<u>Online Supplemental Material</u>

Appendix 1

Detailed description of the technological discontinuity in image sensor industry and relating that change to the characteristics of disruption identified by Bower and Christensen (1995), Christensen (1997), Christensen and Overdorf (2000), and Govindarajan and Kopalle (2006)

To ensure that the CMOS sensors were disruptive, we follow Christensen's (1997) research as well as research by Bower and Christensen (1995), Christensen and Overdorf (2000), and Govindarajan and Kopalle (2006). The six characteristics of disruption identified by these researchers, and the reasons that the advent of CMOS sensors fits those characteristics, are summarized below—

1. Mainstream customers do not value the new features that the disruptive innovation offers

As compared with the CCD, CMOS uses photodiode, capacitor, and transistors. As the capacitor charges, it drains at the end of the capture, and the remaining charge is digitized. Because additional components which are not light sensitive occupy a portion of each CMOS pixel, the 'fill factor'—the percentage of a pixel devoted to collecting light—is about 26 percent, which is considerably lower than that of CCD pixel (which is about 100%, except for CCDs with Inter-Line Transfer, or CCD ILT sensors). Consequently, CMOS sensors suffer from low resolution and the high fill factor makes CCD sensors the ideal choice for both astrophotography and serious photography enthusiasts, who are the mainstream customers of CCD sensor cameras.

2. Disruptive innovation underperforms on the attributes that mainstream customers value

In the early 2000s, as a result of the low fill factor, CCD sensors offered superior image quality and flexibility and remained the choice for high-end imaging applications such as digital photography, broadcast television, and scientific and medical applications (Litwiller, 2001). CMOS, on the other hand, underperformed CCD in picture resolution.

3. The disruptive innovation costs less than mainstream innovations

Technological trade-offs in CMOS sensors resulted in these sensors being initially used only for high-volume, space-constrained applications where image quality requirements were low such as camera-phones (Litwiller, 2001). It is not surprising, therefore, that in the early 2000s, large camera manufacturers employed CCD sensors for the high-end expensive DSLR cameras, but used CMOS sensors for the cheaper point-and-shoot cameras.

4. At the time of introduction, the disruptive innovation appeals to a low-end, price-sensitive customer segment

Commenting on the potential of CMOS, the *New York Times* (2000) noted, 'the new generation of image-sensing chips cost only several dollars apiece, [and] could become a staple of cellular telephones and other hand-held devices and might bring the cost of a consumer video camera below $100.'

The attraction of the disruptive innovation for the price-sensitive customer segment resonates with Christensen and Overdorf's (2000: 69) definition of 'an organization's *values*— 'the standards by which employees set priorities that enable them to judge…..whether an idea for a new product is attractive or marginal…often take[s] the form of decisions to invest, or not, in new products, services, and processes.' The authors (2000: 72) further note that firms such as Seagate and Digital became victims of innovator's dilemma because the disruptive products did not fit their value systems. Similar to the challenge faced by Seagate with 3.5-inch disk drives, CMOS sensors generated lower revenues as compared with CCD. Thus, the lower profit margins from CMOS sensors ensured that the value systems required to manufacture the CMOS sensors were a bad fit with those required to manufacture the CCD sensors. This is consistent with Bower and Christensen's (1995) insights that innovating with a disruptive technology such as the CMOS sensors means going *downmarket*, and not *upmarket*, for incumbents such as the CCD sensor manufacturers (p.47).

5. Over time, mainstream customers value the disruptive innovation

As noted above, in the early 2000s, CCD sensors offered superior image quality and flexibility and remained the choice for high-end imaging applications, such as digital photography, broadcast television, and scientific and medical applications (Litwiller, 2001). However, there were trade-offs associated with CCD technology that created a window of opportunity for CMOS sensors. At that time, while CCDs (more specifically, CCD ILT—the most advanced CCD sensors) were better in the performance features that affected picture quality such as dynamic range (or, the ratio of pixels saturation level to its signal), uniformity (or, the consistence of pixel performance), and shuttering (or, the ability to start and stop exposures), the CMOS sensors offered digitized output and low power consumption at the expense of image quality.

