<running head>Eisler | Exploding the Black Box

<title>Exploding the Black Box

<subtitle>Personal Computing, the Notebook Battery Crisis, and Postindustrial Systems Thinking

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Abstract:

Historians of science and technology have generally ignored the role of power sources in the development of consumer electronics. In this they have followed the predilections of historical actors. Research, development, and manufacturing of batteries has historically occurred at a social and intellectual distance from the research, development, and manufacturing of the devices they power. Nevertheless, power source technoscience should properly be understood as an allied yet estranged field of

electronics. The separation between the fields has had important consequences for the design and manufacturing of mobile consumer electronics. This paper explores these dynamics in the co-construction of notebook batteries and computers. In so doing, it challenges assumptions of historians and industrial engineers and planners about the nature of computer systems in particular and the development of technological systems. The co-construction of notebook computers and batteries, and the occasional catastrophic failure of their compatibility, challenges systems thinking more generally.

<A HEAD>Introduction

What have exploding batteries to do with personal computing, industrial innovation, and the philosophy of the history of technology? At first glance, perhaps not much. Technologists and the scholars of science, technology, and society who study their activities have long considered mobile power sources less interesting than the applications they serve. In marked contrast to consumer electronics, battery technoscience languished for most of the twentieth century until the late 1980s and early 1990s. At that time, a powerful lithium-based rechargeable battery emerged as a key enabler of mobile telephony and computing. Because such power sources are bundled into their applications and are not generally available for retail sale, they command little attention except when they require recharging or replacing. In mid-2006, however, a wave of battery fires in notebook computers triggered the largest consumer electronics recalls in history. Sony batteries in a variety of different notebooks were especially prone to trouble, and so the Japanese firm received the lion’s share of the blame, widely ascribed at the time to poor manufacturing quality control.{1}

These events cast into relief the ways both practitioners of science and engineering and scholars in the social studies of science and technology have gone about making sense of the world. If historians have generally ignored the role of power sources in consumer electronics and mobile computing hardware, they could be said to simply be reflecting the priorities of historical actors. Properly understood as an allied but estranged field of electronics, power source technoscience (comprising electrochemistry and solid state ionics) has been considered “a solution in search of a problem” for much of its history.{2} For a host of reasons, research and development of batteries has occurred at a great social and intellectual distance from research and development of consumer devices, especially mobile computers.

This estrangement between batteries and the devices they power bears directly on the notebook battery crisis and, more broadly, on ways historians and sociologists comprehend contemporary industrial-technological development. The ideas of Thomas P. Hughes have tended to dominate such discussions, and the Hughesian systems axioms (builders, heterogeneous components, and momentum/frontal progress, inhibited by the reverse salient) are familiar staples of the STS conceptual canon.{3} Hughes derived his metaphor of networked service infrastructure from the case of the electrical grid in its early phases of construction in the late nineteenth and early twentieth centuries, and scholars often assume that it applies to the social relations of innovation more generally.{4}

However, the Hughesian model does not exactly apply to some sophisticated consumer commodity technologies, including laptop computers and the batteries within them. Together, these do not form a single physical system—not exactly. Unlike grid infrastructure, moreover, the pace of innovation in commodity electronics has been extremely rapid. And this sector’s dynamism dramatically accelerated at a time when the classic centralized industrial corporation of the sort Hughes was concerned with was undergoing a profound restructuring. The notebook computer battery crisis emerged at a time when electronics engineers were struggling to understand the implications of microprocessor scaling (miniaturization) on the operation of mobile computing systems, especially power demand. This was a period when the trend to outsource and offshore industrial production was well advanced. In the 2000s, discussions of the effects of the decentralization of the US semiconductor industry tended to focus on job loss, but globalization also had profound consequences on the ability of computer engineers to solve physical problems issuing from miniaturization.{5} I argue that offshoring and outsourcing in fact widened the existing intellectual gulf between electronics and battery technoscience and compromised the systems integration of notebook computer technology. Decentralizing industrial production thus set the stage for the battery fire crisis.

We may hence conceive the technosocial agglomeration of the notebook computer in this period as a dynamic system of systems—an inter-network—one whose physical and social components were imperfectly nested. That is, the physical requirements of mobile computing entailed the functional and hence disciplinary convergence of electronics and battery technoscience at a time when the social relations of innovation were increasingly geographically distributed and alienated. Certain assumptions informed (and were engendered by) this agglomeration: that decentralized research, development, and manufacturing facilitated efficient industrial commodification. I refer to these assumptions as postindustrial systems thinking. The notebook battery crisis illustrates the challenges this way of thinking posed to notebook manufacturing at the turn of the millennium and compels a fresh look at the history of computing.

