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Components, Systems and Technological Discontinuities

Lessons from the IT Sector

Jeffrey L. Funk

This paper describes a model that sheds light on the mechanism by which many technological discontinuities occur. The model combines three arguments: 1) incremental improvements in a system's components impact on the performance and design of systems; 2) these incremental improvements in components can lead to discontinuities in system design through their impact on the design trade-offs that are inherent in all systems; and 3) these incremental improvements in components can cause the components to become applicable to completely new systems. This paper uses the model to explain a number of technological discontinuities in the semiconductor, computer and other industries in the IT sector. A final section uses the model to think about the future of the IT and energy sectors.

Introduction

Ever since the work of Joseph Schumpeter, scholars have long recognised that technological discontinuities play an important role in economic growth. Such discontinuities involve large changes in the concepts that underlay a product, the product's architectures, or in some cases create entirely new product categories.[1] For example, the discontinuities of colour television, high-definition television (HDTV), digital television and plasma and LCD-based televisions differ substantially from the many incremental improvements that have been made in, for example, the screen size or resolution of televisions. The discontinuities of the mini and personal computer and personal digital assistant (PDAs) differ significantly from the incremental improvements in processing speeds that have been made in these computers. Similarly, the discontinuities of integrated circuits, microprocessors, new forms of transistors such as MOS (metal-oxide semiconductor) and CMOS (complementary MOS) ones, and new types of application-specific integrated circuits also differ significantly from the incremental increases in the number of bits per memory or processors, or even the number of transistors per chip.

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Furthermore, it appears that the frequency of these technological discontinuities is increasing (See Table 1). For example, Negroponte's $150 XO computer, smart phones, radio-frequency-identification tags (RFID) and networks of "smart dust" may constitute the next discontinuities for computers. New sources of energy represent some of the discontinuities for transportation and electric power. Radical new processes (e.g., nanotechnology), materials and designs (e.g., System on Chip and configurable processors) represent potential discontinuities for semiconductors. Nanotechnology-based devices also represent discontinuities for cancer treatments, liquid crystal displays (LCDs) and sensors. Internet-related technologies represent some of them for an even broader set of industries including photography, television, video, healthcare and music where portability/mobility is an important part of these internet-based discontinuities.

In spite of the increasing frequency of these technological discontinuities, existing models of technological change shed little light on the mechanisms through which these discontinuities occur and thus the sources and possible timing of them. For example, technological discontinuities are considered an exogenous variable in Anderson and Tushman's cyclical model of technological change, the product lifecycle model and Christenson's model of disruptive change. Instead, these models primarily focus on the mechanisms by which *incumbents* fail in technological discontinuities. These models and those built on top of them focus on helping incumbents respond to the discontinuities using such concepts as firm competencies, appropriability, complementary assets, alliances and eco-systems.[1] Although these concepts are important, models are also needed that can help firms, entrepreneurs, governments, research institutions and universities understand the mechanisms by which discontinuities occur and thus their sources and possible timing. Universities

Table 1. Examples of Technological Discontinuities Currently Being Faced at the Beginning of the 21st Century

Industry	Examples of Discontinuities
Photography	1. Movement from film to digital bits and packets 2. New devices (e.g., camera phones) 3. New methods of transferring the data between individuals (fixed versus wireless Internet transfers) and between the devices (e.g., PCs and cameras) that are owned by an individual (e.g., USB and memory cards)
Television	1. Movement from analogue to digital and to high-definition television 2. Movement to a new generation of digital video disks 3. New methods of broadcasting such as over the Internet 4. New mobile devices (e.g., digital tuners in mobile phones)
Music	1. Movement from CDs (compact discs) to digital packets 2. New mobile devices (e.g., i-Pod type devices and mobile phones) 3. New methods of transferring data between mobile and fixed devices (e.g., USB, memory cards, wireless)
Computer	1. Much cheaper computers such as Negroponte's XO computer 2. New mobile devices such as smart phones 3. Networks of RFID tags and smart dust
Semiconductors	1. New types of materials and processes such as nanotechnology 2. New types of designs such as System on Chip (SoC), configurable processors, micro-machines, laboratories on a chip or drug delivery via a chip
Automotive	1. Movement from internal combustion to battery, hybrid, hydrogen or other forms of propulsion
Energy	1. Movement from fossil fuels to renewable energy sources such as solar and wind for electricity production 2. Movement from internal combustion engines to a hydrogen-based vehicles.
Healthcare	1. Movement from internal to external (e.g., Internet) -based information systems 2. Nanotechnology-based treatments for cancer

have a particularly strong need for such models as not only are their faculty grappling with the future, students themselves are making irreversible decisions about their future when they choose their courses.

Models are needed that can help firms, entrepreneurs, governments, research institutions and universities understand the mechanisms by which discontinuities occur

For example, many entrepreneurs, governments, research institutions, firms and universities are now grappling with how to move beyond a petroleum-based economy. They are considering discontinuities such as ethanol, hydrogen, fuel-cell and electric-based vehicles, renewable sources of electricity such as solar, wind, biomass and tidal, and policies for encouraging the development and implementation of these "technological discontinuities". However, the above-mentioned models of technological change provide us with little help in understanding or analysing the factors driving these discontinuities and therefore in saying something meaningful about which of them have the largest chance of success in the future.

