The Genesis of the Pre-Commercialization Innovation Ecosystem: Knowledge Generation, Transfer, and Recombination in the Pre-Commercialization Phase of Charge-Coupled Device Image Sensors—1969-1994

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Dedicated to the memory of MB Sarkar

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Abstract

We explore the genesis of the innovation ecosystem in the pre-commercialization phase of charge-coupled device (CCD) image sensors and find that in this phase, the dominant design is chosen in stages. The time involved in choosing the various product configurations that characterized the dominant design in the pre-commercialization phase was 17 years for CCD sensors. Intense knowledge generation, transfer, and recombination during this time period helped firms in the ecosystem mitigate product performance trade-offs and meet latent demand from potential buyers. Our investigation also reveals that firms' efforts to mitigate product performance trade-offs acted as the genesis of the pre-commercialization innovation ecosystem.

Keywords: Pre-commercialization phase; Incubation of new technology; Innovation ecosystem

Introduction

Strategy and innovation scholars (Anderson and Tushman, 1991; Gort and Klepper, 1982) have explored technological discontinuities and breakthroughs that result in creative destruction (Schumpeter, 1942). Concentrating on the instance of the first commercialization of a product, scholars have examined how firm heterogeneity affects entry, exit, competitive dynamics, and performance as the new technology evolves (Helfat and Lieberman, 2002; Klepper and Simons, 2000; Mitchell, 1991; Sarkar *et al.* 2006). However, by focusing solely on the post-commercialization phase, these studies yield limited insights about product innovation prior to commercialization (Golder, Shacham, and Mitra, 2009).

Recently, Agarwal, Moeen, and Shah (2017), Moeen (2013), Moeen and Agarwal (2017), and others have devoted much needed attention to the critical *pre-commercialization phase* of a new technology's evolution—a time period that begins with an "individual (or group) developing the first concept" to the time when prototypes are refined to develop a working model that "can be sold to a customer" (Golder *et al.*, 2009; p. 167). Extant research also underscores that the pre-commercialization phase can extend for almost three decades in some industries (Agarwal and Bayus, 2002). Building on these prior insights, Moeen (2013; p.17) explored firms' value capture in the pre-commercialization phase of the agricultural biotech industry and highlighted the importance of the pre-commercialization innovation ecosystem in this phase when she noted that the "core firms in the ecosystem" commercialize new technologies to capture value.

Although these recent investigations have expanded our understanding of the role of the innovation ecosystem in the pre-commercialization phase, relatively underexplored are the causal mechanisms that help the pre-commercialization innovation ecosystem to germinate and the role that the ecosystem plays in the evolution of a nascent technology in this phase. To address these relatively under-investigated areas of inquiry, we seek answers to our research questions—"*What is the genesis of the pre-commercialization innovation ecosystem?*" and "*How does the innovation ecosystem affect the nascent technology's progress toward commercialization?*" An exploration of the answers to these questions is critical if researchers and practitioners are to "fully [comprehend] interinnovation relationships" in the pre-commercialization phase of a technology's evolution (Golder *et al.*, 2009; p. 167), which creates opportunities for both entrepreneurial startups and existing manufacturers, and shapes the post-commercialization oligopolistic industry structure (Moeen and Agarwal, 2017).

Using the evolution of charge-coupled device (CCD) image sensors from its conceptualization in 1969 to commercialization in the early 1990s, our investigation reveals that in the context of CCDs, the innovation ecosystem germinated as firms, such as Fairchild Camera and Instrument Corporation, Texas Instruments (TI), and others, that introduced innovative new products to meet potential future demand from the Navy and NASA. Further, we also find that the knowledge flow and recombination activity within the ecosystem leads to a pre-commercialization dominant design—"a standard embodiment of an industry's core technology" (Anderson and Tushman, 2001; p.679). Additionally, our quest to explore answers to our research question helps us uncover surprising insights. We find that the "narrow range" of various product configurations—that characterize a dominant design (Anderson and Tushman, 1990; p. 620)—are chosen by the firms in the pre-commercialization ecosystem over a period of time. The time involved in choosing the dominant design in the pre-commercialization phase of CCD sensors was 17 years. During this time period, firms within the ecosystem engaged in intense knowledge generation, transfer, and recombination to *mitigate* product performance trade-offs and meet latent demand. We also find that such efforts to mitigate product performance trade-offs led to the emergence of key component technologies (Braguinsky and Hounshell, 2016) in the pre-commercialization innovation ecosystem.

In our pursuit to understand the pre-commercialization evolution of CCD sensors, we followed Eggers (2014), Holbrook *et al.* (2000), and Moeen and Agarwal (2017). Using archival data, interviews, both published accounts of industry insiders as well as unpublished and secondary sources of information, we explored how the CCD sensor evolved in its pre-commercialization phase. Dr. Eric Fossum, one of the inventors of image sensors (formerly at Jet Propulsion Laboratories; now at Dartmouth College), provided us with access to all the papers that were presented at the CCD Applications Conferences held in San Diego (1973, 1975, 1978), Edinburgh, Scotland (1974, 1976, 1979), Washington DC (1976, 1977), New York (1986, 1990), and Waterloo, Ontario (1991, 1993). We supplemented information from these sources with information from the United States Patent and Trademark Office (USPTO.gov) website, various electronics and image sensor magazines, and engineering textbooks. Thereafter, as suggested by Eggers (2014), we followed the basic tenets of grounded theory building (Glaser, 2001; Glaser and Strauss, 1967) to review all documents to identify the core ideas of the story at both the micro (point-by-point) and macro (entire series of documents) levels. Next, we categorized key events based on the underlying processes. Further, we counterchecked and validated the anecdotal components of the story with other sources, such as technical reports published by NASA, Naval Electronics Laboratory, and Jet Propulsion Laboratory/California Institute of Technology. Finally, to counterbalance our data collection from the secondary sources, we sought feedback from several industry experts and inventors of image sensors, including Dr. Eric Fossum, Dr. Albert Theuwissen (ex-researcher at Philips), Dr. Cesar Bandera (New Jersey Institute of Technology), and others. Feedback from the experts at various stages of our research helped us "present facts and ask questions" and counter-questions "about possible explanations of these facts" (Bettis *et al.*, 2014; p. 950).

Although the motivation of the paper is to expand our understanding of the innovation ecosystem in the pre-commercialization phase of a new technology's evolution, the processes we identify are generalizable to the broader innovation literature. Scholars (e.g., Acs, 2003; pp.1-2) have noted that innovation ecosystems have affected regional economic developments by fostering entrepreneurial activities not only in the past-- e.g., in cities such as Dayton, OH, in the early 1900s[1]— but also in the present-day Silicon Valley. Despite both academic literature and popular press acknowledging the importance of such ecosystems since the early 1900s (see e.g., http://www.daytoninnovationlegacy.org/index.html), this study is one of the first attempts to explore the genesis of, and thereby extend the burgeoning literature on, innovation ecosystems (e.g. Adner and Kapoor, 2010; Kapoor and Furr, 2015) and our understanding of how such ecosystems affect technological innovations and entrepreneurial activities.

[1] Anecdotal evidence suggests that during the early 1900s, entrepreneurs and inventors such as Charles Kettering, John Patterson, and Wilbur and Orville Wright developed mechanical cash registers, airplanes, automatic starters for cars, anti-knock fuel, and created the "Barn Gang" in Dayton, OH, for collaborative efforts to solve problems (Wallace, 2014).

Additionally, by exploring the origin of a "key technology,"—an innovation that paves "the way for explosive industry growth" (Braguinsky and Hounshell, 2016; p.53—we expand the insights generated by the recent investigations of key new technologies—such as ring spinning frames (used in cotton spinning machinery (Braguinsky and Hounshell, 2016), and the 1993 Nakamura patent on blue LED that revolutionized solid-state lighting technology (Min and Sarkar, 2015)—that are the hallmarks of new technology's evolution. In the process, we contribute to the innovation literature by exploring the creation of innovation ecosystems in the pre-commercialization phase and examining how such ecosystems pave the way for commercialization of a new technology.

Next, we review the extant literature and formulate the questions that frame our research.

Extant literature and Framing Questions

<u>Received wisdom # 1: Firms in the pre-commercialization phase capture economic value within the innovation ecosystem.</u>

Moeen and Agarwal (2017; p. 582) highlight the role of the innovation ecosystem in the pre-commercialization phase and posit that the "majority of investing firms captured economic value by participation in the markets for technology and corporate control rather than by product commercialization." This echoes Moeen's (2013; p.17) observation that firms commercializing a new technology are the "core firms in the ecosystem," whereas firms that engage in alternative modes of value capture, play a supporting role in the ecosystem by providing "complementary capabilities to the commercializing firms." These assertions mirror recent findings in the broader innovation literature (e.g., Adner and Kapoor, 2010) about the importance of the innovation ecosystem in the post-commercialization phase.

However, despite this recent interest in exploring the role of the innovation ecosystem in firms' value capture and the presence of "knowledge bases" during this phase (Moeen and Agarwal, 2017; p. 568), relatively under-investigated is the genesis of a pre-commercialization ecosystem. Accordingly, our first framing question for this paper is—

Framing question # 1: What is the genesis of the pre-commercialization innovation ecosystem? Why and how is such an ecosystem created?

