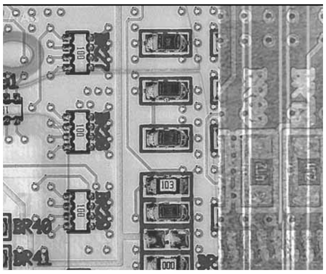
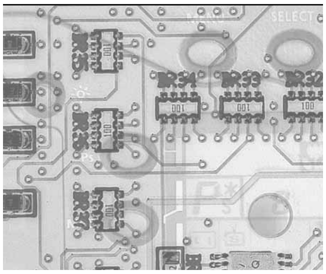
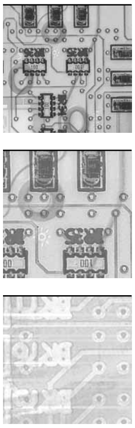




PART THREE

REFLECTIONS



CHAPTER 8

REFLECTIONS ON MOORE'S LAW

David C. Brock

This final chapter offers reflections on and observations about Moore's law and its history as well as predictions for the future. These insights are gleaned from the speakers that the Chemical Heritage Foundation gathered for its 2005 symposium, Moore's Law at Forty,[1] all of whom have been deeply engaged, in different ways, with the extraordinary development of microelectronics and its consequences. The reflections and observations fall into two groups. The first deals with the material realities of Moore's law, the story of chemistry and materials in the semiconductor technology that Moore's law describes. The second addresses the efforts required to create exponential technological change and the consequences of this change.

THE MATERIAL REALITIES OF MOORE'S LAW

The combined perspectives of three individuals—Harry Sello, Elsa Reichmanis, and Raj Gupta—represent a survey of the material reality of Moore's law as based in technologies for creating electronics through the transformation of materials by chemical, physical, and mechanical means. Sello's contribution outlined the diversity of issues that chemists addressed in the early years of the semiconductor industry to establish its basic manufacturing capability. Reichmanis's perspective opened up one facet of Sello's survey of chemical challenges, detailing the story of photoresist chemists' experience of keeping apace with and empowering Moore's law. Finally, Gupta reviewed the general, transformative impact of Moore's law on the industrial sector that has provided the raw materials for the silicon revolution: the chemical industry.

Laying the Foundations: Making Silicon Work

In the mid-1950s Harry Sello was a physical chemist working in a hotbed of organic chemistry research. In this period he took a telephone call during which he was quizzed about semiconductors. Sello had made a name for himself as a chemist during his tenure at the Shell Development Laboratory in Emeryville, California—one of the West Coast's premier industrial research centers. The individual who placed the call to Sello was none other than William Shockley. At the time, Shockley was seeking to gird his new organization—the Shockley Semiconductor Laboratory—with experts in physical and organic chemistry. Sello, who was familiar with Shockley's role in launching the then-new transistor age, needed little convincing to sign on. At Shockley Semiconductor, and then later at Fairchild Semiconductor, Sello worked at the forefront of the manufacturing process development that gave rise to the spread of silicon transistors and integrated circuits. He stood at a primary intersection of the domains of chemistry and the new electronics. Reflecting on the forty-year history of Moore's law, Sello highlighted the chemical issues that set the direction for the semiconductor industry, the path of Moore's law. Sello's highlights reveal not only the early contributions of chemistry to the establishment of the dynamic of Moore's law but also the diversity of roles that a chemist could play in the expansion of the semiconductor industry itself.

At Shockley Semiconductor, Sello worked on chemical issues that spanned the entire manufacturing process. He designed and built a crucial piece of equipment for an early stage of the process—a diffusion furnace. Such a furnace, used to carefully diffuse dopants into silicon wafers to form the crucial junctions at the heart of transistors, was no simple order. The furnace had to produce very high temperatures, and these temperatures needed to remain constant both in time and in space throughout the furnace's interior. Why would the creation of such a furnace fall to a chemist like Sello? As a chemist adept at using heat and furnaces to promote chemical reactions, Sello was a clear choice for the project.

At the other end of the semiconductor manufacturing process line from the diffusion furnaces, Sello confronted another issue, one that was just as suitable for a chemist to tackle. In the batch production of many transistors on a single silicon wafer, the last step before testing and assembling the transistors was their physical separation from the wafer. At Shockley Semiconductor, and later at other firms, process engineers selected acid etching for this separation step. In early examples of this approach, a production worker would add, by hand, a touch of melted black wax to cover each transistor on a wafer. When cooled, the cap of wax protected the transistors from a fast acid etching step that removed the wafer from the transistors. William Shockley found the procedure too crude. At Shockley's prompting, Sello examined a cornucopia of waxes to see if any might be good masks for this etching step as well as being amenable to deposition on the wafers by an evaporation procedure. Shockley and Sello thought, if they could batch produce transistors, they could batch deposit dots of wax.

Sello also worked to introduce the discipline of a more traditional chemical manufacturing operation into the then rather freewheeling use of materials rampant in semiconductor processing. One of Sello's watchwords in this push was "safety," and with it he and several of his colleagues sought to bring the nascent silicon semiconductor industry in line with more established chemical operations in terms of the handling and disposal of powerful reagents. Another of Sello's generalized chemical concerns was the procurement of these very same reagents and other materials. He fought an uphill battle to acquire materials for the laboratory with the required levels of chemical purity. Because transistor manufacturing centered on unprecedented control over the introduction of particular impurities into silicon, the laboratory needed materials that exceeded the purity available in off-the shelf "chemically pure" reagents. Obtaining these ultra-pure materials from suppliers in the relatively small quantities required—bottles rather than tank cars—represented a true challenge.

While many of these challenges awaited Sello when he moved to the newly established Fairchild Semiconductor in the late 1950s, new chemical problems greeted him as well. In particular, Sello joined Fairchild's effort to get its new kind of transistor—the planar transistor—into production. History would later reveal the importance of this effort, for the first planar transistor marked the start of the path of technology development described by Moore's law. The planar transistor, like the first readily manufacturable integrated circuits that would soon follow it, relied on the formation and the use of layers of silicon dioxide on the silicon wafers in the fabrication process. Sello described the importance of this oxide when reflecting on four decades of Moore's law: "The success of the integrated circuit industry is due to that wonderful material that grows naturally on silicon."[2]

One of the key uses of oxide layers in the production of planar transistors and integrated circuits was as a diffusion mask. That is, the oxide layer was physically patterned, leaving some areas of the silicon wafer coated by oxide, and some areas uncovered. The covered areas were closed off from impurity diffusion steps, while the uncovered areas were open to them. In this way, devices were formed. To pattern the oxide layer, Fairchild Semiconductor relied on the technology of photolithography—a technology that has remained at the very core of semiconductor development for the ensuing four decades of Moore's law.

In the lithographic approach, a layer of photoresist—a light-sensitive polymer—was coated on the oxide. The desired pattern was projected onto the photoresist, with the light-exposed regions of the photoresist changing their chemical structure in response. The changed and unchanged regions of the photoresist possessed a difference in how readily they were removed from the oxide by a chemical wash. The photoresist that remained controlled an acid-etching step for the oxide, resulting in the removal of some areas of the oxide but not others. The result was the desired patterning of the oxide for the diffusion operation.

