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Origins and Pathways of Innovation in the Third Industrial Revolution*

Sweden, 1950-2013

Josef Taalbi[†]

Abstract

This study examines the factors that have shaped the long-term evolution of the ICT industry in Sweden, 1950-2013. Exploiting a new historical micro-database on actual innovation output, the driving forces and technological interdependencies in the third industrial revolution are chronicled. The results of this study support some stylized facts about innovational interdependencies in general-purpose technologies: a closely knitted set of industries have provided positive and negative driving forces for the development of ICT innovations. The historical evolution of the GPT surrounding micro-electronics can in this perspective be described as a sequence of development blocks.

Keywords: ICT, General-Purpose Technologies, Innovation Biographies, Network Analysis, Development Blocks

JEL: O3 N14 L16

1 Introduction

What forces shape the long-term evolution of technological systems? The received view unanimously tells us how technological development is an inert process that *takes time*, simply because technology diffusion is characterized by the coordination and coming into place of several complementary technologies and institutional arrangements. There is however no consensus on what forces actually shape the evolution of technological interdependencies. Some accounts have tended to stress the role of innovational complementarities, while others stress more the overcoming of obstacles and imbalances (Dahmén, [1942] 1991, [1988] 1991; Rosenberg, 1969; Hughes, 1987; David, 1990; Bresnahan and Trajtenberg, 1995; Lipsey, Carlaw, and Bekar, 2005; see also Markard and Hoffmann, 2016). Though technological interdependencies have at-

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tracted interest from scholars of innovation and technology, remarkably few studies have investigated empirically from a long-term perspective what driving forces actually matter in the evolution of general-purpose technologies (GPTs) and how the formation of interdependencies in technological systems take place.

This study explores the history (1950-2013) of information and communication technology (ICT) in Sweden through the lens of a new historical micro-database which encompasses in its entirety more than 6,000 innovation output objects (Sjöo, Taalbi, Kander, and Ljungberg, 2014; Sjöo, 2014; Taalbi, 2014). In doing so, it is possible to address empirically several issues raised in the theoretical literature on general-purpose technologies and broader technology shifts that previously have received relatively little attention in empirical work.

The issues at hand are what mechanisms drive the development of innovations in long-run technology shifts and the structure of the interdependencies that shape innovation activity in the long run. By examining innovation biographies, this study chronicles the driving forces of ICT innovation in terms of the obstacles, problems and opportunities that have driven innovation activity in the hardware and software ICT industries from the mid-20th century. Second, we construct an innovation flow matrix (Taalbi, 2014, 2017) to study the supply and use of innovations and to delineate the structure of interdependencies in the ICT technological system.

The paper is organized as follows. Section 2 examines historical perspectives on broader technology shifts and the third industrial revolution. Section 3 discusses the methods and data used in the paper. Section 4 presents basic results on the origin of ICT innovations and narrates main driving forces in the history of the Swedish ICT innovations based on the collected innovation biographies for 1950-2013. Section 5 goes on to investigate the structure of the ICT innovation network in the course of the mid-20th and 21st century. The concluding section discusses the corollaries of the empirical results for the theories of GPTs and long-run economic growth.

2 Perspectives on the third industrial revolution

The history of modern capitalism is certainly intricately shaped by the pervasive and radical technologies that are sometimes called general-purpose technologies (GPTs). Economic historians and economists have come up with several theories and concepts to explain and delimit these broader technology shifts and their interplay with the process of economic development. According to a perspective popular among economic historians we have in modern times seen three major technology shifts, starting with the industrial revolution of the 18th century. A second industrial revolution was based on the combustion engine and electric motor, enabling the electrification of factories and homes and the post-war expansion of automotive vehicle infrastructure. We are now in the midst of a third industrial revolution, centered on the diffusion of two of the most canonical examples of general-purpose technologies: micro-electronics and the Internet, subsumed in the label ICT.

How do such broad technology shifts take place? What do we know about the

evolution of GPTs such as micro-electronics and the Internet? The literature seems to agree on a couple of things. The bulk of the theoretical literature would agree that a GPT is "a single generic technology" that

- i "initially has much scope for improvement",
- ii "eventually comes to be widely used, to have many uses" and
- iii has innovational complementarities, or "many spillover effects", (Lipsey et al., 2005, p. 98)

Using this definition, Lipsey et al. (2005) could single out 24 GPTs, among which in modern times, apart from the computer and Internet, are the steam engine, the factory system, electricity and potentially nano-technology. It appears however that much of the research on GPTs has gotten caught up in discussions of how to appropriately measure the GPT character of particular technologies (Hall and Trajtenberg, 2004; Feldman and Yoon, 2012), which technologies that are GPTs¹, the extent of their productivity effects and in the most critical vein if the notion of GPT is a useful concept to economists and economic historians in the first place (see Moser and Nicholas, 2004; Field, 2008; Bekar et al., 2016).

This study argues that, while far from a useless notion for economic historians, there is scope for enriching the GPT framework by a critical comparison with other historical frameworks proposed to explain the evolution and workings of technological systems. Table 1 relates the broad historical contours of three different frameworks that have been put into use to convey and describe major historical technology shifts: GPTs (Lipsey et al., 2005), techno-economic paradigms (Perez, 1983, 2002; Tylecote, 1992; Freeman and Louça, 2001) and development blocks (Dahmén, 1950; Schön, 2006, 2010; Kander et al., 2014).² Superficially, the frameworks appear to be similar. However, stark differences appear when we scrutinize how technology shifts are described as taking place. This concerns two important aspects of the evolution of technological systems: the mechanisms that drive the formation of interdependencies and the structure (or "topology") of interdependencies in the technology shift. Thus, quite importantly, the TEP and DB frameworks challenge assumptions made in the literature on GPTs. This study will eventually address the mechanisms at play in the unfolding of ICT in Sweden, but first let us see in what way the frameworks differ.

The first facet of interest is what driving forces have shaped the evolution of ICTs. In common to all these frameworks is the basic notion that large technology shifts have a quality of being driven by interdependencies. However, there are some stark differences between what type of interdependencies are put in center. In its canonical form, the theory of general-purpose technologies (Bresnahan and Trajtenberg, 1995; Helpman, 1998; Lipsey, Carlaw, and Bekar, 2005) describes technology shifts in terms of

¹For instance, Moser and Nicholas (2004) argued against a general-purpose character of electricity, with aid from historical patent citation data from the early 20th century. Though the general-purpose character of microelectronics and Internet technologies is uncontroversial, doubts have also been raised by some (notably Gordon, 2000, 2016) with regard to its effects on productivity and its pervasiveness.

²For a further comparison of these frameworks, see Lipsey et al., 2005 and Taalbi, 2016a.

Table 1: Industrial revolutions, major innovations and development blocks

Industrial revolution	Technological revolutions ^a	GPTs	Major development blocks ^b
1st ca 1780	1. Water-powered mechanization of industry	Steam engine, Factory system	Cotton spinning, coal
	2. Steam-powered mechanization of industry and transport	Railways, steamship	Iron Steam engines, Railway infrastructure, Machine tools
2nd ca 1870 (1890) ^c	3. Electrification of industry, transport and the home	Internal combustion engine, Electricity	Electrification
	4. Motorization of transport, civil economy and war	Automobile, Airplane, Mass production	Automotive vehicles and transportation
3rd ca 1970	5. Computerization of entire economy	Computer, production, Biotechnology	Lean Factory automation, Telecommunications, Biotechnology

Note: This table summarizes a broad literature which is only superficially consentient. Periodizations of long waves differ considerably between the Swedish structural cycle perspective (Schön, 2010), the Marxist long wave theory (e.g., Mandel, 1995) and the techno-economic paradigm framework(s) (Perez, 1983, 2002; Tylecote, 1992; Freeman and Louça, 2001). Economic historians (such as Mokyr, 1990; David, 1990; Schön, 2010) tend to employ the notions of three industrial revolutions, whereas the TEP framework discusses technological revolutions.

^a Based on Tylecote (1992), Perez (2002) and Freeman and Louça (2001).

^b Based on Schön (2006;2010).

^c The dating of the irruption of the second industrial revolution differs between authors.

innovational complementarities that emerge between supplier and user sectors. The diffusion of general-purpose innovations is thus induced through the increasing returns between innovation in GPTs and application sectors (AS), forming a coordination game, for which there is a Nash equilibrium (Bresnahan and Trajtenberg, 1995). In other words, the theory of GPTs is essentially a story of positive inducement mechanisms: opportunities and complementarities. Likewise, in the framework of techno-economic paradigms (TEPs), the pulse of technological revolutions is mediated by positive feedback mechanisms: "major innovations tend to be inductors of further innovations; they demand complementary ones upstream and downstream and facilitate similar ones, including competing alternatives" (Perez, 2010, p. 188).