Received wisdom # 2: The pre-commercialization phase is characterized by knowledge flow and "cooperation across various types of firms" (Moeen and Agarwal, 2017; p. 579).

While the previous framing question explored the causal mechanism that results in the germination of a pre-commercialization ecosystem, the second received wisdom leads us to a deeper exploration of the effects of knowledge flow among firms in the pre-commercialization phase of a new technology.

Researchers have observed that the pre-commercialization phase of a new technology's evolution involves cooperation among startup and diversifying firms that eventually leads to the post-commercialization oligopolistic structure in the new industry (Moeen and Agarwal, 2017). Holbrook *et al.* (2000; p. 1024) noted that, during the early stages in the evolution of semiconductors in the 1950s, such cooperation helped Motorola acquire critical knowledge for alloy transistors. Relatively underexplored in the literature, however, are the implications of the knowledge flow across firms in the pre-commercialization phase. Are such knowledge flows directed toward reducing technological uncertainties (Roy and Sarkar, 2016)? Or, do such knowledge flows help firms develop complementary assets, as in the case of biotechnology firms (Pisano, 2006)? To seek the answers to these questions, our second framing question is--

Framing Question # 2: What are the implications of knowledge flow among firms in the pre-commercialization phase? Does such knowledge flow reduce technological uncertainties? If so, how?

Received wisdom # 3: Firms engage in technological investments prior to product commercialization.

Agarwal and Bayus (2002) report that, on an average, invention precedes commercialization by about 28 years and a "significant number of firms" invest in innovative activities during that period (Moeen and Agarwal, 2017; p. 580). For example, in the pre-commercialization period of the automobile—between its invention in 1771 and commercialization in 1890 (Agarwal and Bayus, 2002)—firms such as Daimler and Maybach invested in developing a prototype of a high-revolution 600-rpm gasoline engine with a surface carburetor (Smil, 2010; p.27).

Despite providing valuable evidence of technological investments and the presence of knowledge bases in the pre-commercialization phase, the literature has somewhat overlooked the causal mechanisms that determine the technological investment choices (Moeen and Agarwal, 2017) of firms in this phase. More specifically, the literature is silent on why firms, such as Daimler, *chose* to invest their resources in improving the gasoline engine with a surface carburetor (Smil, 2010). Our third framing question seeks to address this gap in the literature and provide guidance to scholars on how the innovation ecosystem affects firm choices about technological investments in the pre-commercialization phase. Thus, our third framing question is—

Framing question # 3: What role does the pre-commercialization innovation ecosystem play in determining firms' technological investment choices during this phase?

Received wisdom # 4: Innovations in key component technologies lead to improvements in critical product performance features.

Extant research notes that in the pre-commercialization phase, innovations in new materials and key component technologies (Henderson and Clark, 1990) help improve the critical performance features of various products. For example, Funk (2013; p.135) underscores that in the case of LEDs, "scientists and engineers improved the luminosity per watt" aided by innovations in key component technologies such as "new combinations of semiconducting materials, such as gallium, arsenide, phosphorus, indium, and selenium," which helped them to "better exploit the phenomena of incandescence, fluorescence, and electroluminescence." He further noted that, "rapid rate of improvement" in the key component technologies used in "ICs, magnetic tape and discs, optical discs, liquid crystal displays (LCDs), and other electronic components has had a large impact" on product innovations in computers (p. 141).

Despite research highlighting the importance of key component technologies in the pre-commercialization phase, relatively underexplored is the genesis of such technologies. For example, in the investigation of the evolution of Japanese cotton spinning mills (see, e.g., Braguinsky and Hounshell, 2016), yet underexplored is the design and creation of key component technologies such as "ring spinning frames" that affected the future evolution of cotton spinning mills.

Additionally, addressing product performance trade-offs is critical while designing innovative new products. As Dosi (1988; p.1128) notes, "the search process is generally 'focused' by trade-offs involved" among the various performance features of the product such as "between speed, flexibility to different uses, and cutting precision." For example, car manufacturers trade off fuel economy of a car for engine size, weight, and horsepower (Cheah *et al.*, 2008). Such trade-offs guide engineers' efforts as they "try to improve the desirable characteristics that are specific to a certain product, tool, or device, keeping in mind the trade-offs among them" (Dosi, 1988; p. 1129). Relatively underexplored in the literature is an understanding of if and how key components help firms address the performance trade-offs. Accordingly, our fourth framing question is—

Framing question # 4: What triggers the genesis of key component technologies? Do these technologies help firms to mitigate the performance trade-offs in the new products? If so, how?"

Received wisdom # 5: Technological evolution in the post-commercialization phase follows the pattern of an era of ferment, to the emergence of a dominant design, to the era of incremental change.

Extant literature notes that technologies evolve following a predictable cyclical pattern. The emergence of a new technology leads to predominance of product innovation, which is followed by the emergence of a dominant design—"a single configuration or a narrow range of configurations that accounted for over 50 percent of new product sales or new process installations and maintained a 50 percent market share for at least four years" (Anderson and Tushman, 1990; p. 620). Researchers generally agree that a dominant design "marks the end of the era of ferment" and the beginning of an "era of competition based on slight improvements on a standard design" (Anderson and Tushman, 1991; p.28). Further, this period leads to the prevalence of process innovation over product innovation and to a convergence of customer preference, which, in turn, leads to process research and development (R&D) advantage for large incumbents over other entrants (Klepper, 2002).

Given the focus of prior research on the post-commercialization period, relatively underinvestigated in the literature, is an exploration of the evolutionary trajectory of a new technology in the pre-commercialization phase. Are we likely to observe the same pattern—a fluid phase followed by the specific phase (Utterback and Abernathy, 1975)—in the pre-commercialization phase? Accordingly, our fifth framing question is—

Framing Question # 5: Does the evolutionary trajectory of a new technology in the pre-commercialization phase follow the predictions for the post-commercialization phase? If not, how does the evolutionary trajectory in the pre-commercialization phase differ from that of the post-commercialization phase?

Guided by these framing questions, we next explore the context of this paper. We proceed in the reverse-chronological order as we peel away layers of information, starting in the 2000s, then stepping back to late 1993–early 1994, and thereafter, again stepping back in time to the early 1970s, to trace the origin of the pre-commercialization innovation ecosystem in CCD sensors.

Context: Evolution of CCD sensors

October 1993–February 1994: Commercialization of consumer digital still color cameras with Frontside illuminated (FSI) buried channel CCD sensors[2]

Three significant events in this five-month period made this one of the most important periods in the evolution of image sensors for digital cameras. First, in October 1993, Dycam, a camera manufacturer based in California, introduced Model 4 priced at $795, the first color CCD still camera to be sold in the market. Second, within a few months of this new product's introduction, in February 1994, Apple introduced its first digital camera, Quick Take 100 (QT100). The QT100, designed by Kodak and Chinon (Japanese subsidiary of Kodak), priced at $749, weighed one lb. (454g). This revolutionary camera had a 1MB flash memory that could hold eight "high resolution" 640x480 color images, needed three re-chargeable AA batteries, and had Macintosh-only interface cable. Additionally, the QT100 also had an optical viewfinder and a built-in LCD screen, similar to those in digital cameras today. Moreover, unlike the Dycam camera, which stored images in the

[2] Merriam-Webster dictionary defines to "commercialize" as to "exploit for profit." Accordingly, Nerkar and Shane (2007; p. 1160) defined commercialization as the "achievement of first sale of a product or service that makes use of the invention….[measured by] the receipt of the first dollar of revenue" by selling the product in the market. Following this definition, the first commercialized consumer digital still color camera was Dycam 4. Prior to 1993, Sony and others had introduced Video Still Cameras in the 1980s. These cameras were not true digital still cameras. Additionally, in the 1970s, Fairchild had introduced the prototypes of MV-100 and MV-101 cameras, and Procter and Gamble used the latter for quality control. Similarly, Fuji had developed DS-1P in 1988. However, industry experts believe that evidence of these products being sold in the market is non-existent (see also http://www.digicammuseum.com/en/cameras/item/fairchild-mv-101; http://www.digicammuseum.com/en/history). Additionally, following Holbrook (1995; p.156)—who noted that in 1959, Jack Kilby and TI "partook extensively of military R&D funds" for integrated circuits (IC), but commercialization of IC happened in November 1965 when Canon introduced Canola 161 calculator (see http://www.vintagecalculators.com/html/ti_cal-tech1.html)-- we exclude R&D funds and grants provided by government agencies from our definition of commercialization.

volatile RAM, the QT100 stored images in non-volatile Flash EPROM, like modern digital cameras (Santalesa, 1994). Additionally, in order to take pictures, one had to connect the Dycam camera to a desktop computer, whereas the QT100 was a standalone digital still camera as are those of today.

The QT100 heralded in the era of digital photography and in a little more than a decade after its introduction, the market-share of analog film still cameras decreased to almost zero percent (see Figure 1).

