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The economic contribution of information technology: Towards comparative and user studies*

Timothy F. Bresnahan[1] **and Shane Greenstein**[2]

[1] Economics Department, Stanford University, Stanford, CA 99305, USA
[2] Kellogg Graduate School of Management, Northwestern University, 2001 Sheridan Road, Evanston, IL 60208-2013, USA (http://www.kellogg.nwu.edu/faculty/greenstein/)

Abstract. By what process does technical change in information technology (IT) increase economic welfare? How does this process result in increases in welfare at different rates in different countries and regions? This paper considers existing literature on measuring the economic benefits from information technology, emphasizing comparative issues and user studies. Following Bresnahan and Trajtenberg (1995), we call the invention associated with customizing the technological frontier to the unique needs of users in particular regions "co-invention", placing emphasis on understanding how its determinants vary across users in different regions. We develop a framework for understanding the processes behind value-creation, demand-side heterogeneity and co-inventive activity. Then we discuss why these processes make measuring the welfare benefits from advances in information technology particularly difficult. We highlight the metrics currently available for measuring the economic pay-out of the IT revolution and identify which of these vary meaningfully in a comparative regional context. Finally, we finish with observations about further areas of research.

Key words: Measurement of technical change – Information technology – General purpose technology

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Motivation

This paper takes the first steps toward practical measurement of the benefits of information technology when comparing across regions. Our first goal is to clearly exposit the ideas in the existing literature on measuring the economic

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Correspondence to: S. Greenstein

benefits of information technology. Since we are following an empirical research area, that part of our discussion will focus on the links between the practical and the conceptual. For the application of information technology to create economic benefits, what is the conceptually correct measurement framework? What specific measurement problems and opportunities arise in practice? What is the menu of possible metrics in an international context? What are the data limitations? What methods are appropriate?

Our second goal is to begin to address comparative issues with an emphasis on user studies. This is a newer area, and a very exciting one, but one in which there is little work to guide us. Here again, we emphasize the links between the conceptual and the practical. What forces might lead to different rates of realization of economic benefits to users in different regions or countries? How are these forces related to the key concepts in the measurement literature?

Our analysis emphasizes the distinction between inventions that solve general problems and the complementary inventions that solve particular ones. Both must occur for economic welfare to increase. The distinction is often important in the analysis of technology, but it arises with particular force in the analysis of information technology. Technical progress in enabling technologies - what engineers often call the "technological frontier" - is only the first step in the creation of economic well being for users. Invention of general purpose enabling technologies, such as computer hardware and software, telephone transmission technologies, or data networks, permits but does not compel invention of valuable uses.

We follow Bresnahan and Trajtenberg (1995) in emphasizing the importance and nonobviousness of many new applications of IT, calling development of those applications "co-invention" rather than mere customization. With a general purpose technology (GPT) like IT, the economic rate of technical progress depends on the rate of co-invention, not just of invention. Co-invention involves the technology of the using firm's industry and markets, not just IT. Once new applications are (co-)invented, they may be embedded in any of a large number of products or services for wide distribution by sellers of packed software, sellers of semi-custom IT solutions, or by system integrators, turnkey systems vendors or others. Users' investments in co-invention are an especially important part of technological progress in information technology, typically needing time, invention and resources before economic welfare gains are realized.

This shift in emphasis is important to our analysis. When we say that the rate of technical progress in integrated circuits has been rapid, that is a technically accurate statement. However, it is not the same as saying that there has been rapid advance in the economy's ability to make consumers better off by using IC-based devices. The economic definition of the rate of technical progress refers to changes in an economy's ability to transform inputs into consumer welfare. It is this second sense of technical progress which we emphasize in this paper.

The economic importance of co-invention means that the rate of technical progress can vary across countries, even if people in all countries could buy the same computers, the same cell phones, and the same networking gear. Generally speaking, technical knowledge of new invention travels quickly across regions and among OECD countries; so too do new products. Co-invention, on the other hand, is largely local. Regions and industries differ in the amount of co-invention required and the amount supplied.

Accordingly, we think that the development of an appropriate framework for regionally comparative metrics starts from two classic questions in the economics of technology. First, by what process does technical change in information technology (IT) increase economic welfare? How does this process vary internationally and how does it result in increases in welfare at different rates in different places? Second, what metrics are available for the economic payout of the IT revolution? Which of these vary meaningfully in a comparative regional context?

We first develop a framework for understanding the commercialization of general purpose technologies. Emphasizing demand-side factors and co-inventive activity, we then discuss how economic value is created. Then we discuss why measuring the welfare benefits from advances in information technology is particularly difficult. The paper then summarizes three types of studies for measuring technical advance, analyzing the strengths and weaknesses for each approach in light of our framework. The first type is hedonic studies of technical frontiers. The second type is demand studies of technical progress which is embodied in products. The third type is studies of co-invention. Finally, we finish with observations about further areas of research.

General purpose technologies and the commercialization of IT

The development of IT can be viewed in the context of observations about technological convergence (Ames and Rosenberg, 1984), which is the increasing use of a small number of technological functions for many different purposes. Bresnahan and Trajtenberg (1995) develop this notion in their discussion of General Purpose Technologies (GPTs), which they define as capabilities whose adaptation to a variety of circumstances raises the marginal returns to inventive activity in each of these circumstances. As noted in many studies (Helpman, 1998) GPTs tend to involve high fixed costs in invention and low marginal costs in reproduction. The main determinant of their social benefits is the social cost of co-invention, the expenses associated with customizing the GPT to many new applications.

A GPT must be adapted for any new use, and this adaptation takes time and invention. Attempts to customize a malleable technology depend on the location, the firms involved, and time period. Many suppliers, users and locations face the same secular technological trends. *Differences* across suppliers and users at any point in time or over time arise when decision makers face different incentives arising from different local output market conditions, different quality of local infrastructure, different richness of labor markets for talent, or different quality of firm assets. These create a variety of economic incentives for adapting GPTs to new uses and applications.

