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Digital Economics†

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Digital technology is the representation of information in bits. This technology has reduced the cost of storage, computation, and transmission of data. Research on digital economics examines whether and how digital technology changes economic activity. In this review, we emphasize the reduction in five distinct economic costs associated with digital economic activity: search costs, replication costs, transportation costs, tracking costs, and verification costs. (JEL D24, D83, L86, O33, R41*)*

1. *What Is Digital Economics?*

Digital technology is the representation of information in bits. This reduces the cost of storage, computation, and transmission of data. Research on digital economics examines whether and how digital technology changes economic activity.

Understanding the effects of digital technology does not require fundamentally new economic theory. However, it requires a different emphasis. Studying digital economics starts with the question of "what is different?" What is easier to do when information is represented by bits rather than atoms? Digital technology often means that costs may constrain economic actions. Therefore, digital economics explores how standard economic models change as certain costs fall substantially and perhaps approach zero. We emphasize how this shift in costs can be divided into five types:

(i) Lower search costs

(ii) Lower replication costs

(iii) Lower transportation costs

(iv) Lower tracking costs

(v) Lower verification costs

Search costs are lower in digital environments, enlarging the potential scope and quality of search. Digital goods can be replicated at zero cost, meaning they are often non-rival. The role of geographic distance changes as the cost of transportation for digital goods and information is approximately zero. Digital technologies make it easy to track any one individual's behavior. Last, digital verification can make it easier to certify the reputation and trustworthiness of any one individual, firm, or organization in the

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digital economy. Each of these cost changes draws on a different set of well-established economic models, primarily search, non-rival goods, transportation cost, price discrimination, and reputation models.

Early research tested straightforward models of lower costs. For example, the search literature of the late 1990s and early 2000s built directly on earlier models by Diamond (1971) and Varian (1980). As we detail below, empirical work emerged that found some inconsistencies with the simple models, and so richer models and empirical analysis of the cost reductions developed to take account of the subtleties of the digital context.

Other authors have also emphasized the role of lower costs for digital economics (e.g., Shapiro and Varian 1998; Borenstein and Saloner 2001; and Smith, Bailey, and Brynjolfsson 2001). Ellison and Ellison (2005) discuss the implications of these lower search and transportation costs for industrial organization with respect to increasing returns, distance, and two-sided markets. Since their article, the digital economics literature has grown to contribute to the economics of crime, the economics of public goods, organizational economics, finance, urban economics, labor economics, development economics, health economics, political economy, media economics, public finance, and international economics. In this sense, we view digital economics as a way of thinking that touches many fields of economics.

In addition to applying across many fields, these shifts in costs have transformed many aspects of the economy. After providing a brief history of digital technology and the Internet, we discuss each of the cost changes associated with digitization. In each section, we emphasize the key research questions that have driven the area and how they have evolved, and relate them to policy where applicable.

We begin with a discussion of the effect of lower search costs, defined as the costs of looking for information. Lower search costs affect prices and price dispersion. They affect product variety and media availability. They change matches in a variety of settings, from labor markets to dating. They have led to an increase in the prevalence of platform-based businesses, and affected the organization of some firms.

We next turn to zero replication costs, which also affect pricing decisions including the decision to provide a good for free. This has enabled an increase in the provision of public goods such as Wikipedia, raising a number of new questions about the motivations for providing such goods. Zero replication costs create challenges with respect to excludability. Copyright can enforce excludability by using the law to overcome the non-rival nature of the technology. Consequently, copyright has become increasingly important to a variety of businesses and a core policy challenge related to digitization.

Because the cost of transporting information stored in bits is near zero, this has changed the role of place-based constraints on economic activity, whether due to costs of physical transportation or policy. Digitization changes the ways governments can control the flow of information, from advertising restrictions to media blackouts.

We then turn to examine a more recent literature that has identified two other cost changes: Tracking and verification costs. Tracking costs are the costs associated with connecting an individual person or firm with information about them. Low tracking costs enable novel forms of price discrimination as well as new ways to targeting advertising and other information. At the same time, better tracking has made privacy a key issue, generating a great deal of research and policy discussion.

We conclude the discussion of cost changes by detailing changes in verification costs. The rise of online reputation systems has facilitated trust and created new markets. At the same time, such systems are

imperfect, and can serve as platforms for fraud or discrimination.

We finish by discussing the consequences of digitization for countries, regions, firms, and individuals. Digitization has affected productivity, trade, the economic role of cities, domestic and international outsourcing, consumer surplus, and how people spend their leisure time.

2. *Digital Technology: A Brief History*

The history of modern computing begins not with the Internet, but in 1945 with the commercialization of technologies developed during World War II (Ceruzzi 2003). These first machines focused on rapid calculation with little capacity for storing and retrieving information. By the early 1950s, magnetic core memories enabled efficient digital information storage and perhaps the first real non-arithmetical benefit of representing information in bits emerged: the lower marginal cost of reproducing information. Over time, storage technology, software, and hardware improved so that information processing and reproduction became widespread. The software and hardware industries grew rapidly (Ceruzzi 2003 and Campbell-Kelly 2004).

Limited communication between computers limited their effect on the economy. It was with the rise of the Internet—and with it, low-cost, commercial, computer-to-computer communication—that the representation of information in bits began to have a measurable effect on multiple markets. This rise was built on key inventions developed through US military funding in the 1960s and 1970s (Hafner and Lyon 1996 and Greenstein 2015). For example, the Defense Advanced Research Projects Agency (DARPA) funded the invention of packet switching, which breaks down a long message into shorter messages that can be sent through the network and then reassembled upon receipt. DARPA-funded researchers also developed the particular packet-switching standards that define Internet communication: the Transmission Control Protocol/Internet Protocol (TCP/IP). The National Science Foundation (NSF) began managing a network using that protocol in the 1980s, building a reliable infrastructure that was relatively easy to adopt but also restricted to researchers.

Privatization occurred between 1990 and 1995, leading to the modern commercial Internet. The commercial Internet diffused quickly, with universities playing a key role in the diffusion process (Goldfarb 2006). There was near-universal availability and widespread adoption in the United States by 2000 (Greenstein 2000).[1] Over time, new technologies have been layered on top of the basic TCP/IP-based Internet, including browsers, search engines, online shopping, social networks, mobile communications protocols, security standards, customer relationship management systems, and many others. These technologies and others have enabled increased collection and use of data.

During this process, there has been an open question of who should control various aspects of commercial Internet activity, given this historical context of decentralization. Standards are often agreed upon through committees with representatives from industry and academia. Such standards have an influence on which technologies are widely adopted (Rysman and Simcoe 2008). Therefore, standards setting creates winners and losers. Simcoe (2012) examines the incentives in standards development for one such standard-setting organization, the Internet Engineering Task Force, demonstrating that the commercialization of the Internet slowed standards development due

[1] This rapid speed of diffusion proved useful for identification in the empirical papers examining the effect of the Internet on regions, firms, and individuals that we discuss in the penultimate section.

to competing commercial interests. Given their importance, control of hardware and software standards has been controversial.

Echoing this question of control, the earlier literature on the economics of the Internet focused on pricing the sending of information and how it varies with interconnection, competition, and the nature of the content (MacKie-Mason and Varian 1994). In other words, there is a question about the role of Internet service providers in controlling access. Laffont et al. (2003) emphasized how the need for interconnection can affect prices and welfare. This literature emphasized network effects and the challenges of interconnection (Cremer, Rey, and Tirole 2000; Besen et al. 2001; Laffont et al. 2001; and Caillaud and Jullien 2003).

As data transmission became a key aspect of digital technology, the question of net neutrality has become a central research and policy focus. Net neutrality means that an Internet service provider should treat all data in the same way; regardless of the content provider or content, companies cannot pay an Internet service provider to have faster speeds. The net neutrality debate asks whether Internet service providers should exercise control over content. Put differently, net neutrality is the norm that Netflix pays the same to send a gigabyte of data to one of their customers as a small startup would pay to send data to the same customer. Internet services have had a historic norm of net neutrality, though this has been challenged in recent years by Internet service providers and policy makers in the United States and globally. The net neutrality literature therefore emphasizes the role of the connection intermediary (Economides and Hermalin 2012; Bourreau, Kourandi, and Valletti 2015; Choi, Jeon, and Kim 2015; and Goetz 2017). As shown by Lee and Wu (2009) and Greenstein, Peitz, and Valletti (2016), the particulars of the model matter, and the costs and benefits of net neutrality depend on the specific setting.

Therefore, a key theme in the history of digital technology is a tension between openness and control. As we discuss below, this tension is at the center of much of the digital policy literature with respect to copyright, privacy, and discrimination.

3. *Reduction in Search Costs*

Search costs are the costs of looking for information. Every information-gathering activity therefore involves search costs. The basic idea with respect to digital economic activity is that it is easier to find and compare information about potential economic transactions online than offline.

At the beginning of the commercial Internet, there was much discussion among economics researchers around how a dramatic reduction in search costs might transform the economy by reducing prices, price dispersion, unemployment, vacancies, and inventories. Alan Greenspan argued that the information and communications technology (ICT) revolution would reduce the severity of business cycles.[2] The consequences of low search costs were discussed in financial markets (Barber and Odean 2001), labor markets (Autor 2001), and retail markets (Borenstein and Saloner 2001 and Bakos 2001). The ideas in these papers have their roots in the early search literature, which modeled search costs as the costs of gathering information (Stigler 1961, Diamond 1971, and Varian 1980). Reflecting this early focus and solid base of economic understanding, the literature on the effects of lower digital search costs is more established than the other parts of the digital economics literature.

[2] "Information technology has doubtless enhanced the stability of business operations," Federal Reserve Chairman Alan Greenspan, February 26, 1997, testimony before Congress. https://www.federalreserve.gov/boarddocs/hh/1997/february/testimony.htm.

3.1 *Are Prices and Price Dispersion Lower Online?*

Low search costs make it easier for consumers to compare prices, putting downward pressure on prices for similar products. This should reduce both prices and price dispersion. Brynjolfsson and Smith (2000) compare prices of books and CDs at four Internet-only retailers, four offline retailers, and four "hybrid" retailers who had both online and offline stores. They identified twenty books and twenty CDs, half of which were best-sellers and half of which were randomly selected among titles popular enough to be sold in most offline stores. They showed that online prices for these items were substantially lower than offline prices. Relatively low online prices have been shown in a variety of other settings, including insurance (Brown and Goolsbee 2002), automotive products (Scott Morton, Zettelmeyer, and Silva-Risso 2001), and airlines (Orlov 2011).