The emergence of “platform studies” over the last seven years has done much to correct the longstanding bias for hardware that scholars believe had obscured the role of software, programmers, and users in earlier historical accounts.{6} In the platform perspective, computers are multilayered amalgams of hardware and software; components produced by different suppliers are amenable to “translation,” an underlying commensurability between otherwise incompatible systems.{7} However, as with the Hughesian model, the platform axiom was derived from a specific setting: the classic era of home computers and video game consoles from the late 1970s to the early–mid-1990s.{8} Indeed, historians of computing have yet to substantively engage with the mobile device era.{9} And so in the transhistorical perspective of today's platform studies, the industrial production of personal computers appears straightforward. Distributed manufacturing of standardized parts is seen as a key factor in the commodification of the PC, enabling computer companies (Dell being the oft-cited archetype) to cut costs and massively, and unproblematically, boost productivity.{10}

The case of the notebook battery fires challenges these assumptions. It suggests that the longstanding social and intellectual distance between power source and consumer electronics technoscience, aggravated by the gradual decentralization of corporate research, development, and manufacturing from the early 1980s (and often dated to the breakup of AT&T/Bell Labs in 1984), in fact posed considerable engineering and managerial challenges for computer companies as they sought to transition from desktops to notebooks powered by novel lithium ion batteries from the early 1990s.

The notebook battery crisis calls particular attention to the actors' categories of microprocessor clock speed and microprocessor scaling, widely believed to be the most important metrics, respectively, of computer performance and of progress in information technology more generally. Such views have been reinforced by the popularization of Moore's Law, the observation that the trend in miniaturization and integration of transistors correlated with declining manufacturing costs. By the turn of the millennium, Moore's Law had become a dominant metonym of innovation in the information technology sector, persisting even in the face of widespread acknowledgement of the impending physical barriers to scaling.{11} The notebook battery crisis instead revealed that mobile computers were much more than simply a smaller package for smaller microprocessors. In the notebook era, accordingly, assumptions and expectations of performance and compatibility constructed in the desktop era did not always hold.

<A HEAD>Scaling and the Power Paradox

Belief in the microprocessor as the essence of personal computing has long guided the thinking of practitioners, pundits, and policymakers, as well as popular and scholarly chroniclers of science and technology. It underpinned the creation of the SEMATECH consortium, the public-private enterprise of manufacturing research and development initiated in 1987 by the federal government (through the Defense Advanced Research Projects Agency) at the behest of the semiconductor industry. It informed Intel branding from the early 1990s, the Pavlovian ring-tone of the "Intel Inside" campaign representing a noteworthy application of behavioral psychology in the digital age.

And the microprocessor-as-computer equation crucially informed the ways actors defined computer performance. The chief metrics have long been computations per second and, much more importantly in the era of personal computing, cost of computations per second, the latter tied inextricably to Moore's Law.{12} Engineers tended to correlate this economic trend, and the exponential increase in processing power it fostered (as measured by instructions per cycle and clock speed), with other qualities of performance, notably computations per unit of energy (performance per watt).{13}

At the systems level, however, power density did not scale. Packing more transistors together and increasing chip frequency generated heat, boosting voltage and power consumption, a phenomenon that the semiconductor industry seems to have been aware of as early as the mid-1990s.{14} Scaling lowered supply and threshold voltages, but small transistors leaked small amounts of current exponentially as the threshold voltage diminished, meaning that it and the supply voltage had to be increased to control the leakage. In 1999, the director of Intel's Circuit Research Laboratory predicted that power density would become a serious problem in the near future.{15} That moment arrived the following year, opined one IBM researcher at a National Research Council-sponsored symposium in September 2001. Economists and computer technologists, he held, had failed to anticipate the rate of increase of power cost.{16}

The power problem worsened as computer designers added non-computational features.{17} One contemporary critic held that semiconductor makers (notably Intel) used claims of improved performance per watt as a way to mask increasing demands for power at the systems level. What energy savings as were made in central processing units tended to be spent on graphics processing units.{18}

Where mobile computing was concerned, designers faced conflicting, indeed, irreconcilable imperatives. The quality of mobility dictated power as the chief design constraint, but the demand for increased functionality compelled designers to use increasingly powerful processors. Technologists attempted to resolve the resulting thermal problems with cooling devices, voltage scaled to real-time power demand, and above all, parallel systems employing multiple processors of only moderate speed but high efficiency.{19} For some observers, such innovations begot mobile computing all on their own.{20}

However, increasing demands for power also stimulated interest in power source technoscience. Indeed, even before power density became recognized as a serious reverse salient of personal computing, the lithium cobalt oxide battery was an enabler of mobility. On its introduction in the early 1990s, this power source yielded around 90 watt hours per kilogram—triple the energy density of the nickel-cadmium battery, which was then the most powerful rechargeable for consumer electronics applications. Over the next quarter century, designers more than doubled the capacity of lithium rechargeables to 210 watt hours per kilogram.{21} Nevertheless, such progress paled against the exponential pace of transistor scaling. And it came with materials trade-offs that had important implications for applications, dynamics that were not well understood thanks to the intellectual and institutional gulf separating power source and personal computer innovation.

