Measuring the Price of Research and Development Output

By Adam Copeland
Dennis Fixler[1]

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This paper develops a framework for constructing an R&D output price index. Based on a model of the innovator, we show that the price of innovation is equal to the expected discounted stream of profits attributable to the adoption of the innovation. Using this relationship, we construct an R&D output price index using data on NAICS 5417, Scientific R&D services. We compute that R&D output prices increased, on average, by 5.8 percent at an annual rate from 1987 to 2005. Using our price index, we deflate nominal Scientific R&D services revenues and find that real Scientific R&D services revenues grew at an average rate of 2.6 percent. Finally, we propose deflating total R&D nominal expenditures with two price indexes; use our output-based price index for the portion of total R&D expenditures from NAICS 5417 and an aggregate input-cost price index for the remainder of R&D expenditures. Under this strategy we find that real total R&D expenditures grew at an average annual rate of 1.4 percent. Only using an aggregate input-cost price index understates R&D price growth for NAICS 5417. This boosts the real growth of total R&D expenditures over our time horizon, leading to substantial mis-measurement of total R&D expenditures.

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1. The role of research and development (R&D) in the economy has spurred a vast literature. Macroeconomists have analyzed the link between investment in R&D and total factor productivity, while industrial organization economists have considered how market structure and institutions influence the rate of innovation. A wealth of work also examines the link between labor productivity and R&D investment. For the most part, these and other works brush past problems with measurement. Measuring R&D output and its real value, however, are issues underlying all these major questions.

2. In this paper, we focus on measurement; in particular the difficulty of measuring the price of R&D output and constructing a time-series of real R&D output. We begin with the micro-foundations of the problem and model the innovator. Drawing from the recent endogenous growth literature, we consider a profit-maximizing innovator who develops technology-improving ideas that are sold to a downstream firm. We then use this basic model as a framework for analyzing the determinants of the price of R&D output and, specifically, why this price might change over time. A main result of the model is that the price of an R&D innovation is equal to the change in the downstream firm's profits attributable to the adoption of the R&D innovation.

3. Using insights from the model, we analyze the Scientific R&D services industry (North American Industrial Classification System 5417). This industry closely fits our model of innovation because the primary source of receipts for these establishments is the sale of R&D services. Further, over 70 percent of establishments in NAICS 5417 are single unit-establishments, closely hewing to the independent innovator mold used as the basis of our theoretical model. As far as we know, this paper is the first to study this industry for the purposes of learning about R&D output prices. Unlike industries such as pharmaceutical or semiconductor manufacturing, Scientific R&D services provide a clean look at the production of innovation.

4. Even with the Census data on Scientific R&D services, we do not have enough information to directly apply our model and estimate R&D output prices. In general, this is a difficult task since R&D output prices reflect future profit flows attributable to the

adoption of a new innovation. The framework of the model, however, directs us to consider the annual revenue of NAICS 5417 as a stock of ideas multiplied by their appropriate prices. Accordingly, an indirect way to measure R&D output price change is to apply Frisch's product rule. Using the revenue figures from NAICS 5417 along with an appropriate quantity index, we construct a R&D output price index. Our index measures an average annual price change of 5.81 percent over our time frame of 1987 to 2005. Over this period, there is a de-acceleration in the growth rate of price change; for the first half of our sample the average annual price change is 6.53 percent, while in the second half it is 5.01 percent.

5. Using our index, we find that NAICS 5417 real revenues grew at an average annual rate of 2.64 percent. Because the output of these establishments typically contributes to one-quarter of total R&D expenditures, the deflation of NAICS 5417 nominal output has large effects on real total R&D expenditures. For total R&D expenditures, we recommend a two-price-index approach. For those R&D expenditures for which there are market-based data, we recommend using an output-based price index. For those R&D expenditures without any market-based data, we recommend an aggregate input-cost price index. In the national accounts, we implement this idea by deflating NAICS 5417 revenues by our R&D output price index. The remaining R&D expenditures, about three-quarters of total nominal expenditures, are deflated using an aggregate input-cost price index. This stands in contrast to the standard approach of only using an input-cost price index. Indeed, we show that only using an aggregate input-cost price index to deflate nominal total R&D expenditures dramatically overstates the average growth rate of real total R&D expenditures. The differences in real expenditures, of course, lay in the deflation of NAICS 5417 nominal revenues. We show that over an 18 year horizon, the mis-measurement of NAICS 5417 real growth from using an aggregate input-cost price index overstates the level of real total R&D expenditures by $25 billion, or 14 percent.

6. One chief difference between our proposed output-based price index and the usual input cost index is the inability of the later to account for productivity changes in the

Scientific R&D services industry. This significant failing of the input cost approach makes output-based approaches all the more important. Identifying industries such as Scientific R&D services where market data exist, and incorporating this data and its implications about R&D price change is crucial to improving our estimates of real R&D output.

7. Though most of the literature on R&D does not focus on measurement issues, a group of papers have focused on constructing real measures of R&D output. Mansfield et al (1983), Mansfield (1987), and Jankowski (2006) use input-cost price indexes, taking advantage of the data available on R&D inputs costs. The input cost approach assumes no change in the productivity of R&D innovators. This assumption seems at odds with the aggregate data, given that the growth rate of total factor productivity remains fairly constant while the growth rate of R&D expenditures is rapidly growing (Jones (1995), Kortum (1997), Jones (2009)). Another approach to deflating nominal R&D expenditures has been to use a general price index (e.g. Corrado et al (2006)).

8. The rest of the paper is organized as follows. We begin by describing the model of the innovator and derive an equation for the price of R&D output (section 1). We then construct an output price index for Scientific R&D services discuss (section 2). We discuss how this approach yields significantly different predictions about the growth of real R&D output, compared to the case where an aggregate input-cost price index is used, both for Scientific R&D services and, consequently, for total R&D expenditures. We conclude by summarizing our results and discussing how our approach can be implemented for all countries that follow the International Standard Industrial Classification of All Economic Activities.

Section 1: The Model of the Innovator

9. We assume there are two types of agents in our industry model: innovators and firms. Innovators attempt to generate ideas that improve the current level of technology used by the firms. Once an innovator produces a technology-enhancing idea, it is sold to,

and adopted by, a firm. Following the endogenous growth literature and reflecting the nature of innovation, we assume the innovator has market power. Further, firms are assumed to operate in a competitive industry which is a small part of the overall economy.

10. Turning first to the firm, we assume that real output, Y, is given by,

$$Y = AF(L_Y)$$

where $A>0$ is a technology parameter and L_Y is the labor input. Let D denote the inverse demand function and w_Y the wage, then the firm chooses labor in order to maximize

$$AF(L_Y)D(Y,t) - w_Y(t)L_Y,$$

where t is a time subscript.

11. The innovator's problem focuses on increasing the technology parameter, A. To capture different types of technological advances, we assume that innovators produce drastic or non-drastic types of innovation (Arrow (1959)). Non-drastic innovations are relatively minor advances in technology that improve productivity, without dramatically altering the production process or the final goods market. Thus, these innovations are comparable over time. In contrast, drastic innovations are major improvements that are difficult or impossible to compare with past improvements.[2] Examples of non-drastic innovations are the regularly occurring technology improvements in semiconductors. These small improvements lead to more powerful microprocessor chips, but different vintages of chips are still comparable to one another.[3] In contrast, the invention of the semiconductor represents a drastic innovation. Its introduction transformed multiple

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[2] Drastic innovations have also been called "General Purpose Technologies" (Jovanovic and Rousseau (2005)). Jones and Williams (2000) describe non-drastic innovations as those that can be classified within a cluster of technology. Drastic innovations, on the other hand, are those that fall outside the existing cluster of technology. Finally, the BLS in the producer price index for computers determines the manner of quality change along similar lines. The BLS terminology uses revolutionary and evolutionary, where evolutionary implies a quality change of an existing good while revolutionary implies the introduction of a new good.

[3] Aizcorbe and Kortum (2005) develop a vintage-capital model where different generations of microprocessor computer chips are explicitly compared to one another.

markets along many dimensions, making a comparison between the semiconductor and what came before it difficult-to-impossible.

12. We model a non-drastic innovation as an increase in the level of A. A represents the current frontier of technology and includes the cumulation of knowledge from all relevant sources. Formally, a new innovation A' is defined as $A'=\gamma A$ where A is the previous innovation and $\gamma \in [1,\varphi]$. The upper bound on γ reinforces the idea that non-drastic innovation has limited potential for improvement upon the current technology. Innovating is a risky business, where innovators often fail to produce valuable output. To capture the stochastic nature of non-drastic innovation, we denote

$$g(x;\varphi,A,l_A)$$

as the probability of an successful innovation $x \in [1,\varphi]$, where l_A is the innovator's labor input. To capture the idea that more inputs increase the probability of success, we assume that g is increasing in l_A, but at a decreasing rate as g approaches one. Further, while there are many innovators in the economy, we implicitly assume there is zero probability that two innovators successfully produce innovations within the same industry at the same time. Lastly, we include A as an input into the production of ideas, because the current stock of knowledge influences the probability of producing new innovations.[4]

13. Drastic innovation is more sparsely modeled. We assume that a successful drastic innovation results in a $\widetilde{A} > A$ where $\widetilde{A}$ is such a large change that the inverse demand function for the final good shifts out, from D to $\widetilde{D}$. If an innovator chooses to work on producing a drastic innovation, the probability of success is given by $h(A,l_D)$, where l_D is the labor input. As with g, we assume that h is increasing in l_D.

14. Let (L_A, L_D) define the total amount of labor used by all innovators working on non-drastic and drastic innovations, respectively. For the industry as a whole, the probability of a successful non-drastic and drastic innovation occurring is given by $G(A,L_A,\varphi)$ and $H(A,L_D)$ respectively. These industry-level probabilities are built up from

[4] Both Corrado et al (2006) and Jones (2009) emphasize how the current stock of knowledge is an important factors in the production of new innovations.

the individual-level probabilities, g and h, and so they too are increasing in the labor inputs.

15. Using this notation, we can write the non-drastic innovator's problem, which is to choose labor, l_A, so as to maximize profits,

$$\int_1^{\varphi} V(xA)g(x;\varphi,A,l_A)dx - w_A(t)l_A \quad .$$
$$s.t.\ l_A \geq 0$$

where V is the nominal price of an idea and w_A is the nominal wage of researchers. The constraint that labor inputs be non-negative emphasizes that innovators can always exit the market by chosing l_A=0, if the benefits from innovation do not exceed the costs. Because we assume that innovators have market power and innovation-purchasing firms operate in a competitive market, innovators are able to extract all the gains in profits that the innovation-adopting firm receives.[5] Pricing an idea, then, is quite similar to pricing a capital asset. Assets are typically priced according to the future discounted stream of dividends they produce (Lucas (1978)). Similarly, innovations are priced according to the future discounted increases in expected profits the idea will generate for the R&D-adopting firm.

16. To formally define V, we first let $\pi(A',A,t)$ be the nominal increase in firm's profits attributable to the adoption of a new innovation, A', in period t. Let $\left(\widehat{L_Y},\widehat{Y},\right)$ be the profit maximizing choice of labor and output given A' and $\left(\overline{L_Y},\overline{Y}\right)$ be the profit-maximizing choice of labor given A, then we have:

$$\pi(A',A,t) = \left[A'F(\widehat{L_Y}(t))D(\widehat{Y},t) - \widehat{L_Y}(t)w_Y(t)\right] - \left[AF(\overline{L_Y}(t))D(\overline{Y},t) - \overline{L_Y}(t)w_Y(t)\right]$$

Using this notation, the nominal price to the rights of a new, non-drastic, technology improvement A', is, where r is the interest rate,

[5] These are common assumptions in the literature, see for example Kortum (1997), Aghion and Howitt (1992), and Jones (1995).

(1) $V(A^{'};A,r,\varphi,L_A,L_D,N) = \pi(A^{'},A,t) +$

$$\sum_{s=t+1}^{t+N}\left(\frac{1}{1+r}\right)^{s-t}\pi(A^{'},A,s)[1-G(A^{'},\widehat{L_A}(s),\varphi)][1-H(A^{'},\widehat{L_D}(s))]$$

In the formulation above, we assume that profits attributable to the innovation *A'* are driven to zero after *N* periods because of imitation.

17. Equation (1) details how the price of a new innovation depends on several important forces: the stream of future profit flows, the interest rate used to discount them, and the probability of obsolescence. Obsolescence depends on *G*, *H*, and *N*, where the first two terms are the probabilities that a non-drastic or drastic innovation will come along and usurp the market. The last term captures imitation, which ensures that an innovation's flow of profits last at most *N* periods. Obsolescence greatly complicates the problem of pricing an innovation. For a typical capital asset, pricing depends primarily upon the expected future stream of profits and the relevant interest rate.[6] Because innovations face an expected obsolescence rate, pricing new ideas entails an extra dimension of difficulty relative to pricing a capital good.

