Paper to be presented at
the DRUID16 20th Anniversary Conference
Copenhagen, June 13-15, 2016

Genesis of Pre-Commercialization Innovation Ecosystem: Knowledge Recombination in the Pre-Commercialization phase of Charge-Coupled Device vision sensors-- 1969-1994

Raja Roy
Northeastern Illinois University
Management
rroy@neiu.edu

Mitrabarun Sarkar
Temple University
Strategic Management
mbsarkar@temple.edu

Abstract

Building on recent investigations of the pre-commercialization phase of a new technology, we explore the genesis of innovation ecosystem in CCD vision sensors. We concentrate on the time period between 1969, when scientists conceptualized CCD, to 1994, when the first sub-$1000 consumer digital camera was introduced by Apple. Our research reveals that innovation ecosystem germinates when, in the pre-commercialization phase, firms innovate to meet the demand conditions of potential buyers. Unlike the predictions of extant literature, we find that the pre-commercialization dominant design does not mark the transition to incremental improvements. Rather, it leads to knowledge recombination that helps firms mitigate the technological trade-offs associated with meeting the demand from potential buyers.

Jelcodes:O32,O32

Abstract

Building on recent investigations of the pre-commercialization phase of a new technology, we explore the genesis of innovation ecosystem in CCD vision sensors. We concentrate on the time period between 1969, when scientists conceptualized CCD, to 1994, when the first sub-$1000 consumer digital camera was introduced by Apple. Our research reveals that innovation ecosystem germinates when, in the pre-commercialization phase, firms innovate to meet the demand conditions of potential buyers. Unlike the predictions of extant literature, we find that the pre-commercialization dominant design does not mark the transition to incremental improvements. Rather, it leads to knowledge recombination that helps firms mitigate the technological trade-offs associated with meeting the demand from potential buyers.

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

Introduction

Strategy and innovation scholars (Gort & Klepper, 1982; Anderson & Tushman, 1991) have explored technological discontinuities and breakthroughs that result in creative destruction (Schumpeter, 1942). Concentrating on the instance of first commercialization of a product, scholars have examined how firm heterogeneity affect entry, exit, competitive dynamics, and performance (Mitchell, 1991; Tripsas, 1997; Klepper & Simons, 2000; Helfat & Lieberman, 2002; 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 *et al.*, 2009).

Recently, Moeen (2013), Moeen & Agarwal (2015), and others have devoted 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). Building on prior insights by Agarwal & Bayus (2002) and Adner & Kapoor (2010), and using the agricultural biotech industry as the context, Moeen (2013) explored firms' value capture in the pre-commercialization period. She found that firms commercializing a new technology are "core firms in the ecosystem," and those engaging in alternative modes of value capture provide "complementary capabilities to the commercializing firm" (p.17).

A related stream of research has explored the role of demand from potential buyers as the chaperon for product innovation in the pre-commercialization phase of a new technology. For example, Smil (2010; p.39) underscored the importance of potential demand from US Air Force and intercontinental airline operators in the pre-commercialization phase of jet engines. Similarly, Christley (2011; p.26) noted the role of potential demand from

French, British, and US Navy in guiding product innovation in the pre-commercialization phase of diesel engines. Further, Roy (2014) highlighted the importance of potential demand from General Motors, which spearheaded product innovation in the pre-commercialization phase of industrial robot by installing the first prototype, Unimate Prototype #001 in 1959 at a diecasting plant in Trenton, NJ. Moreover, anecdotal evidences also suggest that Louis Pasteur's research in alcoholic fermentation was driven by potential demand from distillers to improve their yield (Vallery-Radot, 1900).

While these prior efforts have, on the one hand, expanded our understanding of the role of pre-commercialization ecosystem in firms' value capture, and on the other hand, have highlighted the role of demand from potential buyers in a new technology's evolution, relatively unexplored is an investigation of the genesis of innovation ecosystem and the role of potential buyers in creating those ecosystems. An exploration of the answers to questions such as, "*How and why are the pre-commercialization ecosystem created*?" "*How does potential demand chaperon product innovation in the pre-commercialization phase*?" and "*How does potential demand affect the genesis of innovation ecosystem*?" is critical if researchers and practitioners are to "fully [comprehend] interinnovation relationships" (Golder *et al.*, 2009; p. 167) among the new entrants; the role of innovation ecosystem (Adner & Kapoor, 2010) in nurturing those relationships in the pre-commercialization phase of a technology's evolution; and how those relationships shape the post-commercialization oligopolistic industry structure (Moeen & Agarwal, 2015).

Using the evolution of charge-coupled device (CCD) vision sensors, from its conceptualization in 1969 to commercialization in 1994, we find evidence that, in the context of CCDs, innovation ecosystem germinated as firms, such as Fairchild Camera and Instrument Corporation, Texas Instruments, and others introduced innovative new products to meet the needs of potential customers, such as Navy and NASA. Further, we also find that knowledge flow and recombination within the ecosystem leads to a pre-commercialization dominant design--"a standard embodiment of an industry's core technology" (Anderson & Tushman, 2001; p.679). However, our findings differ from those of extant literature. Unlike literature's portrayal of the dominant design marking the transition from an era of technological ferment to one of incremental improvements (Anderson and Tushman, 1990), we find that a pre-commercialization dominant design does not lead to an era of "slight improvements" (Anderson & Tushman, 1991; p. 28). Rather, we find that dominant design in the pre-commercialization phase leads to radical product innovations (Henderson & Clark, 1990), which are aimed at mitigating the technological trade-offs involved in meeting the potential demand conditions.

Although the motivation of the paper is to expand our understanding of 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 not only in the past (e.g., in cities such as Dayton, OH—where firms, such as NCR, and individual entrepreneurs developed mechanical cash register, airplanes, automatic starters for cars, and anti-knock fuel) but also in the present day Silicon Valley. Our paper contributes to this broader literature on innovation ecosystems (e.g. Adner & Kapoor, 2010; Kapoor & Furr, 2015) by exploring the genesis of such ecosystems. Additionally, our research complements the critical insights gained from prior investigations of industry evolution. For example, Braguinsky & Hounshell (2015; p.18) noted that one of the "major innovations that paved the way for explosive industry growth" in Japanese cotton spinning industry was the "introduction of ring spinning frames." Although our context is different, our findings help explain the genesis of critical technologies, such as ring spinning frames (as noted by Braguinsky & Holbrrok, 2015) that affect the evolution of a new industry. Taken together, we contribute to innovation and entrepreneurship literature by exploring how ecosystems are created in the pre-commercialization phase, and in turn, how the ecosystems lead to the pre-commercialization dominant design that meets potential future demand.

Next, following Moeen and Agarwal (2015), we use the wisdom received from extant literature to motivate the framing questions that guide our research.

Extant literature and the framing questions for our research

Received wisdom # 1: Firms engage in technological investments prior to product commercialization

Several researchers have provided evidence of a vibrant and technologically active pre-commercialization phase. Research highlights that technological and demand uncertainties associated with a new technology are resolved by "key turning points" in an industry's evolution (Agarwal & Bayus, 2004; p. 109). One such key turning point is the commercialization of the product. Agarwal and Bayus (2002) reported 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 & Agarwal, 2015; p. 16). For example, in the pre-commercialization period of automobiles-- between its invention in 1771 and commercialization in 1890 (Agarwal and Bayus, 2002)-- firms such as Daimler and Maybach invested in developing prototypes of high-revolution 600-rpm gasoline engine with surface carburetor (Smil, 2010; p.27).

Despite providing valuable evidence of technological investments in the pre-commercialization phase, literature has somewhat overlooked the causal mechanism that determines the choice of pre-commercialization firms. For example, literature is largely silent on why firms such as Daimler would invest their resources in improving the gasoline engine with surface carburetor. Our first framing question seeks to address this gap in the literature and provide guidance to scholars about how factors that are exogenous to a firm affect its choices about the technological investments in the pre-commercialization phase. Thus, our first framing question is--

Framing Question # 1: Why do firms choose the innovative activities that they pursue in the pre-commercialization phase? How do exogenous factors, such as technological changes, affect firm choices in this phase?