By the mid-2000s, CMOS sensors had improved in fill factor (Litwiller, 2005) and digital integration of camera-on-a-chip became a reality. Around 2007, the advantage of CCD was largely in the low-light, non-visible wavelength photography (DALSA, 2007) and shuttering (Rashidian and Fox, 2011). However, in the early 2010s, CMOS technology neutralized the shuttering advantage of CCDs.

6. Processes needed to make disruptive products are a bad fit with those required to manufacture the mainstream products

Christensen and Overdorf (2000: 68) further noted that processes are the 'patterns of interaction, coordination, communication, and decision making that employees use to transform resources into products and services…[such as] the processes that govern product development, manufacturing….' In addition to the difference in value systems (discussed in point # 4 above), the difference in processes and activities required to manufacture products with the disrupted and the disruptive technology created innovator's dilemma for Digital (Christensen & Overdorf, 2000: 72). Whereas Digital's processes involved design and manufacture of components used in minicomputers, the disruptive PC business required processes to assemble modular components. Similar to Digital's dilemma, the CCD manufacturers faced a different manufacturing process to make CMOS sensors. For example, unlike CCD, CMOS needed amplifiers in each pixel and therefore CMOS manufacturing processes were dependent on lithography equipment while those for CCD were not (Litwiller, 2005:60). Additionally, CCD manufacturers required specialized dedicated fabs, which they could not use for making other products. CMOS on the other hand, required traditional semiconductor manufacturing processes and fabs.

Thus, following the criteria established by prior literature—Christensen (1997), Christensen and Overdorf (2000), and Govindarajan and Kopalle (2006)—the transition from CCD to CMOS was a disruptive change. It is not surprising therefore that Dr. Wayne Greene (Device Research and Applications Department, HP) noted that CMOS is 'a perfect example of a disruptive technology' (HP Laboratories, 2003).

As we mention on pp. 18-19 of the paper, the emergence of digital image capturing devices that used CMOS sensors (such as picture phones) relied on the new and untested 3G cellular communication technology in the early 2000s (O'Rourke, 2002). Yamada (2001) highlighted these uncertainties when he noted that such services were likely to be "available to only about 4,000 customers in the [Tokyo Metropolitan Area]." Similarly, BBC News ("DoCoMo delays 3G launch" Apr. 24, 2001) underscored the demand and technological uncertainties associated with 3G services and noted that "that many providers are extremely cagey about their expectations for 3G while analyst forecasts for 3G use and revenues vary tremendously. Big doubts appear to remain as to whether the new services will be sufficiently attractive and competitively priced to prompt a mass upgrading by users from their existing 2 or 2.5G phones." For CMOS image capturing device manufacturers, the uncertainties associated with 3G technology translated to the demand uncertainty for the emerging new CMOS products. Compounding the demand uncertainty associated with 3G cellular communication was the fact that this technology was not expected to be available in the US 'until 2006 or later' (O'Rourke, 2002: 37).

Consistent with Bower and Christensen (1995: 47), these uncertainties made it "difficult to predict how big the markets for the [disruptive] technology will be over the long term." In other words, the demand uncertainty associated with CMOS product markets during the 2000s is consistent with the uncertainty that 5.25-inch disk drive manufacturers, such as Seagate, faced when they were challenged by the 3.5-inch disk drives.

Thus, both the challenges—going *downmarket* and *overcoming the demand uncertainty* associated with emerging disruptive technology—of allocating resources for innovations with the CMOS technology are consistent Christensen's (1997) thesis. Additionally, firms with access to in-house users and those without such users faced these challenges. Similarly, firms with and without relevant CTs faced these challenges. Although Bower and Christensen (1995; p. 48) predicts that under the challenges of going *downmarket* and *demand uncertainty*, managers allocate resources to sustaining innovation and "focus resources on fulfilling the requirements of reliable customers," we find that some large CCD sensor incumbents *did* innovate with the potentially disruptive technology and *not just allocate resources to sustaining innovations.*

We endeavor to explain this divergence from Christensen's (1997) predictions. Our theory adds a nuance to Christensen's (1997) theory by pointing out that access to in-house users *and* possession of relevant CTs helped Sony and others to overcome the dilemma.

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Appendix 2

Definition of relevant complementary technology (CT) and our logic for using lightpipes and other technologies as CTs

For our definition of CTs, we rely on Moeen (2013) and Makri, Hitt, and Lane (2010).