18. With equation (1), we now have a complete picture of the non-drastic innovator's problem. The innovator knows that in equilibrium, a successful innovation $x \in [1,\varphi]$, commands a price $V(xA;A,r,\varphi,L_A,L_D,N)$. Because this price looks forward at the impact an innovation has on the downstream market, it does not depend on the innovators' input choice, l_A. Rather, it depends on macroeconomic conditions (A,r,φ) and aggregate labor inputs (L_A,L_D). In particular, as detailed in equation (1), future values of (L_A,L_D) effect the price of an innovation through obsolescence. We assume there are many innovators, and so one innovator's labor choice does not influence the aggregate labor input. Instead, the innovator's labor choice effects the probability that the innovator successfully innovates and the probability distribution of potential innovations, a relationship captured by $g(x;\varphi,A,l_A)$.

[6] Service life determination can also be difficult to measure for some capital assets.

19. The drastic innovator's problem is quite similar to the non-drastic innovator's problem. Letting W denote the nominal price of a drastic innovation $\widetilde{A}$, we can write the drastic innovator's profit maximizing problem as choosing labor, l_D, to maximize

$$W(\widetilde{A})h(A,l_D) - w_A(t)l_D .$$

As before, the price of $\widetilde{A}$ is equal to the increase in profits to the final goods producer attributable to the innovation. The nominal increase in profits attributable to $\widetilde{A}$ in period t is

$$\widetilde{\pi}(\widetilde{A},A,t) = \left[\widetilde{A}F(\widetilde{L_Y}(t))\widetilde{D}(\widetilde{Y},t) - \widetilde{L_Y}(t)w_Y(t)\right] - \left[AF(\overline{L_Y}(t))D(\overline{Y},t) - \overline{L_Y}(t)w_Y(t)\right],$$

where $(\widetilde{L_Y},\widetilde{Y})$ are the profit maximizing choice of labor and output given $\widetilde{A}$ and $\widetilde{D}$.

Using this notation, the nominal price to the rights of drastic technology improvement $\widetilde{A}$ is

$$(2)\ W(\widetilde{A};A,r,\varphi,L_A,L_D,M) = \widetilde{\pi}(\widetilde{A},A,t) + \sum_{s=t+1}^{t+M}\left(\frac{1}{1+r}\right)^{s-t}\widetilde{\pi}(\widetilde{A},A,s)[1-G(\widetilde{A},\widetilde{L_A}(s),\varphi)][1-H(\widetilde{A},\widetilde{L_A}(s))]$$

where M represents the number of periods before imitation completely erodes the flow of profits attributable to the drastic innovation. Comparing equations (1) and (2), we see that the price formulations of non-drastic and drastic innovations are similar. The major difference lies with the change in the inverse demand function that accompanies the adoption of drastic innovations. From a measurement perspective, this difference is crucial because it breaks the comparability of innovations over time. Because drastic innovations have such large effects on the market place, comparing drastic innovations to other innovations is necessarily difficult. Nordhaus (1997) lays out the importance for properly measuring quality change to account for major technological leaps as well as detailing the difficulties inherent in this exercise. In contrast, comparing non-drastic innovations to one another is an exercise in comparing roughly similar objects and thereby the proper focus for the construction of an output price index.

20. Completing the model, we assume a free entry condition for the innovator's market. Hence, in equilibrium the expected profits from both non-drastic and drastic innovation must equal zero, or

$$(3)\quad \int_1^{\varphi} V(xA; A, r, \varphi, L_A, L_D, N)\, g(x; \varphi, A, l_A^*)\, dx = w_A(t) l_A^*$$

$$(4)\quad W(\widetilde{A}; A, r, \varphi, L_A, L_D, M)\, h(A, l_D^*) = w_A(t) l_D^*$$

where l^*_A and l^*_D are the profit-maximizing labor choices for non-drastic and drastic innovators respectively.

21. The model can be used to connect the costs of the labor inputs to the price of an innovation. This relationship is important, because past research often relies on a fixed, proportional relationship between the change in input costs and the change in the price of R&D to construct R&D price indexes (e.g. Mansfield (1987) and Jankowski (1993)). We consider the link between input costs and price only through the non-drastic innovator's problem, though the results outlined below also hold for the drastic innovator's problem. In the model, changes in the input cost, or wages, have two impacts. The first impact of a change in wages is at an individual level, where innovators alter their optimal labor input, l_A. How this change affects innovator's profits depends upon g, as seen through the first order condition of the non-drastic innovator's problem,

$$(5)\quad \int_1^{\varphi} V(xA; A, r, \varphi, L_A, L_D, N) \frac{dg(x; \varphi, A, l_A)}{dl_A} dx - w_A = 0 .$$

As detailed earlier, changes in the labor input effect the probability of an innovation $x \in [1,\varphi]$. The second impact of a change of wages in on the price of innovation, V. Because it is a forward looking measure dependent upon macroeconomic variables, V is not influenced by a single innovator's choice of l_A. But, the collective actions of all innovators will change the price of R&D output. We model this second impact through the aggregate labor input, L_A.

22. Consider the case where wages go up. Given this rise in input costs, some innovators will lower their labor inputs. In the aggregate, this change lowers the

equilibrium level of the aggregate labor input. The aggregate labor input reductions affects the price of an idea by lowering the probability of a successful idea's obsolescence, raising the value and price of a successful innovation. Rising wages, then, increase the price of R&D output through the aggregate labor variable, L_A (see equation (1)).

23. While a positive correlation exists between the input cost of labor and the price of an idea, this is a highly non-linear relationship. First, the changes in wages and aggregate labor inputs are linked through equilibrium conditions, a non-linear relationship. Second, aggregate labor inputs influence price through the non-linear probability function $G(A,L_A,\varphi)$. In this fairly general and simple model, then, there is little hope that changes in input prices will yield reasonable approximations of the change in the price of R&D output, or that an input-cost price index provides a good approximation of the true R&D output price index.

Section 2: Measurement of R&D Output Prices

24. The theoretical model splits R&D output into drastic and non-drastic innovations in order to emphasize that certain types of innovation are especially difficult to compare over time. Because drastic innovations could not be used in comparisons over time without much additional work, we focus on non-drastic innovations, the much more common form of R&D output.

25. Though equation (1) sets out the conceptual framework for the price of an innovation it is difficult to transform it into a concrete measure. Data on profits and the rate of expected obsolescence are required, figures that are, at the very least, difficult to obtain. While the preferred course of action would be to use such data to directly estimate the parameters in equation (1), the absence of data requires a more indirect course.

26. Using the model's framework, we consider R&D output as a group of ideas or innovations. While we consider the generation of knowledge as a flow, the metric for output is a batch of knowledge that can be concretely applied to a production process or turned into a new product. Then using the Frisch product rule, we indirectly compute an output price index by decomposing the movement in the innovator's revenues into price and quantity indexes. According to the Frisch product rule the change in innovator's revenue, R, is equal to the product of price, P, and quantity, Q, indexes (Frisch (1930))

$$(6)\quad \frac{R(t+1)}{R(t)} = P(t,t+1)Q(t,t+1)\,.$$

27. Even taking equation (6) to the data is difficult, because data on prices, quantities and revenues are required, all of which are not readily available. Only a small amount of R&D is licensed or sold in the market place. Furthermore, in certain instances bundles of innovations are traded, obscuring the price of individual assets. Finally, innovations are sometimes given away freely. Open-source software is a prime example, and its adoption by a large number of users suggests it has value. To create networks effects, firms may provide innovations to consumers for free.

28. Because the data exist, a number of researchers have focused on patents and licensing agreements to study the pricing of and returns to R&D output (e.g. Pakes (1985)). From a national accounts perspective, however, only using patent data to construct a price index for all innovation is worrisome, because of the selection effect over which type of innovators sell patents or create licensing agreements.

29. A less-used, but potentially fruitful source is Census industry data on NAICS 5417, Scientific R&D services. Sales of R&D output are the primary source of receipts for these establishments. Because Census collects these data at an establishment level, as opposed to the firm level, these data capture R&D output produced for in-house use as well as R&D output transferred between firms. A question arises whether NAICS 5417 establishments fit the independent innovator modeled in section 2. However, for those

establishments subject to federal tax, 8,644, or 70 percent, are single unit establishments, with the remainder being multi-unit establishments.[7] The fact that the majority of establishments are single units suggests that this industry is populated by independent innovators.

30. With respect to multi-unit establishments, it is true that they could be part of other firms and so the model in section 2 is not representative. Fortunately, of the 3,644 multi-unit establishments, 1,848, or 51 percent, are located in NAICS 5417. This means that NAICS 5417 is the parent industry for these multi-unit establishments and therefore the innovator model likely applies. The next major parent industry, interestingly, is merchant wholesalers. Of the 607 establishments affiliated with merchant wholesalers, 34 are associated with motor vehicles, 93 with computers, and 111 with drugs. Since it is not clear in what sense merchant wholesalers support R&D, one hypothesis is that these merchant wholesalers are in fact representatives of foreign firms and as such they are supporting R&D activity for the foreign firm.

31. In any case, there is no evidence that for this industry the concern over the existence of establishments integrated with a parent reduces the applicability of our model. The remaining 1,189 multi-unit establishments, 33% of the total, are affiliated with many industries. 744 of them are associated with manufacturing, 140 of them with Computer and Electronic Product Manufacturing, 68 with Transportation Equipment Manufacturing, and 161 associated with other industries in Professional, Scientific and Technical Services (that is industries other than NAICS 5417) consisting of 94% of the other than NAICS 5417 affiliated establishments. The remaining 6% of establishments are scattered throughout other industries.

32. Output from all NAICS 5417 establishments flows to both industries and final users (see table 1) and accounts for one-quarter of total R&D expenditures. As an intermediate input, NAICS 5417 output is spread among a number of industries, including pharmaceuticals and semiconductor manufacturing as well as management

[7] 12,288 out of all 15,334 establishments in NAICS 5417 are subject to federal tax.

services. The broad variety in the use of 5417 output is suggestive that studying R&D activity in this industry is representative of R&D activity in the economy.

33. As can be seen on table 1, a substantial portion of R&D services are purchased by final users. Government, for both defense and non-defense services, acquires over 40 percent of NAICS 5417 output, while households and non-profit organizations, labeled as personal consumption expenditures in table 1, use more than 10 percent.

34. While our model describes the sale of R&D output to industries, it can also be applied to sales to final users, with a change in terminology. Rather than producers of a final good, consider final users as cost-minimizing agents. For instance, the federal government seeks to minimize costs when producing defense services. With this change in terms, the same framework described in section 1 applies. Rather than setting price of an idea equal to the discounted flow of expected profits attributable to the adoption of an innovation, however, we use the discounted flow of expected cost-savings.

35. From the Census's Survey of Annual Services, we know the annual revenue flow to establishments in Scientific R&D services. Through the lens of our model, these revenues reflect the summation of prices paid for innovation. These revenues flows, then, can inform us on the change in price for innovation, given we can control for quantity. We assume that the flow of revenue to NAICS 5417 establishments is payment for non-drastic R&D innovations. It is possible, however, that drastic innovations are included in these data, polluting our measure of the change in price of R&D output. The smooth flow of Scientific R&D services' nominal revenues over our 1987-2006 time frame, however, suggests that the probability of a drastic innovation biasing our results is low (see chart A).

Table 1: 5417 Input/Output Use Table

(All industries that used more than 1 percent of total 5417 output)

Industry	Percent of Total Output
Other basic organic chemical manufacturing (325190)	1.4
Plastics material and resin manufacturing (325211)	1.4
Pharmaceutical preparation manufacturing (325412)	3.8
Toilet preparation manufacturing (325620)	1.1
All other chemical product and preparation manufacturing (3259A0)	1.5
Semiconductor and related device manufacturing (334413)	1.4
Search, detection, and navigation instruments manufacturing (334511)	1.1
Motor vehicle parts manufacturing (336300)	1.3
Wholesale trade (420000)	3.9
Management of companies and enterprises (550000)	2.6
Junior colleges, colleges, universities, and professional schools (611A00)	1.8
Personal consumption expenditures (F01000)	10.1
General Federal defense government services (S00500)	20.3
General Federal nondefense government services (S00600)	14.6
General state and local government services (S00700)	5.7

36. Our approach is to find a good indicator of the change in the quantity of R&D output and then use this quantity index to solve for the accompanying price index. We try two different quantity measures: the change in the number of successful patents for NAICS 5417-related R&D and the change in the number of employees in NAICS 5417 establishments. The patent data come from the US Patent and Trademark Office (USPTO). Using a mapping of patents to industries sent to us from the USPTO, we selected the number of successful patents attributed to industries which are heavy users of NAICS 5417 output (see table 1).[8] These industries are: Chemical & Allied Products,

[8] The USPTO categorizes patents into industries based upon information claimed and disclosed in the patent. Patent counts data appearing in this document were prepared under the support of the Science Indicators Unit, National Science Foundation, by the Patent Technology Monitoring Branch, U.S. Patent

Rubber & Miscellaneous Plastic Products, Electrical & Electronic Machinery Equipment, Transportation Equipment, and Professional & Scientific Instruments. While this narrow definition provides the cleanest quantity indicator for NAICS 5417, in practice we found that from 1987 to 2006, this quantity measure moved closely to one based on all successful patents. Consequently, our R&D output price index results changed little when we used different patent-based quantity indexes.

37. The number of successful patents has the advantage of accurately measuring the number of innovations each year. Its does, however, have at least two main disadvantages. First, the propensity-to-patent differs across industries; hence this quantity measure of R&D output may miss upticks in innovative activity in areas where innovators are not inclined to patent (Cohen et al (2000)). Second, U.S. patent regulations have changed over enough of our sample so as to provide different incentives to patent. Hence, a change in patents may reflect a change in regulation, as opposed to a change in the quantity of innovation (Griliches (1990)).