Received wisdom # 2: Component-level knowledge for new products evolves in the pre-commercialization phase and leads to improvements in critical performance features

Funk (2013; p.135) notes that in the pre-commercialization phase, innovations in new materials and components help technologies improve the critical performance features. He underscores that in the case of light emitting diodes (LEDs), "scientists and engineers improved the luminosity per watt by finding materials that better exploit the phenomena of incandescence, fluorescence, and electroluminescence………they found new combinations of semiconducting materials, such as gallium, arsenide, phosphorus, indium, and selenium for LEDs," which affected the performance of those new products. He further noted that "rapid rate of improvement for ICs, magnetic tape and discs, optical discs, liquid crystal displays (LCDs), and other electronic components has had a large impact on higher-level systems such as computers" (p. 141).

Echoing the importance of product-level knowledge in the pre-commercialization phase, Moeen & Agarwal (2015; p.16) suggested that in this phase, the "levels of firm activity........ occur with much greater magnitude" than in the post-commercialization phase. Despite recent research highlighting the importance of component-level knowledge in the pre-commercialization phase, however, relatively underexplored is the genesis of new components. For example, in the evolution of Japanese cotton spinning mills (Braguinsky & Hounshell, 2015), relatively under-explored is the design and creation of the component technologies such as "ring spinning frames" that affected the future evolution of cotton spinning mills. Accordingly, our second framing question is—

Framing question # 2: What is the genesis of the new components? Where do they come from; who "creates" them, and why?

<u>Received wisdom # 3: Firms in the pre-commercialization phase capture economic value within the ecosystem.</u>

Moeen & Agarwal (2015; p. 20) highlight the role of ecosystem in the pre-commercialization phase and posit that "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.170) observation that firms that commercialize a new technology are "core firms in the ecosystem," and firms that engage in alternative modes of value capture, play a supporting role in the ecosystem by providing "complementary capabilities to the commercializing firm." Additionally, Moeen (2013; p.37) also noted the importance of innovation ecosystem when she underscored the importance of "unintentional outcomes," whereby innovations of failed firms are utilized by the surviving ones.

Moeen's (2013) assertion about the importance of ecosystem in the pre-commercialization phase mirrors the recent finding in the broader innovation literature (e.g., Adner & Kapoor, 2010) about the importance of ecosystem in the post-commercialization phase. However, despite this recent interest in the role of ecosystem, relatively under-investigated are the genesis of ecosystem and the potential role of dominant design in helping the ecosystem germinate and flourish. Moreover, exploring the causal mechanism that help the pre-commercialization ecosystem to germinate may help us further explore the factors that affect firms' innovation choices (our framing question #1) and the genesis of new components (our framing question # 2). Accordingly, our third framing question for this paper is--

Framing question # 3a: Where do pre-commercialization ecosystems come from? Are they developed strategically by potential buyers?

Framing question # 3b: What role does the pre-commercialization ecosystem play in determining firms' innovation choices and in the evolution of critical new components?

<u>Received wisdom # 4: The pre-commercialization phase is characterized by "cooperation across various types of firms" (Moeen & Agarwal, 2015; p. 36).</u>

The pre-commercialization phase of a new technology's evolution involves both startup and diversifying firms that cooperate to reduce the uncertainties prevalent in this phase. Such cooperation, eventually, leads to the post-commercialization oligopolistic structure in the new industry (Moeen & Agarwal, 2015). Holbrook *et al.* (2000; p. 1024) noted that, during the early stages in the evolution of semiconductors in the 1950s, Motorola acquired critical knowledge for alloy transistor from RCA. Relatively unanswered in the literature is the implication of information exchange. Do such information exchange lead to knowledge recombination, which in turn, reduces technological uncertainties (Roy & Sarkar, 2016). Or, do such cooperation lead firms to develop complementary assets, as evidenced in the evolution of biotech (Pisano, 2006)? To seek the answers to these questions, our fourth framing question is--

Framing Question # 4: What are the implications of information exchange among firms? Do such information exchange lead to knowledge recombination that, in turn, reduce technological uncertainties?

Received wisdom # 5: Pattern of technological evolution in the post-commercialization phase—era of ferment, emergence of dominant design, and 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% of new product sales or new process installations and maintained a 50% market share for at least 4 years" (Anderson & 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 R&D advantage for large incumbents over other entrants (Klepper, 2002).

Given prior researchers' focus on the post-commercialization period, relatively unexplored in the literature is an exploration of the evolutionary trajectory of a new technology in the pre-commercialization phase. Accordingly, our fifth framing question is—

Framing Question # 5: Do 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 differ from that of the post-commercialization phase?

Guided by these framing questions, next we explore the context of this paper. We explain the evolution of CCD sensors in reverse-chronological order-- starting with commercialization and thereafter, asking follow-up questions to unlock the dynamics of its pre-commercialization evolution.

Context: Evolution of CCD sensors

1994: Commercialization of digital camera: In June 1994 Apple introduced its first digital camera, Quick Take 100 (QT100). It was priced at $749-- the first digital camera priced below $1000-- and was targeted to individual consumers, unlike some of the high-end professional digital cameras introduced earlier (we describe some of these earlier efforts later in the paper). QT100 weighed 1 lb (454g) and was designed by Kodak and Chinon (Japanese subsidiary of Kodak). It 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, it also had the optical viewfinder and a built-in LCD screen as we use in the digital cameras today.

The introduction of this camera heralded the era of digital photography and in a little more than a decade after 1994, the market-share of analog film cameras was down to almost zero percent (see Figure 1).

Insert Figure 1 here

Although QT100 is a path-breaking product, and the first instance of commercialization of a sub-$1K digital camera, it did not happen in a vacuum. There were decades of research, going back to 1970s, that made this product possible. This leads to our first follow-up question --

Follow-up question # 1: Where did the QT100 come from? What is the causal mechanism that made this product feasible?

Early 1980s to early 1990s: Period of intense research and "technological investments" (Moeen & Agarwal, 2015; p.3) by Fairchild, RCA, Texas Instruments, Sony, Matsushita, Kodak, Tektronix, and others

The time period between the early 1980s and early 1990s was one of intense R&D in CCD sensors. One of the most significant innovations during this period was Jet Propulsion Laboratory's (JPL's) Wide Field/Planetary Camera (WF/PC I) which was developed for the Hubble Space Telescope (HST). Eight Texas Instruments (TI) 800*800, 15-micron picture element (pixel), 3-phase CCDs (TI 3PCCD) were used on HST. These CCDs were *buried-channel*; *backside illuminated* (BSI)[1] ones. This effort, however, faced several technological challenges and trade-offs, which affected the evolution of CCD sensors.

Manufacturing efforts of WF/PC I 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 & Elliott, 1994; p. 15). This forced NASA/ JPL in the late 1980s to replace the TI BSI sensors with WF/PC II sensors, which were frontside illuminated (FSI) ones manufactured by Loral Aeronutronics (known as Ford Aeronutronics prior to the 1980s). In addition to HST, several other NASA projects were underway during the 1980s, which also impacted the evolution of CCD sensors. For example, JPL Solid State Imaging (SSI) camera aboard the spacecraft Galileo (launched in 1989) used TI 800*800, 15-micron pixel, virtual-phase CCD (TI VPCCD).

[1] We define the scientific terms used in the context of CCD sensors in Appendix 1.

Yet another research project that helped the commercialization of digital camera was NASA's Electronic Still Camera Project (ESC) (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 1024*1024, 15-micron pixel Ford/Loral CCD constructed at the Lyndon B. Johnson Space Center. The Nikon cameras were modified by placing the CCD sensors at the film plane (Rose, 1991; p.1). The converted camera had similar features as the consumer product including zoom lenses, wide-angle lenses, flash, removable filters, and image intensifiers that provided "low-light capability and modest spectral capability." One of the modified Nikon F4 cameras was flown on the space shuttle Discovery (September, 1991, flight # STS-48) for conducting several experiments related to recording images in monochrome with 8 bits of digital information per pixel (256 gray levels). The CCD sensor (Ford Aeronutronic FA1024L sensor) was developed by JPL and Ford as a part of HST sensor development program (Chapman, 2014; p.2).