It was clear to the scientists, engineers, and technicians of Fairchild Semiconductor that the behavior of the photoresist was critical to the feasibility of the entire lithographic scheme. Sello's photoresist challenge at Fairchild was a problem of "lifting," a tendency for the photoresist to have adherence problems near the edges of features, allowing etchants and other materials to creep underneath the photoresist and attack the device. This was a classical challenge of chemistry and of materials: how could Sello reformulate the resists to improve their adhesion while retaining other desired properties? While he and his colleagues made several advances, adhesion remains an issue with photoresists to the present day.

While problem solving on the manufacturing line required the intervention of chemists like Sello, their process expertise was also required for device design at a fundamental level. Indeed, across the entire history of both the semiconductor industry and Moore's law, there has been a close coupling of device design with manufacturing process. That is, the material realities of an actual, economically advantageous manufacturing process imposed particular "design rules" that device engineers and physicists used to devise new semiconductor products.

For example, a particular manufacturing process will allow a specific range of electrical isolation characteristics. The resulting design rules take this range into account, in the form of spacing limits for various features of a device. In this way, the realities of the fabrication process were embodied in the design of new devices before they ever reached the manufacturing line. Sello himself worked on just such a translation of material reality into design rules in the early years of integrated circuit technology. He identified one cause for the failure of some early integrated circuits: the migration of aluminum material in the metal web of interconnections that lay atop an integrated circuit, electrically connecting its constituent components. In brief, with particular thicknesses and widths of aluminum lines carrying particular amounts of electricity, the aluminum of the lines would migrate, causing gaps in the web of interconnections and a failure of the device. To prevent such occurrences, different thicknesses, widths, and spacings of the aluminum interconnections were required. These requirements were translated into new design rules, so that subsequent devices avoided the migration phenomenon. This feedback of the material realities of the production process into the design of new devices was a sustaining dynamic for the ongoing realization of Moore's law.

Across his decades-long career at Fairchild, Sello spearheaded other efforts in which chemists played an important role in making silicon work to realize Moore's law. Teams of chemists worked to invent new manufacturing processes for new generations of semiconductor devices. For example, a team in the research and development laboratory of Fairchild—consisting of Edward Snow, a physicist; Bruce Deal, a chemist; and Andrew Grove, a chemical engineer—determined that contamination by sodium and other alkali metals was particularly destructive for a promising new form of transistor, the MOS transistor (so named by acronym for the layers of material employed in its formation: metal-oxide-semiconductor). In response to this finding, Sello and a team of process chemists, engineers, and technicians developed a new manufacturing process—the "Planar 2" process—for MOS devices that minimized alkali contamination.

In addition, at the instruction of Gordon Moore, Sello developed a team of chemists and others to provide "sustaining engineering" to existing production lines and processes. When a particular line experienced problems, Sello sent a team of Ph.D.-level researchers to the factory floor to run the line, identify the derangement and resolve it. Closely observing existing processes and developing new ones, chemists like Sello constantly and continually helped to produce the means for the semiconductor industry to realize Moore's law.

While Sello's reflections zeroed in on the central role of the chemist within semiconductor manufacturing process development, he pointed as well to other areas in which chemists made significant contributions. They were key to developing new forms of packaging for silicon chips, which increasingly became the largest factor in the overall cost of a finished semiconductor device. They were also key to technology transfer: getting a process to work in a new geographical and institutional location. These transfers were important within a single firm, for example, when opening a new fabrication facility and between firms in partnerships, acquisitions, or the direct purchase of process technology. In all these areas, looking from the past to the future of Moore's law, Sello predicted that the opportunities for chemists to make important contributions are as great today as they were in the past. Great materials challenges await chemists who will continue to make silicon work, to follow Moore's law in the years ahead, and to exploit new materials—such as carbon nanotubes and organic semiconductors—to extend the possibilities of electronics.

Chemical Imperatives: Keeping to the Curve

Elsa Reichmanis has devoted her entire professional career to accommodating a constant chemical imperative in the ongoing realization of Moore's law: the design and creation of photoresist materials. Photoresists, in Reichmanis's view, have been essential to the realization of Moore's law. Echoing the basic message of Moore's law, Reichmanis maintained that cost has been the primary driver in the semiconductor industry's move from the early era of multi-inch scale transistors to the present nanometer scale devices. An exponential reduction in cost and rise in complexity has been achieved based on a number of factors—most prominently, reduction of feature size, improvement of yields, and increase of wafer size. To realize the first two factors—smaller feature size and improved yields—the burden has consistently fallen on lithography, the primary technology for patterning integrated circuits. Because of their place at the center of lithographic technology, photoresists—and the chemists who design and produce them—have played an essential role.

Photoresists are, as Reichmanis informally termed them, "the gloop laid down on silicon wafers" in order to form patterns. To understand why photoresists are key to fabricating ever-smaller patterns on integrated circuits, a review of the basics of lithographic technology is useful. To start, a silicon wafer is coated with a photoresist—a photoactive polymer-based material. Light is projected through a patterned mask onto the photoresist. In response to this exposure, areas of the photoresist change their chemical properties. After a developing process, the pattern has been transferred to the photoresist. Subsequent etching processes then transfer the photoresist pattern to the underlying substrate. After the pattern has been transferred to the substrate, the remaining photoresist is stripped off, and an additional layer of material is coated onto the substrate. To appropriately pattern these additional layers, the entire lithography sequence involving the photoresist is repeated. In short, integrated circuits are built up from multiple, patterned layers of material. The creation of each and every patterned layer involves the use of photoresist in a lithographic process.

As the semiconductor industry has continually pushed lithography technology in order to create smaller features and achieve improved yields, it has thereby created an ongoing chemical imperative for the innovation of new photoresists. In the development of lithography technology, a principal metric of advance has been the employment of ever shorter wavelengths of light in the process. Shorter wavelengths, paired with new photoresists capable of interacting with them, have allowed smaller features to be created. For the past three decades, lithographic processing has been carried out by using advanced, automated, and expensive manufacturing equipment known in the silicon community as process "tools." During this time the development of lithography technology has necessitated the close collaboration and coordination of a variety of technologists. This has very much been the case in the development of photoresists.

Reichmanis noted that, while chemists like her have no doubt played a large role in the development of photoresists, they have had to calibrate their efforts with those of semiconductor manufacturing process engineers, device designers, and tool designers. As recounted by Reichmanis, the photoresist designer faced, and still faces, a long list of desired properties to be held by the new material. Sensitivity is required, since photoresists must be highly responsive to light to achieve an economical through-put rate for the overall lithographic process. High contrast, or resolution, is needed, for the material must exhibit ultrafine response to the wavelength of light employed to create the smallest possible features, and thus, low-cost devices. High line width control is desired, whereby the photoresist can accept the pattern projected onto it with great fidelity, neither broadening nor narrowing the intended features. The photoresist must produce a tolerable defect density, meaning that the overall performance of the photoresist must contribute to an economically viable overall yield for the semiconductor manufacturing process. Good etching resistance is required, meaning that the developed photoresist is able to properly survive its exposure to powerful etching mixtures in the lithography process through which patterns are transferred to the underlying substrate. Lastly the new photoresist needs good adhesion, meaning that the photoresist will uniformly and consistently stick to the surface of the semiconductor substrate until the stage in the process when the developed resist is removed or stripped from the substrate.