38. Our second proxy for an R&D output quantity index has the advantage of consistently measuring a major input into R&D activity, the number of employees in the industry. The data come from the Bureau of Labor Statistics. An alternative measure of labor inputs would be to only include the number of scientists and engineers in NAICS 5417. This narrow measure would focus on only high-skilled labor inputs that, presumably, are central to the production of innovation. While there is a lack of time-series data on the number of scientists and engineers in NAICS 5417, we also believe this measure of labor inputs to be overly narrow.[9] Technical assistants and other occupations not deemed to be scientists or engineers are likely to be important in the production of

and Trademark Office. Any opinions or recommendations expressed in this document are those of the authors and do not necessarily reflect the views of the National Science Foundation or the Patent and Trademark Office. For more information, see *Review and Assessment of the OTAF Concordance between the U.S. Patent Classification and the Standard Industrial Classification System: Final Report, OTAF, 1984.* We thank Raymond Wolfe and Francisco Moris for assisting us with the USPTO data.

[9] The National Science Foundation collects employment data on the number of scientists and engineers, but only has data for NAICS 5417 from 1998 onwards. In addition to the employment data we use in this paper, the BLS also publishes employment figures by occupation and industry. Unfortunately, for NAICS 5417 these occupation data are only available from 2002 onwards.

R&D. Indeed, with technological progress, the ratio of scientists to assistants in NAICS 5417 establishments is likely to change, a dynamic not captured by a narrow, scientist-and-engineer focused, measure of labor inputs.[10]

39. Unfortunately, this employment indicator for R&D quantity does not account for general productivity change, where the same number of employees generates more ideas. However, we show in appendix A that this measure of real inputs provides a good approximation of the R&D price change for small increases in productivity (i.e. for non-drastic innovations). It is important to emphasize that using changes in labor inputs as an indicator for our quantity index by no means implies that the resulting price index will be close to an input-cost price index. Under our output-based approach, the price index is equal to the change in revenue divided by the quantity index. An input-cost price index, in contrast, does not use any information about the change in revenues.

40. With the caveats about the quality of the data in mind, we use these two quantity indexes to compute the associated price indexes for R&D output (chart B). These two price indexes provide different contours to R&D output price-change. The patent-based price index exhibits steady growth over our sample period of 1987 to 2006, with an average annual growth rate of 4.5 percent. In contrast, the employment-based price index exhibits faster, but slowing growth rates. Over the sample period, the employment-based price index has an average annual growth rate of 6.6 percent. Before 1997, however, prices grew at an annual rate of 7.9 percent, before slowing to an average rate of 5.6 percent for the period after 1997. These different contours lead to significant differences between the real NAICS 5417 revenues associated with each price index (chart A). In particular, the employment-based price index results in a much flatter stream of real NAICS 5417 revenue. Real revenue computed using the employment-based price index grows 20 percent from 1990 to 2006. In contrast, real revenue computed using the patent-based price index grows 90 percent over the same time period.

[10] See Holmes and Mitchell (2008) for an analysis of substitution among high-skilled labor, low-skilled labor, and capital.

41. Because we do not have a set of criteria to judge whether patents or the number of employees is the better indicator of R&D output quantity, we take the geometric mean of the indexes' growth rates.[11] We label this average the Innovators' Output price index, hereafter the Output price index, and, because it combines information on the quantity of R&D from two independent sources, consider it our preferred price index.

42. In addition to the advantage of using information on both patents and total employment, the Output price index also has a non-linear link between the labor inputs and quantity produced. In contrast, the input-cost price index, by construction, assumes a constant, proportional relationship between changes in inputs and changes in outputs. The Output price index's non-linear link between inputs (i.e. employment) and outputs is driven by the averaging of the two quantity indicators. Letting *Q* denote the R&D quantity, *Z* the number of patents, and *E* the number of employees, we assume that

$$\frac{Q_t}{Q_{t-1}} = \left[\frac{Z_t}{Z_{t-1}} \frac{E_t}{E_{t-1}} \right]^{1/2} .$$

This can be written as

$$Q_t = \left[Z_t E_t \right]^{1/2}, \; Q_{t-1} = \left[Z_{t-1} E_{t-1} \right]^{1/2} .$$

The implication is that the quantity index does not have a constant proportional relationship with the labor inputs.[12] This can be seen by taking the derivative of Q with respect to E,

$$\frac{\partial Q_t}{\partial E_t} = Z_t^{1/2} \frac{1}{2} E_t^{-1/2} .$$

It is important to stress this is not a production function, although one can think of a production function extension where *Z* is affected by a lag value of *E*. This result does indicate, however, that our method of construction allows changes in *E* to have a varying impact on *Q*.

[11] In a similar tack, Adams (1990) uses measures of article counts and number of scientists to construct a measure of the stock of knowledge.
[12] This analysis goes through with measures of capital inputs.

43. Using the Output price index, we find that the average price increase of R&D output over the entire sample is 5.81 percent. Reflecting the employment-based price index, the Output price index reports a slowing in the annual price growth rate over the time-horizon. From 1987 to 1997, the average growth rate is 6.5 percent while from 1997 to 2006 it is 5.0 percent (see chart B).

44. Using the Output price index to deflate nominal revenues for Scientific R&D services, we find that real revenue grew at an annual rate of 2.64 percent from 1987 to 2006 (chart C). In comparison, using the aggregate input-cost price index published in the BEA's satellite R&D accounts results in a real revenue series that grows 5.69 percent, more than double the growth rate we find when using our output-based Output price index. Admittedly, the aggregate input-cost price index we use is based on input costs for all R&D performed in the economy, while our Output price index focuses on a narrower slice of R&D activity (see appendix C for a thorough description of the BEA's aggregate input cost price index).[13] However, given that NAICS 5417 output is used across a number of R&D-intensive industries (see table 1), the costs of inputs used by NAICS 5417 should be representative of input costs for all R&D innovators. The sharp contrast in average annual real revenue growth reflects large differences in measured price growth between the output and aggregate input-cost price indexes (see chart D). The aggregate input-cost price index reports that R&D prices grow at an average annual rate of 2.8 percent, less than half the rate given by the Output price index. To fully illustrate the differences between the aggregate input-cost and Output price indexes, we plot them in chart E with a base year of 1987. We do this because setting the base year in the middle of the series (i.e. in 1997), distorts the relationship between the price indexes. By 2006, after 19 years, the Output price index equals 292, two-thirds more than the aggregate input-cost price index, which stands at 173.

[13] Using BLS occupational data on number of employees and the mean wage for NAICS 5417 from 2002 to 2006, we computed a simple labor-cost price index. Over these 4 years, this NAICS 5417-specific index grew faster than the general R&D input-cost price index used in the paper. This difference is most likely due to the inclusion of capital measures in the general R&D input-cost price index. Nevertheless, in the future when more data is available, it would be interesting to determine if NAICS 5417 costs are closely correlated with general R&D costs.

45. When comparing input and output price indexes for an industry, economists typically make inferences about the growth rates of the marginal product of the inputs. The result in charts D and E, that input costs grow faster than output costs, is often interpreted as implying the marginal products of the inputs have negative growth rates. This inference, however, makes several strong assumptions about the underlying industry. As detailed in appendix B, once you account for innovators' market power as well as the uncertainty behind the production of R&D, there is no longer a simple linear relationship behind the growth rates of input prices, output prices, and marginal product. Hence, for the production of R&D, the difference in growth rates between input and output prices does not have a straightforward implication for the growth rates of the marginal product of the inputs.

46. Pushing the argument that NAICS 5417 output is fairly representative of total R&D output, the Output price index could be used to deflate total R&D expenditures. The resulting real total R&D expenditures series is essentially flat; the average annual growth rate is -0.4 percent from 1987 to 2004.

47. Using the single NAICS 5417 price index to deflate all of R&D expenditures is arguable because much of the total comes from government, which is measured on an input-cost basis. Thus our preferred approach is to only use our Output price index on NAICS 5417 output, which makes up about one-quarter of total R&D expenditures. For the remaining three-quarters of R&D expenditures, we use the afore-mentioned BEA R&D satellite account input-cost price index. Using this two price-index approach, we find that real total R&D grows at an average annual rate of 1.4 percent from 1987 to 2004 (see the "Output and Aggregate Input Cost" real revenue series in chart F). Real revenue growth accelerates over this period; from 1987 to 1997 the average annual growth rate of real total R&D is 1.16 percent, while from 1997 to 2004 it is 1.79 percent.

Table 2: Real Total R&D Expenditures, growth rates

Price Indexes used to Deflate Nominal Expenditure Series	1987-2004	1987-1997	1997-2004
Output and Aggregate Input Cost	1.42	1.16	1.79
Aggregate Input Cost	2.05	1.87	2.32

48. In contrast, forgoing our Output price index and only using an aggregate input-cost price index to deflate nominal total R&D expenditures results in real total R&D growing at an average annual rate of 2.1 percent (see the "Aggregate Input Cost" real revenue series in chart F). The input cost approach also results in real total R&D expenditure growth accelerating over this horizon (see table 2 and note these results are independent of the price indexes' base year). Under the input cost approach, however, the difference in growth rates between 1987-1997 and 1997-2004 is 0.45 percent. This is almost two-tenths of a percent less than the 0.63 percent difference in average real revenue growth measured using our two-price-index approach over these same two periods.

49. In chart G we plot the growth rates of real total R&D expenditures based on (i) our preferred approach of jointly using the Output and aggregate input-cost price indexes and (ii) only the aggregate input-cost price index. While the growth rates under these two cases have a strong, positive correlation of 0.823, there are substantial differences in their contours. In particular, the growth rates around 1998 have opposite signs, a result that is driven by the pattern of the patent-based quantity index (see chart B). Clearly, using different deflators for NAICS 5417 has a substantial impact on real total R&D expenditures.

50. To fully reveal the sources of these differences, we plot real Scientific R&D services revenues using the two price indexes, where 1987 is the base year instead of 1997 (see chart H). In 2004, the difference between the two real series is roughly $25

billion, or 60 percent of the level of real Scientific R&D services under the Output price index. Hence, over 17 years the understatement of price growth by the aggregate input-cost price index leads to a dramatic $25 billion overstatement of NAICS 5417 real output. This has a substantial impact on the real total R&D expenditures. With 1987 as the base year, using only an aggregate input-cost price index results in real total R&D expenditures being overstated by 13.7 percent in 2004, relative to the real expenditures series deflated using our preferred method.

Table 3: Real Scientific R&D Services Revenues, growth rates

Price Index Used to Deflate Nominal Revenue Series	1987-2004	1987-1997	1997-2004
Output	3.01	2.64	3.54
Aggregate Input Cost	5.75	6.07	5.29

51. Beyond overstating the growth rate, the aggregate input cost index also generates a real Scientific R&D services revenue series whose growth rates slow over the 1987-2004 period (see chart I). This is in sharp contrast to the real revenue results obtained when using our Output price index. That index generates a real Scientific R&D services revenue series whose average growth rate increases by nine-tenths of a percent between 1987-1997 and 1997-2004 (see table 3).

52. The difference between our Output and the aggregate input-cost price indexes is likely due to the well-known weakness that input-cost price indexes fail to capture changes in productivity. Our Output price index, on the other hand, is able to capture productivity changes by relating the quantity and price indexes with changes in revenue through the Frisch product rule.[14] The significant differences between the Output and

[14] It is possible to construct an input cost price index which accounts for productivity changes (see, for example, Diewert (2008)). In the 2006 satellite account on R&D, the BEA constructed an input cost price index which was adjusted for productivity in the downstream industry (e.g. the pharmaceutical industry). Because this productivity adjustment is based on the economics of the R&D-adopting industry, and not the productivity of the R&D innovator, the BEA's productivity-adjusted input cost price index and our Output price index are not comparable.

aggregate input-cost price indexes highlight the importance of incorporating market data on output, such as revenues, when possible. Identifying industries where such data exist, and incorporating the data into our measures of the price change of R&D output is crucial to improving real R&D output estimates.

Conclusion

53. This paper derives an R&D output price index based on a model of an independent innovator. The price index is computed by using data from NAICS 5417 Scientific R&D services, an industry that mostly consists of independent innovators. Using this Output price index, we find that NAICS 5417 real revenues grew at an average annual rate of 2.64 percent from 1987 to 2006. Turning to the aggregate economy, we recommend using a two-price-index approach to deflate total R&D nominal expenditures. To deflate the portion of total R&D nominal expenditures consisting of NAICS 5417 revenue, we recommend using our Output price index. For the remaining portion of R&D nominal expenditures, about 75 percent of the total, we recommend using an aggregate input-cost price index. Using our recommended approach, we find that real R&D expenditures grew at an average annual rate of 1.4 percent. In contrast, using the often cited alternative approach of using only an aggregate input-cost price index, results in an average growth rate of 2.1 percent for real R&D total expenditures. We demonstrate that these differences in growth rates have substantial impacts of the level of real R&D expenditures. After 18 years, the aggregate input-cost price index approach measures a level of real R&D expenditures that is $25 billion higher than what is found using our recommended two-price-index approach.