Rose (1991; pp.1-6) observed that the NASA ESC project was designed to provide "the means by which a hand held camera electronically captures and produces a digital image with resolution approaching film quality." Scientists aboard space shuttle Discovery tested if images could be stored on removable hard disks or small optical disks, if those images could be converted to a format suitable for downlink transmission, if the digitized images could be enhanced using image-processing software, and if such digitized images could be transferred from the space shuttle to the Johnson Space Center (JSC) ESC Lab using an Orbiter downlink interface, a monitor, and a portable computer to support image processing. While the Shuttle crew operated the ESC, scientists at Autometric Inc. (located in Alexandria, VA) operated a 3M-developed Color Laser Imager (CLI), which produced hard-copies of the images downlinked from the space shuttle to JSC during the mission. The CLI used at JSC was an advanced 300-dpi (dots per inch) color output device capable of printing over 170 photographic images per hour. The Orbiter downlink interface provided both raw and processed images with annotations on the images. The entire process, from taking a picture in orbit to getting a copy on the ground, took less than an hour.

Other significant progress on CCD research during this period included NASA's Mars Observer (MO) launched in 1992 with two Ford/Loral CCDs (1*2048 and 1*3456 pixels); Space Telescope Imaging Spectrometer (STIS), a second generation ST camera, which was scheduled for installation on HST in the mid-1990s, used two 2048*2048, 21-micron pixel Tektronix three-phase BSI CCDs; and Cosmic Unresolved X-ray Background (CUBIC) camera, which used 1024*1024, 18-micron pixel Ford/Loral CCD designed by JPL scientist Dr. James Janesick (Burrows *et al.*, 1992). Additionally, in 1993 HST's TI BSI CCDs were replaced with Ford/Loral FSI CCDs (WF/PC II). As we discuss later, the new sensors avoided not only the problem of quantum efficiency hysteresis (QEH) but also the low yield problem that plagued the manufacturing of TI CCDs with high costs during the 1980s. Although the TI CCDs used in HST were replaced by NASA, the knowledge generated by TI in their decade-long effort to improve the performance of CCDs not only provided critical knowledge to other firms such as Fairchild, RCA, Ford/Loral, Sony, Tektronix, and Matsushita in the pre-commercialization ecosystem, but TI, in turn, also benefited from the efforts of those other firms by recombining knowledge generated at those firms with its own knowledge. Not surprisingly, Clampin (1992; p.2) observed that although the replacement WF/PC II CCDs for HST were not manufactured by TI, those replacement sensors were "based on TI 800*800 format" with 15*15 um pixels, which were originally designed by TI for WF/PC I.

Knowledge flow across pre-commercialization ecosystem in the 1980s:

TI CCDs chosen by NASA for the HST were BSI ones with polysilicon gates. These gates were first used in FSI CCDs, whereas the BSI CCDs were originally designed with aluminum gates. However, on the one hand, BSI gates were harder to manufacture, leading to higher costs. FSI CCDs were about 1/3rd the cost 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 "already successfully implemented by Fairchild and RCA" (Janesick and Elliott, 1992; p. 14) in the 1970s and tried by TI in the late-1970s. TI's experiments to solve the low-yield problem of BSI CCDs and QEH, however, also led to several other technological trade-offs in CCD designs, which had to be mitigated to make CCD commercialization possible. (Janesick & Elliott, 1992). These problems were—

First, TI experiment led to BSI polysilicon gate CCDs but these gates had low QE in the blue/green region of the spectrum (Roper Scientific CCD Primer; http://www.roperscientific.de/itoccd.html; accessed 12/09/15). Additionally, as CCD was thinned for BSI, eddy currents set-up in the thinning drum preferentially etched the corners of the CCD. The corners of the WF /PC CCDs are about 1 micron thinner than the center of the device due to this problem. This characteristic led to nonuniform QE sensitivity across the detector.

Second, mechanical stresses caused the thinned membranes to warp in a concave manner (the "potato chip" factor). This trait made it difficult to focus an image and to make matters worse the shape of the membrane would change and buckle as the device was cooled, making the surface a moving target.

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

These challenges forced TI and other firms to explore ways to mitigate the technological trade-offs involved in improving yield and reducing QEH that plagued the BSI CCDs. Such explorations led to three significant innovations that affected the evolutionary trajectory of CCD sensors.

First, 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 were 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 CCD Primer; http://www.roperscientific.de/itoccd.html; accessed 12/09/15). 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.

Second, the "QE notch" problem with WF/PC I led researchers to look for new coating materials. Ford/Loral WF/PC II CCDs, which were based on WF/PC I CCDs, used lumigen phosphor (Clampin, 1992; p.1), which absorbs UV and some of the EUV (i.e., 500 to 4200 Å) achieving almost 100 % QE.

Third, Tektronix developed a radically innovative hybrid CCD that "backed the frontside of the CCD with a thick ceramic header before thinning, thereby ensuring that the CCD remained flat after thinning. After the device was thinned it was electrically bonded to the package using the "backside" of the bond pad" (Janesick & Elliott, 1992; p.19). Indeed, Tektronix patent (# US 4739382A granted on 04/18/1988; filed 1985) 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 CCDs (patent # US 4656519 filed 10/4/85) and in the following 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's efforts to introduce radical innovations (Henderson & Clark, 1990) that were compatible to both BSI-FT and FSI-ILT CCDs were similar to Shapiro and Varian's (1999; p. 15) observations in the evolution of NTSC color television system, which was compatible with the older black-and-white signals.

Fourth, one of the radical innovations designed to improve QE of BSI CCDs (Janesick and Elliott, 1994; p. 22-23) was *light-pipe*, which was used in WF/PC I but added $5 million to the cost of manufacturing of HST (see US patent # 5365292A filed 02/08/93 by J.R. Janesick; p. 9). Sony later adopted light-pipes for its FSI-ILT CCD sensors used in camcorder and digital camera sensors (Fontaine, 2011).

The evolutionary trajectory of CCD in the 1980s and early 1990s suggest that there was a rich ecosystem of firms such as TI, Sony, Matsushita, Kodak, Ford/Loral, Tektronix, and others. Additionally, there was an active knowledge creation and recombination among the members of the pre-commercialization ecosystem. 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 CCDs for future commercialization?</u>

Invention and early research from 1969 till early 1980s:

On Oct. 19, 1969, Willard Boyle and George Smith of Bell Telephone Laboratory brainstormed on the 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 was 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 vidicon 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 Navy and NASA/ JPL in 1972. NASA was planning for a Large Space Telescope (LST; later renamed Hubble Space Telescope) and Navy was interested in low-light imaging of enemy territory. During the 1970s, film technology was a mature one that was introduced in the 1850s and used in astronomy since 1880s. Large photographic plates were available to map huge regions of sky with resolution of 100 MP (approx.) and were sensitive to broad range of wavelengths--UV and X-ray. However, when placed in earth's orbit, high energy radiation would fog the film, and these films would have to be retrieved by astronauts regularly, which according to the early planners of LST team concluded, was an impractical solution.

The vidicon tubes had disadvantages too. Although these tubes were not vulnerable to radiation, and had produced pictures of 1024*1024 pixel resolution for the Viking and Voyager missions, these were unable to retain images for long exposures and the lifetimes of such tubes were questionable for LST/Hubble's originally planned mission of 15 years. This is because photocathodes degrade over time. 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, were five times more sensitive, and 100 times more sensitive, than tubes and films respectively. Additionally, the output of CCD sensor 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 the output of CCD could be digitized and amplified.

Although the above-mentioned advantages of CCDs over both film and vidicon technology helped attract NASA and Navy's attention to digital imaging, to become viable alternative, CCDs had to improve on several fronts. Whereas both film and vidicon tube could function in ambient spacecraft temperature, CCD detector required significant cooling to eliminate thermal dark charge. Charge-Transfer Efficiency (CTE) was critical and had to be between 0.99999 and 0.999999 for CCDs to perform as expected. Additionally, due to the innovations in the vidicon tube technology in the 1960s, it was estimated 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, and this was a major deterrent for both NASA and Navy. To make CCD popular among scientists, in 1973, workers at the JPL initiated a program to develop high performance large area array CCDs, designed for space-borne navigation and imaging instruments. They built a *Traveling CCD Camera System*, the first of its kind, to be used at major astronomical observatories worldwide.

