Diffusion of Information and Communication Technologies to Businesses

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Abstract

We survey the literature on the adoption and diffusion of information and communication technologies (ICT) in businesses. We identify two key dimensions that have been the focus of most of the literature. First, research can be categorized as focusing on ICT adoption costs or ICT adoption benefits. Second, research can be categorized as focusing on how adoption is influenced by either the internal organization of the firm or by the external environment. Major themes are highlighted as are opportunities for future research.

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1. Introduction

The invention of new technology is only the first step in economic progress. To contribute to economic growth, new technology must first be used in the course of productive economic activity. However, new technology often diffuses unevenly across economic agents. Such variance in adoption rates is important, as it influences the rate of technological progress. It may also be a source of sustainable competitive advantage (Mata et. al. 1995).

Research on information and communication technology (ICT) diffusion to businesses seeks to understand why firms adopt ICT at different rates. Researchers attempt to identify and measure characteristics of the organization and its environment that influence the barriers to ICT investment and the benefit of ICT investment to the organization. By investigating how business characteristics shape ICT investment decisions through their impact on (unobservable) costs and benefits of adoption, this literature is complementary to business-value research, which seeks to identify how observable ICT investment decisions influence observable gross benefits. This line of research is important to understanding the fundamental question in the information systems literature of "Why do some organizations succeed with their information technology investments while others do not?" (Dhar and Sundararajan, 2004).

This review examines research on the diffusion of ICT to businesses. Because of the breadth of this field, we limit the scope of our review in several ways. First, we focus upon recent research on ICT that facilitates communication within and across firm boundaries. Internet technology is one common example of such technology, but it is not the only one.[1] Information technologies with data processing functions but no communications functions are not considered. By lowering the costs of communications, ICTs improve the monitoring and coordination capabilities of organizations. Moreover, they will be most susceptible to network effects: the value of the technology will be increasing in the number of other users. A large theory literature has studied how the communications capabilities of ICT will alter the

[1] Other examples include electronic data interchange (EDI) and automated clearing house (ACH) technology in banking, both of which involve communication that does not occur over the Internet backbone.

organization of firms (Marschak, 2006), their interrelationships (Spulber, 2006), and their location (Gaspar and Glaeser, 1998). Due largely to data constraints, empirical testing of these hypotheses has only been possible over the past 15 years. This review will examine recent advances made in this empirical literature, and highlight areas for future research.

Moreover, we will focus attention upon ICT that involves significant costs of adoption at the organizational level.[2] Thus, our review generally excludes technologies such as cell phones that have significant infrastructure costs but which involve little idiosyncratic adaptation costs at the organizational level to be used successfully. As in any review article, the content of our discussion will be shaped by the extant literature. Thus, our review will include detailed discussion on EDI but less on newer technologies such as RFID for which the literature is presently small.

Last, we examine ICT diffusion through the lens of economic analysis. Economic analysis offers a rich theoretical framework for understanding the diffusion of ICT. Moreover, the increasing availability of micro data has lead to rapid growth in this field. We consider this review to be complementary to other excellent review articles in the information systems (IS) literature that have focused on the diffusion of IT through an organizational lens (Fichman, 1992, 2000), or to research in economics that has reviewed the literature on the diffusion of other technologies (Hall and Khan, 2003). By focusing on the economic analysis of ICT diffusion to businesses, we address a growing area of the literature that has not recently been reviewed.

Table 1 provides an overview of some of the major questions in ICT diffusion research and our framework for addressing them in this paper. Research in this area can be classified as exploring either how characteristics of the organization or of its external environment shape the (net) benefits of ICT adoption. Further, as noted above, some characteristics influence primarily the costs and some influence primarily the benefits of adoption (and some influence both). In Table 1 we classify some of the major questions in diffusion research along these two dimensions, and then indicate with section numbers where research on these questions can be found in the paper.

[2] The main exception is section 7, in which we examine country-level diffusion of Internet technology.

Following the introduction, we begin in section 2 by describing the empirical models that are commonly used in the economic analysis of ICT diffusion, and provide a summary of recent work that examines the economic outcomes from ICT investment.

Sections 3-7 constitute the main body of the paper. In section 3 we describe how organizational characteristics influence the rate with which firms adopt ICT. Some research in this area focuses on the adaptations needed by organizations to successfully implement ICT, the costs of these adaptations, and how firms overcome them. Other research examines the relationship between ICT adoption, organizational characteristics, and individual incentives. In particular, an evolving body of work seeks to understand how the location of firm boundaries and internal decision-making rights influence the speed of ICT adoption.

Section 4 through 7 review literature that examines how an organization's external environment influences the decision to adopt ICT. Section 4 describes how the geographic location of a firm affects the speed of ICT adoption. In particular, we emphasize recent research that examines whether the communications capabilities of ICT imply that the marginal benefit to ICT adoption is highest in rural areas. Section 5 explores research into the extent to which internal and external factors jointly influence an organization's decision to adopt ICT. Section 6 shows how network effects shape the pattern of ICT diffusion. Though prior literature has begun to identify the role of network effects on the diffusion of new technologies, new data sets offer opportunities to draw a tighter link between theory and evidence than has previously been possible. In section 7 we review research on cross-country differences in the speed of Internet technology diffusion. Here we change focus somewhat from the micro-level determinants of firm adoption to macro-level factors that shape differences in country-level ICT diffusion. Moreover, in this section we focus primarily on the diffusion of Internet technology because of the important policy implications of this research.[3] Section 8 concludes.

[3] Because of the different unit of analysis (country versus organization), cross-country differences in Internet use are not included in the framework in Table 1.

2. ICT Diffusion and its Impact

2.1. Diffusion Modeling

Before examining the economics of ICT diffusion, it is necessary to give a brief overview of diffusion research methodology. An excellent literature review of diffusion modeling in economics is Stoneman (2002). In this section we provide an overview of diffusion modeling, highlighting some of the common themes that will appear in our analysis of ICT diffusion.

Adoption is the individual-level decision to use a new technology. Diffusion is the aggregation of a number of adoption decisions. Rogers (1995, p. 5) defines it as “the process by which an innovation is communicated through certain channels over time among the members of a social system.” Diffusion research is then concerned with finding patterns across a large number of adoption decisions.

The earliest economic models of diffusion were epidemic models. These models assumed that the diffusion of new technology is like that of an infectious disease. Non-adopters adopt a new technology when they come into contact with adopters and learn about the new technology. Over time, the number of users increases, leading to an increased probability of any given non-adopter learning about the technology. This increases the rate of diffusion. As more people adopt, the number of non-adopters declines, which decreases the rate of diffusion. This pattern of diffusion leads to the common S-shaped curve on the rate of technology diffusion with respect to time (see Figure 1).

The first modern technology diffusion study was Ryan and Gross (1943). They used an epidemic model to study the diffusion of hybrid corn to Iowa farmers and find that social networks matter. Methods for measuring epidemic effects developed around the same time in sociology and economics. Sociologists Coleman, Katz, and Menzel (1957) were among the first to use epidemic diffusion models outside of an agricultural setting. Their work examined physician choices of new drug prescriptions.

Epidemic models are commonly used to help forecast the rate of aggregate technology diffusion. Bass (1969) uses an epidemic model to help predict the rate at which a product will diffuse.[4] The central themes of these models—communications and social networks—are also prominent in recent economic research on technology diffusion. In section 6.2, we discuss papers that have examined how these themes may have influenced the diffusion of personal computers (Goolsbee and Klenow, 2002), use of online grocery services (Bell and Song, 2004), and early networks such as BITNET (Gurbaxani, 1990).

As noted above, in epidemic models technology spreads through interpersonal contact and information dissemination. These models do not explicitly model the adoption decisions of individual users, nor do they allow for differences in the costs and benefits of adoption by different members of the population. As a result, these models omit many important aspects of economic behavior. Later models explicitly include these elements.

Probit (or rank) models emphasize population heterogeneity. Pioneered by David (1969), the most basic model assumes that the entire population has perfect information about the technology. Individuals (or firms) adopt the technology when the net benefit of adopting is positive. Since the probit model is the one most commonly used in economic diffusion modeling, it is worthwhile to consider it further. In general under the probit model, an establishment *i* will adopt a new ICT at time *t* if the following conditions hold:

$$NB(x_i,t) \equiv B(x_i,t) - C(x_i,t) > 0 \tag{1}$$

$$NB(x_i,t) > NB(x_i,t')/(1+r)^{t'-1} \quad \forall t' \neq t \tag{2}$$

where *NB* is the net benefit of adoption, *B* is the gross benefit of adoption, and *C* is the cost of adoption. All functions represent the present value of profits discounted to time *t.* We let x_i be a vector of firm characteristics that influence the value of adopting the new technology. These equations say that a firm will adopt if two conditions hold—first, that the expected benefits less expected costs (or net benefits) are

[4] Fichman (2000) refers to epidemic models used to forecast the rate, pattern, and extent of technology diffusion as "diffusion modeling studies." For surveys of such studies, see Mahajan, Muller, and Bass (1990) and Mahajan and Peterson (1985).

positive, and second, that the net benefits of adopting at time *t* are greater than the net benefits of adopting any other time $t' \neq t$. A technology diffuses throughout the population because either the benefits of adopting are increasing over time (due, for example, to improvements in the technology as a result of technological change), $\frac{\partial B(x_i,t)}{\partial t} > 0$, or because the costs of adoption are declining, $\frac{\partial C(x_i,t)}{\partial t} < 0$. Most diffusion papers are unable to separately identify benefits and costs and instead identify $\frac{\partial NB(x_i,t)}{\partial x_i}$, the change in the net benefits to adoption that occur as a result of changes in firm characteristics. As Hall and Khan (2003) note, due to high sunk costs of adoption, adoption is usually an absorbing state. That is, we rarely observe organizations "unadopting" a new technology, and analysts rarely worry about this decision in their econometric modeling.

The basic probit model underlies any diffusion modeling that explicitly considers agents' tradeoffs between the costs and benefits of adopting, and it is the workhorse for many of the models we discuss in sections 3-6.[5] However, in contrast to epidemic models, the probit model examines exclusively how internal firm factors shape the benefits to adoption and assigns no role to the behavior of other users. Clearly this may be too limiting. Recent economic models of ICT diffusion have extended the probit model to allow a role for other users' behavior.

In addition to epidemic and probit models, Karshenas and Stoneman (1993) consider two ways in which other users' behavior may influence technology adoption, which they term stock and order effects. Stock models argue that if new technologies are cost-reducing, they will increase the output that a firm produces. As a result, increasing adoption of new technologies eventually decreases the profits of adopters and non-adopters alike. Under certain conditions, the difference in profits between adopters and non-adopters declines over time (Reinganum, 1981), leading to decreasing net benefits from new technology adoption. Stock models assume that the profits among all adopters are identical -- as are the profits among all non-adopters. In contrast, order models assume that the benefits of new adoption

[5] In section 7 the unit of analysis is frequently the country, making it more difficult to identify the underlying economic model that is generating the observed empirical pattern.

decrease monotonically with the number of prior adopters. Despite this, early adopters continue to benefit disproportionately from the technology (Fudenberg and Tirole, 1985). The intuition behind why early adopters enjoy higher profits than later adopters is that there may be first-mover advantages to adoption, due, for example, to the ability of early movers to capture scarce inputs such as labor (Ireland and Stoneman, 1985).

Order and stock effects are examples of negative *network externalities.* That is, the benefits of adopting a new technology are declining in the number of other users. However, the benefits of adopting a new technology can also increase as others adopt, generating positive network externalities.[6] Positive network externalities can further be categorized as direct or indirect. The telephone provides an example of a *direct* positive network externality: the value of adoption relies explicitly on the value of communicating with other users. Alternatively, positive network externalities may be *indirect*, as in the case of video game consoles such as the Sony Playstation: the value of adoption increases in the adoption by other users because of the increased availability of a complementary good (games). Recent research has attempted to understand how direct and indirect network externalities shape user adoption behavior; however the econometric identification issues in this research are daunting. A finding of a statistical correlation between one user's adoption and another's may reflect network externalities. Alternatively, it may reflect unobserved characteristics that are common across users and which increase the value to adoption. In section 6.3 we discuss the conditions under which these models are identified.