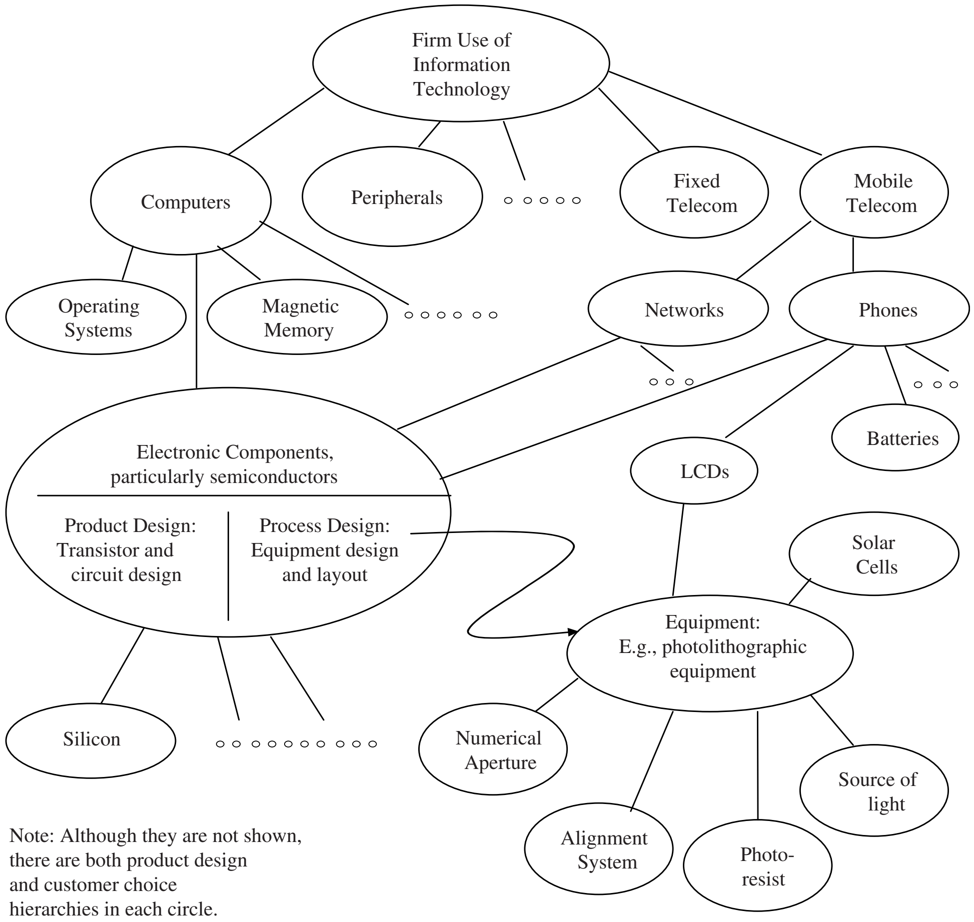
This paper introduces a model that describes the mechanisms by which many technological discontinuities occur and a means by which to analyse the potential sources and possible timing of these discontinuities. The model combines three arguments: 1) incremental improvements in a system's components impact on the performance and design of systems; 2) these incremental improvements can lead to discontinuities in system design through their impact on the design trade-offs that are inherent in all systems; and 3) these incremental improvements in components can cause the components to become applicable to completely new systems. Sections 3—5 apply this model to the semiconductor, computer and other IT-related industries respectively and Section 6 describes how the model could be used to analyse the *future* of the IT and energy sectors.

Key aspects of the model

The first key aspect of the proposed model is the notion of hierarchies. Beginning with research by Herb Simon, the Nobel Prize winner, many scholars have noted the hierarchical nature of both systems and the decisionmaking about such systems. Simon and other scholars have noted that all products, including basic materials such as glass and chemicals, can be represented as multiple levels of subsystems that are organised in a hierarchical fashion or what this paper calls a nested hierarchy of subsystems (NHOS). A parallel hierarchy of firms can also be defined where the differences between the hierarchies of subsystems and firms will depend on the degree of vertical integration in firms. For simplicity, we will assume that the NHOS used to represent the IT sector in Figure 1 corresponds to the hierarchy of firms where each level in the NHOS corresponds to a single industry.[2]

Kim Clark extended the notion of hierarchies in decisionmaking by introducing the concepts of product design and customer choice hierarchies. These hierarchies can be applied to each level (i.e., industry) in the NHOS shown in Figure 1 and they reflect the decision making about markets and products that occur over time in an industry as new products are introduced. The customer choice hierarchy represents a firm's perception of the ways in which customers make choices in the market and thus how firms define market segments and the problems to be solved in each segment. The product design hierarchy represents the hierarchical nature of problem-solving in each segment.[3]

The introduction of new products and services by firms reflect movements both down and up the hierarchies of product design and customer choice in the industry. Following a technological discontinuity and a period of intense technical variation, customer segments begin to emerge and



Note: Although they are not shown, there are both product design and customer choice hierarchies in each circle.

Figure 1. Nested Hierarchy of Sub-Systems in the IT Sector (simplified)

design activity moves from higher-level to lower-level problem-solving where these movements down the hierarchies reinforce the decisions made at higher levels in the hierarchies (See Figure 2).[4] The amount of movements down the hierarchies reflects the degree of similarity between different firms' methods of segmenting customers (customer choice hierarchy) and between different firms' product designs and the degree to which these decisions reinforce as opposed to overturn previous decisions. Large movements down the hierarchies mean that firms are introducing similar products and segmenting customers in a similar way and that these decisions are reinforcing previous

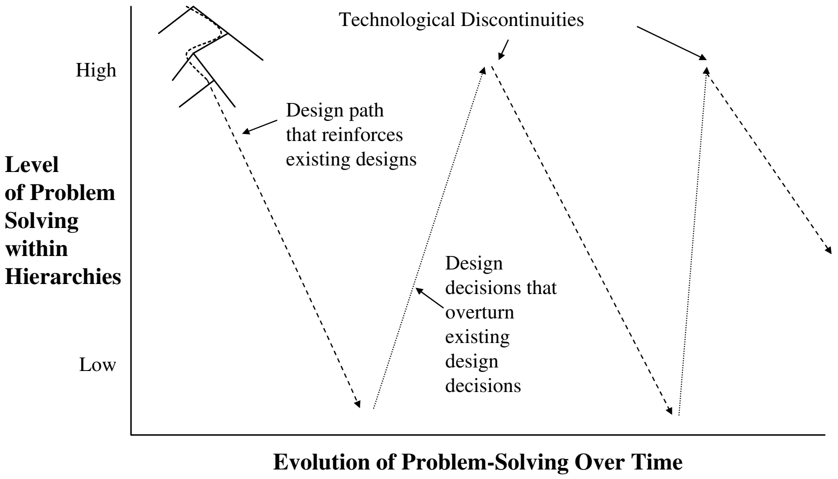


Figure 2. Evolution of Problem-Solving in an Industry Over Time

decisions. Movements back up the hierarchies mean that some firms have redefined the segments or changed the product architectures or technical concepts that underlay the product.