<A HEAD>Engaging an Orphan Technoscience

Necessity is not necessarily the mother of invention, as David Nye reminds us.{22} In no realm of technoscience is this observation more apt than in electrochemical power sources. The commercial lithium cobalt oxide battery was not an original discrete invention, nor did the impetus for it originate in the electronics or computing sectors. In the words of Sony researcher Yoshio Nishi, the technology was a “novel combination” of parts independently developed by a number of groups working for different ends over many years, a well-recognized and richly documented general phenomenon in social studies of science and technology.{23}

The halting and distributed nature of the research, development, and production of advanced power sources could be considered a legacy of what Schallenberg characterized as the inertia that gripped the field of electrochemistry in the wake of the disappearance of electric vehicles from US public roads and of large-scale use of batteries in electric utility systems by the 1920s. In subsequent years, electrical engineers were not stimulated to think in terms of electrochemical solutions to problems.{24} To be sure, corporate research (by Bell Labs, General Electric, Esso/Exxon Research and Engineering, Ford Research Laboratories, Honeywell, Union Carbide, and others) made important contributions to advanced power source technoscience after the Second World War.{25} And the emergence of the conjoined energy and environmental crises in the last quarter of the twentieth century compelled civilian industry to experiment with electric traction systems.{26}

Generally, however, such research had a low priority on most corporate agendas. For its part, the automobile sector wrestled with uncertain economics of large rechargeable batteries. Because power sources have a much shorter lifespan than electric motors, they represent an unprecedented hidden replacement cost, one that automakers were not sure consumers would be willing to pay. For much of the postwar era, most manufacturers of commercial batteries contented themselves with a handful of proven, prosaic, and profitable electrochemical couples (nickel-iron, carbon-zinc, lead-acid, and nickel-cadmium). One exception was the medical sector, where there was a demand for small, powerful, and very long-lived batteries for wearable and implant devices.{27} Generally, however, only US state institutions were willing to fund and procure advanced power sources, mainly for specialized military roles.

Where the lithium cobalt oxide battery was concerned, a host of institutions contributed to its science and technology. The cathode was invented in 1980 by a team at Oxford University led by John B. Goodenough, an American physicist and pioneer of the field of solid-state ionics, the art and science of moving, inserting, and storing ions inside solids without fundamentally changing the structures of the host materials. As a fledgling researcher in Project Lincoln, the effort to develop the computer for the Semi-Automatic Ground System air defense network in the 1950s, Goodenough discovered that the presence of metal oxides in a ferrimagnetic spinel could induce structural changes that bred magnetic discontinuities, and, hence, the quality of switchability.{28}

Solid-state ionics could also be applied to energy storage. The field would stimulate a major shift in the understanding of power source technology at a time when electrochemists believed that the important reactions occurred on electrode surfaces in relation to liquid electrolytes. After moving to Oxford University in 1976, some of Goodenough's research developed in response to the Exxon Corporation's lithium titanium disulfide battery, a project that in turn had been motivated by the possibility that the energy crisis would force automakers to commercialize electric vehicles. Invented by M. Stanley Whittingham, lithium titanium disulfide successfully demonstrated the phenomenon of intercalation, the completely reversible insertion and extraction of ions into electrode host matrices, the basic operating principle of a lithium ion battery.{29}

But the technology could not be commercialized for automobile use because repeated recharging induced a dangerous interaction between its metallic lithium anode and flammable organic electrolyte, a non-aqueous substance made necessary owing to lithium's reactivity with water.{30} Less interested in developing a practical successor to this power source than investigating materials for a powerful cathode, Goodenough drew on his experience with metal oxides, establishing lithium cobalt oxide as a stable insertion compound.{31} However, he lacked a safe anode, and so battery manufacturers were uninterested in his invention.{32}

In principle, carbon was preferable for the anode because it enabled relatively unproblematic reversible lithium intercalation. Over the years, research along these lines was performed at Sanyo (H. Ikeda, 1981), France's Centre Nationale de la Recherche (Rachid Yazami, 1982–83), and the Asahi Kasei Corporation (Akira Yoshino, 1985). From 1985, Sony's Energytec division worked to integrate these ideas in a device intended to replace the nickel-cadmium battery. In a project that owed a good deal to the contributions of Asahi Kasei and Yoshino, the division selected the carbon anode/lithium cobalt oxide combination as the best balance between cyclability, discharge capacity, and safety.{33}

Even so, these materials comprised a highly potent mix. The greatest challenge, held Nishi, was learning how to industrially produce and package them in commodity cells.{34} One problem was how to scale production of cathode material. The existing process yielded fine lithium cobalt oxide particles with large surface area, a fire hazard in the event of a short circuit or external damage to the cell, so Sony had to invent a process to coarsen the granules. Even so, lithium ion battery packs were susceptible to thermal runaway, which could be triggered by a wide variety of events including overcharge, overdischarge, and short circuits. They had to be equipped with numerous safety features including current interrupters and gas vent mechanisms. Perhaps most important was the separator, a polymer membrane that insulated the electrodes and inhibited dendrites (growths of unevenly deposited lithium) and short circuits while offering minimal resistance to ionic transport. Separator micropores were designed to expand and cut off the charge current in the event of a heat spike, the last line of defense against thermal runaway if failure was not sudden.{35}

This, at least, was the idea. Some battery researchers claimed that no safety device was very effective at stopping thermal runaway once initiated.{36} In the case of the separator, an absolutely essential safety material, some specialists associated this problem with poor coordination between original equipment manufacturers and their suppliers. Battery makers did not then cooperate with makers of separators and devoted relatively little attention to membranes compared to electrodes and electrolytes. Generally, such materials were not tailored to specific battery applications but were instead developed for other purposes by suppliers with narrow margins, limited means, and few incentives to conduct original research and development.{37} The simplest and cheapest way of increasing the storage capacity of lithium ion cells was by thinning out separators, a tactic with serious risks.{38}