Moreover, these incentives take time to develop as they co-evolve. One reason for this is that invention is a complex and unpredictable activity in its own right. Another, and not necessarily independent, reason relates to the structure of invention and co-invention. The boundary between activity associated with invention and that associated with co-invention is unclear, blurred by many feedbacks between the two kinds of investment, by communication among firms engaged in either activity, by mobility of personnel, and by selective user investment in reaction to new opportunities. Learning may become localized, particularly when it involves tacit knowledge that does not become widely available (e.g., McKelvey, 1998).

Generally speaking, the agents of change for IT come from one of several groups: end-users within an organization, professional staff (such as the MIS group) within an organization, or third party vendors outside the organization. If the end-user or their staff does much of the adaptation activity, it becomes an extension of other operations and investments. In contrast, if third parties sell related services to users, it may arrive in several different forms, sometimes as equipment, sometimes as consulting about business processes, and sometimes as complements to both.

The rate and direction of adaptation activity are difficult to predict. No single actor can envision how the GPT should operate in all potential applications. Accordingly, when adaptation is valuable, such markets involve experimentation with new business models, new cost structures and new applications. Different vendors take different approaches in translating and customizing general purpose technologies to the unique needs of users and their organizations, solving problems as they arise, tailoring general solutions to idiosyncratic circumstances. This activity helps users experiment, filling gaps between what convergence has made possible and what users find useful.

In other words, if the GPT brings about changes to many parts of the vertical chain of production, then we should expect to see many changes to the organization of the industry, changes in the delivery of services, production methods, distribution channels, spot contracts for suppliers, supplier/buyer relationships, leadership in a product category, and so on. In sum, a GPT alters the underlying pattern of the delivery of products and services at specific places in specific organizations. This is especially true of information technology, which favor business services or geographically local services that tend to be non-tradable (Antonelli, 1998).

One example illustrates many of these points, applications software, a comparatively new industry and product (OECD, 1989). It is supplied by firms whose combined capitalization reaches several hundred billion dollars worldwide. These firms provide services and products at the boundary between the general purpose device, the computer or network, and the special purpose device, the business information system. This existence is complex, and its market structure has many unique features (Mowery, 1996). Packaged software exists in only a few categories of applications. Most software is sold along with consulting services and other products, such as hardware. Many new applications and ideas are designed by lead users or academic researchers, communicated through research channels to lead programmers and designers, then incorporated into commercial products in a variety of formats over time. This product category has also involved a struggle for control of the computer industry (Bresnahan and Greenstein, 1997). It has slowly moved rents from the sellers of computers to the sellers of software and networking. Furthermore, the pace of change and degree of imitation raises new challenges for intellectual property law in international markets, where the rules have been changing in response to recent IT advances and economic globalization, but only slowly. Unsurprisingly, it is difficult to characterize all this co-invention activity in analytically clear terms.

Creating economic value from GPTs

By what process are GPTs translated into economic value? We classify the process into one of four categories: (1) understanding rates of technical advance; (2) understanding user adoption behavior; (3) understanding co-invention; (4) understanding the co-evolution of technical advance, adoption behavior and co-invention.

Rates of technical advance

IT invention consists of a variety of distinct technologies. IT comprises a lot more than the microprocessor. The technical frontier is defined by a stunning variety of distinct technologies: hardware, software, networking and communications, digital and analog systems, operating systems, operations software, tools and applications, communications software, central switches and PBXs, mainframes and microcomputers, storage devices, input devices, routers and modems, TCP/IP-based technologies, proprietary and other open standards, etc. A very wide variety of technical specialties, kinds of IT firms, and modes of invention are involved in advancing these technologies.[1]

This variety means that simply documenting the rate and direction of technical progress in IT is not a trivial activity.[2] Rates and directions differ across products and components. Frontier technology may involve new products or processes, combinations of existing ones, retrofits on vintage components, or new systems of interrelated components.

[1] See Bresnahan (1999) for a list of important technologies and an introduction to the literature on the technological change process that affects them.

[2] The industry of observing market behavior in the IT business world has found it difficult to keep up with the recent explosion in technologies and business. For general introduction to different facets and many “lists of lists”, see e.g., Juliussen and Juliussen (1998), Chai (1996), Hoover’s (1997), International Data Corporation (1995), Meeker and Dupuy (1996), Minoli (1991).

User adoption behavior

There is a wide literature on user adoption of innovation in IT and we cannot summarize it all here. In brief, IT is a particularly interesting example of applications which are not primarily cost-reducing. Often the use of new IT permits improvements in the quality and reliability of products or, especially, services. Furthermore, frontier IT frequently enables the invention of entirely new services and products, which some users value and others avoid.[3] This type of change to the outputs of IT-intensive production processes is among the most difficult kind of quality improvement to value.

At the firm level, these new services may provide permanent or temporary competitive advantages. When the new services are reasonably permanent, the firm may see returns to the investment in the form of increases in final revenue or other strategic advantages. If a new product or service is quickly imitated by all firms, it quickly becomes a standard feature of doing business in a downstream market. The benefits from the new technology are quickly passed onto consumers in the form of lower prices and better products. In this case, the benefits to a firm do not appear as an increase in revenues; but they exist nonetheless, in the form of losses the business avoided. These foregone losses are, however, difficult to value.

Finally, the creation of intermediate goods like software has meant that much of the value to adopting new IT applications and IT capital goods derives from its use in business organizations, where it is deeply embedded business processes (see, e.g., Friedman and Cornford, 1989; Estabrooks, 1995). Accordingly, the business use of IT involves mutual adaptation between business processes and technology. This is especially so as local business units adapt IT to their local business processes (such as billing, account monitoring, and inventory management) or to the delivery of local services (such as retail sales, the delivery of financial data, and entertainment services). Where inventions do migrate easily, all organizations share in a social economy of scale, i.e., when co-invention costs are insignificant, a problem solved once is effectively solved everywhere.