The second key aspect of this model is the notion of design trade-offs. Economic, marketing and information science scholars have long used the concept of trade-offs between cost and various measures of performance to define specific market segments and the demand for specific products and services in each segment.[5] These segments and the trade-offs users make in each segment can be considered part of Clark's customer choice hierarchy. Engineers combine such information about customer needs with information about the trade-offs between different engineering variables in order to consider trade-offs between different types of components and different types of materials, processes and equipment for these components, all of which can be considered part of Clark's product design hierarchy. A casual look at any engineering journal will find figures that display the trade-offs between different engineering variables, albeit in a simplified manner. Formal engineering techniques such as value engineering, quality function deployment and design structure matrices also provide insights into how engineers translate the information about trade-offs between engineering variables and those that customers make between price and performance into engineering decisions about components, materials and processes.[6]

Third, these trade-offs are not constant. Incremental improvements at one level in a NHOS can change the "design trade-offs" for higher levels in a NHOS and thus require firms or even societies to move *back up* the hierarchies of both product design and customer choice at the higher level in the NHOS. Although other scholars have noted that radical innovations in components can lead to modular innovations in systems, this paper argues that many discontinuities, including radical, modular and architectural, can be explained solely in terms of incremental improvements at lower levels in a NHOS through their impact on the design trade-offs that exist in higher levels in a NHOS.[7]

These changes in trade-offs represent a more general mechanism of technology "overshoot" in Clayton Christensen's concept of disruptive technologies. Disruptive technologies often occur when an existing technology "overshoots" existing customer needs where this paper argues that such "overshoots" represent changes in the trade-offs customers make between performance and price or between different measures of performance.[8] In this paper's proposed model, the changes in design trade-offs can occur at both an internal (engineering trade-offs internal to the product) and an external (trade-offs made by customers) level and in some cases such changes can ripple through multiple levels in a nested hierarchy of subsystems. For example, improvements in cars in the second half of the 20th century changed the design trade-offs for cities and thus enabled their inhabitants to redesign them to include suburbs and extended commuting. Similarly, improvements in transportation, communication and computer systems (shown below to have come from improvements in components) in the last 10 years have changed the trade-offs for production systems and one result has been that many now think that the "World is Flat".[9]

The degree to which firms introduce new product designs and consider new customers reflects the degree of movements back up the product design and customer choice hierarchies. And the degree to which firms move back up these hierarchies and introduce new designs and target new customers defines the degree of a technological discontinuity. Although firms often make small moves back up the hierarchies as they redefine customer segments or make small design changes, we are primarily interested in large movements back up the hierarchies. In terms of the largest movements back up the hierarchies, technological discontinuities that are primarily due to movements back up the customer choice hierarchy are called niche innovations by Kim Clark and William Abernathy or disruptive technologies by Clayton Christenson. Ones that are primarily due to movements back up the product design hierarchy are often called revolutionary or architectural innovations.[10]

The fourth key aspect of this model is that these incremental improvements in components can cause the components to become part of multiple NHOSs and such changes can happen quickly and quite unexpectedly. As components are improved for the purpose of a specific type of system, they may become applicable to another type of system and thus can become part of another NHOS and lead to a technological discontinuity in that NHOS. For example, military systems were the main market for semiconductors and ICs in the early 1960s and therefore in the early 1960s semiconductors and ICs could be considered primarily part of the NHOS for military-orientated electronic systems. But improvements in ICs made them applicable to consumer products and they became part of the NHOS for consumer products. Similarly, the different types of equipment used to manufacture ICs were initially part of the NHOSs for both military and consumer-orientated electronic systems. But improvements in these equipment and other changes eventually made the equipment applicable to the production of LCD and they became part of the NHOSs for LCDs. Now it appears that improvements in the equipment for the production of LCDs and other changes are making this equipment applicable to that of photovoltaic solar cells and that continued improvements in semiconductor material technology are bringing new design choices to solar cells. Thus semiconductor processes continue to be an important part of the NHOS for solar cells, equipment for the production of LCDs is becoming a new part of the NHOS for solar cells, many industry participants expect improvements in these semiconductor processes and LCD equipment to drive reductions in cost and improvements in performance for solar cells, and these improvements will probably lead to discontinuities in the energy industry.

IT and the semiconductor industry

Consider the discontinuities that have occurred in the IT sector between 1950 and 1995 (until the emergence of the Internet). Figure 1 summarises the NHOS in this sector, Table 2 summarises several discontinuities that have occurred in each level of this NHOS and Table 3 summarises the ones for semiconductors including the specific moves back up the product design and customer choice hierarchies for them. As shown in Table 3, there have been large movements back up the product design hierarchy for semiconductors in terms of changes in material, transistor and system design. There were changes in materials from germanium to silicon in the 1950s and in transistors from bipolar to MOS (Metal-Oxide Semiconductor) and later CMOS (Complementary MOS) in the 1970s. There have also been changes at the system level from ‘‘combinations of discrete devices’’ to ‘‘combinations of ICs [integrated circuits] and discrete devices’’ and later to combinations of more complex ICs such as memory, microprocessors and other semi-custom designs. The MOS and CMOS ICs and microprocessors also involved changes in the customer choice hierarchies in

Table 2. Examples of Technological Discontinuities in each Level (except the top one) of the Nested Hierarchy shown in Figure 1 (until the Emergence of the Internet)

Level in Nested Hierarchy	Technological Discontinuities
Computers	1. Mainframe computers 2. Mini-computers 3. Personal Computers (PC) 4. Personal Digital Assistants (PDA), laptops, and other mobile devices
Telecommunication	1. Circuit switching for voice 2. Circuit switching for electronic data interchange (EDI) 3. Packet switching
Electronic technologies (particularly semiconductors)	1. Vacuum tube-based designs 2. Silicon transistor-based designs 3. Integrated circuit (IC) based designs 4. Microprocessor-based designs
Photolithographic equipment	1. Contact aligner 2. Proximity aligner 3. Scanning projection 4. Stepper

Table 3. Major Technological Discontinuities and their Impact on the Product Design and Customer Choice Hierarchies for Semiconductors