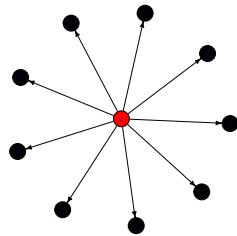
However, a long-standing claim, stressed especially in the framework of development blocks (Dahmén, [1942] 1991, [1988] 1991; Carlsson and Stankiewicz, 1991; Enflo, Kander, and Schön, 2008; Schön, 2010; Taalbi, 2016a) and technological systems (Gille, 1978; Hughes, 1983, 1987), is that systems of technologies to an equal extent evolve in response to technological imbalances and the resolution of critical problems that have to be overcome, adding to the co-evolution between industries. Rosenberg (1969) famously noted that "the history of technology is replete with examples of the beneficent effects of this sort of imbalance as an inducement for further innovation" (Rosenberg, 1969, p. 10). This applies also to more well-known and fundamental innovations. It is well-known that the main imbalance of early steam engines was the loss of steam and that the commercial practicality of steam engines came only through inventions that were directly focused by these critical problems. After years of trying, John Wilkinson's invention of the boring mill (1774) solved the problem of producing accurately bored cylinders. This in turn allowed James Watt to solve the problem of steam loss with his separate condenser in 1776. For another example, the phenomenon of electricity was known long before its economic breakthrough, but it was in the 1890s that innovations of alternating current in a three-phase system solved the critical problem of transforming higher and lower voltage, making possible the expansion of the electricity grid (Hughes, 1983). Previous empirical studies have also stressed to the importance of critical problems in the technological development in parts of the ICT sector (see e.g., Fransman, 2001; Dedehayir and Mäkinen, 2008 and section 4). One is thus not hard pressed to come up with historically relevant examples of the role played by critical problems as focusing innovation activity.

Before carrying on, I wish to make an important clarification to the statement made here. The presence of obstacles and *growth bottlenecks* in the diffusion of GPTs is hardly new to anyone. In fact, it is central to the concept of GPTs (see e.g., David, 1990; Bekar et al., 2016). As the lack of measurable productivity effects of ICT was initially puzzling, famously expressed by Solow,³ David (1990) pointed out that the conjunction of the initial diffusion of ICT with a productivity slowdown, is hardly a conundrum given the collected historical knowledge of the inert and time-consuming diffusion of general-purpose engines in the past; the first and second industrial revolutions were, despite being called revolutions, protracted processes facing obstacles that had to be resolved. For instance, the diffusion of electric power technology "was a long-delayed and far from automatic business", in part due to the switching costs faced in factory

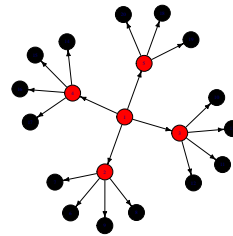
³"We can see the computers everywhere but in the productivity statistics" (cited in David, 1990).

Figure 1: Stylized topologies of technological systems. General-purpose industries in red.

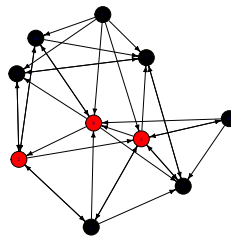
(a) Star-shaped technological system



(b) Tree-like technological system



(c) Technological system with several core industries and high reciprocity



electrification (David, 1990, p. 356). Further, Goldfarb (2005) has shown that the adoption rate of electricity was dependent on (the complexity of) technical obstacles. In brief, both productivity slowdowns and periods of stalled technological development may well characterize GPTs in early stages of their inception.

However, imbalances, technological obstacles and problems have not been fully recognized in this literature as being themselves part of the driving forces and mechanisms that may focus (cf Rosenberg, 1969) innovation activity in the diffusion of GPTs. While recent contributions have taken some steps towards a closer examination of growth bottlenecks (Bresnahan and Yin, 2010; see also Cantner and Vannuccini, 2012), there is a large literature that would suggest that the theory misses or underrates an important mechanism. Accordingly, there is work to be done in order to assess and theorize the explicit role of imbalances and technological bottlenecks in the diffusion of GPTs, alongside innovational complementarities.

The second issue concerns the topology of interdependencies that form in the diffusion of a GPT or a major technology shift. Also with regards to this matter, there are assumptions made in the literature, which have not been examined empirically in a long-term perspective. Stylized pictures of the structure of interdependencies between technologies are contrasted in figure 1. Nodes are taken to be industries producing a

technology and linkages (edges) are taken to imply the supply and use of innovation. Typically, the interdependencies are understood in terms of the relationship between a GPT sector and several application sectors (AS), i.e. sectors that apply the general-purpose engine (Bresnahan and Trajtenberg, 1995). Incidentally, Bresnahan and Trajtenberg (1995) envisioned the supply and use of semiconductors. The technological system is thus posited to have a star-like structure (Figure 1a). Though not pictured, it is often assumed that there are feedbacks and reversed inducement mechanisms from application sectors to the development of the GPT sector.

However, more complicated structures could well be at play, indicated by the notions of technological systems and development blocks. Such a structure is illustrated in figures 1b and 1c, in which several basic technologies interact. In figure 1b the interdependencies are still hierarchical, with little feedback from application sectors, while in figure 1c there is greater reciprocity (Garlaschelli and Loffredo, 2004; see also section 5). There have been some attempts to understand major technology shifts along such lines. A first qualification for understanding the position of ICT in the broader technological system is for instance given by Perez (1983) who developed a typology of the relation between producers and users of new technologies in a "techno-economic paradigm".⁴ In these broad technology shifts, 'motive branches' produce the "key inputs", such as microelectronic components, and have "the role of maintaining and deepening their relative cost advantage" (Perez, 1983). Carrier industries implement the "key input" and induce new investment opportunities: since the 1970s these have been computers, software and mobile phones (Perez, 2010). The "induced industries" follow and innovation is a consequence of the introduction of key innovations in the motive branches. Moreover, the infrastructures, e.g. railroads, electricity, roads and the Internet, are pivotal in a mature TEP. These facets of broader technology shifts are suitable for understanding the position and roles of industries in broad technology shifts.

However, on a yet finer scale the process of formation of complementarities and imbalances are typically temporally localized to certain industries. In particular, the development block approach, originating from Erik Dahmén's ([1942] 1991; 1950) work, sets focus on a core mechanism that allows us to study the diffusion of ICT in greater detail, namely, that broader technology shifts take place by way of sequences of complementarities that are advanced as innovation solves imbalances and tensions. Accordingly, a development block was defined as "a sequence of complementarities which by way of a series of structural tensions, i.e., disequilibria, may result in a balanced situation" (Dahmén, [1988] 1991, p. 138; see also Carlsson and Stankiewicz, 1991; Carlsson, 1995 and Taalbi, 2016a for a comparison between the notion of development blocks and GPTs). In this view the diffusion of GPTs is thus contingent on internal and history-specific driving forces that may develop in discrete steps among smaller sets of interdependent technologies. It is thus plausible that GPTs should form locally and temporally bounded sets of interdependencies that evolve by way of the resolution of imbalances and opportunities supplied. Thus, the diffusion of a GPT can be conceived

⁴The notion of "techno-economic paradigms" describe the successive technological revolutions brought about by sets of radical innovations (Freeman and Louça, 2001; Perez, 2002). The use of 'paradigms' alludes of course to (Kuhn, 2012 [1962]) and stresses that there is a strong direction and sense of progress in technological change.

as a *series of development blocks*. Accordingly, this study hypothesizes that our understanding of the evolution of ICT perhaps can be better informed by analyzing it as temporally localized sets of complementarities and imbalances between technologies or industries, that for some period of time provide the core impetus for further development. Clearly, this makes the historical analysis of imbalances and complementarities the center of attention.