Creating the pre-commercialization ecosystem: Role of demand conditions

Further, to explore if CCD could become a viable alternative to vidicon tubes, in 1972 the Naval Electronics Systems Command (NESC) sponsored a three-phase, 30-month 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. 275). Primary focus of this phase was using CCDs for low-light imaging. During Phase 1, both RCA and TI employed surface-channel CCDs. Fairchild, by contrast, invented and used 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% and that of TI CCD was 99.65%; Fairchild CCD achieved 99.9% CTE. In April 1973, Fairchild was selected to continue the Navy's CCD development program and almost all CCDs manufactured since 1973 were almost exclusively buried-channel ones. Consistent with Benner & Tripsas' (2012; p.285) observations, NESC's decision led to the first standardized "product feature" that helped in the development of CCDs designed later by TI, RCA, Sony, Philips, and other firms.

Other innovation challenges, especially those associated with mitigating the technological trade-offs in CCD sensors lingered well beyond the mid-1970s. 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) and the second phase of NESC's program was exclusively devoted to "blooming" reduction (Campana, 1973; p. 240). The second phase of NESC's efforts resulted in Fairchild developing two sensors for low-light imaging (Wen, 1977; pp. 211-215)—a linear imager of 1728*1 pixels and an area imager of 244*190 pixels—both of which were FSI-ILT sensors "showed excellent transfer efficiency at signal levels well below 100 electrons" (p.216).

Around the same time when the phase I experiments were being conducted by NESC, in 1973, NASA entered into contract # 953673 with TI to investigate the feasibility of using CCD for the optical sensors in spaceborne imaging systems, and formulate recommendations for designing such CCDs. TI recommended an area imager of 400*400 pixels with 22.9μm*22.9μm pixels. These BSI-FT sensors had antireflection SiO coating and achieved CTE of 99.99%. TI suggested polysilicon SiO_2-Al gate structure (TI Final Technical Report 12/3/73 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 dated 12/3/73 p. 1-1).

During the early 1970s, research at TI, Fairchild and other firms, to meet the needs of NESC and NASA, identified critical technological trade-offs associated with designing BSI and FSI sensors (Barbe & White, 1973; see also Anderson 1976; p.283). Whereas the BSI sensors transferred images in "full frames" (FT), FSI sensors transferred images along horizontal and vertical lines (Interline Transfer or ILT). The BSI-FT sensors were better than the their FSI-ILT 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 & White, 1973; pp. 15-19).

Despite being superior in performance, TI Final Technical Report (12/3/73 p. 2-3) noted that BSI sensors have "special problems…..Consequently, 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 cost-performance 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 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 12/3/73 p. 3-9).

Amelio (1974) and Vanstone (1974) echoed the 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 technological 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 concluded that "if blue response is not important, the cost and complexity of backside illumination is probably not justified" (Amelio, 1974; p. 137). Hoagland & 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-ILT 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 camera where small size, low power/low voltage operation, high sensitivity and extreme ruggedness are either desirable or mandatory characteristics."

As a consequence of the experiments conducted at NESC and NASA/Lyndon B. Johnson Space Center, the future evolution of CCD sensors was affected in two ways. First, although the performance of FSI-ILT sensors were inferior, the performance to cost-to-manufacture ratio of these sensors prompted Fairchild, Sony, Matsushita, Kodak, Ford/Loral Aeronutronics, Philips, and others to continue R&D to incorporate CCD into consumer products such as consumer digital video and still cameras. These firms concluded that, *given the technological trade-off*, Fairchild FSI-ILT CCDs were the better suited for future research into camera modules (Monro, 1978). Subsequently, the above-mentioned firms and others started their efforts to manufacture CCD TV camera prototypes by using Fairchild 190*244 and 380*488 FSI-ILT area sensors (Hoagland and Balopole, 1975).

Second, these experiments also prompted the need for further explorations to improve the performance of CCD sensors, especially the BSI-FT ones, and to improve their performance to cost ratio. As Janesick & 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 tubes." Janesick & 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.

Despite the performance-cost trade-offs in BSI-FT and FSI-ILT CCDs, there was significant overlap in R&D for these sensors because they "have a lot in common" (Bosiers *et al.* 2006; p. 3). This led to knowledge flow and recombination among firms such as Sony, Matsushita, Kodak, and Ford/Loral—the leaders in FSI-ILT CCDs and TI, which spearheaded innovations in BSI-FT CCDs.

Knowledge flow across pre-commercialization ecosystem in the 1970s and early 1980s:

Evolution of CCD sensors in the late 1970s and early 1980s was affected by knowledge flow and recombination among the firms in the early ecosystem. In the 1970s, Ford/Loral, which primarily manufactured FSI-ILT CCDs (Janesick and Elliott, 1992; p. 24), developed Germanium CCDs (Patent # US3962578 granted to Aeronutronic Ford on June 8, 1976). Because Germanium exhibits a band gap of half that of silicon and its infra-red (IR) response in space applications was approximately 1.6-microns, TI recombined its own knowledge with that of Ford/Loral and started manufacturing Germanium BSI-FT CCDs (TI patent # US3989946 granted on Nov. 2, 1976). In addition to responsiveness to IR, 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 allowed inversion of all phases and reduced dark noise and rapid removal of residual images (Clampin, 1992). In addition, Ford/Loral also used phosphor coatings for better blue and UV QE. Phosphor coating on the frontside of the CCD converts incident UV photons into longer wavelength photons (Janesick and Elliott, 1992; p. 26). Following this lead, WF/PC II

CCDs used in HST had coronene phosphor, which avoided the QEH problem of lumigen phosphor used in WF/PC I CCDs (Clampin, 1992; p.1).

The TI WF/PC I CCD design for HST shows further evidence of knowledge transfer 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), which was originally developed for FSI-ILT CCDs (White *et al.*, 1974), with its own knowledge of BSI-FT CCDs (see e.g., TI patent # US 3965368 issued on June 22, 1976). Yet another critical part of TI's CCDs for NASA was the use of polysilicon gate. TI built its knowledge on polysilicon gate "to circumvent the aluminum gate shorting problem," a technology that was invented at Fairchild and RCA (Janesick and Elliott, 1992; p. 14). Indeed, TI patent on 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). Thus, product features such as polysilicon gates, which characterized the pre-commercialization innovations of CCD sensors, were the result of knowledge recombination in the pre-commercialization ecosystem. In its quest to develop CCDs for HST, TI not only acquired knowledge from other firms in the ecosystem, but also recombined those knowledge with its own knowledge, such as Advanced Virtual-Phase CCD Technology (TI Patent # US4229752A filed on May 16, 1978).

Additionally, as we noted earlier, the problem with polysilicon gates in WF/PC I CCDs, where QE drops at wavelengths shorter than 540 nm and is essentially zero below 400 nm, led Kodak's Microelectronics Technology Division to develop CCDs with ITO, which 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 ecosystem during 1970s and 1980s in Figure 2.

Insert Figure 2 here

Consequences of knowledge flow across the pre-commercialization ecosystem:

As a consequence of knowledge flow across various firms, and knowledge recombination, in the pre-commercialization 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" (IEEE Spectrum Editorial, 1981). This hurdle was overcome when RCA invented the "checkerboard color filter" (patent # US 4286285A filed 02/04/1980) in the early 1980s. RCA's knowledge was built on prior research at the Bell Telephone Laboratories on color-coding filters for CCDs (patent # US3982274 granted on Sep 21, 1976). Building on RCA's innovation, Sony improved its CCD sensors and in 1980s, installed the first FSI-ILT CCD color movie 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 take-off and landing. Later that year Sony XC-1 was introduced, a color video camera which was intended to show aircraft passengers video images of the cockpit (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.

