Digital Photography and the Dynamics of Technology Innovation

by

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Abstract

Companies heavily and successfully invested in traditional technologies (defenders) often find it difficult to make the transitions to new disruptive technologies, in spite of technological competence and clear opportunity to do so. The core competencies that enabled the firm to excel under the old paradigms become core rigidities when faced with the need to address technological discontinuities.

Products like digital still cameras, DSCs, represent the convergence of multiple rapidly changing technologies in electronics, optics, computers, networks, and software. The emergence and adoption of digital still photography both accompanies and defines a new paradigm in the sharing of images as it attempts to both emulate and replace the previous modalities while creating new market-expanding opportunities.

The emergence of digital still photography has been predicted and promised for several decades. Indeed, it has already managed to replace silver halide altogether in certain market segments previously relied upon by conventional photography firms, and is at present extending beyond the early adopter stage in the broader consumer market. It is a current example of innovation and technological discontinuity, and one that has enough history to permit analysis. It poses a real potential disruptive threat to the incumbent players, some of which have succumbed while others apparently succeeded.

This thesis studies the relationships between the development of the composite technologies in digital photography, the environment in which they operate, the emergence of dominant designs, market diffusion, and the strategies for success employed by leading participants. In the process of studying patterns of entry and exit firms and a detailed look at their products, evidence of a dominant design and support in this industry for the Abernathy and Utterback model of industrial innovation is uncovered. Also revealed is a second wave of innovation in the DSC industry that is firmly established and suggests the onset of a Christiansen-style disruptive dynamic. By studying this specific technological discontinuity in the context of the broader patterns, lessons in adapting to technological change in general are learned.

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Introduction

Digital still photography represents the next step in the technology progression that saw an impressive 100-year dominance of the chemical photographic industry by Eastman Kodak, as highlighted in Utterback's "Mastering the Dynamics of Innovation"[1]. The thesis concentrates on the dynamics of the digital still camera industry, focusing on entry and exits of players, their market focus, and the role of product platforms and standards. An exhaustive study of the industry makeup and history was undertaken, starting with 3rd party reports and databases but augmented with extensive corrections and follow-up investigations.

The thesis concludes that a dominant design has emerged in digital photography. However neither the present designs nor digital photography paradigm will fully supplant the traditional chemical photographic industry, but may themselves be replaced by subsequent technological discontinuities. It further demonstrates that those that have come to dominate the nascent market are those who have thoughtfully applied a platform strategy to efficiently address the growing and changing market. However, in the process of the study, the author was surprised to find the makings of another revolution, which may well re-define the dominant DSC players, who were intended to be the pioneers and attackers of this thesis, as defenders against the next wave.

Motivation – in defense of a perspective

In a conversation with my advisor over a draft executive summary for this thesis, he mused that "you ought to call this thesis 'Digital Photography – A Defenders Perspective'". His point - not a flattering one - was that the tone was not suggestive of market expansion, growth or innovation so much as focused on the replaced technology and imaging paradigms. This criticism was well taken and perhaps deserved, as my own background was heavily biased in the photography industry, even though I had always worked in electronic imaging, do not consider myself much of a photographer, and had never designed traditional cameras or film. There was always the realization that it was the film that generated the cash that funded my programs, and my colleagues and I were often seen in our own firm as an unwelcome representation of the threat to come. However, the defender's posture had not been my intention, and it caused me to question where this had come from.

There are few examples of successful technological innovations that do not build on some predecessor market and technology - although the source market and technology are often quite distinct from one another. The automobile built on the steam engine and the horse and buggy. The telephone built on the

[1] Utterback 1994

telegraph, which built on the postal service. The personal computer replaced the word processor, which replaced the typewriter. The Edison light emulated and replaced gas lamps and candles. New technologies are typically brought to market emulating existing products and services in order to capture the imagination and attention of consumers. The emulated market or industry may see its absolute demise only if the new technology can best the old in most every salient performance metric at a better price[2], and if it is truly innovative it can eventually replace the old paradigm with an entirely new, hopefully more expansive, one. For example, many of us first used a PC primarily to do word processing, which it does better than its predecessors, but the PC would hardly be described as just a word processor today. It was this dynamic that had motivated me to take on this topic for my thesis, to further understand the technology, which I was quite familiar with, in the broader context of history and the present industry wide dynamics, with which I was not.

Outline

In the first chapter, we look briefly at the history of digital still photography in the context of the technology and the early commercial markets where it developed. While digital photography is generally seen in the context of the consumer DSC market today, it was among professional and commercial markets that the groundwork for the present products and markets was laid. Market data is provided to establish the size and potential of the opportunity.

In the second chapter, we look at the digital still camera from multiple perspectives as a product. First we look at its architecture and the technology in the product itself, and then at the product in the larger context of digital photography and the systems in which it operates. The different perspectives yield a hierarchical view of the technology and state of innovation as phased waves as we move up in the hierarchy. What we find is that the technologies that comprise the core subsystems of the DSC arrived at state of incremental innovation preceding the emergence of the dominant design in the DSC itself. This has served as a necessary but not sufficient enabler for stability in the applications of the DSC. These applications environments are still in a state of flux and ferment, which prevents true stability amongst the firms competing to provide for those markets.

In the third chapter, we take a closer look at several market leaders in the DSC industry today. What we find is that the competitors come from four separate industry categories, two of which can broadly be characterized as defenders, and two as attackers. In early 2000, each of the top four market leaders came from a different segment. This provides a context for analysis of the importance of their core

[2] I was surprised to learn from a former VP of Innovation at Singer that the old treadle sewing machine, regarded as a valuable antique by many, was in fact continuously produced and sold up until very recently because there is a real demand for sewing machines in parts of the world without reliable electricity. No doubt some company still successfully makes and sells the best manual typewriter in the world.

competencies and their strategies in the new markets. The four protagonists, Sony, Olympus, HP, and Kodak each fall into one of the groups: respectively consumer electronics, cameras, new media, and film or old media.[3]

In the fourth chapter, we seek evidence in the DSC industry for established "patterns in the dynamics of technology innovation". A database of a surprisingly large number of participant firms was developed and used to analyze market entry and exit in the context of the Utterback and Abernathy model of industrial innovation. Irregular patterns are clarified when the firms are segmented by technology. This first cleavage provides solid evidence of a second wave of innovation in the DSC industry that is suggestive of a Christiansen-style disruptive innovation. In the context of this new perspective, we look back at the industry leaders from the first wave for evidence of their health and participation under the new dynamic. The same database that was used to establish entry and exit data provides a rich source to illuminate the tactics and strategies of both the 1st waves incumbents and the attackers from the second wave. The work concludes with predictions on the future of the industry based on the richer context developed.

[3] The discussion focuses mostly on the US market, which accounts for ~50% of the worldwide market. However, it should be pointed out that Japan leads the US in terms of market penetration of digital cameras, as in most consumer electronics, and nearly matches it in terms of annual volumes. When looking at worldwide market share, the mix and ranking of companies differs, but the same classes of companies are players.

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Chapter 1: Background and History

This work starts with some background and history of the technology and its relationship with traditional photography before moving on to the industry today. From the average consumer's perspective, it seems that digital still cameras represent a fairly new technology -- a mere blip on the historical landscape. Certainly, from the perspective of 150 years of chemical photography this is true. Consumer-level products have only been on the market for 6 years, and market penetration was reportedly only at 5% of US households in early 2000.[4] But like many new and disruptive technologies, this perception belies the fact that developments behind the products have been actively pursued and technologies refined for several decades.

Sensors

The CCD imager is the heart of the digital still camera today. The CCD imager was conceived in 1970 at Bell Labs[5] and developed extensively, primarily for astronomy and scientific and industrial imaging applications, over the next two decades[6]. Many of these demanding applications pushed the performance of the sensor technology to its limits, far beyond where it is applied in the consumer markets today. As far as the CCD itself is concerned, this was really the golden age of "product" innovation in places like Bell Labs, RCA, Fairchild and JPL. These markets continue to drive the technology frontier in electronic imaging today, but primarily in the computer-tethered machine vision industries.

One way to quantify the early commercial and scientific activity around CCD's and digital photography is the volume of patent activity. The advantage of this type of analysis is that data is readily available and rigorously reviewed, and it can generate insights into technology development that precede commercialization[7]. The data gives a concrete indication of the extent to which firms invested in the technology in the 70's and 80's, decades before the first consumer products in this industry appeared.

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[4] Jonathon Rosensweig quoting DataQuest report at PMA 2001.
[5] Boyle and Smith 1970
[6] It is interesting to note that none of the pioneers and early manufacturers of scientific and specialty CCD imagers (eg RCA, Bell Labs, EG&G, DALSA,TI, even Kodak Sensor Division) are players in the larger consumer markets. None of these made the market or process transition from specialty "craft" production into mass production.
[7] Bibliometric analysis is a popular methodology for studying the growth and evolution of technologies and technological communities. It was an earlier focus of this thesis but is not part of the present work following the extensive work of Michael Rappa at MIT.

Table 1: US Patents granted in CCD sensors and digital imaging, through 8/2001[8]

Years	US Patents granted
1976-80	82
1981-85	412
1986-90	2105
1991-95	4136
1996-01	11081

It is difficult to say just who "invented" the digital still camera. There were digital still video offerings by Canon in 1987, typically credited as first. However, video products and still cameras for science and astronomy preceded this. By the mid 80's most of the photographic companies were working on film-less cameras, though commercial products specifically aimed at the traditional photography markets did not appear on the market until the early 1990s. Every year since, the market for portable consumer digital still cameras was predicted to "take off" in the next few years, but its widespread adoption, until very recently, was elusive. For those portable DSCs which did sell during that period, adoption was greatest in business and professional markets where relatively few cameras were used to capture large volumes of images for documentation, record-keeping and publishing.

Publishing

Beyond the development of the CCD sensor itself, much of the foundation for digital photography was laid by the publishing and professional photography industries. The early 1990's saw an evolution in that industry as it shifted to a digital workflow. Published images typically started from film originals, which were sent to service bureaus to create 4-color film separations by what was originally a labor-intensive process of stripping and screening. These separations were then used to create the etched plates for the presses. The art of publishing was often in being able to create plates, which, with some amount of tweaking at the press, could reproduce the desired tone and colors[9]. Digitization, primarily in the guise of film scanners and later in direct digital photography, digitally mastered plates and presses, streamlined the process by eventually eliminating the service bureaus, but in doing so created havoc in the definition and consistency of tone and color. As is so often the case, technological advances in one area drive the need for innovation in related areas.

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[8] USPTO web site advanced text search for (("pixel" AND "sensor") OR "CCD Imager" OR "CMOS Imager" OR "digital camera" OR "digital still camera" OR "electronic still camera" OR "digital photography"). The database pre-1975 is not fully text based, so that searching manually or tracing citations from later patents must be used to discover patents from the early 70's.

[9] The concern for matching colors went beyond the perfectionist ideals of artists, image scientists and photographers, it has very practical application in areas such as fashion retail merchandising, especially for instance in the case of catalog purchases.

This first step in opening up the image publishing industry drove the development of methods and standards for digital color management systems to make WYSIWIG (what you see is what you get) a potential reality. The first digital press systems were run on dedicated high end systems made by companies like Hell Graphics, Scitex and Crossfield, where closed system color calibration and translation could be well maintained. For a given companies workflow, the path from scene -> camera -> (film) -> bits -> plates -> press could be calibrated and controlled, but typically still required a "color expert" to set up and or manage the system. The Apple Macintosh later became the computer platform to democratize "desktop publishing" and color management, and remained so for most of the 90's, with Adobe leading the software development with its PhotoShop™ and Illustrator™ products, and Apple's ColorSync™ and Kodak's KCMS™ color management systems. Nonetheless, color calibration and matching of input, display and output devices within any users' scope remained a formidable challenge for some time, typically requiring technological sophistication or the purchase of pre-matched capture, display, and print components. However, once it was mastered, the workflow for a commercial studio was able to eliminate a several day process in the capture, creation and approval of published material.

Photojournalism

Canon's first electronic still camera was demonstrated at the 1984 Olympic Games to speed images of the games to press. Nonetheless, it would be almost 10 years before portable digital still cameras for photographers were commercially produced. In the interim, leading edge Associated Press photographers would develop 35mm film in canisters in the back of minivans and campers, later adding 35mm film scanners to digitize and send images of breaking news around the world[10].

The first digital cameras for photojournalists, which appeared in the mid 90s, were 1.5 megapixel Kodak DCS backs built on Nikon and Canon camera bodies that sold for over $10,000. They matched the pattern of poor quality relative to film and there was no LCD for instant verification, but the images could be quickly loaded onto a laptop for verification and they did provide speed to press. Arguably, newsprint did not present a challenging output media for the images taken on early digital still cameras, or DSCs, but quality was still an issue as that same photo might potentially have been a candidate for a Pulitzer. While not the largest demographic group, photojournalists were significant users of film as well. Here, as in the case with the publishing industry, the scope of a particular user's system was limited and controllable but still required some level of technological sophistication to manage. The cameras were sold through specialty camera dealers and marketed by a highly educated, dedicated sales force.

[10] This same model, using film scanners as a bridge between conventional and digital photography would be later used by Kodak and others to introduce the consumer market to the possibilities of digital while hoping to stave off the total conversion. This was the essence of Photo-CD and later implementations of pictures on floppy disks and web delivery of digital images scanned from 35mm film.

Studio and Document Photography

Other early markets for digital cameras were the studio photography, "document photography" such as real estate, insurance, law enforcement, forensics, medical and scientific imaging. Each of these industries was also ripe for innovation. In the case of studio photography, participants were used to extremely high prices for cameras, studios and film. In 1994, professional digital portable cameras, camera backs, and scanning backs were introduced by firms like Kodak, Leaf, Megavision, Jenoptik, Rollei, and Minolta at an average price of around $20,000. The cost invested in a $20,000-$40,000 digital studio setup back then paid for itself in savings in film, final and proof, and productivity gained by the elimination of processing delays and $40-$50/frame for scanning if a studio had sufficient volume of work. The studio market distinguished itself from other early DSC markets in its quality consciousness. These systems were also sold through specialty high-end camera dealers, who would typically invest a good deal of time in training and setting up and color calibrating a cameras, scanners, monitors and printers. It was a specialized market niche serviced by a specialized channel.

In the case of document photography, the high fixed costs of the cameras were harder to justify considering the larger numbers of operators and their relative lack of sophistication and care of equipment. These markets were largely dominated by instant photography because of the high value placed on being absolutely sure that the proper scene was captured as well as the timely fit with workflow. Image quality requirements varied by application, but in general were not that high. Even when the Apple QuickTake and Kodak DC-40 first brought prices under $1000, buying an $80 Polaroid camera and paying "a buck a shot" for instant film was still a safer economic bet for most companies in this industry. However, the high film costs and the broader move to a total digital workflow was compelling. Camera manufacturers and systems integrators partnered and marketed directly to large volume users of document images in insurance, law enforcement and real estate. The film suppliers reacted to the threat here and held off the conversion by developing film scanners and hybrid systems dedicated to digitizing their conventional images[11], but, by the time camera prices approached the $500 mark the transition from film in commercial markets was rapid, as cost and instant digital convenience combined to move these markets towards innovation. After some of the larger accounts switched to digital, the sales and distribution channels expanded to access smaller customers.

[11] Another tactic used by the film industry to stave off the conversion of the document photography markets, was to raise the issue of authenticity of digital images. Technology for doctoring film images has been available for many decades, but is less accessible and requires considerable skill in the art. Digital images can be easily and radically modified by anyone with a PC and image editing software. This tactic was especially effective in delaying conversion for the law enforcement, security, and to some extent, insurance industries.

Seeking the Broader Market

For most of the early through mid 90's the technology rapidly improved without significant penetration beyond these "niche" markets into the mainstream consumer market. That which was a natural "pull" for commercial markets proved to be a "push" for the consumer. The integrated systems solutions and training materials that were created for the commercial markets did not have a robust equivalent for the general consumer photographer. Everyone in the DSC business claimed to be losing money in digital as the products and services developed faster than the markets for them. Many of the early consumers who used DSCs purchased them for their businesses but brought them home for other uses. At first they used office computers and printers to work with, print, and distribute the images, but eventually the same equipment started showing up in people's homes. Adobe created inexpensive, yet feature-limited, versions of its $800 PhotoShop product for consumer use that could be packaged with scanners and cameras. Distribution and sales channels progressed from specialty photographic shops and direct sales forces to consumer electronics and computer stores, web outlets, hobby camera shops, and eventually mass-market retail, where brand name and distribution channels played a more important role. We propose that DSCs finally started to move beyond the early-adopter phase[12] in the year 2000 contingent with the development of network externalities such as:

- the widespread penetration and rising performance of the PC and the internet in the broader home market[13]
- improvements in color management, digital and desktop publishing software for editing and sharing images, and the adoption of digital imaging standards
- the falling costs in electronic components, subsystems of DSCs, and personal color inkjet printers
- the development of on-line and, more recently, in-store print fulfillment services.

The commercial history of digital still cameras and digital photography only goes back roughly 7 years, regulated largely by the system-level network effects briefly described above. Table 2 below highlights some of these development in the broader context of the photographic industry going back an additional 20 years to lay the groundwork for the present state of the market and the competitive dynamics between the players that follows.

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[12] See: Rogers 1983. ch 7: "Innovativeness and Adopter Categories p 241-270.

[13] InfoTrends Research group reported in its "2001 Worldwide Low End Digital Camera Forecast Summary" in September 2001 that 50% of US households have access to the internet and DSC household penetration is at the 13-15% level. Given today's dominant use paradigms, internet access could be viewed as a potential limiting factor to market penetration.

Table 2: A sampling of important milestones in the history of digital still cameras[14]

Year	Development in the Digital Imaging Industry
1973	JPL initiates Scientific Grade large array CCD program
1974	First patents for CCD imaging devices granted. Fairchild 100x100 and an 8-inch telescope produces first astronomical CCD image
1976	Canon AE-1 first 35mm camera with built in microprocessor
1978	Konica introduces first point-and-shoot, autofocus camera
1979	RCA 320x512 LN Cooled CCD System sees first light at Kitt Peak National Observatory.
1980	Sony demonstrates 1st consumer camcorder
1980-85	Scitex, Hell, and Crossfield introduce computer imaging systems
1984	Canon demonstrates first electronic still camera at LA Olympic Games. Apple releases Macintosh – the future computer platform leader for desktop publishing
1987	Eastman Kodak announces the 1.4 megapixel CCD for digital cameras. Canon produces RC-760 Still Video Camera with 600,000 pixel CCD, which is used by USA Today to cover special events. [15] Both Kodak and Fuji introduce novel disposable 35mm film cameras
1988	Sony (Digital Mavica) and Fuji announce new digital cameras. Eastman Kodak announces a 4 megapixel CCD. PhotoMac is the first image manipulation program available for the Macintosh computer
1990	Kodak announces the development of its Photo CD system. Adobe Photoshop 1.0™ is the second professional image manipulation program available for Macintosh computers. Dycam releases an electronic camera for business applications (90k pixels B&W). Eastman Kodak prototypes an electronic camera back designed for photojournalists. Tim Berners-Lee develops a new technique for distributing information on the internet – eventually called the *www*.
1991	The Kodak Professional Digital Camera System is introduced Sony releases the SEPS-1000 Digital Studio Camera for modest quality advertising. Rollei and Arca Swiss announce their digital studio camera.
1992	Leaf Systems announces the Leaf camera back for studio cameras (2kx2k), such as Hasselblad or Sinar
1993	Nikon, Canon, Leaf Systems, and others announce new digital cameras for photojournalists and studio photographers
1994	Apple Computer, Sony, and Kodak announce new digital cameras. Associated Press announces the AP/Kodak NC2000 digital camera for photojournalists.
1995	In October, Byte Magazine reviewed DSCs – at under $1000 (barely). Kodak's DC-40, Apple's Quicktake and Logitech's Pixtura - all based on Kodak's design and Casio QV10.
1996	Advanced Photo System (APS) is introduced
1998	Several 1 megapixel digital compact cameras are below the magic $1000 price point. US Sales of Digital Still Cameras exceed 1 million units.
2001	The fifth annual DIMA Digital Camera Shootout at the Photo Marketing Association trade show saw 53 entrants from 18 manufacturers, representing less than half of that years new Digital Still Camera's and vendors in the market.

[14] Compiled from various sources, but primarily extracted from www.eastman.org/5_timeline/5_index.html. Utterback 1994. Chapter 8. Boston: Harvard Business School Press 1994.
[15] Editor's note: References were found to the introduction of the RC-760 from an earliest of 1986 to as late as 1988 at http://www.canon.com/about/history/a_0008.html

Market Size:

Worldwide sales, as shown in Figure 1, topped 12 million units in 2000, compared to a flat but slightly declining 62 million conventional cameras excluding single use, and revenues from digital camera sales reportedly matched those from conventional cameras[16]. Some additional market errata are provided below to provide a sense of scale for the numbers.

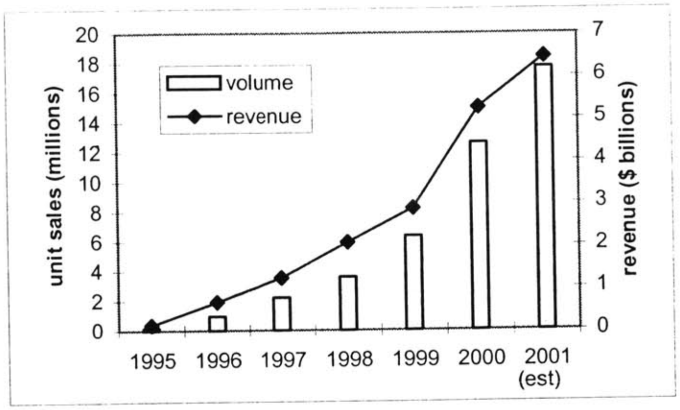

Figure 1: Worldwide DSC sales 1995 to 2001[17]

Some other numbers are provided to help establish scale and perspective:

- $500 million in sales revenues from 0.5 million digital camcorders in 1999[18]
- 5.8 million total US camcorder sales in 2000[19]
- 17 million re-loadable conventional cameras sold in US annually[20]
- 45 million web subscribers in 1999[21]
- 62 million re-loadable conventional cameras sold annually worldwide[20]
- 131 million PC's sold worldwide, 48 million in the US in 2000[19]
- 200 million "active" conventional cameras in the US in 2000[22].
- 250 million single use cameras sold annually in US[20]
- 72 billion amateur film exposures taken worldwide in 1999, growing ~1.5% annually[22]

Renewed Innovations from Defenders

It has been observed that the appearance of a disruptive technology in an established market often spurs new levels of innovation by established competitors[23]. The effect is readily apparent in the case of

[16] Source: InfoTrends Research Group Inc. report of Feb. 2001 "PMA 2001: Preparing for Mass Market Adoption of Digital Photography"
[17] Source: Compiled from various sources, primarily Lyra Marketing and InfoTrends Research Group Inc.. 2001 unit sales are estimated.
[18] Source: NPD Intellect as reported on PhotoHighway's website 2/29/2000
[19] Source: Appliance Manufacturer's Association published by Business News Publishing Co. April 2000
[20] Source: Solomon Smith Barney "Photography & Imaging" industry report 2/24/2000
[21] Source: Jupiter Communications.
[22] Source: Solomon Smith Barney report: "Digital Evolution Becomes the Digital Revolution" – Presented to the PMA, February 23, 2000 by industry analyst Jonathan Rosensweig

conventional vs. digital photography as well. The domestic leader in the competitive response was typically the incumbent, Eastman Kodak, which was also an active player in the development of the digital market. Therefore, these efforts reflect competing concerns within a single company.

The first response is the introduction of single use cameras (SUC) in 1987. The introduction of the SUC served to re-invigorate a stagnating silver-halide photography market, and created a new very low, *disposable*, entry point in the conventional photography market. The product set a new standard for convenience and usability that today is estimated to generate over 20% of the conventional exposures and is expected to show better than average resilience against the digital assault. It can be argued that this was actually unrelated to the development of digital cameras. However, it did occur in the same era as the first still video cameras were appearing and it did have an impact on the later dynamics of the digital camera market by establishing a new ease of use and cost standard. It can also be viewed as a pre-emptive, almost classically disruptive, assault on the conventional value curve, but one that came from within the industry.

The second response was the development of the Kodak Photo CD systems in 1990, four years after the Canon Xapshot and just 2 years after the Sony Mavica[24]. Photo CD, a hybrid of traditional and digital photography, was introduced to promote the centralized scanning and digitization of film. Once scanned, the images were compressed in a novel and proprietary multi-tiered multi-resolution format and stored on digital compact disks. Photo CD came in 2 resolutions, 2kx3k for the consumer and 4kx6k for the professional market. The disks could be read, imported and edited on a computer. For the consumer, there was a Photo CD player, which hooked up to a TV and allowed the images to be viewed at home. There were plans for a home printer and for consumers to re-order prints from the disks. The consumer product never took off with consumers, but was adopted in the smaller professional market. In promoting the product, Kodak drove the development of its centralized film digitization and printing services, drove the improvement of desktop publishing software and color management, and helped to raise the perceived minimum resolution threshold for the emergent digital photography[25]. The strategy may have been successful, because when Kodak and Apple came out with the 0.38 megapixel DC40 in 1995, Kodak was

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[23] Utterback 1994.

[24] Independent of Photo CD, Kodak manufactured and sold several scanning and printing products during this period. Scanners represent a transition product, which enabled the use of legacy and new film-based images in the realm of digital photography. This could also be viewed as a defensive strategy of the film industry, but was likely viewed more as an enhancement or enabler at the time. A separate study of scanners, both film and reflective, would likely show a diffusion curve preceding DSCs by 5-10 years, with similar dynamics in terms of the film, camera, and electronics firms as early players, later supplanted by low-cost vendors from the Far East.

[25] Note that the scanning resolutions of consumer photos for web-based photo finishing rarely exceeds 1k x 1.5k pixels derived from Bayer data today. The Photo CD basic standard of 2k x 3k full resolution pixels, and 4kx6k professional, might be viewed as an example of technology over-performance. In terms of true resolution, it still exceeds all but the very highest end digital cameras.

accused by some critics of trying to sabotage digital photography by coming out with a product that produced inferior pictures.