2.1 An illustration

Given the present suggestion one might ask under which circumstances GPTs would actually evolve as development blocks, i.e. temporally and industrially localized sets of interdependent technologies. To show how the topology of interdependencies might matter for the wider diffusion of GPTs, we briefly consider a formal model of technological interdependencies. Let $d\Phi_j$ be the rate of innovation in industry j , i.e. the increase in quality or "fitness" Φ_i , and let $d\Gamma_i$ be the change in incentives for search. Then we can define a matrix of technological interdependencies, a "technological multiplier matrix", (Cantner and Vannuccini, 2012)⁵ \mathbf{T} with respect to innovation in industry j through

$$d\Gamma = \mathbf{T}d\Phi \quad (1)$$

The multiplier matrix \mathbf{T} specifies the impact of innovation on incentives for innovation in other sectors. Integrating the above-mentioned accounts, there are two main sources of such incentives. Positive inducement takes place by increases in the expected payoffs of innovation in a particular good, or in "innovational complementarities", i.e. technological opportunities that lower search costs (Bresnahan and Trajtenberg, 1995; Klevorick et al., 1995). Negative inducements, technological imbalances, decrease the current payoffs relative to expected payoffs from search.⁶

The actual pattern of innovation is of course a response to incentives. We may write the rate of innovation as

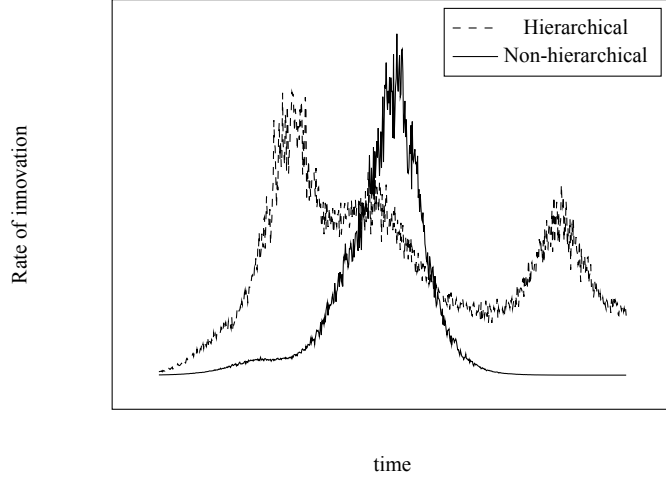
$$\frac{d \ln \Phi}{dt} = \alpha \Gamma \quad (2)$$

where the logarithm guarantees that $d\Phi \geq 0$ and α determines the general rate of innovation as response to opportunities or imbalances. The technological multiplier is, to the extent that innovation responds to technological interdependencies, what governs long-run patterns of innovation. We note that diagonal elements of the technological multiplier matrix should be negative, since improvements in a technology should de-

⁵Analogous to Leontief multipliers (Goodwin, 1949), the term originates from Cantner and Vannuccini (2012), which suggested it to capture the old idea that the introduction of technologies may create conditions for further advances elsewhere. At this juncture the technological multiplier matrix is formalized as the impact of innovation in sector j on *incentives* for innovation in sector i .

⁶We could think of incentives for innovation Γ_i as the excess of expected payoffs from search π_i^e over current payoffs π_i and search costs C_i : $\Gamma_i = \pi_i^e - \pi_i - C_i$. Positive inducement increases expected payoffs, or lowers search costs. Imbalances increase the payoff gap $\pi_i^e - \pi_i$. These ideas are developed further in Taalbi (2016b).

Figure 2: Simulations of the rate of innovation with hierarchical and non-hierarchical multiplier interdependencies



plete opportunities or close imbalances. Second, off-diagonal elements of the technological multiplier matrix, are assumed non-negative.⁷

Solving the first differential equation, the above two equations can be combined to yield

$$\frac{d\Phi}{dt} = \alpha (\mathbf{m} + \mathbf{T}\Phi) \Phi \quad (3)$$

where \mathbf{m} is a vector of integration constants. The solution of this equation is a generalized logistic function:

$$\Phi = (\Psi - \mathbf{T})^{-1} \mathbf{m} \quad (4)$$

with

$$\Psi = \begin{pmatrix} \exp(-\alpha m_1(t - t_1)) & 0 & \dots & 0 \\ 0 & \exp(-\alpha m_2(t - t_2)) & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \exp(-\alpha m_N(t - t_N)) \end{pmatrix}$$

where t_1, \dots, t_N are integration constants determining the midpoints of the logistic functions. From this follows that innovations arrive in a wave-like pattern over time, where α determines the rate of diffusion. The wave-like dynamics owes to the fact that while innovational interdependencies provide stimulus for innovation, improvements eventually exhaust opportunities or close imbalances.

Figure 2 shows simulation results from a model where α is assumed to be a random draw from the uniform distribution. The non-hierarchical technology multiplier matrix

⁷Additional assumptions could imply that the technological multiplier is eventually exhausted at high fitness levels, i.e. approaches 0 for high Φ . Such assumptions are not unrealistic, but can be used to show the same principal result as the present framework.

is a matrix with entries drawn from a uniform distribution. The hierarchical technology multiplier matrix is generated by multiplying a random matrix with the adjacency matrix of a random tree.⁸ Obviously, the topology of interdependencies embodied in \mathbf{T} is important for the character of the evolution of technologies. As visualized in Figure 2, a highly connected, i.e. non-hierarchical, network of innovational interdependencies is quickly exhausted in one single wave. Conversely, a more hierarchical, tree-like or star-like, network will tend to unleash the innovative potential in spurs and innovation will tend to be located at certain industries at a time. Accordingly, we should expect a development block dynamism to be associated with hierarchical network topologies.

3 Methods and data

The aims of this study are to examine both the driving forces, or "origins", of ICT innovation, and the structure and "topology" of interdependencies between ICT industries and other industries against the backdrop of theories of GPTs and development blocks. To this end this study employs a recently constructed longitudinal micro-database, which contains extensive information about single product innovations commercialized by Swedish manufacturing firms between 1970 and 2013 (Sjö, Taalbi, Kander, and Ljungberg, 2014).⁹ This database collects actual innovation objects according to the Literature Based Innovation Output method (LBIO), where articles from trade and technical journals are used as the source of innovation biographies and both qualitative and quantitative information on innovation objects (Kleinknecht and Bain, 1993). This data covers the manufacturing sector and is employed throughout the paper. Moreover, an extension of the database for the engineering industry has been constructed for 1950-1969, here employed as sources for the historical description on early ICT innovations.¹⁰

Over 6,000 innovation objects have been registered through the reading of trade journals for 1970-2013. Trade journal articles provide detailed information on the innovating firm, as well as descriptions of the development and commercialization of individual innovations. This information has been used to produce time series of the commercialization of innovations and to classify innovations according to economic, social and other factors that led to or contributed to their development. Thus, it is possible to simultaneously assess when innovations were launched, and the types of problems and opportunities that drove their development.

The database was constructed by scanning 15 Swedish trade journals, covering the manufacturing industry, for independently edited articles on product innovations. Apart from ensuring a coverage of all major ISIC 2-digit manufacturing industries, these trade journals were selected with the criterion that journals are not affiliated with any com-

⁸The above requirements on the technological multiplier matrix apply, with appropriate parameter choices.

⁹A first version covered 1970-2007. An extension of the database to 2014 was finished in May 2016.

¹⁰Due to the selection, statistical information is not comparable between the data 1950-1969 and the full database 1970-2013, why the early sample is only exploited for a qualitative description of the history of ICT innovation in Sweden.

pany or otherwise biased and that the journal has an editorial mission to report on technological development of the industry. The edited sections of journals were in turn scanned for innovations, defined as *an entirely new or significantly improved good, process or service that is transacted on a market*. Moreover, only innovations developed by Swedish companies were covered, in part since the editorial mission of the trade journals is more or less confined to the Swedish market.¹¹

Table 2 describes the basic data used in this study. The information available in the trade journals has enabled the construction of data about product types of the innovation (ISIC codes) and the user industries of the innovations (ISIC codes). The product types help define our main object of analysis, i.e. ICT innovations, as consisting of 5 industries: computers and office equipment (ISIC 30), electrical apparatus (ISIC 31), telecommunication equipment (ISIC 32), electronic and optical equipment (ISIC 33) and software (ISIC 72).

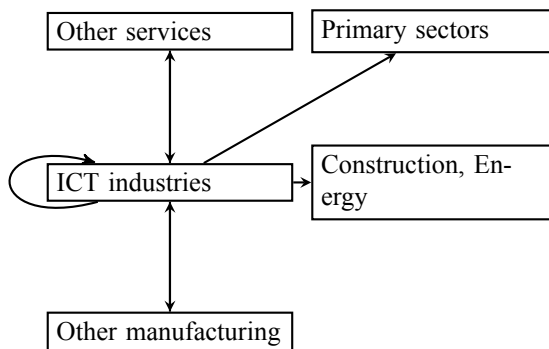
All these variables are possible to study over the period 1970-2013 since the year of commercialization is recorded for all marketed innovations. The information from innovation biographies also allows detailed description of the origins of innovation, which have been classified according to two main categories: technological opportunities (Klevorick et al., 1995) and problem-driven search (Cyert and March, 1963; Rosenberg, 1969; Antonelli, 1989). The distinction of innovations that exploit technological opportunities is based on explicit mentioning in the journal articles of a technology, which contributed to or enabled the development of the innovation. An innovation was considered problem-solving if the development of the innovation was explicitly described as aiming to overcome an obstacle or problem as defined previously. For the problem-solving innovations a note was taken of this textual evidence, which has served as the basis of qualitative descriptions of innovation activity (see Taalbi, 2014 for further details). Those innovations that could not be categorized as opportunity driven or problem-driven innovation were developed to improve a product in some dimension of performance or to accommodate customer requirements and market niches. As these did not account for a large share of the innovations, these are presented jointly as "other".