However, though prices may be lower, substantial price dispersion remains. Brynjolfsson and Smith (2000) show this in their online–offline retail study. Baye, Morgan, and Scholten (2004) use evidence from thousands of products and prices to document large and persistent online price dispersion. Orlov (2011) finds that the Internet increases the intrafirm dispersion of airline prices, but had no effect on interfirm price dispersion. By contrast, the development economics literature measuring the effect of mobile phones on commodity prices suggests that lower search costs reduced price dispersion (Jensen 2007; Aker 2010; and Parker, Ramdas, and Savva 2016).

Given evidence of the persistence of price dispersion online, research turned to explore why price dispersion does not disappear. Of course comparison of online products does not always compare apples to apples. In comparing book prices, the book may be the same, but the retailer is different. Different retailers offer different quality, shopping experiences, and shipping policies. Firms with higher quality may develop stronger brands and therefore command higher prices (Waldfogel and Chen 2006).

Firms selling products can also shape the search process. When consumers search, they assess multiple dimensions of information: price, quality, reputation, shipping fees, time to delivery, color, etc. Lynch and Ariely (2000) demonstrate this for online wine purchasing in a laboratory. If price was available on the first page, consumers focused on price. If consumers needed to click further to learn the price, other attributes became more important for purchase decisions. Fradkin (2017) shows that the details of the search process matter in the context of short-term accommodation platform Airbnb. Structural estimates of the cost of an extra click in the consumer search process suggest they are larger than might be supposed (Honka 2014 and De Los Santos, Hortacsu, and Wildenbeest 2012). This means that consumers stop searching sooner than predicted by models that assume search costs close to zero.

In the presence of search costs, and multiple dimensions of information, firms can partly choose which information has the lowest search costs. Ellison and Ellison (2009a) demonstrate that computer memory chip retailers attract customers with low prices at an online price comparison website, and then show customers other (typically higher quality and higher margin) products once they arrive. Using data from eBay, Dinerstein et al. (2018) emphasizes how the design of the search algorithm on eBay affects markups charged by eBay sellers. More directly, Hossain and Morgan (2006) show that online sellers often hide shipping fees until the final purchase page. Blake et al. (2018) shows a similar phenomenon in the information revealed in ticket prices at an online ticket platform.

Therefore, while prices have fallen, price dispersion has persisted. The initial

predictions of low price dispersion missed the point that search costs are endogenous, and so firms can manipulate the search process in order to sustain higher margins and prices.

3.2 *How Do Low Search Costs Affect Variety?*

Low search costs may mean that it is easier to find rare and niche products (Yang 2013). In this case, digital search might lead to an increase in the proportion of sales going to products that are relatively rarely purchased, a phenomenon dubbed "the long tail" by Anderson (2006). Using data from a retailer with both online and offline channels, Brynjolfsson, Hu, and Simester (2011) document that the variety of products available, and purchased, online is higher than offline. Low search costs may facilitate discovery of relatively unknown products (Zhang 2018).[3]

Low search costs could also generate superstar effects (Rosen 1981). If there are vertically differentiated products and the marginal cost of production is zero, then homogeneous consumers will all agree which product is best and buy it. Consistent with this, Goldmanis et al. (2010) show that the Internet initially led to a relative increase in the number of large offline bookstores and travel agencies.

Bar-Isaac, Caruana, and Cunat (2012) explain how superstar and long-tail effects may result from a reduction in search costs. If products are both vertically and horizontally differentiated, a reduction in search costs may lead to an equilibrium where the most popular and highest-quality products are produced in high enough quantity to be sold to everyone, while niche products are sold through long-tail retailers. The increase in tails at the right and left of the distribution comes at the cost of products in the middle.

The degree to which search costs generate more or less variety depends on the search process endogenously chosen by the firm. Recommendation engines are a key aspect of the online search process. Fleder and Hosanagar (2009) demonstrate this, showing that algorithms that emphasize "people who bought this also bought" move the sales distribution toward superstars. If many people buy Harry Potter, this recommendation engine will recommend Harry Potter to everyone else. In contrast, if the algorithm emphasizes "people who bought this disproportionately bought," relatively unusual items that demonstrate niche tastes will be sold. Empirically, Tucker and Zhang (2011) document that popularity information has asymmetrically large effects for niche products.

Popularity information affects sales in general. Many online platforms sort items by popularity and feature popularity prominently, reducing search costs for this type of information. Showing such popularity information affects purchase behavior not only in retail, but also online lending (Zhang and Liu 2012) and online investing (Agrawal, Catalini, and Goldfarb 2015).

The effect on welfare of this change in variety is not obvious, and so it has been the subject of a rich discussion in the literature. Lower search costs that lead people to buy the products that more closely match their preferences should increase welfare. Consistent with this, Brynjolfsson, Hu, and Smith (2003) show that increased variety increases consumer surplus.

At the same time, improvements in welfare may be small. The increase in matching of products to preferences is, by definition, marginal. The new products offered are the products on the margin of being produced.

[3] In addition to search costs, variety may increase because digital technologies can make inventory systems more efficient, meaning firms can hold millions of products, especially for digital goods that have no physical presence. People may also be less inhibited from purchasing nonstandard items when purchasing on a screen, rather than from a human (Goldfarb et al. 2015).

The superstar effects may be marginal relative to the consumers who bought products in the middle because they were unwilling to pay search costs. For example, Ershov (2017) shows that a reduction in search costs in the mobile app market reduced average product quality. On balance, however, it also shows that the increase in variety led to a substantial increase in overall welfare despite the incremental nature of the new products.

Aguiar and Waldfogel (2016) suggest that this marginal argument misses the substantial uncertainty about product quality for many information goods. In the context of music, they show that several songs and musicians that seem marginal ex ante ended up having substantial sales. Therefore, by enabling such music to get produced, digital markets led to a large change in the relative sales of products. Uncertainty in the process meant better and more music was created.

A great deal of attention has focused on the increase in variety in consumption of media in particular. The Internet might also enable people to only read information that reflects their narrow viewpoint; despite the variety, there is no need to search widely. The latter idea has been emphasized by Cass Sunstein as an "echo chamber" (Sunstein 2001). Consistent with the idea of wide variety available but consumption in echo chambers, Greenstein and Zhu (2012) examine the bias of Wikipedia and show that, while, on aggregate Wikipedia has become less politically biased (toward Democrats) over time, the bias of articles has not changed much. Instead, the political bias has mainly dropped because of the arrival of new, relatively right-wing articles.

By contrast, Gentzkow and Shapiro (2011) show that Internet media consumption is more varied than offline media consumption. Therefore, in this context, low search costs lead to increased variety. Boxell, Gentzkow, and Shapiro (2017) argues that the Internet is unlikely to be responsible for increased polarization of digital content because the increase in polarization is largest for demographic groups with the least Internet usage.

Polarized media may be less concentrated, generating incentives for niche sources to intentionally mislead. Allcott and Gentzkow (2017) show that false news stories about the 2016 presidential election were shared tens of millions of times, though they demonstrate the fake news was unlikely to have changed the election outcome. Long before the attention to fake news in the 2016 election, Antweiler and Frank (2004) examined how anonymous, and potentially misleading, online investing advice affects stock prices. Low search costs—in the absence of a reliable quality filter—meant that this information could be more easily found and shared.

Low online search costs have also transformed the way academic research is consumed. McCabe and Snyder (2015) show that JSTOR led to an increase in citations of included articles at the expense of others. Search costs fell, but because they fell more for some articles than others, it changed the nature of attention to specific articles and ideas. More starkly, Ellison (2011) argues that peer review may be in decline because of low online search costs. In particular, he shows that high-profile researchers do not need to rely on academic journals to disseminate their ideas. They can post online and people will find their work. In other words, similar to the superstar effect in products, low search costs combined with thousands of research articles benefit the superstar researchers.

3.3 *How Do Low Search Costs Affect Matching?*

Reduced search costs facilitate exchange more generally, often enabled by large digital platforms. Dana and Orlov (2014) show that airlines are better able to fill to capacity. Ellison et al. (2014) show that online buyers are better able to find the specific books

they want. Kroft and Pope (2014) find online search through Craigslist decreased rental apartment and home vacancies (though they measure no effect on unemployment). Anenberg and Kung (2015) show that online search enabled the rise of a market for truck-based mobile restaurants ("food trucks"). To the extent that the literature emphasizing matching is distinct from search, the matching literature emphasizes that both sides of the market engage in the search process.

Related to the above ideas, low search costs are likely to increase the quality of matches between buyers and sellers, firms and workers, etc. The labor economics literature has emphasized that the Internet should reduce unemployment and vacancies. Kuhn and Skuterud (2004) find no effect of Internet job search on employment. Kuhn and Mansour (2014) revisit the analysis several years later with updated data and find that individuals that used the Internet in job search were indeed more likely to match to an employer.

The reduced costs of search have led to the development of online "peer-to-peer" platforms dedicated to facilitating matching. The variety of such online matching markets is extraordinary: workers and firms, buyers and sellers, investors and entrepreneurs, vacant rooms and travelers, charities and donors, dog walkers and dog owners, etc. Several of these markets have been dubbed the "sharing economy" because people are able to use unused objects or skills better. Most "sharing economy" platforms are not sharing in the sense learned by kindergarteners: customers typically pay for the "shared" services. Horton and Zeckhauser (2016) emphasize that many of these markets are driven by an unused capacity for durable goods. Low search costs enable such unused capacity to be filled more efficiently.

In a review of the peer-to-peer markets literature, Einav et al. (2018) note that much of the research takes a market design perspective. For example, Cullen and Farronato (2016) examine an online marketplace that matches buyers and sellers of domestic tasks, such as cleaning, moving, and simple home repair. They emphasize the challenges in growing both the demand and supply sides with respect to variation in the quantity of buyers and sellers over time, economies of scale in matching, and geographic density. A key result is that demand fluctuations in this two-sided market lead to changes in quantity supplied rather than changes in prices. Similarly, Hall, Kendrick, and Nosko (2016), Farronato and Fradkin (2018), and Zervas, Proserpio, and Byers (2017) also show that the responsiveness in quantity supplied to changes in demand conditions is a key aspect of peer-to-peer platforms (specifically, Uber and Airbnb). Low search costs provide market demand information that enables supply to enter the market when needed.