The photoresist designer must also aim to secure for his or her new material a set of properties commonly sought for chemical products in general. Among these general desiderata is consistency, that is, that within a given sample the material is uniform. Sufficient shelf life is another; meaning that the material retains its desired properties and functionality for an adequate period. Another crucial attribute is a sufficiently low cost, for the photoresist itself must be an economically viable consumable for it to meet the cost requirements of its semiconductor industry users.

It is one thing for photoresist designers to ascertain a specific set of desired properties for a new material. It is quite another matter to realize these aims and successfully introduce a new photoresist into a new generation of lithographic technology. As Reichmanis recalled, the photoresist community learned an important lesson during the 1980s about the imperatives and vicissitudes of developing a successful new generation of photoresists that would keep apace with Moore's law. In the late 1970s members of the silicon community discerned that the developmental trend of Moore's law would, in roughly a decade, require a new generation of lithography technology. This new lithography technology, they reasoned, would need to move from the use of near and mid-range ultraviolet radiation for patterning integrated circuits to the employment of "deep-UV" radiation. Deep-UV lithography would use shorter wavelength light (254 nm) in order to produce the smaller, lower-cost devices and the increased complexity of integrated circuits that Moore's law predicted. However, as photoresist chemists looked at deep-UV lithography, they concluded that the then-traditional photoresists simply would not work: they would not have the correct absorbance response to the new wavelengths of light. This called for a major step forward in materials design.

In the early 1980s photoresist chemists achieved what Reichmanis termed a "revolutionary change" in the chemistry of photoresists. This advance was the development of the chemical amplification technique, wherein great sensitivity was achieved for the new class of deep-UV photoresists. In the chemical amplification method, a catalytic compound in the photoresist is activated by exposure to radiation in the lithographic process. This activated catalyst, in turn, prompts a cascade of chemical transformations in the photoresist, leading to the desired performance.

While the chemical amplification innovation was an important step forward for the photoresist community, a variety of problems remained with the new material. Adequate etch resistance had yet to be achieved. Indeed, chemical amplification introduced new problems. Chemical amplification required the wafer to be baked at an elevated temperature after exposure to the deep-UV radiation for the photoresist to develop properly. This baking procedure, however, initially caused intolerable changes in the dimensions of the pattern transferred to the photoresist—it had poor line-width control. It would take the better part of the 1980s for the photoresist community to tackle these additional challenges. The new deep-UV photoresists were widely adopted by the semiconductor industry in the late 1980s as part of its embrace of the new lithography technology generation. The photoresist community noted that it had taken nearly twelve years for the new material to move from design to invention to introduction. The community had learned that for it to play its required role in empowering the semiconductor industry to keep up with the developmental curve of Moore's law, they would have to look a decade ahead.

It was with just such a forward-looking orientation that photoresist chemists like Reichmanis greeted the new decade of the 1990s. As had been the case in the late 1970s, photoresist chemists again saw that a new generation of lithography technology was on the horizon. The semiconductor industry showed no sign of deviating from Moore's law, and the new generation of technology, employing still deeper UV radiation (193 nm), would be required to continue the industry's unending "drive to even still smaller features," as Reichmanis put it. However, there was an important difference between the photoresist community's situation in the early 1990s as compared with the late 1970s. In the early 1990s the Semiconductor Industry Association (SIA) had formalized, in great detail, the technological developments that it required for the continued fulfillment of Moore's law. The "technology roadmap" created by the SIA not only explicitly transformed Moore's law from a prediction to a self-fulfilling prophecy, it spelled out what needed to be accomplished, and when. As Reichmanis ascertained, "Advances in the [process] technology today are largely driven by the Semiconductor Industry Association."

In the early 1990s the chemical imperative faced by the photoresist community was to design a new material that was structurally different from earlier photoresists and was functionally superior. Reichmanis played a central role in answering this chemical challenge in her role as a photoresist chemist and as group leader at Bell

Laboratories (where she continues to use chemistry to empower electronic innovations as director of the Materials Research Department). The approach taken by Reichmanis was a design effort that explicitly used the existing photoresist knowledge base to associate each desired characteristic for the new material with a particular "molecular characteristic." A property like the desired radiation response was associated with one set of molecular characteristics or chemistries, while factors like low cost were associated with another set.

The 193-nm photoresists had a much shorter path from initial design to introduction, requiring roughly six years. By the early 2000s these resists were widely used by the semiconductor industry as part of its mainstay lithography technology generation. Yet as Moore's law has continued to be realized by the silicon community, the chemical (and market) imperative for improved photoresists has continued in tandem. Reichmanis predicts both continuity and change for the new generations of lithography technology that lie ahead. On the continuity side of the balance sheet, she is convinced that the chemical imperative will continue and that the key to making the new technologies possible will be new materials. On the side of change, Reichmanis sees new kinds of materials challenges. Soon, she noted, the very size of the polymer molecules of the photoresist will become an important consideration in maintaining an adequate sharpness to line edges in the patterns for devices with features below 30 nm in size. A new consideration for photoresists will therefore be the size of the actual photoresist molecules. Looking out farther still, Reichmanis foresees that an even more radical change in device fabrication technology may be required. This change would be a shift from the traditional "subtractive" process of semiconductor manufacture—in which entire layers of materials are deposited and patterned and unwanted excess material is removed—to an "additive process" in which only the desired material is deposited on the substrate where and when it is needed. Should such a shift occur, it would represent another chemical and material challenge once again at the center of electronics technology.

Feeding the Curve: Flows of Materials and Innovation

In a fundamental sense the semiconductor industry is a chemical industry. For the manufacture of integrated circuits, the semiconductor industry employs chemical, physical, and mechanical processes to add or subtract materials from silicon wafers to fabricate intricate material structures possessing very particular electronic capabilities. While chemical processing lies at the core of the semiconductor industry, where this industry differs from the traditional chemical industry—what sets it apart as a distinct activity—is that a host of disciplines beyond chemistry are involved in the design of its end products. Chemistry, both as a corpus of specialized knowledge about materials and as a constellation of materials produced by industry, empowers the semiconductor industry in crucial ways. Through this strong symbiotic relationship with the semiconductor industry, the chemical industry itself has been transformed.

Raj Gupta is well positioned to comment on this transformation. He has spent the past three decades with the Rohm and Haas Company, most recently serving as the firm's chairman and CEO. Since the middle 1990s he led the development of Rohm and Haas' electronic materials business. Electronic materials have assumed an ever-more prominent focus for Rohm and Haas, a firm with roots in specialty chemicals, resins, and polymers, as epitomized by its most famous product, Plexiglas. Given his long involvement in a "traditional" chemical firm and his role in its development of electronic materials, Gupta judges that the electronics industry has already had a profound effect on the evolution of the chemical industry, "not small time, but big time."