3.1 Studying interdependencies

It is possible to study some of the interdependencies that have shaped the evolution of ICT by examining the supply and use of innovations across industries. This is allowed by the variables "product type" and "user sector" (Table 2). Taalbi (2017) constructs a technology flow matrix for Sweden 1970-2007 by mapping the innovations supplied by industry i to industry j in the entire economy. This study focuses on flows to and from ICT industries during the period 1970-2013. The underlying innovation flow matrix is in principle constructed by counting the number of innovations that flow from sector i to sector j . However, as any innovation may have several user industries, we let each linkage between sectors obtain a weight, such that the sum of all linkages of an

¹¹For further details on methods and selection procedures, see Sjöö et al. (2014).

Figure 3: Simplified map of the flows studied



innovation to industries is equal to one.¹²

The network analysis of this study is only concerned with the flow of innovations that are supplied by, or used by ICT industries, the so-called *ego network* of ICT innovations, illustrated in figure 3 and detailed further in section 5. This enables a description of the linkages between ICT industries and other industries and the potential role played by feedback mechanisms in the technology shift. Through mapping the supply and use of innovations, it is also possible to investigate the structure of technological interdependencies in terms of the two structural aspects of networks referenced above: hierarchy and reciprocity. The hierarchical character is accessed through an investigation of structural characteristics, centrality and weight distributions (cf McNerney et al., 2013). The reciprocity is tested following Garlaschelli and Loffredo (2004).

4 A history of Swedish ICT innovation

This section portrays the history of Swedish ICT innovations through the lens of innovation biographies and data on innovating firms collected in the SWINNO database. The basic results on the long-term structural change of the ICT industry, for 1970-2013, are summarized in Figures 4-6. Figure 4 shows the total number of ICT innovations and the contribution of three broad subsectors: electrical apparatus (ISIC 31), computers and electronic and optical equipment (ISIC 30 and 33), and telecommunication equipment and software (ISIC 32 and 72). It is fairly apparent that ICT innovations have evolved in a pattern of two surges. One surge in innovation activity occurred during and following the structural crisis of the 1970s. Another surge began in the early 1990s, throughout the IT boom of the 1990s, culminating in the mid-2000s. These surges have signified a broader technology shift carried by the exploitation of microelectronics. During

¹² Formally, given a set of N innovations indexed by $k \in \{1, 2, \dots, N\}$, each innovation has a number of observed user industries, denoted U . The weight a for a linkage of innovation k is then $a_k = (1/U_k)$. Assigning each weight to its respective supply and user industry, i and j respectively, we obtain the innovation flow matrix A with elements $a_{ij} = \sum_k (a_{ijk})$.

Table 2: Description of key variables

Variable	Description
Commercialization year	Year of commercialization of the innovation according to journal article.
Product type	The product code (ISIC Rev 2) of the innovation.
User sector	The sector in which the innovation is or is going to be used according to the journal article. User sector specified as industries (ISIC Rev 2), final consumers or general purpose.
Problem solving	The articles cite a problem as an impulse or motivating factor for the development the innovation.
Opportunities	The articles cite a new technology or scientific advance as enabling the innovation.
Other	The innovation was developed to improve the performance or satisfy a consumer demand

the early stages of the microelectronic revolution, ICT innovation was geared towards the development of computers and electronic equipment, more specifically industry automation, through the development of control systems, computer controlled machinery, automation equipment and automatic guided vehicles. Figure 5 also shows that most of the innovations during the period 1970-1989 were driven by the exploitation of new opportunities. ICT innovations were also up until the 1980s developed predominantly by large corporate groups (see Figure 6), such as Asea, Saab-Scania, Electrolux and Volvo. The role played by these large firms in the development of ICT technology during its early stages has been highlighted by others (Carlsson, 1995).

The second surge was, as shown in Figure 4 carried entirely by telecommunication and software innovations. The broad driving forces in the second surge were the wider exploitation of microelectronics and the resolution of imbalances in the Internet and telecommunication infrastructure. Towards the end of the period, as the telecommunications and software innovations were increasingly targeting performance improvement and market niches. As opposed to the early ICT expansion, from the 1980s innovation activity in ICT was increasingly carried out by smaller and younger firms observing market niches or technological imbalances. Though large actors, notably Ericsson, were still important innovators in telecommunications in the 1990s, a strikingly small share of innovations were launched by large firms (with more than 200 employees) by the end of the period.

4.1 Origins of ICT innovation, 1950-2013

As indicated in Figure 5, the history of driving forces of Swedish ICT innovations is to a considerable extent a history of creative response to both opportunities and imbalances emerging between parts of the technological system. The below sections chronicle the history of innovations as mirrored through innovation biographies. The main observed

Figure 4: ICT innovations, total and by subsector (5 year centered moving averages)

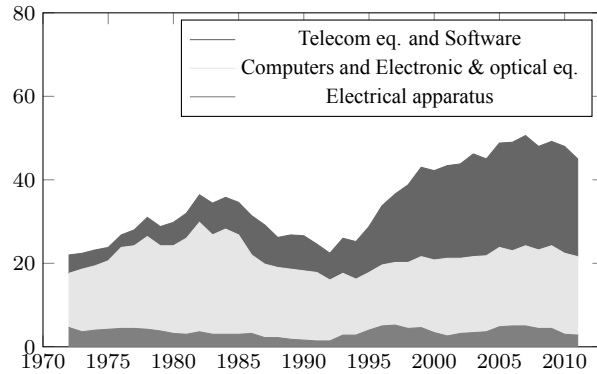
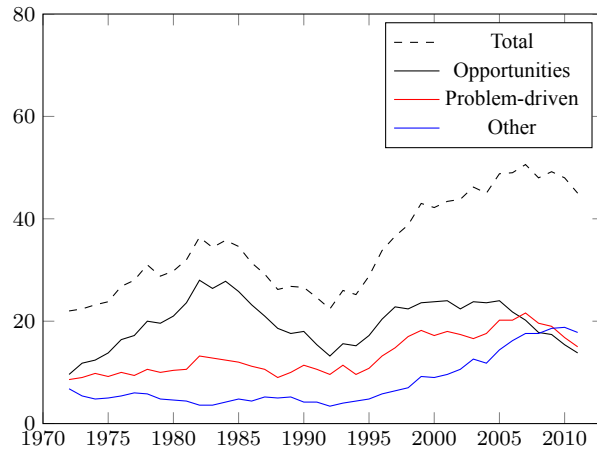
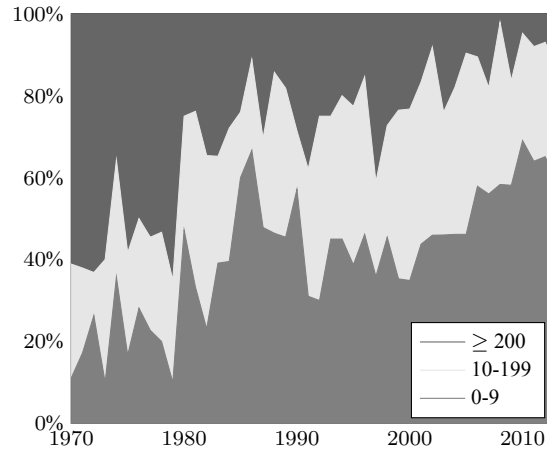


Figure 5: ICT innovations in total and by origins (5 year centered moving averages), 1970-2013.



Note: Due to overlaps the sum of opportunity, problem-driven search and other innovations may not add up to the total

Figure 6: Size distribution of ICT innovators by number of employees, 1970-2013.



imbalances and opportunities that have driven innovations are summarized in Table 3 at the end of this section.

Beginnings, 1950-1969

The early history of ICT was marked by imbalances as strong incentives for innovation. The breakthrough innovations were made on the international scene with the digital computer, called ENIAC (1945), and the transistor (1947).¹³ The first Swedish computers were developed by the Swedish Board for Computing Machinery (SBCM) in the early 1950s. These were called BARK (Binär Automatisk Relä-Kalkylator), and BESK (Binär Elektronisk Sekvens-Kalkylator) (*Teknisk tidskrift* 1950, pp. 193-194; 1953, p. 1007; 1955, pp. 273-281; 281-292). While the research activities of SBCM were later cancelled, the experience from the construction of BARK and BESK lay the basis of the continued development of computers.¹⁴ Meanwhile however, the increasing complexity of transistor-based systems, what has been called the "tyranny of numbers", made assembly costs high, which became a strong imbalance and an incentive for further innovation. Moreover, the size of complex circuits impeded efficiency in computers (Langlois, 2002). These were precisely the problems which motivated two Americans, Robert Noyce at Fairchild and Jack Kilby of Texas Instruments, to (independently) develop the first prototypes of integrated circuits in 1961.

Swedish innovators responded to these problems as well. To overcome the bottleneck of increased data processing power and the increasing requirements for mem-

¹³ENIAC built on an earlier invention developed in the 1930s and 1940s by John Atanasoff and Clifford E. Berry. Alan Turing's electronic computer developed to break the Enigma code is another, perhaps more famous, precursor.