54. Our approach has the distinct advantage of using market-generated data for an industry that produces R&D services, in-line with the 1993 SNA recommendations. Our comparison with the aggregate input-cost price index provides a sense of the potential measurement error associated with that index. Given the illustrated difference between the aggregate input-cost and our output price index, there is ample reason to be cautious about using the input-cost price index to determine R&D output.

55. Though our computed price index is based on NAICS 5417, our approach is implementable in countries that follow the International Standard Industrial Classification of All Economic Activities (ISIC). More specifically, NAICS 5417 is comparable to ISIC 7310 (Research and experimental development on natural sciences and engineering) in ISIC Rev. 3; in ISIC Rev. 4 the comparable industry is 7210, with the same title. De Haan and Van Roojen Horsten (2004) discuss how data from this industry was collected and subsequently used to construct R&D output measures in the Netherlands.

56. The Output price index used patent and employment data, although researchers are free to use other R&D quantity indicators. The OECD regularly collects data from countries on patents and in fact there is a working group on how to make patent statistics more useful to the analysis of innovative activity. A component of that work focuses on valuing patents—which naturally is tied into the price of R&D output. Additionally the OECD compiles country data on the R&D personnel. Thus, in principle, our output price index can be constructed in OECD countries. Though it is true that the level of detail may not be the same, a more aggregate level may still serve to reduce the over-estimation that was found in the U.S. experience. In the U.S., when aggregate patent and R&D employment data were used to obtain the R&D output price index, it was still the case that the aggregate input-cost index was lower than the output-based price index. Consequently, there would be an overestimate of the R&D output if an aggregate input-cost index were used instead of the output-based price index.

Appendix A: Demonstration that the R&D Output Price Index accounts for productivity changes.

A major improvement of the R&D output price index over the input cost approach is ability of the R&D output price index to account, to some extent, for changes in productivity. By construction, an input-cost price index assumes there is a constant proportional relationship between changes in input and output. As a consequence, the input-cost approach will not capture changes in productivity.

In the case where a researcher is able to estimate equation (1) directly, then the resulting R&D output price index will fully account for changes in productivity. This ideal measure of R&D output price change is based on expected profit flows from selling an innovation and so will appropriately reflect any changes in the production of innovation. Following our second-best empirical strategy, however, will also account, in part, for changes in an innovator's productivity. Hence, unlike the input-cost price index, our output-based approach allows for a changing relationship between inputs and outputs. Furthermore, for small changes in an innovator's productivity (i.e. non-drastic innovations to the production of R&D), we show that our R&D output price index provides a good approximation of the true underlying R&D output price change.

Consider output of R&D in two periods, $t=\{0,1\}$. Let Y_t be the quantity of R&D innovations in period t, and denote $D(Y_t)$ as an inverse demand function, providing us with the price of R&D in period t. For simplicity, suppose labor is the only input to R&D production, L, and it is constant in both periods. Furthermore, assume there is a productivity increase, such that $Y_1 = \alpha Y_0$, where $\alpha>1$.

Using this notation, we can write the revenue from the sale of R&D as price times quantity, or $R_t= D(Y_t)Y_t$. Furthermore, we know that the true underlying price change from period 0 to 1 is simply the ratio of inverse demand functions in each period, or

$$(A1) \quad P_{true}(0,1) = \frac{D(Y_1)}{D(Y_0)}.$$

Because there is a positive productivity shock, $Y_1>Y_0$. Given the usual assumption that demand is downward sloping, we have $D(Y_1)<D(Y_0)$, or that the price of R&D output falls from period 0 to period 1.

Given the labor input is the same in both periods, the input-cost price index records no change in the price of R&D, or

$$(A2) \quad P_{input}(0,1) = \frac{L_1}{L_0} = 1.$$

Now we turn to the empirical approach presented in this paper, which relies upon the Frisch product rule. Assume that we only use the employment indicator to construct our quantity index, which allows for a clean comparison with the input-cost approach. Because labor is constant across both periods, our quantity index equals 1,

$$Q_{output}(0,1) = \frac{L_1}{L_0} = 1.$$

Using the Frisch product rule, we solve for the price index,

$$(A3) \quad P_{output}(0,1) = \frac{R_1}{R_0}\frac{1}{Q_{output}(0,1)} = \frac{R_1}{R_0} = \frac{D(Y_1)Y_1}{D(Y_0)Y_0} = \frac{D(Y_1)\alpha Y_0}{D(Y_0)Y_0} = \frac{D(Y_1)}{D(Y_0)}\alpha.$$

Comparing equations (*A3*) and (*A1*), we see the only difference between the price indexes is α. Hence, for values of α close to 1, or for small productivity increases, P_{output} closely approximates the true R&D price change, P_{true}. Hence, for non-drastic innovations, the most common innovations, the proposed output price index should perform well.

As an aside, the performance of the patent-based quantity index hinges upon how well the change in the number of successful patents approximates the change in R&D output. If and only if the patent-based index matches the change in R&D quantity well, will the resulting price index be accurate. As mentioned in the paper, it should also be kept in mind that the technique of averaging an employment-based and patent-based quantity indicator creates a non-linear relationship between employment and output.

Appendix B: The inapplicability of a linear comparison of growth rates of input price and output price indexes.

In this appendix, we review the relationship among input prices, marginal product, and output prices in a competitive setting. We then add uncertainty to the relationship and discuss the complications this adds to an empirical analysis of this relationship. Finally, we demonstrate that considering an environment where firms have market power muddies the elegant relationship among input prices, marginal product, and output prices.

Starting with the standard competitive case, we denote:

p: output price
w: input price
z: inputs
q: production function

A price-taking innovator maximizes profits by choosing inputs to

$$\max_z pq(z) - wz .$$

First order conditions give us

$$(B1) \qquad p\frac{dq}{dz} = w .$$

Denoting *dq/dz* as MP, for marginal product, we take logs of the above expression, rearrange terms, and get

$$\ln(MP) = \ln(w) - \ln(p).$$

The above equation provides us with a linear relationship in the logs of marginal product, input price and output price. If the right hand side is negative, then so is the log of the marginal product. But this only means that marginal product is less than 1-- not that it is negative. Because we want to compare input and output price indexes, we convert the above linear relation into growth rates by differentiating with respect to time, and get

$$(B2) \qquad \frac{\dot{MP}}{MP} = \frac{\dot{w}}{w} - \frac{\dot{p}}{p}$$

where the dot above a variable indicates a derivative of that variable with respect to time. Equation (*B*2) gives us the standard result that the growth rate of the marginal product is equal to the growth rate of input prices minus the growth rate of output prices. Because the growth rate of the marginal product should be non-negative, equation (*B*2) constrains the growth rate of output prices to be no greater than the growth rate of input prices.

Equation (*B*2), however, misses key elements central to the production of R&D. First, the output of R&D is binary because an idea is either produced or not. Effort may accumulate knowledge, but at some point knowledge must be bundled into an idea that can be sold. Further, the production of an idea involves a lot of uncertainty. Using the model detailed in the paper, we incorporate these features in a general way. Let $g(x;\varphi,A,z)$ denote the probability of producing an innovation x, given the parameter φ, the current state of knowledge A, and the input choice z. Departing from the model in this paper, we simply denote the price of an idea as p. This allows for an easier comparison with the deterministic, perfect competitive case described above. Of course, as described in the main body of this paper, this price should be thought of as a function of the future discounted stream of profits associated with the implementation of this idea by a downstream firm. We write the innovator's problem as

$$\max_z \int_A^{\varphi} p(x) g(x;\varphi,A,z)dx - wz$$

where we integrate over all possible outcomes from non-drastic innovation. The first order condition of this problem is

$$(B3) \quad \int_A^{\varphi} p(x) \frac{dg(x;\varphi,A,z)}{dz} dx - w = 0,$$

which is equivalent to equation (5) in the paper. Equation (*B3*) highlights the difficulties with comparing growth rates in the output price, input price and marginal productivity, as done in equation *(B2)*. In particular, there is no longer a linear relationship between the growth rates of input prices and output prices. Further, while the growth rate of the derivative of *g* with respect to *z* plays an important role, little is known about how this derivative changes over time.[15]

Second, even in the case of certainty, it is not clear that equation (*B2*) holds because the innovator does not operate in a perfectly competitive industry. The innovator has exclusive property rights over the innovation for some time period, changing the nature of the problem. To provide an easier comparison to the competitive case, we assume that the firm chooses quantity to maximize profits:

$$\max_z p\left(q(z)\right)q(z) - wz\,.$$

The first order condition is now

$$(B4) \qquad \frac{dp}{dq}\frac{dq}{dz}q(z) + p\frac{dq}{dz} = w$$

where the object on the left hand side is marginal revenue, and the object of the right hand side is marginal cost. Comparing equation (*B4*) to equation (*B2*) highlights how there is no longer a straightforward connection between marginal product, output price and input price. The first term on the left hand side of equation (*B4*) breaks the elegant relationship expressed in equation (*B2*).

Assuming the firm chooses price reinforces the complex relationship between input and output prices:

$$\max_p pq(p) - wq(p)$$

where *q(p)* denotes quantity demanded at price *p*. Taking the derivative with respect to price and manipulating it, we get the standard result linking markups and the inverse of the elasticity of demand with respect to price

$$(B5) \qquad \frac{p-w}{p} = -\frac{dp}{dq(p)}\frac{q}{p} = -\frac{1}{\varepsilon}$$

where ε is the elasticity of demand with respect to price. The difference in growth rates between input and output prices, which alters a firm's markup, is tightly linked to the output product's own-price elasticity.

In summary, we argue that the standard approach for comparing input and output price indexes, as laid out in equation (*B2*), is inappropriate for the production of R&D.

[15] See Doraszelski and Jaumandreu (2007) and Hall (2007) for recent work on estimating R&D production functions, as well as Griliches and Mairesse (1984).

First, an empirical analysis of input and R&D output price indexes is complicated by the significant role that uncertainty plays in the production of R&D. The introduction of uncertainty complicates the relationship between input and output prices and, significantly, no longer allows for a linear comparison of their growth rates (see equation (*B3*)). Second, market power is a central element in the production of R&D. Innovators create a unique product and so are able to set its price. Adding market power to the environment obscures the relationship between input and output prices through the introduction of markups. Adding both uncertainty and market power into the framework results in a complex non-linear relationship among input prices, output prices, and marginal product.

While we cannot use input and output price indexes to make inferences about the growth rates of the marginal product of inputs, we can use our results to provide rough estimates on labor productivity. Using the Output price index we construct a time series for real 5417 output (see chart C). Dividing real output by the number of employees in 5417 provides us with a rough approximation of labor productivity, which we plot in chart J. Reassuringly, this measure of labor productivity rises over our sample period at an average annual growth rate of 1.54 percent.

Appendix C: Description of the BEA's Aggregate Input Cost Price Index

The following was taken from the November 2007 BEA working paper "Estimating Prices for R&D Investment in the 2007 R&D Satellite Account," by Adam M. Copeland, Gabriel W. Medeiros, and Carol A. Robbins.

2.4 Aggregate Input Price Index

The aggregate input price index for R&D output and investment provides a baseline for comparing the alternative price indexes. For the R&D input price index, prices for the various R&D inputs are used to deflate nominal R&D output at the most detailed cost level possible. Because the source data are performer-based, BEA first creates the input price indexes on a performer basis and aggregates them into an aggregate input price index. Using this aggregate input price index and two NIPA-based indexes for R&D funded by the Federal government, an index for non-Federal R&D purchases is derived residually. This non-Federal aggregate input price index is used to deflate business, non-profit, and academic R&D investment.

Unlike the detailed industry price indexes created in the residual intangible asset price index and the detailed output price index, all industry R&D investment is deflated with a single price index, rather than detailed industry R&D input price indexes. Industry specific data on composition of materials and supplies used for R&D are not available by investing industry, and for the largest component of cost, wages and salaries for scientists and engineers, consistent time series by industry were not available.

To create the performer-based indexes, expenditures and input price relatives are aggregated together using a Fisher chain-weighting process described in Equation (10) to generate total real R&D expenditures. The resulting aggregate input price index is calculated as:

$$\frac{P_{R\&D}(t)}{P_{R\&D}(t-1)} = \sqrt{\left(\frac{\sum E_j(t-1) \times \frac{P_j(t)}{P_j(t-1)}}{\sum E_j(t-1)} \times \frac{\sum E(t)}{\sum E_j(t) \times \frac{P_j(t-1)}{P_j(t)}} \right)}$$

Here expenditures with the subscript *j* are inputs to the R&D process, and the price relatives are the prices of each input. Table E lists the price indexes that are used to construct the aggregate input price index for input component for each performer.

For the aggregate business sector (private industry), BEA uses salaries for engineers in R&D organizations to deflate compensation costs for R&D personnel. Materials and supplies, overhead, and depreciation for business sector R&D are deflated using the input price indexes from costs incurred by the R&D services industry (NAICS 5417). These prices are based on detailed data for intermediate input costs available in BEA's industry accounts.

For R&D performed by colleges and universities, expenses for consumption of fixed capital (CFC) are deflated separately from all other expenses. All non-CFC R&D expenses funded by the Department of Health and Human Services are deflated using a biomedical R&D price index that BEA developed for the National Institutes of Health. The remaining non-CFC academic R&D expenditures are deflated using an overall academic R&D price series developed for the National Center for Education Statistics from 1960 to 1995.[16] This overall R&D index is extrapolated for the other years based on the BEA price index for personal consumption expenditures on other education and research.