We begin by explaining the "core" technological capability of a firm. As Moeen (2013: 53) observes, the technological capability is 'a firm's expertise in the technology or scientific disciplinary area.' Thus, in the context of CCD image sensors, knowledge of the silicon substrate array that traps the photon induced charge and causes the negatively charged electrons to migrate to the positively charged gate electrode is the core technological capability. Similar to Teece's (1986: 291) observations, in the case of CCD and CMOS due to licensing of patents by the inventors, "the core technology is easy to imitate… [and] commercial success swings upon the terms and conditions upon which the required complementary assets can be assessed."

In this paper we concentrate on a specific type of complementary assets—CTs. Building on Makri *et al*. (2010: 606) who defined technology complementarity as the 'degree to which [firms'] technological problem solving focuses on different narrowly defined areas of knowledge within a broadly defined area of knowledge that they share' and noted that (607) such complementary knowledge 'facilitate a process of exploration through experimentation with new competencies and technologies… [that] helps extend the scope of invention search, which in turn contributes to richer inventions…' Consistently, Moeen observed that absent such assets, 'customers may not experience the full value of an innovative product' (2013: 54).

In the case of CCD and CMOS, by following these prior observations we argue that relevant CTs helped the customers of those products to enjoy a better product experience. For example, an image sensor, while capturing the electrons, would suffer from "smear" while capturing moving objects. Global shuttering prevented smear and made the product experience better for the customer. Similarly, an image sensor could capture images in low-light conditions, but have high noise or pixelated images. Correlated Double Sampling (CDS) helped CMOS to avoid that noise in low-light conditions, thereby improving customers' product experience.

Similarly, the other relevant CTs mentioned in the paper—Microlenses, Lightpipes, Hole Accumulation Diodes— facilitated exploration 'through experimentation with new competencies' (Makri *et al*., 2010: 607) for the firms and enhanced customers' product experience.

Finally, we illustrate our logic using two illustrations. Figure 1 (Source: Abramowitz and Davidson, n.d.) shows the core technology of the CCD sensor. Of the two CCD pixels, only one has a microlens. Without that CT, a portion of the incoming beam of light is scattered back, thereby reducing the quality of the image—highlighting Makri *et al*.'s (2010) observation that complementary technologies enhance customers' product experience. Figure 2 (Source: Turchetta, Spring, Davidson MW, n.d.) shows the core technology of CMOS sensor and microlens.

Figure 1: CCD pixel core technology with and without microlens
(Source: Abramowitz and Davidson, n.d.; Credit: MolecularExpressions.com at Florida State University)

