even if we performed an iterative process, we do not have ready criteria to judge when we have solved for the correct values.

Equation (20) suggests, however, that there is a constraint we can use to pin down approximate estimates, namely, the long-run relationship between measured TFP and the resources devoted to

R&D. We now explore how to estimate this relationship by exploiting the variation in industry-level measured TFP growth and R&D spending.

In terms of observables, we have industry-level estimates of $\Delta \ln TFP^{measured}$ from EUKLEMS, and, from the above, estimates of $s_N^{Y,G}$. Thus we can run the following regression

$$\Delta \ln TFP_{it}^{KLEMS} = a + b \cdot s_{N,it}^{Y,G} + e_{it} \tag{32}$$

If we compare this with (20), then the estimated a is an estimate of $\Delta \ln TFP^{Y}$ and the estimated b an estimate of $\Delta \ln TFP^{N}$, *i.e.* the two unobservable TFP growth rates. Note also from the above, that $s_N^{Y,G}$ must be computed depending on assumptions for the innovator markup, μ.

To implement this regression as a long-run relationship we used the data for our 19 industries in two cross-sections, 1982 to 1991 and 1991 to 2005, with the cut-off, 1991, representing the end of that economic cycle. In principle of course, $\Delta \ln TFP^{N}$ differs across industries, and thus what the regression will discern are those due to differences in resources allocated to R&D, on average, in a given economic cycle. As our final goal is a price index for the conduct of overall R&D that is consistent with the downstream "using of it", we are not per se concerned about industry specific results or averaging over industries.

Figure 3 shows a scatter plot of the 38 data points we have available for the regression, which suggests a simple linear relationship between the two variables. We experimented with OLS, weighted LS (with weights reflecting each industry's contribution to overall productivity), and estimation with random effects (the method didn't make much difference). We also tested for significance of a shift in the estimate of a across the two time periods (it wasn't significant). That said, because of the relatively small sample, the equation's point estimates did exhibit certain sensitivity to which industries are included, the discussion of which we defer to the robustness section below. In what follows unweighted results are used.

The central results are set out in table 2. Estimation is by random effects with robust standard errors. Each column corresponds to a different measure of $s_N^{Y,G}$ depending on the treatment of μ, the innovator markup. In the first column we see that the implied $\Delta \ln TFP^{N}$, namely the

coefficient on $s_N^{Y,G}$ is 16.9 percent and is precisely estimated. The implied $\Delta \ln TFP^Y$ is 0.531 percent. This suggests that measured TFP is in fact an average of very substantial growth in upstream TFP, i.e., productivity the innovation sector, and much slower growth in the downstream production sector.

The way we use these estimates to obtain the productivity ratio $\theta_j = \Delta \ln TFP_j^Y / \Delta \ln TFP_j^{measured}$ is not quite as straightforward as dividing the constant term relative to the simple average over all industries because our method allows τ to deviate from the steady-state solution on an industry by industry basis. We do, of course, let the ratio vary by time period, with the result that the average values for θ_j with $\mu = 1$, and τ =central estimate are .72 and .61 in the first and second periods of our sample, respectively. These magnitudes imply that, assuming zero innovator excess profits (not unreasonable for a 24 year period), investments in R&D accounted for 34 percent of the average measured gain in TFP growth for the 19 UK industries used in our analysis—and contributed 25 percent of the TFP growth in the market sector as a whole

As noted in the introduction to this section, our use of equation (20) is the ”productivity dual” to the literature that has used a similar specification to infer the gross rate of return to a dollar of R&D spending (e.g., Mansfield 1980; see Cameron 1996 for a review). These and others who pursued the related approach that calculated a R&D stock and regressed the *level* of TFP on it to determine an output elasticity (e.g., Griliches 1980) often ignored the fact that treating R&D as capital implies adjustments to output (as in CHS) or to factor payments (as in Schankerman 1981) to account for the self-production of R&D assets,

Without going through the algebra, we need here to divide the coefficient b by τ to obtain an estimate of the gross rate of return. Using our central estimate of τ implies this rate is still 16.9 percent, a result that is reasonably close to the assumptions that have been fed to the system to this point. (As a reminder, these are: for depreciation, a bit below 15 percent, and for the real rate of return, 4 percent.)