The Federal sector uses a variety of NIPA price indexes for defense and non-defense R&D-related costs such as compensation, intermediate purchases of goods and services, and investment in structures, equipment, and software. These performer-based input price indexes are used in conjunction with a national income and product account (NIPA) price index for total Federal defense and non-defense purchases of R&D and an internally

[16] National Center for Education Statistics, *Digest of Education Statistics*, 2004, Table 35.

developed price index for R&D performed by the Federal government in order to develop the input price indexes for each sector's R&D investment.

To derive a price index for the remaining, non-Federally funded R&D, BEA uses the Federal price indexes described above and the overall (performer-based) price index to derive a residual index for non-Federally funded price index. When the Federal price indexes are combined with this derived non-Federal funder index using a chain-type formula, the total funder-based price index matches the total performer-based index.

Table E. Input Price Indexes: Source Data and Methods for Cost Components and Corresponding Deflation

Cost component	Data and methods for cost component	Method for deflation
Private sector		Aggregate of input price detail for all privately-performed cost components.
Business (industry)		For 1987-2004, aggregate of input price detail. For 1959-86, R&D deflation is performed at the total business level using the GDP implicit price deflator (IPD).
Compensation of R&D personnel	For 1987-2004, NSF reported distribution of wages of R&D personnel by industry.	
Scientists and engineers	For 1987-2004, based on 1987 detail from NSF working paper (Jankowski 1990).	For 2000-04, judgmental estimates based on salaries for R&D scientists and engineers from R&D Magazine salary surveys and BEA's unpublished chain-type Laspeyres salary index based on engineer salaries in R&D organizations from the American Association of Engineering Societies (AAES) annual salary surveys. For 1987-99, BEA's unpublished chain-type Laspeyres salary index based on AAES data.
Support personnel	For 1987-2004, based on 1987 detail from NSF working paper (Jankowski 1990).	BEA unpublished index based on BLS average hourly earnings of production workers in research and testing services.
Materials and supplies	For 1987-2004, NSF reported distribution of R&D materials and supplies by industry.	BEA unpublished composite index for materials in the scientific R&D services industry (NAICS industry 5417) from the KLEMS data in the annual industry accounts.
Other R&D costs (overhead)	For 1987-2004, NSF reported distribution of R&D overhead costs by industry.	BEA unpublished composite index for overhead in the scientific R&D services industry (NAICS industry 5417) from the annual industry accounts.
Consumption of fixed capital (CFC) for structures and equipment	To identify the CFC cost component: For 2001-2004, NSF reported distribution of historical-cost depreciation. For 1959-2000, NSF reported distribution of historical-cost depreciation for 2001 was use To adjust CFC to an economic basis: For 1959-1987, historical-cost depreciation was adjusted to a current-cost basis using the ratio current-cost depreciation to historical-cost depreciation of assets used to perform R&D at private academic institutions. For 1988-2004, estimated by applying the NIPA CFC growth rates for total business.	NIPA price index for depreciation in NAICS industry 5412.
Federally funded research and development centers (FFRDCs) administered by business		Aggregate of input price detail
DOD- and NASA-funded FFRDCs	Weight of expenditures based on R&D obligations to industry-administered FFRDCs for the agencies that define the component.	NIPA price index for Federal defense purchases of R&D services.

Table E. Input Price Indexes: Source Data and Methods for Cost Components and Corresponding Deflation

Cost component	Data and methods for cost component	Method for deflation
HHS-funded FFRDCs	Weight of expenditures based on R&D obligations to industry-administered FFRDCs for the agencies that define the component.	For 1979-2004, NIPA unpublished biomedical R&D price index. For 1929-1978, extrapolated by NIPA personal consumption expenditures price index for "other" education and research.
DOE-funded FFRDCs and all other FFRDCs	Weight of expenditures based on R&D obligations to industry-administered FFRDCs for the agencies that define the component.	NIPA unpublished price index for Federal nondefense purchases of R&D services.
Private universities and colleges		Aggregate of input price detail
R&D expenditures excluding CFC HHS-funded	Estimate of HHS-funded R&D expenditures less research equipment expenditures, which were removed from current expenses and reclassified as investment. Based on HHS R&D obligations to academic performers.	For 1979-2004, NIPA unpublished biomedical R&D price index for academic grants and contracts. For 1929-1978, extrapolated by NIPA personal consumption expenditures price index for "other" education and research.
R&D expenditures excluding CFC non-HHS-funded	R&D expenditures less research equipment expenditures, which were removed from current expenses and reclassified as investment with HHS funded portion removed.	For 1960-95, academic R&D price index from the National Center for Education Statistics. For other years, extrapolated by NIPA personal consumption expenditures price index for "other" education and research.
CFC for structures	Perpetual inventory calculations at current cost, based on gross investment and on investment prices. Gross investment for R&D structures: Calculated as a percent of total NSF reported science and engineering space through 1989 then extrapolated to 2004 based on NIPA price index for gross government fixed investment in educational structures.	Direct valuation: Perpetual inventory calculations based on gross investment and investment prices. Investment prices: For structures, the NIPA index for private fixed investment in nonresidential structures by the educational services industry.
CFC for equipment	Perpetual inventory calculations at current cost, based on gross investment and on investment prices. Gross investment for R&D large equipment: Calculated as a percent of total science and engineering space. For small equipment: NSF reported current fund research equipment expenditures, which were removed from current expenses and reclassified as investment.	Direct valuation: Perpetual inventory calculations based on gross investment and investment prices. Investment prices: For equipment, the NIPA index for private fixed investment in equipment and software by the educational services industry (NAICS industry 61.
Federally funded research and development centers (FFRDCs) administered by private universities and colleges		Aggregate of input price detail
DOD- and NASA-funded FFRDCs excluding CFC	Expenditures for each FFRDC aggregated by Federal sponsoring agency, less research equipment, which were removed from current expenses and reclassified as investment.	NIPA price index for Federal defense purchases of R&D services.
DOE-funded FFRDCs and all other FFRDCs excluding CFC	Expenditures for each FFRDC aggregated by Federal sponsoring agency, less research equipment, which were removed from current expenses and reclassified as investment.	NIPA unpublished price index for Federal nondefense purchases of R&D services.

Table E. Input Price Indexes: Source Data and Methods for Cost Components and Corresponding Deflation

Cost component	Data and methods for cost component	Method for deflation
CFC for structures and equipment	Perpetual inventory calculations at current cost, based on gross investment and on investment prices. Gross investment for R&D structures and equipment: Federal obligations on plant to FFRDCs administered by private universities and colleges and BEA estimated research equipment expenditures, which were removed from current expenses and reclassified as investment.	Direct valuation: Perpetual inventory calculations based on gross investment and investment prices. Investment prices: For equipment, the NIPA index for private fixed investment in equipment and software by the educational services industry (NAICS industry 61); for structures, the NIPA index for private fixed investment in nonresidential structures by the educational services industry.
Other nonprofit institutions serving households	Expenditures for years surveyed by NSF. For years where data are unavailable, Federal funding interpolated or extrapolated by Federal obligations to nonprofit institutions; non-Federal funding interpolated or extrapolated by personal consumption expenditures for foundations and nonprofit research.	NIPA IPD for foundations and nonprofit research.
Federally funded research and development centers (FFRDCs) administered by other nonprofit institutions serving households		Aggregate of input price detail
DOD- and NASA-funded FFRDCs	For 2001-04, expenditures for each FFRDC, aggregated by Federal sponsoring agency categories. For other years, Federal agency obligations to FFRDCs administered by other nonprofit institutions.	NIPA price index for Federal defense purchases of R&D services.
DOE-funded FFRDCs and all other FFRDCs	For 2001-04, expenditures for each FFRDC, aggregated by Federal sponsoring agency categories. For other years, Federal agency obligations to FFRDCs administered by other nonprofit institutions.	NIPA unpublished price index for Federal nondefense purchases of R&D services.
Government sector		Aggregate of input price detail for all government-performed R&D components.
Federal Government	For 1929 to 1950, deflated at the aggregate Federal level. For 1951 to 2004, see detail below.	For 1929 to 1950, deflated in total using the average of the NIPA price indexes for defense and nondefense R&D services. For 1951 to 2004, aggregate of input price detail.
Compensation of employees		Aggregate of input price detail
DOD-funded R&D	Federal obligations to intramural R&D by agency and by cost type.	For 1972-2004, NIPA IPD for Federal defense compensation of general government civilian employees. For 1951-1971, NIPA IPD for Federal defense compensation of general government employees (all).
DOE funded R&D	Federal obligations to intramural R&D by agency and by cost type.	NIPA IPD for Federal nondefense compensation of general government employees.
HHS-funded R&D	Federal obligations to intramural R&D by agency and by cost type.	For 1979-2004, NIPA unpublished biomedical R&D personnel price index. For 1951-1978, extrapolated by NIPA IPD for Federal nondefense compensation of general government employees.

Table E. Input Price Indexes: Source Data and Methods for Cost Components and Corresponding Deflation

Cost component	Data and methods for cost component	Method for deflation
NASA and other Federal agency funded R&D	Federal obligations to intramural R&D by agency and by cost type.	NIPA IPD for Federal nondefense compensation of general government employees.
Materials and supplies		Aggregate of input price detail
DOD-funded R&D	Federal obligations to intramural R&D by agency and by cost type.	For 1972-2004, NIPA IPD for Federal defense installation support services. For 1951-1971, NIPA IPD for Federal defense services.
DOE funded R&D	Federal obligations to intramural R&D by agency and by cost type.	For 1972-2004, NIPA IPD for Federal defense services. For 1951-1971, NIPA IPD for Federal defense weapons support services.
HHS-funded R&D	Federal obligations to intramural R&D by agency and by cost type.	For 1979-2004, NIPA unpublished biomedical R&D nonpersonnel price index. For 1951-78, extrapolated by NIPA price index for Federal nondefense intermediate goods and services purchased.
NASA and other Federal agency funded R&D	Federal obligations to intramural R&D by agency and by cost type.	NIPA IPD for Federal nondefense intermediate goods and purchased services.
CFC on R&D equipment		Aggregate of input price detail
DOD-funded R&D	Perpetual inventory calculations at current cost based on gross investment and investment prices. Gross investment for R&D equipment: BEA estimate of small R&D equipment expenditures (6% of current Federal intramural expenses), which were removed from current expenses and reclassified as investment. BEA estimate of large R&D equipment, which is included in NSF R&D plant expenditure data. BEA assumes 15% of the plant expenditure total is for large equipment.	NIPA price index for Federal national defense investment in equipment and software.
DOE funded R&D	Perpetual inventory calculations at current cost based on gross investment and investment prices. Gross investment for R&D equipment: BEA estimate of small R&D equipment expenditures (6% of current Federal intramural expenses), which were removed from current expenses and reclassified as investment. BEA estimate of large R&D equipment, which is included in NSF R&D plant expenditure data. BEA assumes 15% of the plant expenditure total is for large equipment.	NIPA price index for Federal national defense investment in equipment and software.

Table E. Input Price Indexes: Source Data and Methods for Cost Components and Corresponding Deflation

Cost component	Data and methods for cost component	Method for deflation
HHS-funded R&D	Perpetual inventory calculations at current cost based on gross investment and investment prices. Gross investment for R&D equipment: BEA estimate of small R&D equipment expenditures (6% of current Federal intramural expenses), which were removed from current expenses and reclassified as investment. BEA estimate of large R&D equipment, which is included in NSF R&D plant expenditure data. BEA assumes 15% of the plant expenditure total is for large equipment.	NIPA price index for Federal national defense investment in equipment and software.
NASA and other Federal agency funded R&D	Perpetual inventory calculations at current cost based on gross investment and investment prices. Gross investment for R&D equipment: BEA estimate of small R&D equipment expenditures (6% of current Federal intramural expenses), which were removed from current expenses and reclassified as investment. BEA estimate of large R&D equipment, which is included in NSF R&D plant expenditure data. BEA assumes 15% of the plant expenditure total is for large equipment.	NIPA chain-type price index for Federal nondefense investment in equipment and software.
CFC on R&D Structures		Aggregate of input price detail
DOD-funded R&D	Perpetual inventory calculations at current cost based on gross investment and on investment prices Gross investment for R&D structures: Federal obligations for Federal intramural plant less estimate of large equipment.	NIPA price index for Federal national defense investment in industrial buildings.
DOE funded R&D	Perpetual inventory calculations at current cost based on gross investment and on investment prices Gross investment for R&D structures: Federal obligations for Federal intramural plant less estimate of large equipment.	NIPA chain-type price index for Federal national defense investment in industrial buildings.
HHS-funded R&D	Perpetual inventory calculations at current cost based on gross investment and on investment prices Gross investment for R&D structures: Federal obligations for Federal intramural plant less estimate of large equipment.	For 1997-2004, NIPA price index for Federal non-defense investment in new structures. For 1951-1996, NIPA price index for Federal nondefense investment in industrial buildings.
NASA and other Federal agency funded R&D	Perpetual inventory calculations at current cost based on gross investment and on investment prices Gross investment for R&D structures: Federal obligations for Federal intramural plant less estimate of large equipment.	For 1997-2004, NIPA price index for Federal non-defense investment in new structures. For 1951-1996, NIPA price index for Federal nondefense investment in industrial buildings.
State and local governments		Aggregate of input price detail