<A HEAD>Dell and Sony Do Notebooks

The relationship between Sony and Dell in the development of notebook computer technology, and the application of notebook battery technology, illustrates the challenges postindustrial systems thinking posed to the management of innovation and production. It highlights the ways collaboration across corporate cultures in the era of offshoring and outsourcing conditioned and complicated engineering practice. A pioneering titan of audiovisual consumer electronics, Sony had built its brand on new product development, an approach that compelled the company to develop most of its own parts and informed a substantially vertically integrated corporate structure. By the 1980s and 1990s, Sony had developed a parallel policy of competing in every market niche and producing a wide range of products, which placed a heavy demand on internal resources.{39} In the realm of personal computers, this strategy yielded a notable lack of success. Sony produced PCs and workstations throughout the 1980s, mainly for the Japanese domestic market, but had essentially abandoned the field around the time it was preparing commercial lithium ion power sources for mobile telephony in the late 1980s and early 1990s.{40}

In contrast, Dell specialized in commodifying the PC. Michael Dell attributed his company's spectacular growth in the late 1980s and early 1990s to what he referred to as "virtual integration," a management philosophy emphasizing marketing and logistics over engineering and that took the trend towards vertical disintegration to its logical conclusion. Dell's organizational premises of mail-order direct sales and lean manufacturing had been predicated on the physical characteristics of the desktop computer, which, with its discrete retail components (monitor, case, and keyboard), allowed suppliers to rebadge and directly mail them (notably monitors) to customers. Such methods allowed the Austin-based computer upstart to maintain low parts inventories and a skeleton R&D cadre.{41}

But it proved far more difficult to integrate outsourced parts in notebook technology, the most profitable segment of the personal computer market. Dell's abortive first crack at mobile computing revealed the limits of virtual integration as an engineering principle. Dell's 320/25Sli was considered uncompetitively slow thanks to its Intel 386 microprocessor at a time when the 486 was becoming the norm, but it also had a reputation for unreliability. Some units overheated and smoked thanks to, according to one theory, a faulty interconnect between the capacitor and the AC power supply. There were no reported fires because Dell then used non-flammable nickel metal hydride (NiMH) batteries, which employed water-based electrolyte. Nevertheless, some 17,000 laptops were recalled.{42}

In early 1993, Dell suspended production and restructured its notebook program. However, the new plan preserved the core precepts of the desktop-based marketing and supply chain model. Dell hired away hardware expertise from Hewlett Packard (HP) and Apple, including designers who had worked on Powerbook, led by John Medica. Irvine-based AST Research did the manufacturing.{43} What was novel about the forthcoming Latitude was that it was to be equipped with a new power source. Dell planners made battery life the third most important parameter after price and microprocessor speed. After a protracted debate, they selected lithium ion over NiMH, calculating that it represented the difference between a "good" product and a "superb" one.{44}

The decision reflected the preference of Michael Dell, who had been impressed by a pitch for lithium power that Sony representatives had made in January 1993.{45} Dell's efforts to position itself as a manufacturer of notebooks thus aligned it with Sony's efforts to supply notebook components and thereby retain a hand in the personal computing market. Still, Dell engineers rated the approach as risky. They were aware that lithium ion batteries had only just been introduced in relatively low-power consumer applications and had not yet been tried in portable computers.{46}

When Sony decided to fully reenter the personal computing market in the mid-1990s, it conceived its new Vaio as a premium product optimized for the audiovisual capabilities in which the company had made its name. In keeping with its vertically integrated structure, Sony co-located the design and engineering of the power source and electronics of the Vaio notebook.{47} Where Dell's revamped notebook program was concerned, all that had changed was that planners had added a highly energetic power source to virtually integrated manufacturing.

<A HEAD>The Recalls

By the early 2000s, the divergence in the design and manufacturing of notebook computers and power sources had become deeply entrenched organizationally and epistemically. To a degree, this gap reflected distinct emerging national/cultural approaches to industrial innovation. Although US industry and government had helped stimulate important advances in novel power source technologies, the US consumer electronics sector was not organized to exploit them. Unlike its Japanese counterpart, observed one US industry insider, American industrial power source culture lacked strong connections both with the state and manufacturers of battery applications.{48}

So, too, were American designers of mobile electronics and computers alienated from the exigencies of power source technology. Manufacturers tended to undersize battery cavities for the expected performance or otherwise mismatched them with power source form factors.{49} And as notebook designers introduced faster processors that generated more heat and required more power, lithium ion cell designers increased energy density by thinning separators to make room for more reactive material, creating thermal management problems and narrowed margins of safety.{50}

Economic pressures further eroded these margins, and here the picture of hermetic, non-communicative national innovation systems becomes complicated. Pioneered by Sony, the lithium ion battery sector quickly became a highly competitive, low-margin industry dominated by a few firms, based mainly in Japan. From around 2000 they began to move manufacturing to South Korea and China in operations that, as industry insiders observed, were initially characterized by extensive bugs and high cell scrap rates.{51}

With this shift came an increase in reported problems with mobile devices. Consumer product recalls are a familiar aspect of life in late modern society, and the electronics sector is no exception. As we have seen, Dell had to withdraw some of its first laptops in the early 1990s, and it was not the only company to have to do so. In 1995, Apple pulled its PowerBook 5300 model following failures of lithium ion batteries that in some cases involved fires.{52} Nevertheless, the US Consumer Product Safety Commission (CPSC) issued only a handful of laptop battery recalls in the 1990s.