Co-invention

Co-invention by IT users is a very large part of research and development in advanced economies, larger, for example, than the costs of invention in the IT sectors. This is one of the reasons that IT's diffusion pattern differs from the adoption of innovative technologies in other sectors.

The costs of adaptation and co-invention can be borne by several groups of co-inventors: users within the country or third party vendors from either within or outside the country. If they are borne by third parties, then many issues arise.

[3] See Barras (1990) for a statement of the theory that this is systematic in service applications. See Brynjolfsson and Hitt (1996) for measures of the complementarity between service improvement efforts and IT investments at the firm level. Among others, see Karshenas and Stoneman (1993) on adoption of IT innovations linked to factory processes and numerically controlled machine tools.

Much customized computing software, for example, is sold not as packaged products, but as complements to consultation about business processes. Co-invention often occurs independently in different regions or countries in response to idiosyncratic problems associated with applying frontier IT to new problems in each country.

The ease with which co-inventions arise within a region is a function of its infrastructure, and of the ease with which this infrastructure develops as local demand grows, the ease with which a region's businesses adapts solutions in other countries to the unique circumstances of its own. The ease with which co-inventions spread also depends on the idiosyncracies of the co-invention activities themselves, the clustering of supply of intermediary services (Swann, 1998). Moreover, some knowledge-intensive businesses are not mobile, particularly those oriented towards services and embedded in local business processes (Antonelli, 1998). There are social scale economies in accumulating knowledge, and these tend to accumulate and become self-reinforcing in particular geographic locations (Boschma and Lambooy, 1999).

Other issues arise when users do most of the co-invention themselves, especially when user-specific applications are developed "in-house" – i.e., using employees whose primary motives are to develop firm-specific applications (Friedman and Cornford, 1989). Such solutions do not take advantage of the social scale economies associated with co-invention in other contexts. Occasionally, such "in-house" activity spawns the development of a third-party supply of new software applications at a regional level or country level. This can result when a "lead-user" develops applications with wider applicability than their own firm's narrow needs (Von Hippel, 1988).

These types of issues are most dramatic in the communications segment of new IT applications, because regions greatly differ as to what regulations are in place for voice telephony, and thus as to what incentives exist for a publically regulated telecommunications carrier to adopt technical changes. Communications networks across the developed world differ in their resistance to the change from analog to digital technology for voice communications, in their willingness to develop new services in conjunction with a digital backbone, and in their willingness to allow a thriving, customer-premises equipment market. In turn, these factors influence the business models for TCP/IP-based technology and services, and for the use of frontier networking computing, which combines communications and processing capabilities.

Co-evolution of technical advance, adoption behavior and co-invention

Economic gains do not come solely from the act of invention, but also from the adoption and adaptation of technology by users. This is a well-understood point, as it has arisen in historical episodes of technical and institutional change.[4] For in most important areas of technology, both during periods of invention and then during the realization of great economic gains from these new technologies, most users do not employ products on the technical frontier.

As with other general purpose technologies, changes to the flow of services from new IT evolve slowly if co-invention activity evolves slowly. Only after the passage of time, and the gradual accumulation of many incremental improvements in processes and outputs, will all these changes result in dramatic change. For a variety of reasons, experimentation and learning often can only occur within a market setting. It takes time to translate an invention into a viable commercial product: for business models to be developed; for new distribution channels to be created to spread the invention geographically from its region of origin; for one set of users to learn from another distinct group; and so on.

IT is distinguished from other technologies more by the degree of complexity and variety of the cumulative process. There is not one adoption pattern for characterizing all IT, nor are these patterns necessarily similar to some important historical episodes of diffusion, such as the diffusion of radio, television, the automobile, and so on. It is tempting sometimes to think of IT as the simultaneous diffusion of several tightly coupled interconnected technologies, each with an adoption curve strongly dependent on the other, such as the interrelated development of airframes and jet engines, but this model too is deceptively simple.

In fact new waves of IT invention set off new waves of IT co-invention by users and each wave has its own diffusion curve of adaptation and adoption. For example, the invention of cheap fiber optic cable, one of the key elements in the communications revolution, did not immediately change the capability of phone service nationwide. Performance and features changed in fits and starts, as digital switching technologies, repeaters, and other software that increased fiber's capabilities was developed and adopted. Economic value changed slowly, too, because new fiber networks brought about new services from phone companies and, more important, investments from users in digital equipment. These new services and new investments could only be built, tested, and marketed after the underlying infrastructure improved (Greenstein, Lizardo and Spiller, 1998).

Similarly, such important contemporary technologies as the World Wide Web and enterprise resource planning (ERP) have set off entirely new waves of co-invention.[5] The Web (or at least technologies arising from it) is inducing a great

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[4] There is, of course, a vast historical literature on the technical and economic development of new technology and its translation into economic value (see, e.g., Langlois and Robertson, 1995). Some researchers have compared today's IT revolution to the development of electricity in factories (e.g., David, 1990). For a skeptical comparison, see, e.g., Gordon (2000).

[5] Both of these technologies have elements of applications but also elements of infrastructure - i.e., other applications are being developed that assume their presence. The web is a cluster of Internet technologies that have recently migrated into commercial use in a variety of diverse areas. Most of the key inventions predate widespread commercial development. The most recent dramatic inventions, which are associated with the use of HTML and Web browsers, had their origins in CERN in Switzerland and in the National Center for Super Computing Applications at the University of Illinois. In contrast, ERP software is a new area, provided by new vendors such as SAP and Baan, of company-wide control applications.

deal of new application development. Along with TCP/IP-based technologies, whole new business models are emerging for delivering and using data-related services. Similarly, the unification of distinct systems associated with ERP is permitting a new wave of control of IT and businesses. These changes are not merely the tail ends of a diffusion curve that began long ago; they represent a renewed process. Such processes differ across countries, and across industries within countries.

Why it is difficult to measuring the benefits from advance in IT?