3.5 Price indexes for knowledge assets

Using the terms derived in the previous sections we are now in a position to form the following price change for each downstream industry J

$$\Delta \ln P_J^R = \frac{\Delta \ln P_J^{G,KLEMS} - s_{Y,G,J}^{\ M} \Delta \ln P_J^M - s_{Y,G,J}^{\ K} \Delta \ln P_J^K - s_{Y,G,J}^{\ L} \Delta \ln P_J^L + \theta_J \Delta \ln TFP_J^{G,KLEMS}}{s_{Y,G,J}^{\ R}} \tag{33}$$

And price change for the aggregate

$$\Delta \ln P^R = \sum_{j=1}^{J} \omega_j^{P^R} \left(\Delta \ln P_J^{\ R} \right) \tag{34}$$

(which when multiplied s_R^Y for the aggregate market sector can be shown to be equivalent to the Domar-weighted sum of the contribution of each industry's knowledge price change to the change in aggregate output price change). We compare this result with a similarly-weighted change in industry output prices. The results are shown in tables 3A and 3B.

The tables are set out as follows. The A and B variants show data for two sub-periods, 1982-91 and 1991-05. In each variant, the first data column shows ω, and the second s^R. The third shows the overall weight ω / s^R and the fourth and fifth shows changes in (log) prices: output in column 4 and the weighted sum of labor, material and capital prices in 5. The next two columns show $\Delta \ln TFP^{KLEMS}$ and finally adjusted $\Delta \ln TFP^{KLEMS}$, that is, ΔlnTFP adjusted to be that for the downstream sector using the regression above. The next to last column show the implied $\Delta \ln P^R$ that equals weighted column 4, minus weighted column 5, plus weighted column 7. The final column, as a memo item, shows the weighted change in output prices. The last row of each variant gives the weighted sum of the particular column using the weight ω / s^R for the particular industry.

Consider the results in table 3A. As can be seen from the final row, (weighted) ΔlnP rises quite rapidly, accompanied by rises in factor prices and TFP, with adjusted TFP rising more slowly. Jumping to the final row of table 3B, (weighted) ΔlnP slows down dramatically and the other key terms slow down, but not as sharply. Thus our "residual" price index is falling, on average, in both periods, but falling faster in the second period. It is worth comparing this with the behavior

of (weighted) prices (the memo column), which does not adjust for factor costs or TFP. That rises throughout, but less rapidly in the second period, as did overall U.K final-output price increases.

Figure 4 (Panel A) shows the implied price index for all years, plotted on a log scale with 1997=1, and smoothed with a three-year moving average. We show two lines, our "residual" price index and the (weighted) industry output price index. As may be seen and as suggested by the table, our index for P^R falls more or less continuously, averaging -2.7 percent for the entire period shown. Our index for P^N, not shown, falls at a rate of 2.5 percent per year.

3.6 Robustness checks

We have a number of robustness checks.

1. choice of industries.

Figure 4 (Panel B) shows and index that excludes two industries which have s^R<0.005 in both periods, namely construction and wholesale/retail trade. As the figure shows, compared with the 19-industry index, the 17-industry index moves very similarly. It falls 2.4 percent at an annual rate.

2. choice of innovator mark-up, μ

Figure 6 shows indexes with three different assumptions for μ, μ=1, μ=1.25 and μ=1.5. Changes in μ change s^R and also $\Delta \ln TFP^Y$. The results in Panel B (the 17 industry index) are more stable, but each index moves in similar ways in response to higher assumed markups.