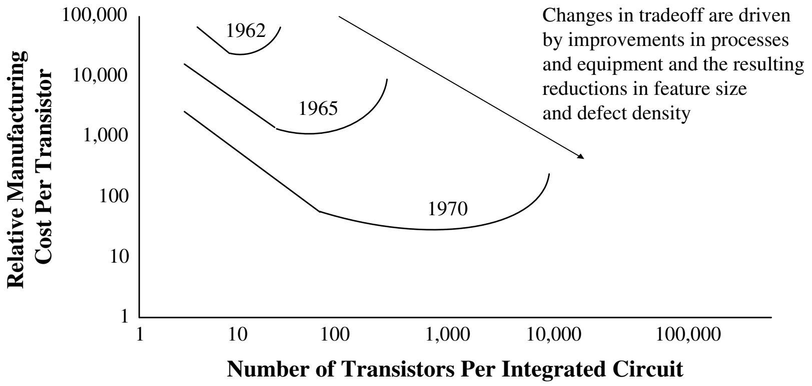
Technological Discontinuities (emphasis on underlined terms)	First Introduced	Movements back up the Hierarchies	
		Product Design	Customer Choice (early users)
Combinations of discrete germanium bipolar transistors and other discrete devices	Early 1950s	Change in material, transistor and system design (from vacuum tubes)	Military and later transistor radios
Combinations of discrete silicon bipolar transistors and other discrete devices	Mid-1950s	Change in material	No changes (still military)
Combinations of bipolar ICs and discrete devices	Early 1960s	Change in system design	No changes (still military)
Combinations of MOS ICs and discrete devices	Early 1970s	Changes in transistor design	Calculators, computer memory
Combinations of CMOS ICs and discrete devices	Mid-1970s	Change in transistor design	Watches and calculators
Combinations of microprocessor, memory, and discrete devices	Mid-1970s	Changes in system design	Aviation, medical, test equipment
Combinations of microprocessors, memory, ASICs, and discrete devices	Early 2000s	Change in system design	Computers

IC: Integrated circuits; ASICs: application specific integrated circuits.

that there was a different set of initial customers (listed in parentheses) for MOS chips (calculators, computer memory), CMOS chips (digital watches) and microprocessors (low-volume equipment) than there were for the previous generations of semiconductors.[11]

These technological discontinuities were driven by incremental improvements in semiconductor manufacturing equipment and the processes this equipment was used in (see Figure 1). For example, improvements in this equipment and the processes they were used in led to reductions in feature size and defect density in the late 1950s. This caused Jack Kilby of Texas Instruments to recognise that the advantages of producing resistors, capacitors and transistors on the same substrate material (i.e., silicon) in a so-called bipolar integrated circuit (IC) would *eventually* outweigh the advantages of using the optimal material for capacitors (Mylar) and resistors (carbon) in discrete components. It also caused Robert Noyce of Fairchild to recognise that the advantages of using a metal layer to connect multiple transistors on a single IC chip (and thus not connecting individual transistors with wires) would *eventually* outweigh the disadvantages of lower yields from placing multiple transistors on a single IC chip. The key word is *eventually*. While other researchers were focused on the day-to-day problems of how best to design and fabricate capacitors, resistors and transistors according to existing trade-offs, Kilby and Noyce considered the implications of improvements in semiconductor manufacturing equipment (i.e., one step lower in the NHOS for semiconductors) for how these capacitors, resistors and transistors would be best designed in the future.

Subsequent improvements in processes and their associated equipment have reduced feature sizes by more than 100 times and defect densities by more than 1,000 times in the last 45 years. The implications of these trends were noted by Gordon Moore in his 1965 article in *Electronics Magazine* that led to the term "Moore's Law". Slightly modified from Moore's original figure, Figure 3 shows



Source: Adapted from Moore, G. Cramming more components onto integrated circuits, Electronics, April 19 1965

Figure 3. Evolution in the Tradeoff (reflected in U-shaped curves) between the Benefits and Costs of Integration in Integrated Circuits

the evolution in the ‘‘optimal’’ level of integration (see U-shaped curves) over time where reductions in feature size and defect density pushed this optimal level of integration towards the lower-right part of the figure. The optimal level of integration represents the trade-offs between the benefits and costs of increased integration that are discussed in the last paragraph and that were analysed by Robert Noyce and Jack Kilby as they were developing the first ICs. Their efforts reside in the upper left-hand corner of Figure 3 in the move from one to multiple transistors on a single IC.

Moore's predictions have largely come true. However, the continued reductions in feature size, which were driven by improvements in processes and manufacturing equipment, have continued to change the trade-offs between performance and cost and between a broader set of performance variables. For example, the reductions in feature size caused power consumption to become a major problem in many electronic products. This caused designers to gradually replace bipolar-based ICs with MOS and later CMOS ICs because the MOS and CMOS ICs use less power than do bipolar ICs. The new markets of calculators and digital watches for ICs represented the moves back up the customer choice hierarchy for MOS and CMOS ICs respectively. Although MOS and CMOS ICs were first used in military applications, it was pocket calculators and digital watches that provided the first large applications for them. In spite of their slower speeds, only MOS ICs could provide the low levels of power consumption that was demanded in pocket calculators. Similarly, only CMOS ICs could provide the low levels of power consumption that were required in digital watches.

Further reductions in feature size and increases in the number of transistors per chip have also made it economical to ‘‘waste’’ silicon space in return for lower design costs. Increases in the number of transistors per chip increase the design cost of ICs and this favours semi-custom designs such as microprocessors and application-specific integrated circuits. Microprocessors, which can be programmed to perform a wide variety of techniques, initially filled the gap between general purpose logic chips and full custom ones. Application-specific integrated circuits such as gate arrays, standard cell libraries and programmable logic devices have filled in other gaps in the trade-off between design costs and the efficient use of silicon space and design costs, which are largely dependent on the expected volume of the electronic system.

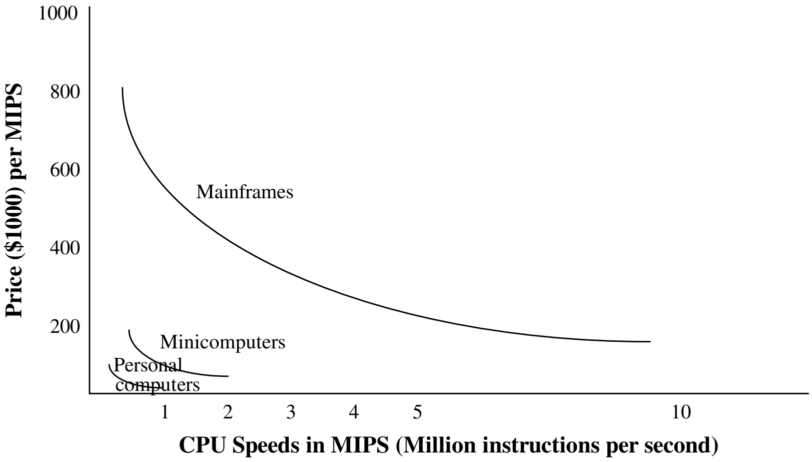
We can take this historical analysis of the semiconductor industry one step further and look at one step lower in the NHOS of the IT sector, which is semiconductor manufacturing equipment (See Figure 1). The most important type of semiconductor manufacturing equipment is called photolithographic equipment. Improvements in this and other equipment have led to reductions in feature size and increases in the number of transistors per chip and thus to many of the discontinuities that are described above. As described by Rebecca Henderson, improvements in this equipment also involved many discontinuities, which she calls architectural innovations, and many of these discontinuities were driven by improvements in the equipment's components such as the light source, numerical aperture and an alignment system. Shortening the wavelength of light used to expose wafers, expanding the numerical aperture and improving the accuracy of alignment systems changed the design trade-offs for photolithographic equipment and thus required their manufacturers to move back up the product design hierarchy several times and introduce new architectures.