There is no direct relationship between investment in IT and productivity as measured by economist's usual methods. More strikingly, it can be deceptive to simply count labor, capital, and IT stock and compare them against output, as one might do for most capital-intensive industries. Both halves of this calculation are in error; Users' co-investment is omitted on the cost side, and if output is measured in standard national accounts, most of the changes (the quality part) are unaccounted for on the benefits side. For an IT advance involving large component of investment in unmeasured co-invention, which varies widely with the levels and types of hardware and with its links to changes in the character of final output, then the errors can be extremely large.

In addition, co-invention involves a high degree of uncertainty in forecasting. When a general-purpose technology advances, it enables new applications that have no historical precedents. Hence, today's users of a new technology find it difficult to imagine or estimate the future elasticity of demand for complementary products arising out of future co-inventions. Even if early versions of a general-purpose technology have partially diffused to leading adopters, whose co-inventive activities have been carefully observed, it will still be difficult to forecast the future. The rest of the population of adopters, who will be using the technology when the prices drop and the capabilities expand, may have different characteristics and needs from the first users. Indeed, co-invention activities may be so unpredictable as to make it difficult to estimate who will be using the technology when the prices drop and the capabilities expand.

History is full of examples where early users and industry leaders badly misforecast future demand. In the cellular phone industry in the United States, for example, leading industry experts at AT&T and at the Federal Communications Commission vastly underestimated the demand for cheap cellular-based mobile communications. The consensus of many experts was shaped by their observation of mobile phone use over radio bands. The largest users of radiophones were ambulances, taxis, and wealthy real-estate agents, hardly a representative group of users for predicting the adoption pattern for cellular phones as prices declined. In another well-known example, IBM's management vastly underestimated the demand for cheap personal computing. Again, this was quite understandable in historical context, even at the world's largest and most commercially successful computer manufacturer; it would have been extremely difficult to foresee the character of the demand for low-cost, personal computing technology (where many custom and shrink-wrapped applications were developed by an independent software industry) by extrapolating from the demand for high cost centrally managed computing in minicomputers and mainframes (where the manufacturers controlled the supply of both hardware and software).

Similarly, it is very difficult now, for example, to forecast even the qualitative nature of the demand for cheap, capable, long-distance networked computing applications. Forecasters can only look at earlier experience with cheap computing (such as PCs and workstations) and with expensive and difficult networked computing applications (such as NetWare and Electronic Data Interchange), but this hardly represents the cost conditions and economic opportunities that future users will face after the deployment of extremely cheap computing capabilities and low-cost, high-bandwidth fiber and wireless communications technologies. These deployments will induce (and already have induced to some extent) the entry into this market of thousands of firms trying to solve co-invention issues that had never previously existed. Similarly, it is difficult to forecast the future shape of Extranet and Intranet technology based on experience with TCP/IP-based technologies, the early users of these were scientists and engineers, primarily in higher education and laboratories. These groups of users engaged in co-invention activity, to be sure, but the issues found in an engineering setting differ significantly from those found in a business setting.

Thus, in general, in many of the waves of invention and co-invention that characterize the IT revolution, it is extremely difficult to find a direct relationship between investment activity yesterday and economic benefits from new technology today.[6] Investment and use differ over time and are associated with different economic goals. The capital stocks differ over time and are associated with only partially overlapping activity, some of it IT capital and much of it, such as software programming and maintenance, not. The supply of goods and services in the co-invention sector may be organized differently over time and associated with solving different problems. The final output from organizations that use IT may also change over time: some of these changes may generate new revenue; some may induce the entry into the market of new firms with business models using the new IT in a radical way; and some may induce exit: the key features of the final output of the new IT may change radically over time.

One final complicating factor enters into a comparative exercise. A proper account of the economic gains from the use of new IT must include the opportunity cost of other inventions not pursued, including the capital losses on technologically advanced equipment and training rendered obsolete. Most new technology replaces an alternative arrangement for achieving the same outcome, diminishing its net value to society. For heroic technologies the opportunity costs of their diffusion is overwhelmed by their benefits. These are technologies with dramatically evolving capabilities which influence the entire economy – such as microprocessors, high-speed communications, and so on.

[6] This is topic of a large literature, of course. See the discussion in Stoneman (1983), Bailey and Gordon (1988), or Gordon (2000).

The complexities of the situation are most easily illustrated by an example. In the 1990s, networked computing based on microcomputers and workstations made a substantial impact on large corporate applications, which had previously been the domain of mainframe computers. But this change was not simply the replacement of high-cost mainframes with low-cost client/server systems. This change enabled organizations to do things that simply could not have been accomplished previously. In some industries and some regions, these changes were dramatic; in others, less so.

The complete social calculation of the costs of networked computing involves four components:

(1) expenditures on the capital cost of equipment by users and the unanticipated capital losses of services from installed equipment;
(2) expenditures on software for the new systems, both by users and by third-party vendors providing the software and consulting services;
(3) transitions-related expenditures, such as the cost of integrating different information systems, and training of new staff, or "adjustment costs" during the transition – expenses that are considerable and usually sunk;
(4) capital losses on the unanticipated portion of services whose value is depreciated by replacement technology, rendered both in terms of the value of in-house programming at using sites and of the whole co-inventive sector of the economy, such as vendors selling software, consulting services, and tools.

Not all of these costs accrue to the same organization or even the same region. These complexities arose because the new IT involved a variety of different technologies, which combined in unexpected ways.

Despite these difficulties, what progress has there been in measurement? This is the topic of the remainder of the paper. First we review standard approaches to measuring rates of technical progress using hedonic techniques. Then we discuss studies that examine the demand for technical progress embodied in new products. Finally, we end with a review of studies of co-invention.