The main review of diffusion research in fields other than economics is Rogers (1995). Emphasizing communications and sociology, Rogers focuses on the role of communications networks in technology diffusion. He details the process through which innovations move from one population to another and discusses the role of five key factors in the individual decision to adopt: relative advantage, complexity, compatability, trialability, and observability. He emphasizes that these factors are only relevant after informative contact with the innovation, and much of this work focuses on the roles of different communications networks in initiating this contact. This contact is achieved by a "change

[6] The description at the beginning of section 6 provides further details on positive network externalities.

agent." The change agent brings an innovation into a new social network and can effectively communicate its benefits. Managers aiming to generate technology adoption should think of themselves as change agents. In their emphasis on how characteristics of the adopter or technology shape the value of adopting, the five key factors are similar to the emphasis on heterogeneous adoption benefits and costs in the probit model. Moreover, Rogers' emphasis on communication and change agents are analogous to the importance of information transmission in epidemic models of diffusion.

2.2. The Impact of ICT Diffusion

There is considerable evidence that ICT investment has a positive impact on firm performance. One line of research has demonstrated using microeconomic production theory that ICT investment had a large impact on company behavior and productivity in the late 1990s. For example, Oliner and Sichel (2000), Jorgenson and Stiroh (2000), and Baily and Lawrence (2001) credit ICT with the rapid growth of the U.S. economy in the late 1990s. Stiroh (2002a) argues that this productivity acceleration was broad-based and finds an increase in productivity related to ICT use in nearly two-thirds of industries from 1995 to 2000. Baily and Lawrence (2001, p. 308) claim about the 1990s, "In particular, there has been a substantial structural acceleration of total factor productivity outside of the computer sector. And there is clear supportive evidence of an acceleration of productivity in service industries that are purchasing [ICT]." In another study of ICT and productivity growth in the 1990s, Brynjolfsson and Hitt (2003) use firm-level data to find that substantial long-term productivity gains result from ICT use.[7] Although these studies focus on the role of generic information technology investment, recent work has demonstrated a link between computer networking and acceleration in establishment-level productivity (Atrostic and Nguyen, 2002; Stiroh, 2002b).

Another line of work has examined how adoption of ICT improves business processes. This "process-oriented" framework (Barua and Mukhopadhyay, 2000) examines the relationship between ICT

[7] For firm-level evidence on the productivity benefits of ICT investment from an earlier time period, see Brynjolfsson and Hitt (1996).

and intermediate process-level variables that are more closely related to ICT investment than the measures of output, sales, or value-added that are traditionally used in production theory studies. For example, Mukhopadhyay and several co-authors have examined the impact of ICT investment on supply chain performance (Mukhopadhyay, Kekre, and Kalathur, 1995; Srinivasan, Kekre, and Mukhopadhyay, 1994; Mukhopadhyay and Kekre, 2002). Hubbard (2003) shows that on-board computers increase efficiency in trucking. Athey and Stern (2002) document the role of ICT in improving emergency health care response outcomes.

Recent research has argued that the link between IT adoption and firm performance will depend on usage. Using data on hospitals, Devaraj and Kohli (2003) argue that ICT use is a much better predictor of performance than is ICT adoption at the firm level. Many firms adopt a technology on the surface, but, unless it is frequently and properly used, it will not have a positive impact and may even have a negative one. We review recent research that has examined IT usage separately from IT adoption in Section 3.5.

In summary, ICT has had an important impact on productivity at both the micro and macro levels. The rest of this paper details patterns in ICT diffusion. We first look at how organizational characteristics influence technology adoption. We then examine the external environment in sections 4 through 7.

3. ICT Adoption and Organizational Characteristics

The decision to adopt a technology can be influenced by factors relating directly to the firm. In this section we consider how organizational characteristics influence ICT adoption.

3.1. Adoption, Internal Firm Organization, and Organizational Change

Bresnahan and Trajtenberg (1995, p. 84) define general purpose technologies (GPTs) as "enabling technologies, opening up new opportunities rather than offering complete, final solutions." Several authors have argued that ICT is a GPT (e.g., Bresnahan and Greesnstein, 1996; David, 1990;

Harris, 1998; Forman, Goldfarb, and Greenstein, 2005).[8] A GPT is an enabling technology that can be deployed in a multitude of ways in many sectors of the economy. However, adapting these general solutions to the needs of individual industries and idiosyncratic users often poses great challenges for organizations.

A large case-study literature has detailed the challenges of implementing general ICT systems to fulfill organizational needs. This case-study literature has shown there to be significant technical development risks when implementing new ICT systems in firms (e.g., Kemerer and Sosa, 1991). Moreover, organizations face significant challenges in adapting business processes and organizational routines to new ICT systems (e.g., Attewell and Rule, 1984; Davenport, 1998; Scott Morton, 1991). Finally, new ICT systems may require a different skill set than may have been previously available, requiring either additional education or skills (Autor, Levy, and Murname, 2002; Levy and Murname, 2004), or they may also be "de-skilling," requiring workers to be less skilled than previously. Despite this rich case study literature, there remains relatively little empirical adoption research in this area that applies an economic perspective. The main work in this area has, instead, explored theories of organizational change.[9]

New information technology often changes the organization of work within firms. Beginning with Leavitt and Whisler (1958), a long-running question within the information systems field is how improvements in information-processing capabilities change the optimal location of decision rights within organizations. Improvements in information-processing capabilities can decrease monitoring costs, leading to lower agency costs when delegating decision-making rights. However, lower costs of information transmission can also lower the costs of centralizing information within the organization by improving the quality and speed of information processing (Gurbaxani and Whang, 1991). A rich case-study and small-sample empirical literature has found support for both hypotheses within the context of

[8] Examples of other historical GPTs include the steam engine (Rosenberg and Trajtenberg, 2004) and the dynamo (David, 1990).
[9] For recent exceptions, see the discussion on research on co-invention in section 5.1. See also Doms et al. (1997) for an econometric examination of the relationship between worker skills and adoption of computer-automated design, numerically controlled machines, and programmable controllers.

information-processing IT (George and King, 1991). Marschak (2004) formalizes many of these ideas in an economic model. However, only recently have there been large-scale empirical studies that examine the relationship between ICT adoption and decision rights within firms.

Hubbard (2000) pursues this debate in the context of trucking carriers' decisions to adopt electronic monitoring technologies. He notes that monitoring ICT can create two benefits for organizations. First, it can lower agency costs. For example, on-board computers in the trucking industry can monitor drivers' speeds. Thus, such technologies increase the value of decentralization, all else equal. Second, monitoring ICT can improve the resource-allocation decisions of managers, for example by monitoring the relative locations of trucks. By lowering information transmission costs, these technologies can also increase the value of centralization. Hubbard shows that both types of monitoring technologies are adopted by trucking firms. Moreover, the likelihood that each is adopted will depend on the relative values of centralization and decentralization across different carriers.

Other research has argued that ICT is more valuable when adopted by firms that use innovative organizational and human-resource practices such as self-managing teams, flatter organizational hierarchies, and broader job descriptions that involve decentralization. Milgrom and Roberts (1990) argue that investments in new technology may have indirect effects that increase the value of utilizing such innovative practices. They say that groups of activities such as new technology investment and organizational variables are complements when an "increase in the levels of any subset of activities implies that the marginal return to increases in any or all of the remaining activities increases." Researchers in the IS literature have argued that there exist complementarities between IS design, worker incentives, and organizational characteristics (e.g., Barua et al., 1995, 1996; Barua and Whinston, 1998).

A number of recent papers have empirically tested the assertions of Milgrom and Roberts (1990). Hitt and Brynjolfsson (1997) and Bresnahan, Brynjolfsson, and Hitt (2002) use a large cross-industry study to show that decentralized decision rights, innovative human resource practices, and workplace investments in human capital are complementary with ICT investment. Brynjolfsson, Renshaw, and Van Alstyne (1997) develop a tool for managers to understand the indirect effects between ICT investments and organizational practices, and how these interactions should shape investment in new ICT. Dunlop and Weil (1996) study the use of ICT and modular assembly (team production) in the apparel industry. They find that modular production is adopted in conjunction with new communication systems like electronic data interchange (EDI) to reduce lead times and inventories.

Empirical research has tested a number of other assertions about which organizational characteristics are complementary with ICT adoption. For example, ICT adoption may be more valuable when coordination costs are high or when real-time coordination is especially valuable. Mendelson and Pillai (1998) show that firms operating in dynamic business environments need to process information more rapidly. These firms are more likely to adopt real-time communication technologies such as pagers and video conferencing, and they are more likely to have EDI connections. Dewan et al. (1998) show that firms with higher coordination costs arising from diversification or vertical integration have greater ICT investments. Banker et al. (2003) find that manufacturing plants that employ customer and supplier participation practices adopt EDI more rapidly. Forman (2005) shows that firms that are geographically decentralized adopt Internet technology more rapidly.

As noted by Athey and Stern (2003), there are significant challenges in testing theories about complementarities solely by looking at investment behavior. As a result, several researchers have sought to test theories relating ICT to human resource practices through an ICT-productivity or business-value approach. Research in this literature generally examines how ICT, organizational practices and their interaction influence labor productivity (e.g., Bertschek and Kaiser, 2004; Black and Lynch, 2001; Bresnahan, Brynjolfsson, and Hitt, 2002; Hempell, 2003) and stock market returns (Brynjolfsson, Hitt, and Yang, 2002).[10] These papers generally proceed by regressing outcome measures on ICT, organizational practices, and interactions of these variables. Research in this area has explored how ICT and labor practices influence outcomes, and provided evidence that the marginal returns to each increase with the presence of one of the others.

[10] For recent reviews, see Barua and Mukhopadhyay (2000) and Brynjolfsson and Hitt (2000). Corrado et al. (2005) provides an overview of recent work that attempts to measure the value of organizational investments.

Empirical work on ICT adoption and organizational change remains a fertile area of research. Despite a rich theoretical and case-study literature in this area, the empirical literature remains small. Hypotheses in this area typically focus on long-run effects. However, data sets that allow for testing these long-run hypotheses are rare. New research has used ICT adoption decisions to examine the influence of medium- to long-run organization-level decisions on short-run ICT adoption decisions. This allows for the identification of complementarities in the short run. In the long run, these complementarities may influence organizational decisions and outputs.

Research in this area has proceeded along two independent lines. Large cross-industry studies such as Bresnahan, Brynjolfsson, and Hitt (2002) have attempted to identify complementarities between ICT investment and organizational characteristics that are common to multiple industries. Single-industry studies such as Hubbard (2000) are able to make very precise statements about the interactions between incentives and ICT in an industry, but at the cost of generalizability. Research in this area should continue along these separate paths to more fully identify the relationships among ICT, incentives, organizational design, and outcomes.

3.2. Adoption and Firm Boundaries

In the section above we described a set of papers that analyze the relationship between ICT investment and the location of decision-making authority within a firm. ICT investment can influence firm organization in another way, by altering the costs and benefits of locating economic activities outside the boundaries of the firm.

One can classify the costs of operations into internal coordination costs, external coordination costs, and production costs (Gurbaxani and Whang, 1991). Production costs refer to the actual physical costs of producing a good or service. Internal coordination costs refer to the costs of managing activities within the boundaries of the firm. External coordination costs represent the search costs of identifying suppliers, the costs of writing contracts, and potential transaction costs arising from opportunistic behavior by upstream and downstream partners (Williamson, 1975). All else equal, market-based exchange should have lower production costs but higher coordination costs (Malone et al., 1987).