The third response was the introduction of the Advance Photo System, or APS in 1996. The new system was co-developed by a consortium of major film and camera vendors, Kodak, Fuji, Nikon, Minolta, and Canon, who pooled and cross-licensed their various patents. Previous attempts by Kodak to introduce new formats such as the "Disk" camera on its own had been failures. The introduction of the APS was intended to not only re-invigorate a stagnating silver-halide photography market, but also to drive out low cost competition through its lock on the intellectual property. Any participant outside the consortium had to pay licensing fees and royalties in order to participate in the APS market. The new system consisted of a new film format in a multi-featured auto-loading film canister, new smaller cameras, and new features in photo finishing such as built-in multi-format capture and print. Most of the features were aimed at improved usability, such as fault-free loading, and the promotion of reprints with the return of every roll via an index sheet of the images on the roll and negatives returned in the cartridge for no-handling archiving. The film also had a weak magnetic film coating on which could be recorded, in the higher end cameras, digital information such as exposure conditions, date & time, and other application specific information. It is also interesting to note that the APS film format used approximately 40% less film per exposure, providing a potential cost savings for the participants, even though the film and system originally sold, and continue to sell at a premium based on its features.

The side effect of APS on the Kodak's digital strategy was in further driving scanning and printing capabilities, as well as a whole new investment in photo-finishing equipment into its mini-labs, primarily for the required index prints. While direct consumer buy-in was slow to start against the large installed base of 35mm cameras, Kodak drove the infrastructure by including APS film in most of its new single use cameras, which were then competitively smaller and lighter. The APS venture can also be looked on as another attempt, like the SUC, to address the technology over-performance of 35mm silver halide.

These efforts did produce short-term boosts to conventional photography to help it stave off the digital "assault". Each addressed some issue of usability, reliability and reprocessability, which were the areas from which digital photography would eventually attack in the consumer market.

Chapter 2: Product and Features

Digital photography can be looked at from several perspectives to gain an understanding of the opportunities and challenges it presents. The primary commercial product associated with digital photography is the digital still camera, or DSC, itself. In order for the product to penetrate the various markets, the DSC, comprised of its composite elements: components, subsystems and their interfaces, had to be developed to a level of performance and cost to be attractive to each of those markets. These elements are combined in the DSC to provide the common features and functionality experienced by the user. The common features and functionality comprise the dominant design of the DSC.

However, on its own, the DSC has little value, but is itself part of a larger system or systems for the sharing and use of the digital images that it captures. In this section, the DSC is revealed as a product itself, and as an element in a larger system. The DSC itself, and its subsystems show evidence of being in a state of incremental change. The physical technology behind the components of digital still cameras was available long before the markets for them were developed. However, the digital marketplace in which it is applied has become a complex web of interactions of products and services each seeking to establish dominance while reacting to innovations in its subsystems, peers, and parent applications. Therefore the product applied within higher-level system of digital photography is still in the midst of several eras of ferment. Thus, the product can be looked at as levels of hierarchy each attaining stability at the level of interfaces, enabling dominant designs to emerge in higher levels and markets as the relevant interfaces stabilize. Early (ie commercial) markets being systems of more limited extent developed first and were managed by smaller firms with local focus. Larger, more distributed systems (ie consumer) require greater levels of standardization in order to develop and coordinated efforts of a broad range of players.

Each perspective, the DSC as the product and the DSC as a component of digital photography, contributes and is necessary to an understanding of the product, its history, and the evolution of the digital photography market. First we will look at the product.

The Digital Still Camera

The digital camera is a classic assembled product, comprised of many different parts and subsystems borrowed from related technologies combined to meet established and emergent needs in a radically different way. It is also considered a complex product, one that requires the coordinated interaction of various electrical, optical and mechanical subsystems within a complex and evolving external environment and system. The product recently went through the transitions from rapid innovation and relatively high variety toward dominant design based on evolving standards. On one dimension, resolution has continuously and steadily improved along with image quality and ease of use while costs and price have steadily dropped. Technology in sensors, batteries, embedded processors and electronics, packaging, memory, and LCD displays are continuously improving as prices drop, and they are quickly incorporated into new designs.

Product Architecture

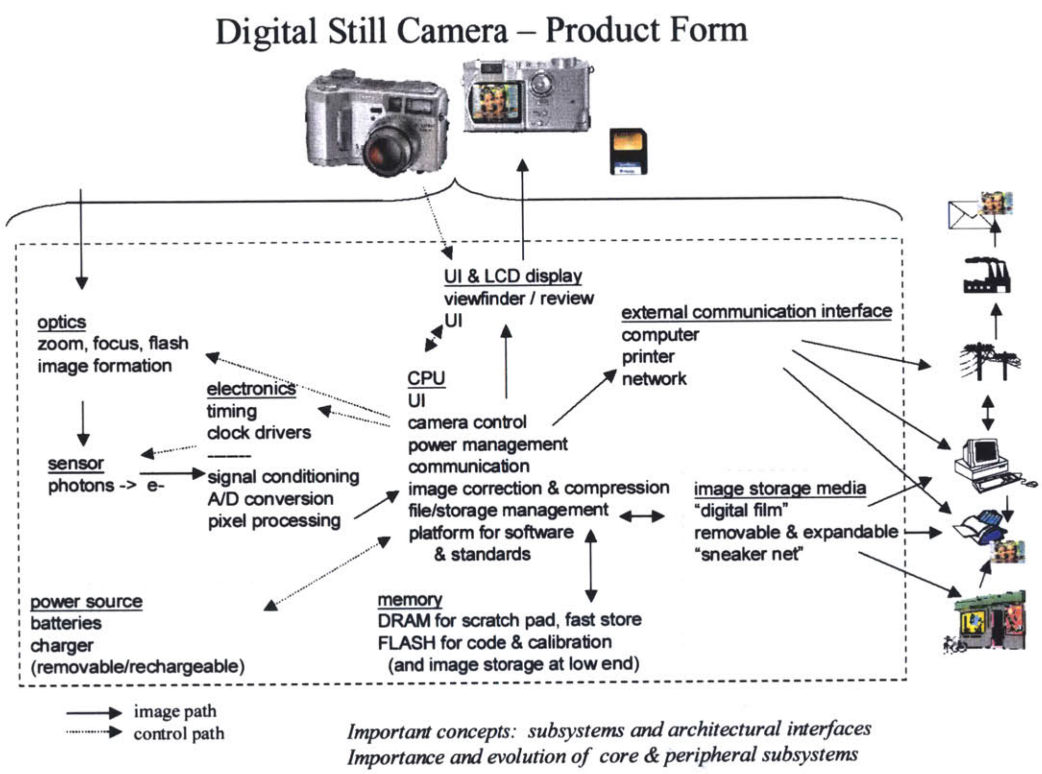

Figure 2: A typical Digital Still Camera architecture

The figure above shows a schematic representation of a typical DSC. The camera is broken down into its major subsystems, which are key elements in the basic functionality of the DSC as well as its cost. Physical architecture and segmentation within actual cameras largely follows that of the conceptual architecture shown. While the products are typically not manufactured in a modular fashion, the interfaces between the subsystems are fairly well standardized so as to permit modular design, and rapid renewal and upgrade of product lines to incorporate the annual performance improvements in each of the available subsystems. This will become apparent when we later look at the rapid introduction of new products in the marketplace. While the detailed design of DSCs is not the main focus of this work, it does add to the context, so each element or subsystem is further summarized along with its functions, trends, drivers and dominant design in Table 4, after first looking closer at the sensor.

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The Sensor

The sensor, whether of CCD or CMOS variety, is the key component of a DSC. It has historically been its single most expensive component, and deserves separate discussion[26]. Its main function is to convert light or photons into electrons for eventual digitization. This component embodies the technological innovation of digital over film-based cameras, which captures a latent image chemically on film for later developing, processing and recovery. Beyond eliminating a consumable, namely film, its inclusion replaces some of the needs for separate electronic exposure[27] and focusing subsystems, as the electronic sensor can provide much of this functionality as well. Together with an electronic LCD display, the sensor can provide instant verification and review or sharing. This brings in the primary salient feature of instant photography, without the high media cost.

Table 3: Smallest diagonal format sensor introduced in a consumer DSC by resolution and year of introduction[28]

ship year \ meg. Pixels	0.3	0.8	1	1.3	2	3	4	5
1995	1/2"							
1996	1/3"	1/3"	1/2"					
1997	1/4"	1/3"	1/3"	2/3"				
1998		1/3"		1/3"				
1999		1/3"			1/2"			
2000		1/4"			1/2.7"	1/1.8"		
2001						1/2"	1/1.8"	2/3"

The trends in sensors include: smaller pixels, more pixels or higher resolution, higher sensitivity and quantum efficiency; better performance including dynamic range, anti-blooming or over-exposure handling; fewer defects; less sensitivity to supply and clock level variations; and some integration of clock drivers and special voltage regulators. Each new generation of smaller pixel pitch yields a smaller sensor format for existing sensor resolutions and allows for higher resolutions at the larger formats as shown in Table 3 above. Thus, a DSC vendor who designed a camera around a 3 megapixel 1/1.8" sensor in the year 2000 could in theory just replace the 3 megapixel sensor with a 4 megapixel 1/1.8" sensor the

[26] At the very low end of the market, the cost of the display may exceed the cost of the sensor today.

[27] It is fortunate that the DSC has a "built-in" exposure meter. The typical CCD has considerably less than ¼ the dynamic range of film, so it is incumbent on the camera's internal software and exposure systems to ensure a decent capture. With film's wider dynamic range, a single use 35mm camera can deliver decent pictures over a far wider range of operating conditions with just a single exposure setting.

[28] Extracted from Lyra DSC database, excluding Professional models. Note that it is apparent from the data, that the newer, smaller pixel designs are more inclined to appear in higher resolution sensors than lower ones, presumably because the higher end of the market can claim higher margins to pay back the investment in capital for the newer processes. Sony has announced production of a ¼" 1.3 megapixel CCD in 2001, but it is not clear if it has been commercially incorporated in DSCs yet. One suspicion is that DSC vendors will be reticent to admit using the smallest geometries to avoid calling attention to poor well capacity or dynamic range, speed, and optical performance, which generally accompany them.

next year, change a little code and the label and have a new camera. As the sensor format shrinks, costs drop, and yields increase, which in the limit drives down prices. This incremental evolution of a dominant sensor design rides on top of what are discontinuous innovations in the semiconductor process technology on which they are based.

Greater numbers of pixels require faster clocking, A/D conversion and pixel processing to deliver similar performance in viewfinder and frame capture rates. Similarly, faster processors and more DRAM are required to process and compress the larger image files in a timely manner, and more memory is required to store the larger digital image files. It is suggested here that the improvements in sensor resolution largely drive the performance increases in the other subsystems; though it could be viewed the parallel incremental improvements enable one other. Certainly, the common element behind each of these trends is "Moore's law[29]". The smaller pixel sizes in DSC's also result in a shorter focal length optical system for a given camera sensor resolution which allows for smaller, more compact designs[30]. However, on the negative side, smaller pixels stress the optical design in terms of depth of field, optical resolution and light-gathering capability or equivalent photographic speed. Moore's Law will help with the photographic speed by reducing feature size and thus improve the fill factor, but the drive for pixel pitches to drop will not continue to drop as resolution is limited by the real physics of diffraction-limited optics of visible light.

The early drivers in sensor technology and design, as described in the previous section, were astronomy and scientific applications. However, it was video applications in camcorders that drove the cost down, and from which the eventual dominant sensor architecture emerged[31]. The prevailing dominant sensor design today is an RGB Bayer-patterned interline architecture, essentially identical to that which is used in virtually every digital and analog camcorder. The "Bayer" pattern means that the pixels are arranged on a rectangular grid with alternating rows of pixels wherein the even rows have alternating red and green filtered pixels, and the odd rows have alternating green and blue filtered pixels as shown in Figure 3. The pixels accumulate a quantity of electrons proportional to the amount of light falling on their surface. The interline structure provides a shielded or covered column of vertical shift registers between every column of pixels, into which the entire frame of accumulated image charge can be shifted or transferred at once(1). Once the entire frame is placed in the column shift registers, it is shifted one row at a time into a

[29] Not based on any laws of physics, "Moore's Law" was based on an observation that the number of transistors per square inch had doubled every year and should continue to do so. It was made by Gordon Moore, co-founder of Intel but at the time director of R&D at Fairchild. See Moore 1965. The "law" has roughly held up ever since for microprocessors and memory chips, though the actual long term rate has been closer to 18 months.

[30] For instance, a 6mm focal length lens provides an equivalent field of view for a 1/3" sensor as a 39mm lens does for a 35mm film camera.

[31] It is worth mentioning the parallel here with conventional photography, in which the dominant 35mm film design is shared between cinematography and still photography.

single horizontal shift register (2), which shifts the discrete "buckets" of image charge out through a single output amplifier(3). Steps (2) and (3) are repeated for each row of the sensor until the entire sensor is read or clocked out. The exposed pixels can be accumulating charge for the next frame while the previous frame is being clocked out.

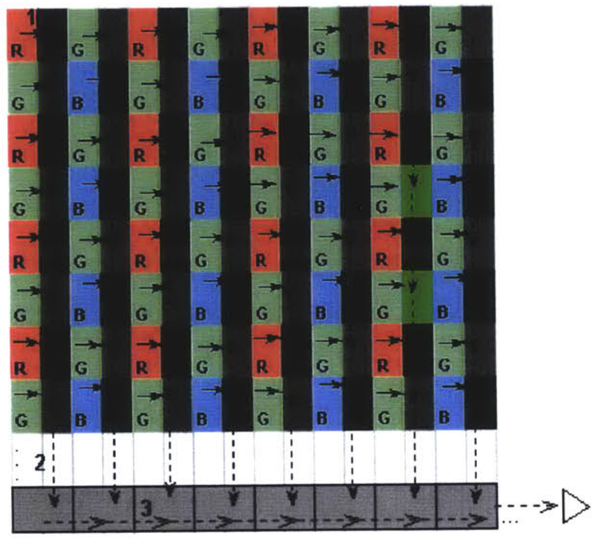

Figure 3: Basic schematic of a Bayer-patterned interline CCD

A 1-megapixel RGB Bayer-patterned CCD has ¼ million red, ¼ million blue, and ½ million green pixels. The reconstructed image has 1 million RGB pixels, which are reconstructed from the raw pixel data through some combination of interpolation and filtering in a color space. Sampling theory describes the aliasing of frequency content above the Nyquist frequency onto lower frequencies. The pathological case is sampling a sinusoidal signal whose frequency is identical to the sample rate. The reconstructed signal is a constant. This is typically avoided by bandwidth limiting of an analog signal before analog to digital conversion to ½ the sampling frequency, called the "Nyquist rate". The sampled color patterns can result in color aliasing at an even lower frequency. The equivalent pathological case would be a pattern of white spots aligned with just the red pixels in Figure 3, which would "alias" to a solid red field after reconstruction. While this pathological case is rare, real-world geometric patterns such as pin stripes and fabrics create havoc in color reconstruction in regularly sampled systems such as this. To compensate, optical low-pass, anti-aliasing filters are used to attempt to eliminate certain high-frequency signals before they reach the CCD sensor. To avoid the pathological case, the optical filter would have to eliminate any frequencies above ½ of the nominal Nyquist frequency. This, arguably tangential, topic is interjected here to suggest to the reader some of the issues that arise in designing cameras. Furthermore, resolution as defined by the number of pixels, is the primary discriminating term used to differentiate camera performance, but can be highly mis-representative of true resolution.

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The interline architecture won out over frame-transfer and partial frame transfer architectures which lack the interline 'shutter' mechanism and therefore require a mechanical shutter[32]. The advantages of the architecture are that it can provide very fast mechanical-shutter-free electronic shuttering for video viewfinder or final pictures. Disadvantages include poor pixel fill-factor or sensitivity due to roughly half of the active pixel area being used for the shift register, and a greater tendency towards aliasing for the same reasons. The Bayer pattern prevailed over vertical striped patterns, more sensitive CMY or CMYG color filter Bayer patterns and different combinations there-of, so that the reconstruction algorithms could standardize. It prevailed over technically superior designs using 3 full-resolution monochrome CCDs aligned on a triple, 3-color chromatic, beam-splitter because of cost. The square pixel grid pattern was challenged by Fuji with its technically superior hexagonal FinePix™ pixel architecture. However, this was well after a dominant design was established, and Fuji has not been able to promote its design much beyond its own products due to the camera-wide system implications.

CMOS Sensors

The latest trend, which may be a technological discontinuity itself, is the CMOS sensor. Unlike the CCD architecture, which uses a 2D "bucket brigade" to move image electrons to a single output sense amplifier, the CMOS architecture uses a row and column multiplexing architecture like that of DRAMs to sense the image electrons at each pixel location directly using an array of column amplifiers or amplifiers at each pixel location. The CMOS sense structures result in a more complicated pixel design, which results in a poorer fill factor for each pixel and therefore the need for larger pixels relative to CCDs. Furthermore, they have poorer sensitivity and dynamic range, and problems matching the multiple sense amplifiers result in fixed pattern image artifacts. While CCD imager technology has been dominant over CMOS, it requires a more complicated fabrication process than the CMOS process technology, which is the basis of virtually all other consumer and commercial integrated semiconductor devices today. CCD sensors also require several different bias voltages and clock levels ranging from 5 to 25 volts.

As stated previously, CMOS pixels are typically more complex, have larger pitches, poorer sensitivity and dynamic range, and are plagued with fixed pattern artifacts. However, they can usually be run from a single voltage, require less power, and can potentially incorporate much of the additional correction circuitry as well as the timing generators, clock drivers, A/D converters, etc. with the sensor on a single chip. It was previously stated that the diffraction limit of visible optics would limit the practical pitch of

[32] It is worth noting that for the latest 4 and 5 megapixel sensors, Sony and its competitors were unable to design a vertical transfer register which could accommodate the required number of rows, and had to switch to an interlaced interline architecture which can provide reduced resolution shutterless video, but requires a shutter for full resolution stills. This largely eliminates any advantage it had over the partial frame architecture, whose higher capacity at the same pitch yields a better sensor. However, it is not always the best technology that determines the dominant design.

pixels on electronic sensors for DSCs, whether CCD or CMOS. However, with Moore's law providing greater and greater densities, the opportunity for CMOS to incorporate more sophisticated sense structures *distributed* at each pixel will give it an advantage in relative rates of performance improvement over CCDs, primarily in the area of reducing fixed pattern artifacts. The CCD sensor has neither the need nor opportunity for such distributed circuit architectures, and can only use the same technology trends for marginal improvements in sensitivity and yield.

The integration of this additional circuitry, which encapsulates the architectural differences between CCD and CMOS sensors, has been used strategically to facilitate easy integration of the CMOS sensor into the typical DSC architecture, as shown in Figure 2. For some very low-end niche markets, an entire set of camera electronics including the CPU, memory, and computer interface circuitry has been incorporated on a single integrated circuit. Lower power and smaller size are key drivers in portable device markets. The first DSCs with CMOS sensors were introduced to the consumer market in 1997. To date, CMOS sensors have only been incorporated at the lowest end of the DSC market, or in a few specialty niche markets such as image capture attachments to PDAs, PC video cameras, and wireless phones with integrated digital image capture. However, the trends show steadily improving performance relative to CCDs and continued encroachment.

Completing the Architecture

The remaining key subsystems, along with their functions, trends, drivers and dominant designs are summarized in the following table.

Table 4: DSC subsystems - functions, trends, drivers and dominant designs.

Sensor	*Function*: The key component that converts light to electrons. *Trends*: Smaller pixels leading to more pixels and higher resolution, better sensitivity, better performance (anti-blooming, fewer defects), use of on-chip micro-lenses to compensate for loss of fill-factor as pixel pitch shrinks, higher process yields, lower cost. *Early Drivers*: Scientific applications drove performance, while video applications drove cost and architecture. Standard architectures and chips sizes help reduce the system cost. Benefits directly from semiconductor feature size, cost, and yield improvements. CMOS will change the game again. *Dominant Design*: Interline, bayer-patterned, 4-phase horizontal clocking, 3-level vertical clocks CCD (Sony, Matsushita, Sharp, etc), with 4:3 aspect ratio. Failed contenders include IBM and Philips with the partial frame transfer architecture and Fuji with its FinePix™ architecture. CMOS will be next generation.
Display	*Function*: Serves as the camera's viewfinder, image review/confirmation/sharing, and camera's GUI. As such, it represents a key feature of DSCs and enabler of one of its disruptive features.

	Trends: Better resolution and finer pitch, viewing angle, brightness for viewing under varied conditions (outdoor/glare). An early major cost factor, today sees lower cost and power. Typical draw of ~2-4W dominates camera power drain. Possible future contenders include OLEDs? *Drivers*: Commonality with video camcorders, PDA's, cell phones, TV "watchmans" etc. *Dominant Design*: LCD 1-2" low temperature polycrystalline TFT module with integrated conversion electronics for analog video input (Sanyo, Sharp, Unitrode, Kopin).
Optics	*Function*: Image formation - project scene onto sensor. *Trends*: Reduced sensor size format and pixel size allow much shorter focal length systems to provide the same angular format as an equivalent 35mm camera. Electronic sensors provide different design challenges from conventional film cameras: * shrinking pixels challenge the lens resolution * regular bayer-patterned sensor requires anti-aliasing compensation, optically and in image reconstruction. * micro-lenses and 3D micro topology of the sensor pixel favors telecentric designs *Drivers*: "IP" - Japan has a lock on zoom optics patents for digital cameras. This had put a squeeze on the Taiwan crowd before Ricoh stepped up in 2001 as a supplier of low-cost integrated modules with zoom optics and Matsushita and Sony sensors. DSC market leader Sony has paired with Zeiss for prestige, and Kodak has used its own IP portfolio to access that of Olympus and others. *Dominant Design*: 2x to 4x zoom at the higher end of the market, and fixed focal length lens at the low end. To date, a glass lens is typical for taking lens, but there are opportunities for plastics at the low end. Quality of optics, as in conventional cameras, can be a significant differentiator in cost and perceived quality.
Media - Memory Cards	*Function*: Media cards are used for digital image storage - the "film" of DSCs. By making the media removable, a single model can cover a wide gamut of users with differing use patterns. The base model is not burdened with the cost of memory, but the user can purchase as many cards or memory as necessary for their application. *Trends*: Higher density and lower costs are tracking electronics in general. The high cost of large format cards creates a secondary market for removable cards, allowing lower base cost for the DSC. *Drivers*: Commonality with laptops, PDAs, MP3 (music) players, and all computers and computer peripherals utilizing FLASH memory. Standardization of interfaces with PCs and availability of inexpensive card readers. Standard file formats, DPOF, etc, make memory cards an optional "sneaker net" to PC's, printers, photo-kiosks, digital mini-labs, etc.. *Dominant Design*: There is no single dominant design, but many competing standards in FLASH memory cards. At the low end, many DSCs do not use removable cards, but have internal FLASH only. Some low-end cameras forego FLASH altogether and store the images in DRAM, though this poses a challenge to battery life. The 3 leading contenders are:

	CompactFlash (and IBM MicroDrive) SmartMedia SSFDC Memory Stick (primarily Sony) Other FLASH based standards are: MMC multi-media card Secure Digital (SD) card Other non-FLASH based: mini-analog floppy, 3.5" floppy diskette, SuperDisk, Clik™ drive, mini CD-RW.
Computer/Network Interface	*Function*: The computer/network interface allows direct communication of the DSC with computer/network/photo-kiosk/photofinisher. In some cases, it overlaps functionally with removable media (sneaker net). *Trends*: Simpler, easier, plug & play. Cables are bad - wireless is good. (Hot shoes or base stations are for personal use only - not standardized.) *Drivers*: PC's, PDAs, cellular peripheral standards. *Dominant Design*: Evolving - follows the dominant low cost standard interface in the PC industry. More recently there are emerging a few wireless products. Popular standards and their potential endpoints at the low end include: USB - PC, printer RS-232 serial - PC (printer – *rare*) IRDa - PC, printer modem - www wireless - printer, PC, www (bluetooth, cellular, etc) and at the high end include: firewire/P1394 - PC SCSI - PC
Electronics	*Function*: control, conversion, communication within camera and without. *Trends*: benefiting from Moore's law, feature size, power and cost are shrinking while speed and performance increase. Early DSC designs relied heavily on general-purpose discrete parts. The growing market has driven greater integration, standard reference designs, and a scalable memory/pixel/functionality platform design approach. *Drivers*: Computers and consumer electronics industry in general. Higher sensor resolutions driving the need for increased speed and lower power. Synergy with digital scanners, camcorders, wireless phones etc pushes price down and performance up. The growing DSC market volume drives prices of components towards their marginal cost. *Dominant Design*: none in specific, but the basic segmented architecture includes. Timing generators and clock drivers CDS & A/D conversion Programmable microprocessor (generally RISC and/or DSP with separate "pixel processing" engine.) DRAM scratch memory Video drivers for LCD or external monitor Higher levels of integration raise the cost for architectural innovations

	such as Fuji's FinePix™ sensor technology.
CPU / Firmware / Software	*Function*: The CPU and code running on it is the platform and the central glue that ties together or integrates the various subsystems: power management, camera control (CCD, lens, UI, etc), file/storage management, and communication. It is the also driving element behind ease of use. *Trends*: Quickly evolving standards requires a scalable, adaptable architecture. Migration to mass markets requires better, easier UI – such as one button point and shoot (and share?). A computer-free paradigm, direct camera to print, web, or wireless has forced adoption of greater capabilities in the camera itself such as scalable upgradeable operating systems to implement the latest file and compressions standards, interface standards, etc. The push for a standard camera interface will drive APIs for more universal host-based camera communication. *Drivers*: Nearly every conceivable device is run by microprocessors and microcontrollers today. Modular processor designs promote application-specific implementations with common general-purpose cores. *Dominant Design*: Programmable microprocessor (generally RISC and/or DSP with separate "pixel processing" engine). OS based - no single dominant standard: eg: SoundVision's Clarity™, Flashpoint's Digita™, Window's CE™, PSOS™, WindRiver™, Green Hills™, etc In any case, the role of software for making the DSC accessible to the wider market, as well as in enabling rapid evolution of the other subsystems should not be under-stated.
Power Supply / Battery	*Function*: Portable power for the DSC and its display. *Trends*: Higher power density. Re-chargable units (NiCAD, NiMH, etc). Better power management within the DSC itself. Early on, spare batteries were called the new consumable or media of digital photography. LCD panels are the biggest drain factor in DSCs. *Early Drivers*: Portable electronics in general: i.e. cordless telephones, cell-phones, PDA's, laptops, toys, etc. *Dominant Design*: There is a split between specialized power cells, which can be costly to replace but space efficient vs. standard battery formats (AA, AAA), between the high and low end of the market.
Packaging / Industrial design	*Function*: Packaging or industrial design. This is not an easily identifiable subsystem per se, but represents a core competence of certain competitors, which definitely impacts competition. *Trends*: Smaller, higher density, cheaper – primarily plastic, and able to be updated frequently. Rapid renewal of product line re-using key modules and subsystems across product lines and generations. *Drivers*: This market tracks consumer electronics in general with the Japanese dominating in miniaturization. *Dominant Design*: DSCs tend to resemble their counterparts in conventional cameras at each level of the market – entry level fixed focus, point & shoot zoom, SLR, but smaller.