3.4 *Why Are Digital Platform-based Businesses So Prevalent?*

Platforms are intermediaries that enable exchange between other players. Digitization has led to an increase in the prevalence of platform businesses, even beyond the peer-to-peer platforms discussed above. Most of the major technology firms can be seen as platform-based businesses. For example, Apple provides hardware and software platforms for others to build applications around. Google provides platforms for bringing together advertisers and potential buyers.

As highlighted in Jullien (2012), there are two main reasons digital markets give rise to platforms. First, platforms facilitate matching. In particular, as in the sharing economy platforms, they provide a structure that can take advantage of low search costs to create efficient matches. Often platforms serve as intermediaries between buyers and sellers, as highlighted in Nocke, Peitz, and Stahl (2007)

and Jullien (2012). In the context of a central role of matching, a rich theory literature has arisen that examines competition and pricing strategy in such platform businesses, with an emphasis on the importance of indirect network effects (for example Baye and Morgan 2001, Caillaud and Jullien 2003, Weyl 2010, Hagiu and Jullien 2011, and de Corniere 2016).

Second, platforms increase the efficiency of trade. They do this through lower search costs as well as other aspects of digitization that we discuss below: low reproduction and verification costs. Hagiu (2012) emphasizes how software platforms enable application providers to serve a large number of customers quickly, with the only requirement that the application serve some particular customer need, reproduce at zero cost, and rely on the platform and the other applications to serve other needs. Interoperability is therefore a key aspect of platforms. There is a large literature on the topic, as reviewed in Farrell and Simcoe (2012). A key contribution of this literature is the emphasis on the strategic nature of decisions on interoperability and standards (Rysman and Simcoe 2008 and Simcoe 2012). A related set of questions examines whether market participants will "multi-home" and use multiple platforms (Rochet and Tirole 2003, Rysman 2007, Halaburda and Yehezkel 2013).

3.5 *How Do Low Search Costs Affect the Organization of the Firm?*

Lucking-Reiley and Spulber (2001) discuss several hypotheses with respect to the effect of the Internet on firm structure in terms of the role of online intermediaries and vertical integration. This literature emphasizes information flow generally, in which search is one key type of information flow. Garicano (2000) shows that low-cost digital information flow could increase centralization by enabling headquarters, and organizational leaders, to understand better what is happening at a distance. On the other hand, Garicano (2000) also shows that low-cost communication could decrease centralization by enabling front-line employees to access information previously only available to senior employees at headquarters. A variety of papers have explored nuances in this trade-off within organizations, emphasizing the importance of the particular technology studied.

Bloom et al. (2014) test this theory directly, using data on European and American manufacturing firms to show that information technology is a centralizing force and communication technology is a decentralizing force. Acemoglu et al. (2007) also discuss the decentralizing role of information technology. For example, Forman and van Zeebroeck (2012) shows that digital communication increases in research collaboration across establishments within an organization. Baker and Hubbard (2003) examines the effect of on-board computers on asset ownership in the trucking industry. They emphasize tracking costs more than search costs and find that aspects of on-board computing that improve monitoring pushed trucking firms to more ownership of trucks while aspects of on-board computing that improve real-time location information pushed trucking firms to less ownership of trucks. Therefore, while adoption of digital technology led to improved efficiency, the effect on organization of the firm in equilibrium depends on the nature of the technology and how its specific features affect trade-offs between competing tensions at the boundary of the firm. McElheran (2014) examines the decision to centralize or delegate IT adoption decisions within firms. Firms with a greater need for integrated processes (digital or otherwise) delegate less. Forman and McElheran (2013) show that this tendency is mitigated by the ease with which IT enables coordination across firms, so that disintegration of the firm boundary can be seen as an extreme form of delegation.

In addition to the effect on the domestic boundaries of the firm, the reduction in search costs (combined with the reduction in verification costs discussed below) has also led to an increase in international hiring and outsourcing. While international outsourcing is not a new phenomenon (Leamer 2007), the recent rise of digital international labor market platforms suggests a different avenue for international hiring. Agrawal, Lacetera, and Lyons (2016) show that online platforms with standardized information disproportionately benefit workers from developing countries. The objective information available online, combined with the ability to send the output of the work (typically information such as data or software code) for free over long distance helps workers who are far from the buyer. Such online labor markets have several important challenges. Using data from online labor markets, Lyons (2017) shows that cross-cultural international teams can be less productive because of communication challenges. Relatedly, Ghani, Kerr, and Stanton (2014) show that employers in the Indian diaspora are more likely to hire Indians online.

4. *The Replication Cost of Digital Goods Is Zero*

The key shift in the production function is not that digital goods have a marginal cost of zero. Simple microeconomic models with zero marginal cost are not so different from models with positive marginal cost. The demand curve slopes downward and firms price where marginal revenue equals zero.

Instead, a key distinction between goods made of atoms and goods made of bits is that bits are non-rival, meaning that they can be consumed by one person without reducing the amount or quality available to others. A common analogy for non-rival goods is that just as one person can start a fire without diminishing another's fire, information can be shared without diminishing the original information.

In the absence of deliberate legal or technological effort to exclude, bits can be reproduced by anyone—not just the producing firm—at near zero cost without degrading the quality of the initial good. As Shapiro and Varian (1998, p. 83) put it, the Internet can be seen as a "giant, out of control copying machine."

Nevertheless, the economics of zero marginal cost, non-rival goods can shift things in favor of producers, consumers, or both. In a static model, as marginal costs fall the potential surplus rises, and so the welfare effect depends on the final price and associated deadweight loss. The final price and deadweight loss depend on legal and technological tools for exclusion (Cornes and Sandler 1986), which relate to the ability to track behavior—the subject of a later section. In this section, we emphasize that the underlying technology enables firms and governments to make a choice not to exclude. This can allow individuals to enjoy the full benefits of the non-rival nature of information-based goods.

4.1 *How Can Non-Rival Digital Goods Be Priced Profitably?*

The non-rival nature of digital goods has led to questions of how to structure pricing of a large variety of non-rival zero-cost goods, should a producer choose to charge. Bundling occurs when two or more products are sold together at a single price (Shapiro and Varian 1998, Choi 2012). Bundling models have a long history in economics. Stigler (1964) and Adams and Yellen (1976) note that a sufficient condition for price discrimination benefit of bundling arises when consumers have negatively correlated preferences. Some people may value an action movie at $10 and a romance at $2. Others may value the romance at $10 and the action movie at $2. Selling the bundle at $12 yields higher profits than selling the action and

romance movies separately. The challenge for firms is to identify such negative correlations in preferences to identify when bundling will increase profits.

Bakos and Brynjolfsson (1999, 2000) recognize that, under certain assumptions, with enough goods and independent preferences, this challenge is overcome. Furthermore, the non-rival nature of information goods means that large numbers of information goods can be bundled without substantially increasing costs. Therefore, a simple and useful insight on the economics of non-rival information goods is that it will sometimes be optimal to bundle thousands of digital products together.

Chu, Leslie, and Sorensen (2011) use an empirical example to show that the intuition of Bakos (1999) applies to relatively small numbers of goods in the bundle. There are also strategic reasons to bundle because it can reduce competition (Carbajo, de Meza, and Seidmann 1990). When bundling has zero marginal cost, such strategic considerations can become particularly relevant (Carlton, Gans, and Waldman 2010; Choi 2012).

Despite the extensive theory work, it is only recently that empirical examples of such massive bundles appeared in the literature, in the form of subscription services such as Netflix for video and Spotify and Apple Music for music. Aguiar and Waldfogel (2018) show that Spotify displaces sales but it also displaces "piracy," or the downloading of music without permission from the copyright holder. They estimate that the reduction in sales and the increase in legal music consumption balance each other so that Spotify appears to be revenue neutral in the 2013–15 time period.

4.2 *What Are the Motivations for Providing Digital Public Goods?*

Information providers can deliberately decide not to exclude. It is somewhat of a puzzle why private actors would choose to create public goods. Two prominent examples of non-rival public digital goods are open-source software and Wikipedia. Both cases involve a deliberate decision not to exclude, and applying established models is somewhat less straightforward than the bundling models highlighted in the preceding subsection.

Lerner and Tirole (2002) ask why software developers would freely share their code with no direct payment. They emphasize two core benefits from open source that do not appear in standard models of public goods. For individual developers, providing high-quality open-source code is a way to signal their skills to potential employers. For companies, improving the quality of open source software may allow them to sell other services that are complementary to open-source software (such as hardware or consulting services) at a premium. Underlying these core benefits is the non-rival nature of the code: digital distribution through the Internet means that (high-quality) open-source contributions can be widely adopted. The literature on the economics of open source that followed has largely supported their hypotheses of career concerns and complementarity (Johnson 2002; Bitzer and Schroder 2005; Mustonen 2005; Lerner, Pathak, and Tirole 2006; Henkel 2009; Xu, Nian, and Cabral 2016).

Wikipedia represents a different important context for the puzzle of why people contribute to digital public goods. Zhang and Zhu (2011) emphasize social benefits related to breadth of readership. In the context of Chinese-language Wikipedia, they show that users care about audience size, and decrease contributions when part of the audience is blocked due to Chinese government policy. Consistent with this idea of a social benefit, Aaltonen and Seiler (2016) and Kummer, Slivko, and Zhang (2015) together provide evidence for a virtuous circle in which more editing leads to more views and more views lead to more editing. Contributions are likely related to the interests of the contributors: Wikipedia leaned sharply Democratic early

on and has gradually become more neutral (Greenstein and Zhu 2012).

Nagaraj (2016) suggests the potential for government sponsorship of digital public goods. He finds that open mapping information led to a substantial increase in mining activity, particularly for smaller firms with fewer resources. Therefore, open data enabled a wider set of participants to succeed.

More generally, the non-rivalrous nature of digital technology could enable consumers and workers in developing countries to access the same information as people in developed countries, conditional on having access to the Internet. In the context of education, Kremer, Brannen, and Glennerster (2013) argue that information technology can improve pedagogy in the developing world. Underlying their argument is an emphasis on non-rival, non-excludable digital information, and the public Internet-based posting of educational materials. Correspondingly, Acemoglu, Laibson, and List (2014) emphasizes that digital education will lead to a more equal distribution of educational resources.