Computers

As most people are aware, many of the improvements in ICs discussed in the last section had a large impact on the computer and other IT-related industries. Referring to this paper's model, improvements in ICs have led to changes in the design trade-offs for higher levels in the nested hierarchy for the IT sector and thus the emergence of technological discontinuities for computers (and to some extent in telecommunication systems in the form of packet systems, local area networks and modems).

For example, Table 2 summarises some of the major technological discontinuities in the computer industry and the movements they caused back up both the product design and customer choice hierarchies.[12] The movements back up the product design hierarchy are represented by the scaled-down nature of these discontinuities and the movements back up the customer choice hierarchy are represented by the new applications and users for them. Improvements in ICs (and magnetic recording density) have enabled firms to develop scaled-down versions of mainframe computers such as mini and personal computers and PDAs that can be considered discontinuities. These scaled-down versions used much slower processors, smaller memory, shorter word lengths and smaller instruction sets, and thus had significantly lower performance than the previous generation of computers. Although many of these design trade-offs only existed within the product design hierarchy, Figure 4 shows how changes in the trade-offs between performance and the ratio of price to performance also required movements back up the customer choice hierarchy. Minicomputers and PCs provided users with different trade-offs between computing cost and speed and thus appealed to new sets of users and depended on new applications (See Table 4).

For example, DEC's PDP-8 is usually considered the first mini-computer. In terms of movements back up the product design hierarchy, the mini-computer was a scaled-down version of the mainframe that used a smaller CPU and a shorter word length (12-bits) and instruction set, which made the mini-computer much cheaper to produce than the smallest IBM System/360 machine. Movements back up the customer choice hierarchy are represented by the differences between the customers and applications for the mini and mainframe computers and the different trade-offs



Source: Adapted from (Smith, 1989)

Figure 4. Relationship Between Prices and Performance (1981 data) for Technological Discontinuities in Computers, which Reflect the Different Trade-offs Between Price and Performance that are Made by Different Users

Table 4. Technological Discontinuities and their Impact on the Product Design and Customer Choice Hierarchies for Computers

Discontinuity	Movements back up the Hierarchies		
	Product Design	Customer Choice	
		Early Users	Early Major Applications
Main-Frame	Add vacuum tubes to punch card equipment	No changes (Existing punch-card users and their business systems)	
Mini-Computer	Scaled-down version of mainframes	Scientific & engineering companies	Engineering analysis and process control
Personal Computer (PC)	Scaled-down version of mini-computers	Individuals (home, university, small business)	Games spread-sheet, word processing
Portable	Scaled-down version of PCs	Different for laptops, PDAs and smart phones	

between price and performance that mini and mainframe computer users were making (See Figure 4). Scientific and engineering departments used mini-computers for product design and process control where they developed their own software and made modifications to the input-output devices. The user's development of software and modifications to the hardware were made possible by DEC's business model that included extensive product documentation and the sale as opposed to only leasing of the mini-computers.

As for the first PC, it was a scaled-down version of the mini-computer that used a smaller CPU, semiconductor memory, instruction set and word length. This made the PC much cheaper to produce than the smallest mini-computer and provided users with a different trade-off between price and performance (See Figure 4). In terms of movements back up the customer choice hierarchy, individuals (including hackers) and small firms were the initial customers where hackers were happy to write their own software and even the first packaged software applications (game and education software) were quite different from those for mini-computers. The new business model was the sale of PCs and pre-packaged software through the mail and in retail outlets such as Computerland.

Looking back over the last 50 years, some of this was predictable. It was inevitable that the increases in the number of transistor per chip cited by Moore in 1965 would lead to the placement of a computer on a chip (i.e. microprocessor) and to new forms of semi-custom chips that have much lower development costs than custom chips or even microprocessors. It was also inevitable that improvements in these new forms of ICs would lead to cheaper computers largely in the form of scaled-down ones. On the other hand, the exact design, the first customers and the timing for each of the discontinuities (along with the appropriate strategies, which are not the subject of this paper) were clearly much more difficult to predict.

Some of this story is consistent with Christensen's theory of disruptive change and this paper's proposed model complements his model. The discontinuities that involved movements back up the customer choice hierarchy were first used by a new set of customers and sometimes involved technology overshoot. For example, mini and personal computers did involve technology overshoot and they were first used by new sets of customers. MOS ICs (calculator manufacturers), CMOS ICs (digital watches) and microprocessors (calculators and low volume equipment) were each also used by a new set of customers. On the other hand, it is more difficult to identify the form of technology overshoot in the examples of MOS and CMOS ICs and microprocessors as Moore's Law applies equally well to all of them. Instead, it is more accurate to say that these examples of discontinuities involved changes in the trade-offs that were used by both the users to select products and the designers to design them and the changes in these trade-offs required firms to rethink the design of and customers for these semiconductors.

Other industries in the IT sector

This paper's proposed model can also be used to explain a number of discontinuities in other IT-related industries such as the mobile phone and television broadcasting industries. Like the computer industry, improvements in semiconductors have driven changes in the design trade-offs and thus the emergence of technological discontinuities for mobile phones.[13] For example, until improvements in semiconductors enabled digital switching in the 1970s, mobile phone systems used a single transmitter to cover a wide geographical area in order to avoid the problems with switching users between different "cells". Improvements in semiconductors and therefore digital switching changed the trade-offs between the cost of switching users between cells and the efficient use of the frequency spectrum. Dividing a mobile phone system into multiple cells enabled the frequency spectrum to be reused in each cell. Although this required expensive switching equipment, the falling cost of digital switches gradually caused the benefits of increased frequency spectrum efficiency to exceed the costs of this switching equipment.