3. relation between $P^N N$ and $P^R R$, τ

Figure 7 shows the index with three different assumptions for τ, corresponding to three different assumptions on ΔR/R, namely ΔR/R=0.003, ΔR/R=0.05 (our central estimate) and ΔR/R=0.07. As these indexes show, the results are not terribly sensitive, and again the 17-industry variant is more stable.

3.7 Implications

In taking our model to the data, we had a number of issues to confront. With most of them resolved and, we believe, a general robustness established, we turn to gauging the importance of this new index. Specifically, once R&D is capitalized in national accounting systems, how does the move raise aggregate value added and how do changes in the stock of R&D contribute to economic growth?

To do this, we proceed as follows. We took the growth accounting estimates in Haskel *et al*. (2007), which applies the CHS method to UK data. We ignored the contributions of certain CHS intangibles (training, design, financial services product development, branding and organizational capital), and retained, as assets, tangible capital, artistic originals and mineral rights, software, and R&D. We first capitalized R&D and evaluated its contribution to growth in value added per hour as the share-weighted change in R&D services per hour using the GDP deflator. The results of this are set out in the upper panel of table 4, which one should think of as UK market sector GDP with R&D capitalized using the GDP deflator for R&D investment. All columns show annualized growth rates and are per hour worked: they are, in column 1, value added; column 2, labor composition; column 3, computer capital; column 4, other tangible capital; column 5, software; column 6, R&D; and column 7, TFP calculated as a residual.[20]

In the middle and lower panels we use the BEA R&D price deflator from their satellite accounts (Copeland, Medeiros and Robbins, November 2007 "Estimating prices for R&D investment in the 2007 R&D Satellite Account", Chart D, page 50) which has a roughly flat then falling shape) and our downstream output price deflator, respectively. There are three interesting effects. First, the contribution of the R&D term rises sharply. Second, value added per hour growth is higher, too. But third, TFP growth hardly changes because the percentage point increase in the R&D capital contribution more or less equals the percentage point increase in output growth. Therefore, in addition to the impact on the growth of R&D, the choice of the R&D investment deflator has implications for the growth of real output and output per hour, two widely-watched indicators of economic activity.

[20] The contribution of artistic originals and mineral rights is very small and not shown in the table.

4. Conclusion

In this paper, we modeled 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. The model was very simple, assuming only the following: that the innovation sector is entirely upstream of the operations sector; the operations (or "downstream") sector produces all final output and is a price-taker for inputs; and the aggregate value of final output equals the sum of all factor payments by business. A way of thinking about innovation and productivity in these two stylized (upstream/downstream) business sectors for purposes of growth accounting was introduced. The markup of the imperfect competition literature was related investments in innovation, thereby linking productivity in this model to customer demand.

The main use of the model was to show how the price of commercially-produced knowledge is related to measured output prices, factor costs, and productivity in the downstream sector, and the application to estimating a price index for UK R&D as private business investment the empirical quest of the paper. The crux of our approach was to exploit price-dual growth accounting relationships, a technique with ample precedence in the literature (e.g., Oliner and Sichel 2000). The way that we pinned down productivity in the conduct of R&D also is related to previous works, namely, the literature on estimating returns using detailed industry and/or microdata (Griliches 1980, Mansfield 1980, Schankerman 1981, among others). At the end of the day, we found that UK R&D investment prices fell about 2.5 percent per year from 1981 to 2005, suggesting that R&D investments (which grew 4.9 percent in nominal terms) over the same period notably contributed to UK economic growth.

Although we identified the upstream sector of our model as the R&D process, the method we used to infer prices for upstream services from downstream business operations is very general, requiring "only" authoritative spending data at the industry level. The boundary we drew for the upstream sector therefore followed the availability of industry-level spending data on R&D as well as the national accounting imperative mentioned in the introduction to this paper. If authoritative industry-level data on business investments in innovation were to exist, our

upstream sector and innovation price measure could have been defined more broadly, for example, as in the literature on intangible capital.

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