In Gupta's experience, the electronics industry has had many different, though interrelated, effects on the chemical industry. Rohm and Haas offers a case study of the general changes that have swept the chemical industry. A new pace and new practices for innovation have emerged in the chemical domain as the semiconductor industry pushed its requirements upstream to its supporting realms. In Gupta's experience, Moore's law has required the chemical industry to move faster and smarter. Supporting this claim, Gupta reviewed in detail the many senses in which the electronics industry has transformed the chemical industry.

Perhaps the most apparent manifestation of this transformation has been the emergence of electronics as a large, new market for advanced materials produced by the chemical industry. The semiconductor industry is one customer for a variety of such advanced, high-value added, but relatively low production-volume materials. Among the electronic materials produced by the chemical industry for the semiconductor industry are photoresists, etchants, dopants, specialty gases, insulators, polishing slurries, and packaging materials. In addition to the range of electronic materials used by the semiconductor industry, other types of electronics firms require advanced materials to create their end-products. Rohm and Haas, for example, manufactures specialty polymeric materials used to create flat-panel, liquid crystal displays for electronic products.

The electronic materials business has grown rapidly, Gupta noted. In terms of sales, electronics materials represent an annual $30 billion business for the chemical industry. By comparison this volume is equivalent to the annual global market for all agricultural chemicals. The agrochemical market took over a century to reach the $30 billion level. Electronics materials achieved the same scale in less than half that time and have consistently sustained 10 percent annual growth. In the case of Rohm and Haas, Gupta explained, opportunities in photoresists, insulating materials, chemical-mechanical polishing consumables, electronic packaging, and circuit boards now account for approximately a third of the company's total sales. However, exploiting these opportunities has required a large investment in innovation. Electronic materials account for 40 percent of the company's global research and development budget.

Several factors contributed to the innovation-intensive nature of electronic materials as compared with traditional chemical products, Gupta said. One factor is the rapid rate of change in electronic materials. Keeping apace with the development of semiconductor technology following Moore's law implies that product cycles for electronic chemicals are much shorter than for traditional chemical products. Chemical firms have lost control of the product cycle for new electronic materials. They must keep up with Moore's law if they want to supply the market need. In contrast to more traditional chemical products over which the chemical industry had greater influence on the innovation and product cycle, the chemical imperatives in the case of electronic materials are increasingly explicitly set by the Semiconductor Industry Association in its continually updated technology roadmap. “They say what performance they need [for new electronic materials],” explained Gupta, “and by which date.” The chemical industry’s challenge in electronic materials is to meet these deadlines, rather than discerning, anticipating, or shaping customer needs. To capitalize on the business opportunity represented by electronic materials, the chemical industry has had to tune its efforts to an externally driven product cycle, delivering the right materials on time. To do so has required the chemical industry to make proportionally larger investments in research and development for electronic materials than for its more traditional products.

A second factor that has contributed to electronic materials’ status as an innovation-intensive market for the chemical industry is the nature of the relationship between the chemical industry and its customers in the electronics industry. In the electronics domain, Gupta noted, the chemical industry experiences intense and rapid feedback about its products from its customers. Not only has the semiconductor industry’s setting of explicit requirements and timetables for the development of new electronic materials increased the pace of innovation, but this pace has also led the semiconductor industry—and other electronics companies—to provide more rapid, detailed feedback to the chemical industry about the performance and quality of new electronic materials products. To respond in kind to this feedback and seize the great market opportunity, the chemical industry further increased its research and development expense and its innovative efforts in electronic materials.

Therefore, given the innovation-intensiveness of electronic materials, the chemical industry has faced a demanding economic equation: electronic materials are high “value-added” products, the cost of adding this value is substantial, and the total volume of materials that are sold are low, compared with many traditional chemical products. To derive profitability and competitiveness from this equation, the chemical industry has had to transform its practices of innovation. In short, the chemical industry needed to invest more in research and development for electronic materials and accelerate its research and development. This shift in focus had a ripple effect inside chemical firms. Other business and technical practices, from marketing to manufacturing scale-up, have required streamlining to prevent them from forming obstacles in the innovation cycle. The demands made by the electronic materials market have necessitated that chemical firms revamp their entire system for product development and delivery. The chemical industry had to refashion itself to more closely resemble its electronics industry customers.

To bring about this change, to move faster and more efficiently from design to product with much tighter product cycles, the chemical industry had to rely on information technology, the end-product of its electronics industry customers. Gupta noted that it has been through the increased adoption of computing technologies in the innovation process and in other business practices, such as supply logistics, that the chemical industry has been able to win profitability in the electronics materials market.

These innovation practices and the growing knowledge base on the electronic structure and behavior of materials driven by the electronics industry is leading the chemical industry to pursue new product avenues in the field of “smart materials.” Ranging from self-repairing coatings to materials that change their bulk properties and even to textile materials that perform electronic functions such as solar power generation, the chemical industry is pursuing smart materials that hold the potential to add another meaning to the phrase "electronic materials." For decades, Moore's law has described the pace of technological change for the electronics industry. The chemical industry had to transform itself so that the electronics industry could realize its developmental curve. This transformation not only promises the continuation of Moore's law, in which the materials challenges will escalate, but also a new generation of innovative materials fusing the chemical with the electronic.

MANUFACTURING THE FUTURE: REALIZING MOORE'S LAW

Moore's law is a description of human activity as well as a statement about the inherent possibilities of silicon semiconductor manufacturing technology. The law connects the work of people with the capabilities of silicon integrated circuit manufacturing through its focus on economics. It lays out a path of economically optimal technology development. Moore's law is different from a scientific law such as the conservation of energy or the law of gravitation. Moore's law is grounded in the ongoing efforts of technologists to push silicon integrated circuit manufacturing forward. Moore's law has not and will not happen of its own accord. It relies on large-scale efforts by technologists directed toward manufacturing the future that it describes. Four of the speakers at CHF's symposium cast light on this central, human dimension of Moore's law. Carver Mead recounted his efforts of the 1960s and 1970s to provide technical evidence for the future possibilities of silicon technology, to instill in the silicon community a belief in the long-term viability of Moore's law, and to motivate the silicon community to invest the effort required to make Moore's law a reality. Patrick Gelsinger reviewed the range and scale of the work that has been required to realize Moore's law in the domain of microprocessor manufacturing and the broad economic consequences of having done so. Rodney Brooks provided a view of how this emphatic future orientation, predicated on continual exponential change, is shaping the forefront of computer applications research. Lastly, AnnaLee Saxenian detailed ways in which the efforts of the technological community to manufacture the future following Moore's law have transformed the geography and organizational forms of industrial activity, and how the realization of Moore's law has reshaped the human effort directed toward continuing it.