Insert Figure 1 here

Although both Dycam Model 4 and the QT100 used *Frontside illuminated* (FSI) CCD sensors with *buried channel*, there was a competing CCD sensor—the *Backside-illuminated* (BSI) CCD sensor with *buried channel.* [3] NASA used the BSI CCD sensors for the Hubble Space Telescope (HST) when it launched in 1990. The third significant development of this period occurred in December 1993, when NASA replaced the original HST Wide Field/Planetary Camera I (WF/PC I) *that used BSI sensors*, with the WF/PC II camera *that used FSI sensors*, thereby effectively ending R&D in BSI CCD sensors.

Although the Dycam Model 4, Apple QT100, and NASA's replacement camera for HST used FSI sensors with buried channel, there were decades of research, going back to the 1970s, which made the sensors capable of meeting latent needs of potential customers. This leads to our first follow-up question—

[3] In the Appendix, we define the scientific terms used in the context of CCD sensors, and explain the differences between sensors with FSI and BSI as well as differences between *buried channel* and *surface channel.* BSI sensors transferred images in "full frames" (FT) and therefore were also referred to as BSI-FT sensors. FSI sensors, on the other hand, transferred images along horizontal and vertical lines (Interline Transfer or ILT)—also referred to as FSI-ILT sensors. In this paper, we refer to buried-channel BSI-FT and buried-channel FSI-ILT sensors as simply BSI and FSI sensors, respectively.

Follow-up question # 1: Where did the FSI CCD sensors used by Dycam, Apple, and NASA in 1993–1994 come from?

To seek an answer to the follow-up question, we dig into the pre-commercialization period of CCD sensors. We follow the sequence of steps described below—

First, we examine the technological developments in the early 1990s that converged the potential demand from consumer product and scientific instrument manufacturers, and led to the establishment of FSI CCD sensors as the pre-commercialization dominant design for digital still color cameras and ended the reign of BSI CCD sensors as the choice for manufacturers.

Thereafter, we investigate the technological innovations during the 1980s when several manufacturers sought to overcome the product performance trade-offs associated with both FSI and BSI CCD sensors.

Finally, we explore the genesis of both FSI and BSI sensors during the 1970s, and seek to understand how and why consumer product manufacturers chose the FSI sensors, while the scientific community adopted BSI sensors. We also investigate how, during this period, all the firms adopted buried channel CCDs over surface channel CCDs, and thereby the former became an integral part of the "narrow range of configurations that accounted for over 50 percent of new product sales" (Anderson and Tushman, 1990; p. 620) of the eventual dominant design.

Early 1990s: Convergence of potential demand and establishment of buried channel FSI CCD sensors as the pre-commercialization dominant design.

Prior to introducing Model 4, in 1990, Dycam introduced Model 1, the first true "completely" digital still camera to be sold in the market (Source: http://www.digicamhistory.com/1990.html). Priced at $995—the first digital camera priced below $1000—the Model 1 took black and white pictures using a 376*240 pixel CCD sensor and was targeted to individual consumers, unlike some of the high-end professional digital cameras introduced earlier (we describe some of the cameras introduced during the 1980s later in the paper) (Needleman, 1991). These cameras used FSI CCD sensors and operated through a desktop computer, similar to the Dycam 4 cameras discussed earlier.

Convergence of demand occurred when the scientific community switched from BSI to FSI CCD sensors. Although Apple and Dycam built their cameras using FSI CCD sensors, one of the most significant events during the early 1990s was Jet Propulsion Laboratory's (JPL) *decision* to replace the WF/PC I camera *that used the BSI CCD sensors* originally developed for HST by TI. These original CCD sensors were 800*800, 15-micron picture element (pixel), 3-phase CCDs. Manufacturing efforts of WF/PC I BSI sensors, since the beginning, were plagued by very low yield because "tens of thousands of devices had to be fabricated to obtain a couple hundred good chips" (Janesick and Elliott, 1994; p. 15). Additionally, in April 1990, after the launch of HST, NASA realized that the BSI sensors used in HST WF/PC I had focus and quantum efficiency hysteresis (QEH) problems (Biretta, 1993). Within a few months, NASA decided to replace HST's original TI BSI CCDs (WF/PC I) with Ford/Loral FSI CCDs (WF/PC II). This decision to replace buried-channel BSI by buried channel FSI sensors acted was a milestone in the evolution of CCD sensors and converged the potential demand from consumer product and scientific instrument manufacturers, thereby *establishing the buried channel FSI sensors as the pre-commercialization dominant design*.

In addition to HST, yet another NASA research project that helped the commercialization of digital cameras with FSI sensors during this time period was its Electronic Still Camera (ESC) project (Janesick and Elliott, 1992; p. 4). The objective of this project was "to evaluate the utility of the ESC for commercial applications in areas such as close range photogrammetry, terrestrial monitoring, and near real-time capabilities" (Rose, 1991; p.3).

The cameras used in the project were Nikon 35-mm F3 and F4 bodies with FSI 1024*1024, 15-micron pixel Ford Aeronutronic FA1024L sensors. Constructed at the Lyndon B. Johnson Space Center, these cameras had the CCD sensors placed at the film plane of the Nikon cameras (Rose, 1991; p.1). The converted camera had features similar to the consumer product models, including zoom lenses, wide-angle lenses, a flash capability, removable filters, and image intensifiers that provided "low-light capability and modest spectral capability" (p.1). One of the modified Nikon F4 cameras traveled on the space shuttle *Discovery* (September, 1991, flight # STS-48) to conduct several experiments related to recording images in monochrome with 8 bits of digital information per pixel (256 gray levels). The CCD sensor "was developed by JPL and Ford Aerospace [Ford Aerospace was sold to Loral Corporation in 1990] as a part of the Hubble Space Telescope sensor development program" (Chapman, 2014).Although the decision to transition from BSI to FSI CCDs by NASA in 1990 was a milestone in the pre-commercialization phase of CCD sensors and established buried channel FSI sensors as the pre-commercialization dominant design, the process of establishing the various product configurations that were part of the eventual dominant design lasted several decades, beginning in the early-1970s. Technological progress during this period faced several challenges, and firms' efforts to mitigate these challenges affected the evolution of both FSI and BSI CCD sensors. This leads us to investigate knowledge generation, recombination, and evolution of the key component technologies during the 1980s.

1980s: Knowledge generation and flow from BSI CCD sensors to FSI CCD sensors, and vice versa, to mitigate product performance trade-offs

We explore the evolution of key component knowledge and knowledge flow during the 1980s in two stages. First, we explore knowledge generation and flow across firms to mitigate product performance trade-off and the consequences of such efforts in the evolution of BSI sensors.

Thereafter, we explore similar efforts in the evolution of the key component technologies used in FSI sensors.

Mitigating product performance trade-offs in BSI sensors using knowledge generated by FSI CCD manufacturers:

As discussed earlier, TI manufactured the WF/PC I CCDs initially chosen by NASA for the HST and manufactured by TI. These sensors were BSI ones, which used the key component technology, polysilicon gates. Incidentally, the original design of BSI CCDs utilized aluminum gates; the polysilicon gates first appeared in FSI CCDs. However, on the one hand, BSI gates were harder to manufacture, leading to higher costs. FSI CCDs cost about 1/3rd of BSI CCDs (Janesick and Elliott, 1994; p. 16), leading TI to a decade-long experiment to improve the yield of BSI CCDs (Janesick and Elliott, 1992; p. 19). On the other hand, the aluminum gates were prone to "shorting problem," which prompted TI to change its design to polysilicon gate technology, which was "already successfully implemented by Fairchild and RCA" (p. 14) for manufacturing FSI CCDs in the 1970s. Indeed, TI's patent on the key component technology—the polysilicon gate (# US4027381 (granted on June 7, 1977) cited Bell Lab patent # US3924319 (granted on Dec. 9, 1975) and Fairchild patent # US3931674 (granted on Jan.13, 1976), highlighting the *recombination* of TI's own knowledge with those generated by the FSI sensor manufacturers to mitigate the product performance trade-offs.

Further, TI's experiments to solve the low-yield and QEH problems of BSI CCDs, led to several more product performance trade-offs in CCD design, and consequently, to subsequent efforts to mitigate such trade-offs (Janesick and Elliott, 1992). We describe these trade-offs below.

First, although TI developed BSI sensors with polysilicon gate, these gates had low QE in the blue/green region of the spectrum (Roper Scientific, n.d.). Additionally, during the thinning of

CCD for BSI, “eddy currents set-up in the thinning drum preferentially etched the corners of the CCD. The corners of the WF /PC I CCDs were about 1 micron thinner than the center of the device due to this problem. This characteristic led to nonuniform QE sensitivity” and inferior quality photograph (Janesick and Elliott, 1992, p. 21).

Second, mechanical stresses caused the thinned membranes of BSI sensors to warp in a concave manner (the “potato chip” factor). “This trait made it difficult to focus an image….[t]o make matters worse the shape of the membrane would change and buckle as the device was cooled” making focusing on a target almost impossible (Janesick and Elliott, 1992, p. 21).

Third, TI used phosphor coating on CCDs to convert incident UV photons into longer wavelength photons (Janesick and Elliott, 1992; p. 26). However, coronene phosphor used in TI WF/PC I CCDs resulted in a "QE notch” between 3900 and 4200 Å wavelengths, where coronene is not sensitive.