Investments in ICT can lower the costs of internal coordination; this will decrease the costs of managing large enterprises, enterprises that are geographically dispersed, enterprises that are diversified, and enterprises that are vertically integrated. However, ICT investments lower the costs of market transactions, as well, by lowering the communication and coordination costs required to undertake arm's-length transactions with external parties and by lowering the risks of opportunism on the part of trading partners (Clemons et al., 1993). Malone et al. (1987) argue that the marginal impact of ICT investment will be greater on external coordination costs than on internal coordination costs. This leads to the conclusion that ICT investments facilitate more market transactions and less vertical integration.

Empirical work that has researched the relationship between ICT investment and vertical integration across multiple industries has generally supported the assertion that ICT investment will lead to more market-based transactions. Research in this area usually proceeds by examining whether changes in the dollar value of ICT spending are associated with an increase or decrease in vertical integration. Brynjolfsson et al. (1994) use Bureau of Economic Analysis investment data to show that greater ICT investments are associated with a significant decline in average industry firm size. Hitt (1999) examines these hypotheses empirically at the firm level using a panel of 549 large firms. He explores how ICT investments influence vertical integration and internal diversification. He argues that a negative relationship between ICT investment and vertical integration implies that ICT decreases external coordination costs, while a positive relationship between ICT and diversification implies that ICT decreases internal coordination costs. He shows that ICT investment leads to a significant decline in vertical integration and a smaller increase in diversification. Moreover, he shows that increases in vertical integration lead to less ICT investment.[11]

[11] Acemoglu et al. (2004) also examine the role of general technology investment and vertical integration. They find a negative relationship between intensity of R&D and investment and vertical integration.

Other papers have explored this relationship from the other direction: do firms with greater internal and external coordination costs have greater ICT investments? Dewan et al. (1998) show that vertical integration is negatively related to the level of ICT investment, and that ICT therefore has a larger impact on external coordination costs than on internal coordination costs. They also demonstrate that diversified firms will have greater levels of ICT investment. Thus, their results are consistent with the results of Malone et al. (1987) and Hitt (1999). Kraemer, Gibbs, and Dedrick (2005) also find that firms that are more global are more likely to adopt business-to-business electronic commerce. This result may reflect higher coordination costs among global firms, but it may also reflect the effects of stronger competition or external pressure from trading partners.

While cross-industry studies have consistently found that ICT investment is associated with less vertical integration, a set of recent single-industry studies have found less consistency in this relationship. These studies have generally examined the adoption of industry-specific ICTs, as opposed to the dollar value of ICT spending. By focusing on a single industry, these studies are able to precisely examine how ICT investments influence incentives and coordination costs among firms within a particular industry environment. However, as always, this precision comes at a potential loss of generalizability.

Building on the work of Hubbard (2000), Baker and Hubbard (2003, 2004) examine the role of ICT adoption on the organization of firms in the trucking industry. They argue that while some margins of ICT investment primarily lower coordination costs, other margins of ICT investment also lower monitoring costs, improving agents' incentives. The effects of ICT on monitoring and coordination create differing predictions on how ICT will influence firm boundaries based on the margin of ICT investment and the characteristics of the firm.

Baker and Hubbard (2003) examine the decision of shippers—purchasers of trucking services—to own their own trucking fleets or to contract for carrier services. They show that adoption of certain kinds of ICT leads to more shipper ownership of trucks (vertical integration) by improving monitoring capabilities (and thereby lowering agency costs associated with complex job designs). In contrast, they also find that other margins of ICT investment enhance coordination capabilities that improve the comparative advantage of for-hire trucks, thereby leading to less shipper ownership of trucks.

Baker and Hubbard (2004) investigate how ICT investment influences the decision of truckers to own their own trucks. They show that driver ownership of trucks declines with adoption of on-board computers that improve monitoring capabilities. These on-board computers decrease the agency costs of trucker ownership by lowering monitoring costs.

Some recent single-industry studies have also examined how vertical integration influences the short-run decision to adopt new ICTs. In contrast to studies that look at the impact of ICT investment on firm boundaries, these papers have consistently found vertical integration and ICT adoption to be complements. This literature has generally focused on the contracting costs of making interorganizational ICT investments. For example, less vertically-integrated firms find interorganizational Internet investments less valuable because downstream partners may appropriate some of the surplus generated by the new investment. Moreover, ICT investments such as e-commerce that create new distribution channels may be harder to implement when retailers and producers are different firms because of potential channel conflict. In other words, while long-run studies argue that ICT investments reduce the frictions associated with market transactions, short-run studies demonstrate that such frictions can have significant effects on the speed of ICT adoption.

Forman and Gron (2005) investigate how vertical integration influences adoption of electronic commerce applications in the insurance industry. In their context, electronic commerce influences the distribution relationship between insurers and insurance agents. They argue that insurers that are vertically integrated with their agents will have lower transaction costs of adopting electronic commerce technologies. Their work demonstrates that such insurers adopt e-commerce technologies faster than similar insurers who are not vertically integrated.

Gertner and Stillman (2001) examine how vertical integration influences the incentives of apparel firms to offer their products online. In their setting, transaction costs and channel conflict each play a role in increasing the costs of Internet adoption for apparel firms that do not own the distribution channel.

They provide evidence that vertically-integrated apparel retailers who also own retail outlets such as the Gap started to sell products on-line sooner than non-integrated apparel companies like Nautica.[12]

In all, the current literature on ICT investment and firm boundaries draws on a rich array of theoretical perspectives—transaction costs economics, property rights theory of the firm, principal agent theory—and arrives at a broad array of conclusions. Although cross-industry research suggests that, on average, ICT investment may lead to smaller, less vertically-integrated firms, single-industry studies suggest there may be substantial heterogeneity in the effects of ICT investment on firm boundaries across industries and technologies. More research is needed to identify the link between ICT investment, agent incentives, and organizational outcomes. Moreover, prior research has identified some differences in the short-run and long-run relationship between ICT and firm boundaries. To the extent possible, future research should explore how this relationship changes as organizations adopt, implement, extend, and maintain new ICT innovations.

3.3. Adoption and Size

Prior research in the diffusion of innovations literature has consistently shown a positive relationship between organization size and innovativeness (Rogers 1995). The most common reasons offered for this relationship are economies of scale (Kimberly and Evanisko, 1981), slack resources (Eveland and Tornatzky, 1990), access to outside resources (Attewell, 1992), and ability to bear adoption risks (Hannan and McDowell, 1984).

Recent work on ICT adoption has continued to show a positive relationship between firm size and adoption. Large-scale descriptive studies on Internet use have shown that even as late as 2000, adoption of basic Internet technologies such as email varies with establishment size, and that small establishments rarely adopt complex technologies such as e-commerce (e.g., Census 2002; Charles, Ivis, and Leduc,

[12] Helper (1995) and Lane (1991) have also found a positive relationship between relationship “closeness” between suppliers and buyers and general (non-IT) technology adoption. These papers focus on how tighter relationships between upstream and downstream firms increase the stability of demand and thereby decrease the risks of new technology adoption.

2002; Forman, Goldfarb, and Greenstein, 2002).[13] Academic research has also shown a positive relationship between size and ICT adoption (e.g., Astebro, 2002; Banker et al., 2003; Forman, Goldfarb, and Greenstein, 2006; Hubbard, 2000; Kauffman et al., 2000).

Measures of size are typically included as a control in recent research on firm adoption of ICT. However, the theoretical reasons for why size influences adoption are not widely understood. Empirical research has been unable to inform theory because of the difficulty in separately identifying the various explanations for this phenomenon. This prevents researchers from making strong statements about why size influences technology adoption. One notable exception is Astebro (2002, 2004), who demonstrates that faster adoption of computer-aided design and computer numerically-controlled machine tools among large manufacturing plants is due to the large non-capital investment costs such as learning that are required to use these technologies. Future work should seek to further understand how and why size influences technology adoption.

3.4. Technical Infrastructure

Some research has also emphasized how prior IT investments influence the value of adopting new ICT. Tornatzky and Fleischer (1990) list technological context as one of the key aspects of a firm's adoption decision in their TOE framework.[14] Because prior work has found that IT investments can also capture organizational differences (e.g., Bresnahan and Greenstein, 1996; Forman, 2005), we include technical infrastructure under organizational characteristics in our framework.

Technical infrastructure can influence the value of new technology adoption because compatibility with new innovations influences the costs of adoption. Rogers (1995) lists compatibility as one of his five key factors influencing an individual's decision to adopt new technology. However, prior investments in hardware and software can also proxy for an organization's overall technology

[13] A similar relationship has also been found in the adoption of knowledge management practices. See, for example, Kremp and Mairesse (2004).
[14] The TOE framework identifies three key components that influence an organization's technology adoption decision: technological context, organizational context, and environmental context.

competence (Bharadwaj, 2000) or technological sophistication (Raymond and Paré, 1992). Technological sophistication reflects the number and diversity of information technologies used by organizations, and is a key component of IT sophistication (Raymond and Paré, 1992). Iacovou et al. (1995) note that organizations with high levels of IT sophistication are less likely to feel intimidated by technology and are more likely to have access to the technological and managerial resources necessary to adopt new technologies. Other empirical research has also demonstrated that IS departments with higher levels of technical competence or more recent infrastructure investments are more likely to adopt new ICT (e.g., Forman, 2005; Zhu et al., 2003; Zhu and Kraemer, 2005). However, Forman (2005) and Zhu et al. (2006) have shown that if such investments are specific to prior generations of ICT, they may in fact slow adoption.[15]

3.5. Adoption, Assimilation, Intra-Firm Diffusion, and Usage

The adoption of new ICT involves four separate decisions that may occur at separate time periods. One decision is simply whether to adopt ICT at all. This is the decision most commonly studied in the literature on ICT diffusion, and is often labeled inter-firm diffusion (Battisti and Stoneman, 2003, 2005). The second decision involves which capabilities of an innovation to use—variously labeled infusion (Cooper and Zmud, 1990), assimilation (Fichman and Kemerer, 1997, 1999), and depth of adoption (Astebro, 2004). The third decision refers to the rate at which new technology displaces old within the organization, and has been labeled intra-firm diffusion (Astebro, 2004; Battisti and Stoneman, 2003, 2005). The fourth decision is the individual-level long-term decision of how often to use the technology.[16]

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[15] Prior investments in related technologies can also create switching costs that can influence IT vendor choice. For more on empirical research in this area, see Chen and Forman (2006), Chen and Hitt (2006), Forman and Chen (2005), and Greenstein (1993).

[16] These distinctions are only relevant if assimilation costs, intra-firm diffusion costs, and usage costs are not perfectly anticipated by the firm. If firms have perfect foresight, then the issues relating to these factors can be mapped back into the first decision on firm-level adoption.

Recent research has explored the relationship between the first two decisions: that is, the extent to which an organization may not fully assimilate or deploy all of the features of an ICT innovation once the organization adopts it. In most survey-based research, organizations report whether they have a particular application installed. However, patterns of assimilation may differ systematically from that of installation if there exist significant post-investment costs of using new ICT and if these costs are unknown or uncertain *ex ante* to potential adopters (Fichman and Kemerer, 1999). Empirical work examining process innovations such as software development tools or CAD/CNC tools has demonstrated that these differences exist and can be significant (Fichman and Kemerer, 1999; Astebro, 2004).

As a result, some argue that researchers should focus on technology assimilation rather than adoption (Fichman and Kemerer, 1997, 1999). For example, Fichman and Kemerer (1997) show how related and unrelated knowledge and learning economies influence the assimilation of software process innovations, while Zhu and Kraemer (2005) demonstrate how technology competence, financial commitment, competitive pressure, and regulatory support influence e-business use. Because assimilation is a newer concept, little is known about how the factors influencing assimilation differ systematically from those influencing adoption. Astebro (2004) shows that plant size and learning costs influence adoption of CAD/CNC tools more than they do assimilation. Cooper and Zmud (1990) show that task-technology fit plays an important role in understanding whether an organization adopts Manufacturing Resource Planning but is less successful in explaining assimilation.