Believing in the Future: Moore's and Murphy's Laws

Carver Mead is a prominent figure in contemporary electronics, having been a contributor to the unfolding of Moore's law across the past four decades. Mead's career has had a single institutional base for fifty years—the California Institute of Technology. He has made key contributions to the design of semiconductor devices and has trained several generations of undergraduate and graduate students at Caltech who became key contributors to the development of semiconductor science, technology, and industry. It should come as no surprise that in his reflections on the course of Moore's law, Mead focused on inspiration—on his work in the electronics community to foster a strong belief in the future of semiconductor technology itself and of the great rewards that would justify the Herculean efforts required to make Moore's law a reality.

Mead earned all his degrees—from the bachelor's to the doctorate—in electrical engineering from Caltech, and he joined its faculty in 1959. As a resident transistor electronics expert, Mead soon encountered a Caltech alumnus who had returned to the campus on a recruiting trip—Gordon Moore. The two semiconductor-oriented "Caltechers" impressed one another in their first meeting, leading to an ongoing professional and personal connection. During their first meeting, Moore supplied Mead with an envelope stuffed with transistors. Mead was then teaching a course in transistor electronics, but the high cost of transistors prevented Mead from having his students work on individual projects with transistors. Moore, as a leader of Fairchild Semiconductor, was able give Mead a huge supply of "cosmetic reject" transistors—those that functioned but could not be sold because of some minor flaw. Mead's students would be able to build actual projects using real transistors, and from Moore's perspective, they would be learning on Fairchild products to boot. Learning by doing with advanced electronics was a way for Mead to form, in his students, a confidence in their future in electronics and the future of electronics itself. Moore's supplying of Mead with important means for building a belief in the future became a leitmotif of their ongoing relationship.

Throughout the early 1960s Mead commuted weekly from Caltech in Southern California's Pasadena to Fairchild Semiconductor on Northern California's San Francisco Peninsula—the region that would come to be known as Silicon Valley a decade later. On these visits, Mead would spend an entire day at Fairchild Semiconductor working with members of its research and development laboratory. At day's end, Mead would meet with Moore, the head of the laboratory, for a "decompression" session. It was during one of these regular sessions in the middle 1960s—around the time of the original publication of Moore's law—that Moore pursued a line of questioning with Mead that would come to shape the latter's activities for several years. At this time Mead was studying the role of electron tunneling—a quantum mechanical effect—in transistors. Moore was aware of this work and asked Mead, "Doesn't electron tunneling limit how small we can make a transistor?" Mead replied, "It certainly would." At very small distances—like those in an extremely small futuristic transistor—electrons would jump across barriers, in effect causing parasitic currents that would ruin the operation of the transistor. To Mead's reply that electron tunneling would place a lower limit on the size of the transistor, Moore asked, "How small is that?"

For Mead, reflecting later on his long association with Moore, this was typical of Moore's thinking: "Every single question was absolutely obvious, and I hadn't thought at all about it." Moore's inquiry set Mead on a train of investigations that would lead Mead to become a traveling spokesperson for the future of microelectronics. The first step was Mead's consideration of Moore's central question: How small could you make a transistor? As Mead dove into the problem around 1967, he uncovered several "prophecies of doom" lurking in the semiconductor community. Typical of these prophecies was a belief that if one made devices significantly smaller and packed many of them into a single integrated circuit, the heat generated by the power consumption of the many small devices would heat the chip to the point where it would melt. But as Mead looked at the physical realities of shrinking devices, this and other prophecies did not seem right. He decided to launch his own inquiry with a simple first step. What would happen with the simplest form of scaling? Mead calculated what would happen if he were to scale down the physical dimensions of the device, scale down the voltages, and scale up the concentrations of dopants in the imagined devices so that the various layers of the device maintained the same size fractions as existing devices. In these calculations, the device kept the same proportions, just much smaller.

The results surprised him. Mead found that with such simple scaling, transistors would exhibit an increase in speed. But when combined in an integrated circuit, the power used per unit of area would remain constant. Put differently, the power used per unit of speed would improve as the *cube* of the scaling factor. The amount of energy needed to perform a computation would geometrically, exponentially reduce as the devices were made smaller. The smaller you went, the better things got. Mead reworked his calculations several times because his result was "obviously a violation of Murphy's law, big time." What Mead had calculated was that as integrated circuit producers increased the complexity of chips on the exponential path that Moore had laid out in 1965, shrinking the sizes of the transistors on the chips would result in an exponential improvement in their performance. By making transistors smaller and cramming more and more of them onto a single chip, electronics would not only become cheaper, they would also become better.

Unsurprisingly, when Mead presented these results in the late 1960s, the semiconductor community reacted with great skepticism. In technology, as in so many areas of human activity, one seldom encountered phenomena that consistently flew in the face of Murphy's law. However, as silicon practitioners investigated Mead's result on their own, others began to concur. By the late 1960s Mead had instilled in himself—and in a growing constellation of silicon technologists—a belief in the future of miniaturized electronics. Electronics would improve as you made them smaller, so the rewards would be commensurate with the efforts required to do so. However, Mead reasoned, he had not yet answered Moore's original challenge. Transistors would get better as you made them smaller, but how small could you go? How long would this promising future last? Mead would soon argue that this promising future based on the continuing violation of Murphy's law would last for decades, with great returns reaped from following Moore's law.

In 1972 Mead, along with his graduate student Bruce Hoeneisen, had articulated a more formal answer and published it in a series of two papers.[3] Mead and Hoeneisen determined that there was nothing to prevent the construction of a workable transistor with features measured on the order of 0.15 microns—that is, fifteen hundredths of a millionth of a meter. As Mead recalled, at the time their proposition seemed "ridiculously" small. Transistors of the day had features measured in thousandths, rather than millionths of a meter, to say nothing of fractions of millionths. In the early 2000s, however, transistors with features at this very same 0.15-micron level had become the workhorse device for the semiconductor industry, and far smaller devices were planned for eventual mass production. But back in 1972 Mead coupled his ridiculously small lower limit for transistor size with a ridiculously large prediction for the resulting workable complexity of an integrated circuit—a single chip containing 10 million transistors. While Mead had succeeded in spreading a belief among the silicon community that a future of "smaller is better" was real, he encountered significant resistance to his papers of 1972. Many researchers had difficulty accepting that this future would last as long as Mead thought.

In response, Mead began what he today calls a personal crusade, a barnstorming crisscrossing of the country to "convince people that it really was possible to scale devices and get better performance and lower power" and that these possibilities had no immediate end in sight. As Mead recalled, an important aspect of his presentations to the silicon community was proof that not only were the benefits and future of scaling down devices possible, but that they were also actual. Mead presented evidence that the semiconductor industry was already in the process of realizing this future. To make his case, he turned to Moore. By this time, Moore had cofounded a new firm, Intel Corporation, which had introduced an impressive array of breakthrough semiconductor devices, including DRAM memories and the microprocessor. Over the years Moore had updated his plot of semiconductor complexity versus time that he originally published in 1965, adding new data points to his plot as Intel introduced new devices. His curve, his law, was holding fast. "Every time I'd go out on the road," Mead recalls, "I'd come to Gordon and get a new version of his plot." As Mead traveled throughout the silicon community in the early 1970s, he succeeded in building a belief in a long future for the technology, using Moore's plots as convincing evidence. In doing so, Mead also played a key role in fusing Moore's law with this belief in the future of electronics and building an expanding awareness of both. While Mead may not have been the originator of the phrase *Moore's law* (its precise origins remain murky), he undoubtedly acted as its charismatic Johnny Appleseed.