The abovementioned challenges with BSI sensors forced both FSI and BSI sensor manufacturers to explore ways to mitigate the product performance trade-offs involved in improving yield and reducing QEH that plagued the BSI CCDs. Such explorations led to several significant innovations that encouraged knowledge flow from BSI to FSI sensors and recombination of such knowledge by FSI sensors manufacturers to mitigate product performance trade-offs in FSI sensors.

<u>Mitigating product performance trade-offs in FSI sensors using knowledge generated by BSI CCD manufacturers</u>:

One of the innovations that improved the QE of BSI CCDs (Janesick and Elliott, 1992; p. 22-23) was *light-pipes* used in WF/PC I, which added $5 million to the cost of the manufacturing of the HST (see US patent # 5365292A filed 02/08/93 by J.R. Janesick; p. 9). Light-pipes trap light beams and prevent color cross talks, thereby improving the resolution of pictures. Sony adopted light-pipes for its FSI CCD sensors used in camcorder and digital camera sensors (Fontaine, 2011).

Additional efforts to mitigate product performance trade-offs included Kodak's Microelectronics Technology Division developed CCD with Indium Tin Oxide (ITO) gate (Patent # US 4732868A; filed 03/30/1985), which provided higher light throughput and had higher QE than other FSI CCDs. Although QE of BSI CCDs was higher than that of FSI CCDs with ITO gate, the latter was cheaper and therefore, "an excellent price and performance option" for consumer electronic products (Roper Scientific, n.d.). Several subsequent CCD innovations by Sony and others (see, e.g., Sony patent # US 4908711A filed on 06/02/1988) were based on Kodak's ITO innovation. Ford/Loral used Kodak's innovation to design the WF/PC II sensors, which replaced TI CCDs in HST in the 1990s.

Further, the "QE notch" problem with WF/PC I led researchers to look for new coating materials. Ford/Loral WF/PC II FSI CCDs, which borrowed several pieces of key knowledge from WF/PC I BSI CCDs, used lumigen phosphor (Clampin, 1992; p.1)—a material that absorbs UV and some of the EUV (i.e., 500 to 4200 Å) achieving almost 100 percent QE.

Additionally, Tektronix developed a radically innovative hybrid CCD that "backs the frontside of the CCD with a thick ceramic header before thinning is performed. This method guarantees that the CCD will remain flat after thinning….After the Tek device is thinned it must be electrically bonded to the package" using the 'backside' of the bond pads (Janesick and Elliott, 1992; p. 21). Indeed, Tektronix patent (# US 4739382A; filed 5/31/85) claimed a "hybrid" FSI-BSI device that "integrated circuit package comprising a substrate of dielectric material having two main faces, at least one integrated circuit die mounted on one main face of the substrate, a temperature sensing resistor incorporated within said at least one integrated circuit die, and a film resistor adhered to the opposite main face of the substrate" (p. 4 of patent). Also, in 1985, RCA invented a hybrid BSI ILT CCD (patent # US 4656519 filed 10/4/85). The "Summary of the Invention" section of this patent claims—

> *"This [invention] makes possible an interline transfer imager, that is constructed on a semiconductive substrate in which photoconversion of the radiant energy image takes place, and that is back-illuminated to obtain a higher fill factor than found in front-illuminated interline transfer imagers."*

In 1986, following RCA's invention of the previous year, Matsushita filed a patent for a hybrid frame-interline transfer (FIT) CCD, which combined the benefits of both FSI and BSI CCDs. The efforts of Tektronix, RCA, and Matsushita to introduce radical innovations (Henderson and Clark, 1990) that were compatible to both BSI and FSI CCDs were similar to Shapiro and Varian's (1999; p. 15) observations in the evolution of the NTSC color television system, which was compatible with the older black-and-white signals.

In a nutshell, the evolutionary trajectory of CCDs in the 1980s suggests that a rich ecosystem of firms (such as TI, Sony, Matsushita, Kodak, Ford/Loral, Tektronix, and others) existed. Additionally, there was an *active knowledge generation, flow, and recombination activity among the members of the pre-commercialization ecosystem,* which led to innovation in key component technologies, such as polysilicon gates, which in turn, helped firms mitigate the product performance trade-offs. The developments during this period raise our next follow-up question about the genesis of the ecosystem.

<u>Follow-up question # 2: What is the genesis of the ecosystem that helped foster innovations in CCDs during the 1980s?</u>

To seek an answer to this follow-up question, we had to investigate the technological changes that led to the development of the FSI and BSI CCDs in the 1970s.

From 1969 until the mid-1970s: Invention of CCD sensors and evolution of latent demand for digital imaging

On Oct. 19, 1969, Willard Boyle and George Smith of Bell Telephone Laboratories brainstormed using a blackboard for about 30 minutes and invented the modern CCD sensors. A CCD sensor consists of light-sensing elements arranged in a two-dimensional array on a silicon substrate, which traps the photon-induced charge and causes negatively charged electrons to migrate to the positively charged gate electrode. External voltages applied to each pixel's electrodes control the storage and movement of charges accumulated during a specified time interval. The primary motivation for this invention came from Jack Morton of Bell Labs Electronic Technology, who was a strong supporter of magnetic-bubble memory using semiconductors and "picture-phone."

In the early 1970s, the substitutes to CCDs included chemical films and vision tubes. NASA used vidicon tubes in the Mariner mission (1962) and was planning to use those for the Viking I and II launches in 1975 and Voyager I and II launches in 1977. Bell Labs introduced CCD to the Navy and NASA/JPL in 1972. NASA was planning for a Large Space Telescope (LST; later renamed Hubble Space Telescope) and the Navy was interested in low-light imaging of enemy territory. During the 1970s, film technology was mature, introduced in the 1850s and used in astronomy since 1880s. Large photographic plates were available to map huge regions of sky with a resolution of 100 MP (approx.) and they were sensitive to a broad range of wavelengths—UV and X-ray. However, when placed in Earth's orbit, high energy radiation would fog the film, and astronauts would regularly have to retrieve these films, which the early planners of the LST team concluded was an impractical solution.

The vidicon tubes had disadvantages as well. Although these tubes were not vulnerable to radiation and produced pictures of 1024*1024-pixel resolution for the Viking and Voyager missions, they were unable to retain images for long exposures and, due to photocathodes degrading over time, the lifetimes of such tubes were questionable for LST/Hubble's originally planned mission of 15 years. CCDs, by contrast, could stare at objects for several hours, leading to longer exposures needed in low-light conditions. At both visible light and near IR spectrum, CCDs were five times more sensitive, and 100 times more sensitive, than tubes and film respectively. Additionally, the output of CCD sensors was proportional to photon input, whereas films exhibit non-linear response and become less sensitive with more exposures. CCDs also had large dynamic range (>3000), were geometrically stable, consumed less power (estimated at =< 10 mW for LST), and its output could be digitized and amplified.

Although the abovementioned advantages of CCDs over both film and vidicon technology helped attract NASA and the Navy's attention to digital imaging and created the latent demand for CCDs to become a viable alternative, manufacturers had to mitigate several product performance trade-offs. For example, to perform, CCD sensors required significant cooling to eliminate thermal dark charge. Additionally, the Charge-Transfer Efficiency (CTE) was critical and had to be between 99.999 percent and 99.9999 percent for CCDs to perform as expected. Further, due to the innovations in vidicon tube technology in the 1960s, the belief was that CCDs had to reach the resolution of 1024*1024 picture format to become a viable alternative. Moreover, CCDs were not responsive to UV lights, which was a major deterrent for both NASA and the Navy. To make CCDs popular among scientists, in 1973, workers at JPL initiated a program to develop high-performance large area array CCDs, designed for space-borne navigation and imaging instruments, and built a *Traveling CCD Camera System*, the first of its kind, used at major astronomical observatories worldwide.

The genesis of the first standardized product feature of the future dominant design

To explore if CCD sensors could become a viable alternative to vidicon tubes, in 1972 the Naval Electronics Systems Command (NESC) sponsored a three-phase, 30-month research program. During Phase I, three manufacturers—Fairchild, RCA, and TI—were funded to develop and deliver 12 500*l line imagers and 12 100*100 area imagers (Campana, 1973; p. 235). The primary focus of this phase was using CCDs for low-light imaging. During this phase, both RCA and TI employed surface channel CCDs. Fairchild, by contrast, invented *buried channel* in its CCDs (US Patent # US3853634 granted on Dec. 10, 1974). As a result, whereas the CTE of RCA CCD was 99.8 percent and that of the TI CCD was 99.65 percent; Fairchild CCD achieved 99.9 percent CTE. In April 1973, NESC selected Fairchild to continue its CCD development program and almost all CCDs manufactured since 1973 exclusively utilized buried channels. Consistent with Benner and Tripsas's (2012; p.285) observations, NESC's decision resulted in CCD manufacturers choosing the buried channel as a *standardized* product feature that eventually led to the dominant design.