That changed dramatically in the 2000s, when there were no fewer than twenty-one such recalls, with an especially strong linkage between Sony and Dell. Nine recalls occurred before 2005, going virtually unnoticed in the press. Of these, Dell was involved in four, more than any other manufacturer. The first three (in October 2000, May 2001, and December 2005) were relatively small and based on a handful of reported events. The first two involved Sanyo battery packs manufactured in Japan. Encompassing some 27,000 packs for the Latitude and Inspiron models, the 2000 recall advised that the battery could short-circuit even when not in use.{53} The 2001 recall involved 284,000 units for Inspiron notebooks, by far the largest such event to date, and came with the warning that the batteries were susceptible to overcharge.{54} Sandwiched between these events was a recall of 55,000 Sony batteries for Compaq Armada notebooks in October 2000.{55}

Of the remaining four recalls in this period, two (in August 2004 and May 2005) involved Apple Powerbook G4 notebooks using LG Chem-brand packs built in Taiwan. A total of ten incidents of overheating were traced to internal shorts.{56} Of the remaining pre-2006 recalls, the most notable involved HP in October 2005. Based on sixteen reports of overheating, it affected 135,000 packs worldwide, the largest recall to date, and involved batteries assembled in China and Taiwan by an unidentified manufacturer.{57}

Among other things, the 2006 recalls were notable for their unprecedented size in relation to the number of reported incidents. On August 15, on only six reports of overheating, Dell recalled 4.2 million Sony lithium ion battery packs manufactured in Japan and China for Latitude, Inspiron, Dell Precision, and XPS notebooks. Representing 15 to 18 percent of Dell's laptop production for the period, it was the largest recall of consumer electronics to date.{58}

The scale of the recall on so few reported incidents foreshadowed a brewing controversy. It was no secret that Dell and Sony had long known that something was amiss. On the day of the recall, the New York Times cited a former Dell employee who claimed the PC maker had suppressed hundreds of incidents of catastrophic failures dating back to 2002.{59} On August 18, InfoWorld quoted a Sony official who admitted that as early as October 2005, Dell and Sony had agreed that the failures traced to cell shorting were induced by microscopic metallic contaminants. Rather than issue a recall, Sony made unspecified production changes in February.{60}

But although in the wake of the August 15 recall Dell and Sony again concurred that quality control problems were persisting, they did not agree on the cause. Dell theorized that contamination occurred at the end of Sony's manufacturing process, when cell cans were capped and crimped, and was confident the manufacturer had fixed the problem.{61} From Sony's perspective, the question was less clear. In describing its remedial work, all the company would publicly admit was that it had strengthened protective cell barriers and linings, a defensive move suggesting that it did not know where in its process the fault lay. A researcher at Sandia National Laboratory opined that contamination was occurring somewhere mid-stream, as sheets of anode, separator, and cathode material were wound into rolls before being deposited in cell cans.{62}

Interestingly, the CPSC did not endorse the contamination theory. Without denying its quality control woes, Sony also pointed to faulty notebook design. Noting that cell configuration, thermal management, and charging protocols varied across the industry, the company suggested that responsibility for battery packs lay with computer manufacturers. Ultimately, argued Sony, thermal runaway was being triggered by notebook systems issues unique to Dell. Other manufacturers agreed, insisting that their own pack designs were sound.{63}

Almost as soon as this theory was introduced, it began to unravel. On August 24, on nine reports of overheating, Apple recalled 1.1 million Sony powerpacks manufactured in Japan, China, and Taiwan for iBook G4 and PowerBook G4 notebooks. The second largest recall in consumer electronics history, it affected around a third of the notebooks Apple had sold since October 2003.{64} On September 28, Sony initiated a global replacement program for certain battery packs, reiterating that the potential of contaminants to cause short circuits depended on the systems configurations of particular notebooks.{65} The same day, Lenovo/IBM recalled over 520,000 packs manufactured in Japan and China for ThinkPad notebooks after one ignited at the Los Angeles International Airport.{66} Shortly thereafter, Sony planned its own broad recall of battery packs containing its cells, with one analyst suggesting that the company had been motivated by the ban airlines had placed on such packs and the increasing political pressure to restore confidence so that it could be lifted.{67} Three weeks later, with PC makers now uniting to blame Sony for faulty parts, the company recalled 3.4 million packs manufactured in Japan, China, Taiwan, and Malaysia for Fujitsu, Gateway, Toshiba, and, for the first time, Sony notebooks.{68}

By late October, Sony had withdrawn some 9.6 million battery packs. Its reputation and pocketbook considerably dented, the company continued to insist that computer makers bore some measure of responsibility.{69} The record of recalls in this period suggests there was something to the claim, for only one involved Sony batteries in Sony computers, and it was a cautionary, not incident-based recall. Vaio laptops appeared to have been relatively trouble-free at the time. Years later, Goodenough seemed to confirm the Sony account. He suggested that the problem ultimately traced to improperly charge-balanced packs, wherein some cells received more charge than others. When this occurred, lithium plated unevenly on the anode, forming dendrites that could induce a short circuit.{70}