The third area of research on ICT diffusion examines the rate with which new technology displaces old within an organization, termed intra-firm diffusion. Research in technologies as diverse client/server computing (Bresnahan and Greenstein, 1996; Ito, 1996), CNC tools (Battisti and Stoneman, 2003, 2005), electronic mail (Astebro 1995), and videoconferencing (Kraut et al., 1998; Tucker 2005) have shown a significant lag between initial adoption and widespread diffusion within an organization. Depending upon the innovation, the internal spread of new ICT innovations may be driven by individual user adoption decisions or by organization-level capital stock adjustment decisions. This distinction has important implications for the factors driving intra-firm diffusion, and for the modeling technology used by the econometrician. User studies in this area have examined how social networks and network externalities influence user decisions to adopt new communication technologies (Astebro, 1995; Kraut et al., 1998; Tucker 2005).[17] [18] In contrast, studies that examine firm-level capital adjustment patterns have emphasized adjustment costs (Bresnahan and Greenstein, 1996; Ito 1996), as well as the importance of available complementary technologies and managerial techniques (Battisti and Stoneman 2005).

The fourth area of research relates to individual-level long-term usage within the firm. Behavioral and psychological approaches are particularly important in this area. In particular, much of this research draws upon the "Technology Acceptance Model (TAM)", based on the Theory of Reasoned Action from social psychology (Davis, 1989; Davis et al., 1989). The TAM model predicts that perceived usefulness and perceived ease of use are key to predicting long-run usage. The idea is that factors that influence behavior, such as user characteristics and system design, do so indirectly through attitudes and subjective norms.

The TAM has proven to be a robust model that is frequently employed to study user acceptance of information technology—as of January 2005, the Social Science Citation index reported 511 citations for Davis et al. (1989). It has also inspired several extensions. Szajna (1996) improves on the details of the model and provides further tests. Venkatesh and Davis (2000) extend the TAM model to explain perceived usefulness and ease of use in terms of social influence and cognitive instrumental processes, naming their model TAM2. Kim and Malhorta (2005) show that belief updating, self-perception, and habit help explain usage behavior when added to the TAM.

Most research on assimilation, intra-firm diffusion, and usage has been able to demonstrate that there are significant differences in the factors influencing adoption versus these various subsequent decisions. Despite the challenging data requirements, recent gains have been made in this area. Goldfarb and Prince (2005) show differences in Internet adoption and usage patterns at the household level. Their

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[17] We discuss the role of social networks in technology adoption further in section 6.
[18] A related literature on media richness theory has explored user choice of different communication media, and how this choice is shaped by communication needs and the characteristics of the media. See, for example, Daft and Lengel (1984), Daft et al. (1987), Markus (1994), and Hinds and Kiesler (1995).

work demonstrates that the demographic characteristics of early adopters are very different from those of heavy users. Battisti and Stoneman (2003) note, however, that our knowledge of this process is much less developed than our knowledge of inter-firm diffusion. As a result, this is an important area for future research.

4. Geographic Differences in Adoption

In the previous section, we described how ICT can reshape the nature of contractual relationships along the value chain. Until recently, a somewhat less-explored notion is how ICT can alter the geographic dispersion of economic activity.[19] The open question is whether ICT leads to more or less concentration in economic activity; that is, whether ICT is a complement or substitute to urban agglomeration. Research in this literature commonly examines whether ICT adoption and use is more or less common in cities. Less commonly, research in this literature has also examined whether ICT use leads to clustering or dispersion in the location decisions of economic agents.[20]

One school of thought argues that ICT reduces the costs of performing isolated economic activities, particularly in rural settings, even when deployment costs are high. In this view, ICT decreases the costs of coordinating economic activity that occurs across long distances within and between firms. These distance-related coordination costs may be in addition to those arising from communication across firm boundaries (Section 3.2). For example, these costs may arise due to time lags inherent in transporting physical goods across long distances, or due to the costs of face-to-face communication among geographically separated individuals.

This hypothesis argues that the gross benefits for ICT adoption will be decreasing in the size or density of a firm's location, other things equal (Cairncross, 1997; Forman, Goldfarb, and Greenstein, 2005). There may be several potential explanations for this hypothesis. First, while all business

[19] This research builds upon the seminal work of Griliches (1957), who examined the economic factors shaped the geographic variance in hybrid seed adoption.
[20] Kolko (2002) refers to increasing clustering of economic activity as concentration, while shifts in economic activity away from places where it has traditionally been concentrated as convergence.

establishments benefit from an increase in capabilities, establishments in rural or small urban areas derive the most benefit from overcoming the disadvantages associated with a remote location. Second, establishments in rural areas lack substitute data communication technologies for lowering communication costs, such as fixed private lines. Third, advanced tools such as groupware, knowledge management, web meetings, and others also may effectively facilitate collaboration over distances. These alternative explanations all lead to the same empirical prediction: that ICT and urban agglomeration will be substitutes.

A second school of thought argues that ICT will lead to increasing concentration of economic activity. There are two reasons why ICT may lead to increases in concentration. First, increases in the size or population density of a location may increase the marginal benefit to electronic communication (Gaspar and Glaeser, 1998). This view argues that improvements in electronic communications will increase the prevalence of face-to-face meetings, thereby increasing the value of locating in cities.[21] Moreover, increases in location size will increase the availability of complementary products and services that increase the net benefits of ICT investment. For example, urban areas may offer: (1) availability of complementary information technology infrastructure, such as broadband services;[22] (2) labor-market thickness for complementary services or specialized skills; and (3) knowledge spillovers and earlier access to new ideas (Duranton and Puga, 2004).[23] Each of these concepts leads to the same empirical prediction: ICT use and urban agglomeration will be complementary.

4.1. Adoption of ICT across urban and rural areas

[21] This view is consistent with that of IS researchers who study how different types of communication media have different levels of information richness (Daft and Lengel, 1984; Daft et al., 1987). Media such as face-to-face communication, email, and telephone communication differ in terms of feedback capability, communication channels, utilization, source, and language (Bodensteiner, 1970; Holland et al., 1976). As a result of these differing capabilities, these media may be used to transmit different kinds of information.

[22] By 1998, almost all but the poorest and most remote geographic areas were serviced by dial-up Internet Service Providers (Downes and Greenstein, 2002). Yet, broadband access was disproportionately an urban technology (U. S. Department of Agriculture, 2001; Crandall and Alleman, 2002)

[23] These are closely related to the three major reasons given for industrial agglomeration (e.g., Marshall, 1920; Krugman, 1991).

Adoption papers in this literature generally proceed by examining differences in ICT use across urban and rural areas. However, as noted above, differences in location may affect the value of ICT in several ways. A major challenge for empirical papers in this literature is to identify how these competing forces simultaneously shape geographic variation in ICT adoption and use.

Using a large survey of Internet use among U.S. firms, Forman, Goldfarb, and Greenstein (2005) show that, on average, firms in large cities adopted Internet technology faster than those in small cities or rural areas. However, they demonstrate that this pattern is due in part to the disproportionate presence of ICT-intensive firms in large locations. Controlling for industry composition, they find a very different relationship between location size and ICT adoption. They show that use of Internet technology for basic purposes like email or web browsing is more likely in rural areas than in urban areas, other things equal. This is particularly true for technologies that involve communication between establishments, which are associated with ending economic isolation. However, use of frontier Internet technologies is more common in cities, even with industry controls. This is particularly true for Internet technologies used for within-establishment communication. They argue that this pattern is consistent with better complementary resources in cities to help overcome the co-invention costs for complex Internet technology.

Sinai and Waldfogel (2004) examine how location shapes the use of Internet technology among individuals. Like Forman, Goldfarb, and Greenstein (2005), they find evidence of both complementarity and substitutability between Internet use and cities. In particular, they provide evidence of increasing availability of local online content in large cities. Individuals use the Internet more when there is more local content; however, controlling for content, individuals in large markets use the Internet less. On balance, there is no systematic relationship between Internet use and geographic location.

In contrast, examining individual use of electronic communication technologies among French firms, Charlot and Duranton (2006) find increasing use of all electronic communication technologies within cities. This is consistent with evidence found in Gaspar and Glaeser (1998).

Research that has examined investment in Internet infrastructure among suppliers of Internet services has also found a complementary relationship between city size and ICT investment. Kolko

(2000) shows that domain name registrations are especially prevalent in medium and large cities. Downes and Greenstein (2002) and Greenstein (2000) show that, in the mid 1990s, one important barrier to Internet adoption was local availability. Internet access was simply not available in isolated areas. By 1998, however, almost all areas had access, and by 2000 almost all had more than one provider in their local market. Availability ceased to be a barrier to adoption. Augereau and Greenstein (2001) find evidence of an urban bias in the adoption of high speed enabling Internet technology—56K modem and ISDN—among Internet service providers in the 1990s. This bias likely reflects the impact of larger local market demand and greater local competition on the incentives for suppliers of Internet services to invest in new ICT.

4.2. Evidence of how ICT use influences location patterns

A related question asks how the adoption of ICT influences the location decisions of firms. Given that widespread interorganizational communications are a relatively new phenomenon, it has been difficult to test this hypothesis using current data because insufficient time has elapsed to understand how ICT use influences firm location decisions. However, a small number of papers have begun to investigate this important question.

Kolko (2002) defines employment convergence as the tendency for an industry to become more uniformly distributed geographically over time. He shows that while there exists an overall trend toward employment convergence, ICT-intensive industries exhibit slower convergence than others. However, he also demonstrates that slower convergence is not due to ICT usage per se, but rather is because ICT-intensive industries tend to value more highly the complementary resources found in cities. In particular, ICT-intensive industries hire more highly-educated workers who are disproportionately found in cities. Controlling for labor market effects, he finds that the direct effect of ICT use is to speed convergence.

Fitoussi (2004) argues that ICT adoption might allow firms to relocate employees to remote locations. Alternatively, it might make local assets even more important if ICT and face-to-face communication are complements. Based on a sample of Fortune 1000 manufacturing firms, he shows that there is unlikely to be massive relocation due to the advent of the Internet. He also finds that Internet use does induce cost saving through reduced communication costs.

4.3. Future Research

The relationship between ICT adoption and firm location remains a fruitful area of research. Although the studies above have provided some useful findings on this subject, they have only scratched the surface. These papers demonstrate a variety of different relationships between ICT use and location size, depending on the use of the technology, its complexity, and the importance of complementary resources that depend on market scale. More research is needed on different technologies in different settings in order to understand exactly what features of a location shape ICT use.

Future work should also investigate how ICT use affects the long-run location decisions of firms and the agglomeration of economic activity. For example, inexpensive communications may mean that establishments relocate from high-cost, high-density areas to low-cost, low-density areas. These remain open questions, however. Further work should compare the location decisions in industries where interorganizational ICT use is prevalent with those in other industries. This will help complete the picture of how the Internet affects geographic variance in productivity and employment.

Furthermore, future work should continue with regard to how pooled local resources influence ICT investment decisions. These resources have the potential to significantly alter co-invention costs by providing access to highly skilled resources that firms may not have internally. For example, one open question is how the thickness of local labor markets and third-party services firms influences the ability of firms to overcome co-invention costs. A further question is when do firms rely on external channels to overcome co-invention costs and when do they choose to use internal resources. Forman, Goldfarb, and Greenstein (2006) represent one step toward addressing this question.

Finally, increasing use of ICT may eventually decrease the costs of using externally sourced resources such as ICT services firms. This premise lies behind much of the recent movement to ICT and business-process offshoring. Surprisingly, to date there has been no systematic empirical work that has examined this issue. This represents an important area for future research.