The challenges associated with mitigating the technological trade-offs in buried channel CCD sensors lingered well beyond the mid-1970s. Whereas Phase I of NESC's efforts highlighted the potential utility of BSI CCDs over the FSI ones, in approaching the resolution of vidicon tubes (Campana, 1973; p. 237), Phase II of NESC's program was exclusively devoted to "blooming" reduction (p. 240). The second phase of NESC's efforts resulted in Fairchild developing two sensors for low-light imaging (Wen, 1975; pp. 111-115)—a linear imager of 1728*1 pixels and an area imager of 244*190 pixels—both of which were FSI sensors "showed excellent transfer efficiency at signal levels well below 100 electrons" (p. 118).

In 1973, around the same time that the Phase I experiments were being conducted by NESC, NASA entered into contract # 953673 with TI to investigate the feasibility of using CCDs for the optical sensors in spaceborne imaging systems, and to formulate recommendations for designing such CCDs. TI recommended an area imager of 400*400 pixels with 22.9µm*22.9µm pixels. These BSI sensors had antireflection SiO_2 coating and achieved CTE of 99.99 percent. TI suggested polysilicon SiO_2-Al gate structure (TI Final Technical Report, 1973, p. B-7) and its efforts culminated in a "18-month Development Program that is to be completed near the end of the calendar year 1975 with the delivery of CCD Sensors and the demonstration of compliance with specified performance characteristics" (TI Final Technical Report 1973, p. 1-1).

During the early 1970s, research at TI, Fairchild, and other firms to meet the needs of NESC and NASA, identified critical product performance trade-offs associated with designing BSI and FSI sensors (Barbe and White, 1973; see also Anderson 1976; p.283). The BSI sensors were better than their FSI counterparts in photoelement responsivity (the efficiency with which photons are absorbed by the pixel), vertical modulation transfer function (MTF—the loss of frequency response due to transfer inefficiency), and effective integration time (Barbe and White, 1973; pp. 15-19).

Despite being superior in performance, TI Final Technical Report (1973, p. 2-3) noted that BSI sensors had "special problems…..[c]onsequently, experiments on thinning are proposed during the first six months of the Development Program. An optimum means of bonding the chip to a rigid disk, perhaps a ceramic, before thinning, in order to control the surface flatness better, will be developed during these experiments." The report also highlighted the trade-off and observed that the changes needed in CCD sensors to reduce blooming (or the loss of electrons to adjacent pixels) would significantly add to the cost. The report paved the way for the use of buried channel FSI sensors in commercial products and concluded that—

> "….*in the present application which calls for a replacement of the silicon vidicon having smaller size, weight, and power consumption, but not necessarily higher anti-blooming performance, that this feature is a luxury*

not worth its cost…..it is anticipated that there will be few occasions when the intrascene contrast will be high enough to necessitate saturation of a pixel, and hence blooming should present no undue limitation to the performance of the sensor" (TI Final Technical Report, 1973; p. 3-9).

Divergence of potential demand and coevolution of FSI and BSI sensors

The abovementioned trade-offs sowed the seeds of divergence of potential demand for FSI and BSI sensors. Amelio (1974) and Vanstone (1974) echoed the performance trade-offs associated with BSI and FSI sensors and noted that in the infrared spectrum, FSI performs better than BSI, but the latter is optimum for relatively high modulation transfer function (MTF) and QE at all visible wavelengths. Efforts to improve infrared responsivity with thicker substrates in BSI faced further product performance trade-offs—it led to a substantial loss of MTF for most of the visible spectrum. The alternative was to use FSI with a thicker substrate, which does not degrade the visible spectrum MTF, but this alternative too involved a trade-off—QE of such sensors are low. The loss of QE is more prominent in the blue spectrum for FSI sensors, but researchers conclude that, "if blue response is not important, the cost and complexity of backside illumination is probably not justified" (Amelio, 1974; p. 137). Hoagland and Balopole (1976; p. 21) reported the results of experiments conducted at NASA/Lyndon B. Johnson Space Center (under contract # NAS 9-14844) to assess the performance of FSI CCD sensors. They noted that, "CCD image sensors of the buried-channel interline-transfer type have features which makes these devices particularly useful for solid-state TV cameras where small size, low power/low voltage operation, high sensitivity and extreme ruggedness are either desirable or mandatory characteristics."

Thus, as a consequence of the experiments conducted at NESC and NASA/Lyndon B. Johnson Space Center, firms such as Fairchild, Sony, Matsushita, Kodak, Ford/Loral, Philips, and others continued with the R&D to incorporate the FSI sensors—which were inferior in overall performance but had a better performance-over-cost-to-manufacture ratio—into consumer products such as consumer digital video and still cameras. These firms concluded that, *given the product performance trade-off*, Fairchild FSI CCDs were the better suited for future research into camera modules (Monro, 1978). Subsequently, the abovementioned firms and others started their efforts to manufacture CCD TV camera prototypes by using Fairchild 190*244 and 380*488 FSI area sensors (Hoagland and Balopole, 1975).

Although FSI CCD sensors became the choice for potential consumer product manufacturers, the scientific community, led by TI and NASA/JPL, concentrated on innovations with BSI CCDs scientific applications. Subsequently, both the FSI and BSI sensors co-evolved with knowledge flow and recombination activity among the manufacturers.

From the mid-1970s to the early-1980s: The genesis of the innovation ecosystem to facilitate knowledge generation, flow, and recombination activity

The experiments at NESC and NASA prompted the need for further product innovations exploration to improve the performance of CCD sensors, and to improve their performance-to-cost ratio, for both BSI and FSI sensors. As Janesick and Elliott (1992; p. 13) highlighted, "it became clear from these early studies that a special R & D effort was necessary to combine the best attributes of all CCD technologies known at the time. JPL then contracted Texas Instruments to work on a scientific sensor based on backside illumination, full frame, buried channel, with pixel counts equivalent to or greater than the vidicon tube." Janesick and Elliott (1992) also noted that the cooperation between NASA/JPL and TI progressed for "over a decade" and resulted in "many breakthroughs" for CCD sensors (p.13).

Despite the performance-cost trade-offs in BSI and FSI CCDs, there was significant overlap in R&D for these sensors because they "have a lot in common" (Bosiers *et al.* 2006; p. 149). This led to knowledge generation, flow, and recombination, between and among BSI and FSI sensor manufacturers, which benefited both the manufacturers of FSI CCDs (such as Sony, Matsushita, Kodak, and Ford/Loral) and BSI CCDs (such as TI).

In the 1970s, Ford/Loral, manufacturer of FSI CCDs, developed germanium CCDs (Janesick and Elliott, 1992; p. 7), (Patent # US3962578 granted to Aeronutronic Ford on June 8, 1976). Because germanium's band gap is half as that of silicon and the former's infrared (IR) response in space applications better than that of the latter, TI *recombined* its own knowledge with that of Ford/Loral and started manufacturing germanium BSI CCDs (TI patent # US3989946 granted on Nov. 2, 1976). In addition to responsiveness to IR, the density of germanium is greater than that of silicon and, therefore, the X-ray response is about 20 keV. Moreover, Ford/Loral also developed multi-pinned CCDs, which reduced dark noise and allowed removal of residual images (Clampin, 1992).

The TI WF/PC I CCD design for HST shows further evidence of knowledge flow and *recombination* across the ecosystem. For example, following the lead of Fairchild, these sensors were buried channel ones. In addition to building on the innovations of Ford/Loral and Fairchild, TI also *recombined* Westinghouse's knowledge of correlated double sampling (CDS), originally developed for FSI CCDs (White *et al.*, 1974), with its own knowledge of BSI CCDs (see, e.g., TI patent # US 3965368 issued on June 22, 1976). In its quest to develop CCDs for HST, *TI not only acquired knowledge from other firms in the ecosystem, but also recombined that knowledge with its own knowledge*, such as Advanced Virtual-Phase CCD Technology (TI Patent # US4229752A filed on May 16, 1978).

Thus, the innovation ecosystem emerged in the mid-1970s to facilitate knowledge flow and recombination, which was necessary to mitigate product performance trade-offs of both FSI and BSI CCD sensors.

Similar flow and recombination in the 1980s followed the knowledge flow and recombination of the 1970s, as we discussed earlier; for example, the problem with polysilicon gates in WF/PC I CCDs. In this case, QE drops at wavelengths shorter than 540 nm and is essentially zero below 400 nm, which led Kodak's Microelectronics Technology Division to develop CCDs with ITO. This, in turn, led to *further recombination* of knowledge such as the hybrid CCDs by Tektronix and Matsushita. We summarize the knowledge flow across the pre-commercialization innovation ecosystem during the 1970s and 1980s in Figure 2.

Insert Figure 2 here

Consequence of knowledge flow across the pre-commercialization innovation ecosystem: Commercialization of CCDs

As a consequence of knowledge flow across various firms, and knowledge recombination, in the pre-commercialization innovation ecosystem, firms in the ecosystem overcame several challenges. For example, in the early 1980s, firms crossed a big hurdle for CCD sensors—"the development of a single, high-resolution chip that can supply all three primary colors" (Barrier, 2011; p. 26). This hurdle was overcome when RCA invented the "checkerboard color filter" (patent # US 4286285A filed 02/04/1980) in the early 1980s. RCA built its knowledge on prior research at the Bell Telephone Laboratories on color-coding filters for CCDs (patent # US3982274 granted on Sept. 21, 1976). Building on RCA's innovation, Sony improved its CCD sensors and in the 1980s, installed the first FSI CCD color video cameras in a B747 aircraft of ANA. Of the two cameras installed, one provided the view of the cockpit and the other that of the landing gear during takeoff and landing. In 1980, Sony introduced its XC-1color video camera intended to show video images of the cockpit to the aircraft passengers (http://www.digicamhistory.com/Sony_XC-1.html). Within two years of Sony's XC-1 introduction, NEC Corp. invented the resin microlens (Patent # US 4667092A filed on 12/22/1982) to improve picture resolution of CCD pixels.