There are, however, situations in which welfare may decrease because of a decision not to exclude digital goods from widespread copying. The decision not to exclude non-rival goods can reduce the incentives to produce information goods, a subject we discuss below in the context of copyright policy. It can also create negative externalities. For example, Acquisti and Tucker (2014) show that policies that mandate "open data" by government may lead to data leakages (or privacy breaches) that affect individuals' welfare offline. Openness, almost by definition, implies a reduction in privacy. Relatedly, Acquisti and Gross (2009) show that using public data online makes it possible to predict an individual's social security number. This feeds back, in general, to the idea that while non-excludability may be attractive in principle, it can lead to questions of appropriate data security practices (Gordon and Loeb 2002 and Gal-Or and Ghose 2005), especially if costly investments in data security also are a public good.

While digital technology creates public goods, zero marginal cost of production can also create public bads, such as spam (Rao and Reiley 2012) and online crime (Moore, Clayton, and Anderson 2009). These have led to policy responses such as the US Controlling the Assault of Non-Solicited Pornography And Marketing Act of 2003 (CAN-SPAM). Another example of digital spam is junk telephone calls, the automation of which has been enabled by digital technologies. Petty (2000) and Varian, Wallenberg, and Woroch (2005) evaluate the role of the federally sponsored "Do Not Call" list in preventing potentially intrusive direct sales calls and find positive effects.

That said, the economics of such bads are relatively straightforward. In contrast, the more challenging policy question for non-rival digital goods is whether the government should intervene through copyright policy to enforce excludability despite the non-rival nature of the goods.

4.3 *How Do Digital Markets Affect Copyright Policy?*

As the Internet first diffused in the late 1990s, copyrights of music (and text) were often ignored as people freely posted copyrighted goods online. Because of the non-rival nature of digital information, one posted copyrighted item could be useful to millions of people, potentially replacing sales. At the same time, music industry revenue began to fall (Waldfogel 2012a) and this was widely blamed on changes brought by the Internet.

Optimal enforcement of copyright has therefore been a key focus of the digital economics literature. The early work focused on the revenue consequences of free online copying. This was referred to as "file sharing" to those who believe it should be allowed, and as "piracy" by those who didn't. The

direct effect of free online copying of media is that revenues from the sale of copies of that media fall. At the same time, revenues could rise if the free copies are merely sampled and consumers buy what they like (Peitz and Waelbroeck 2006). Revenues could also rise for complementary goods like live performances (Mortimer, Nosko, and Sorensen 2012). Finally, revenues could rise if the free copies are limited to developing markets for products with network effects (Takayama 1994). Empirically, though a small number of studies have found positive effects (Oberholzer-Gee and Strumpf 2007), most studies have found that free online copying reduces revenues in music (Rob and Waldfogel 2006, Zentner 2006, Liebowitz 2008, and Waldfogel 2010), in video (Rob and Waldfogel 2007; Liebowitz and Zentner 2012; Danaher, Smith, and Telang 2014b; Danaher and Smith 2014; and Peukert, Claussen, and Kretschmer 2017), and in books (Reimers 2016). This echoes a non-digital historical literature (Li, MacGarvie, and Moser 2015; and MacGarvie and Moser 2015) suggesting a continuity between policy governing digital technologies and earlier policies.

How does copyright affect the creation of new works? This is a more difficult research question, as it requires some attempt to measure counterfactual quality and quantity of goods had copyright law not existed (Varian 2005; Waldfogel 2012b; and Danaher, Smith, and Telang 2014b). Waldfogel (2012a) addresses this challenge using two measures of music quality: historical "best albums" lists and usage information over time. In both cases, he shows that the quality of music began to decline in the early 1990s and stopped declining after the arrival of free online copying in 1999. Why did quality rise despite declining revenue? He argues that simultaneously with the decline in revenue came a decline in the cost of producing and distributing music. Digitization affected the supply side as well as the demand side, and so quality rose. Results are similar in movies (Waldfogel 2016) and books (Waldfogel and Reimers 2015). This contrasts with the economic history literature, which suggested that copyright alone could increase the quality of creative output (Giorcelli and Moser 2016).

In addition to affecting incentives to innovate, digital challenges to copyright protection may affect incentives to build on prior work. Williams (2013) demonstrates this point in a different intellectual property context and shows that intellectual property protections limit follow-on innovation in gene sequencing. Heald (2009) shows that copyrighted music is less used in the movies than non-copyrighted music. Nagaraj (2018) shows that copyright protection of old sports magazines reduces the quality of Wikipedia pages decades later. This phenomenon is not unique to the digital context. Biasi and Moser (2018) show that eliminating copyrights of German books during World War II led to a substantial increase in US scientific output, measured by PhDs in mathematics and patents that cited the German books.

Another challenge for copyright policy driven by the shift in costs of replication is that it has made it easier for other firms to replicate digital content and attempt to aggregate it. This practice has been particularly prevalent in the news media, where policy makers have been encouraged to take action to protect the interests of the newspapers that actually originated this news content. However, in general the work in economics that has evaluated the effect of these aggregators has been to emphasize that such aggregation promotes more exploration, rather than necessarily cannibalizing content (Calzada and Gil forthcoming; Chiou and Tucker 2017; Athey, Mobius, and Pal 2017).

Overall, copyright law is more important in digital markets because goods can be copied at zero cost. Stricter enforcement of copyright appears to increase revenue to the copyright holder, increase some incentives

by potential copyright holders to innovate, but reduce incentives by others to build on copyrighted work. Nevertheless, the literature also shows that, despite ease of copying, digitization has not killed creative industries because production and distribution costs have fallen and because the technology has caught up to facilitate copyright enforcement.

5. *Lower Transportation Costs*

Related to replication being costless, the cost of transporting information stored in bits over the Internet is near zero.[4] Put differently, the cost of distribution for digital goods approaches zero and the difference in the cost of nearby and distant communication approaches zero.

In addition, digital purchasing technologies have reduced transportation costs. Consumers buy physical goods online, particularly when offline purchasing is costly or difficult (Goolsbee 2000; Forman, Ghose, and Goldfarb 2009; and Brynjolfsson, Hu, and Rahman 2009). Furthermore, Pozzi (2013) shows that consumers also use online shopping to overcome the transportation costs of carrying things from the store. In this way, the Internet facilitates stockpiling, allowing people to buy in bulk when a discount appears because delivery means there is no need to carry the large quantity of items purchased.

Therefore, for information, digital goods, and physical goods, transportation costs are lower online.

[4]While transportation costs could be positive and even high due to network congestion, in practice this has not been an issue. Early on, such network congestion was a key focus of the literature. For example, one of the first volumes on Internet economics, Mcknight and Bailey (1998), has several articles on congestion pricing. This early literature on backbone competition and congestion ended up influencing our understanding of the economics of net neutrality discussed above (Cremer, Rey, and Tirole 2000; Laffont et al. 2001; Besen et al. 2001; and Laffont et al. 2003).

5.1 *Does Distance Still Matter If Transportation Costs Are Near Zero?*

Low transportation costs for information mean that the cost of distribution for digital goods approaches zero and the difference in cost of nearby and distant communication approaches zero.

The potential implications of low transportation costs have been explored in the popular press. Cairncross (1997) suggests that this fall in the costs of transporting information would lead to a "death of distance." Isolated individuals and companies would be able to plug into the global economy. Rural consumers would benefit by having access to the same set of digital products and services as everyone else. There would be a global diffusion of knowledge. Friedman (2005) identifies several of the same themes in predicting a "flat world," in which businesses anywhere could plug into the global supply chain and produce. Being in the United States would not confer a meaningful advantage relative to India. Both Cairncross and Friedman suggested the potential arrival of a global culture, in which everyone everywhere would consume the same information, an idea with its roots in McLuhan (1964). This idea is implicit in the trade model of Krugman (1979): countries consume the same goods as transport costs approach zero. Rosenblat and Mobius (2004) formalize some of these ideas in a different context, using a network model of collaboration in which long distance collaboration rises but coauthor similarity in other dimensions (such as field of research) also rises.

A less extreme question than "Is distance dead?" is "Does distance matter more or less than it used to?" The most definitive answer to that question comes from Lendle et al. (2016). They compare cross-border sales on eBay with international trade data. They demonstrate that, while distance predicts both online and offline trade flows, distance matters substantially less on eBay.

The digital economic literature has emphasized what factors influence the extent to which distance still matters.

As Lemley (2003) notes, "No one is 'in' cyberspace" (p. 523). Therefore, offline options matter. Balasubramanian (1998) examines the importance of offline options using a circular city/Salop (1979) model with the cost of using the direct retailer as constant for all locations, but the cost of using the stores located around the circle dependent on transportation costs. The model shows that the benefit of a direct (online) retailer will be largest for those who live far from an offline retailer. Forman, Ghose, and Wiesenfeld (2008) provide evidence to support this model, demonstrating that when a Walmart or Barnes & Noble opens offline, people substitute away from purchasing books on Amazon. A number of other studies also demonstrate how offline retail affects online purchasing. Related models include Loginova (2009) and Dinlersoz and Pereira (2007), which examine the role of loyalty to the offline store in driving the more price sensitive customers online. Empirically, Brynjolfsson, Hu, and Rahman (2009) show that online sales at a women's clothing retailer are lower from places with many offline women's clothing stores. This effect is driven by the more popular products that are likely to be available in a typical offline store. Choi and Bell (2011) shows that online sales of niche diaper brands are higher in places where they are unlikely to be available offline. Goolsbee (2001), Prince (2007), and Duch-Brown et al. (2017) all show substitution between online and offline sales of personal computers. Gentzkow (2007) demonstrates substitution between the online and offline news in Washington DC. Seamans and Zhu (2014) and Goldfarb and Tucker (2011a, 2011d) demonstrate substitution between online and offline advertising. Gertner and Stillman (2001) show how channel conflict interacts with vertical integration and show that vertically integrated apparel retailers went online first. In their review of the literature on online–offline competition, Lieber and Syverson (2012) provide some additional evidence that offline options affect online purchasing. Similarly, in the digital media context, evidence suggests that online media consumption substitutes for, and is replacing, offline media consumption (Wallsten 2013 and Gentzkow 2007).