¹⁴Main players in the early development of computers during the 1950s and 1960s were L. M. Ericsson, Facit (Åtvidaberg Industrier AB), AB Addo, SAAB, Standard Radio & Telefon AB. These firms were all well-established, having started in the 1930s or earlier (respectively, 1876, 1906, 1918, 1937 and 1938). Facit and SAAB developed their own versions of BESK under the names "Facit EDB" and "SARA" respectively.

ory space, Swedish firms (e.g. SAAB and AB Åtvidaberg Industrier) developed magnetic tape memory to enable information storage without requiring large physical space (*Teknisk tidskrift* 1958, pp. 1175-1179; *Verkstäderna* 1958:10, p. 356). From this experience, especially SAAB was able to continue development of process control equipment, the innovations MTC-6 (launched 1965) and MTC-7 (launched 1967) being especially notable. By the late 1960s, firms in the machine-tool industry were integrating numeric control equipment into new machine tool innovations, which was the beginning of an ensuing factory automation.

Irruption, 1970-1989

The key event in the modern history of ICTs was of course the development of the microprocessor, developed by Intel in 1971. Now, the information processing capacity of a digital computer was contained on a single chip and could be mass-produced at low cost. This was the decisive development that would enable the explosion in numeric capacity and the wider diffusion of computers and micro-electronics (Bresnahan and Trajtenberg, 1995; Langlois, 2002). Our innovation biographies lend evidence to the fact that strong incentives towards product innovation emerged from the opportunities of the new microelectronics based technologies. The diffusion of microprocessor based technology enabled new generations of machinery and instruments for control and measurement with vastly improved performance. At the core of the wider application of microprocessors in factory automation lay control systems and computer equipment. Numeric Control (NC) systems had already been introduced into machinery during the course of the 1960s, but predominantly among large firms. Asea was one of the pioneers of the development of commercially available Computer Numeric Control systems (CNC) with its introduction of Nucon in 1972 and Nucon 400 in 1977 (*Ny Teknik* 1972:3, p. 4; *Verkstäderna* 1977:4, p. 90). Swedish firms also lay at the forefront of the development of robots. ASEA Robotics (ABB Robotics after 1988) was a market leader in this field, launching several notable robot innovations during the period studied. ASEA's IRB 6 launched in 1973, was the first wholly electrical micro-processor controlled robot commercially available. ASEA began research and development in 1977 of a new robot system based on computer based image processing technology. The result, "ASEA Robot Vision", was commercialized in 1983 (*Ny Teknik* 1983:37, p. 3; *Verkstäderna* 1983:13, pp. 44-46).

The development of micro-electronics also enabled the solution of technological imbalances in the 1970s. A case in point is the introduction and further development of automated guided vehicles (AGV). Before the breakthrough of micro-electronics, the control systems were hampered by bulkiness and limited capacity. Solutions to these problems were made possible as integrated circuits and microelectronics were developed, which led to several development projects during the 1970s, notably involving the firms Netzler and Dahlgren, Volvo and Tetra Pak. Such technologies were an integral part of the Swedish factory automation industry (Carlsson, 1995).

Our innovation biographies also convey that the critical problems were in themselves important incentives towards innovation during the 1970s. As it were, transformation during the 1970s had both 'positive' and 'negative' sources.¹⁵ Also in the

¹⁵ One should note that apart from technological imbalances, the crisis of the 1970s also brought out a

improvement of the 'key input', micro-electronic circuits, there were imbalances that became the target of the development of new technology. Some innovations were directed towards solving critical problems in the development of smaller circuits. In the 1970s, a demand emerged for printed circuit boards (PCB) with higher packaging density. The problem with underetching, however emerged as a limiting factor. Perstorp AB was one of several international manufacturers to initiate search for a laminate material with thinner copper plates (*Ny Teknik* 1974:33, p. 10; *Modern Elektronik* 1975:2, p. 25-26). Similarly, the manufacturing of masks for integrated circuits with the technology then available (photographic lithography) tended to become a production bottleneck due to the complexity of mask patterns (*Elteknik* 1976:7, p. 22-28). In response to these bottlenecks, one firm, Micronic, developed a new method for the production of masks for integrated circuits.

In the 1980s, a wave of entrant firms emerged aiming to exploit new opportunities (for description and examples, see Taalbi, 2014, chapter 7). Many of these small firms specialized in developing computer aided design (CAD) and computer aided manufacturing (CAM) innovations, based on previous advances in robot or control systems technology. During the course of the 1980s, the factory automation industry however came under increased competitive pressure and many Swedish suppliers of machine tools and flexible manufacturing systems were forced out of business. A similar fate was suffered by the Swedish computer industry during the economic crisis, 1990-1993. At that time new forces of growth had emerged. The emphasis of ICT innovation in the 1980s lay on factory automation, but the 1980s also saw the entry of a handful of ICT firms in the segment of home electronics, notably Axis Communications and Array Printers, which became largely successful during the 1990s. As seen in Figure 4, the pattern of ICT innovations subsequently shifted its focus from factory automation towards the growing telecommunication and data communication industries.

Infrastructure, 1990-2013

Innovation activity during the period 1990-2013 can be described as being driven by the opportunities stemming from computerization and imbalances and opportunities that emerged the expansion of telecommunications and Internet. The main breakthroughs had been made in the 1980s, but it was not until the abolishment of state-owned Televverket's monopoly with the Telecommunications Act of 1993 that a veritable expansion took off. For instance, mobile telephone networks were pioneered in Sweden with NMT (Nordic Mobile Telephone system), invented by Östen Mäkitalo and launched in 1981 by Ericsson. Similarly, the first Swedish network was connected to the Internet in 1984. Internet did not however become publicly available in Sweden until 1994, when a small start-up firm, Algonet, connected Internet with the Swedish telephone network. In the ensuing expansion, Ericsson naturally accounted for a large share of innovations. Ericsson for instance developed the first wap phone (2000), the first Bluetooth product and

negative pressure to transform. Facing negative performance, some firms were pushed to diversify their production towards growing markets in electronics. For example, Sweden's first personal computer called ABC 80 was launched on the Swedish market in 1978 and had been developed by the three Swedish companies Luxor Industri AB, Scandic Metric AB and Dataindustrier AB to meet the difficulties arising from a saturated market in home electronics (TV and audio systems) (*Verkstäderna* 1978:12, p. 67; 1981:5, p. 40; *Ny Teknik* 1981:12, pp. 8-9).

the first mobile telephone supporting both Bluetooth and MMS (Multimedia Messaging Service). However, the deregulation of Telecom markets and the launching of Internet signalled the burgeoning opportunities ahead and a wave of new firms emerged, acting on the new opportunities. These new firms typically developed innovations that were aiming to solve critical problems in the deployment of Internet and Telecommunication networks. Transmission systems, network switches and electronic components for data and telecommunications were responding to obstacles to the introduction of e.g. broadband access technologies such as DSL, transmission standards such as ATM or Voice-over-IP. One of many instances of this dynamics between network standards and network components, is ATM (Asynchronous Transfer Mode) that was developed to fulfil the requirements of broadband, enabling digital transmission of data, speech and video and to unify telecommunication and computer networks. For this technology, fast circuits were needed. Ericsson developed an ATM circuit, AXD 301 for broadband networks aimed to increase performance and fulfil security requirements (*Ny Teknik* 1994:19, p. 4). Netcore (later renamed Switchcore) launched a circuit that could handle both ATM and IP technology. The technology came from a research project in which Ericsson Components, Saab Dynamics, the Royal Institute of Technology and the Universities of Linköping and Lund participated (*Elektroniktidningen* 1997:19, p. 4; *Ny Teknik* 1998:25-32, p 16-17). The circuit was customized for IP switches and routers for the Gigabit Ethernet standard. With increased traffic, the data switch was a capacity bottleneck, but with Netcore's circuit it became possible to build faster and cheaper switches. Optotronic developed a circuit for data communication in fiber optic networks, Ethernet in particular (*Ny Teknik* 2000:35, p. 16). The lack of network processors compatible with the requirements of fast routers, prompted Xelerated to develop and launch a network processor capable of 40 Gbyte/second in 2006 (*Ny Teknik* 2001:22, p. 12-3; 2002:20 Part 2, p. 7; 2007:20, p. 12)

Similarly, the introduction of mobile voice-over-ip (VoIP) technology was shaped by obstacles. This was the case, in particular, as the technique was developed for data transmission and not speech traffic. Of the commonly most well-known innovations for VoIP was Skype, launched in 2003 (*Telekom idag* 2005:4, p. 47; 2005:8, p. 38; 2006:7, p. 38-9). Several other development projects were aiming to overcome these obstacles in the introduction of voice-over-ip technology. For instance, Nanoradio was started in 2004 to solve the problem of how mobile phones could cope with VoIP. The then-available wlan circuits were power consuming and Nanoradio developed a small wlan circuit that enabled a fast synchronization of mobile telephones (*Ny Teknik* 2005:17 "IT", p. 14; 2006:8, p. 4; *Telekom idag* 2005:1, p. 19).¹⁶

A last noteworthy imbalance that spurred innovation activity, was the problem of Internet and data communication security. In the early 1980s there were a few Swedish innovations aimed to prevent database hacking, or computer thefts. With the expansion of Internet technology, and as more transactions were carried out over the Internet several firms also emerged in the late 1990s that were attempting to eliminate obstacles to

¹⁶Another example is Ericsson Research that developed a technology "to solve the basic problems with the mobile Internet" (*Ny Teknik* 2000:41, p. 22; 2000:42, p. 16; 2001:41, p. 10; translation by the author). A major problem was that IP phones would be more expensive to use than GSM mobiles, if the then best-practice Internet technology was used. The result was an IP-protocol that could solve transmission problems and could double the capacity in mobile IP networks.