As we discussed earlier, these innovations culminated in NASA's decision to replace the original BSI sensors in HST with FSI sensors in 1990. Prior to this, in 1989, by recombining knowledge generated by various firms in the ecosystem, Kodak introduced the Ecam (Electronic Camera). Designed by Steve Sasson and Robert Hills, this camera was the first modern digital single lens reflex (SLR) camera that looks and functions like today's professional models. "It had a 1.2 megapixel sensor, and used image compression and memory cards. But Kodak's marketing department was not interested in marketing this product because "it would eat away at the company's film sales" (Estrin, 2015). Also in 1989, Fuji introduced its first digital camera, DS-X priced at $20,000. In 1990, Nikon introduced its DSC 1 with Kodak CCD and Nikon F3 body for $25,000, and in 1991, Fuji introduced DS-1 for $5,000. In 1991, Sony introduced its SEPS 1000 digital video camera priced at $30,000. Early 1993 saw the introduction of the Dycam Model 4 and in 1994, Apple's QT100 consumer digital still color camera appeared on the market at a price below $1000.

Discussion: Theoretical implications of our findings

Our research suggests that the path leading to the establishment of pre-commercialization dominant design is a nuanced one, and is interspersed with knowledge generation, transfer, and recombination among various firms in the pre-commercialization innovation ecosystem. Next, we juxtapose our findings with the theoretical mechanisms identified by extant research, and discuss the implications of the empirical evidence provided above.

Our first framing question was— What is the genesis of the pre-commercialization innovation ecosystem? Why, and how, is such an ecosystem created?

Consistent with Moeen (2013) and Moeen and Agarwal (2017), we find evidence of a pre-commercialization ecosystem. Further, we extend Moeen (2013) and find evidence that the ecosystem develops to meet latent demand. In the context of image sensors, the innovation ecosystem germinated when firms tried to mitigate the product performance trade-offs associated with FSI and BSI CCD sensors in order to meet the potential demand of NESC and NASA. Further, our research suggests that knowledge flow across the firms in the ecosystem, which mitigates the product performance trade-offs, leads to the development of key new components, such as the polysilicon gate. Thus, our first stylized finding is—

Stylized finding # 1: Ecosystems evolve when firms engage in technological investments (Moeen and Agarwal, 2017) to mitigate the product performance trade-offs associated with meeting the needs of potential buyers.

Our second framing question was— "What are the implications of knowledge flow among firms in the pre-commercialization phase? Does such knowledge flow reduce technological uncertainties? If so, how?"

We find that knowledge flow among firms in the innovation ecosystem leads to knowledge recombination, which, in turn, mitigates product performance trade-offs associated with improving the performance feature that large, potential customers value. Knowledge recombination to mitigate product performance trade-offs is relatively underexplored in the literature, which prompted Moeen and Agarwal (2017; p.582) to note that researchers generally "abstract away from nascent industry contexts…..due to informational challenges" in this phase of the technology's evolution. Addressing this relatively underinvestigated area of research, we find that knowledge flows from Fairchild, RCA, Ford/Loral, to TI led to knowledge recombination to mitigate the product performance trade-offs associated with improving CCD sensor's performance. Thus, our second stylized finding is—

Stylized finding # 2: Knowledge generation, flow, and recombination across firms in the pre-commercialization ecosystem helped firms mitigate the product performance trade-offs associated with developing the product that met potential buyers' demand.

Our third framing question was—"What role does the pre-commercialization innovation ecosystem play in determining firms' technological investment choices during this phase?"

We find that firms in the pre-commercialization phase compete to meet potential demand from buyers (e.g., NESC and NASA in our case). Unlike demand conditions in the post-commercialization phase, the potential demand in the pre-commercialization phase is a latent one (Kotler, 1973) where the knowledge—of how to satisfy potential demand by mitigating the product performance trade-offs associated with improving the critical performance features—evolves over time. For example, Phase I of NESC's program led the CCD sensor manufactures to adopt buried channel—first used by Fairchild—as the product configuration that would be used in the eventual dominant design. Phase II of NESC's program involved efforts to mitigate the product performance trade-offs associated with improving the performance of CCD sensors by reducing blooming. Similarly, TI's efforts to meet latent demand from NASA led to technological investments, which, in turn, led to innovations such as CCD sensors with germanium, polysilicon gate structure, ITO gate, and multi-pinned CCDs. In their quest to meet latent demand from potential customers, firms rely on knowledge transfer and recombination within the ecosystem. This leads us to our third stylized finding—

<u>Stylized finding # 3: The pre-commercialization innovation ecosystem helped firms transfer and recombine knowledge to meet latent demand from potential customers.</u>

Our fourth framing question was—"What triggers the genesis of key component technologies? Do these technologies help firms mitigate the performance trade-offs in the new products? If so, how?"

Consistent with prior research, we find that to meet the potential demand of NESC and NASA, firms transfer and recombine knowledge, which, in turn, leads to key component technologies such as light-pipes that are needed to mitigate product performance trade-offs, such as QEH, to meet potential demand. For example, TI utilized the knowledge of a polysilicon gate—originally designed by Fairchild and RCA to mitigate shorting problems of aluminum gates in FSI sensors—and recombined that with its own knowledge to create gates for BSI sensors. Thereafter, Kodak and other manufacturers used this key component. Thus, our fourth stylized finding is--

Stylized finding # 4: The efforts of firms in an innovation ecosystem to mitigate product performance trade-offs to meet potential demand by transferring and recombining knowledge, usher in new key components.

Our fifth framing question was—"Does the evolutionary trajectory of a new technology in the pre-commercialization phase follow the predictions for the post-commercialization phase? If not, how does the evolutionary trajectory in the pre-commercialization phase differ from that of the post-commercialization phase?"

Prior research suggests that dominant design marks "the end of the era of ferment" and begins an "era of competition based on slight improvements on a standard design" Anderson and Tushman (1991; p. 28). In the context of this paper, FSI sensors eventually became the dominant design. In the post-commercialization phase of CCDs, Sony commanded about 50 percent market share in CCD manufacturing in the late-2000s and early 2010s (Techno Systems Research, 2012).[4] CCDs manufactured by Sony, Matsushita, Kodak, and others in the post-commercialization phase were buried channel FSI sensors based on Fairchild CCDs designed in 1973.

Following the first phase of experiments at NESC in the early 1970s, Barbe (1975; Table III, p. 52) noted that Fairchild's buried channel CCDs had distinct advantages over surface channel

[4] This is consistent with Anderson and Tushman (1990), who defined dominant design as a "narrow range of [product] configurations that accounted for over 50 percent of new product sales… and maintained a 50 percent market share for at least four years" (p. 620). Suarez (2004) and Benner and Tripsas (2012) make similar observations. Because of the lack of sales in the pre-commercialization phase, we follow prior research and define the dominant design in the pre-commercialization phase as the narrow range of product configurations that accounted for over 50 percent of prototypes manufactured by the firms during this period. Fairchild's buried channel FSI CCD fits this definition of pre-commercialization dominant design.

CCDs manufactured by TI, RCA, and Bell Labs. Amelio (1974; p. 137) also highlighted that, "the issue of buried channel vs. surface channel mode has been resolved. It is clear that buried channel not only provides several major advantages in performance, but also simplifies device design and operation." The Fairchild buried channel design, thereby, became the first product configuration to be chosen by the manufacturers; as we discussed earlier, CCDs manufactured by Sony, Tektronix, Ford/Loral, and others were based on Fairchild's buried channel design.

We observe that in the pre-commercialization phase of CCD sensors, the dominant design is chosen in phases. The time—between choosing the buried channel configuration in the mid-1970s and the FSI sensors over the BSI sensors in the early 1990s—was almost 17 years. During this time period, product innovations were associated with mitigating the product performance trade-offs associated with two types of buried channel sensors—the FSI and BSI ones and the two product designs, FSI and BSI, coevolved. Eventually, despite the product performance trade-off—whereby the response of Fairchild's FSI sensors in the blue spectrum lagged that of BSI sensors (Barbe, 1975; Table VIII, p. 59) and the charge-collection area of BSI sensors are twice as large as those in FSI sensors ensuring that the "lens used with the ILT array will have to be about twice the area of that used with the FT array" Beynon and Lamb (1980; p. 103)—Fairchild's buried channel FSI design was chosen by NESC for further research, and paved the way for future CCDs for commercial applications by Sony, Sharp, and others.