The Dominant Design

Dominant design concepts, pioneered by Abernathy and Utterback[33], have been applied to a vast array of products and technologies. Tushman and Murmann[34] argue that the levels of analysis are often confused, but the concept is most often in practice applied to the subsystem and interface, or linking mechanism. Furthermore, all core systems must be in a state of incremental change as a prerequisite for a dominant design at the product level. Certainly, looking at the multiple competing and changing component and subsystem designs and standards in Table 4, it is hard to imagine the a dominant design has emerged. However, what we do see is that while the subsystems themselves are subject to continuous and mostly incremental innovations, the basic architecture of the DSC has been settled for some time, is readily appropriable, and the interfaces between the subsystems are either stable, or relatively well understood and easy to accommodate as they evolve. New incremental innovations are quickly adopted by the industry. Product lines and platforms are annually renewed. New models proliferate based on a limited number of options among a limited set of subsystems by successful competitors, as we shall see in later sections[35]. These are all indications of an industry in the incremental or specific state.

The list in Table 4, through focused on the internal architecture, contains some of the enabling elements or features of DSCs which have fostered radical innovation in its target markets. The dominant design on the product level is a single set of design features that satisfy most users needs across a broad range of market segments. The author proposes at this point that the sensor, the LCD display, a computer or network interface, and removable/expandable media combine to form the dominant design features of a DSC today.

- The sensor provided the means for direct digitization and the elimination of film.
- The LCD display provides the means of instant verification, review and sharing, as well as the UI to enable potential specification and direction of output for future computer-free use models.
- The network or computer interface provides the direct information connection for image sharing with the wider digital world.
- The removable/expandable media allows one camera to serve a wide variety of usage patterns, and has become a secondary external camera interface (sneaker net).

We shall investigate in later sections the implications of the technology adoption rates of these dominant design features, but we include them here for reference.

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[33] Abernathy and Utterback 1978
[34] Tushman and Murmann 1998
[35] See also the 2001 lineup of Canon product in Figure 16 in the Appendix for a visual example.

Table 5: Technology adoption rates of proposed dominant design features by year of product introduction for CCD-based DSCs[36]

1994	1995	1996	1997	1998	1999	2000	2001	
100%	100%	100%	100%	100%	100%	100%	100%	electronic image sensor
100%	100%	97%	97%	96%	97%	97%	99%	computer interface[37]
0%	0%	3.6%	1.4%	15%	36%	82%	96%	pnp computer interface[38]
100%	82%	55%	61%	91%	93%	94%	98%	removable media[39]
0%	18%	41%	75%	87%	93%	89%	96%	LCD image viewfinder/display[40]

Note that no element besides the LCD image display was unavailable in some form back in 1994, when there were only around a dozen cameras on the market, most of which were costly professional models. Market diffusion has not been strictly limited by the availability of the technical elements of the DSC, but by their accessibility at a reasonable cost and by the external factors associated with the software and networks that enable their ease of use in the broader application context.

Digital Photography

The DSC itself is of little use beyond the capture of images and viewing them on a tiny LCD display. The real value in the DSC comes from the instant availability and portability of its output in a world dominated by digital information and networks. The fluid nature of the DSC's digital output provides the possibility for discontinuous innovation and renewal in every market and industry that relies on images, as well as the creation of new markets that were never possible under the old dominant paradigm. From this perspective, the DSC is just another component or subsystem in a complex value chain that has dynamics that are coupled yet independent from those of the camera itself.

Conventional Photography System

A system-level comparison of digital to conventional photography, as shown in Figure 4, is instructive here. The functional model is a simple three steps: capture, develop/print, and view/share/store. In conventional photography, the user typically captures 12, 24 or 36 images on a roll of 35mm negative or "color reversal" film. The taking device could be anything from a highly sophisticated, electronically-

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[36] Data derived from secondary analysis of a Lyra DSC product database.

[37] Any standard computer interface bus. The entries less than 100% are largely explained by Sony's Mavica FD line which use floppy disks for removable storage and often did not include a direct computer interface. The FD line was extremely popular in the US so figures adjusted by volume would show a much bigger dip. However, the popularity of the FD line was precisely because the 3.5" floppy disk was itself a de facto standard computer interface.

[38] The term pnp stands for "plug and play", and is true for USB, P1394 or FireWire, or a custom "docking station". It is differentiated here as an indicator of ease of use for unsophisticated users, but is derived from and largely follows adoption in the PC industry as a whole.

[39] The sample size in 1994-5 was very small, but early products focused on functionality more than price. Adoption initially dropped to bring the cost of products down, then improved as costs of memory cards dropped.

[40] In 1999, a number of very aggressively priced, low-featured CMOS cameras entered the market. Several challenged low-end CCD cameras dropped features like displays and removable cards to compete the next year. This may account for the dip in the LCD adoption and removable memory in 2000.

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metered and focused, microprocessor-controlled SLR to a $5 fixed exposure, fixed focus, single-use point and shoot camera. Interface standards from the film cartridge to the camera and the C-41 development process are rock solid. The film may come from a wide variety or manufacturers with different characteristics. The exposed film is sent to a mini-lab or central mail-order photo-finisher, where the latent image on the film is developed, recovered, corrected and printed as a single or with duplicate copies, and the prints are returned to the customer. Print formats are generally 3.5x5" or 4x6" or occasionally 5x7".

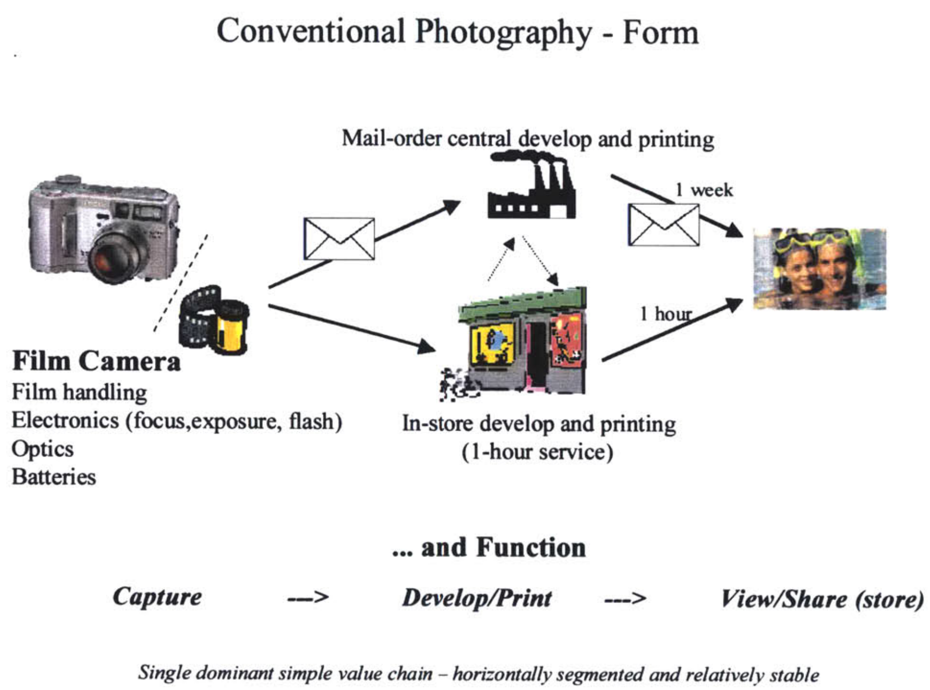

Figure 4: Conventional photography - dominant paradigm

The point of choice or decision for the user is at the time each picture is taken. All pictures are printed, regardless of quality or eventual value to the customer. The majority of the system's complexity is concentrated on the developing/printing stage because the vast variety of conditions under which the film was exposed, and in the film itself[41]. There is a latency of a minimum of 1 hour, but typically much more, and the point of delivery is almost certain to be discontinuous from the point of capture, so that customers

[41] It should be pointed out that most consumers do not appreciate just how robust the conventional film system is. Consider that hundreds of millions of photographs are taken fairly reliably on single-use cameras which have essentially no exposure control system – just one exposure setting for an incredible gamut of scenes, yet, between the high dynamic range of negative film and the corrective care taken in printing, most of the prints come out fine.

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generally do not see the picture until the source of the captured image is a distant memory[42] and they rarely see more than one instantiation of the print[43]. The final print is viewed, and if not discarded, shared, and perhaps stored in a photo-album or shoebox, or mailed on to a friend or relative. Film formats have changed over the years, but the print is the standard, archived currency of conventional photography.

Digital Photography System

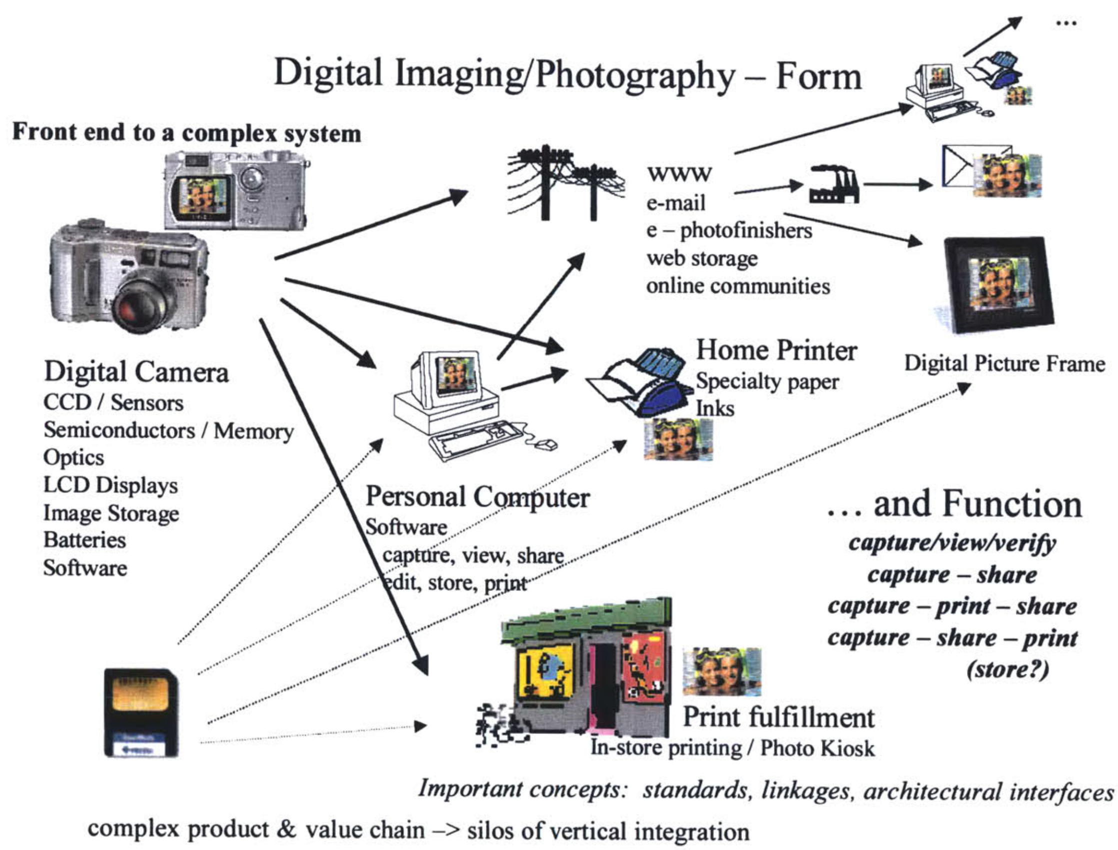

Figure 5: Digital Photography dominant paradigm(s)?

Contrast the traditional modality with that of digital photography as illustrated in Figure 5. The single functional model for conventional photography has been replaced by at least 4 paths: capture/view/verify; capture, share; capture, print, share; or capture, share, print. The process unit for digital photography can be as small as 1 picture or as large as the capacity of one's memory card. There is no economic penalty to

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[42] The one notable exception to this statement is the case of instant photography invented by Edwin Land, founder of the Polaroid Corporation. Instant photography eliminates the print delivery latency, and also reduces the unit of capture to 1, but in other aspects is similar to the conventional photography. The developing and printing functionality are integrated into the camera itself.

[43] It is not uncommon for consumers who do order re-prints of images from negatives to find and perhaps be disappointed that the re-prints rarely match the original print. The especially true when changing print size formats whose aspect ratio does not match, so that the images are cropped differently.

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taking and later discarding images. The captured image can be viewed on the camera's LCD display immediately, and can optionally be printed on personal portable or desktop printers as soon and as often as desired, or sent to one of the traditional print fulfillment venues electronically. Traditional print fulfillment uses the same standard output formats as traditional film, but direct thermal, inkjet and desktop printing are unconstrained. New photo-kiosks and digital mini-labs are emerging as alternatives to the 1-hour film labs in malls and retail outlets. Furthermore, the user can bypass printing, and share or store the image electronically via any number of digital information networks, via the PC, or in some cases directly device to device. Image manipulations for corrective or creative purposes, which are largely inaccessible under traditional photography, are relatively ubiquitous and easy to use on the PC. Secondary recipients and users of the digital images have the same opportunities to re-use the image as the one who captured it, giving the image more potential life and opportunities. The possibilities result in a much more complex and poorly defined product and value chain.

On the negative side, the capability of creating a quality image is distributed and must be redundantly available throughout the system, which adds cost and complexity to the system. An image is, and can be, reproduced on a seemingly endless number of platforms, so that variation in representation is blatantly obvious and potentially problematic[44]. Color management and image file standards attempt to minimize this, but color, color gamut and tonality are very difficult to make consistent. Furthermore, cropping of images when commercially printed on 4x6 media is a regular complaint of users of these services.[45] In the absence of printed output, there is little secondary economic activity generated by digital photography beyond the various services provided for sharing or storing images. On the positive side, the easy transmission and sharing of images creates almost endless possibilities for new enterprises – pictures on mugs, calendars, cakes, business cards, greeting cards, electronic picture frames in consumer markets; instantaneous and ubiquitous advertising in commercial markets; and distributed yet connected security, documentation and information sharing for business and government.

[44] Author's note: I had not considered this to be an issue until I heard several unsolicited complaints from digital users, both in terms of color and cropping. Color is subject to interpretation, and depends on the gamut and chromaticity of the reproducing and viewing medium. User studies typically show that both professional photographers and consumers claim to prefer realistically rendered photographs, but when given a choice between multiple renditions, overwhelmingly show preferences to over-saturated, more brilliantly colored photographs.

[45] Over 75% of DSC models introduced to date use a computer-centric, 4:3 aspect ratio, which is the 1906 international screen viewing standard. When printed full-bleed on the most popular 4x6 print size, 11% of the image is cropped vertically. Some smaller amounts of cropping occurs as well between various standard print size formats, but cropping is more of an issue with digital imaging because the user is more likely to compare the print to the original electronic file than a traditional user would to a film negative.

The advantages of digital imaging explain its rapid adoption in commercial applications, however, the complexity of the new digital photography paradigms may help to explain its failure to displace conventional photography in the broader consumer market. One of the more popular treatments of disruptive innovation today is that of Clayton Christiansen and "The Innovator's Dilemma"[46]. Christiansen starts with the disk drive market to propose that disruptive innovations: are typically simpler and cheaper than the dominant products of a market; are inferior when compared with the products they replace using the dominant performance criteria of that product class; typically move from a minor niche market where they have some ancillary performance advantage, into the low-end, less lucrative niches of the dominant market; and finally, as their performance improves; chips away at the disrupted market from the bottom up.

While one can find some parallels with the story of the DSC, it is typically brought up as a counter-example to Christiansen's theory[47]. This is because of the higher cost and complexity of the DSC relative to conventional photography[48], which given Christiansen's arguments might exclude it from being a disruptive innovation. Whether or not it classifies as disruptive under Christiansen's model, digital photography is undoubtedly innovative and has disrupted the way money is made in the photographic industry. Furthermore, its presence is fully established as there does appear to be a dominant design in the DSC product itself – in that a common set of features and architectures which broadly fulfill the needs of a wide and diverse set of customers defines the product class. However, there is no single dominant use pattern in consumer digital photography at the system level, which still very much exhibits the patterns of a fluid stage of innovation[49]. In industry after industry and market segment after market segment, users are still in the process of defining the use pattern of the products.

Thus, it seems that the level at which we analyze the product makes a difference on the stage of innovation or evolution which we attribute to the industry. Components and subsystems as described in the previous section appear to be in a continuous state of innovation; keeping aligned with independent

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[46] Christensen 1997. Note that the main point of the book is not the definition of disruptive innovation so much as it is the difficulty that incumbent firms have in making the transition because of the low performance and profitability of the innovation and its initial market focus.
[47] Christiansen himself points out that the DSC does not fit the model in a 1998 interview with Amazon.com's Harry C. Edwards. see http://www.moneyhaven.com/entrepreneurs/innovate.html . Although in the introduction of his book published the previous year, "Digital photography" vs "Silver halide photographic film" is listed first in a table of 24 examples of Disruptive Technologies. See Christiansen 1997, pg xxv.
[48] Personally, I think that Christiansen mis-analyzed the DSC story. As described in the previous chapter, the DSC first made its inroads into the photography market in the studio and doc-photo markets, where the digital paradigm was in fact cheaper and simpler than the traditional work-flows when considered at the right level. The move into the consumer market is more problematic, but if one considers cheap e-mail and web DSCs as the on-ramp for the consumer market, then time may bear out his theory in the photography market as well. One can't always identify a trend until it happens...
[49] This will be covered more later. See :Chapter 4: Patterns in the Dynamics of Technology Innovation.

evolutions in external systems, incorporating improvements, driving cost down and quality up[50]. As we demonstrated in Table 5, above, the DSC itself as defined by its external features has been largely well defined and is also in a stage of incremental innovation improving price and performance. However, the improvements are progressing along at least two dominant trajectories, digital photography as a replacement for film photography on several levels and digital photography as a communication capture device for the computer, web and e-mail. The split is evident in the product introduction map in Figure 6, where the largest single resolution class has remained at 640x480 pixels, primarily suited and intended for e-mail and web applications, while a second grouping marches up annually with higher resolutions, presumably targeting publishing and photographic applications. There are indications of new minor trajectories emerging as well in the very low-resolution products, but they will be covered later.

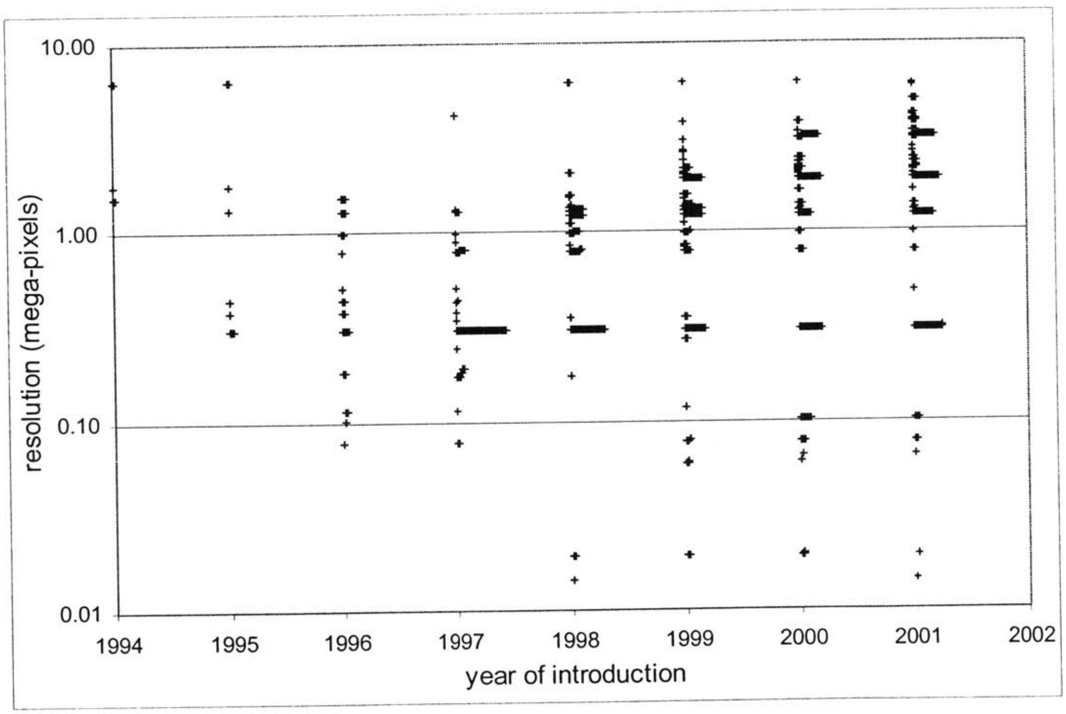

Figure 6: New DSC product introductions by year and resolution[51].

The DSC itself, particularly at the low end, is quickly approaching a commodity product[52]. However, the lack of a compelling dominant use model in "digital photography" itself has kept the larger digital

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[50] Rebecca Henderson made an extensive study of photolithography technologies in the production of integrated circuits showing generation upon generation of technological discontinuities driving process improvements, which drive the cost and performance of the semiconductors at the base of most of the disruptive innovations today. To the extent that the discontinuities at one level are incorporated in such a way as to not disrupt the interfaces between components and subsystems at a higher level, a complex hierarchy of technology can exhibit multiple patterns at multiple levels or layers without disturbing the others. However, it may prove an interesting thesis topic to delve deeper into these cross-layer dynamics. There may be an interesting story there in the context of the CCD/CMOS battle unfolding today.

[51] Compiled from the modified Lyra database of DSCs. Each camera is represented by one cross mark, and long bars represent multiple introductions at that resolution in that year. The 2001 entry for 0.3 megapixels is 25 entries.

photography market in a fluid pattern[53]. Competitors in the market are focusing on the applications and network externalities in an attempt to carve out a profitable position in the value chain, which begins with, but is no longer defined by the DSC. The dominant paradigm for "sharing" and/or "printing" has become the hot battleground for profitability. It is suggested here that while the application environment fails to achieve a specific pattern there will be uncertainty in the future growth of the industry as a whole and the value of the complementary assets of today's dominant competitors.

Storage – the sleeper function

What will become the standard for "store" for all these new digital images? This aspect of digital photography is often overlooked, but may prove a critical element in long-term adoption. The answer may depend to a large extent what becomes the standard for "share" – electronic or print form. Digital photographs have incredible immediate portability across space, but lack permanence. The electronic digital photo has the potential to become both instantaneously ubiquitous and as transient as the moment captured. The print, in its present conventional form is relatively stable and accessible in its archival form to the extent that most consumers take it for granted. Consumers are very comfortable poring over a photo album or leafing through an envelope of vacation photos[54], but do not typically gather round the computer terminal socially. Newer output technologies such as inkjet and thermal media are improving in archivability, but typically still fade over time[55], though it will take some time for that reality to sink in.

There are wide varieties in usage patterns among photographers, even in traditional markets. There are those camera enthusiasts who value the creativity in taking the photograph more than the resulting print. Others take photos for immediate or delayed social sharing and get joy in giving the photos away. For many users, photographs are an important record of personal and family events, and a mechanism to bring the family together. They serve to both communicate and as a memory aid. Many photos are viewed only once, typically after receiving the prints or several times over the short term. Other photos have, or through circumstances attain, emotional value, are kept into one's old age and are often passed to and valued more by subsequent generations.

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[52] see also Figure 9 on page 61 and Table 9 on page 66.

[53] This is not to suggest that the traditional photography markets are not highly segmented and without flux. Certainly one would expect differences in use patterns from a serious hobbyist that spends $1000 on a nice SLR from my mother-in-law with her $20 focus-free point-and-shoot, who takes hundreds of family photos but always manages to cut people's heads out of the picture. Nonetheless, both use the same film technology and print process.

[54] The vacation slide show lamentably saw its demise over the last few decades when a generation of consumers raised with video games and a remote control to access 50 channels realized the torture of a presentation medium whose rate of progress was beyond their control.

[55] Early problems with fading over a long period plagued the first instant films. Polaroid addressed these shortcomings early on, but those that promote 35mm over instant photography still cite it as an concern.

The electronic form is problematic in the long term due to the relatively short popularity half-life of electronic storage media (i.e. tape, hard drive, 5.25" floppy, 3.5" floppy, mini-floppy, zip, magneto-optical, CD, DVD, mini-disk, FLASH, etc.) and file standards, compared to the lifetime of people who rely on photographs as a preserver of memories as opposed to as a communication tool. Businesses that rely on electronic images will have databases and IT departments to manage changes in technology, and there have been a number of companies started to provide image storage, sharing and archiving for consumers – often for free. However, many of these companies went under with the Internet bust, a possibility that threatens the loss of the images. Others have had to start charging for their services. This may make sense for those who require remote access for business access, but any charge is more expensive than the cost of keeping a photo album or shoe-box full of pictures around the house for home use, and few services offer more security.

Photographs, for many consumers, carry an emotional attachment and comfort as a repository of memories. To the extent that photographs in the digital age do not get relegated to the transient, this need will still have to be addressed, and may prove a compelling argument for traditional print fulfillment of digital photographs.

Why choose digital photography?

Many of the reasons for a user or user group to switch to adopt digital photography were covered in the historical coverage of the industry, but are summarized here for clarity. The positive attributes of digital photography compared to conventional include: immediacy of output, potential raw materials cost reduction (i.e. total cost of ownership), immediate image verification, rapid sharing, image reprocessability[56], mutability and re-use, and the novelty or high-tech factor. The negative attributes include the higher price of DSCs themselves, the higher level of complexity that results in poor ease of use among the less computer literate, lower image quality compared to film, and less pervasive channel penetration. While the trend in the negative attributes is towards convergence with traditional photography, in the fundamental limit they are unlikely to meet. This suggests that in the long run, while digital photography will continue to erode traditional film markets while building the computer imaging market, it is unlikely in the foreseeable future that it will fully displace traditional film photography.