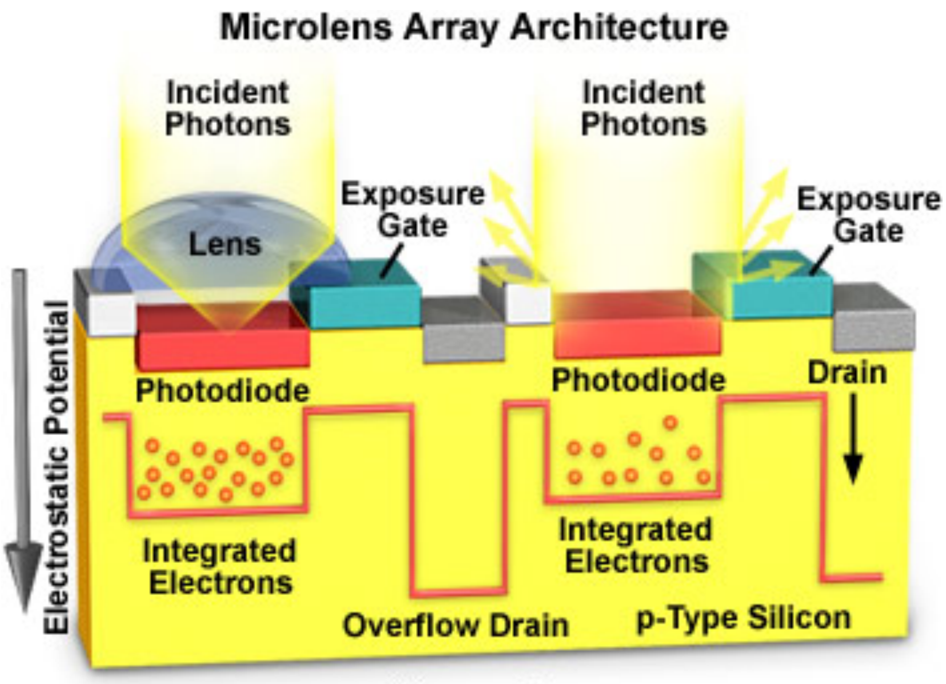
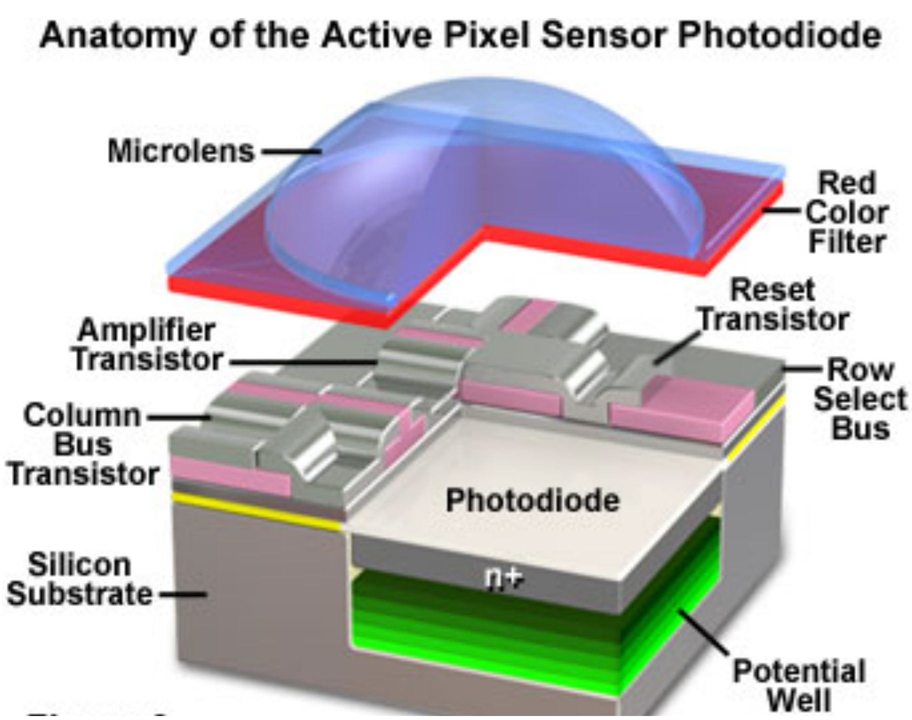


Figure 2: CMOS pixel core technology and microlens
(Source: Turchetta, Spring, Davidson MW, n.d.; Source: Abramowitz and Davidson, n.d.; Credit: MolecularExpressions.com at Florida State University)



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Appendix 3

Relevant CTs used in CMOS

i) Global or electronic shuttering: CMOS sensors had traditionally relied upon rolling shutters that created spatial distortion, or smear, for moving images as shown in Figure 1 below.

Electronic shuttering, the ability to start and stop light collection, has been used in CCD to prevent such smearing. CCD manufacturers created 'masked' transfer channels to block the light. This allows the sensor to transfer the entire image to the masked channels, stop the exposure, and shift the data, a method often referred to as the CCD ILT.

With CMOS sensors, electronic shuttering uses a similar mechanism of transistors in each pixel to control the connection between the light-sensing photodiode and the charge storage capacitor. Because transistors are not light sensitive, they act as 'masks' to prevent smear, but create performance trade-off due to reduced picture resolution. A CMOS sensor requires a five-transistor pixel structure to achieve global shuttering, thereby making the trade-off more acute. Therefore, while the complementary CCD shuttering technology improves CMOS sensor performance on picture smear, it reduces light sensitivity. To address this performance trade-off, CMOS manufacturers came to rely upon other relevant CTs, such as microlens, that were used originally used in manufacturing CCD sensors.