As far as the popular media was concerned, the battery crisis peaked in late 2006. Nevertheless, relatively small battery recalls continued for years afterwards, involving a variety of cells in a variety of laptops, eventually even Sony's Vaio.{71} Notwithstanding HP's keenness to publicly express its understanding of the importance of battery pack management, lithium batteries in its notebooks gave the most trouble in this period. Between 2008 and 2011, the CPSC tallied some eighty-nine incidents and twenty-one injuries involving HP notebooks, the largest numbers to date on both counts, triggering three consecutive annual recalls. In 2012, the company paid a modest civil penalty for failing to report incidents in a timely manner, the only manufacturer so sanctioned to that time.{72}

<A HEAD>Epilogue

What does the notebook battery crisis reveal of the history of computing in particular, of contemporary industrial innovation in general, and of the role of the historian in comprehending events? On the one hand, it qualifies and enriches the platform perspective while cautioning against transhistorical systems thinking about industrial innovation. Vertical disintegration helped manufacturers rapidly commodify the desktop personal computer, but also seriously complicated the engineering and manufacturing of the mobile computer. Lessons of systems integration learned in the desktop context did not necessarily apply to mobile computing.

A few contemporary analyses did touch on this phenomenon. One paper produced for a workshop organized by the National Academy of Engineering in 2006 linked the complex manufacturability of notebook computers to the battery failures and implied a connection with the disintegration of work practices.{73} Other observers more explicitly made this connection. Reliability engineer Michael Pecht noted that notebook manufacturers favored batteries with high power and long run-time, and, thus, the most volatile chemistries. Guided by the principle of planned obsolescence, manufacturers assumed that consumers would throw away and replace old handheld devices long before aging batteries became a problem. Accordingly, they devoted hardly any research to battery reliability and safety, with consequences aggravated by the rapid global dispersal of supply chains.{74}

For their part, economists and business management analysts have been increasingly concerned with the problem of how to coordinate distributed supply lines.{75} Science policymakers have long associated innovation with vertically integrated institutional structures and advocated for their creation in governmental contexts as a means of bolstering national economic growth.{76}

The story of the notebook battery crisis furthers understanding of the social relations of globalization by showing the influence of corporate decentralization on material practices of science and engineering in the consumer electronics and personal computing sectors. It illuminates behaviors and coping mechanisms of actors in negotiating the imperfectly nested realms of the postindustrial inter-network, notably improvisation and exploiting the user experience of faulty consumer goods.{77} In the short term, the scapegoating of Sony likely mystified understanding of how batteries related to power density and the packaging of notebook technology. Eventually, however, industry's ad hoc approach to the presumptive anomaly of power density did enrich the systems thinking of certain semiconductor manufacturers, to judge by their acceptance of the "megahertz myth" and of other metrics of computer performance besides central processing unit speed.{78}

Over time, consumer product recalls became an additional crucial element of postindustrial corporate epistemology, a phenomenon scholars of business management have observed in other manufacturing environments, notably the automobile sector.{79} Recalls served to socialize the risks of offshored and outsourced development and manufacturing. As consumer product crises have burgeoned in recent years, the prospect of formalizing their study has appealed to business studies.{80} Conceiving product recalls as a characteristic postindustrial way of knowing may also provide historians and sociologists of contemporary science and technology with a useful means of understanding the dynamics of imperfectly nested systems in the vertically disintegrated corporate milieu.

<A HEAD>Bibliography

Altice, Nathan. I Am Error: The Nintendo Family Computer/Entertainment System Platform. Cambridge, MA: The MIT Press, 2015.

Aspray, William, ed. Chasing Moore's Law: Information Technology Policy in the United States. Raleigh, NC: SciTech Publishing, 2004.

Borkar, Shekhar. "Design Challenges of Technology Scaling." IEEE Micro 19, no. 4 (1999): 23–9.

Brodd, Ralph J. Factors Affecting US Production Decisions: Why Are There No Volume Lithium-Ion Battery Manufacturers in the United States? Gaithersburg, MD: National Institute of Standards and Technology, 2005.

Brown, Clair, and Greg Linden. "Offshoring in the Semiconductor Industry: A

Historical Perspective.” Brookings Trade Forum (2005): 279–322.

Campbell-Kelly, Martin, William Aspray, Nathan Ensmenger, and Jeffrey R. Yost. Computer: A History of the Information Machine. Boulder, CO: Westview Press, 2014.

Ceruzzi, Paul E. A History of Modern Computing. Cambridge, MA: The MIT Press, 1998.

_____. Computing: A Concise History. Cambridge, MA: The MIT Press, 2012.

Chang, Sea-Jin. Sony vs. Samsung: The Inside Story of the Electronic Giants’ Battle for Global Supremacy. Singapore: John Wiley & Sons, 2008.

Committee on Condensed-Matter and Materials Physics. The Physics of Materials: How Science Improves Our Lives. Washington, DC: National Academy Press, 1997.

_____. Condensed-Matter and Materials Physics: Basic Research for Tomorrow’s Technology. Washington, DC: National Academy Press, 1999.

Committee on Condensed-Matter and Materials Physics 2010. Condensed-Matter and Materials Physics: The Science of the World Around Us. Washington, DC: The National Academies Press, 2007.

Committee on Materials Science and Engineering. Materials Science and Engineering for the 1990s: Maintaining Competitiveness in the Age of Materials. Washington, DC: National Academy Press, 1989.