Today, four decades into Moore's law, Mead has seen the realization of his belief in the future and sees it extending further into the future. "For the past thirty years," Mead reflects, "we've basically made the same device and just made it smaller, and smaller, and smaller, and smaller without doing anything else." To make transistors smaller still from today's level, pushing beyond his 1972 limit of 0.15-micron devices down to the level of 10 nanometers, Mead sees the continuing importance of chemical innovation. New materials will be needed, but the promising future will continue.

As a prime example, Mead pointed to the effort to develop new, high dielectric constant insulating materials and to integrate them into semiconductor manufacturing processes. Up to the present, the natural oxide of silicon—silicon dioxide—has been used as the insulating material for microelectronics. The use of silicon oxide as an insulator has brought with it a classic trade-off that limits the miniaturization of devices. To have low gate current (a good thing), one needs a thin oxide layer. However, thin oxide layers increase the tunneling current (a bad thing). Replacing the insulating oxide with a new, specially engineered material will avoid this "either/or" dilemma, rendering it a "both/and" situation where size reduction can continue apace. Yet, Mead noted, such changes in materials will present, however rewarding, significant challenges: "It's no longer good old SiO_2. That means [the technological challenge] is harder because we were given a gift when an acceptable semiconductor has a fantastic insulator as its native oxide." That materials innovations are key to the continuation of Moore's law should come as no surprise given Mead's perspective: "It's a chemical process that makes integrated circuits, through and through."

Relentless Pursuits: Life at the Leading Edge

Intel's Patrick Gelsinger has spent his entire professional career at the leading edge of integrated circuit technology, advancing Moore's law. Gelsinger, a Stanford-trained electrical engineer, cut his silicon teeth on two important projects in the development of microprocessors—Intel's i286 and i386. These microprocessors, each a notable advance from its predecessor, helped to establish Intel's x86 microprocessor architecture as the dominant computer architecture of the past two and a half decades. Gelsinger was the chief designer of the highly successful i486 microprocessor, which led to his increasing responsibilities in the technological and business development of Intel's microprocessor franchise. He served as the first chief technology officer of Intel and is currently its senior vice president and general manager of the Digital Enterprise Group, where he continues to develop microprocessor and other silicon technologies for business computing and communications. During his two and a half decades with Intel, Moore's law has been a consistent presence for Gelsinger. Describing his long experience of living with Moore's law, Gelsinger said, "The relentless march continues on."

By at least one measure, this relentless march of Moore's law has led to a change of two orders of magnitude during Gelsinger's career alone. Since the original publication of Moore's law in 1965, transistor count (the number of transistors on a single integrated circuit) has served as a primary measurement of integrated circuit complexity and the power of semiconductor technology. In 1985 Intel introduced the 386 microprocessor for which Gelsinger had served as a key engineer. The 386 had a transistor count of 275,000, one hundred times the transistor count of Intel's first microprocessor from the early 1970s. Four years later in 1989, Intel launched the microprocessor for which Gelsinger served as chief architect, the 486. This was the first microprocessor to cross the 1 million mark in transistor count. A second order of magnitude increase in transistor count came in 2005, with Intel dual core microprocessors boasting 1.7 billion transistors on a single chip.

The great increase in computing power represented by the exponential growth in transistor count is equaled in importance by the closely related, second metric of Moore's law: the manufacturing cost of a transistor, Gelsinger underscored that as transistor count has grown by several orders of magnitude, the cost per transistor has dropped exponentially. From a cost point of tens of dollars for a single planar transistor circa 1960, in the early 2000s the semiconductor industry achieved a cost scale of nanodollars (billionths of a dollar) per transistor. This geometric cost reduction has been reached despite dramatic cost increases in semiconductor manufacturing. As the manufacturing cost of transistors has plummeted, the expenses of lithography, production equipment and building semiconductor factories or "fabs" have risen precipitously. However, Gelsinger noted, these manufacturing costs simply represent a capital investment challenge. What matters most is the continued realization of cost reductions per delivered transistor.

Gelsinger observed that it is precisely this cost reduction (as Moore foresaw in 1965) that has been the primary driver for the proliferation of electronics and their adoption across the globe and across social and economic sectors. This dissemination of electronics, propelled by the continued cost reduction, has had dramatic consequences in Gelsinger's perspective. For example, the semiconductor industry has become an important economic entity in its own right. In the early 2000s, it was a $200 billion industry (as measured by annual sales). Moreover, the semiconductor industry was the basis for an even larger economic sector, the information technology industry, which by this same time had become a $1.2 trillion global industry.

According to Gelsinger, the impact of Moore's law has been greatly amplified through the adoption of semiconductor electronics by other segments of the economy. The semiconductor industry, Gelsinger noted, is on its own a relatively small contributor to the gross domestic product (GDP) of the United States, approximately 3 percent. However, the industry has had an order of magnitude impact on economic productivity gains, with every element of GDP touched by the adoption of semiconductor electronics. The automotive, entertainment, financial, retail, and manufacturing sectors have all been transformed by the exponential decrease in the cost of semiconductor electronics.

For an illustration of these transformations, Gelsinger focused on the communications sector. It took an entire century for the communications industry to place one billion phone lines in service. Since 1973, the communications industry has, in contrast, put three billion mobile phones into service. In three decades, then, through the adoption of semiconductor electronics, the communications industry has tripled the entire connectivity of the previous century of the telephone industry. The world has witnessed a shift from one sixth of its population being "connected" to one half.

To keep semiconductor electronics on the path of Moore's law of expanding transistor counts and falling costs, Gelsinger noted that the manufacturing technology has become increasingly complex. Reflecting the fundamental role of the transformation of materials in semiconductor manufacturing, Gelsinger suggested that a count of the number of chemical elements involved in the manufacturing process is a good gauge of the general complexity of the process. For example, in the past two decades this elemental count has nearly quadrupled. In the 1980s, a dozen chemical elements were used in the manufacturing process. In the early 2000s, fifty-one elements were used. Gelsinger summarized: "We have seen this explosion, this resurgence, of the criticality of understanding materials science and chemistry at the core of our processing technology."

Looking to the future, Gelsinger forecast that this elemental count will increase as the semiconductor industry continues is "relentless pursuit" of Moore's law. While silicon will continue to provide the basic "scaffolding" for this continued development, the semiconductor industry will need to bring more and richer chemical and materials properties into silicon to continue the developmental trend of exponential performance improvement and cost reduction. Gelsinger envisions a future point at which the electronics components industry will need to diverge significantly from the traditional silicon technology path to continue the developmental trend of Moore's law that the silicon technology itself made possible. Such divergences may include the supplanting of metal interconnection technology with new technologies based on carbon nanotubes or silicon photonics. New structures may be needed to replace or accompany the traditional transistor design. Materials other than silicon may be required for the basic starting substrate for new components. Nevertheless, the exigencies of continuing the performance and economic trends of Moore's law will drive these divergences from the core silicon technology.