Standard approaches to measuring the rate of technical progress

Each new computer generation has larger memory, bigger screens, different input output devices, and more capabilities. Some of those new capabilities derive from improvements in application software or system software, or from the use of software from Internet sources. Some of the performance improvement is a result of better printers, faster external storage devices, and better networking connections. In other words, the technical frontier is commercialized into new products and services in a wide variety of ways, sometimes as new products, and sometimes as new features of existing products.[7]

[7] These trends are so widely established in industry publications. An overview may be found in Juliussen and Juliussen (1997) or ITI (1997).

In general, the frontiers in IT are moving out in many different directions. Not all of this movement is easily observable; it occurs at different paces and there are no uniform standards for measuring progress in technology over time. Some changes correspond with standard engineering measures of component or system performance, but some do not. Moreover, some technical changes find their way immediately into the products largely bought by users and some only find their way into products with delay. It is rarely the case that users in two countries or regions have access to exactly the same components at exactly the same stage of technical development. It is not uncommon for the situation in two countries to be close - but how close? Answering this measurement question requires adapting to the specific market circumstances and technologies in question.

There is a well known literature in empirical economics associated with the hedonic estimation of computing industry outcomes. These studies provide some insight into the rate of technical improvement in hardware across a class of products.

The computing industry has experienced a dramatic decline in price per unit of features, and hedonic curves are a simple way to summarize that change over time. Hedonic techniques also take into account changes in prices along the entire product line; such changes affect the adoption of behavior of both users with intense demands and those with less intense demands. Similarly, hedonic estimation provides an answer to the deception associated with Moore’s law, which focuses only on the advance of the biggest microchip. It is not the doubling of the best processor’s speed per se that leads to economic benefits. Rather, economic benefits are associated with all chips along a wide spectrum of sizes, applications, and firms, getting both better and cheaper.

There are many estimates of price changes in computing using hedonic estimates (e.g., Triplett, 1989; Dulberger, 1989; Gordon, 1989; Berndt and Griliches, 1995). All show rapid declines in price per feature and performance. Recent research on advances in packaged software suggests that many of the same trends are found in PC software too (Gandal, 1994; Lichtenberg, 1993). Remarkably, the literature offers very few estimates outside of these limited few categories. There has been especially little work on communications (Flamm, 1989, 1998, are exceptions). One would expect to find interesting trends in many different component markets of the IT revolution; there is much room for documenting these changes.

Hedonic estimation is far from a panacea. For one thing, a price fall is not identical to an increase in buyer value. Researchers have turned from computer hedonic estimates to approximate “back-of-the-envelope” demand estimates. When technical change has been dramatic and the second decimal place does not matter, these rough measures give an idea of change in demand from rapid rates of change in supply-price. The inspiration for these exercises goes back to Griliches’ (1957) examination of the welfare benefits deriving from the development of hybrid-seed Corn. Recent applications of this approach to IT (specifically computers) include Flamm (1989) and Brynjolfsson (1996). These researchers were justifiably cautious about using their calculations of IT stocks to make inferences about economic welfare. Thus, it is unsurprising that these techniques have not been used for cross-country comparisons.

The gap between hedonic estimates and actual welfare is further explored by Trajtenberg (1989), and is worth emphasizing. Buyers differ in their valuations of different parts of the product space (e.g., some types of buyers especially value high-speed computing while some especially value decentralized computing at low speeds). Many buyers place great importance on "stretching" the product space, or on "filling it in." The hedonic technique also says little about the presence or absence of complementary goods, nor does it inform a researcher's understanding about the substitution between the good under investigation and other goods. Finally, these methods do not provide an accounting for heterogeneity in suppliers' ability to provide inventive products, nor for heterogeneity in users' valuations of the new products. Raff and Trajtenberg (1997) further develop these issues in their analysis of the hedonic estimates for the early U.S. automobile market. In that setting, it is especially difficult to trace the direct relationship between the hedonic estimates and meaningful changes in users' welfare because the relevant features of the product change so much over time.

Few researchers have used hedonic methods for cross-country comparisons of technical achievement in high technology. In this spirit, Luzio and Greenstein (1995) compared the hedonic functions for PC hardware for the United States and Brazil as a way to estimate whether Brazil's import ban policy resulted in high domestic costs. They demonstrate that Brazil's closed PC industry was years behind in technical achievement (and much more expensive for a given set of characteristics in a given year) across a wide class of products. These trends were widely observed but never quantified. Hence, the hedonic estimates were quite useful.

This example does not suggest, however, that hedonic estimates could or should be applied to all cross-country comparisons of technical achievement. The data requirements in the Brazil and U.S. comparison were substantial (i.e., product level data for many months for both countries), the econometric estimates needed many observations to pin down the estimates, and the economic situation was extreme (Brazil had a complete ban on imports while the United States was technological and commercial leader in the industry). Extreme differences such as this hardly resemble comparisons among OECD countries, however. We expect that hedonic estimates would likely be uninformative about differences among OECD countries, except in very special circumstances. Similarly, hedonic estimates may be useful for comparisons between OECD and non-OECD countries when the relevant data exists.

In general, therefore, hedonic estimation tends to be less illuminating about trends over time and not about cross-country differences in technical achievement. Part of the problem is that OECD countries, where most IT investment takes place worldwide, do not tend to vary much in technical achievement as long as they remain relatively open. These is also an inherent variability in the econometric estimation of hedonic surfaces; estimates are mildly sensitive to specification and other robustness issues (Triplett, 1989). Hedonic estimation is a useful tool in situations of dramatic difference, such as change over time. We conjecture that dramatic differences less frequently arise between OECD countries at any point in time.

Measuring user demand for embodied technical progress

The value that users gain from technical progress differs according to what use they make of the new technology. Thus, the same decline in price or increase in performance may be valued quite differently by two different groups of users. Hence, to completely measure the consequences of changing technical frontiers, any research must account for user differences in demand.

One organization may be taking advantage of lower costs from frontier technology, while another may take advantage of greater capabilities, for examples; further, these differing motives for adoption may change over time. The first adopters of workstations were engineering firms, whose workers wanted high-end computing in a more convenient format than they could get when using minicomputers. Later adopters were employing workstations for basic networking functions, such as running local area networks, hosting e-mail, regulating web access, and so on. The value of these applications differed across firms - and, even more so, across international boundaries.