Table E. Input Price Indexes: Source Data and Methods for Cost Components and Corresponding Deflation

Cost component	Data and methods for cost component	Method for deflation
R&D expenditures excluding CFC	For years available from NSF (varied), R&D expenditures excluding R&D plant less BEA estimated research equipment. For other years, interpolated or extrapolated by Federal obligations to state and local governments; non-Federal funding interpolated or extrapolated by NIPA state and local government consumption and gross investment estimates.	NIPA IPD for "other" education and research and NIPA IPD for foundations and nonprofit research.
CFC for structures and equipment	Perpetual inventory calculations at current cost, based on gross investment and on investment prices. Gross investment for R&D structures and equipment: Federal obligations on plant to state and local governments and BEA estimated research equipment expenditures, which were removed from current expenses and reclassified as investment.	Direct valuation: Perpetual inventory calculations based on gross investment and on investment prices. Investment prices: For equipment, the NIPA index for state and local fixed investment in equipment and software; for structures, the NIPA index for state and local fixed investment in health care structures.
Public universities and colleges		Aggregate of input price detail
R&D expenditures excluding CFC HHS-funded	Estimate of HHS-funded R&D expenditures less research equipment expenditures, which were removed from current expenses and reclassified as investment. Based on HHS R&D obligations to academic performers.	For 1979-2004, NIPA unpublished biomedical R&D price index for academic grants and contracts. For 1929-1978, extrapolated by NIPA personal consumption expenditures price index for "other" education and research.
R&D expenditures excluding CFC non-HHS-funded	R&D expenditures less research equipment expenditures, which were removed from current expenses and reclassified as investment with HHS funded portion removed.	For 1960-95, academic R&D price index from the National Center for Education Statistics. For other years, extrapolated by NIPA personal consumption expenditures price index for "other" education and research.
CFC for structures	Perpetual inventory calculations at current cost, based on gross investment and on investment prices. Gross investment for R&D structures: Calculated as a percent of total NSF reported science and engineering space through 1989 then extrapolated to 2004 based on federal plant obligations to academic R&D performers.	Direct valuation: Perpetual inventory calculations based on gross investment and investment prices. Investment prices: For structures, the NIPA price index for state and local government fixed investment in educational buildings.
CFC for equipment	Perpetual inventory calculations at current cost, based on gross investment and on investment prices. Gross investment for R&D large equipment: Calculated as a percent of total science and engineering space. For small equipment: NSF reported current fund research equipment expenditures, which were removed from current expenses and reclassified as investment.	Direct valuation: Perpetual inventory calculations based on gross investment and investment prices. Investment prices: For equipment, the NIPA price index for state and local government fixed investment in equipment and software.
Federally funded research and development centers (FFRDCs) administered by public universities and colleges		Aggregate of input price detail
DOD- and NASA-funded FFRDCs excluding CFC	Expenditures for each FFRDC, aggregated by Federal sponsoring agency, less research equipment.	NIPA price index for Federal defense purchases of R&D services.

Table E. Input Price Indexes: Source Data and Methods for Cost Components and Corresponding Deflation

Cost component	Data and methods for cost component	Method for deflation
DOE-funded FFRDCs and all other FFRDCs excluding CFC	Expenditures for each FFRDC, aggregated by Federal sponsoring agency, less research equipment.	NIPA unpublished price index for Federal nondefense purchases of R&D services.
CFC for structures and equipment	Perpetual inventory calculations at current cost, based on gross investment and on investment prices. Gross investment for R&D structures and equipment: Federal obligations on plant to FFRDCs administered by public universities and colleges and BEA estimated research equipment expenditures, which were removed from current expenses and reclassified as investment.	Direct valuation: Perpetual inventory calculations at current cost, based on gross investment and on investment prices. Investment prices: For equipment, the NIPA index for public fixed investment in equipment and software by educational services industry (NAICS industry 61); for structures, the NIPA index for state and local fixed investment in educational buildings.

BLS Bureau of Labor Statistics
CFC Consumption of fixed capital
DOD Department of Defense
DOE Department of Energy
HHS Department of Health and Human Services
IPD Implicit price deflator
KLEMS K-capital, L-labor, E-energy, M-materials, and S-purchased services; BEA production framework
NASA National Aeronautics and Space Administration
NAICS North American Industrial Classification system
NIPA National Income and Product Accounts
NSF National Science Foundation
SIC Standard Industrial Classification system
Note. A Fisher chaining methodology used for aggregation of cost and sector detail.

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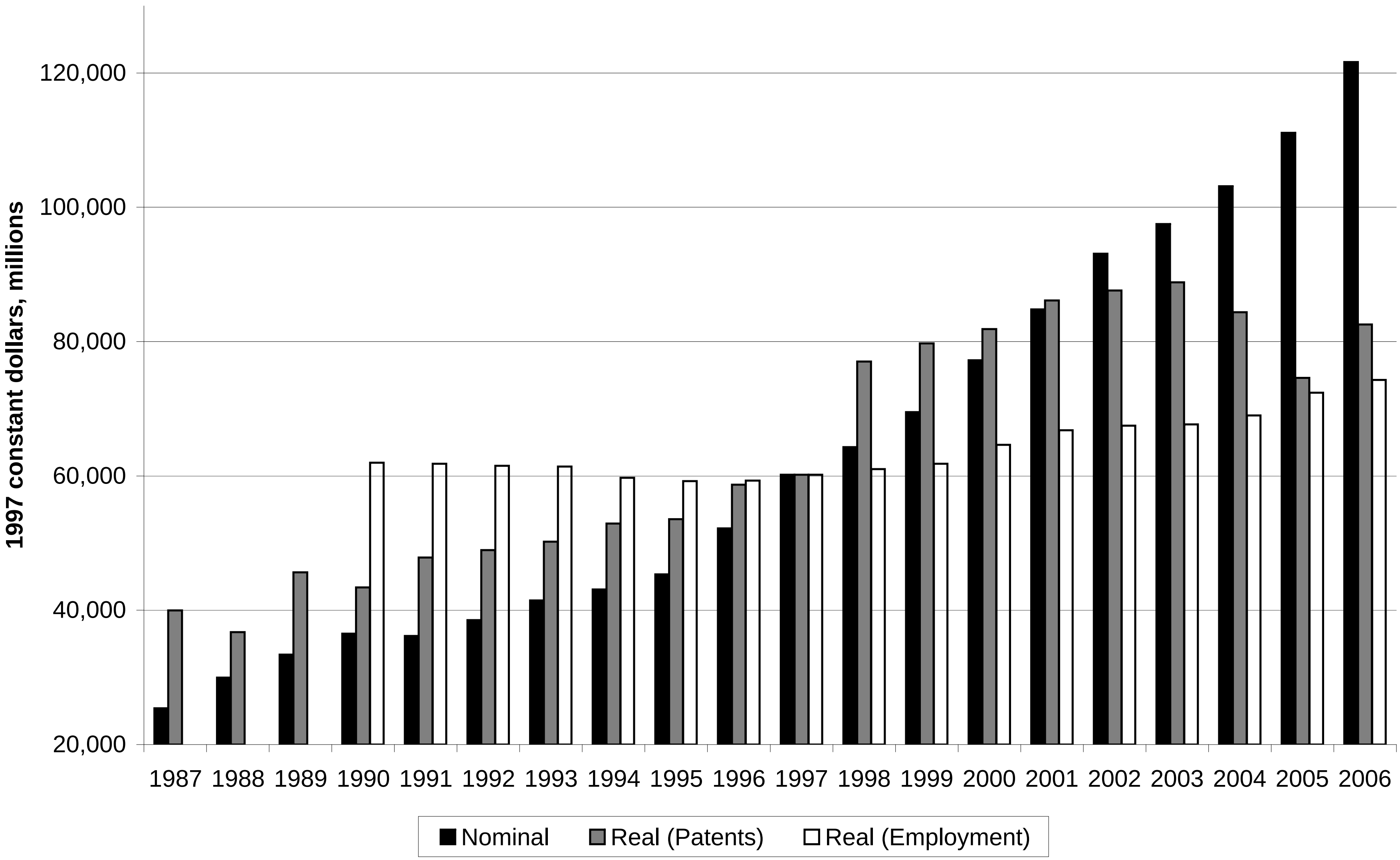
Chart A: NAICS 5417 Nominal and Real Revenues



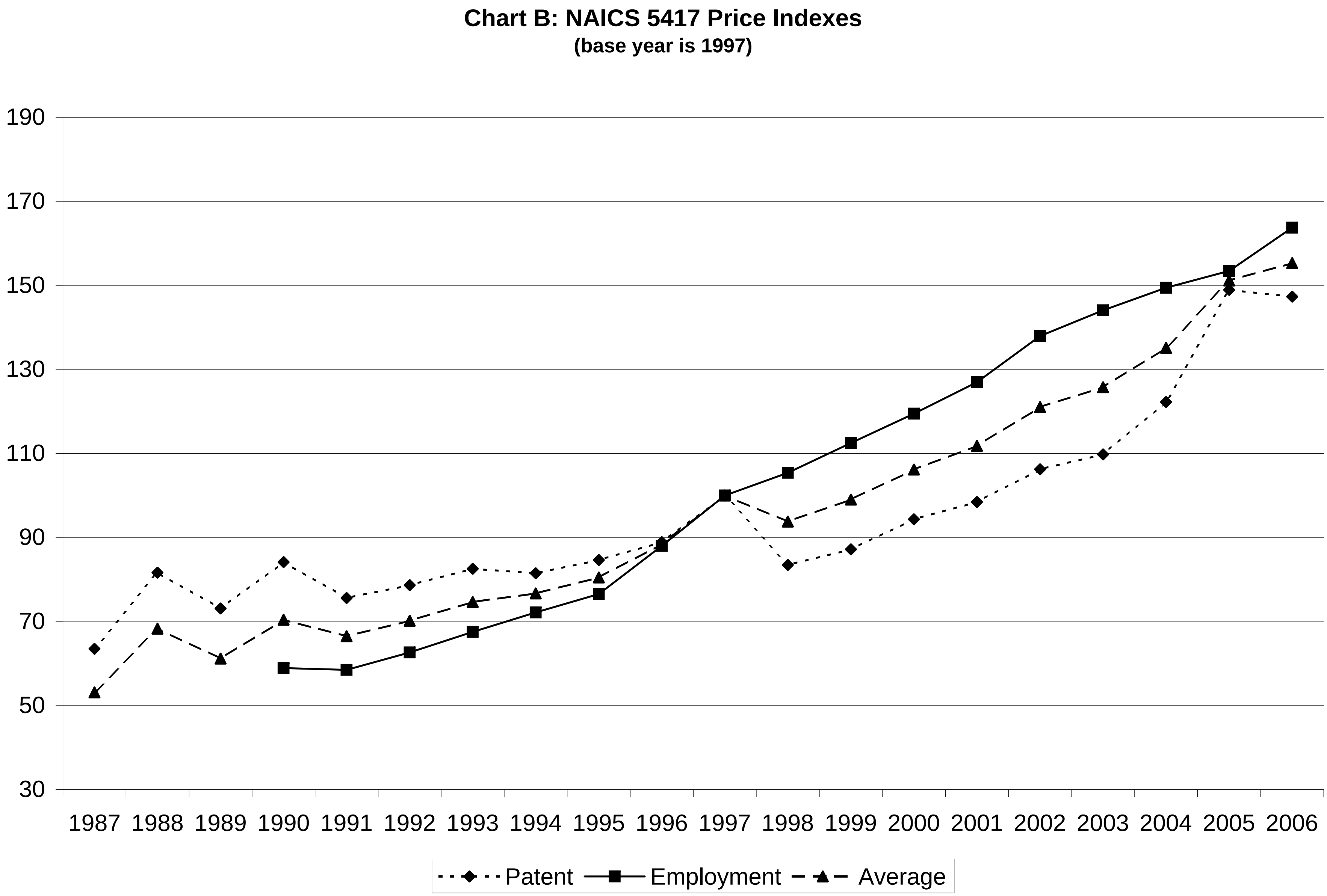
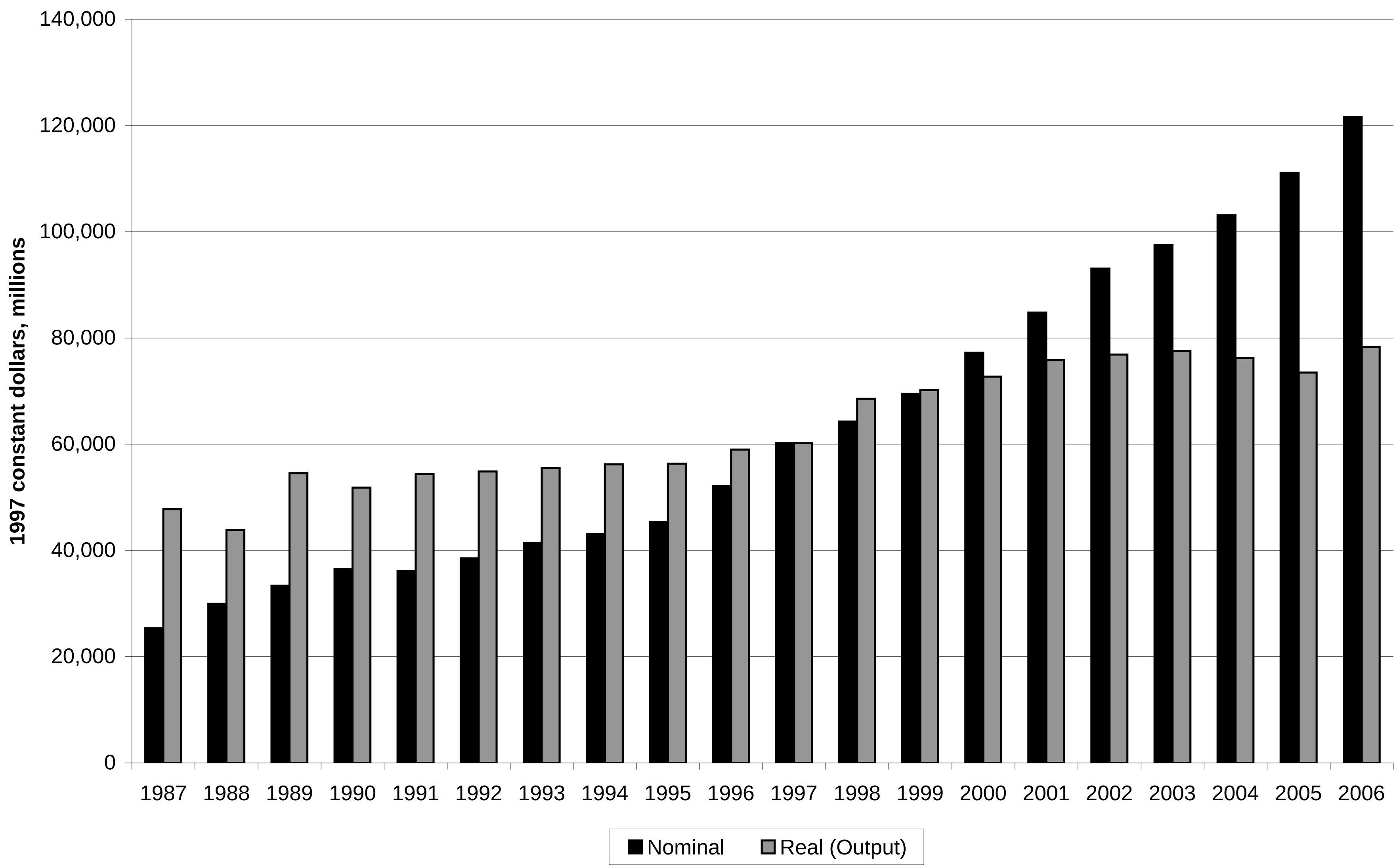