In addition to the offline option, the fact that tastes are spatially correlated also matters for the persistent role of distance. Blum and Goldfarb (2006) examine the international Internet surfing behavior of about 2,600 American Internet users, and demonstrate that Internet surfing behavior is consistent with the well-established empirical finding in the trade literature that bilateral trade decreases with distance (Overman, Redding, and Venables 2003; Anderson and van Wincoop 2004; and Disdier and Head 2008). In other words, even for a product with zero shipping costs (visiting websites), people are more likely to visit websites from nearby countries than from faraway countries. This relationship between distance and website visits is much higher in taste-dependent categories (and loses statistical significance in the non-taste-dependent categories). Distance matters because it proxies for taste similarity. Alaveras and Martens (2015) replicates this core result using much richer data on website visits by users in a large number of countries. Sinai and Waldfogel (2004) also shows that highly populated areas produce more content, and that because tastes are spatially correlated in the sense that people are more likely to consume local media than distant media, people in highly populated areas are particularly likely to go online. This geographically specific nature of tastes is also reflected in the consumption of digital goods such as music (Ferreira and Waldfogel 2013) and content (Gandal 2006). Quan and Williams (2018) demonstrate that accounting for spatial correlation in tastes

reduces the estimated consumer surplus from increased online variety by 30 percent.

In addition to offline choices and spatially correlated tastes, another factor that explains the continuing role of distance is the presence of social networks. Much online behavior is social, and social networks are highly local (Hampton and Wellman 2003). Therefore, while zero transportation costs of information mean that you can communicate with anyone anywhere in the world for the same price, the vast majority of most people's email comes from those who either live at the same home or work in the same building. Gaspar and Glaeser (1998) speculate that because of the spatial correlation of social networks, the Internet may be a complement to cities. More efficient communication would be especially important for those who communicate frequently. In other words, though the relative costs of communication fall more for distant communication, the overall importance of local communication might mean that cities benefit most.

Agrawal and Goldfarb (2008) provide some evidence in support of this hypothesis by showing that as new universities connected to a 1980s Internet-like network, they increased their collaboration rate with those already connected. The biggest change in collaboration rates were for co-located universities in different quality tiers. The paper emphasizes the likely local social networks of researchers in the same city. Looking at online "crowdfunding" of music, Agrawal, Catalini, and Goldfarb (2015) provide further evidence of the importance of local social networks by showing that musicians' early funding tends to come from local supporters who the musicians knew prior to joining the crowdfunding platform. As a musician gains prominence on the website, the later funding often comes from distant strangers.

Finally, in the absence of the improvements in verification discussed below, trust is easier locally. Hortacsu, Martinez-Jerez, and Douglas (2009) shows that same-city sales on eBay and MercadoLibre (a Brazilian electronic commerce platform) are disproportionately high, likely because some products are observed and delivered in person. Furthermore, Forman, Ghose, and Wiesenfeld (2009) shows that Americans follow the online product recommendations of others who live near them.

5.2 *Can Policy Constrained by Geographic Boundaries Shape Digital Behavior?*

Early work worried that the Internet could undermine local regulation and national sovereignty (Castells 2001). The results of some research is consistent with this idea: Online sales have been higher where the difference between online and offline tax rates is highest (Goolsbee 2000, Ellison and Ellison 2009b, Anderson et al. 2010, and Einav et al. 2014). When local regulation prohibits offline advertising, similar online advertising is more expensive (Goldfarb and Tucker 2011e) and more effective (Goldfarb and Tucker 2011a). This substitution suggests that online and offline markets should be considered together in the context of antitrust (Goldfarb and Tucker 2011f; Brand et al. 2014).

At the same time, regulation can mean that users experience the Internet differently in different locations. At the extreme, regulation can prohibit certain content, making the experience of using the Internet different across locations. Zhang and Zhu (2011) examine the effect of the blocking of Wikipedia in China in October 2005 on the motivations of others outside China to contribute. Therefore, a key online website was available in some places and not others. More generally, some countries regularly block access to certain websites, changing the nature of the Internet across locations.

Regulation can also change what users find available across locations. Copyright policy leads to variation in the availability and consumption of media across locations

(Gomez-Herrera, Martens, and Turlea 2014; Chiou and Tucker 2017; Athey, Mobius, and Pal 2017; and Calzada and Gil forthcoming). Privacy policy leads to different advertising and different website success (Goldfarb and Tucker 2011d and Tucker 2015). Trademark policy leads to different search experiences (Chiou and Tucker 2012 and Bechtold and Tucker 2014).

Therefore, when regulation does not reach into the online sphere, the zero transportation costs of information in the online channel generate a disproportionate benefit of online information in regulated contexts. However, when regulation does reach the online sphere, it can have a substantial effect on the nature of the Internet across locations.

6. *Lower Tracking Costs*

The first three drops in costs, those associated with search, replication, and distance, were well discussed in the early digital economics literature. However, the importance of the lowering of the next two costs we discuss, tracking and verification, has only become clear in the last decade.

Digital activity is easily recorded and stored. In fact, many web servers store information automatically, and firms have to make a deliberate decision to discard data. Reductions in tracking costs enable personalization and the creation of one-to-one markets, leading to renewed interest in established economic models with asymmetric information and differentiated products such as price discrimination, auctions, and advertising models.

6.1 *Do Lower Tracking Costs Enable Novel Forms of Price Discrimination?*

The ability to use digital technologies to track individuals enables personalized markets. Several economists recognized this potential for digital price discrimination as the Internet commercialized in the late 1990s (Shapiro and Varian 1998; Smith, Bailey, and Brynjolfsson 2001; and Bakos 2001). Even first-degree price discrimination seemed like it might become more than a theoretical curiosity.

One form of price discrimination that has received a great deal of attention in the theory literature on digital markets is behavioral price discrimination (see Fudenberg and Villas-Boas 2007, 2012 for reviews). This literature emphasizes that the low cost of collecting digital information makes it easier for companies to price discriminate based on an individual's past behavior. The research builds on a large price discrimination literature that does not specifically emphasize digital markets (Hart and Tirole 1988; Chen 1997; Fudenberg and Tirole 2000). Broadly, the research explores the benefits and costs of identifying previous customers for monopolies (Villas-Boas 2004) and competing firms (Shin and Sudhir 2010; Chen and Zhang 2011). Fudenberg and Villas-Boas (2012) summarize this literature to conclude that under monopoly, firms benefit from the additional information, but under competition the information may increase the intensity of competition. Furthermore, the benefits of the information to a monopoly may lead consumers to strategically withhold information. In other words, consumers become privacy sensitive (Taylor 2004; Acquisti and Varian 2005; Hermalin and Katz 2006). In the opposite direction, rules that restrict the flow of information hurt firms' ability to price discriminate and therefore may leave some consumers unwilling to buy at the offered prices (Taylor and Wagman 2014; Kim and Wagman 2015).

Another form of price discrimination that has received attention in the digital economics literature is versioning. Bhargava and Choudhary (2008) provide a model of versioning when variable costs are zero. Fay and Xie (2008) explore versioning based on probabilistic selling. For example, airlines and hotels offer low-price versions of their products on Priceline.com, in which there is

buyer uncertainty about the specific product being bought.

Empirical support for digital price discrimination is limited, despite the rich theoretical discussion of the potential for personalized pricing. For example, versioning is a basic form of third-degree price discrimination that precedes most digital markets (Maskin and Riley 1984; Deneckere and McAfee 1996; Corts 1998; Fudenberg and Tirole 1998). Rao (2015) provides experimental support for the value of versioning digital products, demonstrating that online, limited-time "rentals" can increase profits by segmenting high- and low-value consumers. Despite the ease of even this most straightforward form of price discrimination, Shiller and Waldfogel (2011) argue that digital firms may not be versioning, or more generally price discriminating, as much as would be optimal. In particular, they puzzle over the surprisingly uniform nature of pricing for digital music. They argue that uniform pricing of music appears to lead to lower-than-optimal profits for firms, but do not provide a clear answer to this puzzle. While there is evidence of broad versioning of online media (Chiou and Tucker 2013; Lambrecht and Misra 2017), the theoretical literature on digital price discrimination seems to be ahead of the empirical work and of firm practices. While there is evidence of first-degree price discrimination in higher education (Waldfogel 2015), the only online research example we found is Dube and Misra (2017), who demonstrate the feasibility and profitability of targeting many prices to different customers of an online service based on a large number of characteristics.

6.2 *Why Has There Been a Shift in Academic Emphasis from Personalized Pricing to Personalized Advertising?*

Given the emphasis of the theoretical literature on the ease and practicality of behavioral price discrimination and the potential for personalized pricing of goods online, it is perhaps a surprise that for many of these goods, consumers face a price of zero (Evans 2009). Therefore, perhaps the most striking effect of the creation of low online tracking costs has not been to use personalized profiles to charge different consumers different prices, but instead to show these different consumers more appropriate, relevant, and profitable advertising.

Variants of these ideas appear in a rich theory literature on two-sided markets, emphasizing the digital context (Baye and Morgan 2001; Anderson and de Palma 2009, 2013; White 2013; Athey, Calvano, and Gans 2018). Baye and Morgan (2001) demonstrate that an information intermediary will price low to consumers, while charging advertisers a high enough price that some choose not to participate. Anderson and de Palma (2009) and Athey, Calvano, and Gans's (2018) papers each model consumer attention as scarce and explore advertiser competition for that attention. Athey, Calvano, and Gans (2018) emphasize that if an advertiser wants to send a message to a customer offline, they need to rely on noisy signals based on media demographics. In contrast, online targeting technology is such that an advertiser can target a particular consumer. In the presence of multiple media outlets and multi-homing by consumers, the equilibrium outcome is that online advertising prices can be much lower than offline advertising prices even though the online advertising is in fact more useful to the advertiser. However, Gentzkow (2014) argues that the price of attention is not lower online than offline, which challenges this prediction.

Perhaps because of these forces, many of the largest online companies—in terms of revenues, profits, and users—are advertising-supported. Low-cost tracking means that what distinguishes online advertising from offline advertising is that it is targeted (Goldfarb and Tucker 2011b, Goldfarb 2014). This difference is highlighted in

models that explore competition between online and offline advertising (Athey and Gans 2010, Bergemann and Bonatti 2011, and Johnson 2013). Athey, Calvano, and Gans (2018) and Levin and Milgrom (2010) use very different models to demonstrate that better targeting may not help online media. Athey, Calvano, and Gans (2018) show that improved tracking can increase competition between media outlets. Levin and Milgrom (2010) show that too much targeting can lead to insufficient competition among advertisers for the user attention sold by a monopolist media firm.