Building on the prior efforts described earlier and recombining knowledge generated by various firms in the ecosystem, in 1989, 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 it. Mr. Sasson was told they could sell the camera, but wouldn't-- 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 DSC 1 was introduced 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. This was followed in 1994 by Apple QT100, the first consumer digital camera priced below $1000.

Theoretical Implications of our findings

Next, we juxtapose our findings with the theoretical mechanisms identified by extant research, and discuss the theoretical implications of the empirical evidences provided above. *Our first framing question was-- Why do firms choose the innovative activities that they pursue in the pre-commercialization phase? How do exogenous factors, such as technological changes, affect firm choices in this phase?*

We find that firms in the pre-commercialization phase compete to meet the potential from buyers (e.g., NESC and NASA in our case). The race to meet the potential demand conditions led the CCD sensor manufactures to adopt the buried-channel CCD as the dominant design, which was first used by Fairchild for NESC's project. Similarly, TI's efforts to meet the demand of NASA led to several innovations such as CCDs with germanium, polysilicon gate structure, ITO gate, and multipinned CCDs. Thus, our first stylized finding is--

Our stylized finding # 1: Potential demand channelizes product innovation in the pre-commercialization phase.

Our second framing question was—What is the genesis of the new components? Where do they come from; who "creates" them, and why?

Consistent with prior research, we find that, to meet the demand of NESC and NASA, new technological systems (e.g., the TI CCD) indeed "borrow components from existing technological systems" (Ng and Funk, 2013; p.23). These components, such as light-pipes in the case CCD sensors, helped firms mitigate technological trade-offs, such as the QEH, to meet the potential demand. Thus, our second stylized finding is--

Our stylized finding # 2: Efforts to mitigate the trade-offs involved in meeting the potential demand usher new components.

Our third framing question was— Where do pre-commercialization ecosystems come from? Are they developed strategically by potential buyers?

Consistent with Moeen (2013) and Moeen & Agarwal (2015), we find evidence of pre-commercialization ecosystem. Further, we extend Moeen (2013) and find evidence that this ecosystem develops to meet potential demand. In the context of vision sensors, the innovation ecosystem germinated when firms tried to meet the demand conditions of NESC and NASA. The efforts to mitigate the trade-offs associated with meeting the potential demand led to the development of FSI-ILT and BSI-FT CCD sensors. However, there are considerable knowledge flows across the firms in the ecosystem. Thus, our third stylized finding is--

Our stylized finding # 3: Ecosystems evolve when firms engage in technological investments (Moeen & Agarwal, 2015) to mitigate the technological trade-offs associated with meeting the needs of potential buyers.

Our fourth framing question was—What are the implications of information exchange among firms? Do such information exchange lead to knowledge recombination that, in turn, reduce technological uncertainties?

We find that information exchange between firms in the ecosystem lead to knowledge recombination, which, in turn, mitigates technological trade-offs associated with improving the performance feature that potential large customers value. Knowledge recombination to mitigate technological trade-offs is relatively underexplored in the literature. Moeen & Agarwal (2015; p.22) notes that researchers generally "abstract away from nascent industry contexts…..due to informational challenges" in this phase of the technology's evolution. We find that knowledge flows from Fairchild, RCA, Ford/Loral, to TI led to knowledge recombination to mitigate the technological trade-offs associated with improving CCD sensor's performance. Thus, our fourth stylized finding is--

Our stylized finding # 4: Knowledge recombination in the pre-commercial ecosystem helps mitigate the technological trade-offs associated with developing a product that can meet the performance feature that potential buyers demand.

Our fifth framing question was—Do 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 differ from that of the post-commercialization phase?

Unlike the suggestions of prior innovation research, which has primarily concentrated on the post-commercialization phase (Moeen & Agarwal, 2015), we find that dominant design in the pre-commercialization phase neither marks "the end of the era of ferment" nor begins an "era of competition based on slight improvements on a standard design" as predicted by Anderson and Tushman (1991; p. 28). In the post-commercialization phase of CCDs, Sony commanded about 50% market share in CCD manufacturing the late-2000s and early 2010s (see *2nd Half 2011 CCD/CMOS Area Image Sensor Market Analysis* accessed from http://www.t-s-r.co.jp/e/report/4125.html). However, CCDs manufactured by Sony, Matsushita, Kodak, and others were buried-channel FSI-ILT sensors based on Fairchild CCDs, designed in the early 1970s.

Scientists and engineers had realized the advantages of buried-channel over surface-channel and the trade-offs associated with FSI-ILT and BSI-FT sensors in early 1970s. Following the first phase of experiments at NESC, Barbe (1975; Table III, p. 52) noted that Fairchild's buried-channel CCDs had distinct advantages over surface-channel 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." Barbe (1975; Table VIII, p. 59) pinpointed the trade-offs associated with FSI-ILT and BSI-FT sensors when he noted that the spectral response of Fairchild's FSI-ILT sensors in the blue spectrum lagged that of BSI-FT sensors manufactured by RCA, TI, and Bell Labs. Beynon & Lamb (1980; p. 103) also noted the trade-off and suggested that the charge-collection area of FT sensors are twice as large as those in ILT sensors and the "lens used with the ILT array will have to be about twice the area of that used with the FT array." Nonetheless, the Fairchild design of FSI-ILT with buried channel was chosen by NESC for further research, *despite* the performance trade-off whereby better QE in blue spectrum for BSI-FT sensors was traded off for lower cost and complexity of manufacture for FSI-ILT sensors. This paved the way for future CCDs by Sony, Matsushita, Kodak, Ford/Loral and others.

The Fairchild design, thereby, became the dominant CCD design[2] and, as we discussed earlier, CCDs manufactured by Tektronix, Ford/Loral, Sony, and others were based on Fairchild's design. Thus, although the design that eventually becomes the post-commercialization dominant design builds on the pre-commercialization one, as compared to the post-commercialization dominant design, which leads to the era of incremental change, the pre-commercialization dominant design leads to product innovation as firms address the trade-offs involved in designing the products. Consistently, although Fairchild's innovations led to genesis of the low-performance-low-cost FSI-ILT CCDs with buried-channel as the dominant design, research continued on mitigating the trade-off and lowering the cost of BSI-FT CCDs. As we highlighted earlier, knowledge flow, and recombination, among the firms that manufactured CCD sensors was aimed at mitigating the technological trade-offs in CCD sensors. Accordingly, our fifth stylized finding is about the potential boundary conditions of the extant dominant design theories that have primarily focused on the post-commercialization phase—

Our stylized finding # 5: Dominant design in the pre-commercialization phase does not lead to the era of incremental innovation, which leads to the elaboration of the dominant design

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

through process R&D. Rather, a dominant design in this phase opens the door for more product innovation to mitigate technological trade-offs associated with the design.

We summarize our findings in Table 1 below.

Insert Table 1 about here

In addition to the above-mentioned stylized findings, our research also leads to other critical insights about the pre-commercialization phase. While literature generally portrays post-commercialization dominant design (or, innovation shock, the precursor to a dominant design; see Argyres *et al.*, 2015) as a technological innovation, "a novel composition of elements" that has "a substantial surge and acceleration in demand…… that was generally unexpected by market participants" (p. 219), the post commercialization dominant design in CCD sensors was the result of demand-pull from potential customers such as NESC and NASA.

Additionally, we also expand the literature on markets for technology (Arora *et al.*, 2001). Whereas this literature has largely abstracted "away from nascent industry contexts, often assuming non-existence of markets due to informational challenges" (Moeen & Agarwal, 2015; p.22), we find evidence of information exchange among TI, RCA, Fairchild, and others. We also observed 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 vision sensor, WF/PC I, which was launched on April 24, 1990.