Research on urban/rural differences in technology usage has important public policy implications. Rural areas are often the recipients of telecommunications subsidies. The argument for subsidizing rural areas relates to the high fixed costs of building telecommunications infrastructure in low-density areas. If there are positive externalities to having the entire nation online, then subsidizing rural areas may make sense. However, the results of Forman, Goldfarb, and Greenstein (2003) suggest that firms in rural areas have already adopted the Internet in large numbers. Further subsidies would simply provide money to firms that would adopt anyway. Advocates of subsidies need to provide more compelling evidence that adoption lags in rural areas.

5. Tradeoffs between Organization and Environment

Many adoption decisions depend on the interaction of factors that are external and internal to the firm. For example, adapting GPTs to the idiosyncratic needs of organizations often relies on complementary inputs that can be obtained from inside the organization or from external sources (Bresnahan and Greenstein, 1996). Moreover, strategic decisions relating to rival actions and the optimal timing of investment relate to both internal and external factors. This section explores all of these issues.

5.1. Co-invention

Bresnahan and Greenstein (1996) argue that GPT's require complementary investments ("co-invention") to adapt general technologies to the idiosyncratic needs of organizations. Such co-invention can involve great time and expense and may involve both organizational change as well as technical adaptation of the organization. Because these changes arise within the boundaries of the organization, co-invention theory draws upon some of the same ideas on organizational characteristics that were discussed in section 3. However, co-invention theory emphasizes the role of third-parties in enabling the transformations necessary for new technology adoption. As a result, research drawing upon co-invention theory spans both the organizational and environmental perspectives on technology adoption.

In their study of the firm adoption of client/server networking technology, Bresnahan and Greenstein (1996) demonstrate that co-invention costs can be a significant barrier to technology adoption. They further demonstrate that co-invention costs are highest among high-value users because ICT is most embedded in the business processes and legacy investments in such organizations. As a result, high value users may be slow to adopt new ICT innovations such as client/server. They use this result to explain the slow conversion of many data-processing centers from mainframe to client/server technology. Though Bresnahan and Greenstein (1996) is unique as an econometric study that shows how co-invention can be used to explain firm-level ICT adoption, other studies have used co-invention to explain macro-diffusion patterns. For example, Forman (2005) argues that the rapid diffusion of Internet technologies such as access to the World Wide Web and email can be explained by their low co-invention costs. In contrast, technologies such as consumer electronic commerce or business-to-business integration require substantial co-invention, and have consequently diffused more slowly.

A technology that requires significant co-invention to be useful is likely to face resistance. Therefore, for the technology to diffuse within a firm, management must be an effective change agent. Rogers (1995, p. 346-54) argues that effective change agents have high social status and technological competence but are otherwise similar to their target group. He maintains that managerial attempts to drive technology adoption must adhere to these principles. Co-invention therefore implies that ICT adoption and usage will be particularly driven by effective management.

Co-invention can be accomplished either through innovative activity by users or by third parties. For example, third parties such as ICT outsourcing firms or Internet Service Providers may have economies of scale advantages because of their ability to spread the fixed costs of innovation across multiple clients (Ang and Straub, 1998; Greenstein, 2001). Use of third-party resources may be less costly in cities since such locations may have thicker labor markets for complementary services or specialized skills such as outsourcing. In such cases, thicker markets lower the price of obtaining workers to perform development activities in-house and/or lower the price of obtaining co-invention services such as contract programming. Forman, Goldfarb, and Greenstein (2006) show that, if third party resources are less costly in cities, adoption of frontier technology will be faster, other things equal. Wheeler (2005) shows that computer adoption is increasing in the employment of a firm's local industry even controlling for the population of a city, suggesting that these third-party resources may be industry-specific.

Firms may utilize internal or external channels or both when adapting new ICT. In other words, these channels substitute for one another (Forman, Goldfarb, and Greenstein, 2006). Forman, Goldfarb, and Greenstein show that organizations with little ICT capabilities but that are located in a city are at least as likely to adopt new ICT as similar organizations with greater capabilities but that are located in smaller areas. Thus, a variety of papers have demonstrated how co-invention costs shape the diffusion of new information technology across firms, industries, and locations.

While these papers have demonstrated the importance of co-invention to new technology adoption, relatively little work has explored how firms overcome co-invention barriers. One reason is the stringent data requirements required for such analysis. For example, to identify how ICT outsourcing influences co-invention costs, the econometrician faces the daunting task of identifying two simultaneous discrete decisions: outsourcing and adoption. In the absence of quality instruments, such analysis requires a time series of data, preferably in a single-industry setting. One such paper is Borzekowski (2004), which examines the joint decision to outsource ICT and adopt Internet technology by credit unions. Borzekowski demonstrates the importance of controlling for unobserved adopter heterogeneity, which has a significant impact on the outsourcing decision. He demonstrates that, controlling for buyer type, the decision to outsource has little effect on the Internet adoption decision.

Despite the wealth of case study evidence, there is still much research to be done in this area. With the exception of Bresnahan and Greenstein (1996), little work has examined how co-invention shapes the diffusion of other ICT. The co-invention necessary to adopt Internet technology is likely to differ substantially from that in the transition from mainframe to client/server. For example, a current challenge for many firms is the electronic integration of vertical supply chains (e.g., Reddy and Reddy, 2001). Besides the obvious technical challenges of enabling communication between heterogeneous software systems, a major challenge to these integration efforts are incentive problems related to the misuse of this information by supply chain partners. Co-invention is also likely to differ across industries and, as noted above, may be based on the location of the firm and its external environment. In other words, more work needs to explore how co-invention shapes the diffusion of ICT across different industries and locations.

In addition, more empirical work is needed to understand how firms undertake co-invention. When do firms decide to develop new ICT projects in-house, and when do they rely on third parties? Do spillovers play an important role in obtaining new ideas necessary for co-invention? How do a firm's co-invention activities evolve after initial adoption?

5.2. Strategic Issues in Technology Adoption

Firms often face strategic tradeoffs in the decision of when to adopt a new technology. A rival firm's adoption may influence its own adoption. New strategic opportunities may depend on technology adoption choices. For example, Debruyne and Reibstein (2005) show that retail investment brokers adopt ecommerce in response to similar rivals. In particular, all else equal, a particular broker is much more likely to adopt ecommerce in the quarter after its closest rival adopts.[24] In another exploration of the strategic value of adoption, Sadowski, Maitland, and van Dongen (2002) examine the Internet adoption decisions of 264 small and medium Dutch enterprises. They use a rank (logit) framework to show that adoption is not based on current strategic factors such as intensity of competition, but on potential strategic opportunities relating to future communication requirements. Management adopts the technology in anticipation of future needs.

One recent area of research in the ICT investment and adoption literature has used real options analysis to understand the optimal timing of ICT investment decisions. These studies argue that

[24] In section 6 we consider additional ways in which one user's adoption may influence the adoption decisions of others.

traditional financial analysis of IT investment projects such as NPV are inadequate for IT projects with inherently high uncertainty (McGrath, 1997). The value of such options will depend upon internal organizational and external factors.

Dos Santos (1991) makes an early case in the IS literature for why NPV analysis undervalues ICT investment projects and provides a numerical example of how real options analysis can improve ICT investment decisions. Kumar (1996) shows that, unlike financial options, the value of real options can go up or down with the variance of second-stage projects. Benaroch and Kauffman (1999, 2000) provide a case for using real options analysis to model the timing of ICT investment decisions and show how the Black-Scholes and binomial pricing models can be used for this purpose. Further, they apply an approximation of the Black-Scholes model to study a real investment decision, the Yankee 24 banking network's decision to provide point-of-sale (POS) debit card network to member firms. They further discuss the assumptions needed to use models designed for the pricing of financial instruments within the setting of an ICT investment decision, and demonstrate the robustness of real options analysis to changes in these assumptions. Other research has used Magrabe's (1978) formula for valuing the exchange of one asset for another to evaluate IT investment decisions. Kumar (1996, 1999) has used the Magrabe formula to value decision support systems (DSS). Taudes et al. (2000) uses the Magrabe formula to examine the decision to adopt SAP R/3 at a central European manufacturing firm.

Schwartz and Zozaya-Gorostiza (2003) argue that application of the Black-Scholes model involves strong assumptions that are sometimes not consistent with reality. For example, the Black-Scholes model only applies to European options, while most real options are American options since managers have discretion over when to exercise the option. Further, Black-Scholes assumes there is an underlying tradable asset, while most IT investment projects do not typically involve tradable assets. Schwartz and Zozaya-Gorostiza develop new models for valuing IT investments. They develop separate models for when managers wish to value IT projects in which they develop an IT asset and for when they wish to acquire an IT asset, depending upon the time it takes to start benefiting from an IT asset after the initial investment.

Fichman (2004) develops a conceptual model that draws from both the real options and ICT adoption perspectives. Drawing upon four streams of research from the innovation literature—technology strategy, organizational learning, innovation bandwagons, and technology adaptation—he discusses the factors that lead to increases and decreases in real options value. One potential area for future research could be to test some of these assumptions. This would require a broader cross-section analysis than has generally been used, however, and would be challenging because of the detailed data required to execute options-pricing analysis.

6. Network Effects

The term "network effect" has been used to describe a number of different phenomena in the literature. Researchers have used "network effects" to refer to three distinct concepts: direct network externalities, indirect network externalities, and social network effects.

In the economics literature, a "network effect" is another name for a positive externality. For this reason, we will refer to this type of network effect as a "network externality". There are two types of positive externalities: direct and indirect. The simplest example of a technology that exhibits direct network externalities is the telephone. If only one person owns a telephone, it has no value. The benefits of using a telephone are increasing in the number of other users. An indirect network externality exists when increasing consumption of a good leads to the provision of complementary goods.[25] For example, more people adopt a video game system when more firms produce content for it, and similarly more firms produce content for a system when more people adopt it. Another example of this type of network externality is a local Yellow Pages directory. More people use it if there are more advertisers, and more people advertise if there are more users (Rysman, 2004). While software and operating systems often display such indirect network effects related to complementary inputs such as compatible software and user skills (e.g., Gandal, 1994; Shapiro and Varian, 1999), information-processing ICT does not exhibit direct network effects. This is a key difference between information-processing IT and ICT.

[25] Rohlfs (2001) provides numerous case studies of direct and indirect network externalities.

In sociology and communications, “network effects” usually refer to the communication of ideas through social ties. The rapid diffusion of Hotmail email is an example of social network effects. New customers learned about the product from friends through email. Rogers (1995) gives a detailed literature review. These models are driven by the importance of personal interaction in learning about a new technology. As mentioned in section 2.1, epidemic models of diffusion rely on communication of ideas through social ties, though modern work generally attempts to measure social network effects using probit models. Manski (1993) discusses the difficulties of econometrically identifying social network effects separately from underlying similarities among people in the same communication network or from positive externalities.

Recent literature on ICT diffusion has focused on identifying some type of network effect, but has been unable to separately identify social network effects from network externalities. In this section, we first give a brief review of the theoretical literature on network externalities. We then discuss papers that examine network effects that may arise either from social network effects or from network externalities. These papers do not separately identify the source of network effects. Our focus in this section will be on empirical work that identifies any type of network effect using revealed preference data on adoption decisions; however we also mention some papers that use a survey-based approach. Finally, we describe the small number of papers that have identified positive network externalities in ICT diffusion using data on adoption decisions.

6.1. Theoretical Literature on Direct and Indirect Network Externalities

A large theoretical literature has developed showing the implications of network externalities. This literature has shown how network externalities can lead to under-adoption of a new technology or adoption of a technologically inferior product, and has examined at length how network externalities can influence supplier strategies, including the decision of whether to produce compatible or incompatible products. This literature is far too extensive to survey here; for comprehensive reviews see Farrell and Klemperer (2004) and Spulber (2006). Instead, we briefly review early results on how network externalities influence technology adoption, as these are the results that have been empirically tested most frequently. We also note several theory papers in the IS literature that have examined adoption of interorganizational systems (IOS). These latter works provide an interesting contrast with empirical work on the adoption of IOS, as we shall see below.