This better targeting has led to a thriving literature that measures advertising effectiveness. Because ad messages are sent to individuals in bits (rather than broadcast through billboards and newspapers), it is relatively easy to identify consumers that see ads, to randomize which consumers see ads, and even to track those consumers through purchase. Until recently, this was very difficult, and so there were few studies that could deliver credible empirical measures of advertising effectiveness. Low tracking costs make it relatively easy to run field experiments online, and large scale field experiments have been the focus of the recent literature.

Research on online advertising effectiveness has been largely conducted by research economists working with industry. For example, Lewis and Reiley (2014) use a field experiment on 1.6 million Yahoo customers that connects online advertising to offline department store sales. They find that online advertising increases offline sales in a department store. Blake, Nosko, and Tadelis (2017) show that in many cases, search engine advertising—the key revenue generator for Google—does not work. In particular, they demonstrate with a large field experiment at eBay that consumers will often click on the "organic" link anyway and navigate to the advertiser's page. They argue that much search engine advertising is wasted. Simonov, Nosko, and Rao (2018) use data from Microsoft's Bing search engine to show that the results for eBay may be driven by the strength of eBay as a particularly well-known brand. Less well-known advertisers seem to benefit from search advertising.

While much better than prior ways to measure advertising effectiveness, there are still substantial challenges. Correlational research, even with detailed data, typically yields inaccurate measures of advertising effects because the signal-to-noise ratio for advertising's effect on sales is low (Lewis, Rao, and Reiley 2015; Gordon et al. 2016). Furthermore, even with experiments, advertising effects are subtle relative to the variance in purchase behavior, and so studies need to be highly powered (Lewis and Rao 2015).

A large literature also emphasizes the role of targeting as a distinct and important feature of online advertising. Goldfarb and Tucker (2011c) shows that targeted banner advertising is effective, but only as long as it does not take over the screen too much. Targeting works when subtle, in the sense that it has the biggest effect on plain banner ads, relative to how it increases the effectiveness of other types of ads. Lambrecht and Tucker (2013) and Tucker (2012a) demonstrate the effectiveness of other types of online advertising targeting.

As noted above, online media support their business by selling scarce consumer attention to advertisers. New technologies are emerging that allow consumers to block advertising online. Such ad blocking may reduce revenues and, perhaps counterintuitively, increase the quantity of ads shown to those without ad blockers (Anderson and Gans 2011). In a test of these ideas, Shiller, Waldfogel, and Ryan (2018) use data on ad blocking and website visits to show that widespread use of ad blockers may decrease the quality of websites on the advertising-supported Internet.

6.3 *Why Are Online Goods and Services Often Sold by Auction?*

The rise of online advertising, along with individual-level tracking technologies, has created a difficult pricing problem: how can a firm choose prices for thousands of advertisements that might be priced differentially to millions or even billions of customers? As economists have long-recognized, auctions are a particularly useful tool for price discovery. Consequently, digital markets typically use auctions to determine prices for advertising. Auctions are also used to price some other goods.

Originally, advertising on Yahoo!'s search page in the 1990s was priced according to a standard rate. Goto.com's insight—that an auction could leverage the fact that the value of advertising depended on the search term—led to a new way to price discriminate in advertising. Rather than price for the search page, price could be at the level of the search term. Google and Bing's ad auctions run on this insight. A large literature has arisen to develop auction formats for this context (Varian 2007; Edelman, Ostrovsky, and Schwarz 2007; Levin and Milgrom 2010; Arnosti, Beck, and Milgrom 2016). Today, advertising auctions, particularly for display advertising, often take into account additional information provided by online tracking technologies, such as websites visited in the past and products observed.

Less related to tracking costs, online auctions have also been used for price discovery for goods, most notably on eBay. An early review of the auction literature is provided in Ockenfels, Reiley, and Sadrieh (2006). They emphasize that the transactions costs of conducting and participating in auctions are lower in the digital context. Furthermore, many digital goods are not standardized in the sense that buyer valuations vary over time and location, and so the price discovery function of the auction is particularly useful. This idea also appears in Varian (2010), which describes the benefits of computer-mediated transactions with respect to decentralized price discovery, and therefore more finely based price discrimination. While auctions for goods (rather than advertising) still exist online, Einav et al. (2017) show that goods auctions are in decline as online markets have matured. The prominent role of auctions in economic theory means that a separate literature has used the digital setting as a context to test long-established theory. This research, pioneered by Lucking-Reiley (1999), is not about digital markets per se, but uses the digital context to inform a broader theory literature (Roth and Ockenfels 2002, Bajari and Hortacsu 2003, and Einav et al. 2018).

6.4 *How Do Digital Markets Affect Privacy Policy?*

Low tracking costs have led to a renewed interest in the economics of privacy, as highlighted by a recent review in this journal (Acquisti, Taylor, and Wagman 2016).

In general, the economics literature on privacy, both offline and online, grapples with the question of how privacy should be treated in terms of the consumers' utility function. Should economists treat privacy as an intermediate good—that is, a good whose value simply lies in the way it can moderate the achievement of another good—or as a final good—that is, a good that should be enjoyed and valued for its own sake (Farrell 2012)? Much policy making is grounded on the idea that privacy is a final good where a distaste for others intruding on or gathering knowledge about an individual's personal domain is valid as a driver of an individual's utility. However, much of the theoretical literature analyzes privacy as an intermediate good because of the implications for personalized pricing that are discussed above (Taylor 2004, Acquisti and Varian 2005, Hermalin and Katz 2006).

Privacy regulation can affect the nature and distribution of economic outcomes (Goldfarb and Tucker 2012a). Edelman (2009) and Lenard and Rubin (2009) emphasize that there is a trade-off between the use of online customer data to subsidize zero-price goods and advertising performance. Goldfarb and Tucker (2011d) show that European privacy regulation that restricted online tracking led to a substantial decline in the effectiveness of online advertising in Europe. Johnson (2014) estimates the financial effect of privacy policies on the online display ad industry, suggesting that an opt-in policy or a tracking ban would reduce welfare substantially, though an opt-out policy would have little effect. Johnson's paper is very useful for understanding the effect on publishers (rather than advertisers) of privacy regulation.

Kim and Wagman (2015) show that regulation of sharing financial information increased defaults on loans during the financial crisis. Miller and Tucker (2009, 2011) show that US healthcare privacy regulation reduced hospital adoption of electronic medical records, leading to worse health outcomes. On a more positive note in favor of privacy, Tucker (2014) shows that firm-implemented privacy controls designed to encourage consumers' perceptions of control can actually enhance the performance of online advertising. Tucker (2012b) compares this result with work that suggests there may be benefits from addressing consumer privacy concerns, building on research that illustrates how perceptions of control influence privacy concerns in general (Brandimarte, Acquisti, and Loewenstein 2012).

In general, the precise nature of privacy protection can be expected to matter a lot for the direction of innovation: it is not a matter of a simple binary choice to have privacy protection or not. This is emphasized in Miller and Tucker's (2018) work, which shows that different types of privacy protections had very different effects on the adoption of personalized medicine technologies: regulations that gave consumers control over disclosures enhanced adoption, but regulations that imposed consent requirements decreased adoption.

Privacy regulation puts a cost on tracking information flows. The welfare effects of these costs may be ambiguous.

First, there may be knock-on effects to industry structure from privacy regulation. Campbell, Goldfarb, and Tucker (2015) show that because privacy regulations typically require firms to persuade their consumers to give consent, which in turn imposes a cost on the consumer, small firms and new firms are disproportionately affected because it is harder for them to obtain consent under the regulation.

Second, welfare complications of privacy policies are also hard to assess due to a privacy paradox, where consumers state an affinity for privacy, but then act in ways that are not consistent with this stated preference. Athey, Catalini, and Tucker (2017) provide some evidence about the extent to which small incentives, distracting information, and small navigation costs can lead to a gap between stated privacy preferences and actual behavior. Furthermore, assessing the value of privacy is complicated for many reasons, including that privacy preferences for the same individual change over time (Goldfarb and Tucker 2012b).

Third, much of the work in the economics of privacy has understandably focused on questions relating to industrial organization, there are also implications of digital technologies and privacy for the economics of national security. In addition to improving the ability of firms to track consumers, digital technology allows government crime-fighting agencies to track a broad swathe of the population. Marthews and Tucker (2014) show that increasing consumer awareness of government data use leads to increased privacy-protecting behavior among consumers in their interactions with firms.

7. *Reduction in Verification Costs*

The reduction in tracking costs has also led to a reduction in costs associated with the verification of identity and reputation. This was not anticipated by the early literature in economics because the earliest reporting on the Internet suggested that it would be a vehicle for anonymity—"On the Internet, nobody knows you're a dog."[5] Furthermore, in addition to tracking cost falling, digital technologies have also made it easier to verify identity and also create a digital reputation.

In the absence of such technologies, a long-standing solution for firms to provide credible information about quality was to develop a reputation in the form of a brand (Tadelis 1999, Smith and Brynjolfsson 2001, and Waldfogel and Chen 2006). However, digital markets involve thousands of small players. Furthermore, these small players can be unfamiliar to potential customers. Einav et al. (2017) estimate that 88 percent of online Visa transactions are with a merchant that the customer does not visit offline. Alternative mechanisms to brand-based reputations are needed. The literature on verification costs builds on economic models of reputation, exploring when the experiences of previous buyers and sellers can enable market exchange in the presence of asymmetric information about quality and trustworthiness. This emphasis on reputation models distinguishes the literature on verification costs from the literature on tracking costs, which emphasizes price discrimination, advertisement targeting, and other forms of personalization.

7.1 *How Do Online Reputation Systems Facilitate Trust?*

The most common such mechanism is an online rating systems in which ratings from past buyers and sellers are posted for future market participants to see. The marketplace that has received the most attention in the literature is eBay. As mentioned above, one reason eBay has received so much attention by economists is that it provided a useful setting to test auction theory. Another reason relates to reputation mechanisms. eBay recognized the challenges of getting people to buy from strangers whom they will not meet in person (Resnick and Zeckhauser 2002 and Livingston 2005). To address this issue, they built, and continually adapted and improved, a ratings system. The effectiveness and development of this ratings system has been the subject of hundreds of papers in economics and management. For example, Ba and Pavlou (2002) shows how a ratings system can enable trust in the absence of repeated interactions. A number of papers empirically demonstrate that better-rated sellers have higher prices and higher revenues (Melnik and Alm 2002, Livingston 2005, Houser and Wooders 2005, and Lucking-Reiley et al. 2007). Cabral and Hortacsu (2010) demonstrates differences between positive and negative feedback, emphasizing how the ratings system acts as a disciplining force in the marketplace in which sellers with low ratings exit from eBay's platform.