Table 3: A characterization of imbalances and opportunities among Swedish ICT innovations

Sub-period (ca)	Industries	Imbalances	Supplied opportunities
1950-1970	Circuits, magnetic tape memory and data machines	Increasing complexity of transistor-based systems, insufficient memory space	Integrated circuits, magnetic tape memory
1960-1989	Factory automation and automated guided vehicles	Insufficient capacities of control systems	Numeric and computerized numeric control eq., electronics-based industrial robots
1970-1980	Laminate for electronic components, micro-chip production technologies	Under-etching, bottlenecks in production of integrated circuits	Laser lithography technologies
1980-2013	Secure payment and secure identification technologies	Security issues in Internet networks	E.g biometric identification technology
1990-2013	Telecommunication networks and components	Capacity requirements of network standards	Development of network standards (e.g. ATM, VDSL, voIP)

secure transaction online and e-commerce: in particular the problem of secure transactions. Some innovative start-up firms were targeting this bottleneck, e.g. Surfbuy and Buyonnet. Other firms developed systems for secure identification online or in mobile phones, exploiting fingerprint recognition technology.¹⁷

Summary

Our analysis shows that the dynamics of innovation activity has undergone vigorous transformation. A summary is given in Table 3. One major result is that ICT innovation took place in two surges: one focused on computers and factory automation and a second focused on communications and Internet infrastructure. It is also clear that opportunities and imbalances have shifted between technology 'components' and 'networks'. The early history of ICT was characterized by the high assembly costs, and insufficient memory space, resolved, e.g., through the integrated circuit. This enabled the development of drastically improved computerized numeric control systems, resolving an imbalance in the burgeoning factory automation. In the broader expansion surrounding Internet and telecommunication networks, the imbalances were fre-

¹⁷Fingerprint Cards and Prosection are firms notable for developing biometric systems (e.g. Fingerprint Cards' fingerprint recognition system for mobile telephones).

Figure 7: Count of microelectronics based innovations, 1970-2013.

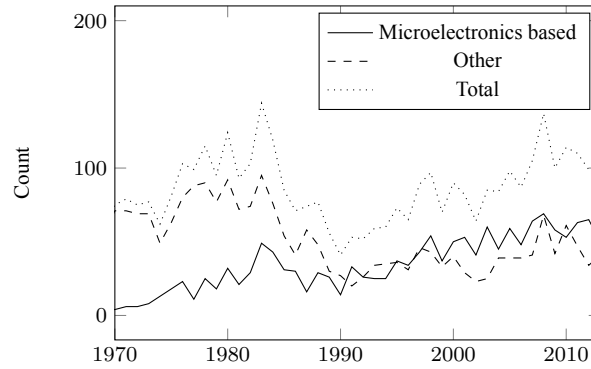
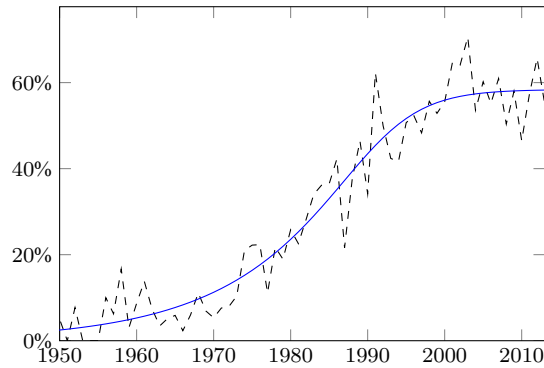


Figure 8: Share of innovations based on microelectronics, 1950-2013 and logistic curve.



Note: The generalized logistic curve (Richards, 1959) was fitted according to $y(t) = \frac{K}{(1 + \tau e^{-\alpha(t-\beta)})^{1/\tau}}$ where K , τ , α and β are estimated parameters.

quently related to insufficient capacity of network components or standards (see also Fransman, 2001). In other words, the opportunities and imbalances that have driven innovation have widened from pertaining to the key input and industrial applications to infrastructural investment. Thus, innovation biographies suggest that innovation activity has evolved in temporally localized sets of opportunities and imbalances that one could label development blocks.

5 Pathways of innovation in the third industrial revolution

We now turn to an analysis of the interdependencies that have been created in the evolution of ICT. Following the notion of microelectronics as a 'key input' (Perez, 1983; Freeman and Louça, 2001) we first briefly examine the broader role played by microelectronics in overall innovation activity since the basic innovations of the transistor, the integrated circuit and the microprocessor. We then examine the structure of interdependencies that have emerged between ICT industries ("carrier industries") and other sectors.

Figures 7 and 8 show the count and share of Swedish innovations exploiting microelectronics in their core functions, as inferred from trade journal articles. What is especially striking is the apparent S-shaped curve of the percentage of microelectronics based innovations, converging towards an average share of 58% (culminating at 70.6% in 2003). This share may seem low given the pervasiveness of microprocessors, computers and electronics, but can in part be explained by the still large share of e.g. pharmaceuticals, plastic and metal innovations, as well as electrical, non-electronic machinery and transport equipment.

Visualized in Figure 9, the most salient industries exploiting microelectronics, 'carrier' industries in Perez' terminology, are machinery and various electronic equipment and software - in brief the ICT industries. While this is unsurprising, it is more surprising that no other industries except machinery equipment innovations have, to a significant extent, exploited micro-electronics in their core functions.

The structure of innovational interdependencies

The pathways of innovations in these 'carrier industries' can be more readily analyzed through mapping the flow of innovations between industries. Some of the innovations were classified as being of a general-purpose character (Figure 10), i.e. as being possible to use across the board. This measure allows an immediate corroboration of the general-purpose character of ICT industries: some 40% of all ICT innovations were aimed for use throughout the industry up until 2000, as compared with some 15% on average in other industries. ICT innovations have thus, unsurprisingly, a clear general-purpose character.

The remainder of the ICT innovations were developed for specific industrial use. These industry-specific ties formed by ICT innovations inform of local interdependencies that have played a role in the evolution of ICT. These evolving interdependencies are analyzed in an innovation flow matrix, which maps the number of innovations that

Figure 9: Count of microelectronics based innovations in 'carrier industries', 1970-2013.

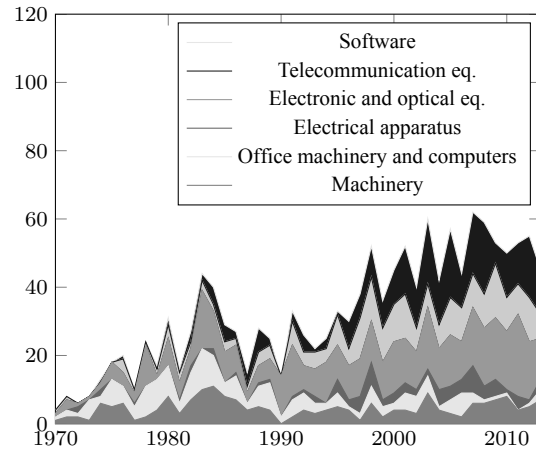
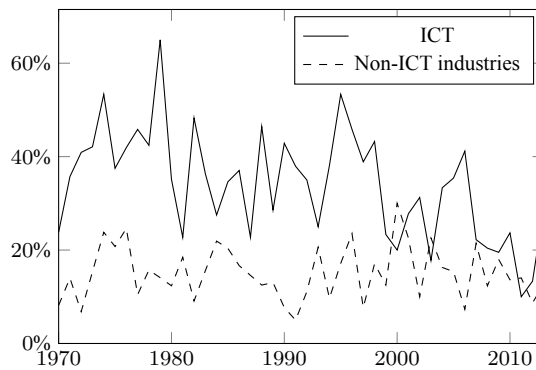


Figure 10: Share of general-purpose innovations among ICT and non-ICT industries, 1970-2013.



are supplied by industry i to industry j . The innovation flow matrix is understood as a so-called directed weighted network, which means that both the count of innovations and the direction of the connections between industries matter. For a directed weighted network, each edge from node $i \in V$ to another node $j \in V$, has a weight. Using matrix notation, the intersectoral supply and use of innovations can be expressed as a $N \times N$ matrix \mathbf{A} , with elements a_{ij} the amount of innovations supplied by industry i to industry j (see section 3.1 for underlying considerations).