When network externalities are present, user adoption influences the utilities of past and future users of a technology; however these externalities are not internalized. In other words, the private benefits of adoption differ from the social benefits. This diversion of private benefits from social ones can engender a number of equilibrium outcomes that are not social welfare-maximizing. For example, it can create “excess inertia” when an industry is trapped in an inferior standard, and can also create “excess momentum” when users move to a new standard that “strands” users of the existing standard (Farrell and Saloner, 1986a, 1986b). Katz and Shapiro (1986) show that sponsored technologies have a strategic advantage over technologies that are not sponsored and may be adopted even when they are inferior.[26] [27]

A number of theory papers in the IS literature have looked at the role of network externalities in adoption of electronic data interchange (EDI) and other interorganizational systems (IOS). A common theme is the presence of *negative* network externalities: increases in network size decrease the value of adopting EDI. These negative externalities are similar to what Karshenas and Stoneman (1993) refer to as stock effects.[28] Riggins et al. (1994) show that in buyer-driven networks, buyers may provide a subsidy in the second period of a two-period game to encourage marginal suppliers to adopt. These latter-stage subsidies may distort first-period adoption incentives for suppliers, leading to slower network growth and lower buyer profits. Wang and Seidman (1995) also examine the impact of competitive externalities in the adoption of EDI systems. Like Riggins et al. (1994), they argue that supplier benefits from adopting EDI will be decreasing in the number of other suppliers who adopt. Also, a buyer’s profits will be increasing

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[26] A sponsor is an entity with property rights to a technology and who may make investments to promote it.
[27] Choi and Thum (1998) extend Katz and Shapiro (1986) by examining how waiting alters their conclusions. Further, they find that consumers do not appropriately value network effects and adopt too early. Au and Kauffman (2001) extend Choi and Thum’s (1998) work to explain the adoption of electronic billing and find that, due to network externalities, agents may adopt a new technology too early even when the next technology may be superior.
[28] Karshenas and Stoneman (1993) show that stock effects play little role in explaining the diffusion of CNC machine tools in the UK.

in the number of suppliers that adopt; however, the marginal profit from supplier adoption decreases monotonically with the number of adopters. They show that buyers will offer a price premium to suppliers that adopt EDI, while prices offered to non-adopters will fall from their *ex ante* levels. This leads to a concentration in the production of upstream inputs, a result that is consistent with empirical evidence showing that EDI use tends to decrease the number of suppliers that are used. They further examine conditions under which buyers may require sellers to adopt or provide a subsidy to encourage adoption.

Other research has examined how network externalities influence the adoption of other kinds of interorganizational systems. Nault and Dexter (1994) examine how franchise agreements influence electronic network size and franchise incentives for investment. Parthasarathy and Bhattacherjee (1998) find that the presence of indirect network externalities can reduce the likelihood that an adopter of online services will eventually discontinue use of the service.

While traditional theoretical work that has examined the adoption of IOS has focused on the adoption of proprietary EDI applications, new business-to-business applications based on Internet protocols create new decisions for buyers adopting IOS. Buyers can choose to adopt extranet systems that are based on Internet protocols but which maintain the “one buyer to many sellers” characteristics of traditional EDI systems. Alternatively, they can opt to join electronic markets that lower the search costs of identifying low prices but which may also provide lower incentives for suppliers to make noncontractible investments. Dai and Kauffman (2005) examine this tradeoff, finding that a buyer’s decision on an e-procurement approach will depend upon the importance of four factors: (1) lower search and operation costs; (2) the importance of information-sharing between suppliers; (3) the extent of competition in the supplier market; and (4) the desired levels of supplier relationship-specific investments.

6.2. Evidence of Network Effects of any kind in ICT

Empirical research in network effects faces two inherently challenging identification problems. First, observed statistical correlations in user behavior in cross-sectional regressions may be the result of an underlying relationship between one user's adoption decision and another's, or may simply reflect common unobserved factors that increase the likelihood that both users adopt. For example, if an econometrician observes that two firms in the same location adopt ICT, this result may be due to network effects or to unobserved lower adoption costs in that location. In the absence of long panels of data with sufficient cross-sectional heterogeneity, these alternative explanations are not usually separately identified.

Second, even when network effects are themselves identified, it is often the case that the source of the network effects are not. In this case, the term "bandwagon effects" is often used. Bandwagon effects may be the result of network externalities, social network effects, or even competitive effects. Stated succinctly, the bandwagon hypothesis argues that "the probability of adoption by a firm at a given date is positively related to the proportion of firms in the industry that have already adopted" (Jensen, 1982).

Goolsbee and Klenow (2002), Goldfarb (2006), and Bell and Song (2004) examine the impact of network effects on Internet adoption by consumers. Goolsbee and Klenow (2002) use instrumental variables estimation to examine the importance of local spillovers such as learning and network externalities on consumer home PC adoption. They show that these spillovers are connected to Internet usage and argue that this provides evidence of network effects in adoption. Though they are able to demonstrate that network effects exist, they are unable to show whether they are the result of direct externalities related to use of email or the Internet, or whether they are related to learning spillovers. In other words, they are unable to separately identify network externalities from social network effects.

Goldfarb (2006) is also able to identify network effects without separately identifying these phenomena. He shows that the impact of prior university attendance on Internet use is much higher for people who attended university in the mid-1990s than for others. This is not true of other computing technologies such as word processing. Universities may have taught students to use the Internet, suggesting a social network effect. Alternatively, network externalities may be the driving factor: students may have an extra benefit from using the Internet because they know more people online. Bell and Song (2004) find strong neighborhood effects in the adoption of online grocery services, but they do not separately identify social network effects from spurious correlation due to the fact that people with similar preferences often choose to live in the same neighborhoods.

A number of papers have examined network effects using a survey approach. Iacovou et al. (1995) develop a model using Rogers' (1995) diffusion theories to understand how organizational readiness, external pressure, and perceived benefits influence EDI adoption and examine the applicability of this framework using seven case studies. They show that external pressure from trading partners plays an important role in determining whether an organization adopts EDI. Chwelos, Benbasat, and Dexter (2001) extend this model and use it to examine EDI adoption by a group of over 300 Canadian purchasing managers. They break the effects of external pressure into four constructs: competitive pressure, dependency on trading partner, trading partner power, and industry pressure. They find that external pressure plays a significant role in explaining EDI adoption, in particular they find competitive pressure and trading partner power influenced adopter intentions. This research supported findings in earlier work on EDI adoption that found a role for competitive pressure and trading partner power (e.g., Premkumar and Ramamurthy, 1995; Premkumar et al., 1997; and Hart and Saunders, 1997 and 1998).[29]

Surprisingly, despite the extensive body of work that has examined how network effects and competitive pressure have influenced EDI adoption, relatively little work has examined how such factors influence adoption of Internet technology by firms. Currently, firms are migrating from traditional EDI to Internet-enabled supply chain applications (Saloner and Spence, 2002). Like EDI, these applications automate the transfer of information between trading partners, saving on labor costs and decreasing error rates. However, by integrating with existing enterprise applications, they also allow for the possibility of real-time knowledge of production and inventory levels of trading partners. A small number of papers

[29] For a recent example of how external pressure may influence EDI adoption as viewed through a sociological lens, see Teo et al. (2003). They show that mimetic pressures, coercive pressures, and normative pressures all have a significant influence on firm decisions to adopt EDI.

have begun to investigate the role of network effects on Internet-enabled IOS. Bertschek and Fryges (2002) find that bandwagon effects play a role in the adoption of business-to-business electronic commerce among 3000 German firms, while Forman (2005) finds they influence adoption of advanced business applications in a sample of over 6000 U.S. firms.[30] Neither is able to identify between competing explanations for bandwagon effects. Moreover, neither is able to control for unobservable differences in preferences across industries or locations. Zhu et al. (2006) use survey methods to show that network effects significantly influence firm decisions to adopt Internet-based IOS.

There exists a disconnect between the theory and empirical literatures on how competitor adoption influences the speed with which organizations adopt IOS. While theory work emphasizes how negative network externalities reduce the incremental benefit of adopting IOS for later adopters, empirical work focuses on the role of bandwagon effects, generally finding a positive relationship between competitor adoption and the speed with which an organization adopts IOS. Researchers that wish to reconcile these findings will need to identify network effects from unobserved heterogeneity.

6.3. Evidence of Positive Network Externalities in ICT

A handful of studies have separately identified network externalities from social network effects. These studies have examined adoption of enabling network infrastructure that is subject to strong network externalities but which is unlikely to be subject to social network effects.

As noted above, network externalities arise when the value for participating in the network increases in network size. Saloner and Shepard (1995) examine how network size increases the speed with which commercial banks adopt proprietary ATM technology during 1971-1979. Using the number of bank branches as a proxy for network size, they find that banks with many ATM branches adopt ATM technology earlier than banks with fewer branches (controlling for the number of depositors), suggesting the presence of network effects. Kauffman, McAndrews, and Wang (2000) examine banks' decisions to

[30] Another exception is Lee and Cheung (2004), who find that environmental factors are one of the key drivers of Internet retailing.

join the Yankee 24 electronic banking network. In contrast to Saloner and Shepard (1995), they examine how the potential size of an interorganizational banking network influences the decision to adopt a new ATM technology. They demonstrate that, other things equal, larger potential network size increases the speed of adoption; they also show that the banks with a larger investment in proprietary network technology adopt more slowly because of lower net benefits from an interorganizational network.

While the papers above attempt to identify how potential network size influences the adoption of new ICT through network externalities, a second class of papers seeks to explicitly measure the externality that arises from user adoption. Rigorously identifying whether such network externalities exist is difficult for the reasons described above. As Gowrisankaran and Stavins (2004) note, time series data are inadequate because price and costs are decreasing over time while quality is increasing. Use of cross-sectional data also presents problems since local differences may be caused by unobservable heterogeneity in supply or preferences. In general, identification is only possible when the analyst has long panels with sufficient cross-sectional heterogeneity. Gowrisankaran and Stavins (2004) utilize a panel data set to demonstrate that network externalities influence commercial banks' adoption of automated clearing house (ACH) electronic payments systems. In their application, direct network effects are likely the most important. For ACH to work, bill payers and payees have to coordinate on a method of payment, and their banks must support that method. They use three separate reduced-form analyses to demonstrate the presence of network effects: (1) fixed-effects estimation, (2) instrumental variables, and (3) a quasi-natural experiment using the adoption decisions of small, remote branches of banks.

Tucker (2005) examines how network externalities shape intrafirm adoption of videoconferencing technology. Her very detailed data enable her to measure communication patterns within a firm, and to show that network effects arise from externalities related to communication with other firm employees, rather than spillovers related to learning. Network externalities arise only for adoption by employees that communicate with likely adopters frequently. Moreover, the adoption decisions of employees who are "information brokers" that communicate directly with many other employees are most important in shaping others' adoption decisions. Moreover, she finds that the influence of network externalities varies across individuals. Tucker's research is the first in the economics literature to empirically identify such heterogeneity in the causes of network externalities and how they influence adoption behavior.

Network externalities have also played a role in the adoption of enabling Internet technologies. Augereau, Greenstein, and Rysman (2004) show how network externalities can influence users' decision of which standard to adopt. They examine the adoption of competing 56K modem technologies by Internet Service Providers in 1997. Prior to standardization by the International Telecommunication Union (ITU), these model standards were incompatible. Adoption and choice of 56K modem technology by ISPs was influenced by network effects: the value of adopting a particular model technology was increasing in the number of consumers with 56K modems and the particular technology they had adopted; however, the value of standard adoption was decreasing in the number of competitors offering the same standard. Network effects in this market operate at the local level because of flat-rate local pricing of telephone service in the US. Augereau, Greenstein, and Rysman demonstrate that network effects have a significant impact on consumers' choice of model technology in this market. Further, they show that despite these network effects, local ISP markets failed to standardize, as ISPs chose to differentiate their offerings rather than conform to a common standard. In other words, while consumer adoption of a 56K modem standard exhibited positive externalities, firm adoption exhibited negative externalities.