ii) Microlenses: While designing a global shutter to enhance picture quality, CMOS manufacturers faced the same hurdles that the CCD manufacturers had faced in the 1980s (see, e.g., Popovic *et al.,* 1988). The 'masking' due to ILT in CCD ensures that only a fraction of each pixel is light sensitive, which affects sensor resolution. Microlenses, or tiny lenses that are usually a few micrometers in diameter, concentrate the light onto the photosensitive part of the sensor. First used in CCD, this microlens technology was transferred to CMOS sensor to improve picture quality. For example, Toshiba, a manufacturer of CCD sensors (see e.g., Yamada *et al*., 2000), patented CCD sensors with microlens in 1991 (Application # US 07/813,037; Fling date: Dec 24, 1991). Thereafter, Toshiba patented CMOS sensors with microlens in 2003 (Application # JP 2003416946A; Filing date: Dec. 15, 2003) and advertised CMOS sensors with microlens (see e.g., https://www.toshiba.com/taec/adinfo/cmos/pdf/PopQuiz_InformationFL.pdf accessed April 27, 2017).

iii) Correlated double sampling (CDS): Traditionally, one of the advantages of CCD over CMOS has been the low noise level in low-light applications. CMOS manufacturers relied on correlated double sampling technology, which was first used in CCD ILT sensors to overcome that challenge (Rashidian and Fox, 2011). CDS removes fixed-pattern noise and correlated temporal noise. Westinghouse Laboratory in Baltimore pioneered CDS in 1973 for use in CCD (Fossum, 1994) and, eventually, Sony, Sharp, and Toshiba utilized this CT (see e.g., Toshiba patent # US4683580A; Filing date Aug. 7, 1985). NASA/Jet Propulsion Laboratory used CDS in CMOS image sensors in 1994 (Fossum, 1998). Later CMOS sensor manufacturers adopted CDS (Luŝtica, 2011; see also Toshiba patent # JPH09247535A; Filing date: Mar. 12, 1996).

In his research, Theuwissen (2007; pp.23-24) noted the importance of CDS—which was 'popular in CCD image sensors'-- in reducing thermal noise, thereby improving the picture resolution of CMOS sensors. Highlighting the importance of CDS as a relevant CT, he underscored that CDS 'is the preferred choice for CMOS image sensor pixels…. [which] really boosted the introduction of CMOS image sensors into commercial products. Apparently history is repeating: the CCD business really took off [in the 1980s; see Teranishi *et al*., 1982] after the introduction of the pinned photodiode.'

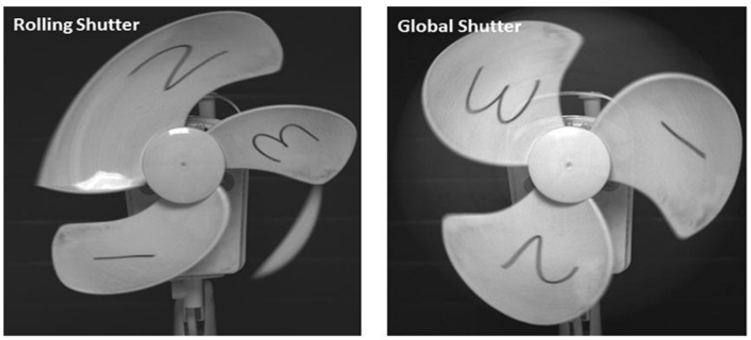
iv) Lightpipe or light shield: These are deep via etched from the passive layer down to the diode surface of the pixel, and then applying a special polymer with a high refractive index. This design traps the light and eliminates color 'cross talks.' The technology for lightpipes, originally developed for X-ray astrophotography using CCD sensors (Bell, 1987), was subsequently adopted by Sony for the IMX046 (8.11 Megapixel, 1.4 µm Pixel 1/3.2-inch) CMOS sensor in 2009 (Fontaine, 2011).

Dr. Albert Theuwissen observed that the secret of the success of Sony's IMX174 CMOS sensor, which exceeded the performance of Sony's ICX274 CCD sensor, 'lies in the design of the light shield. IMX174 is using a tungsten light shield that looks like a copy of the lightshield [*sic*] of a CCD ILT.' He further commented on April 21 that, 'the light shield comes extremely close to the Si-SiO_2 interface, exactly as it did in the past with the CCD-ILT' (Image Sensors World, 2015a). Referencing Morimoto *et al.'s* (1992) documentation of the advent of lightpipes for CCD sensors, he compared the lightpipes used therein during the 1990s to those used in Sony's IMX174 sensor in 2014 (see also Point Grey, 2015) to show the continuity of knowledge in the relevant CT, such as lightpipes.

v) Hole Accumulation Diode (HAD): CCD photodiodes enable electrons to escape and allow free electrons to enter the diode, thereby deteriorating the quality of a picture. In 1984, to solve this problem, Sony introduced the first sensor with buried photodiode—the Hole Accumulation Diode (HAD) CCDs, which used a Hole Accumulation Layer (HAL) to cover the photodiode and block electrons from escaping and entering the photodiode. With miniaturization of pixel sizes, CMOS manufacturers faced similar problems of free electrons. Sony transferred complementary CCD technology to CMOS sensors to develop the HAD CMOS (Nixon *et al.*, 1996; Sony, 2000), which later evolved into the CMOS IMX174 sensor.