Further improvements in semiconductors continue to change the trade-offs between the efficient use of the frequency spectrum and other variables such as price and in doing so have enabled second and third-generation systems of mobile phones to be implemented. Second-generation systems transmit digital as opposed to analogue signals between phones where sophisticated "digital receiver algorithms" convert analogue voices into digital signals and vice versa. The sophistication of the algorithms determines the capacity of a specific "cell" and more sophisticated algorithms such as CDMA (code division multiple access), which is used in third-generation systems, require faster microprocessors and other digital chips. In this way, improvements in semiconductors have changed the trade-offs between the costs and benefits of digitalisation, not only in mobile phones but also in digital recording for both music and video. Digital phones, compact discs (CDs) and digital video discs (DVDs) could not be implemented until the cost of ICs had fallen to the point that the advantages of digitalisation exceeded the higher data requirements and thus costs of them.[14]

Improvements in semiconductors have changed the trade-offs between the costs and benefits of digitalization

Improvements in a much broader set of components are now driving the next technological discontinuity for mobile phones, the mobile Internet. Improvements in not just semiconductors, but also liquid crystal displays (LCDs), batteries and mobile phone infrastructure (which is also largely based on improvements in semiconductors) have changed the trade-offs implicit in the design of a mobile phone network and made the connections between the mobile phone and internet possible. Although wireless data networks have been in use since the 1980s, improvements in the components have now made a consumer-based mobile Internet possible.

Interestingly, the improvements in LCDs and other flat-panel technologies such as plasma and organic light-emitting diodes (LED) are largely driven by improvements in the processes and equipment that are used to make semiconductors. Improvements in semiconductor processes and manufacturing equipment led to reductions in both the horizontal and vertical feature sizes in semiconductors of which the reductions in the vertical dimension are of particular relevance to LCDs. Equipment used for purifying the air, creating a vacuum, growing silicon, depositing other materials in thin films and, to a lesser extent, creating patterns on these layers (the horizontal dimension) are applicable to both semiconductors and LCDs. This equipment became applicable to LCDs as passive-matrix LCDs were replaced by active matrix LCDs in the 1980s (which use thin-film transistors) and the volumes of these new LCDs reached a level at which semiconductor manufacturing equipment could be economically used in their production in the 1990s.[15]

The biggest market for flat panel displays is now television and television provides another example of this paper's proposed model albeit one that shows how firms can also be initially overly optimistic about the emergence of a technological, discontinuity by implicitly over-estimating the improvements at lower levels in a NHOS.[16] For example, the slower than expected improvements in cathode ray tubes, a key component in televisions, caused firms to overestimate how fast colour and later high-definition television (HDTV) would diffuse. Although the US government and broadcasters agreed on standards for colour television in 1953, the high cost of colour picture tubes (and the challenges of creating a critical mass of colour programmes) prevented the sales of colour televisions from exceeding those of black and white televisions until 1968. European countries that delayed the definition of a colour standard saw a much smaller time lag between the setting of colour standards and the diffusion of colour television than the US did.

In HDTV, the US, Europe and particularly Japan initially overestimated the rate at which prices for large television screens, which were needed for consumers to benefit from HDTV, would fall. This and the realisation by US firms that improvements in semiconductors would make digital television possible is one reason why US firms turned their attention from HDTV to digital television in the early 1990s. The rapidly falling prices for set-top boxes, which are driven by improvements in semiconductors, suggest that this decision and those by governments to set aggressive timetables for digital television were good decisions. It has only been recent improvements in LCDs and other flat-panel technologies that are now making large television screens economical, which is increasing consumer interest in HDTV.

Looking forward: IT and energy

How can we use the proposed model to say something about the future? Assuming that Moore's Law continues to hold, we can say that continued increases in the number of transistors per chip are and will lead to new forms of discontinuities in both the semiconductor and computer industries.[17] For example, many argue that the reduced feature size and increased numbers of transistors on a chip are leading to changes/discontinuities in the semiconductor industry such as the increased use of System on a Chip (SoC), the use of configurable processors on an SoC, the customisation of such processors for specific applications, the integration of antennas on these chips, the reconfiguration of these chips wirelessly after they have been installed in the field, the use of a broader number of materials on these chips, the placement of test and other laboratories facilities on a single chip, and the smart delivery of drugs via ingested chips.[18] With respect to the latter two cases, a variety of sensors and machines can be placed on a chip and chemicals can be placed in a cavity of a chip where both of these features enable the production of small portable testers and of drugs that can target specific parts of the body and often the infected parts of the body.[19] The exact markets for these products and whether and how incumbents will be able to adapt to them are separate questions that can be better addressed when we understand what is technologically driving the emergence of them as possible discontinuities.

These improvements in semiconductors along with those in flat-panel displays, batteries and other technologies will impact on computers, mobile phones and other devices. It is inevitable that new forms of computers that cost less than $150 will appear. Similarly, it is likely that the interface of mobile phones will be dramatically improved, that RFID tags will eventually have enough transistors on them to function as a computer, and that RFID tags, smart dust and other devices will become decentralised networks of computers that are connected by small antennas and short-range wireless technologies. Thinking about the technological drivers of these discontinuities is a somewhat different question from thinking about how firms will or should deal with them.

It is also likely that continued improvements in computers, semiconductors and LCDs will indirectly impact on the way in which humans produce and use energy and the way in which technological discontinuities may emerge for energy systems. For example, as mentioned earlier, semiconductor manufacturing equipment has become part of the NHOS for LCDs and it appears that LCD manufacturing equipment is becoming part of the NHOS for photovoltaic solar cells. Semiconductor manufacturing equipment became applicable to the production of LCDs as the volumes of active matrix LCDs reached the point at which this high-volume equipment could be economically applied. This is one reason why the prices of 42-inch flat panel displays have dropped from about $7,500 to $1,500 in the last three years.[20]