Subsequent to the establishment of the first product configuration of the eventual dominant design in the mid-1970s, as we noted earlier, knowledge generation, flow, and recombination continued among the firms in the ecosystem to mitigate the trade-offs associated with improving the performance of low-cost FSI CCDs and lowering the manufacturing cost of high performance BSI CCDs. Our research indicates that the pattern of technological evolution in the pre-commercialization phase is different from that of the post-commercialization phase. Although we do find evidence of a prolonged era of ferment in the pre-commercialization phase—from the mid-1970s through the early 1990s—the time period between choosing the various product configurations that would form the pre-commercialization dominant design, we do not find evidence of an era of incremental change during this phase.

Accordingly, our fifth stylized finding specifies the boundary condition of the extant dominant design theory, which primarily focuses on the post-commercialization phase. The fifth stylized finding is—

Stylized finding # 5: The "range of [product] configurations" (Anderson and Tushman, 1990; p. 620) that characterizes the pre-commercialization dominant design, is chosen over a period of time. Product innovation in the interim time period opens the door for co-evolution of new product designs, new key component technologies, and efforts to mitigate product performance trade-offs associated with product design.

We summarize our findings in Table 1 below.

Insert Table 1 about here

In addition to the abovementioned stylized findings, which are specific to the pre-commercialization phase of a new technology's evolution, our research also leads to other critical insights about the broader innovation literature. While literature generally portrays the genesis of a new technology as the consequence of either demand pull or science push, our investigation shows a more nuanced process than that which literature portrays.

Demand pull perspective (Schmookler, 1962), on the one hand, relies on the assumption that manufacturers recognize the needs of potential customers (Dosi, 1984; Mowery and Rosenberg, 1979). However, researchers note that this line of thought "simply ignores, or denies, the operation of a complex and diverse set of supply side mechanisms which are continually altering the structure of production costs" (Mowery and Rosenberg, 1979, p. 142).

Science push perspective, on the other hand, owes its intellectual heritage to Holland's (1928) research, and advocates that pure science research leads to invention, which, in turn, leads to new and innovative products. Scholars have criticized this line of thought as a linear model (Rogers, 1983) of technological progress.

Our investigation reveals that, consistent with Scherer's (1982; pp. 236-237) observations, reality likely lies somewhere in between the abovementioned two perspectives, and that "[b]oth the pull of demand and…. technological opportunity… must be taken into account for an adequate conception of how technological change occurs." Rather than a science push or demand pull, we find evidence of *commercialization pull* in the pre-commercialization phase where both potential demand from customers and technological opportunity play a role in technological progress toward eventual commercialization. The commercialization pull perspective is consistent with Dosi's (1984; p. 10) assertion that "[*a*] *priori* recognition of a need" is necessary but not sufficient for technological progress.

Additionally, our research expands the literature on markets for technology to the pre-commercialization phase (Arora, Fosfuri, and Gambardella, 2001). Whereas this literature has largely abstracted "away from nascent industry contexts, often assuming non-existence of markets due to informational challenges" (Moeen and Agarwal, 2017; p.582), we find evidence of knowledge flow among TI, RCA, Fairchild, and others. We also observe that firms recombine knowledge generated at other firms with their own knowledge to meet demand from potential large buyers. For example, following the NESC experiments in 1973, which established the technological superiority of Fairchild's buried channel CCDs over TI's surface channel CCDs, NASA conducted several more experiments with TI to explore the performance of buried channel ones. As we highlighted earlier, to build buried channel CCDs, TI borrowed knowledge not only from Fairchild but also from Westinghouse and others to meet NASA's demands for the HST image sensor, WF/PC I, which launched on April 24, 1990.

Limitations: Despite following prior research and building on wisdom available in the literature, our research has its limitations. One of the limitations is that we investigate knowledge transfer among the members of the pre-commercialization innovation ecosystem only in one industry. Our reliance on a single industry does not allow us to explore if this is true for the pre-commercialization phase of other industries as well. For example, prior studies allude to the role of innovation ecosystems in biotech (Pisano, 2006), agricultural biotech (Moeen, 2013), semiconductors (Holbrook *et al.*, 2000), and Global Positioning Systems (Worth and Warren, 2009) and highlight the role of large institutions such as the National Institutes of Health, the National Science Foundation, and the Defense Advanced Research Projects Agency may have played a lead role in the genesis of innovation ecosystems. Future research may investigate if knowledge transfers among the members of pre-commercialization ecosystem played a role in overcoming the challenges of technological trade-offs associated with meeting the demand of potential buyers.

Yet another limitation of our paper is that we cannot explain why early members of the innovation ecosystem—such as TI, RCA, Fairchild, Sony, Matsushita, Kodak, Philips, and others in the context of CCD—exchanged information and recombined knowledge to refine the product design. Do potential buyers strategically make such knowledge flow possible? Are firms in the pre-commercialization phase motivated to recombine knowledge to overcome the initial uncertainties associated with developing the product that meets the needs of large institution buyers? These are some of the critical questions that to be addressed in future research.

Additionally, our paper does not explore how the movement of researchers from one firm to another affects the innovativeness of firms during the pre-commercialization phase. Such a movement of knowledge can be critical for the evolution of a new technology.

Despite these limitations, ours is one of the first studies to contribute to the innovation literature by highlighting that commercialization of a new technology is the outcome of an iterative process enacted within an innovation ecosystem. The process consists of efforts to mitigate product performance trade-offs, which encourage firms to generate, transfer, and recombine knowledge to create new key components. The use of these new components lead to further trade-offs, which, in turn, lead to more knowledge generation, transfer, and recombination. The iterative process leads to the commercialization of a new technology.

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Table 1: Summary of the theoretical implications of our study

Received Wisdom	**Our framing questions**	**Our findings**	**Novel Theoretical Implications**
Firms in the pre-commercialization phase capture economic value within the innovation ecosystem.	*What is the genesis of the pre-commercialization innovation ecosystem?* *Why and how is such an ecosystem created?*	Ecosystems evolve when firms engage in technological investments to mitigate the product performance trade-offs associated with meeting the needs of potential buyers.	Genesis of the pre-commercialization ecosystem is tied to needs of potential buyers. Our research suggests that the knowledge flow across firms in the ecosystem leads to the development of new key components.
The pre-commercialization phase is characterized by knowledge flow and "cooperation across various types of firms" (Moeen and Agarwal, 2017, p.579).	*What are the implications of knowledge flow among firms in the pre-commercialization phase?* *Does such knowledge flow reduce technological uncertainties? If so, how?*	Knowledge generation, flow, and recombination across firms in the pre-commercialization ecosystem helped firms mitigate the product performance trade-offs associated with developing the product that met potential buyers' demand.	Knowledge flow among firms in the innovation ecosystem leads to knowledge recombination, which, in turn, mitigates product performance trade-offs associated with improving the performance feature that large, potential customers value.
Firms engage in technological investments prior to product commercialization.	*What role does the pre-commercialization innovation ecosystem play in determining firms' technological investment choices during this phase?*	The pre-commercialization innovation ecosystem helped firms transfer and recombine knowledge to meet latent demand from potential customers.	Unlike demand conditions in the post-commercialization phase, the potential demand in the pre-commercialization phase is a latent one where knowledge evolves over time.
Innovations in key component technologies lead to improvements in critical product performance features.	*What triggers the genesis of key component technologies?* *Do these technologies help firms mitigate the performance trade-offs in the new products? If so, how?"*	The efforts of firms in an innovation ecosystem to mitigate product performance trade-offs to meet potential demand by transferring and recombining knowledge, usher in new key components.	Firms recombined knowledge with their own knowledge to create new key components.

Table 1 (contd.)

Received Wisdom	Our framing questions	Our findings	Novel Theoretical Implications
Technological evolution in the post-commercialization phase follows the pattern of an era of ferment, to the emergence of a dominant design, to the era of incremental change.	*Does the evolutionary trajectory of a new technology in the pre-commercialization phase follow the predictions for the post-commercialization phase?* *If not, how does the evolutionary trajectory in the pre-commercialization phase differ from that of the post-commercialization phase?*	The "range of [product] configurations" (Anderson and Tushman, 1990; p. 620) that characterizes the pre-commercialization dominant design, is chosen over a period of time. Product innovation in the interim time period opens the door for co-evolution of new product designs, new key component technologies, and efforts to mitigate product performance trade-offs associated with product design.	Our research indicates that the pattern of technological evolution in the pre-commercialization phase is different from that of the post-commercialization phase. Although we do find evidence of a prolonged era of ferment in the pre-commercialization phase in the time period between choosing the various product configurations that would form the pre-commercialization dominant design, we do not find evidence of an era of incremental change during this phase.