Chart B: NAICS 5417 Price Indexes
(base year is 1997)
190
170
150
130
110
90
70
50
30
1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006
Patent
Employment
Average

Chart C: NAICS 5417 Nominal and Real Revenues: the Output Price Index



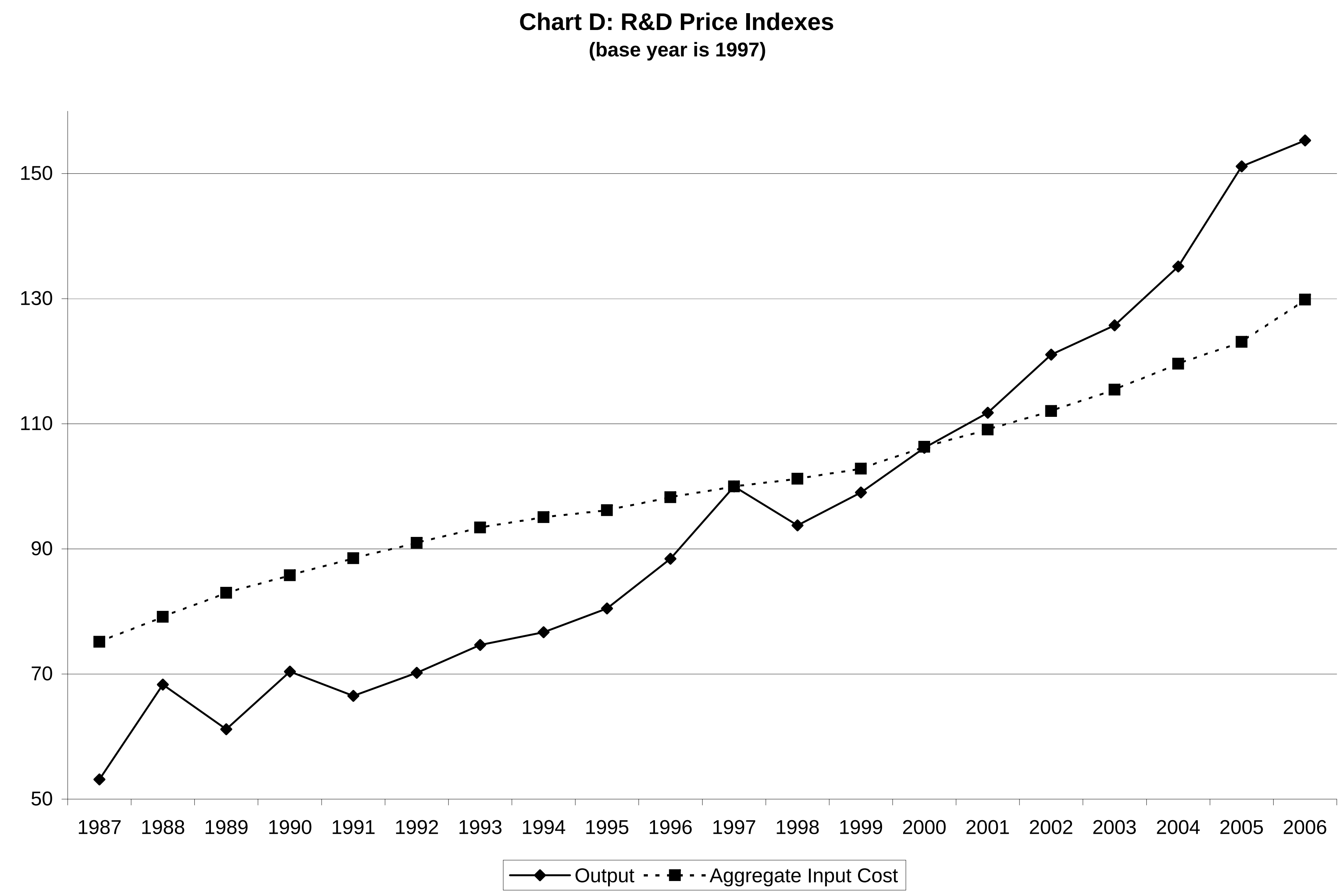


Chart D: R&D Price Indexes
(base year is 1997)
150
130
110
90
70
50
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
Output
Aggregate Input Cost

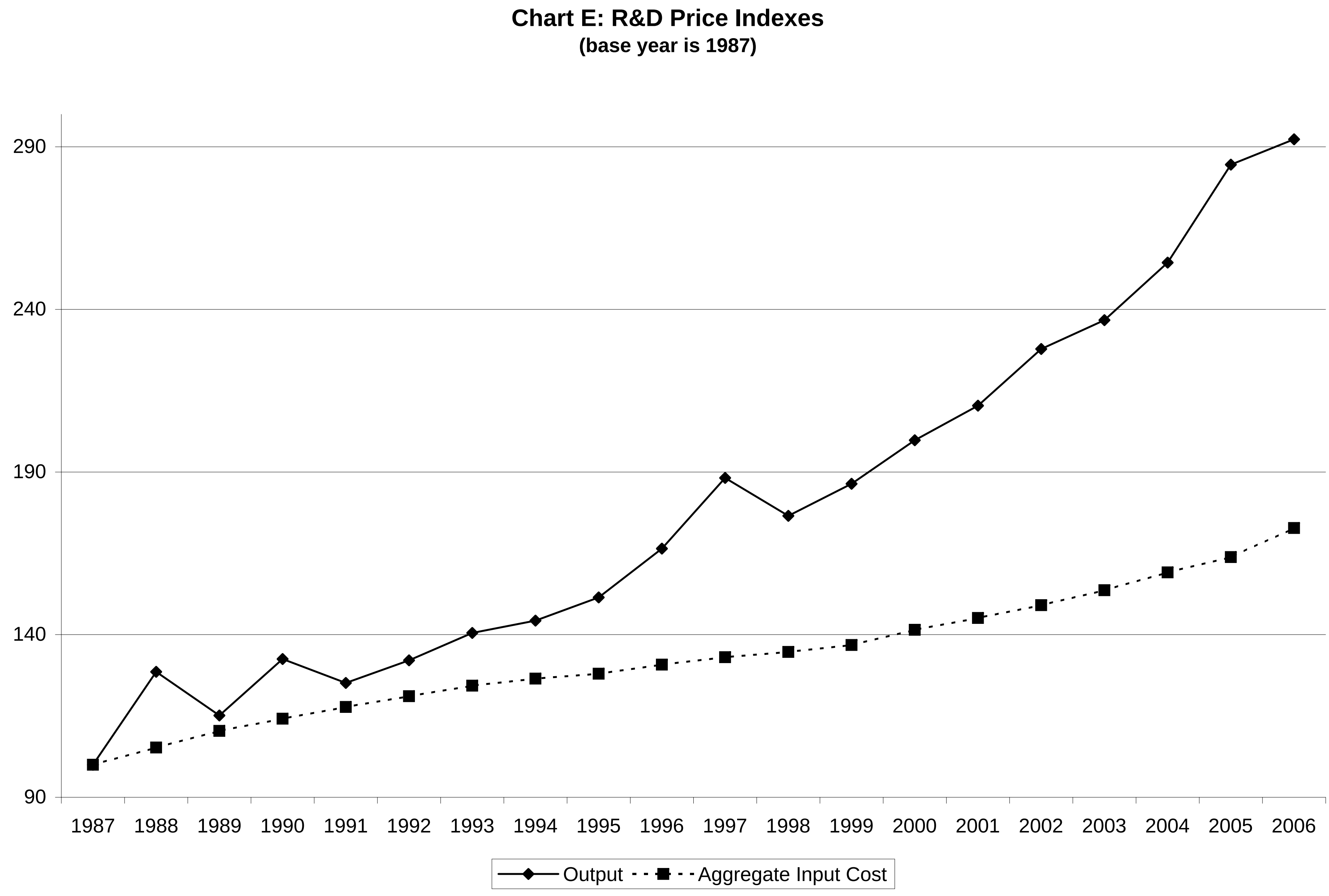
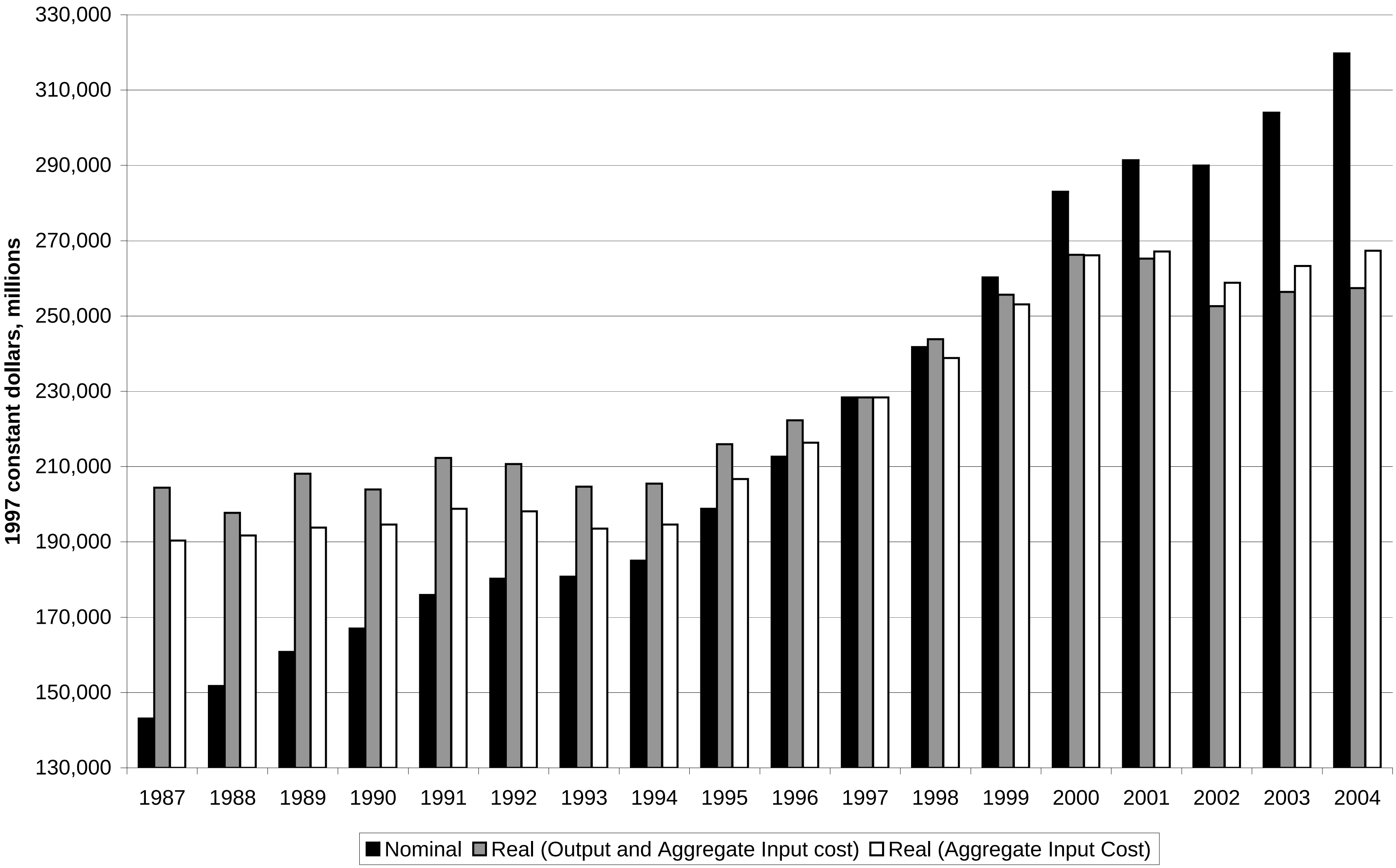