Comparison of Image Quality

Dynamic range describes the ability of the media to capture details from the brightest highlights to the darkest shadows. The best photographic films have a dynamic range of roughly density 3.6, which translates loosely to 12-bits in a linear digital space. The best consumer level CCDs typically register less

[56] Reprocessability is defined here to mean the ease with which the images can be edited, modified, and reprinted.

than 10 or 11 bits. The high dynamic range can be important to professional photographers, however the typical scene captured by consumers has less than 8-bits of dynamic range[57], and the gamut of most print media is far lower still.

Resolution describes the ability of the media to capture image detail. In practice, it is highly affected by the optical system that creates the image, but where optics are not the issue, the limit is dictated by the fine grain structure of the capturing media[58]. For film, the size of the silver-halide grains dictates ultimate resolution. It varies widely with various companies' emulsions and film speed. However, a typical 100-speed 35mm film at medium contrast has a resolving power of roughly 65 line-pairs/mm. There is no direct analogy, but this can be crudely compared to 130 pixels/mm, which would be equivalent to a 14-megapixel sensor for a 35mm sized frame. However, here again, a 1-megapixel DSC is typically regarded as having sufficient resolution to create an acceptable consumer-quality photographic 4x6 print, so it can be argued that conventional photography is guilty of technological over-performance. In the context of e-mail and web postings, the popular 640x480 VGA resolutions, which have only 0.3 megapixels, provide a good compromise between image size and quality.

Comparison of Costs

In the year 2000, revenue from sales of conventional cameras was equal to DSCs according to a report from PMA. Volumes were ~5:1 conventional:digital excluding single use cameras. While highly unscientific, this suggests an average 5:1 price premium for a DSC. The product mix for DSCs is probably biased more towards the high end than conventional due to the lower market penetration, which is biased towards early adopters who will tend to be biased towards the higher-end products. This is born out in a quick check of the Sunday circular advertisements, which shows the lowest end DSC's in the $30-$50 range, while you can buy a re-usable 35mm camera with film and batteries for $6 or less[59]. At higher price points, a given DSC costs 3-5 times a similarly positioned conventional point and shoot camera. At the professional level, a digital back can add $10-$20,000 on top of the cost of the camera body and lenses. See Figure 9 on page 61 for a more complete competitive landscape.

To be fair, the total cost of ownership, or TCO, would include film and development costs for conventional photography, and for digital includes print or media costs, and perhaps batteries and

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[57] This excludes specular reflections, which are typically clipped or saturated on both traditional film and in DSCs.
[58] This may not be the case with some of the finer 2.5 and 3 micron pixels in the finest geometry CCDs. At these sizes, diffraction limited optics become necessary to avoid restricting resolution optically, and even then, apertures must be opened up, losing depth of field for resolution. This is one of the reasons why there is a market for 24x36mm 8um pitch CCDs at the high end, and why the industry reserves its finest pixel pitch sensors for the video market where image quality is less important, and not still photography market.
[59] In the latest Boston Sunday Globe circulars 12/1/01, there were offers of re-loadable 35mm cameras "free" after mail-in rebates. The offers included a roll of film and batteries.

memory storage cards. However, this is very much a use issue, and the use demographics of the digital camp are still very much in flux. Regardless of the TCO, there is the general tendency of consumers to be more sensitive to up-front fixed costs than deferred usage cost. Per print, conventional output is cheaper than DSC, but the expectation is that far fewer exposures per capture are printed and print prices will likely converge with increasing digital print volumes[60].

Customer Segments and Factors for Product Adoption

Companies selling both traditional and digital cameras and accessories segment the market in order to focus products and features against classes of customers. Products tailored to the different segments differ not so much in basic architecture, but in levels of sophistication, quality and features. Much of the segmentation attempts to build on the parallels with traditional photography.

Budget buyers: web appliance and toy camera users: The primary use for the digital camera in this group is to post snapshots on the Web, e-mail them to friends, and perhaps print them in small sizes. These are buyers of cameras in the price range of $30-$150, and currently with about 640x480 pixels. Some of these cameras are specifically designed for kids, and are called toy cameras because of their low price and quality, and because they are marketed by companies like Tomy and Mattel[61]. These users naturally care a lot for the price of the product, and image quality is relatively low on their priority. This segment is relatively new with the digital cameras[62], and constitutes the low-end and largest volume segment of the market. In the context of traditional photography, this market might be the biggest threat to that portion of single-use cameras that are used for quick documentation or what might be regarded as "throw-away" images. It may also be that this market can co-exist as a separate entity from photography altogether.

Mainstream: This segment would in the conventional cameras segment be buyers of regular point-and-shoot cameras. When this segment buys digital camera they currently have to spend more money on a digital camera than they otherwise would have spent on a conventional camera. This segment is itself highly fragmented. It includes family photography, whose main use is to take snapshots to e-mail to friends and family, post on the Web, or print in sizes smaller than 8 by 10 inches. For this group it is important to have a DSC that is easy enough for the whole family to use – in other words usability is high

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[60] An informal survey shows digital prints cost $0.39 to $0.49 apiece from on-line services while a roll of 24 can be developed and printed for $6 to $9 for 4x6 double prints, which is only $0.13 to $0.19 per print or $0.25 to $0.37 per exposure. Many photofinishers are providing scanning services for conventional film as an option with developing.

[61] The use of the term "toy" could also be to denigrate the products by the makers of "serious" cameras.

[62] Many industries seem to have recently discovered kids and teens as demographic with very high spending power or influence there-of. Polaroid's I-zone instant camera is an example of an extremely popular "conventional" camera expressly made for kids that hit the market coincident with the take-off of digital photography, but managed to be the highest volume camera model on the market for several years straight.

up on the priority list, along with price. The price range is between $200-$400, and currently with around 1-3 megapixels. It also includes students, whose the use pattern is similar to the family segment, but are less sensitive on the usability, and perhaps rank lower on emotional attachments to photographs. Many of them are very computer literate, and like experimenting with new gadgets. A camera with video capability is often wanted. Also included in this group might be small offices and businesses.

Amateur photographers/hobbyists: This group covers those in the conventional camera market from the upper end of the mainstream consumer to semi-professional SRL user. To this segment, the image quality is very important, and so is the flexibility in operating the camera manually if needed to achieve the desired creative results. The users purchase accessories and different lenses and tend to turn to the more traditional camera makers for their new digital camera. They desire creative control over not only the taking of the images, but spend more time processing, manipulating, enhancing and re-using the images, and demand high quality in the final output, be it electronic or print. The cameras in this segment start at around $400-$600, with 2-3 megapixels or more.

Professional segment: The professional segment goes after the more serious of the hobbyists amongst whom money is even less an issue and to those earning their bread and butter in commercial, studio or freelance photography. Systems here range to several thousand or tens of thousands of dollars and encompass a broad range of specialty and niche markets. Here, too, there is a large installed base of traditional equipment, and offerings in this segment include high priced linear and area digital camera backs to leverage the heavy investment this group has in optics and systems. This group drives the high end niches of the market.

What are the factors and important elements that promote or inhibit growth of the digital still camera market? The issue is made more complex with the fact that digital cameras really are parts of a whole system that require many elements. With the conventional camera, all you needed was the camera itself, film and to deliver the film for developing. The digital camera however, usually depends on being hooked up to a computer, requires different skills for printing and possible sharing over the Internet. From this follows several factors that will continue to have an impact on adoption. The issues that most often have been discussed as important elements are:

1. Falling costs and rising performance of personal computers. As having access to a PC is today perceived as necessary for most digital camera owners, the penetration of PCs will influence the number of potential buyers.
2. Falling costs and rising performance in color printers and digital cameras.
3. Improving ease-of-use of software and applications for editing pictures, displaying the pictures on a screen, and electronically sharing.
4. Continued penetration of internet access outside of the office environment.

5. Broadband, wireless and "3G" networks. Increased connection speed will make downloading and uploading pictures less time consuming and increase the enjoyment of picture sharing. The online photo finishing services are today, to a certain degree, inhibited by the painful upload of pictures. As more devices that combine wireless access and picture taking show up, fast wireless connections may open up new ways of instantly sharing pictures with friends and family.
6. The widespread emergence of digital mini-labs and digital photo printing kiosks in local communities. This market is just starting to appear, largely in response to the popularity of DSCs. It is hoped that this will help promote the DSC to users who do not own or are uncomfortable or inconvenienced using personal computer based imaging solutions.

Today's solutions for digital cameras, as mentioned above, predominantly still require hookup to a computer. Greater penetration of digital cameras beyond this barrier will be possible to achieve once systems are developed that eliminate the computer as it is today. HP introduced solutions for computer-free printing to its inkjet printers, and most of the other market leaders have quickly followed – each typically with their own custom printers sold as "accessories" to their DSCs[63]. In addition, Kodak has introduced a line with a permanent base station attached to the computer, in which the DSC sits to charge its batteries and automatically transfer images. But this is just the beginning. There are many opportunities for developing systems around digital cameras making the use of them as easy as for conventional cameras. There are new direct modem and wireless offerings[64], and new living room appliances for displaying the pictures on either TVs or novel digital picture frames as are being sold by Polaroid and Sony. There will be advanced software running in the background, enabling printing and sharing, however this will be transparent for the user. Much of this depends on the ubiquitous computing paradigm being promoted in the industry today. This may further the technology adoption, but probably only with the technologically advanced and early adopters. The majority and laggards will probably not see this technology, and will require another operational paradigm for the widespread adoption of this innovation.

[63] Direct connection to printers is becoming more in vogue recently, typically with matched camera and printer systems. However, it should be noted that this is not a new idea. Ricoh offered a dye-sublimation printer back in 1987 that connected directly to its RDC-2 camera.

[64] One of the interesting services promised by the integration of digital photography and wireless network communication is the use of an "always on" networked DSC or video camera as a personal security device and deterrent to crime. A person wearing this device could immediately broadcast their location and the identity of an assailant before the crime even started.

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Chapter 3: Four Market Leaders: Four Approaches: Four Strategies

One of the creative aspects of a technological discontinuity, or disruptive innovation, is that it provides the opportunity for a redefinition of roles and participation in an affected industry. The conventional photography industry has largely been in a specific state for decades, characterized by no real change in participation and battles primarily between established competitors for distribution of market share based on incremental innovations. The emergence of digital photography provided the opportunity to redefine which key competences would command control of the market and the value of the complementary assets of the traditional players as well as new entrants.

The dominant players in the DSC market today fall into 4 broad categories:

1. The traditional silver halide *film* companies
2. The traditional higher-end 35mm *camera* companies
3. The consumer *electronics* companies
4. The inkjet *printer* or "new media" companies.

Each company and category brings different competencies and vulnerabilities to the market. Some were pioneers or explorers in the technology and others patient exploiters. The first two can be broadly considered defenders and last two attackers, though we will later question that distinction. While one might speculate that one group or another would dominate based on their background, what we see instead is that the four US market share leaders and protagonists, Sony, Olympus, HP, and Kodak each fall into a different category.

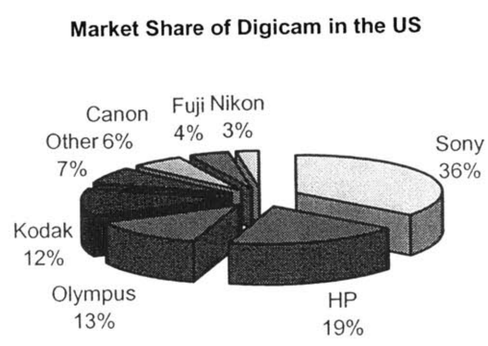

Figure 7: 2000 Market Share in the US for Digital Still Camera Source: PC Data

Each of the four market leaders has arrived at its place in the present market from a unique origin and with a different technology/market migration. Today, all four are strong players in the market, with broad product-line offerings suggesting strong product platform strategies. All reach beyond the digital cameras themselves to offer a variety of auxiliary products and/or services in recognition that the DSC is no more

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than a component in a solution of communication through imagery. Nonetheless, all four have come to share market leadership. The graph above shows the distribution of market share as of early 2000. Sony is by far the undeniable market leader. The actual market share is highly volatile over time, but Table 11 in the appendix shows that these four players have been significant contenders for several years.

Four Leading Market Players

Film & Processing – the old media:

The film companies, which are the primary defenders, have had to face internal battles on the allocation of resources between conventional and digital imaging. The film markets still dwarf digital, so they must take a dual strategy of adopting the new while maintaining market share in the old. Kodak is the predominant competitor here, but other members of this group are Fuji, Agfa, Polaroid, and Konica. Kodak, has traditionally been a very vertically oriented company, to the extreme of raising its own cattle to ensure the quality of the gelatin for its film, and it has approached digital photography in the same way. However, it gave up the manufacture of its conventional camera very early in its history when they could be produced better and more cheaply elsewhere, and retrenched to the domination of film and processing.

Kodak has taken a broad and ubiquitous leadership approach in digital photography, with recent annual investments of $500 million in R&D associated with digital photography and services alone. However, it has been criticized for lacking focus and delivering over a decade of losses in digital. The company has followed the previous move in outsourcing conventional cameras by announcing the outsourcing of all manufacturing, including digital cameras earlier this year.[65] This might not be a bad strategy as digital cameras approach commodity status. Kodak will no doubt continue to brand and sell digital and conventional cameras, leveraging the power of the yellow box. But its real challenge is to maintain access to and dominance of the image output business. Its strategy here covers both web-based and traditional photo finishing, it's mini-labs and popular point of sale photo-kiosks, and its offerings of photo-quality inkjet papers and high end silver printers. This is considered both a growth opportunity and a serious threat to Kodak, as conventional film has been a relatively flat business for decades and is expected to decrease within a few years due to the growth of digital. Nonetheless, Kodak's level of investment in this digital imaging is probably unrivaled, making big bets and taking big risks, but making it a real shaper of the markets that will definitely determine its future.

More than any other single competitor, Kodak has driven the standards and protocols to promote digital photography at the network and systems levels. They were founding members of the 'Photographic Imaging Manufacturers Association' or PIMA, the 'Digital Imaging Group' or DIG, and the

[65] Kodak owns a 51% stake in the Japanese company, Chinon, which manufactures the majority of Kodak's low and mid-level camera offerings already.

'International Imaging Industry Association' or I3A, which formed from the merger of the first two. They have developed and promoted standards such as: PhotoCD, JPEG2000, DIG35 and FlashPix file standards; ICC color profiles; the 'Digital Picture Order Format' or DPOF; the 'Picture Transfer Protocol' and 'Internet Imaging Protocol' or IIP. This might be viewed as altruistic, if it were not Kodak's primary strategy to channel digital images to their centralized output. Isolated compatibility between individual cameras and home printers can provide local solutions to individual customers, which could play well for HP or Sony, but to truly grow the market for printed output, Kodak realizes the strength and need for standards which will allow them to make better prints from *anyone's* camera, and this plays into its strength in image science and processing.

For Kodak, printing and output of images from digital source was in fact quite competency enhancing. They are arguably the leaders in transforming images taken under an incredible gamut of conditions on some incredibly poor cameras by incredibly unsophisticated users and producing decent pictures. The competency destroying element or threat was the loss of the film. It is therefore not surprising that one of Kodak's early focuses was on the development and sale of the CCD imagers, the single highest value component in the new technology and the direct replacement of sensitized film.[66]

Kodak's key threat is the prospect of a world of print-free photography. Its present play is to dominate output through different venues – central print and distribute, traditional and new digital mini-labs, photo kiosk, home printing inkjet specialty papers. They know how to make good pictures better than others. Roberts suggests that in situations of new markets and new technologies, various partnering and acquisition strategies are appropriate[67]. Kodak has good partnering skills and has leveraged them to complement its strengths with the appropriate and timely knowledge from the broader industry. Market access partnerships have included:

Kodak – Apple (DSC as computer peripheral)
Kodak – AOL (DSC as web-based input device)
Kodak – Scientific Atlanta (DSC as home web-based input device via cable)
Kodak – Sprint PCS (DSC as wireless input device)

The early effect of digital photography has grown the total output market, but predictions are for erosion of traditional based on parallels to historical trends, so it will need to find a way to replace the lost revenues. Based on its early struggles and high investments, Kodak may be losing stamina for the

[66] It has only been in the last year that Kodak's imager division has been allowed to freely sell its products on the open market. Previously, there was a policy against selling to companies that competed with Kodak. This has no doubt hampered its ability to make competitive sensors. In 2000, annual sales of CCD and CMOS sensors hit $40 million as reported by Kodak's sensor division - a relatively small amount when considering that Sony sells 3.8 million area sensors (units) monthly.
[67] see Roberts and Berry 1985

continued battle on various fronts. Kodak has not been able to take the same market lock in sensors that they did with film. Its first DSC's were professional models built on Nikon and Canon camera bodies and lenses. It has pulled back on manufacturing and suggests that it will not produce its own cameras in the next transition, but will need to drive the demand for prints in order to sustain its output and survive.

The extensive investment in intellectual property has been strategically important for Kodak. It exercised rights to some critical DSC patents earlier this year, and has been able to leverage them as a bargaining tool for cross-licensing agreements that stipulate that 'Print@Kodak' services will be included with other companies' digital cameras. Both Sanyo and Olympus[68] have recently entered cross-licensing agreements with Kodak. This is a significant step for Kodak, since it needs to find the means to capture the digital photo printing market in the future.

Camera:

The camera companies, like Olympus, Canon, Nikon, Minolta and others, have a history of making high quality cameras for the professional or serious camera hobbyists. Thus, to them, the DSC simply represents applying new technology to an existing market and customer base. Canon first put a microprocessor in one of its cameras in 1976. The following decades saw incrementally more electronics packed into cameras to automate the exposure, focus, advance, and flash, with more sophistication culminating recently in features such as tracking the photographers eyeball to optimize focus location. The step to replace the film with a CCD sensor and the cartridge with a memory card was not a particularly difficult transition, but one that can be viewed as evolutionary and that builds on their existing competencies in precision mechanics, fine optics and microelectronics. This was a necessary step in order to fulfill demands from their brand sensitive customers. These are the companies that have maintained a dominating presence in the conventional SLR and higher end point-and shoot market. They will probably maintain their high-end, high margin focus and not progress down into the larger mass market any more than they did in the lower end of the 35mm market. However, just as in the conventional 35mm market they may see more and more competition from Taiwan, Korea, China and others in the far east as the low-cost manufacturers get better at making their products.

Thus, the key for Olympus, Canon and the others will be to maintain a stronghold in the mid and high-end photography, whether conventional or digital. This is definitely not a real growth strategy, and will probably not play in the new low-end "disintermediated" markets. On the other hand, unlike HP and Kodak, they do not depend or count on revenues from media to maintain their market, so the switch from conventional to digital can potentially be viewed as an even exchange. The real issue here is whether the

[68] The Olympus agreement also gave Kodak access to Olympus' optics patents.

proliferation of low-end throw-away images expands long term interest in photography, or whether we're just seeing a short-term interest boost in photography as a whole that will go away as consumers swing to other new gadgets. Are the buyers of digital camera today genuinely interested in photography, or do they enjoy the experimentation of a new media while ready to switch to new electronic gadgets when they appear? For the computer analogy, did the proliferation of the printed and electronic word through the computer age increase or decrease overall the business of publishing or novel writing?

Printers – the new media:

The inkjet companies, notably HP and Epson, are participating in digital cameras for the consumables. They are the next generation consumable media companies, in the great tradition of Kodak, Fuji and Polaroid. They stand to grow the entire market by increasing digital printing – focusing on their own inkjet printers in the home or office. HP was the first to guarantee color consistency between its low cost image capture and print products. It was the first to provide a means to print directly from a consumer DSC to printer without a computer. The opportunity is quite compelling. Text typically covers less than 5% of a printed page in ink and is done on plain copy paper for pennies per sheet. In contrast photos can be printed on premium coated inkjet photo paper at $1 per sheet or more, and the ink can cover the paper edge to edge, literally soaking lower grade papers.

HP could afford to lose money on its digital camera's to the extent that they increase consumables on the print side. They have done relatively well on a market share basis, but with relatively few products and have been more price aggressive than the other main competitors[69]. HP has a reputation for thoroughly developing their technology before bringing it to market, and in following a sound, broad platform strategy once they do. This was evident in their inkjet printers and remained so with the digital still camera. Their first 'PhotoSmart' camera product was a quickly designed compliment to the scanner and printer computer peripherals that it accompanied, but its later designs followed a serious platform architecture incorporating a common thoughtful architecture whose key components were bid out to the key sensor and IC manufacturers[70]. Their line of inkjets competes with laser jet technology in the office facing the same total cost of ownership challenge that digital photography posed to instant in the document photography market. Inkjet technology is more compelling in the small office/home office, or just in the home.

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[69] See Figure 15 in the appendix for a view of HP's products on the larger market landscape. Their aggressive pricing strategy may be to compensate for the lack of a solid brand connection with photography, or it could reflect their sourcing strategy.

[70] Since this was originally researched, HP withdrew production of its two flagship products based on a special CCD line made primarily for it by Philips. Their remaining lower end products are less impressive, but cost competitive.

While Kodak has seen most of its growing pains in the midst of the conversion to digital, HP went through its major transition earlier in the move from a test and medical diagnostics company into computers and peripherals over the last decade. It managed its separate businesses with financially, organizationally and geographically separate divisions. Its organizational structure allowed it to more easily make the targeted investments in the new technologies and markets. Also, unlike Kodak, HP has been able to do so with lower investments by specifying and buying key components and making strong vendor relationships rather than making heavy investments in camera-specific components technology[71]. This strategy, along with its more timely entry into the market, may make HP a more nimble competitor.

The key to their success is in building the use of the home printer *beyond* that of a computer peripheral, to additional modalities such as home photography operating with *or without* the benefit of a computer[72]. Interoperability between different manufacturers color input and output devices has been a major impediment to personal color printing even on the desktop, but by controlling both the input and output device, HP has a major opportunity to change the game. That much said, their opportunity with low-end imaging as it moves to PDA's, cell phones and direct networks may be a disappointment, but if quality in those devices exceeds the present levels, then it could still play. On the higher end, they have formed a joint venture with Kodak to try to bring inkjet solutions to the in-store digital mini-lab.

Consumer Electronics:

The consumer electronics companies, such as Sony, are strictly in the business to grow their economies of scale in hardware. Their DSCs share many of the same components with their digital video and audio products, and build on Sony's quality brand name. From Sony's perspective, the digital still camera was a natural extension from its camcorder and consumer electronics business. Sony provided the CCD sensors and the chipsets that drive them for all of their own imaging devices as well as those of many of their "competitors". The quality of their area and linear sensors has been highly regarded and considered second only to Kodak's in the industry on quality, but first on value. Their popular "Memory Stick" FLASH technology is shared across their video and audio products. For Sony, this is the magic "glue" that seamlessly ties together their cameras, printers and digital picture frames.

Sony's play in digital cameras mirrors its dominance of the consumer audio and video markets, where it masters the technology of the key components in the products and pursues a vertical hardware strategy within the products themselves, and does so profitably. Its apparent goal is the dominance and redefinition of the home entertainment market, in the process perhaps usurping the home computing

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[71] HP's R&D investments in these markets are estimated to be about 1/10[th] of Kodak's. HP's line of DSCs are manufactured in China, Malaysia, and the Philippines.

[72] HP and Kodak have partnered in a joint venture to develop inkjet-based digital mini-labs for in-store digital photo finishing.

environment from Intel and Microsoft. Their weakness in terms of digital still cameras tends to be more in the software and photographic sciences. They should be able to adapt to the CMOS transition[73], but may likely stumble and lose dominance in imagers and their present architecture with the rise of CMOS. On the other hand, Sony is also heavily invested in entertainment, audio and video content, and moving into networks, so they may be well positioned for the next generation.

Table 6: Sony's FD - floppy disk product line.

model	year of introduction	resolution (megapixels)	optical zoom
MVC-FD5	1997	0.31	1x
MVC-FD51	1998	0.31	1x
MVC-FD7	1997	0.31	10x
MVC-FD71	1998	0.31	10x
MVC-FD73	1999	0.31	10x
MVC-FD81	1998	0.79	3x
MVC-FD83	1999	0.85	3x
MVC-FD85	2000	1.23	3x
MVC-FD87	2001	1.23	3x
MVC-FD91	1998	0.79	14x
MVC-FD88	1999	1.23	8x
MVC-FD90	2000	1.63	8x
MVC-FD92	2001	1.63	8x

optical zoom shown against sensor resolution by year:

res \ year	1997	1998	1999	2000	2001
0.31	1x , 10x	1x , 10x	10x		
0.79		3x , 14x			
0.85			3x		
1.23			8x	3x	3x
1.63				8x	8x

Sony has a history of success in consumer electronics, which is exemplified by the case of the Sony Walkman. Susan Sanderson and Mustafa Uzumeri[74] did a case study of the Sony Walkman, and attributed their success to a combination of rapid model changeover, variety, and model longevity. In DSCs as well, Sony has been the most prolific brand of DSC's on the market, with 41 models introduced over the last 6 years as shown in Table 11 in the appendix, and the market share leader. The FD series of comprises one of three lines of Sony DSCs based on media. The FD series uses floppy disks, and the other two use Memory Stick™ and CD-R. Even after Sony introduced its own standard in FLASH cards,

[73] Sony, HP/Agilent and Kodak have designed and marketed CMOS imagers, but except for a few isolated cases, they have not integrated them into their own DSC's. Sony has explicitly stated its intention to avoid the low end of the market and to continue to charge a price premium for their brand name.
[74] Sanderson and Uzumeri 1995

the Memory Stick™ the FD series remained strong, especially in the US where the model MVCFD75 was the top ranked DSC by unit and dollar share as late as the first three quarters of 2001, and six FD series cameras made the top 25 list by volume. One of these, the MVC-FD73 was introduced back in 1999, which would have classified it as a "classic" in Sanderson's study. Looking at the table of Sony floppy disk models below, we see 13 models based on 5 sensor resolutions and 5 optical zoom configurations over 4 years. In spite of minor upgrades from year to year, several of the products show up repeatedly for two or three years in a row. Some of them have resolutions as high as 1.6 megapixels, whose uncompressed images are 3.5 times as large as the capacity of a floppy. Sony also has two other lines based on Memory Stick and CD-R storage media, many of which would share optics and sensors with this line, but which generally target the middle and upper ends of the consumer DSC market.