Discussion

Motivated to seek the answers to our framing questions, we followed Holbrook *et al.* (2000), Eggers (2014), and others to understand the pre-commercialization evolution of CCD sensors. Using archival data, interviews, published accounts of insiders as well as unpublished ones, and secondary sources of information, we explored how CCD sensors evolved in its pre-commercialization phase. As suggested by Eggers (2014), we followed the basic tenets of grounded theory building (Glaser *et al.*, 1967; 1999). Initially, we reviewed all documents to identify the core ideas of the story. Our analysis was at both the micro (point-by-point) and macro (entire series of documents) levels. Next, we categorized key events based on the underlying processes. Thereafter, we counterchecked the anecdotal components of the story with patent data. Finally, we discussed the factors and findings in details with industry experts Dr. Eric Fossum (inventor of Complementary Metal Oxide Semiconductor sensors at JPL); Dr. Albert Theuwissen (ex-researcher at Philips) and others, who provided feedback on factual changes presented here. These steps helped us to "present facts and ask questions" and counter-questions "about possible explanations of these facts" (Bettis *et al.*, 2014; p. 950).

Limitations: Despite following prior research and building on wisdom available in the literature, our research has its limitations. One of the limitations of our paper is that we identify knowledge transfer among the members of the pre-commercialization ecosystem. Our reliance on a single industry does not allow us to explore of this was true for the pre-commercialization phase of other industries as well. For example, prior studies have alluded to the role of innovation ecosystems in biotech (Pisano, 2006), agricultural biotech (Moeen, 2013), semiconductors (Holbrook *et al*., 2000), and Global Positioning Systems or GPS (Worth & Warren, 2009). While large institutions such as National Institute of Health, National Science Foundation, and DARPA may have played a lead role in the genesis of innovation ecosystems, future research needs to 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 information exchange 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 buyer? These are some of the critical questions that need to be answered in future research.

Nonetheless, ours is one of the first studies to systematically explore the genesis of the innovation ecosystem in the pre-commercialization phase of a new technology.

References

Acs, Z. J. 2003. Innovation and the Growth of Cities. *Edward Elgar*: Cheltenham, UK.

Adner, R. & Kapoor, R., 2010. Value creation in innovation ecosystems: How the structure of technological interdependence affects firm performance in new technology generations. *Strategic Management Journal*, 31(3), pp.306-333.

Agarwal, R., Bayus, B. L. 2002. The market evolution and sales takeoff of product innovations. *Management Science*, 48(8): 1024-1041.

Agarwal, R. & Bayus, B.L. 2004. Creating and surviving in new industries. *Advances in Strategic Management*, 21, pp.107-132.

Amelio, G.F. 1974. The Impact of Large CCD Image Sensing Area Arrays. *Proc. CCD 74 Int. Conf, Edinburgh*, pp.133-152.
Anderson, R.L. 1976. An evaluation of charge-coupled devices technology. FAA Report No. FAA-RD-76-198; October 1976. Prepared for Department of Transportation, Federal Aviation Administration, Systems Research and Development Service, Washington, D.C.
Anderson, P. & Tushman, M.L., 1990. Technological discontinuities and dominant designs: a cyclical model of technological change. *Administrative Science Quarterly.* 35 (4): 604–633.
Anderson P. & Tushman M.L. 1991. Managing through cycles of technological change. *Research-Technology Management* 34(3): 26-31
Anderson, P. & Tushman, M.L., 2001. Organizational environments and industry exit: The effects of uncertainty, munificence and complexity. *Industrial and Corporate Change*, 10(3): 675-711.
Argyres, N., Bigelow, L. & Nickerson, J.A., 2015. Dominant designs, innovation shocks, and the follower's dilemma. *Strategic Management Journal*, 36(2), pp.216-234.
Arora, A., Fosfuri, A., & Gambardella, A. 2001. *Markets for Technology: The Economics of Innovation and Corporate Strategy*. MIT Press.
Barbe, D.F. 1975. Imaging devices using the charge-coupled concept. *Proceedings of the IEEE*, 63(1): 38-67.
Barbe, D.F. & White, M.H. 1973. A Tradeoff Analysis for CCD Area Imagers: Frontside Illuminated Interline Transfer vs. Backside Illuminated Frame Transfer. In Proceedings, *CCD Applications Conference*, Naval Electronics Laboratory Center, San Diego (pp. 18-20).
Baum, J.A., Korn, H.J. & Kotha, S., 1995. Dominant designs and population dynamics in telecommunications services: Founding and failure of facsimile transmission service organizations, 1965-1992. *Social Science Research*, 24(2), pp.97-135.
Benner, M. J. & Tripsas, M. 2012. The influence of prior industry affiliation on framing in nascent industries: the evolution of digital cameras. *Strategic Management Journal*, 33(3): 277-302.
Bettis, R., Gambardella, A., Helfat, C. and Mitchell, W., 2014. Quantitative empirical analysis in strategic management. *Strategic Management Journal*, 35(7), pp.949-953.
Beynon, J.D.E. & Lamb, D.R. 1980. *Charge-coupled devices and their applications*. McGraw-Hill: London, UK.
Bosiers, J. T., Peters, I. M., Draijer, C., & Theuwissen, A. 2006. Technical challenges and recent progress in CCD imagers. *Nuclear Instruments and Methods in Physics Research* Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 565(1), 148-156.
Braguinsky, S. and Hounshell, D., 2015. History and Nanoeconomics in Strategy and Industry Evolution Research: Lessons from the Meiji-Era Japanese Cotton Spinning Industry. *Strategic Management Journal*: Forthcoming.
Burrows, D.N., Garmire, G.P., Lumb, D.H. & Nousek, J.A., 1992. The CUBIC Experiment. In X. Barcons & A.C. Fabian (EDs.) *The X-ray Background* (Vol. 1, p. 277). Cambridge University Press.
Campana, S.B. 1973. Charge-Coupled Devices for Low Light Level Imaging. *Proceedings of 1973 Image Sensor Conference.* http://www.imagesensors.org/Past%20Workshops/Dick%20Bredthauer%20Collection/1973%20San%20Diego/1973%2030%20Campana.pdf (Accessed on on January 14, 2016).
Chapman, T.J. 2014. NASA Nikon F4 Electronic Still Camera. Accessed from http://www.onevisionphoto.com/nasaF4ESC.htm on January 14, 2016.
Christley, J. 2011. *US Submarines 1900-35*. Osprey Publishing: Oxford, UK.

Clampin, M. 1992. WFPC-II CCDs. Accessed from http://www.stsci.edu/hst/wfpc2/documents/isr/wfpc2_ccds.pdf on January 14, 2016.
Eggers, J.P. 2014. Competing technologies and industry evolution: The benefits of making mistakes in the flat panel display industry. *Strategic Management Journal*, 35(2): 159-178.
Estrin, J. 2015. Kodak's first digital moment. New York Times, Aug. 12, 2015.
Fontaine, R., 2011. A Review of the 1.4 µm Pixel Generation. *Image Sensor Workshop 2011*. http://www.imagesensors.org/Past%20Workshops/2011%20Workshop/2011%20Papers/R02_Fontaine_Review.pdf (Accessed on January 19, 2016).
Funk, J.L., 2013. What drives exponential improvements? *California Management Review*, 55(3).
Funk, J.L. and Magee, C.L., 2015. Rapid improvements with no commercial production: How do the improvements occur? *Research Policy*, 44(3): 777-788.
Glaser, B. G. & Strauss, A., 1967. *The discovery grounded theory: strategies for qualitative inquiry*. Aldin, Chicago.
Glaser, B.G. 1999. The grounded theory perspective: Conceptualization contrasted with description. Sociology Press.
Golder, P. N., Shacham, R., Mitra, D. 2009. Innovations' origins: When, by whom, and how are radical innovations developed? *Marketing Science*, 28(1): 166-179.
Gort, M., Klepper, S. 1982. Time paths in the diffusion of product innovations. *Economic Journal*, 92(367): 630-653.
Helfat, C. E., Lieberman, M. B. 2002. The birth of capabilities: market entry and the importance of pre-history. *Industrial and Corporate Change*, 11(4): 725-760.
Henderson, R.M. & Clark, K.B., 1990. Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms. *Administrative Science Quarterly*, pp.9-30.
Hoagland, K. A. & Balopole, H. L. 1975. CCD-TV Cameras Utilizing Interline-Transfer Area Image Sensors. *Proc of the 1975 International Symposium on the applications of CCD*, San Diego, CA, October 1975.
Hoagland, K.A. & Balopole, H. 1976. Solid state, CCD-buried channel, television camera study and design. *NASA STI/Recon Technical Report* # N76-3041 accessed from http://ntrs.nasa.gov/search.jsp?R=19760023333 on January 19, 2016.
Holbrook D, Cohen WM, Hounshell DA, Klepper S. 2000. The nature, sources, and consequences of firm differences in the early history of the semiconductor industry. *Strategic Management Journal* **21**(10-11): 1017-1041.
Janesick, J. & Elliott, T. 1992. History and advancement of large array scientific CCD imagers. In *Astronomical CCD Observing and Reduction Techniques*, Vol. 23: p.1.
Kapoor, R. and Furr, N.R. 2015. Complementarities and competition: Unpacking the drivers of entrants' technology choices in the solar photovoltaic industry. *Strategic Management Journal*, 36(3), pp.416-436.
Klepper S. 2002. Firm survival and the evolution of oligopoly. *RAND Journal of Economics* 33(1): 37–61.
Klepper, S., Simons, K. L. 2000. Dominance by birthright: Entry of prior radio producers and competitive ramifications in the US television receiver industry. *Strategic Management Journal*, 21(10-11): 997-1016.
Mitchell, W. 1991. Dual clocks - Entry order influences on incumbent and newcomer market share and survival when specialized assets retain their value. *Strategic Management Journal*, 12(2): 85-100.
Moeen, M., 2013. Reconfiguration Strategies, Entrepreneurial Entry and Incubation of Nascent Industries: Three Essays. *Unpublished PhD Dissertation*, University of Maryland.