One appealing approach is to examine the demand for goods that embody the technical progress. In IT, this means measuring the demand curve for IT-bearing capital goods. One area of recent advance looks at the demand for individual IT products, specific models of computer, say, using product level data. This literature estimates the demand for products directly, using information about heterogeneity in firms. This is a possible way to account for the importance buyers place on new products that provide new services. In his study of CT scanners, for example, Trajtenberg (1989) found that the increasing capability of the scanner was associated with an increasing ability to perform important medical procedures - i.e., move from body scans to head scans. There was a link between the technological capabilities of the scanners and the uses they could fulfill (which was also linked to the surplus they could generate).

This point applies beyond CT scanners. The method also potentially offers the ability to measure the importance of limited substitution between products for welfare calculation. First, if existing technological varieties of IT simply cannot accomplish a task, the new varieties may open up new uses, generating surplus. Or, if the development of the technology permits firms to customize it to the particular needs of buyers, it may lead them to “fill in” the product space with more and more designs. To the extent that this filling in results in increases to human welfare, this approach will also measure such increases. Differences in needs across countries may lie behind different valuations of changes to IT; hence, Trajtenberg’s study could be useful in a comparative context.

These insights require a great deal of data to support them. The researcher needs user data of a kind that exists for very few markets, even in IT. The data must describe the same users over a sufficiently long period of time. It must describe changes in the products over time, especially the features that matter for buyer choice. It must describe the choices made by the users at any point in time and over time. Finally, it must correctly characterize the costs of acquiring and setting up the product. This last requirement is especially limiting, because prices almost always correlate with unmeasured quality. The full generality of approach is also open to question because in IT users often purchase many substitute technologies, not just one product at a time. In that case, demand estimation is even harder to do than it looks. For example, how does one estimate the demand by an organization for hundreds of PCs from several different suppliers? From an econometric standpoint, one's approach depends on how much theory one is willing to accept as a substitution for unavailable data. As illustrated by Hendel (1995), this type of estimation is possible, but quite difficult.

Another approach to measurement takes advantage of data on market expenditure data over time, with models of investment. For example, using duality index theory and marketwide data for use and price indices, Bresnahan (1987) estimated the returns from improvement in computing in financial services. This was an estimate of the derived demand for computing at the industry level (banking services being the industry in question). Duality theory provides a link between inputs and an index of technical change. This method, like several others we analyze, assumes that preferences do not change much over time, in other words, that the demand function is stable over the time period in question. It also abstracts away from changes in demand due to co-invention activity. But it succinctly captures a dramatic change in the use of IT in one IT-intensive sector of the economy and translates it into an appropriate welfare measure. While some robustness issues remain, as with hedonic estimation, these concerns are overwhelmed by the dramatic nature of the change over time.

This approach has not yet been employed for cross-country comparisons in the demand for IT capital stocks. It requires the collection of extensive data very specific to particular industries over time. The researcher needs the same expenditure data for the same inputs in the industries. The approach also is only appropriate under a certain set of conditions, where duality theory applies (e.g., competitive output markets) and where co-invention costs are not severe. These are not trivial constraints in practice; regulatory institutions play a large role in investment behavior in the communications industries of many countries.

Finally, some researchers have tried to use the same data as that found in hedonic estimation, but interpret it through models of demand. In effect, these models attempt to build heterogeneity in users into demand by assuming it takes a certain form. Then the researcher builds an aggregate demand curve from these assumptions about heterogeneity in the demand: this allows the research to move from product level information or expenditure data to regional or industry-level demand.

Hausman (1997) measures consumer demand from variation in local price and quantity data in the mobile cellular telephone market. This is an interesting market to study because of its policy implications; the rapid growth in market demand was not anticipated by most experts in industry and government regulators. Hausman uses a representative agent model and identifies key parameters of the differences in demand across regions. He concludes that the welfare gains arising from the new product were substantial. Like hedonic estimation and some of the other techniques described here, this technique has some potential robustness problems (e.g., welfare estimates are somewhat sensitive to specification of demand intercepts). Yet, as with the other methods, it seems well suited fur use in a dramatic situation, such as the cellular phone market in the 1980s and 1990s. The changes were substantial over time and the method should estimate a large benefit to users and so it does.

Greenstein (1996) assumes a vertical demand model for mainframe computer hardware bought in the late 1960s, 1970s and early 1980s. Products differ in quality only, and consumers substitute among products in this dimension. While this is a highly restrictive specification for demand and economic welfare for this time period, Greenstein shows that even this model leads to the conclusion that increases in the product space were important for economic welfare. In his model, these stretches account for a substantial fraction of welfare from technical change, though they are realized relatively slowly.

In Bresnahan, Stern, and Trajtenberg (1997), PC hardware demand in 1986 and 1987 is characterized in two dimensions: closeness to a technical frontier and association with a branded provider. They show that these features of the product were key to understanding the private gains made by innovating in this market in this time period. While the papers emphasize private returns to features of the product, they do lead too to the inference about the importance of stretching technical frontiers for economic outcomes.

These approaches represent considerable progress in advancing the methodology of measuring surplus. They are, however, still in a prototype, "laboratory" level of development, and it would take a great deal of effort to bring them to the practical level one would need for working with a national or international statistical system. Moreover, these estimates of demand are only scratching the surface of the factors that determine international differences in the economic benefits from IT. In virtually every case above, we do not observe what we really want to measure. To get to the welfare calculation, therefore, the researcher needs to make substantial leaps and theoretical assumptions based on extensive information gathering. In every case, these methods only really work if supplementary information helps identify many of the unseen factors shaping behavior. And, once again, virtually none of these methods directly identify co-invention expenses, though they may point indirectly to an unexplained slowness in the rate of adoption.