Paths to success

Each of these four market players has come to a dominant place in the market. As they are presently leading other similar competitors, their execution of strategy holds promises sound lessons. The paths are shown in the figure below. All four have some initial competence in either the technologies of markets of interest and valuable brand names. Kodak is shown with its bid to transfer its traditional photographic print business through a new digital capture technology. Olympus is translating its art of capture from a film output to a direct digital medium. HP is expanding its inkjet printer business from text and graphics into photography. Last of all Sony is extending its consumer electronics expertise and video technology to a new application.

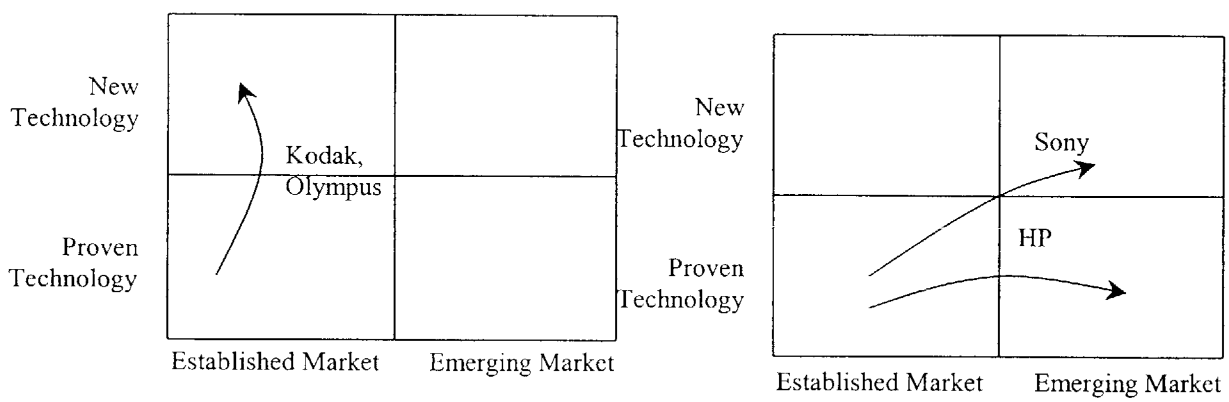

Figure 8: The technology migration path taken for each of the market leaders into DSCs.

All four are large, well established branded companies in their respective industries, and each has an impressive R&D capability. However, none can be singled out as the major innovator or inventor of digital photography. As discussed in previous sections, the DSC and digital photography brings together technologies beyond the scope of any one company or industry. The emergence of the DSC in photography does not represent a revolutionary innovation, but an integrative one, which brought technologies and subsystems developed for other distinct markets and applications together to serve the needs of several old industries in new ways. Marco Iansiti makes the argument that it is this capability that may be more important in industries such as this, and each of the market leaders has shown a proven competence in technology integration[75].

Table 7: Strengths and technical competence of market leaders

Competitor	Competence	Acquire/Borrow/Partner
Film: Kodak	image science, print delivery, sensor technology[76], software (developed), standards building, brand	Optics, electronics, computers and network solutions, competitive manufacturing
Camera: Olympus, Canon	optics, electronics integration, camera design, competitive manufacturing	sensors, software
Consumer Electronics: Sony	sensor technology, consumer electronics – vertically integrated, competitive manufacturing	optics, camera technology, software
New Media / Printer: HP	output, connectivity, computers and systems integration	image science, competitive manufacturing – almost exclusively OEM/ODM

The capabilities that the four market leaders brought to the table to develop the market may not continue to hold sufficient value as the product becomes a commodity. Each had some competence that was relevant on the product side during the initial growth of the market, however the number and nature of the competitors today indicates that much of the technology has become highly appropriable. The only competitor among this group of four leaders, which faces a significant competence-destroying aspect of the discontinuity, is Kodak - in terms of its strength in film chemistry. However, this can be balanced off by its image science strengths, which are transferable, and the potential for overall growth in demand of printed output with digital, where their print chemistry has been a major beneficiary. Contrast this with the instant film company, Polaroid, whose products were the earliest to be displaced by digital, and which failed in attempts to promote its instant film as an output media for digital capture.

Many other competitors that had supplied components or subsystems have made attempts to enter the market, though few have had significant successes without brand recognition. Examples include lens suppliers Minton optics on the low end, and Kyocera on the higher end with a very well regarded SLR level camera. On the electronics side, Hitachi, Mitsubishi, Sharp, Philips, Sound Vision, Intel, Panasonic and others have fielded reference designs and cameras in attempts to get their components into the products. Entry based solely on strength in individual components, especially when there are multiple substitutes and the firms lack other unique complementary assets, are not commonly successful.

[75] See Iansiti and West 1997. See also, Iansiti 2000
[76] Kodak, Fuji, and Polaroid each developed their own CCD sensor design and fabrication capabilities.

Other new entrants are OEM manufacturers, whose capabilities have been developed for better-known brands but then attempt to establish their own brands. Concord Camera is a good example of this. Teece and others cover the topic of appropriability regimes and innovators not capturing the value from their innovation[77]. He also questions the wisdom of contracting out manufacturing to countries where imitators are common and intellectual property is poorly protected. This may be especially relevant as the product enters the specific state where low cost manufacturing is the key focus of innovation. On the other hand, if companies like Kodak and HP are able to guide the shape of the systems in which the DSC operates so as to direct the output where they can extract a greater value, then it may be appropriate for them to cede the DSC business itself, as it becomes a commodity.

Convergence advocates argue that the next generation of imaging devices attached to or incorporated into PDAs or cell phones may augment or usurp the present groups' push into the broader market. New players from the telecommunications camp may be the market leaders of tomorrow. Already, Sharp, Mitsubishi, Samsung, Sanyo and Toshiba have introduced cell phones into the Japanese market that incorporate crude digital cameras. Sharp, Kodak and Handspring have sold DSC modules for PDAs. The next generation may see images (still photo and video) as a transient but instantaneously ubiquitous experience. If this next wave is more of a classic Christensen disruption, then all 4 of our top contenders today may be goners. However, it is our belief that there will still be various market segments that are differentiated based on performance, which will be provided by some of today's dominant players in those markets.

[77] See Teece 1987

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Chapter 4: Patterns in the Dynamics of Technology Innovation

There has been much study done on the evolution and disruption of markets, and the dynamics of technical innovation that drive them, in a wide variety of industries. The studies have revealed certain repeated patterns, which have implications on the nature of competition in an industry over time. This section is dedicated to illuminating evidence of some of those patterns in the modern history of digital photography. This is done to gain perspective into the present state of the industries evolution and, by analogy to the broader trends, provide some insight and predictors of the future trends.

Hypotheses

In the previous sections, we reviewed the history of digital photography, and established digital photography as a disruptive innovation to conventional photography. It was further proposed that a dominant design was evident in the product of the DSC, but that there was still significant innovation occurring in the broader systems in which the product is applied.

In spite of the fact that the industry appears to the consumer to be in a nascent stage, the author proposes in this section that the DSC industry has already matured significantly. The transition from the fluid state is several years old, and that the original entrants are facing further reductions in membership as the technology enters a specific state. The evidence suggests further that there are actually two product cycles in play, and the present dominant design has been subject to a technological innovation in its subsystems. This new innovation, specifically around CMOS imaging, threatens the present industry structure with a new wave of entrants just as digital photography starts to penetrate the mainstream market. As a result of this second dynamic, at least two of the four present market leaders show signs of imminently losing ground in the DSC market, and the others may be seriously constrained.

Methodology

This section takes another look at the history and present state of the DSC industry in the context of the "Dynamic Model of Innovation" first introduced by Abernathy and Utterback[78] and further developed by Utterback[79]. Data is presented that largely supports the model, but questions some aspects of it. The data is then looked at closer in the context of Clayton Christiansen's treatment of disruptive innovation[80]. On the basis of the models' fit and the determined state of innovation of the industry, we then discuss strategies for survival and lessons for and from today's competitors.

[78] Abernathy and Utterback 1978
[79] Utterback 1994
[80] Christensen 1997.

One of the more difficult problems in quantifiably analyzing business trends is coming up with a reliable and unbiased source of data. Many individual companies will provide background market data showing their own dominance in an industry, but when one digs into the statistics there is usually some creative accounting going on to either promote or misrepresent the companies competitive position for strategic ends. There are a number of independent marketing firms, which make a business of collecting and analyzing information for various industries, and then selling the composite data back to the member organizations. This data can be considerably less biased, though variations in methodologies and the sources of data can create significant distortions and reconciling the data from different sources is often nearly impossible. Moreover, access to this data is expensive and therefore often out of the budget for a master's thesis. Given the size of the traditional photography market, and the high hopes of the digital photography market there are several organizations that monitor and provide rich information on both, such as the Photographic Marketing Association[81], InfoTrends[82], and Lyra[83], which are cited throughout this work.

Sources of data

As an employee of the Polaroid Corporation, I had limited access to the Lyra web site through the company's marketing department up until September, 2001. In addition to supplying market research and analysis to the industry, Lyra maintains a database of digital still camera new product announcements by brand, announce date, introductory list price, and additional features going back to 1995. The data can be accessed via a search engine on the web by date or company brand, and for each camera they supply a link to a summary feature table for that camera. However, there is no method for extracting or analyzing the database as a whole. The website uses the common gateway interface, or cgi, protocol for extracting the data and building the html pages for each listing camera. By reverse-engineering their protocol, I was able to write a 2-phased program with National Instrument's LabView, to first acquire roughly 50 html pages of camera listings, then extract from these pages the links to 960 individual camera entries[84]. The second phase accessed each of the 960 individual camera html-based tables, extracted the 49 table entries per camera from the html source and built a new database out of the data. This data set served as a starting point for much of the analysis in this thesis. In retrospect, this was the easy part.

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81 www.pmai.org
82 www.infotrends-rgi.com
83 www.lyra.com
84 The author is indebted to Israel Ruiz, who took the time to demonstrate how he had similarly procured the data from the US Patent Office for his 2001 MIT master's thesis: "Pharmaceutical Technology Innovation: The Development of AIDS Drugs", using Visual Basic macros in a Microsoft Excel spreadsheet. Labview proved a simpler programming environment for this author, but the methodology was the same. If the tools are of interest as an example to future readers, I would be happy to provide them and any insights to those who contact me through the MIT Sloan alumni network.

Caveats

The raw data from Lyra was an excellent and serendipitous find for this effort, but in its raw form it left much to be desired. Many of the 49 table categories were not filled for many cameras. There were inaccuracies and duplications. The author spent a number of weeks cleaning up the database. For example, many cameras were listed multiple times due to multiple introductory announcements for the same camera; perhaps re-released for the Mac or PC platform. Other DSCs were introduced under different model names for different geographical markets, and in many cases this was explicitly pointed out in an "overseas equivalent" database entry. These were excluded, as were others that were obvious duplications based on comparisons of the 49 table entries and perhaps images of the cameras themselves. The author did not eliminate cases where multiple companies differently branded a common OEM camera, so for instance, one low-end camera may be branded 3 or 4 times by companies such as Agfa, Ricoh, Polaroid and Vivitar. This issue is one of the prickly issues with consumer electronics in general, where one company may do the OEM or ODM manufacture of a product and several others sell it under their own brand name. Roughly 8% of the cameras in the final listing fall under this category of multiple instantiations of roughly the same camera.

Nomenclature for several categories changed over the years, so the data types would require revision before any analysis could be done. New categories were added for some of the dominant design studies that were primarily interpreted from existing data. Many of the entries were not complete, and in some cases the author sought secondary sources to fill in missing data, particularly for more recent products that could be checked on the web or in stores. If uncertain, the data was left blank, so that some of the analysis could only be applied to a portion of the population. In these cases, results are reported as percentages to avoid confusion, so if a list price was not reported and could not be confirmed, then that camera was left out of any statistics or plots on pricing.

Pricing data for the analysis was not all in US dollars, especially where cameras were introduced only in Japan or Europe. The pricing data in the charts uses currency conversion rates on 9/1/2001, which may introduce distortions in relative pricing for some older products. In addition, all cost comparisons were done using the vendor's introductory suggested list price. Typically the list price greatly exceeds the street price, and does not reflect price erosion from year to year. Furthermore, different vendors use different pricing strategies for list versus street price. The price erosion from year to year is less problematic because the data shows that most of the bigger players renew their entire product line every year or two. Looking at any given brand's lineup from one year to the next, one sees repetition of many of the products, which will get a new model name, new skins and packaging, and a few minor feature changes or upgrades, and most importantly - a new lower list price.

The data set is only complete up to September 30, 2001. This means that there will be omissions for the last year and annual comparisons will be somewhat distorted. The author made no attempt to estimate the last quarter of this year by trend analysis, but let the data stand as collected. The data set also includes a mix of high-end professional camera backs, tethered scanning backs, and a few anomalous niche products. Where deemed appropriate, the analysis excludes these products to highlight the trends in the broader consumer market only.

After all of the sorting and searching, the data set was reduced from over 960 to 758 digital still cameras models. Given the extent of the reductions, one can be sure that there are still erroneous entries and omissions within. For the reasons just outlined, it is recommended that the data in this thesis be given credibility for highlighting qualitative trends and values, but not looked to as a scientifically accurate source.

The database did not contain any retrospective information about market share. The author hoped to perform some comparisons of feature adoption and strategy against success in the marketplace. The author did find various sources reporting market share by brand and in some cases product. However, the composite data is a mix of unit market share and revenue market share; rankings are US or worldwide. To illustrate the issue, in one source Polaroid was ranked 6th with a 3% unit market share in the US in the first ¾ of 2001, but had only 0.3% of revenues because it brands some very popular but very low-end cameras in the domestic mass-market channel. On the worldwide list from the same source, it did not make the top ten list, and from other sources covering the same year, it did not make any list. In addition, many players in the market have subsidized business models, so it is not always clear whether a company is profitable in a business line, even if it is selling the most products. Furthermore, some reports are based on factory shipments and others on sell-through[85], which could account for some discrepancy in a growing market. Some are based on limited distribution channels, so it is difficult to make conclusive claims. Most sources of market data were forward-looking, and included only 2-3 years of historical data and 5-10 projected. Several of these projections pulled from historical sources allowed the author to piece together a 6-year history[86], but the consistency of methodology between segments of data can be

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[85] An iMerge report from 5/2001 reports year 2000 DSC sell-through of 3.8 million units, while a Lyra report from 2/2001 reports year 2000 US DSC sales of 6.1 million units – presumably based on factory orders or shipments. For 1999, Lyra reports worldwide DSC unit sales of 5.5 million, while InfoTrends claims the number is over 8.3 million.

[86] Taking several snapshots of market predictions also gives one an opportunity to evaluate the market projections of the market analysts. In general, many of the estimates proved fairly reliable, within +/- 20% going out a few years if

questioned. Nonetheless, the scope of the following analysis is not intended to look quantitatively at the success of individual companies and products, but to look at the growth of the industry as a whole. For this purpose, the data is expected to be sufficient.

Dynamic Model of Innovation

The model of innovation introduced by Abernathy and Utterback describes a product, technology or industry progressing through a series of phases: a fluid phase marked by rapid product innovation and immature markets; a transition phase in which the market acceptance grows, a dominant design emerges, and the locus of innovation moves from product to tightly linked product and process; and finally a specific phase in which product and process are tightly linked, innovations are incremental and competition shifts to cost emphasis on highly standardized products. The characteristics of the three phases are summarized in Table 8, and discussed in context with the DSC industry below. *Italicized* entries represent the author's estimate of the best description of the present state of the DSC industry.

Table 8: Significant Characteristics in the Three Phases of Industrial Innovation[87]

	Fluid pattern	Transitional pattern	Specific pattern
Innovation	Frequent major product changes.	Major process changes required by rising volume	*Incremental for product and with cumulative improvement in productivity and quality*
Source of innovation	Industry pioneers; product users	*Manufacturers; users*	*Often suppliers*
Innovation stimulated by	Information on users' needs and users' technical inputs	Opportunities created by expanding internal technical capability	*Pressure to reduce cost and improve quality*
Product line	Diverse, often including custom designs	Includes at least one product design stable enough to have significant production volume	*Mostly undifferentiated standard products*
Production process	Flexible and inefficient; major changes easily accommodated	*Becoming more rigid, with changes occurring in major steps*	Efficient, capital intensive, and rigid; cost of change is high
R & D	Focus unspecified because of high degree of technical uncertainty	*Focus on specific product features once dominant design has emerged.*	*Focus on incremental product technologies, emphasis on process technology.*
Equipment	General purpose, requiring skilled labor	*Some subprocesses automated, creating "islands of automation"*	Special purpose mostly automatic with labor tasks mainly monitoring and control
Plant	Small scale, located near user or source of innovation	*General purpose with specialized sections*	Large scale, highly specific to particular products
Cost of process change	Low	*Moderate*	High
Competitors	Few, but growing in	*Many, but declining in*	Few; classic oligopoly with

we are to believe subsequent reporting. However, discrepancies between sources for the same periods occasionally differ by over 30%.

[87] Reprinted with permission from Utterback 1994. pg 94. Parts of the table originally appeared in Abernathy and Utterback 1978.

	numbers with widely fluctuating market shares	*numbers after emergence of dominant design*	stable market share
Basis of competition	Functional product performance	Product variation; fitness for use	*Price*
Organizational control	Informal and entrepreneurial	*Through project and task groups*	Structure, rules and goals
Vulnerability of industry leaders	*To imitators and patent challenges*; to successful product breakthroughs	*To more efficient and higher-quality producers*	*To technological innovations that present* superior *product substitutes*

For the most part, the DSC industry itself seems to be entering into a specific phase, as was discussed in the previous chapter. However, it does show some elements of the transitional phase, primarily in the areas of process, plant, equipment, competition and organization. Utterback covers some of the anomalies of his model in the same chapter of his book when looking at the abilities of Japanese industry to maintain low costs with high product variety among one or more product platforms and smaller production runs[88]. This issue appears particularly relevant here as well, given the dominance of the Japanese in this market and their apparent ability to maintain a broad yet competitive product line while renewing it almost annually. A good example of this is outlined by Sanderson in the case of the Sony Walkman[89], wherein flexible automation with "Sony Multi-Assembly Robot Technology" allowed them to minimize cost while maintaining the flexibility to change lines and designs frequently. Furthermore, consumer electronics in general, upon which DSCs are built, typically experience accelerated product life cycles, which would discourage producers from getting highly specific in process.

Innovation and Competition

According to the model, after the emergence of the dominant design, competition between firms tends to focus on price between what are mostly undifferentiated products. Segmentation of the market follows, with product offerings differentiated along fewer performance axis, but with a proliferation of offerings along those axis.

In the case of the DSC, product performance is mostly defined by resolution against price. Further competitive differentiation through performance is by optics quality and optical zoom, levels of sophistication in camera control, audio and video capture, software bundles and accessories. Competition by price is dominant[90], but industrial design, quality and brand can add value. Other elements of the dominant design are mostly common, except at the lowest end of the market or in niche segments. New

[88] See also, Womack, Jones and Roos 1990 and Meyer and Lehnard 1997
[89] Sanderson and Uzumeri 1995.
[90] A 2001 customer survey by Lyra ranked the top reported factors in the purchase of a DSC as: *1) Price*, 2) Brand, 3) "Total Package", 4) Resolution, 5) Image Quality, 6) Product Review, 7) Print Quality, 8) Storage, 9) Availability at purchase location, 10) LCD display, 11) Optical Zoom, 12) Product recommendation

product introductions by resolution were shown in Figure 6, and are shown Figure 9 below plotted against introductory list price. Higher resolution sensors and cameras appear every year, with the latest offerings displacing the higher tier products of the previous year, typically bundled with the higher performance features. The price is driven down for lower resolution products, which are either de-featured to compete more on cost, or features become democratized or common commodities[91]. The incremental performance-level innovations appear mostly as waves of new higher resolution products. The increased competition can be seen in the figure by the annual price compression of lower-tier products, which parallels what we see in the computer industries.

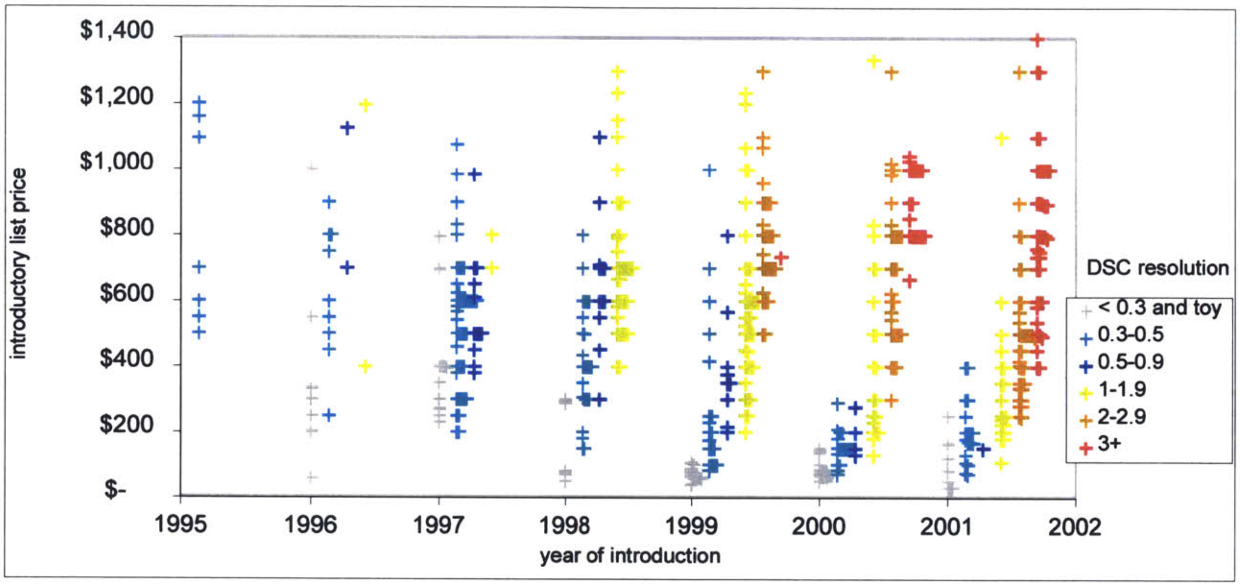

Figure 9: New DSC introductions by year, resolution, and price[92]

Competitors: Indications Based on the Number of Firms, Entry and Exit

Studies have shown a repeated pattern of entry and exit around a new innovation. Entry starts at a moderate pace, with the total number of firms growing rapidly as the market develops and peaking around the time of an established dominant design. After the dominant design emerges, exits exceed entries and the total number of competitors decreases, being dominated by a few major competitors. Utterback and

[91] Example of the relegation of what were once performance features to commodity status are the LCD displays, USB interfaces, basic image editing software, and even some of the zoom lenses. An example of a de-featured camera is the lowest priced DSC advertised in the Sunday 12/27/01 issue of the Boston Globe's circulars: a $25 Argus camera with unspecified resolution, fixed focal length lens and no LCD viewer or removable memory card.
[92] Note that most of the highest priced cameras in the "3+" category in the year 2001 are actually new 4 and 5 megapixel models. This explains the anomalous appearance of price growth in this category. In addition, there are a considerable number of products that were introduced at higher price points, but were arbitrarily cut off of this graph as the author considers these to be "professional" models. *** If this is a b&w copy, see Appendix 4.

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Abernathy originally proposed the pattern, and Utterback and Suarez illustrated the pattern for 8 industries in a 1991 study[93].

The Lyra database provides a good opportunity to investigate this pattern in the DSC market. For the purpose of this analysis, market entry was determined by the year in which the firm announced its first DSC product. Exit was more difficult to track, because firms rarely publish their intention to exit a market, and firms and distributors will continue to sell product as long as possible even after abandoning new product development or going out of business altogether. Nonetheless, it was observed that most active competitors would renew a good portion of their product lines annually. In only 8% of the cases did a firm skip one year without announcing a new product, and in only 2 cases out of 94 did a firm skip 2 years between new product announcements. Therefore, the absence of new product introductions after an active period in the market might be used as an indication of firm exit[94].

The results, plotted in Figure 10 below, revealed some interesting findings. When data for all DSC competitors was first plotted, it showed continued growth with several perturbations and one local peak for entries in 1997 and another minor peak in 1999. From a systems dynamics perspective, this suggests higher order interactions and greater complexity than suggested by the basic model. The author first sought correlation of the perturbations with external market events to no obvious conclusions. The entries were then sorted according to the sensor technology of each firm's first announced products. Most firms entered the market with CCD sensors before 1999. However, the majority of the new entrants in the last two years entered the low-end of the market with CMOS technology, which has a lower cost and quality. After sorting the firms thus, the classical Abernathy & Utterback pattern emerged for the CCD-based technology, with the CMOS-based entrants appearing as a separate emergent discontinuous wave[95].

This product-level discontinuity will be tracked further in later discussions. However, it is important to note here that the technological discontinuity does not appear at the consumer level. The DSCs made with CMOS cameras appear along the same continuum of products continuing the same trends as established by their CCD predecessors at the lower end of the market. At least in the DSC market, the impact of the CMOS sensor is fully encapsulated within the product itself. Tushman[34] would describe the sensor as a "core" subsystem, and to the extent that we see technological discontinuities in this context,

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[93] Utterback and Suarez 1993.
[94] Technically then, the author is using "lack of activity" as a surrogate for market exit. Similar techniques are employed in the field of bibliometrics, using publishing or patents to track active participation of firms and individuals, but the author acknowledges the possible sources of error here.
[95] Note that the data on exits for new firms entering with CMOS technology is highly suspect given that most entries are only 1-2 years old and have not established either a solid market foothold or a sufficient stream of products to be noticed in their absence. There are no really strong identifiable players in this newer technology segment yet, so any conclusions are tenuous at best. This will be best verified over time.

we would expect this to serve as a potential catalyst to disrupt the dominance of veteran firms in a classical Christiansen-style disruption.