Research on network externalities has important implications for public policy. The positive network externalities associated with ICT imply that the private benefits to adoption may be lower than the overall welfare effect of an individual adoption decision. Subsidies then can lead to improved efficiency. Implementation of this idea, however, is difficult. If people who receive the subsidy would have adopted anyway, then the tax distortions from the subsidy may outweigh the benefits in overcoming the externality. Therefore, while there is a theoretical argument for government policy to subsidize ICT, it is difficult to implement in practice.

7. Internet Diffusion Across Countries

A number of studies have sought to understand cross-country differences in the rate of Internet diffusion. These studies argue that if Internet use has a substantial positive impact on the rate of productivity growth, then cross-country differences in Internet use can exacerbate existing income inequalities between countries. However, some authors have argued that adoption of ICT such as the Internet can offer the opportunity for late-industrializing countries to catch up with richer countries (e.g., Kagami and Tsuji, 2001, Steinmuller, 2001).

One of the most persistent findings in all of these studies is that Internet use is correlated with per-capita income: Internet technology diffuses fastest in rich countries (e.g., Comin and Hobjin, 2003; Beilock and Dimitrova, 2003; Chinn and Fairlee, 2004; Kiiski and Pohjola, 2002; Hargittai, 1999; Wong, 2002; Dewan et al., 2005). This is true even when one compares differences in adoption rates within groups of industrialized countries such as the OECD (Kiiski and Pohjola, 2002) and geographic regions such as Asia (Wong, 2002). Antonelli (2003) provides one explanation for this finding, arguing that new technological change may be "biased" in that it may increase the productivity of inputs with relatively low factor prices in the country of origin. Antonelli argues that ICT fits this profile, as it is a skilled-labor and capital-intensive technology that is unskilled-labor saving. Thus, he argues it is much better suited for developed countries such as the U.S. than for developing countries. Antonelli argues that ICT is complementary with many of the managerial and organizational changes listed in section 3.1 and that have been undertaken in the U.S. As a result, he argues that new innovations in ICT work to increase the competitive advantages of developed nations such as the U.S. James (2003) argues that ICT produced with poor countries in mind can overcome this difficulty. He argues that much of the current framework for thinking of ICT adoption is inappropriate for developing countries.

Several studies have also sought to understand how a country's governmental institutions can encourage or discourage the diffusion of new ICT such as the Internet. Comin and Hobjin (2003) and Beilock and Dimitrova (2003) argue that ICT diffuses more quickly to democratic countries and those with political freedom, while Oxley and Yeung (2001) argue that rule-of-law plays a major role. Chinn and Fairlee (2004), Hargittai (1999), Kenney (2003), and Wallsten (2003) show that telecommunications and regulatory policy are also important in explaining cross-country diffusion rates. Some studies have argued that Internet use will diffuse more quickly to countries with higher education (Chinn and Fairlee, 2004; Kiiski and Pohjola, 2002; Dewan et al., 2005). Telecommunications infrastructure also influences the rate of Internet diffusion (Beilock and Dimitrova, 2003; Chinn and Fairlee, 2004). Kiiski and Pohjola (2002) argue that Internet access prices are an important determinant of the rate of Internet diffusion. In contrast, Hargittai (1999) finds they play little role. Dewan et al. (2005) show that telephone costs influence the rate of Internet diffusion; this is particularly true at low levels of penetration.

Another factor that may influence Internet use is language. Since most web sites are in English, English language countries may have an advantage in Internet use. Several cross-country studies of the Internet have explored the role of English language use in diffusion (e.g. Hargittai, 1999, Kiiski and Pohjola, 2002); however these studies have generally been unable to uncover a systematic role for language. The role of English in Internet adoption remains an open question.[31]

Overall, the empirical evidence supports the view that, in the short run at least, Internet technology has diffused fastest to industrialized nations with greater income, more open political institutions, and with more-developed telecommunications infrastructures. At this aggregate level of analysis, these studies suggest that there is an international digital divide between rich and poor country use of the Internet. Some authors argue, however, that this divide may be narrowing over time (Dewan et al., 2005).

One challenge faced by researchers studying the cross-country digital divide is the difficulty in controlling for unobserved cross-country differences. Countries differ in complex political, cultural, and economic ways that are impossible to control for in any regression. Developed and developing countries are particularly different. Hypothesized relationships are difficult to identify because covariates may pick up other unobserved differences across countries.

[31] Other studies have examined how national cultural differences impact ICT adoption. For example, Png et. al. (2001) demonstrate in an multinational study that high uncertainty avoidance lowered the speed of frame relay adoption.

Some researchers have attempted to address the problem of unobserved country-level differences by comparing countries within similar global regions or demographics. Kiiski and Pohjola (2002) examine OECD countries, while Wong (2002) and Kraemer and Dedrick (2002) show there exists significant variation in Internet use among Asian countries.[32] While such studies must still face some residual inter-country differences, they do allow for easier comparisons among countries than studies that are not so restricted. Other studies have sought to understand how income and other factors affect the use of Internet technology at different points along the diffusion path (Dewan et al., 2005). By examining how Internet use is shaped among Internet-intensive countries and non-Internet-intensive countries, this research is able to compare Internet use among countries that are more similar, removing some of the problems of unobserved heterogeneity.

Another strategy that has been used to understand the factors influencing country-level Internet investment is to pursue case studies on individual countries. For example, Brousseau and Chaves (2004) compare the diffusion of Internet-based e-commerce technology in France to that in Denmark and Germany. One finding in their paper is that the existence of a prior e-commerce technology that preceded the Internet influenced the speed with which French businesses and individuals adopted Internet technology and the manner in which they used Internet technology. Tachiki et al. (2004) study the diffusion of e-commerce in Japan.[33] They find that *keiretsu* adopted business-to-business technologies quickly but were slower than small- and medium-sized enterprises at adopting business-to-consumer technologies.

Finally, many studies have addressed country-level differences by shifting the unit of observation from the country to the organization or, in some cases, to the individual. Some studies have examined how factors such as telecommunications infrastructure, regulatory policy, and education influence an organization's decision to adopt ICT in a single-country setting. Gandal (2006) uses this strategy to

[32] Kauffman and Techatassanasoontorn (2005) have found evidence of multinational regional contagion in the diffusion of wireless technology.
[33] For other examples of country-level case studies of e-commerce diffusion, see Kraemer et al. (2002), Tan and Ouyang (2004), Tigre (2003), Wong and Yuen-Ping (2004).

examine the role of language on ICT diffusion. He studies Internet use in Quebec, whose population speaks both English and French. He finds that Internet use among French-speaking 20-45 year-olds in Canada is significantly lower than that of similar English-speakers. Several U.S. studies have also examined how factors such as education and government policy influence Internet adoption. For example, Goldfarb (2006) examines the role of education on Internet use within the U.S, while Goolsbee (2000) shows how high local sales taxes in the U.S. made online purchasing more appealing.

While single-country econometric studies represent a useful way of examining the factors influencing Internet penetration, thus far such studies have used primarily data from developed countries. However, some research has argued that the theoretical models created for industrialized countries (and the associated empirical results) may not apply to developing countries because of differences in culture, regulatory climate, and economic environment (e.g., Austin, 1990; Rosenzweig, 1994; Xu et al., 2004). To overcome this difficulty, several studies have examined organization-level adoption of Internet technology using mixed samples of firms from developed and developing countries (Xu et al., 2004; Zhu et al., 2002; Zhu and Kraemer 2005). These studies confirm the importance of the local regulatory environment on e-business. Moreover, they also find a role for organizational factors such as firm size and scope, technology competence, and competitive pressure. More studies that include developing country data are needed.

In summary, there is considerable evidence of variance in Internet use across countries, suggesting the presence of what some authors have titled an international digital divide. Though differences in income explain most of this variance, a variety of other factors have been found to explain the residual not explained by income differences. Identifying the causes and consequences of this divide is difficult because of unobserved country-level heterogeneity and because the frameworks created for understanding diffusion in rich countries may not apply in developing countries. A number of approaches have been used to overcome these difficulties, including focused empirical approaches that look at similar countries or that look at Internet use within a particular country, and case studies that are able to explain in detail how the Internet is used within a country. Considerable progress has been made, but much more work needs to be done to resolve the conflicting evidence in the current literature.

8. Conclusion

In this review, we have examined how internal organizational factors and external factors such as geography and network effects influence business adoption of ICT. Although research on diffusion has a long and rich history, the communication capabilities of ICT have led to a number of new research topics. In particular, the rapidly developing communication capabilities of ICT over the past 20 years have given rise to new ways that ICT can influence the economic and geographic relationships between firms. Adoption research provides one lens through which to understand who benefits most from new capabilities. It examines how factors such as organizational investments, economic relationships, and geographic location shape the returns to new ICT adoption. Such studies form a useful complement to other approaches, such as business-value studies, that also explore the economic effects of ICT.

We have explored the diffusion of ICT from a variety of perspectives; however it is apparent that research has only scratched the surface on many of these topics. As noted above, one reason is that many of these questions have been driven by new developments in ICT. Tests of a technology's ability to reduce the costs of geographic isolation were only relevant with the lower costs of communication engendered by ICT in general, and the Internet in particular. Moreover, the micro data sets necessary to test many of these hypotheses have only recently become available: by its very nature, adoption research requires detailed data on a heterogeneous pool of economic agents. Our understanding of ICT adoption will continue to improve as more micro data sets become available.

This review has highlighted a number of issues that require additional exploration. While there is an understanding that internal factors matter, there is little work that provides a deep understanding of how co-invention occurs in ICT adoption. Moreover, additional research is needed to understand the relationship between ICT investment and the economic organization of firms. Research in this area would complement existing business-value work on the same topic. Moreover, additional research is needed to develop an understanding of the intensive margin of ICT investment beyond adoption. The core remaining questions about the impact of location on adoption relate to the effect of Internet use on isolated areas. Does Internet access substitute for cities? Do we see an increase in telecommuting? How does new ICT influence the location decisions of firms? The core problem with respect to network effects involves separately estimating network externalities from social network effects. This is an excellent topic for future research.

Further research is also needed to understand cross-country differences in the diffusion of Internet technology: additional empirical and case-study research that examines Internet diffusion within countries other than the U.S. would be especially helpful in this regard. Finally, there are many opportunities to study how government policy influences ICT diffusion. From India to the United States, numerous government policies have been implemented over the last ten years that aim to encourage ICT adoption. Solid empirical work estimating the impact of these policies will provide us with an important understanding of what works and why.