Furthermore, since most IT use is by business, these methods also do not directly address how the benefits from new technology get captured by business, nor how these benefits are distributed to the purchasers of the final products. Differences among organizations also arise because firms specialize in different activities - even firms in the same industry. For example, the first U.S. adopters of fiber optic cable for telecommunications were the long-distance telephone carriers. They had sufficient volume along their main trunk lines to justify the transitional expense of laying fiber optic cable, solely for the cost-reducing benefits. Later adopters in traditional telecommunications, primarily local exchange companies, adopted fiber with greater capabilities; the costs associated with laying fiber on their main trunk were lower, and substantial benefits were associated with increasing the reliability and capabilities of the systems to end users. Greater capabilities enabled firms to offer new services and users to retrofit their data services to phone lines. At the same time other competitive exchange providers laid fiber for purposes of carrying phone and data traffic in specific regions, especially dense urban areas where the traffic levels defrayed the costs. Such differences, endemic within one industry, also show up across regions.

Towards measuring co-invention

Co-invention activity attempts to resolve issues associated with adapting general advances in IT to the unique circumstances of an enterprise in a unique situation. These expenses are often sunk, yielding benefits within a firm but providing no lessons that can be sold outside the firm. These expenses become greater the more idiosyncratic and complex the adaptation, and the more difficulty the enterprise has in adapting tools from outside the firm to its problem (see, for example, Bresnahan and Greenstein, 1997).

The key observation here is that the determinants of co-invention lie on the boundary between the enterprise's needs and the general solutions offered by firms that commercialize frontier IT. Factors both inside and outside IT-using organizations determine co-invention costs. Co-invention varies across countries because enterprises vary across countries but also because differences in supply conditions vary across countries. To completely appreciate the determinants of co-invention expenses researcher must observe the adoption process inside organizations and the supply of new solutions from outside the firm. Collecting data on such complex activity involves many compromises. It is difficult to find metrics to compare across enterprises, regions, and countries. Frequently, no body of researchers or government organization has devoted any attention to collecting the pertinent data over time.

In a comparative context, one may often only observe the "shadow" of co-inventive activity, not the activity itself. Commercial industry watchers only track a selective set of activities, not the whole array of activities underlying co-invention activity.

A number of researchers have tried to measure the consequences for firm performance, usually in terms of productivity at the firm level, from the use of IT. The primary goal of this research is to unlock the source of co-invention costs for new IT, analyze the factors that complement the use of IT in an organization, or understand the reasons for resistance to the adoption.

For example, a series of papers begin with a simple approach, investigating the relationship between firm performance, measured as either sales or accounting profits, and investment in investment in IT hardware. Using standard production function methods, these authors find that IT contributes an inordinate amount to explaining outcomes (e.g., see Brynjolfsson, 1996; Lichtenberg, 1993). Further refinements on this approach add information, either about the organization or management of the firm, or about the determinants of co-invention. But these methods cannot do much to make precise which of those two things is the driver. Suppose, for example, that a study shows that companies that invested in IT had higher sales growth and higher profitability, particularly in Europe. There would be two possible conclusions: that the rate of return to investment in IT is higher for European societies, or that there is a bigger difference between forward-looking European firms and backward-looking ones than is found on other continents. These two situations would be very hard to tell apart based on the data gathered.

The literature has begun to make interesting progress on this difficult problem. Brynjolfsson and Hitt (1997), for example, add to the mix data on the degree of centralization or decentralization within corporations, finding correlation between investment in modern IT and decentralization of authority. They argue that IT enables firms to give more authority to its middle managers. In the same spirit, Hubbard (1998) examines the use of computing and global position systems in trucking firms, arguing that their adoption is primarily aimed at monitoring activity in realtime or lowering coordination costs within firms.

Bresnahan and Greenstein (1997) examine the factors slowing down or speeding up diffusion of networked IT at mainframe users. They argue that adoption of client/server technology is being held up by organizational complexity and idiosyncratic computing applications, which drive up adjustment costs. Both of these factors increase co-invention costs for new IT at organizations with complex and specific uses for their large-scale systems. Bresnahan and Greenstein conclude that the largest source of gains is linked strongly to factors that reduce co-invention costs over time.

Bresnahan and Greenstein (1996) conclude that co-invention costs were strongly correlated with the benefits of new networking technology. Hence, their study raises questions about the relationship between order of adoption and benefits from diffusion. The users with the highest gross benefits may be late adopters because they are waiting for co-invention costs to decline, as the supply of complementary goods increases. In computing, for example, these complementary goods may be associated with lowering the costs of transition from old investment to new, with software for programming large and complex new applications employing a new platform, and so on.

In general, these papers have only scratched the surface of comparative determinants of co-invention expenses and benefits. All these approaches leave many issues unaddressed. Further research could examine other measures of firm output. Many of the determinants of co-invention are geographically local, but no authors have identified clear determinants of them.

Evaluating research strategies for the future

We envision a future for studies associated with understanding differences between regions/countries in the determinants of the technical frontier, differences in the determinants for final demand, and differences in co-invention across regions. There has not been much research on variation in demand for information technology and it would be informative, but difficult, to extend existing studies towards understanding comparative differences in the demand for IT. Finally, research is just starting to understand co-invention activity in the US. There is enormous room for many studies on the sources of variation across regions in determinants of co-invention for advanced IT.

The determinants of adoption of frontier IT outside of North America

We hope to see more studies of the adoption of IT by enterprises located outside of North America with emphasis on comparative themes. Despite an abundance of statistics about the sales of IT across the world, there have not been many comparative studies of the determinants of demand for advanced IT capital.[8]

For example, how should researchers interpret such widely-cited statistics as the rapid diffusion of mobile communications to populations in Scandinavian countries? Is this indicative of higher demand, greater benefits, or lower costs to this technology there? Differences between countries in new networking technology, PCs, and other computing also beg to be studied. Are the widely-cited statistics about wider diffusion of PCs in the US linked to particular business activities? If so, what kind of IT activity exists in those same activities in Europe and Japan? Did the early adoption of Minitel in France lead French businesses to integrate with new applications using IP-technologies or did Minitel represent a sufficient substitute? Did it lead to a secondary business for applications, which then aided or hindered co-invention on other information technology activities?