Here we restrict our study to the flows to and from ICT sectors (see also figure 3). Formally, with the set of ICT sectors \mathcal{I} we define the entries of the ICT ego network \mathbf{W} as

$$w_{ij} = a_{ij}\delta_i + a_{ij}\delta_j - a_{ij}\delta_i\delta_j \quad (5)$$

where δ_i and δ_j equal 1 for $i, j \in \mathcal{I}$, otherwise zero. From this adjacency matrix we can define core statistics that inform about the structure of flows between ICT industries and other industries. The theory section outlined two main characteristics of networks of interest: hierarchy and reciprocity. We are first of all interested in describing to what extent innovation activity is characterized by a star-like structure or rather a non-hierarchical structure where several industries have played a large part. This can be done by the describing centrality nodes (industries) and weight distribution (cf e.g., McNerney et al., 2013).

The simplest notion of centrality is node strength. The out-strength of an industry is defined as the column sums of the innovation flow matrix

$$k_i^{out} = \sum_j w_{ij} \quad (6a)$$

and the latter as the row sums

$$k_j^{in} = \sum_i w_{ij} \quad (6b)$$

The notion of eigenvector centrality expands on this basic understanding of centrality, by noting that nodes are more central in the network if they have strong linkages to other central nodes. Since this measure is recursive, we look for a positive vector $v_i \geq 0$ that solves the eigenvalue problem

$$\sum_j v_j w_{ij} = \lambda v_i \quad (7)$$

λ is taken as the maximum eigenvalue of v_i as, per the Perron-Frobenius theorem, this guarantees a positive eigenvector.

The reciprocity of a network can be defined in terms of the degree to which outward flows between industry i and j is also reflected by feedback innovation flows from industry j to industry i . We measure this following Garlaschelli and Loffredo (2004) as the correlation coefficient:

$$\rho = \frac{\sum_{i \neq j} (w_{ij} - \bar{w})(w_{ji} - \bar{w})}{\sum_{i \neq j} (w_{ij} - \bar{w})^2} \quad (8)$$

where w_{ij} as before denotes the flow of innovations to or from ICT industries, w_{ji} the reciprocal flows, and \bar{w} the average flow in the ICT ego network.

In the present context, our interest lies in accounting for the main flows to and from and ICT industries, but also the dynamics of the linkages between ICT industries and other industries. The distribution of out- and in-strength of industries in the ICT ego network shows that most industries have low out- and in-strength, while only a few industries have high out- and in-strength, an indication of a strong hierarchical network structure. 4.7% of the industries supplied more than 100 innovations. Similarly, 1.9% of the industries used more than 100 innovations. The distribution of weights displays a power-law distribution $\propto w_{ij}^{-1.53}$. A similar pattern is found for eigenvector centrality (Figure 11c), where a small fraction of the industries have high forward/backward centrality. These results thus inform us of a hierarchical structure, where some nodes play the role as principal suppliers or users of innovation, and where most nodes have only a small number of innovations. In Figure 12, the strength reciprocity and the edge reciprocity of the network clearly indicate a highly asymmetric network, where industry ties are not reciprocated.

To provide further intuition for these results, Figures 13a and 13b visualize the "ego network" of ICT industries, i.e. the number of innovations used in ICT industries, or supplied by ICT industries over the periods 1970-1989 and 1990-2013. The layout of the network applies the Fruchterman-Reingold algorithm to a fast greedy community detection algorithm (Clauset et al., 2004), which groups closely related industries. The figures indicate a star-shaped supply structure for some of the ICT industries, notably measuring instruments, computers and software, implying that these industries are mainly suppliers of innovations, while using relatively few innovations.

For a qualitative breakdown of the interdependencies among ICT innovations, Tables 4a and 4b display the industries with highest shares of innovations flowing to and from the ICT sectors. In the first half of the period, main user sectors of ICT innovations were health care (11%), final consumption (9%), other business activities (6%) and publishing and printing (6%). Most of the supply of innovations to ICT industries were from other ICT industries: measuring equipment accounted for 30%, computers 13%, medical equipment 9% and software 7%. In total 87% of the innovations used by ICT industries were supplied by other ICT industries. The second half of the period, saw a more pronounced shift in the user sectors towards final consumption (17%), health care (9%) as well as the software, telecommunication equipment and service industries (together these account for 13%). Meanwhile, the share of the total supply of innovations to ICT sectors was from the ICT sectors: software (22%), measuring instruments (21%), telephones (11%), computers (6%) and medical equipment (9%) alone accounted for 69% of all innovations used in ICT.

In brief, we have a picture of ICT industries supplying broadly to other industries, mostly for health care, final consumption or developed for general-purpose use, while ICT industries are users of innovation almost uniquely from other ICT industries. Thus, the main dynamics in the evolution of ICT industries has taken place within the ICT sectors, as suggested in the canonical GPT model (Bresnahan and Trajtenberg, 1995), with little feedback from what Perez (2010) has called 'induced industries'.

Figure 11: Centrality in the ICT ego network, 1970-2013

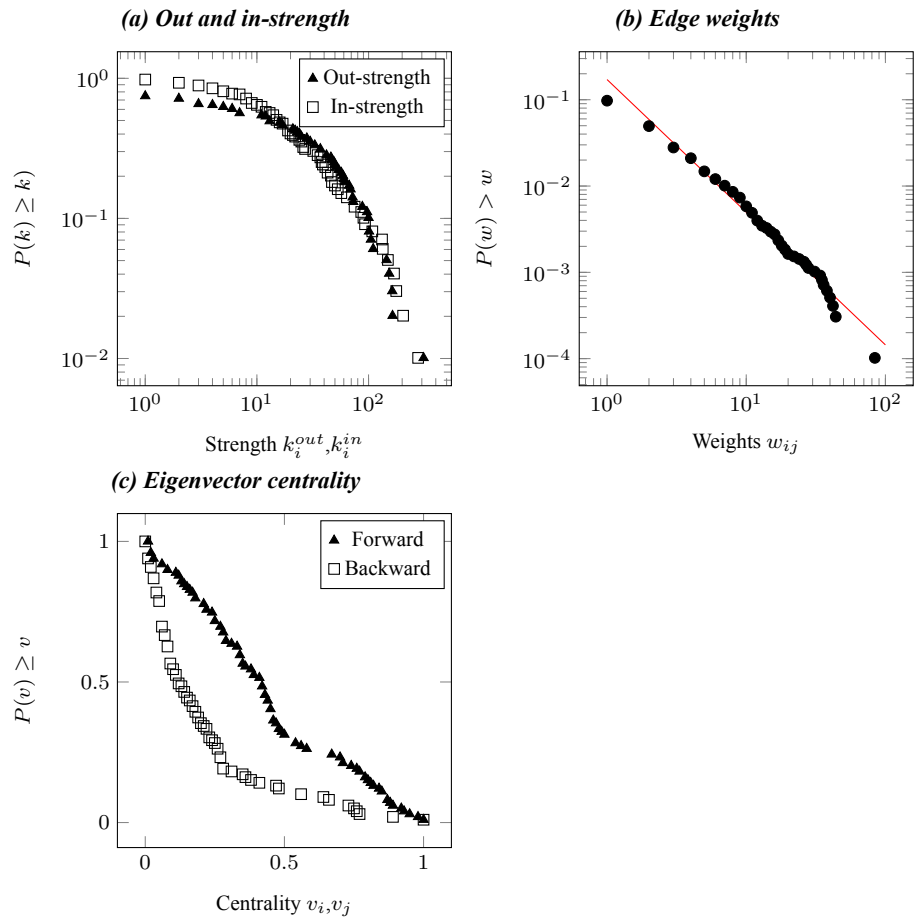


Figure 12: Network reciprocity, 1970-2013

(a) Strength reciprocity. $\rho = -0.038 [P > 0.1]$ (b) Edge reciprocity. $\rho = -0.011 [P > 0.1]$

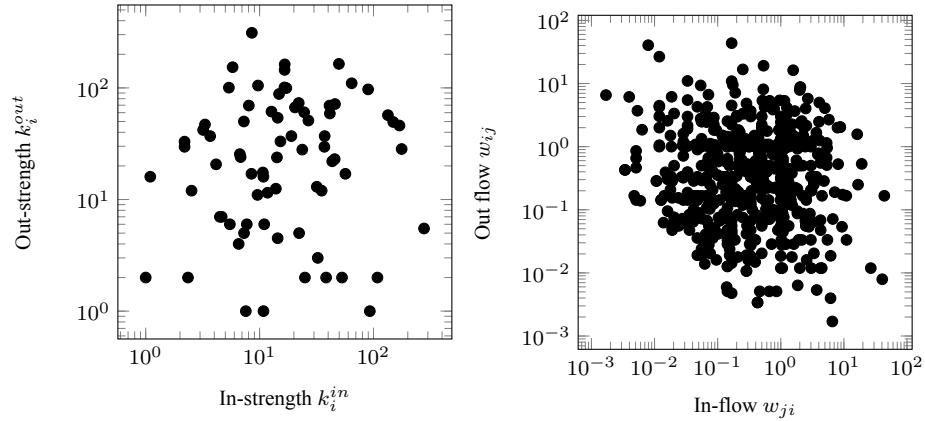


Figure 13: Ego network of the ICT industries based on absolute flows of innovations. Layout by communities, applying the fast greedy community detection algorithm (Clauset et al., 2004).