Similar things are now happening in photovoltaic solar cells. The ability to apply processes from the semiconductor industry (e.g., cheaply deposit multiple layers of materials on different types of silicon and other substrates) to the production of solar cells was one factor driving improvements in these cells during the 1980s and 1990s. The price of solar cells dropped from $22 per watt in 1980 to less than $3 per watt in 2007. Now the production volumes for solar cells have reached the point at which high-volume LCD manufacturing equipment can be economically used to produce solar cells. Applied Materials, the world's largest supplier of semiconductor manufacturing equipment and the second-largest supplier of LCD equipment, began adapting for the production of solar cells in 2006. It now expects $400m in sales from the photovoltaic solar cell business in 2007 and $1bn by 2009. The CEO of Applied Material believes that his company's equipment can help drive the price of solar cells below $1 a peak watt, which would rival grid-delivered fossil fuel power.[21]

These improvements in equipment, semiconductor processes and other components of the NHOS for solar cells are impacting on the trade-offs between using solar versus grid-delivered fossil fuel power and on those between using different types of photovoltaic systems. Key solar system design decisions include the choice of materials, the thickness of them, and whether or not to use mirrors to concentrate the sun's rays on to these solar cells. Amorphous silicon is the cheapest and least efficient (about 10 per cent), polycrystalline silicon is more expensive and efficient, and single crystal silicon is the most expensive and efficient (about 25 per cent) form of silicon-based solar cell.[22] A material called CIGS (Copper Indium Gallium Selenide) reportedly provides similar levels of efficiency but much lower costs than single crystal silicon when nano-sized particles of it are made into a liquid and rolled on to a metal conductor using printing press-type equipment.[23] The highest efficiencies (but with the highest costs) can be achieved through the use of multiple layers of thin-film semiconductors in which each layer is designed to capture a different part of the sun's frequency spectrum. The cost and performance of mirrors and tracking devices (including the IC controls for them) also impact on these trade-offs between efficiency and cost because the use of them can increase the amount of sunlight that reaches the solar cells.[24] All of these design decisions and their interactions with specific customers, which can be analysed in terms of movements back up both the product design and customer choice hierarchies, can be considered part of a possible discontinuous change from conventional to solar photovoltaic electricity systems or also as part of multiple discontinuous changes from one type of solar system to another.

It is possible to use this paper's methodology to analyse photovoltaic solar cells in much more detail, to do the same thing for other types of energy systems, and to compare these energy systems (See Table 5). Such an analysis would require an understanding of the alternative compositions of these energy systems, the relationship between the components and subsystems in each alternative system, and the rates of improvements in the relevant subsystems and components. The results from such an analysis could provide us with a better understanding of how the performance of these different energy systems might change over time. Contrast this paper's approach with the typical analyses of energy systems that primarily focus on the *existing* performance of final systems and that almost always ignore improvements in components and thus assume that if there are improvements in them, all components will undergo the same rate of change.[25]

This paper strongly disagrees with these assumptions. All components are not undergoing the same rate of change, there is data on which components are undergoing faster rates of change

Table 5. Selected Energy Systems and their Relevant Sub-Systems and Components

Energy System	Discontinuity	Relevant Sub-Systems and Components (components shown in parentheses)
Vehicles	Ethanol	Crops (cultivation, harvesting, distribution), processes (liquefaction, fermentation, distillation), distribution
	Hydrogen	Hydrogen (electricity, electrolysers, distribution system), hydrogen storage tank, tank control unit, fuel cell stack (membranes, catalysts), electric motor
	Electric/Hybrid	Batteries, controller, regenerative braking, electric motor/generator
Vehicle Systems	Intelligent Highway Vehicle System	Vehicles, antennas, on-board control systems, centralised control systems
Electricity	Solar/Photovoltaic	Semiconducting materials such as silicon, including single crystalline, polycrystalline, and amorphous silicon (silicon growth equipment), thin-film processing techniques (deposition, diffusion, and etching equipment), mirrors, and mechanical tracking (motors and controllers)
	Wind	Propellers, support structure, electrical generator
	Solar/Thermal	Mirrors (heliostat), receivers, steam turbine, electrical generator, cooling tower
	Nuclear	Reactor core, fuel assembly, control rods, heat exchanger, steam turbine, cooling tower, electrical generator

Sources: Ewing, R. 2007. Hydrogen: Hot Stuff, Cool Science, Masonville, CO: PixyJack Press; Scheer, H. 2005. The Solar Economy, London: Earthscan.

than others, and we can use this data to better understand the future performance of systems and the possibilities of discontinuities occurring in them. Understanding the future performance of systems, the discontinuities that might occur in these systems and the bottlenecks in subsystems and components are clearly important issues in the energy and other sectors that involve complex systems and this paper's model can help us address these types of issues.

Discussion

This paper has described a model that can help entrepreneurs, governments, research institutions, firms and universities better understand the mechanisms by which discontinuities occur and thus the sources and perhaps timing of them. A key aspect of the proposed model is how incremental improvements in components impact on the performance of systems. In particular, incremental improvements at one level in an NHOS can change the design trade-offs for higher levels in a NHOS and require firms or even societies to move *back up* the hierarchies of both product design and customer choice at a higher level in a NHOS. In moving back up the product design and customer choice hierarchies, firms are considering radical new designs and new segmentations of customers where the latter may include new sets of lead customers.

Using the examples presented in this paper (and a few not covered so far), Table 6 categorises the ways in which improvements at one level in a NHOS have changed the internal and external trade-offs that existed at higher levels in a NHOS for several technological discontinuities. Starting at the top of Table 6, the internal trade-offs that engineers make between different materials or components were impacted on by the different rates of improvements in manufacturing processes for these different materials or parts. For example, greater improvements in processes for semiconductors (in particular silicon) than for vacuum tubes led to the discontinuity of transistors (and for the move from germanium to silicon transistors).

Table 6. Categorisation of Changes in Design Tradeoffs that Enabled Technological Discontinuities

General Tradeoffs	Examples of Detailed Tradeoffs	Factors Driving Changes	Technological Discontinuity
Trade-offs made by engineers (i.e., internal): between			
Different types of materials	Between germanium and silicon	Different rates of improvement for different equipment and processes	Silicon transistors
Different types of parts	Between vacuum tubes, transistors, and integrated circuits		Solid-state radios and televisions
Component and System Performance	Between optimal material for component (e.g., capacitor, resistor) and system (IC)	Reductions in feature size and defect density	Integrated Circuits
Analogue and digital design	Between lower data needs of analogue and higher quality of digital	Better ICs	CDs and DVDs
	Between higher costs and higher spectrum efficiency of digital	Better ICs	Digital phones and televisions
Tradeoffs made by customers (i.e., external): between			
Price and performance	Between price and processing speed	Better ICs	Mini and personal computers
	Between price and memory capacity	Magnetic recording density	Smaller disk drives
Different measures of performance	Between heat/power dissipation and speed	Reductions in feature size and defect density	MOS and CMOS ICs
Different types of user costs	Between fixed (development costs) and variable costs (efficient use of silicon space)	Reductions in feature size and defect density	Microprocessors and ASICs

The trade-offs that engineers make between component and system performance were also impacted on by improvements in semiconductor processes. For example, reductions in the density of defects when producing transistors reduced the disadvantages in lower yields that came from placing multiple devices on a single IC. These reductions in defect density and in feature size also reduced the disadvantages from using a sub-optimal material, silicon, for resistors and capacitors as the benefits from placing all components on a single IC appeared.