Committee on the Offshoring of Engineering. The Offshoring of Engineering: Facts, Unknowns, and Potential Implications. Washington, DC: The National Academies Press, 2008.

Cortada, James W. The Digital Hand, vol. 3: How Computers Changed the Work of American Public Sector Industries. New York: Oxford University Press, 2008.

_____. The Digital Flood: The Diffusion of Information Technology Across the US, Europe, and Asia. New York: Oxford University Press, 2012.

_____. “How New Technologies Spread: Lessons from Computing Technologies.” Technology and Culture 54, no. 2 (2013): 229–61.

Consumer Product Safety Commission (CPSC). “CPSC, Dell Announce Recall of Batteries for Notebook-Computers.” CPSC Recalls. 13 October 2000. http://www.cpsc.gov/en/Recalls/2001/CPSC-Dell-Announce-Recall-of-Batteries-for-Notebook-Computers/ (accessed 6 July 2013).

_____. “CPSC, Compaq Announce Recall of Notebook Computer Battery Packs.” CPSC Recalls. 27 October 2000. http://www.cpsc.gov/en/Recalls/2001/CPSC-Compaq-Announce-Recall-of-Notebook-Computer-Battery-Packs/ (accessed 6 July 2013).

_____. “CPSC, Dell Computer Corp Announce Recall of Notebook Computer Batteries.” CPSC Recalls. 3 May 2001. http://www.cpsc.gov/en/Recalls/2001/CPSC-Dell-Computer-Corp-Announce-Recall-of-Notebook-Computer-Batteries/ (accessed 6 July 2013).

_____. “CPSC, Apple Announce Recall of PowerBook Computer Batteries.” CPSC Recalls. 19 August 2004. http://www.cpsc.gov/en/Recalls/2004/CPSC-Apple-Announce-Recall-of-PowerBook-Computer-Batteries-/ (accessed 6 July 2013).

_____. “CPSC, Apple Announce Recall of iBook and PowerBook Computer Batteries.” CPSC Recalls. 20 May 2005. http://www.cpsc.gov/en/Recalls/2005/CPSC-Apple-Announce-Recall-of-iBook-and-PowerBook-Computer-Batteries/ (accessed 6 July 2013).

_____. “CPSC, Hewlett-Packard Company Announce Recall of Notebook Computer Batteries.” CPSC Recalls. 14 October 2005. http://www.cpsc.gov/en/Recalls/2006/CPSC-Hewlett-Packard-Company-Announce-Recall-of-Notebook-Computer-Batteries/ (accessed 6 July 2013).

_____. “Dell Announces Recall of Notebook Computer Batteries Due to Fire Hazard.” CPSC Recalls. 15 August 2006. http://www.cpsc.gov/en/Recalls/2006/Dell-Announces-Recall-of-Notebook-Computer-Batteries-Due-To Fire-Hazard/ (accessed 6 July 2013).

_____. “Lenovo and IBM Announce Recall of Thinkpad Notebook Computer

Batteries Due to Fire Hazard." CPSC Recalls. 28 September 2006. http://www.cpsc.gov/en/Recalls/2006/Lenovo-and-IBM-Announce-Recall-of-ThinkPad-Notebook-Computer-Batteries-Due-to-Fire-Hazard/ (accessed 6 July 2013).

_____. "Sony Recalls Notebook Computer Batteries Due to Previous Fires." CPSC Recalls. 23 October 2006. http://www.cpsc.gov/en/Recalls/2007/Sony-Recalls-Notebook-Computer-Batteries-Due-to-Previous-Fires/ (accessed 6 July 2013).

_____. "Hewlett-Packard Agrees to $425,000 Civil Penalty for Failure to Immediately Report Lithium Ion Battery Packs." CPSC Recalls. 23 January 2012. http://www.cpsc.gov/en/Newsroom/News-Releases/2012/Hewlett-Packard-Agrees-to-425000-Civil-Penalty-for-Failure-to-Immediately-Report-Lithium-Ion-Battery-Packs/ (accessed 31 July 2014).

_____. "Sony Recalls VAIO Flip PC Laptops Due to Fire and Burn Hazards." CPSC Recalls. 1 July 2014. http://www.cpsc.gov/en/Recalls/2014/Sony-Recalls-VAIO-Flip-PC-Laptops/ (accessed 31 July 2014).

Cringely, Robert X. "Safety Last." New York Times, 1 September 2006.

Crompton, T.R. Battery Reference Book. 2nd ed. Oxford: Butterworth-Heinemann, 1995.

Darlin, Damon. "Dell Will Recall Batteries in PCs." New York Times, 15 August 2006.

_____. "Apple Joins in a Recall of Batteries," New York Times, 25 August 2006.

_____ and Barnaby J. Feder. "We Ask So Much Of Our Batteries." New York Times, 16 August 2006.

Dedrick, Jason, and Kenneth L. Kraemer. "Impact of Globalization and Offshoring on Engineering Employment in the Personal Computing Industry." In The Offshoring of Engineering: Facts, Unknowns, and Potential Implications, 125–136. Washington, DC: The National Academies Press, 2008.

Freiberger, Paul, and Michael Swaine. Fire In The Valley: The Making of the

Personal Computer. New York: Hill-McGraw, 2000.