(a) 1970-1989

(b) 1990-2013

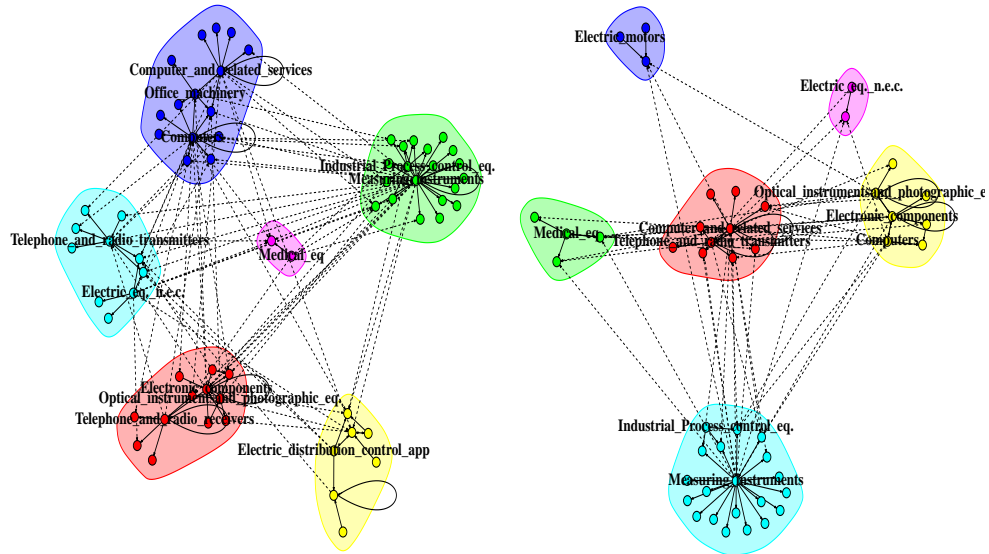


Table 4: 20 industries with strongest linkages to ICT, 1970-1989 and 1990-2013 (shares in total number of innovations supplied or used by ICT industries)

<i>(a) 1970-1989</i>				<i>(b) 1990-2013</i>			
Industry	User of ICT	Supply to ICT	Total link-ages	Industry	User of ICT	Supply to ICT	Total link-ages
1. Measuring instruments	1%	30%	15%	1. Software	2%	22%	12%
2. Computers	1%	13%	7%	2. Measuring instruments	0%	21%	11%
3. Health care	11%	0%	5%	3. Final consumption	17%	0%	9%
4. Medical eq	0%	9%	5%	4. Telephone and radio transmitters	4%	11%	7%
5. Final consumption	9%	0%	5%	5. Electronic components	3%	7%	5%
6. Electronic components	5%	4%	5%	6. Medical equipment	1%	9%	5%
7. Telephone and radio transmitters	1%	7%	4%	7. Health care	9%	0%	5%
8. Software	1%	7%	4%	8. Computers	1%	6%	4%
9. Other business activities	6%	0%	3%	9. Optical instruments and photographic eq.	1%	5%	3%
10. Optical instruments and photographic eq.	0%	6%	3%	10. Telephone and radio receivers	1%	4%	3%
11. Publishing and printing	6%	0%	3%	11. Post and telecommunications	3%	1%	2%
12. Basic metals	4%	1%	3%	12. Research and development	4%	0%	2%
13. Electrical equipment n.e.c.	0%	5%	2%	13. Electricity, gas and water supply	4%	0%	2%
14. Industrial process control eq.	0%	4%	2%	14. Motor vehicles	3%	0%	2%
15. Telephone and radio receivers	1%	2%	2%	15. Electric motors	0%	3%	2%
16. Electricity, gas and water supply	4%	0%	2%	16. Pulp and paper	3%	0%	2%
17. Land transportation	3%	0%	2%	17. Other business activities	3%	0%	1%
18. Construction	3%	0%	2%	18. Electrical eq n.e.c.	0%	3%	1%
19. Wood	3%	0%	1%	19. Basic metals	2%	1%	1%
20. Office machinery	1%	2%	1%	20. Wood	2%	0%	1%

6 Conclusions

The results of this study convey several facts about the long-term evolution of ICT innovation. In particular, four main results emerge, some of which have been predicted in previous theoretical literature:

- Both innovational complementarities and imbalances have greatly mattered as driving forces of ICT innovation
- The diffusion of GPTs is a localized process, confined to certain industries in certain points of time, strengthening an interpretation of the evolution of GPTs as a series of development blocks.
- The network of ICT innovation is hierarchical and locally "star-like". That is to say that interdependencies take place mainly between what Perez has called the "key input" and "carrier industries", with little feedback from "induced industries".
- The actors behind ICT innovation have changed from large incumbents with experience in the traditional electrical sector to small entrant firms observing market niches and new opportunities, which stresses the disruptive impact of GPTs on industrial structure.

First of all, the evolution of ICT has been shaped by both innovational complementarities, i.e. opportunities, and the sequential appearance of imbalances that has focused innovation activity in discrete phases of industrial development. An embryonic development in computers and automation can be observed from the mid-1950s in Sweden. Following the invention of the microprocessor in a large number of innovations followed, being driven both by the opportunities entailed and the resolution of imbalances. A last surge began in the early 1990s, throughout the IT boom of the 1990s, culminating in the mid-2000s.

This relates to the second main result. The shifting patterns of driving forces motivate a view of the diffusion of the GPT of microelectronics in terms of sequences of development blocks in which significant innovations were often driven by attempts to overcome major obstacles and imbalances, while other innovations drew on technological opportunities created elsewhere. The early history of ICT was characterized by the high assembly costs, and insufficient memory space, resolved through the e.g. integrated circuit. This enabled the development of drastically improved computerized numeric control systems, resolving an imbalance in the burgeoning factory automation. With the 'big bang' of the innovation of the micro-processor, salient opportunities emerged for innovation in factory automation. Towards the 1990s, the sources of innovation activity had shifted - in part through a painful process of dismantling the domestic computer industry - towards the expansion of Internet and telecommunication infrastructure. A large set of innovations were now centered on solving imbalances created in the mismatch between technological capacities and requirements. Moreover, the focal point of innovation activity shifted from industry oriented innovation activity, towards consumer electronics in the 1990s.

Third, both the qualitative analysis and a quantitative analysis of the network of innovations provide support for an interpretation that this dynamic in the diffusion of ICT as a general-purpose technology was largely contained *within the ICT industry*, rather than stemming from feedback mechanisms between ICT industries and other industries. This is reflected in a hierarchical structure and locally star-like structure of the innovation networks.

A last result is that the ICT industry transformed from being driven by a few large actors developing automation technologies, such as Saab and ASEA (later ABB), evolving into a large development block being increasingly dominated by smaller actors. In the beginning of the 1950s, automation technology and computers were mainly developed in research laboratories of institutes and a few large Swedish firms. Already towards the mid 1980s a considerable set of actors had emerged that produced innovations in a number of inter-related areas such as industrial automation machinery, automated guided vehicles, telecommunication equipment, computers and electronic components. As telecommunication markets were deregulated in the 1990s, a further wave of entrants followed and towards the end of the period studied only a minor part of ICT innovations were developed by firms with more than 200 employees.

These results amount to a clear message about the long-term evolution of GPTs. In particular, this study has argued that the ICT industry in Sweden can be understood as the diffusion of a general-purpose technology in terms of several development blocks, localized in time and centered both on a set of opportunities and imbalances. Rather than a smooth process, the structure of technological interdependencies is hierarchical, and locally star-like. The localization of opportunities and imbalances should be of the utmost importance to policy oriented towards innovation system and GPTs. In particular, our results would stress that the allocation of knowledge and resources towards the resolution of structural and technological imbalances are key.

The limitations of this study lie in being restricted studying innovation output data. Though this data is a unique source of qualitative information on the sources of innovation and the character of inter-industrial interdependencies, not all types of interdependencies and imbalances can be studied by looking uniquely at innovation networks. The results would therefore with advantage investigate the claims made pertaining to the topology of interdependencies using other types of longitudinal data, e.g. industrial economic output data and patent citation networks, and by improving methods for the detection of critical problems, technological imbalances and growth bottlenecks (see e.g. (Dedehayir and Mäkinen, 2008, 2011; Bresnahan and Yin, 2010)).

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