Moeen, M. & Agarwal, R. 2015. Incubation of an Industry:Heterogeneous Knowledge Bases and Modes of Value Capture. *Robert H. Smith School Research Paper* No. RHS 2628172. Available at SSRN: http://ssrn.com/abstract=2628172.

Monro, C.R. 1978. Performance Evaluation of CCD Imagers. *Proceedings, 1978 International Conference On The Application Of Charge Coupled Devices, San Diego.* http://www.imagesensors.org/Past%20Workshops/Marvin%20White%20Collection/1978%20Papers/1978%201-5%20Munro.pdf (Accessed on January 14, 2016).

Ng, P.S. and Funk, J.L., 2013. When do new technologies become economically feasible? The case of three-dimensional television. *Technology in Society*, 35(1): 22-31.

Pisano, G., 2006. Can science be a business? *Harvard Business Review*, 10: 1-12.

Rose, J.T. 1991. *Electronic Still Camera Project.* Office of Commercial Program, NASA, DC.

Roy, R. 2014. Exploring the Boundary Conditions of Disruption: Large Firms and New Product Introduction With a Potentially Disruptive Technology in the Industrial Robotics Industry. *IEEE Transactions on Engineering Management*, 61(1): 90-100.

Roy, R., & Sarkar, M.B. 2016. Knowledge, firm boundaries, and innovation: Mitigating the incumbent's curse during radical technological change. *Strategic Management Journal*: forthcoming.

Sarkar, M.B., Echambadi, R., Agarwal, R. & Sen, B., 2006. The effect of the innovative environment on exit of entrepreneurial firms. *Strategic Management Journal*, 27(6), p.519.

Schumpeter, J. A. 1942. *Capitalism, Socialism, and Democracy.* New York: Harper.

Shapiro, C. & Varian, H.R. 1999. The art of standards wars. *California Management Review*, 41(2): 8– 32.

Smil, V. 2010. *Two prime movers of globalization: the history and impact of diesel engines and gas turbines.* MIT Press.

Suarez, F.F., 2004. Battles for technological dominance: an integrative framework. *Research Policy*, 33(2), pp.271-286.

TI Final Technical Report. 1973. Accessed from http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19740009054.pdf on January 14, 2016.

Tripsas M. 1997. Unraveling the process of creative destruction: Complementary assets and incumbent survival in the typesetter industry. *Strategic Management Journal* **18**(s 1): 119-142.

Tushman ML, Anderson P. 1986. Technological discontinuities and organizational environments. *Administrative Science Quarterly* **31**(3): 439-465.

Vanstone, G.F. 1974. Future developments in charge-coupled devices. *Proc. CCD 74 Int. Conf, Edinburgh,* http://www.imagesensors.org/Past%20Workshops/Dick%20Bredthauer%20Collection/1974%20Scotland%20Conference/1974%2031%20Vanstone.pdf

Vallery-Radot, R. 1900. *La Vie de Pasteur* (Translated by Devonshire, R. L.). Garden City Publishing Co., New York.

Wen, D.D. 1977. Low light level performance of CCD image sensors. In R. Melen and D. Buss (Eds.) *Charge-coupled devices: Technology and application*, IEEE Press, New York. p.207-217. Reprinted from *Proceedings of 1975 Naval Electronics Lab. Center International Conference on the Application of Charge-Coupled devices*, Oct. 29-31, 1975, pp. 109-119.

White, M.H., Lampe, D.R., Blaha, F.C. & Mack, I.. 1974. Characterization of surface channel CCD image arrays at low light levels. *IEEE Journal of Solid-State Circuits*, 9(1): 1-12 (accesed from http://www.imagesensors.org/Past%20Workshops/Dick%20Bredthauer%20Collection/1973%20San%20Diego/1973%2005%20White.pdf on January 18, 2016).

Worth, H.E. & Warren, M., 2009. *Transit to Tomorrow: Fifty Years of Space Research at the Johns Hopkins University Applied Physics Laboratory*. Johns Hopkins University Applied Physics Laboratory: Baltimore, MD.

Table 1: Summary of the theoretical implications of our study

Received Wisdom	**Our framing questions**	**Comparison of Received Wisdom with our findings**	**Novel Theoretical Implications**
Firms engage in technological investments prior to product commercialization	Why do firms choose the innovative activities that they pursue in the pre-commercialization phase? How do exogenous factors, such as technological changes, affect firm choices in this phase?	*Extant explanation in received wisdom*-- Commercialization is "an endogenous outcome of firms' technological investments and the associated knowledge evolution during the incubation period" (Moeen & Agarwal, 2015; p. 35). *Our finding*: Large institutional buyers help create pre-commercialization innovation shock that channelizes future product innovation and guides firms' choices.	Role of large institutional buyer in the emergence of demand condition in the pre-commercialization ecosystem.
Component-level knowledge for new products evolves in the pre-commercialization phase and that leads to improvements in critical performance features	What is the genesis of the new components? Where do they come from; who "creates" them, and why?	*Extant explanation in received wisdom:* Firm experimentation leads to the development of new components. *Our finding*: Efforts to mitigate the trade-offs involved in meeting the potential institutional demand usher new components.	Firms' experiments to mitigate the technological trade-offs associated with the product lead to component innovations in the pre-commercialization phase.
Firms in the pre-commercialization phase capture economic value within the ecosystem.	Where do pre-commercialization ecosystems come from? Are they developed strategically by potential buyers?	*Our finding:* Ecosystems evolve when firms engage in technological investments to mitigate the technological trade-offs associated with meeting the needs of large institution buyer.	Genesis of the ecosystem is tied to demand from institutional buyer. Ecosystems evolve when firms recombine knowledge generated by the firms in the ecosystem to meet the demand of the institutional buyer.

Table 1 (contd.)

Received Wisdom	Our framing questions	Comparison of Received Wisdom with our findings	Novel Theoretical Implications
Pre-commercialization phase is characterized by cooperation across [various] types of firms" (Moeen & Agarwal, 2015, p.36)	What are the implications of information exchange among firms? Do such information exchange lead to knowledge recombination that, in turn, reduce technological uncertainties?	*Our finding:* Information exchange between firms in the ecosystem lead to knowledge recombination, which, in turn, mitigates technological trade-offs associated with improving the performance feature that potential customers value.	Knowledge recombination to mitigate technological trade-offs is relatively underexplored. Moeen & Agarwal (2015; p.22) notes that researchers generally "abstract away from nascent industry contexts…..due to informational challenges" in this phase of the technology's evolution.
Pattern of technological evolution in the post-commercialization phase—era of ferment, emergence of dominant design, and the era of incremental change.	Do the evolutionary trajectory of a new technology in the pre-commercialization phase follow the predictions for the post-commercialization phase?	*Our finding:* Dominant design in the pre-commercialization phase does not lead to the era of incremental innovation, which leads to the elaboration of the dominant design through process R&D. Rather, a dominant design in this phase opens the door for more product innovation to mitigate technological trade-offs associated with the design.	Instead of marking the transition from the era of ferment to the era of slight improvements, dominant design in the pre-commercialization phase marks the beginning of the period when firms innovate to mitigate the technological trade-offs associated with product design.