The trade-offs that engineers make between analogue and digital designs were impacted on by improvements in ICs. For example, improvements in ICs reduced the importance of the higher data needs of digital (and thus higher costs) over analogue designs and caused other advantages of digital designs such as higher quality, easier editing and higher spectrum efficiency to become more important. For example, digital audio formats such as CDs and DVDs provided users with higher quality and more compact means of storing music and movies. Digital mobile phones and televisions also provide higher quality and more efficient use of the frequency spectrum than do analogue designs. With respect to mobile phones, improvements in ICs have been changing the trade-offs in mobile phone system design for more than 40 years, have led to three technological discontinuities (analogue, digital and third generation systems), and now are enabling more sophisticated data services.

As also shown in Table 6, customers make trade-offs between price and performance, between different measures of performance, and between different types of costs (i.e., external trade-offs). For example, the trade-offs between price and processing speed for computers have been impacted on by improvements in ICs. Different users of computers make different trade-offs between price and performance and improvements in ICs gradually changed the trade-offs between them, thus enabling the change from mainframe to mini and later personal computers.

Users also make trade-offs between different measures of performance and different types of costs. For example, reductions in feature size changed the trade-offs that system engineers (i.e., IC users) made between heat/power production and speed in ICs. As the heat from ICs increased with smaller feature sizes, system engineers favoured the lower power consumption of MOS and later CMOS devices. Similarly, reductions in feature sizes also increased the number of transistors on a chip and thus the development costs of those chips. This caused many users of ICs to favour the lower development costs of programmable devices such as microprocessors and application specific circuits (ASICs) such as gate arrays, standard cells and programmable logic devices.

In addition to these design trade-offs that are inherent in a NHOS, the exact timing of the discontinuities depends on how firms use these improvements to rethink their products and customers. For products in the IT sector, firms were forced to rethink the material, transistor and system designs for semiconductors and the scale of computers and hard disk drives. In terms of customers, movements back up the customer choice hierarchy reflect changes in the users and applications and any movements back up this hierarchy may reduce the improvements in performance and cost that are needed for growth in the discontinuity/new product class to occur. For example, the demand for portable calculators made it possible for MOS ICs to diffuse before their speed had reached the level of bipolar ICs and the demand for digital watches made it possible for CMOS ICs to diffuse before their speed had reached the level of MOS ICs. The demand for various types of low-volume aviation and other equipment made it possible for microprocessors to diffuse before their speeds had reached the level of central processing units in mainframe or mini-computers. The existence of scientific and engineering applications made it possible for mini-computers to diffuse before they had achieved the processing speeds of mainframe computers and the existence of hackers made it possible for PCs to diffuse before they had achieved the processing speeds of mini-computers.

Movements back up the customer choice hierarchy reflect changes in the users and applications

The final contribution of this paper is in how improvements in components can have an impact on multiple NHOSs. Although ICs were initially used in military systems, improvements in ICs made them applicable to consumer products and therefore these ICs became part of the NHOS for consumer products. Similarly, the different types of equipment used to manufacture ICs became part of the NHOSs for both military and consumer-orientated electronic systems. Improvements in semiconductor manufacturing equipment and the similarity between ICs and LCDs eventually made this equipment part of the NHOSs for LCDs. Now it appears that improvements in equipment for the production of LCDs are making them part of the NHOS for these solar cells just as semiconductor processes have been part of the NHOS for solar cells for many years. It is quite likely that improvements in semiconductor materials and processes and the equipment used in LCDs will lead to dramatic improvements in the performance-cost ratio for these solar cells and thus various types of technological discontinuities.

Improvements in photovoltaic solar cells clearly have implications for how to move beyond a petroleum-basedeconomy, which was raised in the introduction as an important motivation for this paper. The increasing prices of petroleum are changing the trade-offs by which societies design their transportation and other systems and including the environmental costs of oil and other carbon-based fuels in these prices would further change these trade-offs. However, rather than implementing a ‘‘Manhattan Project’’ for a hydrogen-based economy as some suggest, this paper’s model suggests that decision makers should be considering how improvements in components are changing the trade-offs in the NHOS for energy and transportation systems. Considering these improvements in components would help us to make better decisions about how to move beyond the petroleum-based economy.[26]

Conclusions

This paper has introduced a framework that is a first step towards understanding the mechanisms by which discontinuities occur and thus a means by which governments, entrepreneurs, research institutions and corporations can better understand the sources and possible timing of them. Simply stated, incremental improvements in components are a major source of technological discontinuities in systems. The timing of the discontinuities depends on the steepness of the improvements in the components, the existence of new customers and applications who may view trade-offs between, for example, price and performance differently than existing customers do, and the way in which these improvements impact on the design trade-offs in the system.

Utilising the proposed framework

Although there are a number of ways in which firms can use the proposed framework, it is possible to summarise one method in a few simple steps:

1. Define the NHOS in which your product or service exists;
2. Plot the improvements that are occurring at lower levels in your NHOS;
3. If your product or service exists or may become a part of multiple NHOS, you need to consider these other NHOSs;
4. Consider the improvements that are occurring at the lower levels in these NHOS;
5. Analyse how these improvements are impacting on the design trade-offs for your product or service;
6. Analyse how these changes in the design trade-offs may impact on different customers, both existing and potentially new ones;
7. Analyse how these changes in the design trade-offs enable or require new product or service designs, in particular new architectures;
8. Analyse how these changes in the design trade-offs enable or require new business models or sales or service channels;
9. Make sure that you consider a wide range of potential new customers when doing numbers 5, 6, 7, and 8.

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Biography

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