The overwhelming impact of Moore's law in the arena of computing—microprocessors—has added computing performance as a new and crucial factor to the innovation goals and trends of microprocessor producers. As Gelsinger noted, there are two central dimensions of computing performance: speed and power. Speed performance is the amount of computing that a device delivers per unit of time. Power performance is the amount of computing that a device delivers per unit of energy consumption. For the past two decades of Moore's law speed performance dominated in the realm of microprocessors. The frequency of microprocessors—the number of instruction execution cycles per second—was continually increased. With the miniaturization inherent in Moore's law, microprocessors were packed with ever more devices so that a greater number of instructions could be executed in each cycle. The speed performance of computing greatly increased. There were more instructions executed in each cycle, and more cycles were squeezed into a single second. While this increase of speed performance was exponential, it lagged the doubling of microprocessor complexity according to Moore's law. For each doubling of complexity, a 1.6 or 1.7 gain in speed performance was realized. Within this developmental pattern, power performance exhibited an ominous trend. Squeezing more cycles into a single second to achieve greater computation per unit time was extremely energy intensive. Power consumption expanded exponentially.

In the early 2000s this power consumption problem, Gelsinger recounted, led microprocessor producers to refocus their attentions on power performance. This refocus precipitated, in Gelsinger's estimation, the greatest shift to date in microprocessor architecture: the shift to multiple cores. Simply put, multiple core microprocessor architecture involves the creation of multiple, coordinated computing engines on a single piece of silicon. Multiple cores allow the microprocessor to execute a greater number of instructions per cycle. Thus, the multiple core microprocessor has better power performance: it delivers the same amount of computation with reduced energy consumption. The practicability of this new multiple core architecture, Gelsinger highlighted, is predicated by Moore's law. Multiple core microprocessors require an enormous quantity of components to form the computing engines. In order to pack this quantity of components into an area of silicon that can be manufactured with suitably economic yields, continued miniaturization of components will be required, in keeping with Moore's law.

To illustrate this connection, Gelsinger discussed the connection between the number of cores planned for future multiple core microprocessors and the planned new generations of semiconductor manufacturing technology. The semiconductor industry uses a nomenclature based on length to designate generations of manufacturing technology. This nomenclature reflects the fundamental place of miniaturization in the development of this technology. The measurement used is the silicon channel length in a transistor between the source and the drain—in other words, the length of the path that electricity takes in traversing a transistor. The current generation of dual core microprocessors is fabricated using a 65-nm manufacturing process. The next generation planned by the semiconductor industry, the 45-nm process, is predicted to afford microprocessors with four cores. The 32-nm process technology, planned for 2009, is anticipated to make eight core microprocessors a practicality. The future trajectory of microprocessor development has been planned according to Moore's law. The intent, Gelsinger said, is a revolution in the history of computing: in the multiple core era, the exponential growth of computing performance will overtake the exponential growth of device complexity described by Moore's law.

Riding the Tiger: Gearing Up for Exponentials

Rodney Brooks finds exponential developments like Moore's law in many areas of science and technology. Brooks is a noted robotics and artificial intelligence researcher, a founder of the robot manufacturer iRobot, and the director of MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL). For Brooks, a range of factors cause exponentials in the development of science and technology: the level of adoption of a technology, the expectation of an exponential, and the cross transfer of an exponential from one domain into another. With the continuation of Moore's law predicted for at least the coming decade and a half, Brooks noted that computer technologists today face the challenge of preparing for this continuing exponential. Their challenge is to prepare to capitalize on the exponential expansion of computing power that is anticipated in the immediate future.

Brooks reviewed examples from MIT's CSAIL of how today's computer scientists are exploring computer applications that are presently computationally intensive—requiring hours or days to run on state-of-the-art computers. With the continuation of Moore's law and its rise of computing power and its lowering of cost, these applications could become widespread in our everyday lives. Brooks began with examples that could become commonplace given thirteen doublings of computing power. Thirteen doublings—assuming one doubling every two or three years on the trajectory of Moore's law—would constitute the length of a single technologist's career.

Brooks's first example was the generation of a three-dimensional model of an object from a single, two-dimensional digital photograph of it. Today, such an application requires hours of computation in order to perform reasonable inferences; for example, determining what the back of a building looks like from a photograph of its front. With thirteen doublings of computing power, such a task would only require several seconds. His second example was "motion magnification," where the dynamics of motion in a video clip is proportionally exaggerated, offering researchers "new ways of looking at the world." Again, while motion magnification requires hours of computation today, with thirteen doublings the process could occur in real time. Another of Brooks's examples was the use of video footage to build a model of the facial movements that an individual makes when speaking and then using this "synthetic" speaker to simulate the individual saying new dialog, singing new songs, and even speaking in different languages. With thirteen doublings, such simulation will require seconds instead of days, and the line between the "actual" and the "synthesized" will become even more difficult to discern.

In the arena of digital photography, Brooks noted, the changes that have already been anticipated by the continuation of Moore's law are profound and will have consequences that spill over into other technological domains. With the exponential growth in the number of pixels registered by the charged-coupled device (CCD) detectors in digital cameras, and the cost reduction in detectors pursuant to Moore's law, digital photography has largely replaced film photography. Today's challenge is how to best process all these pixels for display to the human eye. The challenge is to adapt display technology so that it can contend with an exponential increase in the power of digital photography described by Moore's law. For example, Brooks reviewed how researchers at CSAIL are investigating using computers to control an overlapping array of digital projectors to create ultrahigh-definition displays. By replacing mechanical precision of alignment and adjustment with computation, several doublings of computing power could render such a digital projector array as a path to future commonplace ultrahigh-resolution displays.

In the realm of microprocessor technology, Brooks forecasts that the continuation of Moore's law in the shift to multiple core architectures will push the effects of this exponential well beyond the bounds of semiconductor technology. He believes that the development of microprocessors with increasing numbers of cores will "change the whole structure" of computing. Software engineers and computer scientists will need to restructure their practices for creating software, and as they do, their practices will feed back into new designs of multiple core microprocessors: a reciprocal transfer of exponential effects circulating between hardware and software.

The exponential expansion of, and cost reduction for, data storage technology is closely coupled to the exponential of Moore's law for semiconductor devices. Brooks sees the effects of the continuation of Moore's law for data storage as having a profound impact on social life, in terms of the distribution of and access to information. Brooks presented his case using an evocative unit of "personal storage," the iPod. For the past several years there has been a doubling of storage every year on a $400 iPod, Brooks noted. Each year's new $400 iPod has twice the storage capacity of last year's model. If this trend continues, in just over ten years, an iPod could contain the text of all the books held by the Library of Congress. In twenty years a $400 iPod could store every movie ever made. This simple example shows the potential that continued technological potentials have to reshape our relationships with information, putting vast quantities of it instantly at our fingertips, says Brooks.