Research into international telecommunications is quite common, but tends to focus on regulatory issues. In contrast, we would like to understand how different regulatory rules over customer-owned communication equipment influenced the use of (and demand for) innovative combinations of computing and communications hardware and software in business environments. Similarly, it is well-known that the EEC adopted GSM as a standard for digital cellular phone networks, while no standard was mandated for North American companies, who fought over CDMA versus TDMA. If an user behavior is brought into consideration, what trade-offs influence the payback from these different modes for determining digital communication standards? How are these technologies reorganizing the business processes? One regulatory difference across countries that can only matter through demand is the pricing rules for local wireline telephone access. This creates variation in demand for wireless services, which demand my lead in turn to any of a number of important developments in the wireless area for

[8] Roller and Waverman (1996) is a step in the right direction.

those countries with high wireline prices. Low wireline prices, on the other hand, contribute to demand for internet access services. Ubiquity of wireline internet access may be a driver of some kinds of e-business, while widespread adoption of wireless data services may draw others. Thus regulatory differences, mediated by demand forces, may lead to large differences in future developments.

Finally, and quite simply, it would be useful to replicate Bresnahan and Greenstein (1996, 1997) on the diffusion of networked computing in other countries. Did co-invention influence the adoption of networked computing in other countries as much as it did in the US?

The geography of demand

Co-invention involves the customization of frontier technology to the needs of enterprises doing business at a specific time in a specific place. Research has only recently begun to place emphasis on "place" when the discussion turns to advanced IT. These issues are salient to studies of the commercialization of the Internet worldwide and the commercialization of new communication technologies more generally.

Because so many communications and broadcasting systems across the globe involve significant government regulation of partially or wholly monopolized communications facilities, the rate and direction of convergence in networking applications often depends on regulatory and government decisions, not just technological feasibility and entrepreneurial commercial initiatives. Since so many important examples of convergence in the modern era involve communication technology, it is important to bring these factors into consideration (for example, see Crandall and Waverman, 1995). For example, the convergence of wire-line and wireless technology in the United States depended on rules governing the development of analogue cellular and digital wireless applications over the publically governed spectrum. Though the typical cellular phone may deliver a lower quality sound than experienced in land-line phones, it is still good enough for the human ear to discern. It partially replaces the traditional plain old telephone service over land-line technology (while also working with it), and also enables valuable mobile and convenient communications which the land-line technology could not provide.

There is also wide interest in understanding the Internet's geographic features, because these features have consequences for the development of "universally accessible" Internet, and for the locus of growth and economic development in a region.[9] More speculatively, other computer and technology policy analysts anticipate the arrival of virtual communities and business relationships, linked by highspeed telecommunications systems, which will be independent of geographic constraints. Such speculation, however, presumes relatively ubiquitous and available low-cost network access. In the absence of low-cost access, virtual

[9] See, e.g., Moss and Townsend (1996), Greenstein, Lizardo and Spiller (1997), Greenstein (1998), or the citations on http://www.geog.ucl.ac.uk/casa/martin/geography_of_cyberspace.html.

communities could develop communities over some geographic spaces, but be stratified by income, application, or density of region. Yet, little research has analyzed the geographic patterns of adoption of IT technologies for non-business use.[10]

Finally, the most commonly cited information on the geographic diffusion of the Internet comes from the Matrix Information and Demography Services (MIDS) of Austin, Texas (See http://www4.mids.org/), which has been analyzing the location of 'hosts', computers connected to the Internet. Yet, it is not clear that there is any relationship between location of host computers and access to Internet technologies for business and personal use, nor is there any necessary relationship to degrees of economic advance in the region. The state of these statistics indicates that there is room for development of much better indices of regional IT development.

The nested adoption of electronic commerce

Co-invention takes time and necessarily occurs in sequence. As the conditions that determine one first diffusion pattern change, and as users co-invent in reaction to new opportunities, so too do the conditions that determine the adoption of Internet technologies.[11] Hence, a latter episode of diffusion can be nested within the factors that determined the first episode. Any sufficiently complex co-invention activity will result in the nesting of some adoption episodes in others. For example, innovations in personal computing and networking influence the diffusion of on-line retailing. Innovations in search engines leads many firms to alter their web pages, which further induces changes in interactive access technology, which induces further adoption of software and so on. There has been very little attention paid to the how the sequence of development of electronic commerce shapes its performance. Is the United States gaining short term advantages or long terms disadvantages by being the strong first mover? How are there biases presently in the resolution of tensions between retrofitting and green-field development of the value chain of electronic commerce?

Some statistical research has analyzed the patterns of adoption of IT technologies for non-business use.[12] This is clearly an important determinant of industry structure in electronic commerce, as the diffusion of so many business models and new applications presumes ubiquity or an experienced user base. Yet, adoption and use of the Internet at home depends on historical or previous investments, particularly in such key infrastructure such as PCs, cable lines and local digital phone equipment. That is, the diffusion of electronic commerce had historical determinants in the diffusion of PCs, which was not oriented towards the diffusion of electronic commerce for many years. These were determined by many factors, such as the age, income and profession of residents of a household, as well as

[10] See Kridel et al. (1997).
[11] See Jimeniz and Greenstein (1998), Clemente (1998), Kridel (1997) and Tedlow (1996).
[12] Some recent contributions include Kridel et al. (1997), Goolsbee and Klenow (1999), or Goolsbee (1999).

the conditions of schools, libraries and retail service facilities in a local region. Does this portend development of non-PC based models of electronic commerce at the home? Will the have/have-not split in access to electronic commerce be determined by the factors which shape PC adoption?

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