Additionally, CMOS sensor manufacturers also relied on the CT of *backside illuminated (BSI)* CCD sensors, which emerged in the 1970s (see, e.g., Shortes *et al.*, 1974), to develop the BSI CMOS sensors in the 2000s. For example, Sony's patent application for the BSI CMOS sensor in 2005 (Application # US 11/208,960; Filing date: Aug 22, 2005) cites its own patent for BSI CCD sensor (Application # US 07/776,212; Filing date: Oct 15, 1991).

Figure 1. Rolling shutter vs. Electronic shuttering (Source: Andor.com, n.d.)



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Appendix 4

Discussion of Kodak's access to relevant CTs

The lack of access to in-house users at Kodak was consistent with its corporate strategy. According to George Fisher, ex-CEO, Eastman Kodak was a 'horizontal firm because in a digital world, it is much more important to pick out horizontal layers where you have distinctive capabilities. In the computer world, one company specializes in microprocessors, one in monitors, and another in disk drives' (Galaza and Fisher, 1999: 46). Chinon was eventually acquired by Kodak in 2004 (Eastman Kodak Company, 2004a) and continued to design and manufacture the point-and-shoot cameras. Also in 2004, Kodak acquired the CMOS business of National Semiconductors (Eastman Kodak Company, 2004b). In the same year it announced a joint venture to manufacture CMOS sensors with IBM and introduced its first CMOS sensor in 2005 (Business Wire, 2005) followed by the introduction of its first CMOS point and shoot camera, manufactured by Chinon in July 2007 (Yoshida, 2007). However, within two years of the introduction of its CMOS camera, Kodak sold its CMOS sensor assets in 2009. It is interesting to note that although Kodak sold its CMOS assets, it continued to introduce CCD sensors with some of the highest picture resolution. For example, in 2007 it introduced a 50MP CCD sensor—a picture resolution that Canon's EOS 5DS camera surpassed in April 2015 (Sources: http://www.kodak.com/ek/us/en/corp/aboutus/heritage/milestones/default.htm; https://photographylife.com/are-you-ready-for-50-mp-cameras). In 2009, Kodak introduced an innovative new CCD sensor that could absorb infra-red rays and did not have microlenses (Source: http://image-sensors-world.blogspot.com/2009/09/kodak-full-frame-ccd-in-new-leica-m9.html).

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Appendix 5

Explanation of our classification of Reticon/EG&G, Tektronix, and Ford Aeronutronic as firms *with* access to in-house users and *without* relevant CTs

We explain why the firms EG&G/Reticon, Tektronix, and Aeronutronic Ford are classified as having *access to in-house users of the disruptive CMOS technology* without access to relevant CTs—

i) Reticon/EG&G: This firm was a manufacturer of CCD sensors used in cameras and scanners for machine vision systems, medical instruments, and nuclear power plants (Raanes and Bottenberg, 1993; Lear, 1984). They also manufactured image capturing devices for satellites and planetary spacecraft (NASA-Deep Space 1 and Lick Observatory, San Jose, CA (Rayman *et al*., 2000; Cizdziel, 1990; see also http://www.digicamhistory.com/Spacecraft%201980s%20and%2090s.html). As we highlight on page 13 of our paper, manufacturers of these image capturing devices were some of the earliest ones to adopt CMOS technology. Thus, this firm had access to the in-house users of the potentially disruptive CMOS technology. Our search of the patent database with Reticon/EG&G as the assignee and the relevant CTs—mentioned on pages 16–21—confirm its appropriate classification in Table 7.