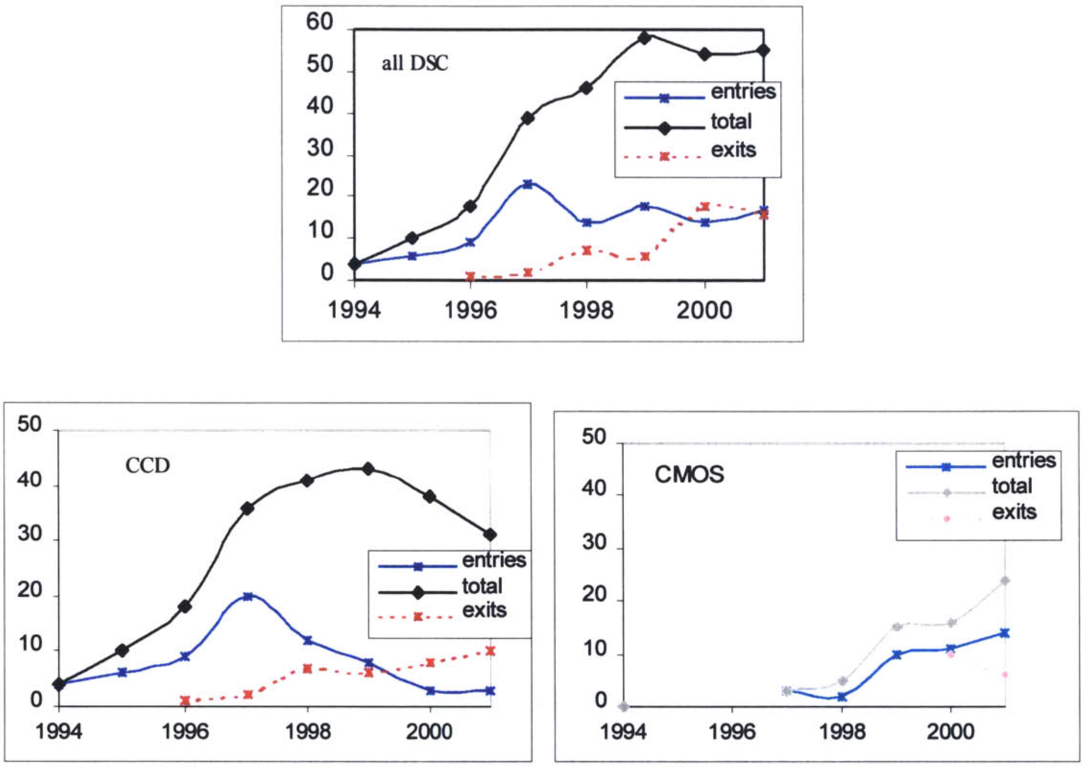

Figure 10: Entries and exits of firms in the DSC industry[96]

Utterback and Suarez[93] suggest that the period of greatest performance improvement accompanies the flood of entrants into the market, which is clearly 1997, and that cost reductions will peak during the period of exit. The peak number of entrants correlates with the same year that the last element of the dominant design exceeded the 50% model penetration mark as shown in Table 5. Figure 10 above confirms that the exits are just warming up, and cost reductions can be observed in the clumping of product entries on the bottom of Figure 9.

Looking at the data in Figure 10, the question arises whether the decline in the number of competitors in the CCD camp is due to competitive dynamics within the group such as crowding of the market, or is the result of a predatory move by the newer CMOS entrants. The CMOS sensor is a by-product of the push for competitive cost reduction. Certainly, there were indications of the future long before the peak of CCD firms in 1999 or even the reduced influx of firms in 1998. Back in April of 1996, Fisher-Price started to market a £40 monochrome 0.1 megapixel CMOS camera with a mini-thermal printer for output. It had no computer interface or storage cards, and it was never fully launched. A UK company

[96] See Table 11 in the appendices for a raw data on which these figures are based.

called VLSI Vision Ltd was marketing inexpensive CMOS sensors for toys during the same period. Looking at Figure 12, it appears that the first CMOS cameras on the market did not carve out the lowest performance or price points on the market. However, there were several very low-cost sub-VGA DSCs on the market in 1998, and over the next few years, the CMOS offerings began to totally dominate the low-end VGA and lower resolution segments of the market, while leaving the megapixel and higher resolutions alone. Margins in the lowest segment got so thin, that the big name players would not touch them. Whether CMOS will stay at the low end is yet to be seen, as there are at least three 1.3 megapixel CMOS sensors available now.[97]

Indicators of the Change from Product to Process Innovation

The emergence of a dominant design should accompany the shift from a focus of product innovation in the industry to one of process innovation, competition dominated by price over features, and domination of economics of scale. Looking for evidence to support this, we see in Table 11 on page 97 that the market leaders represent major brands with the capabilities for large scale production, though it should be pointed out that many of these branded entrants use OEM suppliers for their DSCs. The smaller players that had a role in developing many of the early commercial markets have either disappeared or have continued to focus on the smaller niches. Looking at the DSC itself, if you were to dissect the cameras on the market before 1997 or 1998, you would find a great number of discrete chips and components from dozens of manufacturers crammed onto printed circuit boards[98]. Today's products have much higher levels of integration with single chips of chip sets handling the majority of camera functionality[99]. At the very low end for a few specialty niches, single chip CMOS cameras, integrating the sensor, drive electronics, embedded processors, memory and computer interface are available today. These architectures deliver incredible value for their functionality but require lock-in to architectures and many performance features at the design level.

Another place we see a commoditization of the DSC market in the concentration of a majority of the DSC market volume originating from low-cost branded and OEM manufacturers in the Far East. The year 2000 Taiwan Photonics Buyers Guide listed over 20 OEM manufacturers of DSC's and over 20 more

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[97] The large number of entrants into the CMOS segment may be a bit misleading. Looking at the actual data in Table 11 in the appendix, we see that the majority of the "CMOS" firms have only a single product in a single year. Most of these firms are either toy companies or companies most people have never heard of. Hazard rates appear to be very high in this group, and if any survive, it will likely only be a very few. On the other hand, three-year CMOS veteran KB Gear achieved 5% unit US market share in 2000 with a single product, and has remained on the charts in 2001.

[98] With the possible exception of Sony, which has differentiated itself on the level of vertical integration in its electronics.

[99] LSI Logic's (now Zoran's) COACH camera on a chip, Sierra Imaging's Raptor, SoundVision's Clarity, Sony's image processing chip set, specialty DSC processors by Philips, TI, Analog Devices, etc.

listed for DSC lenses. Many or most Taiwanese vendors these days are supported by factories on mainland China. The Lyra database also contained an entry for 'country of manufacture' for each camera model. Unfortunately, over 32% of the entries were originally blank. The author hoped to differentiate Japan from the rest of Asia, but given the poor reporting in this category, chose to group Japan with Asia as a whole. To come up with a more credibly sized data set, cameras branded by Japanese companies are assumed to have been manufactured in either Japan or Asia. Cameras branded by non-Japanese Asian companies were assumed to be manufactured somewhere in Asia[100]. The author also visited a few consumer outlets and checked for labels indicating country of manufacture for many current models to fill in some data points of personal interest. All other "unknown" entries were left blank. The results, shown in Table 9, dramatically show the trend of manufacturing shifting to the Far East.

Table 9: Place of manufacture for all DSC models by year of introduction, 1993-2001[101]

manufactured in	1993	1994	1995	1996	1997	1998	1999	2000	2001
Asia	0%	6%	65%	45%	80%	79%	82%	88%	86%
US, Europe, Israel	100%	88%	29%	45%	18%	21%	13%	3%	3%
(unknown)	0%	6%	6%	11%	2%	0%	5%	10%	11%
model count	1	16	17	47	95	116	147	136	174

It is acknowledged that the shift of manufacturing to a location of possibly lower labor and tooling costs does not necessarily indicate a focus on "process innovation", so the inclusion of this data here may be misleading. However, it does indicate an emphasis on cost, and typically a shift from craft toward volume manufacturing.

Discontinuous Product Change

Periods of incremental change within the "specific" phase of an industry are brought to an end by the emergence of some "disruption" that puts the industry back into an era of ferment. The disruptions are not clean or distinct, but typically result in overlapping cycles for some period. Thus, the emergence of digital photography has not ended the evolution of conventional photography, and the emergence of CMOS sensor technology has not established the end of dominance CCD technology. Nonetheless, each disruptive emergence creates a new dynamic, uncertainty, and focus within all or some parts of the competitive landscape. The locus of highest growth rates tends to be associated with the discontinuity as well, though the discontinuity may spur growth in the both sectors, and the long term effects on the

[100] These assumptions were substantiated by complete agreement with 100% of the reported data, and seemed reasonable based on the author's own experience. For instance, Sony's cameras are all listed as either manufactured in Japan, or blank, yet Sony manufactures some of its consumer electronics in Taiwan and Malaysia.

[101] Source data was a modified version of the Lyra data set. Note that this selection includes high-end professional models, including camera backs. The statistics are for the number of models introduced by year, and may not be representative of the total volume or revenue associated with those cameras.

disrupted industry is not clear until the disruptive technology itself has entered the transitional or specific stages.

Technology Over-Performance

Christiansen's popular treatment of disruptive technology innovation the disk drive industry discusses the concept of technology over-performance. Firms in mature industries, in the process of catering to their most demanding customers and seeking higher margins, develop the product or technology beyond the needs of the common user. A new technology, one that typically performs poorly on the performance metrics of the mature technology, emerges, often from a remote market. The innovation typically has some unique attribute that makes it attractive in some niche market. At the time of its first appearance, incumbents denigrate the innovation and its market as trivial and inconsistent, which may in fact be the case relative to the bulk of their business. In time, the mature incumbents will gladly cede their lowest margin niches to the attackers as the new technology improves in performance. Over time, the new technology improves to the point where it eventually encroaches on the family jewels of the mature market, as the upstart organizations that introduced the innovation to the market follow their own need to grow their margins and move upscale.

As discussed earlier, the case of CCD-based digital photography has been cited as a counter-example to Christiansen's theory[102], primarily because the technology in the context of consumer photography, while it does perform poorly relative to film based on the previously prevailing criteria of resolution, speed and image quality, was not cheaper or simpler, but on the surface the cameras are more expensive. That point can be disputed if one looks at some of the commercial markets where this author contends digital photography is cheaper and simpler, especially when taking a systems level perspective. It is also counter to the model because several defenders of the old technology have apparently overcome the dilemma successfully and, in the case of the film-defenders such as Kodak, they had to adopt new value propositions. The technology did originally come from outside the industry, but many leading-edge customers of conventional photography demanded a transition and so conventional firms in many cases took the lead. While not "sustaining" in the context in which Christiansen uses the word[103], digital solutions were required by Kodak, Canon and Olympus in order to maintain their most demanding customers who would evolve with or without them. The early adopters of digital technology in the professional and commercial markets may have been "fringe", but they were not new customers, but the

[102] Christiansen himself stated that he didn't think that the CCD-based camera would disrupt the film industry, but that cameras based on CMOS sensors could in a 1998 interview with Amazon.com's Harry C. Edwards. see http://www.moneyhaven.com/entrepreneurs/innovate.html .

[103] See Christiansen 1997. pg xv: "What all sustaining technologies have in common is that they improve the performance of established products, along the dimensions of performance that mainstream customers in major markets have historically valued."

most demanding of film customers, and most creative and quality conscious of the camera customers. However, regardless of whether one accepts the total Christiansen premise, the concept of technology over-performance in terms of image quality is, and was, definitely a factor with conventional photography. The concept is graphically illustrated in Figure 11 below.

The trajectory of CCD-based digital photography is now well established. The latest premium sensor in Sony's consumer DSC product line is a 5 mega-pixel, 2/3" CCD that is featured in four different firms' DSCs on the market in 2001, all of which list over $900. In a conversation with a Sony CCD marketing manager, it was suggested that the 3 mega-pixel sensor was their single best seller in 2001 as it represented the newest hot performance point, but that the expectation was that 2 mega-pixels would be the sweet spot in the future. This intuitively makes sense because a well-designed camera with a 2 mega-pixel camera can take very good consumer-level photographs, and with the price compression trends in sensors, the 2 mega-pixel DSC will be cost-effective for the basic mainstream-priced photographic DSC.

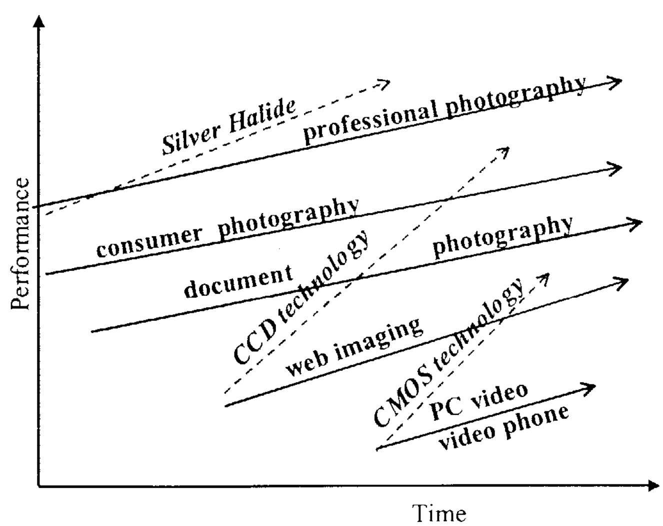

Figure 11: Technology trajectory map of imaging technologies and target applications.[104]

The interesting dynamic that is unfolding now is associated with the CMOS technology discontinuity. Christiansen predicted in a 1998 interview that cameras based on CMOS imagers, not CCD, could be

[104] It should be noted that this is a "notional" chart at best indicating trends. Performance in this context would be a combination of resolution and dynamic range. However, comparison with other presentations in this work should make it clear that both the requirements of markets and the capabilities of the technologies applied to them are far broader and complex than suggested by the chart.

disruptive to the film industry[102]. In this paper, the author has viewed the *CCD*-based digital photography as disruptive to the film industry – primarily from the business and commercial markets, and the CMOS-based DSCs as disruptive to the CCD-based competitors. Christiansen simply puzzles over the role of the CCD-based cameras because they do not fit the model, and skips to the CMOS products. In either case, the CCD phalanx that is now successfully plowing into the consumer photography market is seeing its flank attacked by the new low-cost CMOS products being manufactured in the Far East. CMOS imagers first appeared in niche markets for toys, "photo-phones", wrist-watch cameras, pen-based cameras, web-video cams, hybrid audio MP3-enabled DSCs, and PDA-attachments. Most of the market leaders are concentrating on the higher end of the DSC market in order to preserve or grow revenue and margin. Even though the components divisions of Sony, Kodak, and Agilent[105] all make CMOS sensors, they have disproportionately few offerings in that segment of the market. Christiansen argues that in order to be successful in overcoming the transition, a company should spin-off or create significant organizational separation between those responsible for the new from the old. In support of this, there are several companies, with which this author is familiar, that have roots developed in Kodak and Polaroid, that are pursuing CMOS imaging components and products. The case of Crystal Digital described in the next section may be an example of this[106].

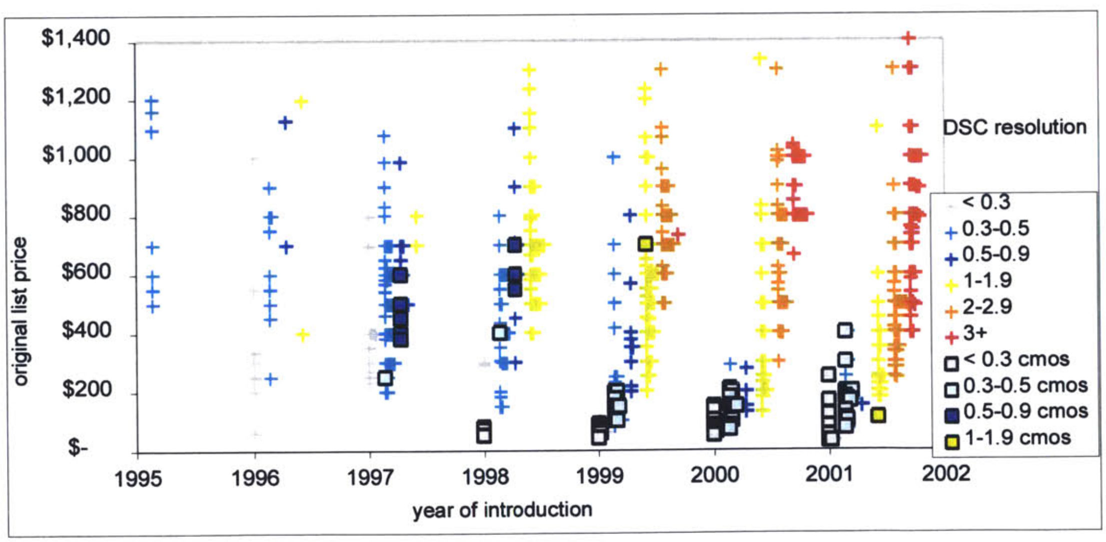

Figure 12: CMOS DSCs on competitive landscape

[105] HP spun off Agilent Technologies in 2000.

[106] Another good example is start-up Kodak spin-off Foveon, which developed two 16-megapixel CMOS-based professional camera backs and is working on some interesting advanced CMOS technology with backing from National Instruments.

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As we see in Figure 12, CMOS-based DSCs have come to totally dominate the lowest resolution end of the market, which are those DSCs primarily used for e-mail and web applications. The resolution split above and below a mega-pixel, with a void around the 0.8 mega-pixel range that was observed in Figure 6, is shown to be heavily demarcated by CMOS vs. CCD in 2000 and 2001. The CMOS-based cameras are just beginning to work their way up-scale with the single mega-pixel data point in 2001. Comparing this to the focus of today's DSC market leaders in Figure 15 of the appendix, it is clear that they have largely abandoned this market segment. This appears to be a classic "Christiansen disruptive" dynamic, where the first wave is following the leading performance curve in a bid to grow or at least maintain margin and ceding the lower-margin low end of the market to a class of products based on a technology that is cheaper and performs poorly relative to CCDs.

The following quotes come from an interview with Jim Malcolm, Sony's marketing manager for digital still cameras and printers earlier this year. Early in the interview, he discusses the popularity of the Sony 0.3 megapixel floppy-disk Mavica line:

> "Many people have been thinking about the digital photography market as speeds and feeds," says Malcolm, but he says that digital photo is defined by "consumer expectations." He suggests that is one reason why the Mavica has been so popular: people who use it like it. "*If it meets expectations, then it's good enough*," says Malcolm, who adds that it seems that the Mavica line, with VGA resolution, floppy disk storage, and 10x zoom, has what consumers want.
>
> The Mavica FD75 has consistently been one of the best-selling products in the market, and the Mavica line represented a "significant portion" of all the LCD-panel digital cameras Sony sold in 2000. The digital photo industry "does not want to recognize that they got beat by a floppy disk," comments Malcolm.

Later in the same interview, when asked about the low-cost models flooding the market, he responds:

> Malcolm acknowledges that digital camera prices are eroding, but Sony believes it can hold the line on its camera prices because of its name and the high quality of both its products and its technology. "We use high features, functionality, and quality as our weapons," he says, while "Others may need to use price [as their weapon]." Most important to Sony is "that we give customers high-quality, high-performance products that meet or *exceed* customers' expectations."[107]

Certainly, Sony has proven its ability to leverage its brand name to charge some premium on its consumer electronics products in the past. It will be interesting to see how this one unfolds. If the 2 megapixel CCD is expected to be the sweet spot of the broader market, and if there are already a few 1.3 megapixel CMOS sensors ready for market[108], it will not be long before CMOS will reach that "sweet spot".

[107] Extracted from Lyra web report: "The Digital Camera Market: Vendors' Views of the 2001 Market". 4/18/2001

[108] Zoran has announced a single chip camera with a 1.3 megapixel CMOS sensor. Connexant markets a 1.3 megapixel CMOS camera reference design. SoundVision markets a camera reference design using the Motorola/Kodak 1.3 megapixel sensor.

CCDs fight back

The first chapter concluded with a discussion of the response of conventional photography to the digital emergence of digital photography. A similar response of the CCD camp to the emergence of CMOS might be seen within the DSC product as well. The introduction of a significant number of low-end CMOS products in 1999 put pressure on the CCD vendors as many new entrants were choosing the lower-cost alternatives. As seen in Figure 10, this was the year that the number of CCD-based DSC firms reached its peak. In the following year, there was a reduction both in the number of firms selling CCD-based DSCs, and more significantly in the number of new product introductions, even while the total market size was growing. The CCD suppliers: Sony, Sharp and Matsushita aggressively dropped their prices, accelerated the release of 3 and 4 megapixel sensors, and provided several integrated support chips for their CCDs. Though the number of CCD-based vendors continued to drop, in 2001 the number of CCD-based new product introductions rebounded and the ratio of new CCD-based products per firm reached an all-time high. At the same time, the number of CMOS vendors was increasing, but new product introductions per firm dropped[109]. The results are shown dramatically in Figure 13 below. The majority of the new product growth for the CCD-based DSCs in 2001 was in the 2-2.9 and 3+ megapixel products, as can be seen in Figure 12. The data suggests that the introduction of CMOS sensors created a renewed competitive effort in the CCD camp. Utterback would content that these reversals are usually temporary, but it is too early to predict the long term dynamic in this case.

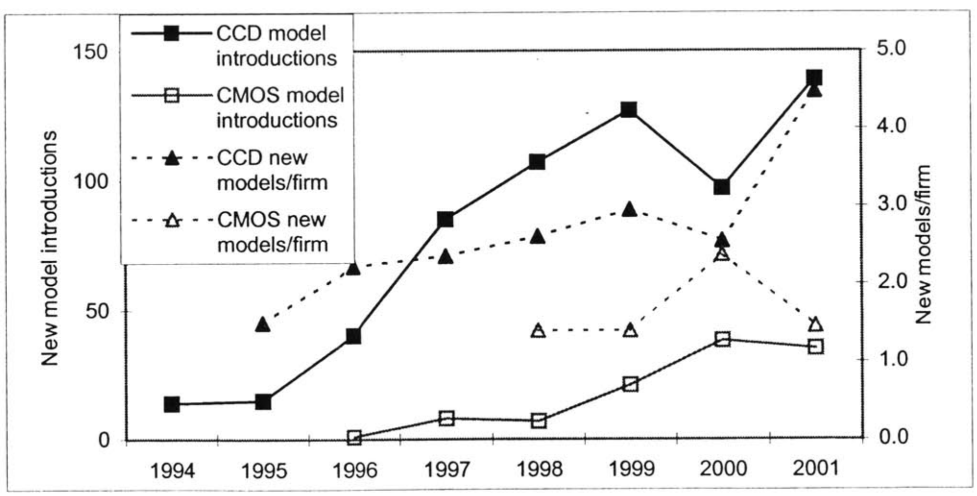

Figure 13: New CCD and CMOS-based DSC introductions per year.

[109] Note that the data for 2001 is only complete up through September. While this omission will distort the actual numbers, it should not affect the trend significantly.

A note on semantics:
One of the tactics of employed by innovators seeking to introduce a disruptive innovation is to adopt the language and artifacts of the technology they seek to displace as a means to foster understanding and advance market acceptance. This was well illustrated by Utterback in the classic case of Edison's electric "candle" in which Edison not only adopted the semantics and the shape of the bulb, but also sought to use the gas-pipe infrastructure to pipe his electricity into homes and businesses.[1] It can be seen in countless other examples from the steam engine to the microwave oven. However, defenders who seek to dominate the new markets can use a similar tactic.

The use of the term "digital photography", as opposed to "digital imaging" or "digital capture" is not only an attempt to build on the ubiquitous photography market, but also an opportunity for "defenders" to maintain some claim of ownership of the new innovation by linking its image in the consumer's mind back to their core competencies. The product is an image acquisition device, or camera, and its output is information in a series of 1s and 0s[110]. The photograph, or print is an optional product of a secondary use of that data, and those who use these semantics would no doubt like to steer the consumer towards that application of the data in their domain. The differentiating features of DSC's are its immediate verification as well as its potentially seamless connectivity through today's digital networks to any digital port and application in the world. The strengths of the product would suit it best as a communication device or information tool. These features should be the focus of any expansive innovative opportunities in digital imaging.

If this argument were true, one would expect to see a difference in semantics around DSCs between the "defenders" and the "attackers". The defenders would reinforce the language of photography, while the latest innovators might stress the uses of digital for new markets. As an informal experiment, the author visited the web sites of several major DSC players, as well as new entrants, to test their use of semantics. Some findings follow.

[110] Recall that the first digital still cameras were called still video recorders or digital still video cameras. This name more accurately reflected their origin and application at the time.

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Kodak: The company's web site: www.kodak.com features the words picture, photo and photographer on the home page. The link to "digital cameras and technology" brings up a page whose first line is a link for "How to Get Started in Digital Photography". The Kodak "EasyShare System"[111] lays out the digital paradigm for Kodak: "shoot, touch, share". The 3-step proposition hearkens back to the 1st Kodak roll camera in 1888: "pull the cord", "turn the key", and "press the button". The third step in the new sequence, "share" is illustrated with an LCD monitor and a stack of printed photos. Kodak understands the opportunity in the proliferation of color images, but it is still the media – a printed photograph – that is subliminal endpoint of the new paradigm.

HP: It takes two links from the company website: http://www.hp.com, through "printing and digital imaging" and "scanners, digital imaging and photography" to get to "digital photography" on the home and home office link. The word photography is prominent, and the product line is called 'PhotoSmart', sharing the photo-centric perspective with Kodak. However, HP wants you to print the photo at home and the consumer DSC page prominently features "Got Ink", and links from the camera pages to "-> printers, and then some."

Canon: At www.canon.com, you first have to decide what part of the world you're in, but in a few clicks you are surrounded by an impressive line-up of eleven "Digital Cameras", two "Digital Photo Printers", and three "Film Scanners". If we didn't already know it, the numbers alone tell us that this company is all about "capture". Of the eleven DSCs, there are: three 4-megapixel models, three 3-megapixel models, one 2.6-megapixel model, three 2.1 megapixel models, and a single token 1.3 megapixel model[112]. Of these, six have a 3x optical zoom, one each at 10x and 2x, and two, digital cousins of the popular film-based EOS models, use replaceable lenses. These products occupy the upper echelons of the consumer DSCs. There is no question here that the DSC is all about photography, and that serious photography is all about a quality camera.

[111] The graphic or product picture for each of the following company discussions was copied from promotional materials on the respective company's web site which is listed with each company description.
[112] See Canon's DSC line up in Figure 16 in the appendix.