He noted the continued exponential development of what he calls the "silicon revolution" will change politics through redefining and expanding the list of major issues which society might address. The proliferation of sensor networks and wireless networks along with an exponentially increasing number of connected cameras in the environment will open up new possibilities for data mining and news reporting, along with enhanced security and privacy concerns. Similarly, an exponential increase in the amount of individual genetic information that is generated, stored, and used for identification purposes has the potential to change society with benefits of efficiency and security weighed against new forms of identity and privacy concerns. Continued geometric expansion of pure computing power, driven by Moore's law, could unlock new practices for data analysis and pattern recognition for scientists, technologists, and other researchers. Furthermore, this continued exponential in computing power could transform the human-machine interface through advanced, real time, voice and vision recognition as well as direct silicon-animal interfaces, that is, neural interfaces building on today's reality of hearing, vision, and motion control implants. As with any other dimension of human endeavor, Brooks noted, "that is the way of the silicon revolution: we are going to see things change in our lives. Some will be good. Some will be bad. We will have to work on what we want, and what we do not, and see where it leads."

Following the Law: Silicon Valley Goes Global

For AnnaLee Saxenian, Moore's law means more than the dramatic technological and economic changes wrought by the exponential development of semiconductor electronics. Saxenian, dean of information management and systems and professor of city and regional planning at the University of California, Berkeley, has studied the transformative effects of Moore's law on important social institutions: the way in which we organize work and companies, as well as the regional geography of industrial activity. As she noted, this dimension of social change brought about by Moore's law began with the transformation of Silicon Valley and has thereafter steadily gained a global scope.

The rise and development of Silicon Valley as an industrial region, distinctive for its system of business practices and organization, was spurred by three distinct technological waves: the integrated circuit wave of the 1960s and 1970s, the personal computer wave of the 1980s, and the Internet wave of the 1990s. In these successive waves of technological change, driven at their base by Moore's law, Saxenian said, the distinctive features of Silicon Valley as an industrial district were established. These features include a pervasive culture of entrepreneurial risk-taking and experimentation empowered by venture capital financing, the widespread adoption of specialization as a competitive strategy, high interfirm labor mobility and information exchange, and thriving community organizations (hobbyist clubs and engineering societies). These factors have facilitated the development of a local capacity for collective learning, adaptation, and technological dynamism that has brought the region such success, Saxenian concluded.

Nevertheless, Saxenian stressed, Silicon Valley possessed international features and connections from its earliest days. In the 1960s the Silicon Valley network extended to such countries as Malaysia and Singapore, to which the semiconductor industry increasingly shifted assembly operations, and to European countries, where Silicon Valley-based semiconductor firms established operations, subsidiaries, and joint ventures. Domestically, the Silicon Valley network grew to include semiconductor fabrication facilities in other states and a supply chain extending to the East Coast.

Though largely unrecognized, perhaps the most important dimension of Silicon Valley's global network in these decades was that of worker migration. The proportion of foreign-born workers in the United States' science and engineering workforce has grown steadily, so that by 2000 their proportion reached 38 percent. This percentage is even greater at higher degree-levels. Many of these foreign-born workers received their education in the United States, with the majority hailing from South and East Asia. Silicon Valley, Saxenian said, captured the lion's share of these foreign-born, U.S.-trained engineers. This "brain drain," from the perspective of the nations of South and East Asia, served as a crucial basis for Silicon Valley's professional labor supply, forming an essential, international component to the region's enabling network.

The story of this global network of labor migration, Saxenian pointed out, did not end there. Working in Silicon Valley, these foreign-born professionals learned how to be technologists, managers, and entrepreneurs. As a group these foreign-born professionals were more entrepreneurial than their domestic counterparts, as measured by the rate at which they started new firms. With the maturation of this community of Silicon Valley-based, foreign-born technologists, Saxenian observed, has come an important shift in the region's global orientation. In the past, Silicon Valley benefited from the "brain drain" from East and South Asia. Today, it is learning to live with "brain circulation" between the region and rising foreign centers of high-technology industry such as India, China, Taiwan, and South Korea.

It is in this contemporary period of brain circulation—the migration of entrepreneurial technologists to Silicon Valley and then back to their home countries (sometimes in multiple iterations within a single career)—that Saxenian discerned a new pattern in the international expansion of the Silicon Valley network with the subsequent establishment of dynamic foreign centers of high-technology industry. She cited Taiwan and India as examples. In the 1980s Taiwanese technologists established Taiwan as the "foundry" extension of Silicon Valley. They established cutting-edge semiconductor manufacturing firms that produced integrated circuits designed by "fabless" Silicon Valley firms. This wave of success accelerated brain circulation of technologists from Silicon Valley back to Taiwan and the development of a specialized manufacturing infrastructure in the country along the lines of Silicon Valley. Today this Taiwanese activity has coalesced into an industrial district in its own right. While still connected to Silicon Valley, it has become more than just its appendage. Evidence for this shift, Saxenian noted, can be seen in Taiwanese firms' recent moves into Mainland China for manufacturing semiconductor devices and such consumer products as personal computers. Moreover, as was the case with Taiwan's development of an autonomous high-technology district though its relationship with Silicon Valley, the extensions of Taiwanese, Silicon Valley, and other networks into China are increasingly leading to the development of similarly connected, though autonomous, regional Chinese districts.

In Saxenian's estimation, the same pattern can be noted in the case of India. For design capacity, centers like Bangalore have increasingly become an important aspect of the Silicon Valley network. This success in semiconductor design and in software is accelerating brain circulation between Silicon Valley and India, leading to the development of increasingly autonomous high-technology districts across the country. In regions like Taiwan, India, and China, new firms are developing new products with adequate performance and cost features to serve the large potential market represented by the populations of these rapidly developing countries. For Saxenian, the consequences of both this brain circulation and the development of new high-technology industrial districts will generate some of the largest issues of the next decades.

Moore's law continues to change the face of technology and with it the economic geography of the world. In the years ahead the questions on everyone's lips will be: How fast will this dynamic spread to other parts of the world? How will new products and technologies begin to help the lives of residents of the developing world across Africa, Latin America, and other regions? What new applications and products will serve the needs of these new customers? The current state of affairs augurs a potential new exponential: the adoption of semiconductor electronics by a geometrically increasing proportion of the world's population. Fundamentally connected to Moore's law, the consequences of this new exponential for the future could be just as transformative and unforeseeable as it has been in the past.

ENDNOTES

1. For the complete program of the Moore's Law at 40 symposium, see pages 109–110 of this volume.
2. All of the quotations in this section, unless otherwise noted, are drawn from presentations made at the Moore's Law at 40 symposium. Transcriptions are archived at the Chemical Heritage Foundation, Philadelphia.
3. B. Hoeneisen and C. A. Mead, "Fundamental Limitations in Microelectronics—I. MOS Technology," *Solid State Electronics* 15:7 (July 1972): 819–829; B. Hoeneisen and C. A. Mead, "Limitations in Microelectronics—II. Bipolar Technology," *Solid State Electronics* 15:8 (August 1972): 891–897.