Chart E: R&D Price Indexes
(base year is 1987)
290
240
190
140
90
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
Output
Aggregate Input Cost

Chart F: Total R&D Nominal and Real Expenditures



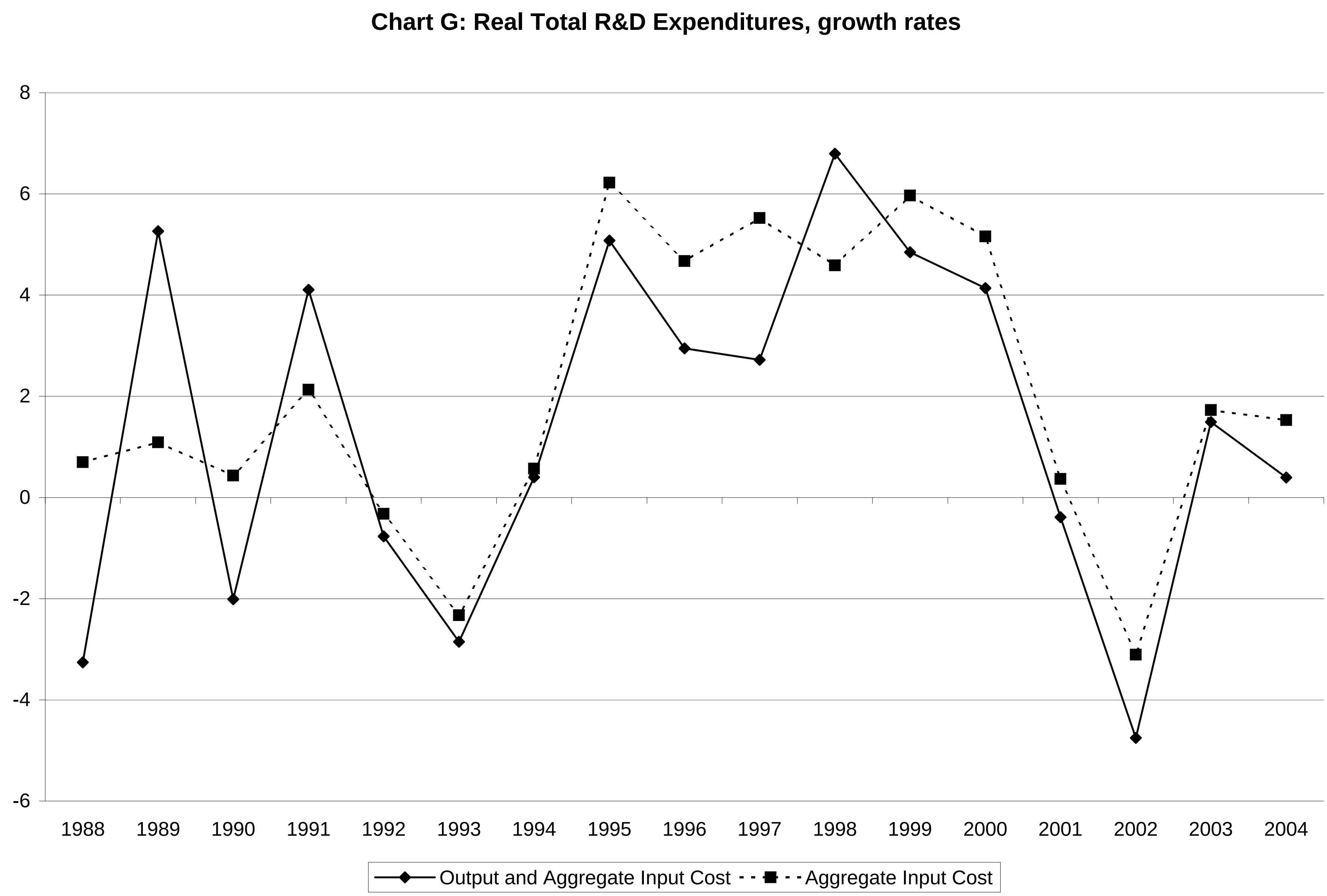


Chart G: Real Total R&D Expenditures, growth rates
8
6
4
2
0
-2
-4
-6
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
Output and Aggregate Input Cost
Aggregate Input Cost

Chart H: NAICS 5417 Nominal and Real Revenues

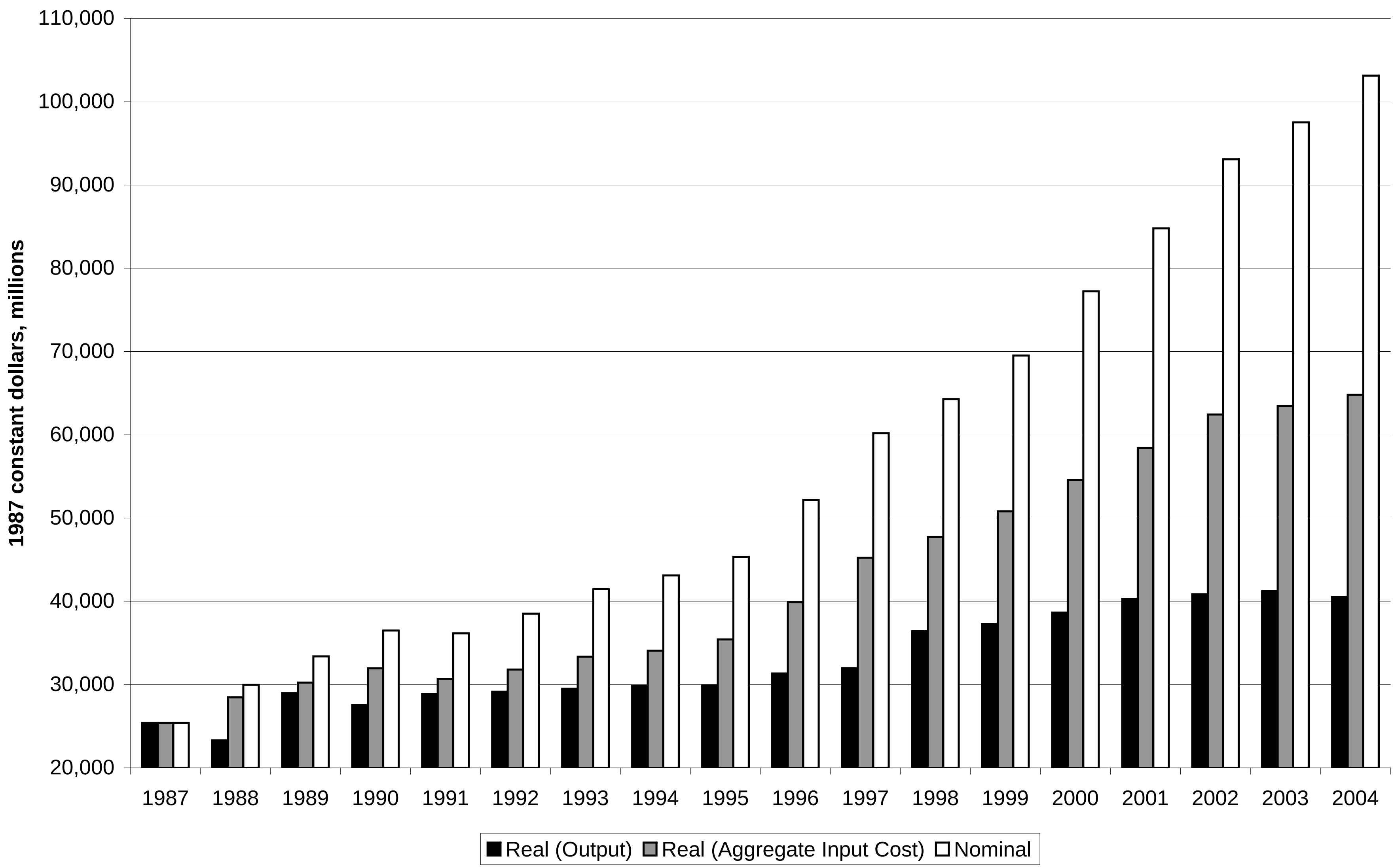


Chart I: NAICS 5417 Real Revenues, growth rates

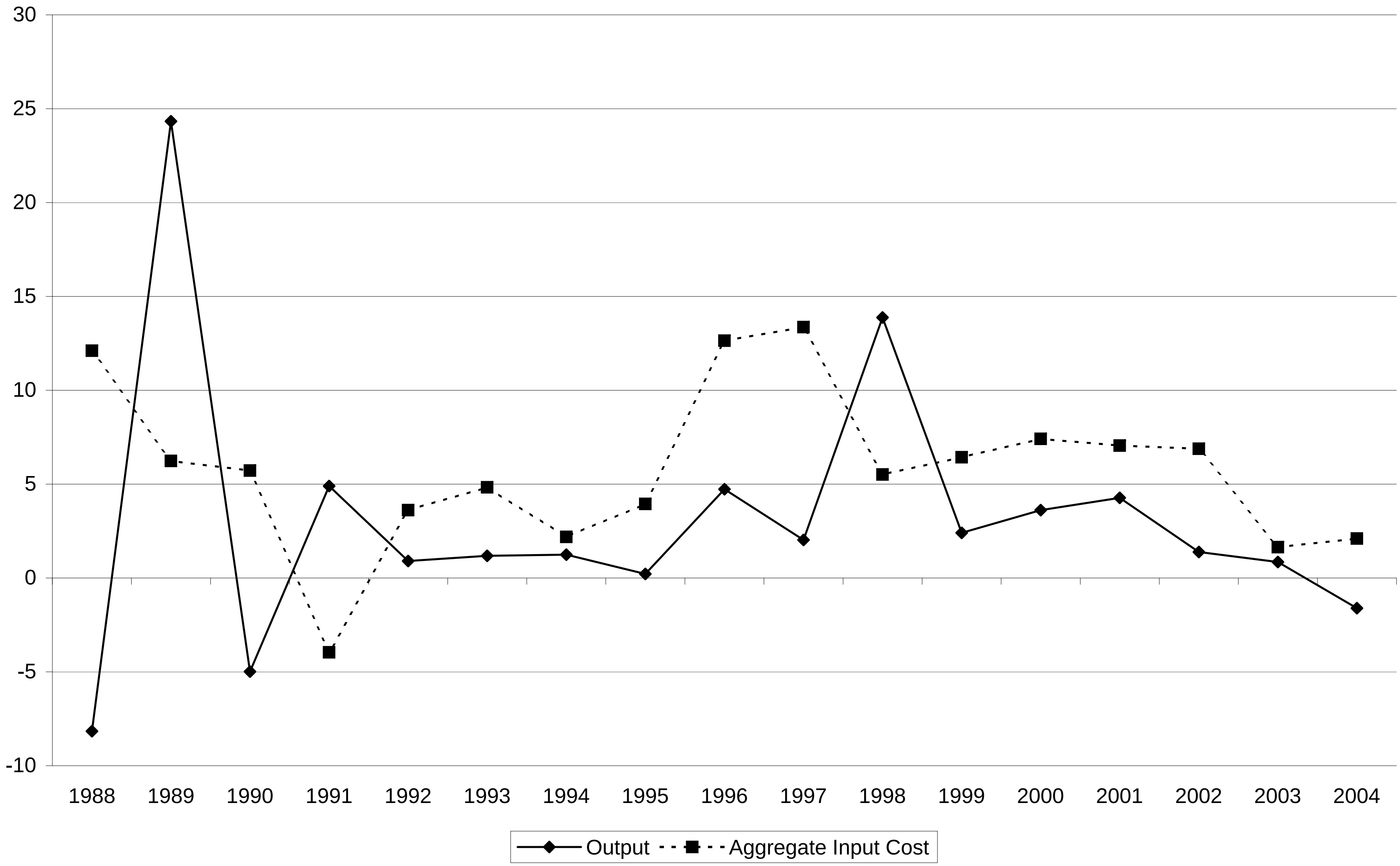


Chart J: NAICS 5417 Labor Productivity