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

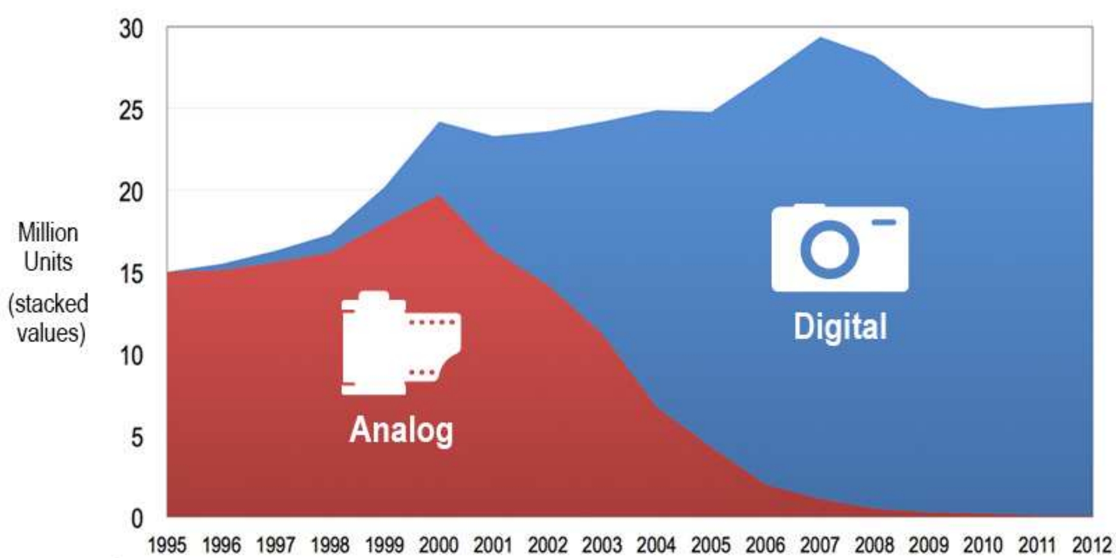
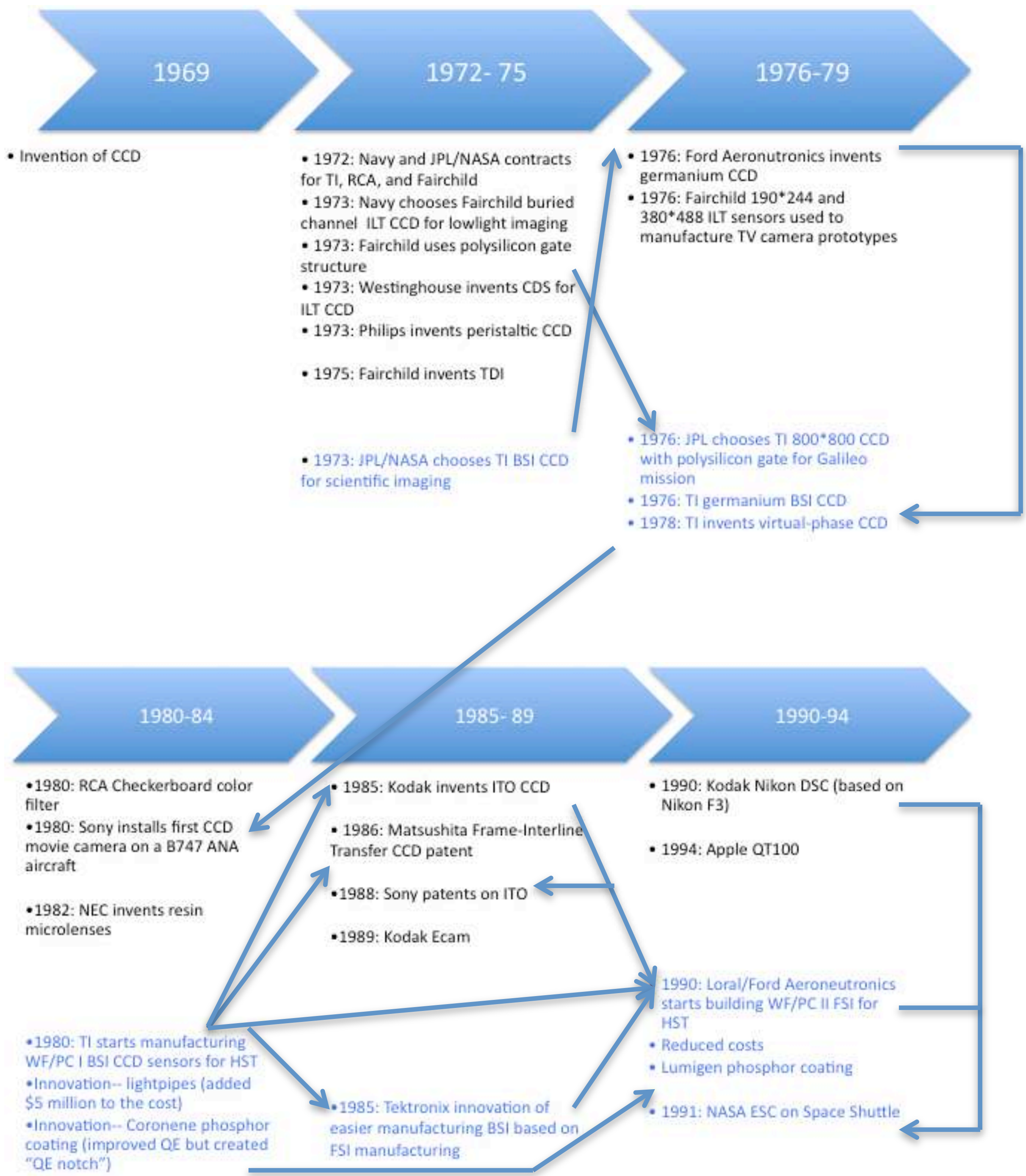


Figure 2: Timeline of pre-commercialization evolution of CCDs during the period 1969-1994 *(Knowledge flows are represented by arrows; black font represents innovations in FSI-ILT CCDs and blue font represents innovations in BSI-FT CCDs)*



Appendix 1: 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 & 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 neighbor. Blooming therefore produces a vertical streak in the picture (Source: http://www.andor.com/learning-academy/ccd-blooming-and-anti-blooming-the-principle-of-blooming)

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 & Elliott, 1992).

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).

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).

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).

Light-pipe: 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." Lightpipes 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 (Source: http://photo.net/learn/optics/mtf/).

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 (Source: http://www.mssl.ucl.ac.uk/www_detector/ccdgroup/optheory/ccdoperation.html) 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 & 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 (Source: http://hamamatsu.magnet.fsu.edu/articles/ccdsnr.html)

Reference

Anderson, R.L. 1976. An evaluation of charge-coupled devices technology. FAA Report No. FAA-RD-76-198; October 1976. Prepared for Department of Transportation, Federal Aviation Administration, Systems Research and Development Service, Washington, D.C.

Bell, Z. W. 1987. An Image Segmentation Algorithm for Nonfilm Radiography. In Review of Progress in Quantitative Nondestructive Evaluation (pp. 773-779). Springer US.

Felber, P. 2002. Charge-coupled devices. Project submitted to ECE, Illinois Institute of Technology.

Janesick, J. & Elliott, T. 1992. History and advancement of large array scientific CCD imagers. In Astronomical CCD Observing and Reduction Techniques (Vol. 23, p. 1).