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Figure 1: The typical pattern of diffusion

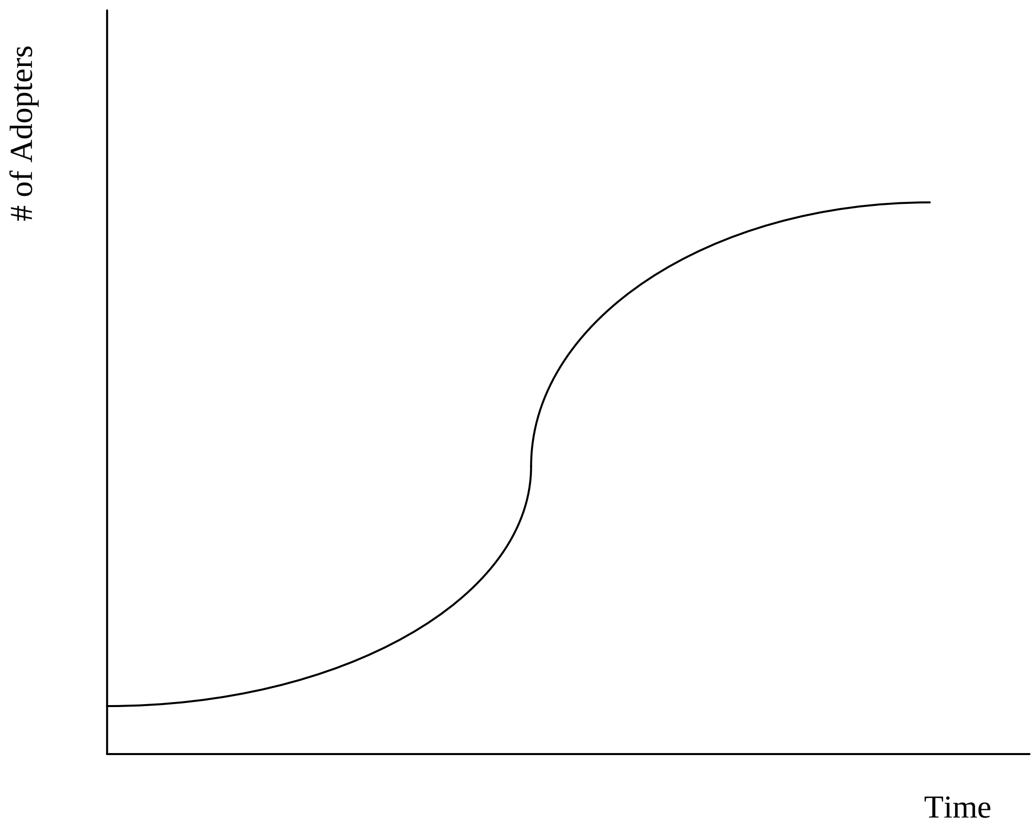

Table 1: Summary of Research on ICT Diffusion

	How Adopter Characteristics Influence the Net Benefits of Internet Adoption	
Source of variation in adopter characteristics	Adoption Costs	Adoption Benefits
Internal Organization	How do firm boundaries influence the speed of ICT adoption? (3.2) How does firm size influence the speed of ICT adoption? (3.3) How do prior investments influence the speed of new ICT adoption? (3.4) How does co-invention shape the diffusion of ICT? (5.1)	How does ICT influence the optimal location of decision-making rights within firms? (3.1) Which organizational characteristics are complementary with ICT? (3.1) How does ICT investment influence firm boundaries? (3.2) How does firm size influence the speed of ICT adoption? (3.3)
External Environment	Is ICT use a complement or substitute for urban agglomeration? (4.1) How does co-invention shape the diffusion of ICT? (5.1) Do network effects shape the adoption of ICT? (6.2) How do network externalities shape the adoption of ICT? (6.3)	Is ICT use a complement or substitute for urban agglomeration? (4.1) How does ICT use influence the location decisions of firms? (4.2) Do network effects shape the adoption of ICT? (6.2) How do network externalities shape the adoption of ICT? (6.3)

Table presents major research questions in the literature on ICT adoption classified along two dimensions: variation in adopter characteristics and how adopter characteristics influence the net benefits to adoption. Numbers represent section numbers where topics are covered.

Table 2: Summary of Research on ICT Adoption and Organization Characteristics (Section 3)

Open Question	Papers	Results
How does ICT influence the optimal location of decision-making rights within firms? (3.1)	Gurbaxani and Whang (1991); George and King (1991); Marschak (2004); Hubbard (2000); Barua et al. (1995, 1996); Barua and Whinston (1998); Hitt and Brynjolfsson (1997); Bresnahan, Brynjolfsson, and Hitt (2002); Dunlop and Weil (1996)	ICT can lead both to centralization and decentralization of decision-making rights, depending on the technology and organization characteristics. To date, cross-industry empirical work has suggested that decentralization predominates.
Which organizational characteristics are complementary with ICT? (3.1)	Mendelson and Pillai (1998); Dewan et al. (1998); Banker et al. (2003); Forman (2005)	ICT adoption is more valuable for firms that operate in dynamic business environments, firms with higher coordination costs, and firms that encourage participatory behavior by value chain partners.
How does ICT investment influence firm boundaries? (3.2)	Gurbaxani and Whang (1991); Malone et al. (1987); Clemons et al. (1993); Brynolfsson et al. (1994); Hitt (1999); Dewan et al. (1998); Kraemer et al. (2002); Baker and Hubbard (2003, 2004)	Decreases in coordination costs engendered by ICT lead to less vertical integration. However, decreases in monitoring costs may lead to more vertical integration.
How do firm boundaries influence the speed of ICT adoption? (3.2)	Forman and Gron (2005); Gertner and Stillman (2001)	Decreases in vertical integration lead to increases in frictions that slow ICT adoption, other things equal.
How does firm size influence the speed of ICT adoption? (3.3)	Kimberly and Evanisko (1981); Eveland and Tornatzky (1990); Attewell (1992); Hannan and McDowell (1984); Charles, Ivis, and Leduc (2002); Forman, Goldfarb, and Greenstein (2002, 2006); Astebro (2002, 2004); Banker et al. (2003); Hubbard (2000); Kauffman et al. (2000)	Size is positively correlated with adoption. However, most studies are unable to identify the theoretical explanation for this empirical result.
How do prior investments influence the speed of new ICT adoption? (3.4)	Tornatzky and Fleischer (1990); Bresnahan and Greenstein (1996); Forman (2005); Bharadwaj (2000); Raymond and Pare (1992); Iacovou (1995); Zhu et al. (2003); Zhu and Kraemer (2005)	Firms that have made more recent ICT investments or that have more experience with ICT will adopt faster, ceteris paribus. However, if these investments are embedded they may lead to slower adoption.

Open Question	Papers	Results
How does intra-firm diffusion differ from inter-firm diffusion? (3.5)	Fichman and Kemerer (1997, 1999); Attewell (1992); Astebro (1995, 2004); Battisti and Stoneman (2003); Battisti et al. (2004); Copper and Zmud (1990); Goldfarb and Prince (2005); Kraut et al. (1998)	There is considerable evidence that the pattern of ICT usage differs from that of adoption. However, theoretical development and empirical testing of the reasons behind these differences are at an early stage.
How do individuals use ICT once it has been adopted by an organization? (3.5)	Examples include Davis (1989); Davis et al. (1989); Szajna (1996); Venkatesh and Davis (2000); others.	The TAM model has focused on how perceived usefulness and ease of use predict long-run usage.

First column describes major questions that explore how organizational characteristics influence ICT adoption. Second column describes some of the major papers that have addressed these issues. Third column describes a generalization of the results of these papers.

Table 3: Summary of Research on Geographic Differences in Adoption (Section 4)

Open Question	Papers	Results
Is ICT use a complement or substitute for urban agglomeration? (4.1)	Forman, Goldfarb, and Greenstein (2005); Gaspar and Glaeser (1998); Duranton and Puga (2004); Sinai and Waldfogel (2004); Charlot and Duranton (2006); Kolko (2000)	Empirical work has shown that ICT can be either a complement or substitute. Depending on the technology, the benefits of ICT use can either be increasing or decreasing in location size. Cities often contain complementary resources that can increase the net benefits of ICT use.
How does ICT use influence the location decisions of firms? (4.2)	Kolko (2002); Fitoussi (2004)	ICT use leads industries and firms to become more evenly distributed geographically.

First column describes major questions that explore how geographic location influences ICT adoption. Second column describes some of the major papers that have addressed these issues. Third column describes a generalization of the results of these papers.

Table 4: Summary of Research on Tradeoffs Between Organization and Environment (Section 5)

Open Question	Papers	Results
How does co-invention shape the diffusion of ICT? (5.1)	Bresnahan and Greenstein (1996); Forman (2005); Forman, Goldfarb, and Greenstein (2005, 2006); Borzekowski (2004)	High co-invention costs lead to slower adoption of new ICT.
Does real options analysis lead to better decisions for when to adopt ICT? (5.2)	Dos Santos (1991); Kumar (1996); Benaroch and Kauffman (1999, 2000); Taudes et al. (2000); Fichman (2004)	Real options analysis can lead to better timing of adoption decisions.

First column describes major questions that explore how organization and environment influence ICT adoption. Second column describes some of the major papers that have addressed these issues. Third column describes a generalization of the results of these papers.

Table 5: Summary of Research on Network Effects (Section 6)

Open Question	Papers	Results
How do network externalities shape technology adoption? (theory work) (6.1)	Farrell and Saloner (1986a, 1986b); Katz and Shapiro (1986); Riggins et al. (1994); Wang and Seidmann (1995); Nault and Dexter (1994); Dai and Kauffman (2005); others	When network externalities are present, the private benefits of adoption differ from the social benefits. This can lead to a variety of sub-optimal equilibrium outcomes, including "excess inertia" and "excess momentum."
Do network effects shape the adoption of ICT? (6.2)	Goolsbee and Klenow (2002); Goldfarb (2006); Bell and Song (2004); Gurbaxani (1990); Iacovou (1995); Chwelos, Benbasat, and Dexter (2001); Premkumar and Ramamurthy (1995); Premkumar et al. (1997); Hart and Saunders (1997, 1998); Bertschek and Fryges (2002); Forman (2005)	The probability of adopting by a given date is positively related to the proportion of firms in the peer group that have already adopted. However, most research has been unable to identify whether this empirical pattern is caused by network externalities, knowledge spillovers, or other "bandwagon effects."
How do network externalities shape the adoption of ICT? (6.3)	Saloner and Shepard (1995); Kauffman, McAndrews, and Wang (2000); Gowrisankaran and Stavins (2004); Augereau et al. (2004).	Larger network size increases the speed of adoption when there exist common standards, other things equal. When standards are not set and can be used to differentiate, adoption may exhibit negative network externalities.

First column describes major questions that explore how network effects influence ICT adoption. Second column describes some of the major papers that have addressed these issues. Third column describes a generalization of the results of these papers.

Table 6: International diffusion of Internet Technology (Section 7)

Open Question	Papers	Results
What is the relationship between per capita income and Internet diffusion?	Comin and Hobjin (2003); Beilock and Dimitrova (2003); Chinn and Fairlee; Kiiski and Pohjola (2002); Hargittai (1999); Wong (2002); Dewan et al. (2005)	Per capita income is positively correlated with Internet diffusion.
What is the relationship between government institutions and Internet diffusion?	Coming and Hobjin (2003); Beilock and Dimirova (2003); Oxley and Yeung (2001); Chinn and Fairlee (2004); Hargittai (1999); Kenney (2003); Wallsten (2003)	Internet diffusion has been faster among countries that are democratic, those with political freedom, and that have rule-of-law. Telecommunications and regulatory policy also play a role.
What is the relationship between country-level education and Internet diffusion?	Chinn and Fairlee (2004); Kiiski and Pohjola (2002); Dewan et al. (2005)	Internet use will diffuse more quickly to countries with higher education.
What is the relationship between existing telecommunications infrastructure and Internet diffusion?	Beilock and Dimitrova (2003); Chinn and Fairlee (2004); Kiiski and Pohjola (2002); Hargittai (1999); Dewan et al. (2005)	Internet diffusion is faster in countries with better telecommunications infrastructure. The relationship between Internet diffusion and telecommunications prices is less clear.
What is the relationship between English language use and Internet diffusion?	Hargittai (1999); Kiiski and Pohjola (2002); Gandal (2006)	There is no clear consensus in the literature.
(How) can developing countries use ICT to catch up to developed countries?	Antonelli (2003); James (2003)	There is no clear consensus in the literature.

First column describes major questions that explore the international diffusion of Internet technology. Second column describes some of the major papers that have addressed these issues. Third column describes a generalization of the results of these papers.