Therefore, the original emphasis of the reputation literature was as a platform for establishing trust in long-distance transactions. Dellarocas (2003) recognizes early on that the application of these feedback mechanisms was not limited to online exchange. Instead, Dellarocas argued that such mechanisms would enable a variety of market activities, both online and offline. As long as incentives to deviate are not too high, such systems can provide credible quality signals in a variety of settings (Dellarocas 2003 and Cabral 2012).

One key application is to provide information on product quality. Rather than enhance information about a particular seller, ratings

[5] The *New Yorker* on July 5, 1993.

can inform consumers about the best products available within a platform. It might be in the platform's interest to provide such information so that consumers are directed to the highest-quality products. Comparing changes in reviews on Amazon relative to Barnes & Noble, Chevalier and Mayzlin (2006) demonstrate that positive reviews lead to higher sales.

More recently, the literature has focused on how online tools reduce verification costs in offline settings. Luca (2011) shows how online restaurant reviews on Yelp affect restaurant demand, particularly for independent restaurants. Overall, his results suggest that Yelp led to a decrease in the share of chain restaurants relative to independents. Hollenbeck (2018) finds a similar result for hotels.

It is easier to establish an online reputation using online reputation mechanisms, but the mechanisms for damaging that reputation in the form of consumer complaints have also become easier. Historically, complaints were registered with letters, and then calls into call centers. Social media enables rapid widespread communication of complaints to both the firm and a wider audience. Gans, Goldfarb, and Lederman (2016) use data from Twitter to explore ideas on the relationship between market power and consumer voice first sketched out in Hirschman (1970). They show that consumers are more likely to voice their complaints via Twitter in locations where airlines have a higher share of flights. In turn, airlines are more likely to respond to consumers in these markets. Tucker and Yu (2017) show some positive effects of digital technologies, in that the use of mobile apps to receive complaints can actually advantage less-educated consumers who are more likely to suffer from employee–consumer discrimination in the treatment of their complaints.

A benefit of improved online verification procedures for individuals has been the ability to more securely and easily make payments. This is demonstrated by Economides and Jeziorski (2017), who show the power of using mobile devices to digitally verify identity in Tanzania. They show that this power enables the use of mobile payments networks to transfer money to others, but also, equally importantly, to transport money over short distances. People appear to deposit cash after work, walk home, and then pick up the cash at home. The verification system enables easy deposits and withdrawals, thereby reducing the risk of robbery. Digital verification, in the form of DNA databases, has also been shown to reduce crime (Doleac 2017).

As technology improves, verification may continue to become easier. Researchers have speculated that the blockchain is a promising technology for reducing verification costs further (Catalini and Gans 2016). Blockchain is a technology that combines insights from game theory and cryptography to enable the exchange of value between two distant untrusting parties without the need for an intermediary. Transaction attributes, or information on the agents involved, can be cheaply verified if stored on a distributed ledger. This means that trust in an intermediary could be replaced by trust in the underlying code and rules that define how the network can reach agreement. Currently, most of the literature on blockchain technologies focuses on specific applications of the technology such as cryptocurrencies (Böhme et al. 2015 and Catalini and Tucker 2017). However, if blockchain technologies achieve the promise highlighted in Catalini and Gans (2016), then we might see a diverse literature emerge over the next few years on the consequences of low-cost verification—and the associated changing role for intermediaries—across a variety of empirical settings.

7.2 *Is There a Role for Policy in Reducing Reputation System Failures?*

Given the important role of such systems in generating demand, it is perhaps unsurprising that the economics literature has focused on questioning when reputation systems fail. Often the failures relate to incomplete ability to verify the person doing the rating online. One type of failure relates to a selection bias: not all consumers provide ratings. Nosko and Tadelis (2015) show evidence of such a selection bias, in which buyers with a bad experience do not bother to rate the seller. They instead stop buying from any sellers on the platform into the future. Poor service by a seller therefore creates an externality. The failure of the reputation systems hurts the platform, rather than the individual seller. Another type of failure relates to direct manipulation of the ratings by the firms or their competitors. Mayzlin, Dover, and Chevalier (2014) and Luca and Zervas (2016) show evidence of manipulation, in which firms seem to give themselves high ratings while giving low ratings to their competitors. This evidence of manipulation suggests that ratings systems alone are insufficient.

The challenges of ratings systems were recognized relatively early in the digital economics literature. Consider the market for collectible baseball cards. When buyer and seller are in the same place, the buyer can inspect the quality of the card in the store. They can look for rips, folds, or frayed edges. Online, quality is hard to assess. Jin and Kato (2006) provide evidence of fraud in these markets. They show that the online reputation system is insufficient in many ways. In a companion paper (Jin and Kato 2007), they show how a professional grading industry grew to help solve the information asymmetry between buyers and sellers online. Stanton and Thomas (2016) shows the value of online intermediaries in providing information beyond platform ratings by examining worker and firm behavior on an online labor market. They show that new workers benefit from affiliating themselves with an agency.

The platforms also work to improve their reputation systems. Fradkin, Grewal, and Holtz (2017) document two experiments made at Airbnb with this aim: offering monetary incentives to submit reviews and implementing a simultaneous review process to reduce strategic reciprocity. Hui et al. (2016) show, in the context of eBay, that platforms benefit by having both reputation systems and regulations to expel bad actors.

In each of these cases, it has been the private sector that has reduced these reputation system failures. To the extent that there has been a role for policy, it has been in the enforcement of contracts and prevention of fraud. At this point, the literature does not point to a specific digital policy with respect to reputation systems failures.

One aspect of policy related to verification is the nature of intellectual property tools such as trademarks. Trademarks allow customers to verify whether a brand is indeed the brand it claims to be. Chiou and Tucker (2012) and Bechtold and Tucker (2014) document that, online, consumers use trademarks to search proactively. The trademark therefore serves two purposes: it verifies identity and it provides a path to search for related products. Trademark policy needs to be narrow enough to facilitate search related to trademarks, but broad enough to ensure that such search does not sow confusion on brand identity.

7.3 *How Do Digital Markets Affect Antidiscrimination Policy?*

A second policy issue driven by changes in verification relates to discrimination. If people were indeed truly anonymous on the Internet, then there could be no direct discrimination. However, the drop in verification costs and the ability to identify an

individual and also their characteristics makes discrimination possible (and potentially low cost) in a digital environment.

The question, then, for policy makers is whether there is something unique to the online setting that requires additional regulation beyond existing antidiscrimination law. One area where this is hotly debated is in the use of algorithms to parse data and automate the allocation of resources and decision making. This is investigated in Lambrecht and Tucker (forthcoming), which shows that algorithms may lead to apparently discriminatory outcomes for innocent reasons. In particular, they show that ads for STEM education are disproportionately shown to men by online algorithms because advertising to men is less expensive overall than advertising to women, and so advertisers who are indifferent to gender end up showing their ads to men more often.

Broadly, on the one hand, while tracking is easier, such tracking may focus on dimensions that are legally and morally less controversial, such as preferences rather than race. If digital transactions mean that gender and race information is not revealed, then discrimination may fall. Morton, Zettelmeyer, and Silva-Risso (2003) show that Internet car purchasing reduces gender- and race-based price discrimination. Cullen and Pakzad-Hurson (2017) show that a reduction of privacy of wages in online platforms decreases pay differences across workers (though it also reduces average pay).

On the other hand, if gender, race, or other sensitive information is revealed, it is possible that, in the absence of other information, discrimination is high. For example, Ayres, Banaji, and Jolls (2015) and Doleac and Stein (2013) show that sellers receive lower prices when a black hand is shown with the item than when a white hand is shown. Acquisti and Fong (2013) present the results of a field experiment to study how employers use information on social networks to filter the suitability of employees. They find considerable use of social networking sites for potentially discriminatory purposes. Similar results have been found in a variety of other online contexts (Pope and Sydnor 2011 and Edelman and Luca 2014).

Both online and offline, discrimination is prevalent. Open questions remain as to whether discrimination is more prevalent online or offline, and as to whether policies aimed at reducing online discrimination specifically will reduce discrimination overall, or simply push discrimination into another setting.

8. *Consequences of Digitization for Economic Actors*

As people spend more time consuming digital media and buying products online, and as business and government increasingly use digital technology, it suggests a broader question: how does storing information in bits rather than atoms affect welfare? As search, reproduction, transportation, tracking, and verification costs fall, has that had an effect on the economy?

Broadly, the literature has tackled this question in four different ways: country-level effects, region-level effects, firm-level effects, and consumer-level effects.

8.1 *Country-level Effects*

The macroeconomic productivity literature with respect to Internet technology has its roots in the Solow (1987) claim that "you can see the computer age everywhere but in the productivity statistics." This "productivity puzzle" persisted for many years. A large growth accounting literature has arisen to examine this puzzle and measure the overall effect of digital technologies on the economy. While we view this literature as beyond the scope of this article, Jorgenson, Ho, and Stiroh (2008) and Bloom et al. (2010) both summarize it to suggest that there was a

post-1995 productivity surge that was largely driven by digital technology investment and usage.

Still, measuring the productivity shifts is difficult. Haltiwanger and Jarmin (2000) lay out several of the anticipated challenges in measuring the effect of the digital economy: service industry output, data on digital technology spending, price deflators, et cetera. A key challenge relates to intangible capital (Corrado and Hulten 2010), which has been found to affect productivity measurement in both the United States and the United Kingdom (Corrado, Hulten, and Sichel 2009; and Marrano, Haskel, and Wallis 2009). Soloveichik (2010) takes on this measurement challenge and identifies about $65 billion in intangible capital related to books, movies, music, and television.

A different stream of work on country-level effects examines how digital communication may affect trade flows for digital and physical goods. Freund and Weinhold (2004) provide suggestive evidence that the Internet increased trade in physical goods due to a reduction in the cost of international communication. The asynchronous nature of email communication may be particularly important for reducing the cost of communication across many time zones (Borenstein and Saloner 2001). Gomez-Herrera, Martens, and Turlea (2014) suggest, however, that this increase may disproportionately benefit English-language countries. Several of the papers highlighted earlier in this review demonstrate that the Internet facilitated trade in digital services (Blum and Goldfarb 2006, Alaveras and Martens 2015, and Lendle et al. 2016), and this might lead to offshoring of certain jobs (Tambe and Hitt 2012). While there is some debate about whether distance matters less overall than it did prior to the diffusion of the Internet (Leamer 2007, Cristea 2011, and Krautheim 2012), our reading of the literature is that those papers that focus on the direct effect of the Internet find a decrease in the role of distance in trade (Freund and Weinhold 2004, Clarke 2008, Lendle et al. 2016, and Hui forthcoming), while other papers identify other weaker forces moving in the opposite direction. Consistent with an effect of easy international communication on trade, Gorodnichenko and Talavera (2017) show that exchange rate pass-through is faster online.