ii) Tektronix: This firm was a manufacturer of CCDs used in cameras and scanners. Tektronix was one of the world's largest manufacturers of image capturing devices for oscilloscopes—instruments that track and plot changes in electrical signals over time. Oscilloscope manufacturers favored CMOS sensors over CCD sensors early on (Finkelstein and Ginosar, 1998). As mentioned on page 21 of the paper, Tektronix had access to the in-house users of the potentially disruptive CMOS technology. Our search of the patent database with Tektronix as the assignee and the relevant CTs mentioned on pages 16-21 confirm its appropriate classification in Table 7.

iii) Aeronutronic Ford (later renamed Ford Aerospace): This firm was also a CCD manufacturer of technology used in image capturing devices. This firm manufactured CCDs used in cameras for satellite systems and spacecraft, such as NASA-CRAF and NASA-Stardust. It also built the CCD sensors used in WF/PC 2 Hubble Space Telescope in 1993. Additionally, Aeronutronic Ford manufactured cameras for low-light aerial surveillance and remote sensing equipment in its in-house Intelsat division, and scanners for video conferencing (Price *et al*., 1992). As mentioned on page 13 of our paper, this firm had access to the in-house users of the potentially disruptive CMOS technology. Our search of the patent database with Aeronutronic Ford as the assignee and the relevant CTs mentioned on page 16 confirm appropriate classification in Table 7.

Thus, we classify all three firms as part of the quadrant III (see Table 7 of our paper) that include firms with *access to in-house users of disruptive CMOS technology* and without the *possession of relevant CTs from mainstream CCD technology*.

We find that Reticon/EG&G, Tektronix, and Aeronutronic Ford failed to avianize themselves during the disruptive change to CMOS sensors from CCD sensors.

Counterchecking our assertion with industry experts:

To enable triangulation, we returned to our experts to ask about the validity of our claim that Reticon/EG&G, Tektronix, and Aeronutronic Ford did have access to in-house users but did not have the relevant CTs. One of our experts commented that, "Absolutely, Reticon fits the criteria." Additionally, another expert noted that, "Your classification is correct. Tektronix and Ford Aeronutronic's CCDs were well-known in astronomy," a field that favored image capturing devices with a high dynamic range provided by CCDs during the early-to-mid 1990s and also that these firms had access to in-house users. We, along with this expert, also examined the relevant scientific papers published in the 1990s and 2000s to investigate if these firms had access to CTs, which examination validated our conclusion. Our experts concurred, and one of them noted that after the extensive search, he too, found "no mention of any CTs."

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Appendix 6

Reason for not including entrepreneurial entrants in our theory building

We explain our logic in two parts—

a) *Reason we do not include entrepreneurial entrants in CCD sensors*: The history of image sensors reveals that in the pre-commercialization phase of CCD sensors (Roy and Sarkar, 2016), NASA and the U.S. Navy relied on large diversifying firms such as Texas Instruments, Fairchild Semiconductors, Ford Aeroneutronics, and others to develop the first workable CCD sensors. The later entrants were also large diversifying firms such as Kodak, Philips, Sony, Matsushita, Sharp, and others.

b) *Reason we do not include new entrants in CMOS sensors*: The focus of our study is to understand what helped large CCD manufacturers to strategically renew themselves during the disruptive challenge from CMOS sensors. This is consistent with extant disruption literature (Christensen, 1997) that underscores the challenges of large incumbents in responding to the disruptive changes. Just as CMOS had new entrants, Christensen (1997) noted that during the transition from the 5.25-inch to the 3.5-inch disk drive, although large incumbents in the 5.25-inch disk drive, such as Seagate, faced the 'innovator's dilemma,' new entrepreneurial entrants, such as Conner Peripherals, did not face similar challenges.

   Subsequently, Adner (2002), Danneels (2004), and others, have expanded our understanding of the causal mechanism of "innovator's dilemma" for large firms such as RCA and DEC. Prior research has explained how, for example, the value systems and processes of these large manufacturers led them to deliberately ignore the disruptive threat (Christensen and Overdorf, 2000).

Given the strong suggestion in prior work on disruption that large incumbents, in particular, will find the hurdle of "innovator's dilemma" extremely challenging, we felt this was a relevant issue to investigate in order to push the theories of disruption and strategic renewal forward.

Thus, to be consistent with prior literature, we investigate the strategic renewal of large incumbent firms that faced the challenge of disruption, such as Sony and Sharp, and did not include the new entrepreneurial entrants into CMOS sensors.

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