Figure 1: Market-share of digital and analog cameras since 1994

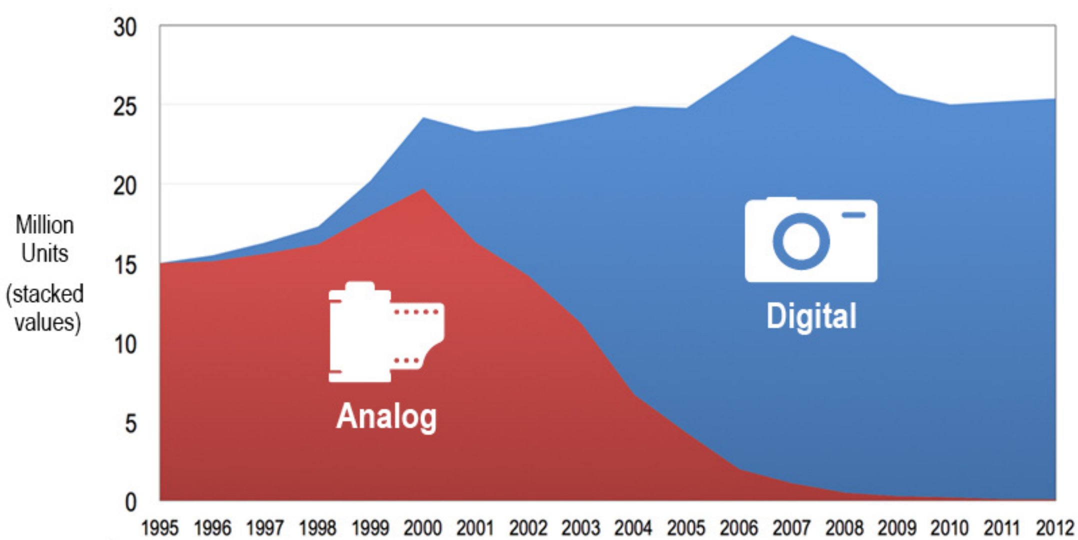
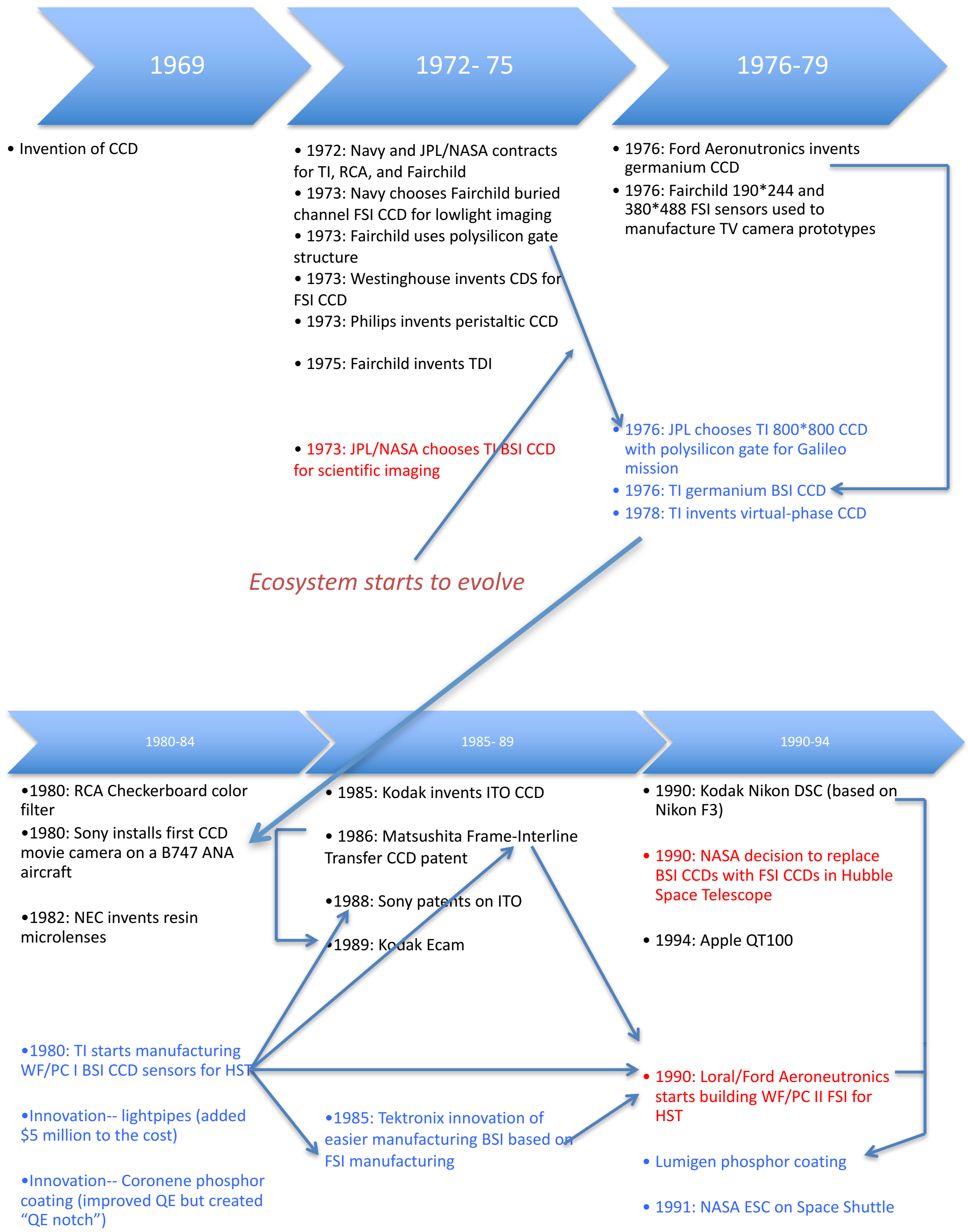


Figure 2: Timeline of pre-commercialization evolution of CCDs during the period 1969-1994

(Arrows represent knowledge flows; black font represents innovations in FSI CCDs, and blue font represents innovations in BSI CCDs)



Appendix: Definitions

Backside-illuminated (BSI) CCD: The problems encountered in frontside illuminated CCD imagers can be eliminated when the device is illuminated on the backside, where the device must be thinned to prevent significant lateral diffusion of the photogenerated minority carriers. After thinning, the silicon surface must be accumulated to minimize carrier recombination at the back surface. Finally, an antireflection coating is deposited on the backside to improve the optical transmission. (Anderson, 1976). The positive voltage induced in the oxide layer creates a backside depletion region and a corresponding backside potential well in the silicon that attracts and collects photogenerated electrons (Janesick and Elliott, 1992).

Blooming: "Blooming occurs when the charge in a pixel exceeds the saturation level and the charge starts to fill adjacent pixels. Typically, CCD sensors are designed to allow easy vertical shifting of the charge but potential barriers are created to reduce flow into horizontal pixels. Hence the excess charge will preferentially flow into the nearest vertical neighbours [*sic*]. Blooming therefore produces a vertical streak [in the picture]" (Andor Technology Ltd., n.d.)

Buried channel CCD: "In a buried channel device, charge packets are confined to a channel that lies beneath the surface 'buried' in the silicon. In contrast to surface channel operation, the CTE for buried channel CCDs is amazingly high" (Janesick and Elliott, 1992, p. 9).

Charge Transfer Efficiency (CTE): "The effectiveness with which the transfer process occurs is measured by the Charge Transfer Efficiency (CTE). Typically, charge may be transferred with an efficiency greater than 99.999% per pixel" (SITe Introduction to CCD, 1994, p. 12).

Dynamic range: The difference between a brightest possible source and the faintest possible source that the detector can accurately see in the same image is known as the dynamic range.

Frame-Transfer (FT): The image is transferred from the image array to an opaque storage array.

Front-side illuminated (FSI) CCD: "In the front illuminated mode of operation, incident photons must pass through a passivation layer as well as the gate structure in order to generate signal electrons. Photons will be absorbed in these layers and not contribute to the signal" (SITe Introduction to CCD, 1994, p. 13).

Inter-Line Transfer (ILT): "Each pixel includes both a *photodiode* and a separate opaque *charge* storage cell. The image charge is first quickly shifted from the lightsensitive PD to the opaque V-CCD. Inter-line transfer "hides" the image in one transfer cycle, thus producing the minimum image smear and the fastest optical shuttering" (Felber, 2002, p. 12).

Light-pipes: These are fabricated by etching a deep via from the passive layer down to the diode surface, which is followed by a placing a special polymer with a high refractive index. This design traps the light and eliminates color "cross talks." Light-pipes were developed for X-ray astro-photography using CCD sensors (Bell, 1987).

Modulation Transfer Function (MTF): The modulation transfer function is a measure of the transfer of modulation (or contrast) from the subject to the image. In other words, it measures how faithfully the lens reproduces (or transfers) detail from the object to the image produced by the lens (Alper, 2011).

Photoelement Responsivity (PE): The photoelement responsivity is the efficiency with which photons are absorbed and the resulting photoelectrons are collected.

Quantum Efficiency (QE): "The percentage of photons that are actually detected is known as the Quantum Efficiency (QE). For example, the human eye only has a QE of about 20%, photographic film has a QE of around 10%, and the best CCDs can achieve a QE of over 80%. Quantum efficiency will vary with wavelength" (McFee, n.d.)

QE Hysteresis (QEH) happens when CCD sensors do not respond in the same way to light levels over their whole dynamic range (200nm-1000nm).

Surface channel CCD: CCD sensors in which the charge packets are stored and transferred along the surface of the semiconductor (i.e., at the Si-Si02 interface). Charge can become trapped in interface traps found at the surface severely limiting CTE performance (Janesick and Elliott, 1992).

Thermal dark charge: The "number of electrons thermally generated within the silicon structure of the CCD, which is independent of photon-induced signal, but highly dependent on device temperature. The generation rate of thermal electrons at a given CCD temperature is referred to as dark current" (Fellers and Davidson, n.d.)

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