8.2 *Region-level Effects*

Another question is the extent to which the Internet has led to redistribution of economic benefits within countries and, in particular, between cities and rural areas. Gaspar and Glaeser (1998) notes that digital communication could be a substitute or a complement to cities. Overall, the literature suggests that the biggest beneficiaries of digital technologies and data have been in large urban areas. The prime early beneficiaries of online media were in urban areas because the highest quality online content was produced in urban areas. This might be one reason why Savage and Waldman (2009) find that urbanites have higher willingness to pay for broadband. Eichengreen, Lafarguette, and Mehl (2016) show that efficient electronic communication in foreign exchange markets led to an increase in offshore currency trading and the consequent agglomeration of currency markets in London and a small number of other major financial centers. Forman, Goldfarb, and Greenstein (2012) shows that wealthy cities were the primary beneficiaries of the business Internet.

The mechanism through which cities appear to have benefited has been shown to depend on agglomeration effects, particularly with respect to skilled workers in local labor markets. Forman, Goldfarb, and Greenstein (2005, 2008) show that Internet adoption by businesses is higher in cities and in large companies but the advantage associated with being in a city or a large company

are substitutes for each other. This indicates the importance of agglomeration effects. Dranove et al. (2014) finds similar results for hospitals.

In contrast to the above work, there is some evidence that Internet adoption has some benefits for isolated individuals and rural areas. Autor (2001) and Gaspar and Glaeser (1998) speculated that the Internet might reduce the need for task-specific workspace, thereby increasing the prevalence of "telecommuting" and reducing the need for home and work to be nearby. Kolko (2012) shows that broadband disproportionately benefited people in low density areas in terms of employment, though the overall effect is small. Furthermore, while the primary result in the Sinai and Waldfogel (2004) study cited above is that urban areas have higher quality Internet content, they also show that isolated individuals consume disproportionately more Internet news. For example, blacks in white neighborhoods consume more Internet news. Finally, Forman, Goldfarb, and Greenstein (2005) show that basic Internet technologies have (perhaps disproportionately) benefited rural and isolated cities.

Overall, two forces are at play. Agglomeration effects mean that cities disproportionately benefit. Low-cost communication, however, can benefit the geographically isolated. In any particular context, the overall result depends on the balance between these forces. Generally, the more difficult the technology is to use, the more likely that agglomeration effects dominate.

8.3 *Firm-level Effects*

As noted above, the growth accounting literature has suggested a compelling link between digital technology investments and productivity growth at the country level; however, causal inference is difficult with macro-level measurement. There is a large and growing literature that documents a direct link from digital technology adoption and usage to productivity growth at the firm level. By using micro data and various econometric techniques to address selection, omitted variables bias, and simultaneity, this literature has found that digital technology adoption and usage does enhance productivity. However, the story is not as simple as it seems at first. Only some types of firms experience improved productivity. Various factors enhance or mitigate this relationship, including organizational change, skills, geography, regulation, firm size and age, and the potential for spillovers and/or network externalities.

Reviews by Brynjolfsson and Saunders (2010) and Draca, Sadun, and Van Reenen (2009) conclude that ICT adoption and usage increase firm performance. This conclusion is driven by a large number of papers and a variety of settings. The correlation between IT and productivity is even stronger when ICT investment is modeled with a lag (Brynjolfsson and Hitt 2003).

There are also specific case studies on the effects of ICT on productivity. Baker and Hubbard (2004) show that ICT improved productivity in trucking. Jin and McElheran (2017) show improved productivity in manufacturing. Agrawal and Goldfarb (2008) show that BITNET increased academic productivity at middle-tier universities. In health care, Athey and Stern (2002) show that ICT, in the form of Enhanced 911, improved emergency response; Miller and Tucker (2011) and McCullough, Parente, and Town (2016) show that electronic medical records (EMRs) improve patient outcomes; Dranove et al. (2014) show that EMRs reduce hospital costs in the presence of complementary skills but not otherwise; and Lee, McCullough, and Town (2013) show that EMRs increase hospital productivity.

Bloom, Sadun, and Van Reenen (2012) use a large-scale multi-country firm-level panel database on ICT and productivity.

Their database contains 19,000 firms in thirteen EU countries over eleven years, plus a smaller panel of US firms over the same time period. They conclude that ICT does increase productivity, though they find considerable heterogeneity in this effect across countries and type of firm. They emphasize the importance of organizational capital, showing that US multinationals operating in the United Kingdom experienced the same productivity miracle as US-based establishments. In contrast, other multinationals (and other firms) in the United Kingdom did not. The title communicates the idea well: "Americans do I.T. better." They argue that US firms are organized in way that allows them to use ICT more efficiently. This essential role of organizational capital and organizational structure in making productive use of ICT investments is a recurring theme elsewhere in the literature (Bresnahan, Brynjolfsson, and Hitt 2002; Brynjolfsson and Saunders 2010; Garicano 2010; Tambe, Hitt, and Brynjolfsson 2012; and Brynjolfsson and McElheran 2016).

In addition to change in the organizational structure, the most effective use of advanced ICT also involves "coinvention," the process of adapting ICT to the organization's needs (Bresnahan and Greenstein 1996). Such process innovation is easiest for firms in places that have a pool of local ICT expertise to draw on (Forman, Goldfarb, and Greenstein 2008; and Dranove et al. 2014). This of course reflects the extensive literature on skill-biased technological change, which is long and beyond the scope of this review. As reviewed in Acemoglu and Autor (2012), given that prior generations of IT are skill-biased, it is perhaps unsurprising that use of the Internet to enhance productivity is also skill-biased. Correspondingly, in the context of the Internet, Akerman, Gaarder, and Mogstad (2015) provide evidence that broadband diffusion in Norway disproportionately benefited skilled workers.

8.4 *Consumer-level Effects*

Measurements that focus on productivity or national income accounts do not measure consumer surplus. To the extent that much of the most valuable content online is free, measures of productivity and GDP may miss a potential increase in consumer surplus driven by the Internet (Scott and Varian 2015; Brynjolfsson, Eggers, and Gannamaneni 2017; Greenstein and McDevitt 2011; and Goolsbee and Klenow 2006). With time use data, Wallsten (2013) demonstrates that we are spending an increasing proportion of our leisure time online, substituting for offline leisure (including television), and to a lesser extent work and sleep. Also with time use data, Goolsbee and Klenow (2006) estimate a consumer surplus of $3,000 per person-year in 2005. Goldfarb and Prince (2008) shows that this effect is heterogeneous. Overall, rich educated Americans are more likely to adopt and therefore, overall consumer surplus disproportionately goes to the wealthy. At the same time, conditional on adoption, lower-income people spend more time online. Therefore, among adopters, consumer surplus (at least relative to overall consumption) is higher for lower-income people.

Many studies arrive at specific estimates of the consumer surplus from Internet-related technologies. Greenstein and McDevitt (2011) measures the consumer surplus associated with broadband diffusion at $4.8 to $6.7 billion between 1999 and 2006. Brynjolfsson and Oh (2012) estimate the consumer surplus from free online services to be close to $100 billion. Cohen et al. (2016) estimate billions of dollars in consumer surplus from the UberX car service alone.[6]

[6] Greenstein and Nagle (2014) estimate an intangible benefit of digitization distinct from consumer surplus: the value of open source. It shows that open source software Apache generates at least $2 billion in unmeasured benefits to the US economy.

Brynjolfsson, Eggers, and Gannamaneni (2017) provide perhaps the most comprehensive estimate of the consumer surplus of the Internet by using (incentive compatible) choice experiments. For example, in one study, they asked people how much they would need to be paid in order to not have access to Facebook for a month. They then implemented the result by actually blocking their respondents' access to Facebook in exchange for payment. They estimate a value of Facebook of about $750 per user per year, or $18 billion for the United States. They also generated user-level survey estimates of the consumer surplus from other free online services such as search engines ($16,000 per user per year) and online video ($900 per user per year).

Before concluding, it is important to recognize that there are other, perhaps negative, changes to overall welfare that may result from shifts in Internet consumption that are not captured by these surplus measures. Belo, Ferreira, and Telang (2014) show a reduction in grades associated with schools adopting broadband, perhaps because online games distracted students. Bhuller et al. (2013) argue that Internet diffusion may have increased sex crime, likely due to increased consumption of pornography (not because of reporting or matching between offenders and victims). Similarly, Chan, Ghose, and Seamans (2016) suggest an increase in racial hate crimes associated with the Internet, and Falck, Gold, and Heblich (2014) suggest that Internet availability reduces voter turnout in elections.

9. *Conclusions*

Across a variety of fields, economists examine how digital technologies change economic activity. While these papers often have different perspectives and cite different literatures, a core theme is that digitization has reduced a number of specific economic costs. We have identified five such costs: search, reproduction, transportation, tracking, and verification. These themes inform our understanding of the nature of digital economic activity, and of the interaction between digital and non-digital settings.

In defining the scope of this article, we drew boundaries. For example, we did not discuss work on skill-biased technical change. Because skill bias is not primarily driven by the storage of information in bits, and because there are several other reviews of that literature, we instead refer to Katz and Autor (1999), Acemoglu (2002), Goldin and Katz (2008), and Acemoglu and Autor (2012). Similarly, we limit the discussion of the digital technology growth accounting literature, referring the reader to Jorgenson, Ho, and Stiroh (2008) and Bloom et al. (2010). We also limited our discussion on three topics that have already received reviews in the *Journal of Economic Literature*: privacy (Acquisti, Taylor, and Wagman 2016), online auctions (Bajari and Hortacsu 2004), and telecommunications pricing and universal service (Vogelsang 2003).

This overview highlights that changes to economic behavior that result from the change of costs inherent in the digital context are not as obvious as basic economic models might imply. Key open questions remain with respect to each of the cost changes highlighted. Further, other categories of costs may shift downwards as digital technology evolves.

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