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Olympus: The home site of www.olympus.com also requires the visitor to navigate through the globe to the Americas. From www.olympusamerica.com, the consumer pop-up menu permits a direct link to "Filmless Digital Cameras", "APS and 35mm Film Camera", "Binoculars", "Photo Printers", "Voice Recorders", "Eye Trek", or "3-D Technology". The digital cameras page introduces the line of cameras for "The most realistic digital image yet" with "TruePic™ digital color technology".

E-20N
5.0 Megapixel

There are three lines of cameras: the D, C, and E series. The six point-and-shoot style D-series for "a perfect introduction to digital photography" run 1.2 to 4 megapixels of which half have zoom lenses. The ten C-series cameras for "the avid photographer" run 2 – 4 megapixels all of which have zoom optics. The three E-series are powerful digital SLRs for the "professional digital photographer and serious amateur" and feature new 4 and 5 mega-pixel models. This is another site that puts the camera at the center of photography, but at the same time has a product line that covers some of the lower segments. The accessories allow you to "print true photographic images".

Sony: From www.sony.com, which appears to know I speak English, it is only one link to the "Digital Imaging" page, where one is told that "The 5.24 megapixel DSC-F707 Cyber-shot® digital camera has a menu of features and options to create a imaging experience like no other". This is starting to sound innovative, and there is no mention of "photo" yet. Sony also has three lines of cameras: the eight "Cybershot" cameras run 1.3 to 5 megapixels with all but two having zoom optics; the two "CD – Mavica" models which are nearly identical with 3x zoom and 2.1 or 3.3 megapixels; and the three "FD-Mavica" models with 0.3 to 1.3 megapixels and 10x to 3x optical zoom respectively[113]. The line is differentiated not on user segments, but on storage media: FLASH "memory stick" cards in the "Cybershot"; CD-R for the "CD-Mavica"; and floppy disks for the "FD-Mavica". The lead-in on their "Cybershot" line, which features their 5 megapixel unit and three units featuring a "state-of-the-art Carl Zeiss™ Vario-Sonnar Lens", is "Only Sony is this stylish". Apparently, fashion is a way to maintain margin as the market becomes commoditized. There is no mention of "photography" in any of the Cybershot or CD-Mavica pages, though it is mentioned once on the FD-Mavica[114] page and prominently on the page advertising their four "Digital Photo Printers".

[113] It is worth noting that Sony made the most expensive 0.3 megapixel or VGA resolution camera on the market in 2001, with a list price of $399, and it uses a floppy disk drive for storage. To be fair, it does have a 10x optical zoom, but the premiums that they supposedly can charge are amazing. Furthermore, Sony has successfully bucked the dominant design of using FLASH memory cards in its cameras with the floppy disk, FD series, which has been a perennial best seller in the US, and now with its CD-R models.

[114] It seems an anomaly that the word photography shows up in conjunction with Sony's DSCs only on the page with their 3 lowest resolution offerings. It makes one wonder about the "photo quality" of their photo-printers...

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It appears fairly clear that the DSC camera is tightly linked to the roots of each of these market leaders, and photography is a prominent part of it – for defenders and attackers alike. The camera companies stress capture, the media companies link their output, and Sony does a bit of both without making it obvious. It should be pointed out that all of these companies offer some digital photo printers that can be paired with their own DSCs to make prints without the aid of a PC. Now lets look at some of the newest entrants and potential threats to the incumbents[115].

SiPix is a new entrant in 2001 with a very interesting background. The company is a spin-off of a Taiwanese OEM camera manufacturer, NuCam, now headquartered in California with an office in Europe. It is reportedly funded with a $100 million investment by Goldman-Sachs. The parent company, Sipix Group Holding LTD, is headquartered in the Cayman Islands. SiPix has announced six new cameras: 3 DSCs and 3 combination DSC/PC video cameras; and three "pocket printers" one A6 monochrome thermal and two mini color thermal printers (print sizes 1.25x1.6" and 2x2.25") which can make prints directly from the cameras. Their products are very aggressively priced, and some competitors have accused them of taking huge losses gain market share and shake out the marketplace. None of the cameras or printers are described in terms of photos, photography or photographers. The www.sipix.com home site refers to its products as "Digital Imaging Appliances" apparently not wanting their cameras and printers to be compared to photographic products.

KB Gear, on the web at www.kbgear.com , sells "Digital Gear for your Digital Life". It has been around since 1994, introducing its 0.02 megapixel CMOS JamC@m in 1998, and following it up with a 0.3 megapixel CMOS JamC@m2 in 1999 and the JamC@m3 in 2000. The latest camera was its first with an LCD panel and removable storage. It was introduced with a $99 list price but can be purchased retail for under $50. The company was founded in 1994, has 25 employees and is based in Eden Prarie, Minnesota. The Lyra database originally listed their cameras as manufactured in the US, but Concord Camera reports that it makes the JamC@m3 in its factory in China, and the previous two models were likely manufactured in that area as well. The company markets a rugged DSC for kids and teens, along with an MP3 player, a funky sound recording/morphing/mixing device and a graphics tablet for drawing your own web site. The company is all about teens and style – and the products are all "*Jammin*." There is no mention of photography, but there are "digital pix" and you can "turn your JamCam photos into digital

[115] These relative unknowns were chosen either because they have encountered recognized market success, as in KB Gear, or because they appeared in Table 11 in the appendix with the greatest numbers of products for new producers in 2001.

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postcards in a snap". The company's products are listed in the "toy" category in the Lyra database, but the JamC@m3 is also sold bundled some new PC systems and it achieved an impressive 5-7% total US unit market share in 2000.

Crystal Digital, on the web at www.crystal-digital.com , is based in Rochester, NY, and was founded in March, 2000 by a 25 year veteran of Kodak to design, manufacture and market low cost, high quality CMOS cameras. They came out with their line of very low-end fixed-focus DSCs in 2001: a 0.02 megapixel "wearable[116]" CMOS camera, a VGA CMOS dual-mode DSC/PC-video camera, and a 0.8 megapixel DSC based on a Sony CCD. They also sell a $300 4x6" dye-sublimation color photo-printer which prints from CompactFlash memory cards. They do not say where their products are manufactured, but the company information page mentions that the "inclusion of products from foreign manufacturers will provide the balance needed to be an effective and cost efficient corporation", which is probably code for "China". The web site is very bare-bones, with only the very basic specifications given on their products. There is no real discussion of the products or savvy marketing, and an ominous lack of the words photo, photograph or photography for a company based in Rochester, NY.

Minton Optic Industry, on the web at www.minton.com.tw is a Taiwanese manufacturer of branded and OEM/ODM DSCs. From its founding in 1985 to 1998, Minton was primarily a film camera manufacturer, but merged with a multi-media company in 1998 and broadened its product line. They entered the DSC market in 2001 with six CCD-based DSCs, two each at 0.3 megapixels, 1.2 megapixels and 1.9 megapixels. At each resolution, only one has an LCD display, and most of the entries seem to share the same industrial design and tooling. Though much better designed than Crystal's, their website does very little promotion of their products beyond showing them and listing their specifications. Furthermore, their S-Cam line of cameras is probably poorly named for even a low-end line of cameras.

The selection of new entrants above, chosen strictly on a basis of the strength of the number of products introduced in 2001, does show a lack of emphasis on the photographic aspects of digital imaging, which at least partially supports the hypothesis. Their product lines are focused more on the lower quality ends of the market and the communications modalities, while the product lines of the major branded players

[116] The camera comes with a strap to hang it around one's neck.

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from the first wave are focusing on the relatively higher-end digital photography branch. Those of the new companies that do put something into marketing their goods, are stressing, style, cost, "digital appliances", and "digital gear". Though the previous section lists companies like HP and Sony as attackers of traditional photography, these new firms can be viewed as the attackers of the first wave of "digital photography" companies, all taking advantage of what is now highly appropriable technology to attack from the bottom with a low-cost, low overhead model.

Strategies for Survival

Timing of Entry

Utterback contends that the best time for a company to enter an industry is during the period of highest learning, which is typically right before the establishment of the dominant design. Based on our study, this would have to be in the 1994-1997 time frame. Companies that enter too early may not have the stamina to outlast the early iterations and churning, while those that enter too late may miss the opportunity to garner market share. Others scholars focus on the importance of first mover advantage, wherein the first to market can gain market share without the competition, charge a higher margin for his product, lock-in customers and channels, and potentially establish a intellectual property defense. In the case where there are low barriers to entry and where markets are slow to develop, a fast follower with the ability to capitalize manufacturing facilities and a low manufacturing cost will enter with the latest commonly available technology and may have an advantage in not having invested in early R&D and market development.

Based on the history presented, the earliest entrants are Canon[117] (1987), Kodak (1991 or 1994), Sony (1988 or 1994), Apple (1994), and Dycam 1995, three of which are still active players and are among the market leaders. The last two followed Utterback's pattern when it exited the industry in 1996[118] and 1998. Olympus entered the market in 1996 with two popular models, and HP followed the next year in 1997 with its PhotoSmart, which promised color fidelity when used with its PhotoSmart Inkjet printers. However, it should be noted that none of the market leaders today can be considered pure digital camera players but sell digital cameras in the context of a larger business. Some of these are an essentially subsidized business, which makes determining the success of individual products difficult to ascertain.

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[117] Canon has not been a major market share winner until recently in 2001. While it had a few products on the market continuously, it has limited its exposure early on claiming to be waiting for the market started to take off. When it did enter in force in 2001, it came on out with 8 new products in several families in one year – a significant platform coup.

[118] In 1996 Apple divested most of its non-core business and spun-off Flashpoint to continue with the software support of QuickTime and embedded camera operating systems. Flashpoint still participates in the embedded camera OS market and has recently played a role in mitigating some of the damage done by Kodak's patent play in Spring 2001.

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Another factor that muddies the business analysis is that many of the branded entrants do not actually manufacture or design the products, but purchase them from OEM and ODM sources in the Far East.

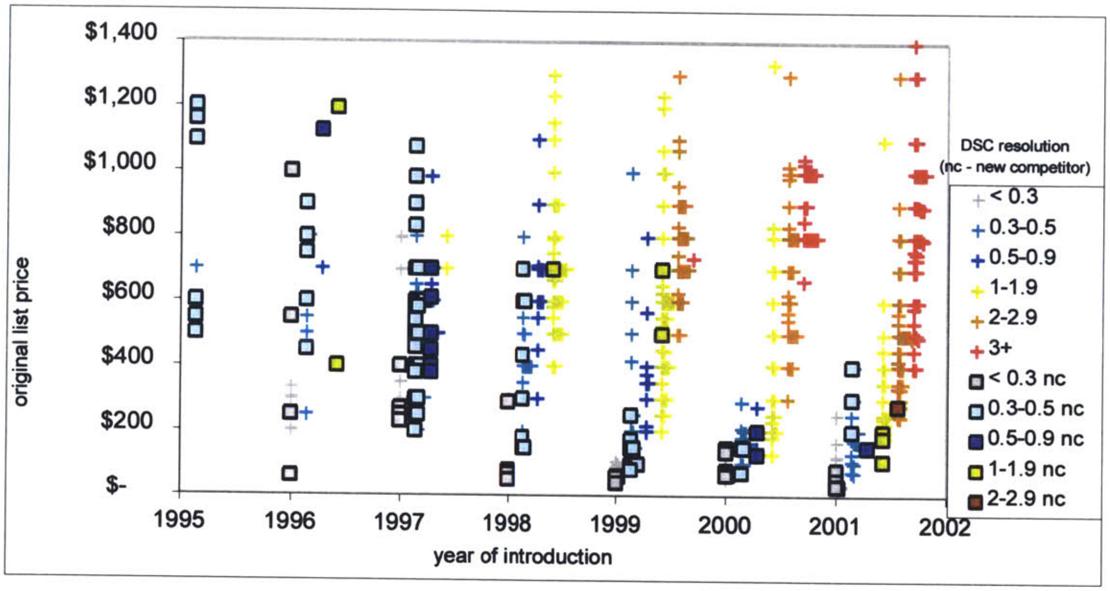

Figure 14: New competitor entry price and resolution strategy by year

The timing of entry also has a bearing on the competitive strategy that an organization can adopt. Those that enter before the emergence of the dominant design were competing primarily on features and performance. The data in Figure 14 shows that the entrants through 1997 cover the entire landscape of price and performance. However, starting in 1998, and fully apparent by 2000, new entrants are concentrated on the low-cost, low-margin, low-performance end of the spectrum. The earlier entrants thus dominate the higher-performance segments. Figure 15 in the Appendix documents the competitive roadmaps of the dominant players in the market in detail, and all but HP have stayed very close to the performance front with products in the highest available resolutions each year.

Survival of the Fittest

The trend on the number of firms in the industry shown in Figure 10 and the Utterback and Abernathy model that it supports, suggest that there will be further reductions in the number of competitors in the industry. Furthermore, the disruptive trend with CMOS-based cameras suggests that new entrants will usurp at least the low-end, and perhaps the bulk of the consumer market. So is there any indication of which firms will survive?

The data plotted in Figure 13 suggests another way to possibly look at the relative health or vigor of a competitor or competitive technology. The number of new model introductions per year, on a per firm or aggregate basis might be a good indicator of effort by the competitors, or even suggest a platform efficiency. Granted, it may be a difficult reach if not combined with market success or the scope of

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market segments addressed by the companies. However, combined with market success data, as was done in Table 11 in the appendix, and copied into Table 10 below for the market leaders, some correlation between new introductions and market success is suggested[119]. If so, then we might use the trend of new product introductions to suggest the future health of given competitor. Intuitively it makes sense that firms who extend their product lines in a market that is growing in size and scope would likely see greater sales and revenue. Certainly, those firms whose product lines are contracting, in a market that is growing in scope and size as the number of firms contracts, would be expected to lose market share and competitive viability[120]. If this were the case, then looking just at today's market leaders, one notices that the camera firms, Olympus and Canon, and the consumer electronics firm, Sony, are poised for improved market success, while the media companies, Kodak and HP, are showing signs of weakening.

Table 10: New DSC introductions by year for the market leaders.

Brand	Entry	1995	1996	1997	1998	1999	2000	2001	Total
Sony	1996		1	5	4	6	10	15	41
Kodak	1994	1	3	2	7	9	8	7	37
Olympus	1996		2	5	3	6	8	11	35
Canon	1996		1	2	1	*4*	*3*	8	19
Hewlett-Packard	1997			1	2	*1*	5	3	12

Taking a more detailed look at each of these competitors' offerings on the industry-wide product map shows another perspective on this argument. The charts in Figure 15 in the appendix show that, in addition to fewer new product introductions by HP and Kodak, their individual products are focused on the low-price end of their respective categories. One can surmise from this that they are either very competitive on a manufacturing cost basis[121], or they are each losing the power of their brand name to charge a premium or to compete on higher-end features in the consumer market[122]. It is also interesting that HP and Kodak had enjoyed subsidized business models early-on based on the hope to grow their output media business. As the DSC industry approaches a specific stage, these competitors have chosen to focus less on the DSC and vertical integration within digital photography, and more on the system-level services that bring any vendor's DSC output to their media, or the output services themselves. This

[119] A closer inspection of the data suggests that there may be a lag in the market success indicator, for instance see Canon, Panasonic and Sharp in 1998, JVC in 1999, Epson in 2000. It makes good sense that products introduced in one year might have a good deal of market effect into the following, especially when many companies introduce products in the second half of the year to try and impact the Christmas sales season. However, the inconsistencies in the market data I was able to procure were so bad, that rigorous analysis based on it was not warranted.

[120] A valid exception may be the case where a company's previously introduced products are such strong competitors, like Sanderson's 1995 study of Sony's "classic" walkmans, that the scope and size of their product line increases even as new introductions decrease.

[121] Kodak's DSC's are make by Chinon and HP's DSCs are manufactured in China, Malaysia, and the Philipines.

[122] Balancing this argument, it should be pointed out that Kodak has consistently had some very strong offerings in the professional niches, where they employ their own sensors and competitively manufacture and sell professional camera backs.

tendency for individual competitors to start out vertically oriented and then to focus on a portion of the value chain where they have a clear advantage as the industry matures is a widely studied phenomenon.

Of the remaining market leaders, Canon and Olympus have managed to carve out a similar market position in the DSC market as they had in the conventional market, namely dominating in the market segments for the professional photographer, serious hobbyist, and brand-conscious consumer where brand and quality have an impact. They will continue to be challenged on the lower end of their market where cost is the major basis of competition, but they managed to compete well in the higher segments in the conventional camera market and will likely continue to do so in digital. Sony has translated its domination in consumer electronics to carve out the middle of the market. Buoyed by its vertical integration in the component technology of DSCs, it is the most likely to make the margin-busting conversion to CMOS with its own sensors, when the technology reaches the right level of performance. However, it will face stiff competition from below[123].

The low end of the market will likely continue to be hotly contested by firms who will have to compete solely on low-cost manufacturing, and most of the present participants have no other obvious complementary assets to differentiate them. Utterback extends the model of product and process innovation to multiple waves in his book[124]. He suggests that the number of competitors in the 2nd wave of innovation, in this case CMOS-based DSCs, will be fewer than in the first, presumably because the market leaders in the first wave had established complementary assets such as brand, manufacturing and distribution channels that would serve as competitive barriers to entry. What we see in Figure 10 and Figure 14 is that the new entrants in CMOS are competitive primarily based on low-cost manufacturing. For the most part, these firms have few other complimentary assets, have not entered on any major architectural innovation, and are not themselves the source of the technological innovation on which their products are based. Most of their products are based on standard reference designs provided by component suppliers, are uninspired, and perform poorly. Given this, it is unlikely many of them will survive at all in the long run. What they do have in their favor is that they are participating in the portion of the DSC market which can be considered expansive or additive to the traditional photographic market – namely input devices for computer, web and network-based communications. The higher-end DSCs are arguably just substitutes for conventional cameras in the realm and application of photography.

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[123] Sony has been a market leader in the development of CCD sensor technology and they the consuer market in quality, but companies like Sharp, Matsushita, and Samsung have similar product lines, do not lag far behind in newer introductions, and tend to compete aggressively on price. In the CMOS sensor arena, there are a whole new group of competitors. If it were not for the fact that Sony is in the DSC business as well, then it might do well by advertising its sensors through partners with a "Sony Inside".

[124] Utterback 1994. pp 99-101.

The Next Frontier

What the previous data shows is the probable emergence of a new S-curve or technological discontinuity on the subsystem or technological level of the DSC, explicitly in the wave of new competitive entrants using CMOS sensor technology. It should be noted that while this discontinuity represents a potentially new price/performance position, it is not necessarily recognizable to the consumer in the context of digital photography. Yes, she may see a step decrease in price for some of the lower-price offerings, but this is neither inconsistent nor discontinuous with the previous trends with CCD technology. The CMOS-based cameras are predominantly focused on the computer and web-based imaging applications, but they replaced CCD-based cameras there, as opposed to creating that market.

Looking out into the marketplace, competitors should be looking for other signs of new innovations or technological discontinuity, which will establish itself in a new market segments, niche or use pattern outside of the existing applications. These could either be opportunities for growth or sources of new unanticipated competitors. Many new opportunities come under the broader context of "digital convergence", in that product offerings bring together existing digital technologies to revolutionize existing markets.

Most of what is seen is emergence of hybrid multi-function products combining attributes from different segments, but often compromising some performance measure in either or both categories. Examples of these are the DSC/MP3 players, DSCs that take video and audio clips, and digital camcorders with higher resolution sensors for capturing stills. Others are combinations of products that may have previously been used together while separate entities such as: PDAs with plug-in or integrated digital still capture modules; DSCs with integrated modems or wireless cellular interfaces; or the newest cell phones with internet connectivity for the www and e-mail, and built in digital image capture modules.

There are already four of the "photo-phones" on the market in Japan[125], where they have been popular with the youth market. The application is being enabled by the combination of very low-cost CMOS imaging modules and the new "2.5G" and expected "3G" digital cellular networks which have the capacity to accommodate images. The promoters of the new networks look to wireless imaging as one of the "killer apps" to promote its widespread acceptance[126], just as it is images that demonstrate the difference between a dial-up modem and broadband. The providers of

[125] The graphic to the right is a Sharp "J-Phone" model J-SH07 copied from a Sharp web advertisement.
[126] A classmate, Moise Solomon, has been studying software-defined radios and the wireless industry as the focus of his thesis, and I have enjoyed many helpful discussions about the potential overlap of these industries.

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the CMOS imaging modules look to photo-enabled phones as one of the highest potential volume applications of their products. The resolution in these devices today is far from acceptable to create photographs to preserve memories, as these are images that are only 100K pixels or so. However, over time this embedded technology will become more widespread and quality will improve to where it may be good enough for some applications. Although this may be a threat for both the conventional and DSC industry leaders, the more positive way of looking at this is that by making photography more ubiquitous, the prominence of images is raised and there are more opportunities for their secondary use. The challenge for existing players is to find ways to participate, either with products and imaging modules, or by providing ancillary products and services such as finding ways to store, organize, access, and perhaps to turn those digital images into hard copy output.

Pundits today argue that the next wave may come from further convergence of technologies – the wireless web-enabled PDA, the photo-phone, the wireless digital camera with video and audio clip capture, the DSC/MP3 player. There have been scattered offerings in each of these categories, which could arguably be part of another period of ferment. These developments deserve careful scrutiny by the players in the market today. This is also an example of what is called "technological disintermediation", a term that refers to the idea that imaging becomes a feature bundled into other consumer electronics, as opposed to a being a distinct solution in and of itself. If this occurs, it might move the ownership and leadership in the industry to the leaders of the dominant technology of those platforms. Perhaps it will be the network and content providers that will dominate those markets. Just as a cell phone today is essentially a free accessory to a wireless contract, the digital camera may become part of that accessory market. On the other hand, perhaps the extent of immediacy of digital imaging itself will reach a level of "technology over performance". How many of us need or want pictures of our friends and family beaming to us as we drive down the freeway?

Conclusions and Summary:

In this thesis, a thorough case study of digital still cameras in the larger context of digital photography has been presented. This study, has shown that:

- Digital photography has posed a disruptive innovation to conventional photography, though its evolution does not follow the popular Christiansen "disruptive" pattern.
- A dominant design has emerged and is identified in digital still cameras on a product level.
- While the DSC itself, and its subsystems shows evidence of being in a state of incremental change, the product applied within higher-level systems is in the midst of various eras of ferment as the application environments are still largely being defined. Looking at it from a hierarchical viewpoint, the DSC has required it's core subsystems and interfaces to reach a state of incremental innovation in order for a dominant design to emerge there, and now the DSC, as a component of higher order systems is enabling new dominant designs to develop at those levels.
- The markets for DSCs are divided primarily between digital imaging as a replacement for older conventional photography, and new markets for digital imaging in various electronic communication medium such as web, e-mail and now photo-phones.
- The firms, which have dominated the first wave of the DSC market, are a mix of conventional "defenders" which have maintained a presence and new entrants. All are strong participants with broad product lines based on platform strategies, strong brand names, and backed by relevant complementary assets.
- It is primarily by low-end imaging devices that address the new communications markets. These market applications were originally addressed by the low-end offerings of CCD-based DSCs and the firms that built those markets.
- CMOS imaging technology represents a technology discontinuity in the core subsystems of a DSC. It provides a new lower-cost but lower quality opportunity for the evolution of those markets.
- It is primarily new entrants, with little connection to either conventional photography or the first wave of digital photography, which have applied CMOS technology to the DSC market. When the DSC participants are segmented by technology, their industry participation supports the Abernathy and Utterback model of industrial innovation for two distinct waves. The first wave of CCD-based firms is in the post-transition phase seeing a steady decline of firms participating even as the market and number of new product offerings grow. The second wave of CMOS-based firms is just starting to take off, but does not show the same strength as the first wave.
- Firms entering the market with CMOS-based cameras in the second wave have focused primarily on these newer markets where image quality requirements are not that stringent. These market

dynamics show the makings of the start of a Christiansen-style market disruption for the first wave of DSC firms.

Lessons:

Technological innovations progress through market segments in which their unique attributes have the greatest contribution. In the case of digital photography, the first markets that could sustain the early high costs were in the professional and business markets. In order to capture those markets, early players had to provide systems' level solutions targeted to industry needs, not just products. To progress to a larger consumer market, the nature and scope of the system-wide complementary assets necessary to support the innovation significantly increased, and still pose the limiting restrictions to widespread market diffusion there.

The emergence of digital photography and its history to date have been a troubling case for the modern popular model proposed by Christiansen, in that the innovation was not obviously simpler or cheaper, and in that many incumbent firms managed to make the transition. Kodak, for one, invested heavily, embraced and largely shaped digital photography from the beginning, primarily because it appeared to them inevitable and an incredible media potential was at risk. In fact, Kodak entered digital photography at the high end primarily because its most demanding customers in professional photography *were* demanding those products in order to lower their costs and improve their workflow, which was largely moving to digital. It leveraged the assets it developed here to be an early strong competitor in the first wave. Kodak will likely not participate in the second wave because the focus of the second wave, low-resolution e-mail and photo-phone pictures which are unlikely to end up printed on Kodak media, is not strongly related to its customer base. Thus, it is the second wave that will likely resemble the typical Christiansen disruptive innovation and threaten Kodak's participation and perhaps digital photography in the long run. This interpretation of the data helps to explain the trouble resolving the conflicts between this case and Christiansen's model. However, it might also be noted that this pattern of providing the camera early on and then retrenching to media and print fulfillment once other suppliers are more capable and a path to Kodak media is established, is one that has historical and strategically valid precedence with Kodak, which is focusing on the renewed media stream more than the camera hardware.

It was also possible for the camera incumbents, such as Olympus and Canon, to successfully make the transition to the new technology in the first wave, because they could leverage their complementary assets in optics, electronics, and camera technology to the new market and acquire those necessary to adopt the new technology. They will likely retain their previous higher-end camera market positions regardless of the technology: conventional, CCD or CMOS. For the most part, the transition was competence enhancing, and they were able to partner for the sensors and software. Their strength in the high end will likely grow as higher resolution sensors become more accessible, and the optics, high-end use features, and general camera quality for which their conventional products are well regarded increase in relevance[127]. However, as the industry matures, they will not likely participate in either the expanded electronic imaging markets or the low-end of the DSC market now falling to the second wave.

Market leaders HP and Sony represent the new entrants of the first DSC wave. HP has positioned itself as a new media player, hoping to leverage digital imaging to increase its inkjet market. The DSC and its technology are complementary to its line of computers and computer peripherals, and it has been able to leverage compatibility and connectivity to be competitive. However, it is not clear if it will play in the next wave either, when margins continue to erode and standardization in the industry results in fewer compelling reasons to select HP. HP's participation could likely follow that of Kodak, with a retreat from capture once a solid link to its output media is established. Its best bets now are in bundling sales of DSCs with its computers, printers and/or scanners. Sony on the other hand, is vertically oriented in the market and the DSC has strong ties to their entire consumer electronics lines of products. It has consistently dominated the market in both DSCs and the sensors that had been the key core subsystem with strong, rapidly renewed product lines and efficient product platforms. It has faced margin-eroding imitators in most of its other consumer electronics successes, and will likely survive the second wave of the DSC assault as well.

The lessons from the entrants in the second wave are not yet clear. As a group, they are mostly focused on low-cost as a competitive strategy with little other complementary assets. Their offerings are based on the low-cost, low-quality CMOS offerings of subsystem and component vendors. Competition will be fierce here, and the most cost-efficient producers will likely prevail. Few are burdened with large research and market development expenses, as they are for the most part capitalizing on the groundwork and infrastructure developed by the first wave. The lessons from the CMOS-sensor vendors are that it is best to focus on new, emerging markets and applications to develop markets. The early CMOS entrants that went after the higher quality markets have done poorly, but where low power, small size, high levels of integration, and low cost were more important than image quality they have succeeded. Working from this foothold, they may succeed in improving the technology to where it works its way up-market.

[127] The inference here is that there is no need to buy premium lenses and features for a camera that only takes 1 megapixel or less, but when one is shooting for quality with >4 megapixels one may want a better camera and invest in a solid brand name.

Areas of future work:

The database of camera introductions developed for this thesis has provided hard evidence to support models of innovation proposed by Utterback and Abernathy as well as Christiansen, while posing some questions to the latter. The distinct separation of the CMOS-based entrants was unexpected when this work was begun, and it has yet to be fully played out. The fate of the second wave, both the firms selling the product and those providing the CMOS subsystems, should be of continued interest and provide evidence for those who question the value of virtual firms and low-cost manufacturing as a primary strategy. This would warrant follow-up investigation after a few years time. The passage of time should also provide better insight into the effectiveness of the strategies of the players in the first wave. The time-compression of industry life cycles makes it hard to discern which players are really healthy in the near term. After a few years, a more rigorous study of hazard functions[128] for the dominant players today could be studied, and much of what was left to speculation in this work can be replaced with hindsight.

[128] The author is thinking of the level of rigor applied in the study of the disk drive industry in: Christiansen, Clayton M., Suarez, Fernando F. and Utterback, James M. "Strategies for Survival in Fast-Changing Industries". *Management Science*, Vol 44 No . December 1998

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Appendix 1: DSC new product introductions by brand

Table 11: DSC firms sorted by number of products introduced, year of entry, and brand[129]

key [130]:

reported as 5% + unit or $ market share by one of several sources in a given year

made a list of top vendors in the given year

Brand	Entry	1994	1995	1996	1997	1998	1999	2000	2001	Total	Sensor at entry
Sony	1996			1	**5**	**4**	**6**	**10**	**15**	41	CCD
Fuji	1995		1	1	3	6	*10*	**8**	*9*	38	CCD
Kodak	1994		1	**3**	**2**	**7**	**9**	**8**	**7**	37	CCD
Olympus	1996			*2*	**5**	**3**	**6**	**8**	**11**	35	CCD
Casio	1996			**4**	**5**	4	3	6	5	27	CCD
Canon	1996			1	2	**1**	*4*	*3*	**8**	19	CCD
Ricoh	1995		1	1	2	4	3	2	3	16	CCD
Agfa	1996			1	1	2	*6*	*5*	*1*	16	CCD
Toshiba	1997				1	2	*4*	*2*	*6*	15	CCD
Sanyo	1997				2	3	3	4	2	14	CCD
Polaroid	1996				2	1	*3*	**4**	*3*	13	CCD
Nikon	1997				2	*3*	**3**	*2*	*3*	13	CCD
Epson	1996			**2**	**2**	1	4	*1*	*2*	12	CCD
Hewlett-Packard	1997				1	2	*1*	**5**	**3**	12	CCD
Panasonic	1997				4	*4*	*3*	1		12	CCD
Minolta	1994				2	2	1	2	4	11	CCD
Konica	1997				2	3	1	1	4	11	CCD
Samsung	1997				1	1	2	4	3	11	CCD
Vivitar	1997				5	0	1	0	5	11	CCD & CMOS
Pretec	1997				1	3	2	2		8	CCD
Kyocera	1997				1	1	2	1	1	6	CCD
UMAX	1997				2	1	1	2		6	CMOS & CCD
JVC	1998					*2*	*0*	2	2	6	CCD
Largan	1998					2	2	2		6	CCD
Minton	2001								6	6	CMOS & CCD
Jenoptik	1994					1	1	0	3	5	CCD
Pentax	1997				1	0	0	2	2	5	CCD
Sound Vision	1997				2	2	1			5	CMOS
Leica	1998					1	2	2		5	CCD
Tomy	1999						1	4		5	CMOS
Mustek	1997				1	2	1			4	CCD
Philips	1997				1	3				4	CCD
Sharp	1997				4	*0*	*0*			4	CCD
Yashica	1997				1		2		1	4	CCD
Relisys	1998					1	3			4	CCD
Sampo	1998					1	1	0	2	4	CCD
Takara	2000							3	1	4	CMOS
Dycam	1995		1	0	2					3	CCD
LG Electronics	1997				2	1				3	CCD
Kocom	1998					1	1	1		3	CCD
Praktica	1998					2	0	0	1	3	CCD
Digital Way	1999						1	0	2	3	CCD
Aiptek	2000							2	1	3	CMOS
Crystal Digital	2001								3	3	CMOS
SiPix	2001								3	3	CCD
Rollei	1994	1						1		2	CCD
Apple	1995		1	0	1					2	CCD
Chinon	1995		1	1						2	CCD

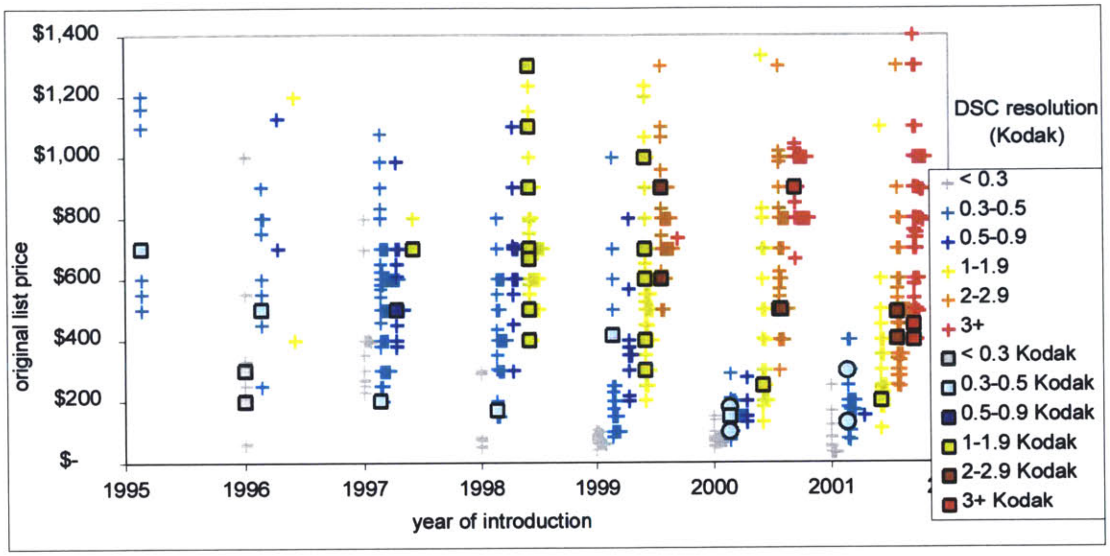
[129] Source of data is the modified Lyra database. High-end professional models are generally excluded from the tally, with a few exceptions to include major participants or to establish a year of entry.

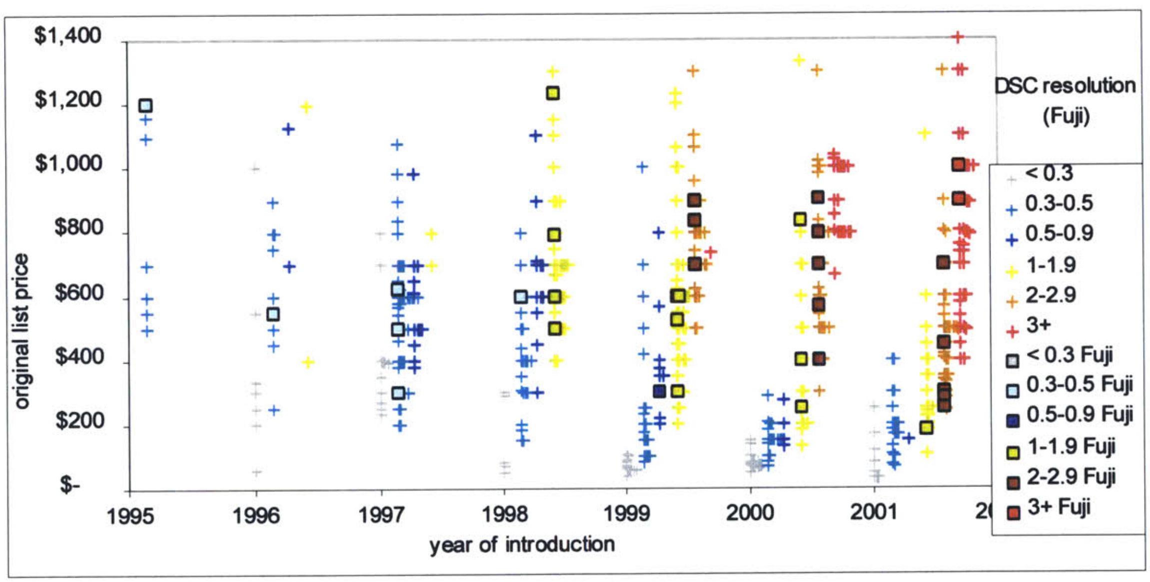
[130] Note: Sources for market share were primarily reports by Lyra and InfoTrends. However, there was much disagreement on the numbers in various sources. In addition, most of the numbers were based on US data only. Brands such as Fuji and Casio, which are not marketed as much in the US are therefore under-ranked.

Brand	Entry	1994	1995	1996	1997	1998	1999	2000	2001	Total	Sensor at entry
NEC	1997				2					2	CCD
Kinon	1998					1	1			2	CCD
Mattel	1998					1	1			2	CMOS
Altima	1999						2			2	CMOS
Argus	1999						1	1		2	CCD
I/OMagic	1999						1	1		2	CCD
Purpose	1999						1	1		2	CCD
RCA	1999						2			2	CCD
Achiever	2000							2		2	CMOS
Handspring	2000							1	1	2	CMOS
Bandai	2001								2	2	CMOS
CMC Magnetics	2001								2	2	CMOS
Concord Camera	2001								2	2	CMOS
icam	2001								2	2	CMOS
Dakota Digital	1995		1							1	CCD
Obsidian	1996			1						1	CCD
Sega	1996			1						1	CCD
Mag Innoscan	1997				1					1	CCD
Mitsubishi	1997				1					1	CCD
Plus	1997				1					1	CCD
Ansco	1998					1				1	CCD
NuCam	1998					1				1	CCD
Quark	1998					1				1	CCD
Tekom	1998					1				1	CCD
Digital Dream	1999						1			1	CMOS
Ezonics	1999						1			1	CMOS
Grandtech	1999						1			1	CMOS
Hasbro	1999						1			1	CMOS
IXLA	1999						1			1	CMOS
KLH Audio Systems	1999						1			1	CMOS
Korea Broadcast Telcom	1999						1			1	CCD
Phoenix	1999						1			1	CCD
Tatung	1999						1			1	CCD
Tiger	1999						1			1	CMOS
Toymax	1999						1			1	CMOS
Chicony	2000							1		1	CCD
Digitra Systems	2000							1		1	CMOS
D-Link	2000							1		1	CCD
GOTOP	2000							1		1	CMOS
Hitachi	2000							1		1	CCD
Hudsontech	2000							1		1	CMOS
Long Well Electronics	2000							1		1	CMOS
Oregon Scientific	2000							1		1	CMOS
Provincial Products	2000							1		1	CMOS
Yahoo!	2000							1		1	CMOS
Creative	2001								1	1	CCD
Desay	2001								1	1	CMOS
DG.cam	2001								1	1	CMOS
Focus Camera	2001								1	1	CMOS
Joinford	2001								1	1	CMOS
Nichimen	2001								1	1	CMOS
SMal Camera	2001								1	1	CMOS
Varo Vision	2001								1	1	CMOS
Vco	2001								1	1	CMOS
Xirlink	2001								1	1	CCD

Appendix 2: Individual Firm Product Roadmaps

Figure 15: Product roadmaps of Kodak, HP, Olympus, Sony, Canon and Fuji[131]





*** If this is a black and white copy, see Appendix 4 for a description of the diagram.

[131] Note that these charts are incomplete, insofar as they do not show products for which either list price or resolution were not stated. They also do no show professional products whose list price exceeded $1400 and certain hybrids. This absence is significant for Kodak and to a lesser degree for Olympus and Sony, but did not affect HP. The specific products indicated by a circle for HP and Kodak are CMOS-based cameras.

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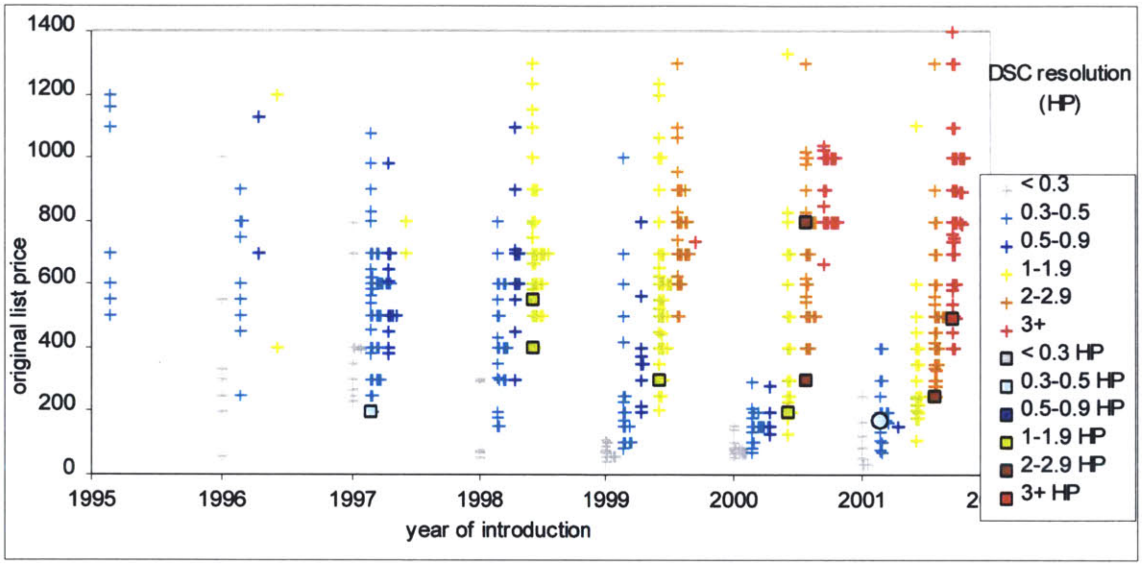

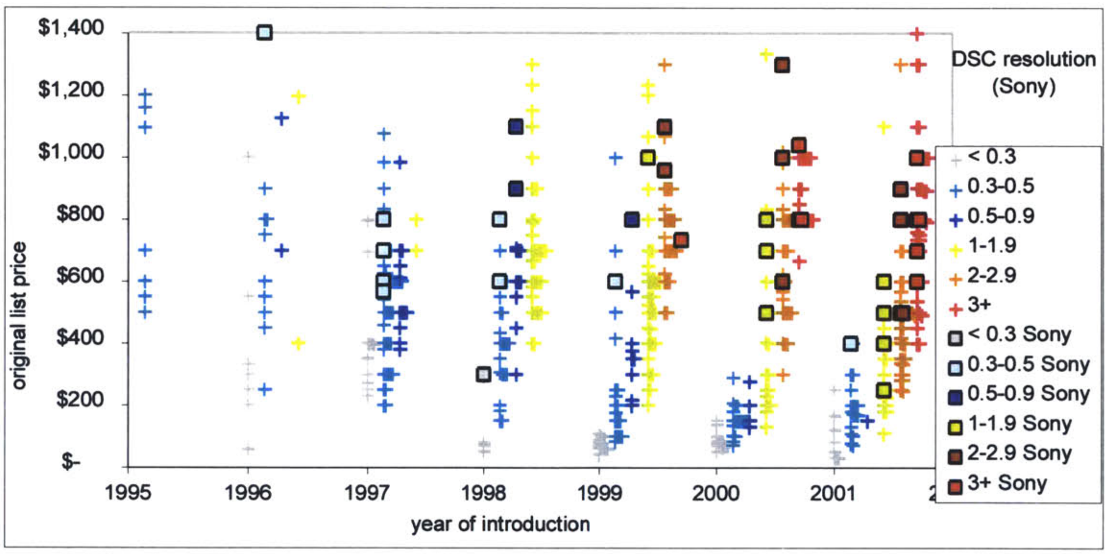

*** If this is a black and white copy, see Appendix 4 for a description of the diagram.

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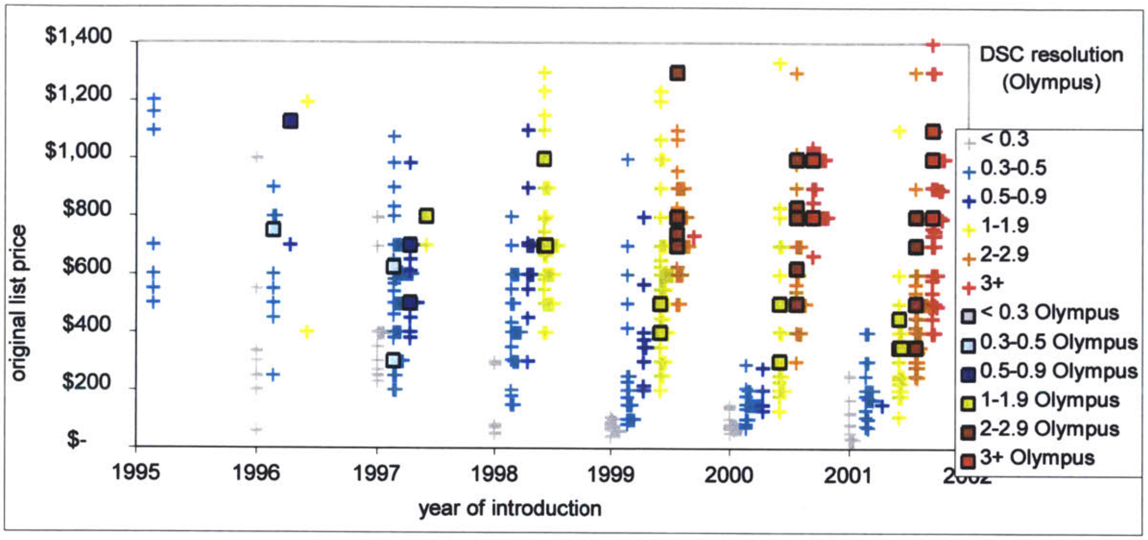

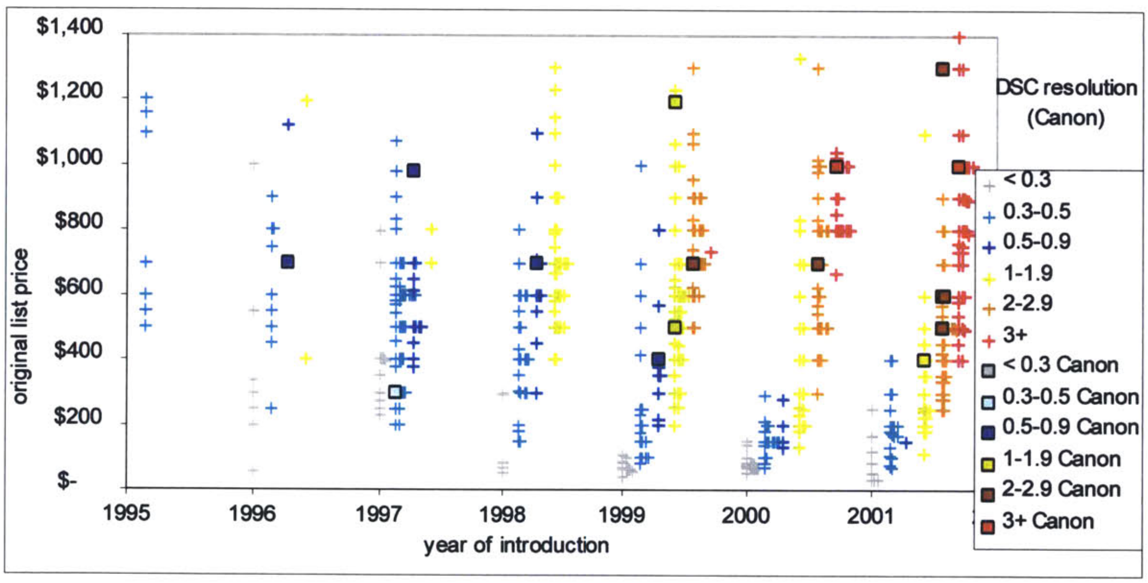

[132]

*** If this is a black and white copy, see Appendix 4 for a description of the diagram.

[132] Comparing this chart and the data set on which it was based with Canon's own product information in Figure 16 and on its website, illustrates the missing data for the last quarter of 2001, which would have shown Canon to be even stronger in the higher end of the market.

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Appendix 3: Canon 2001

Figure 16: Canon's 2001 product line

Canon's 2001 product line, extracted from www.canon.com, features 11 models, which show probable shared-use of several key components including:

CCD sensors:
three at 4M, three at 3M, one at 2.6M, three at 2M, and one at 1.3M

Zoom optics:
one at 10x, seven at 3x (four designs), one at 2x, and
two with removable lenses shared with conventional line

Industrial design:
four sets of two share basic design.
Several products, especially the EOS and digital Elph series
closely resemble their film equivalents.

Computer interfaces:
two with IEEE 1394, nine with USB

Memory cards:
all use Compact Flash storage cards

Appendix 4: Clarification of price/resolution product introduction charts.

The author acknowledges that the charts used to demonstrate product introductions by year against price for six product categories may not reproduce well for black and white copies. The author feels that the charts, as presented in color, are able to capture and convey far more information than would be possible in black and white. Furthermore, the data sets presented are far richer than, and would be significantly compromised by, simple summary statistics.

A detailed description of the format of the charts is provided here so that those readers who are working with black and white copies can still decipher the data within.

For each year, there are six segments or product categories by resolution in megapixels. The left-most entries, which are exactly vertically aligned with the tick marks for each year, are for <0.3 megapixels segment. For 1995, there are no entries in this category. There is a '+' representing each new product entry, and multiple entries at nearly the same price and segment are offset slightly to the right, resulting in a horizontally smeared '+' for clusters of competitively priced and featured products. Successively higher resolution categories are started to the right of the first. There is only one category, '0.3-0.5' megapixels for 1995. There are four categories or segments represented in 1996, 1997 and 1998. All six categories are represented for 1999, 2000 and 2001. The horizontal separation between the start of successively higher-resolution categories for each year is equivalent to a set of 7 individual products at a single price in one segment.

The data shown in Figure 9 represents the base data set, which is repeated in Figure 12, Figure 14, and Figure 15. The latter sets of figures also contain data overlays for specific cameras that are highlighted in the particular figure. The spatial layout for the overlays is identical to that of the base data, but the symbols are typically small squares.

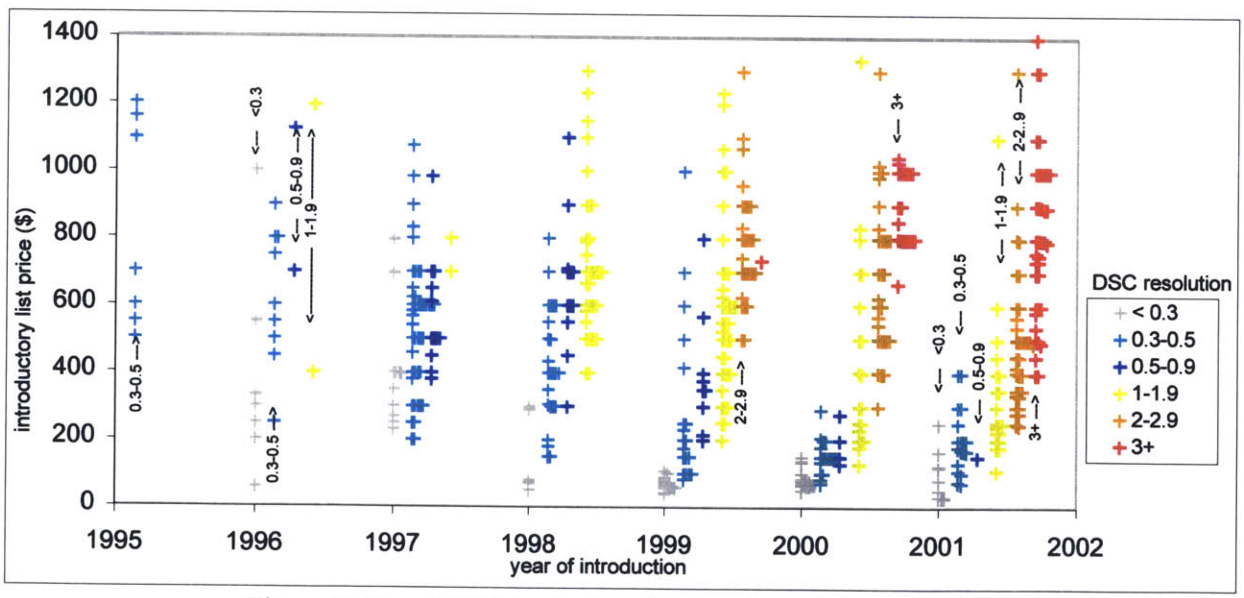

Figure 9: New DSC introductions by year, resolution, and price