Gadde, Lars-Erik. “Moving Corporate Boundaries: Consequences for Innovative Design.” Journal of Supply Chain Management 49, no. 4 (2013): 12–26.

Gazzard, Alison. Now The Chips Are Down: The BBC Micro. Cambridge, MA: The MIT Press, 2016.

Goodenough, John B. “Rechargeable Batteries: Challenges Old and New.” Journal of Solid State Electrochemistry 16, no. 6 (2012): 2019–29.

_____, K. Mizushima, and T. Takeda. “Solid-Solution Oxides for Storage-Battery Electrodes.” Japanese Journal of Applied Physics 19 (1980): 305–13.

_____, and Youngsik Kim. “Challenges for Rechargeable Li Batteries.” Chemistry of Materials Review 22, no. 3 (2010): 587–603.

Greenman, Catherine. “Laptop Batteries Are Linked to Fire Risk.” New York Times, 15 March 2001.

Haigh, Thomas. “The IBM PC: From Beige Box to Industry Standard.” Communications of the ACM 55, no. 1 (2012): 35–7.

Haunschild, Pamela R., and Mooweon Rhee. “The Role of Volition in Organizational Learning: The Case of Automotive Product Recalls.” Management Science 50, no. 11 (2004): 1545–60.

Hughes, Thomas P. Networks of Power: Electrification in Western Society, 1880–1930. Baltimore: The Johns Hopkins University Press, 1983.

_____. “The Evolution of Large Technological Systems.” In The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology, edited by Wiebe Bijker, Thomas P. Hughes, and Trevor Pinch, 45–76. Cambridge, MA: The MIT Press, 2012.

Isaac, Randall D. “Semiconductor Productivity and Computers.” In Productivity and Cyclicality in Semiconductors: Trends, Implications, and Questions – Report of a Symposium, edited by Dale W. Jorgenson and Charles W. Wessner, 49–55. Washington, DC: The National Academies Press, 2004.

Jones, Kathryn. “Dell Recalls Thousands of Notebook Computers.” New York Times, 9 October 1993.

Jorgenson, Dale W., and Charles W. Wessner. “Introduction.” In Measuring and Sustaining the New Economy – Report of a Workshop, edited by Dale W. Jorgenson and Charles W. Wessner, 9–27. Washington, DC: National Academy Press, 2002.

_____. “Preface.” In Productivity and Cyclicality in Semiconductors: Trends, Implications, and Questions – Report of a Symposium, edited by Dale W. Jorgenson and Charles W. Wessner, xiii–xviii. Washington, DC: The National Academies Press, 2004.

Kageyama, Yuri. “Sony Apologizes for Battery Recall.” Associated Press, 24 October 2006.

Kalaignanam, Kartik, Tarun Kushwaha, and A. Meike Eilert. “The Impact of Product Recalls on Future Product Reliability and Future Accidents: Evidence from the Automobile Industry.” Journal of Marketing 77, no. 2 (2013): 41–57.

Kane, Yukari Iwatani. “Sony Apologizes for Battery Recall.” Wall Street Journal, 25 October 2006.

Kanellos, Michael. “Can Anything Tame the Battery Flames?” CNET News, 15 August 2006. http://news.cnet.com/Can-anything-tame-the-battery-flames/2100-11398_3-6105924.html (accessed 17 August 2013).

Ketchen, Jr., David J., Kaitlin D. Wowak, and Christopher W. Craighead. “Resource Gaps and Resource Orchestration Shortfalls in Supply Chain Management: The Case of Product Recalls.” Journal of Supply Chain Management 50, no. 3 (2014): 6–15.

Koomey, Jonathan G., Stephen Berard, Marla Sanchez, and Henry Wong. “Implications of Historical Trends in the Electrical Efficiency of Computing.” IEEE Annals of the History of Computing 33, no. 3 (2011): 46–54.

Krazit, Tom, and Michael Kanellos. “Dell to Recall 4 Million Batteries.” CNET News, 15 August 2006. http://news.cnet.com/Dell-to-recall-4-million-batteries/

2100-1044_3-6105486.html (accessed 24 June 2013).

Lohr, Steve. “Dell’s Second Stab at Portables: High-Stakes Effort By Computer Maker.” New York Times, 22 February 1994.

Lombardi, Candace. “Sony Plans Its Own Battery Recall.” CNET News, 3 October 2006. http://news.cnet.com/Sony-plans-its-own-battery-recall/2100-1044_3-6122234.html (accessed 6 July 2013).

MacArthur, Donald, George Blomgren, and Robert A. Powers. Lithium and Lithium Ion Batteries, 2000: A Review and Analysis of Technical, Market and Commercial Developments. Westlake, OH: Robert A. Powers Associates, 2000.

Magklis, Grigorios, Greg Semeraro, David H. Albonesi, Steven G. Dropsho, Sandhya Dwarkadas, and Michael L. Scott. “Dynamic Frequency and Voltage Scaling for a Multiple-Clock-Domain Microprocessor.” IEEE Micro 23, no. 6 (2003): 62–8.

Magretta, Joan. “The Power of Virtual Integration: An Interview with Dell Computer’s Michael Dell.” Harvard Business Review (March-April 1998): 72–84.

Maher, Jimmy. The Future Was Here: The Commodore Amiga. Cambridge, MA: The MIT Press, 2012.

Maleki, Hossein, and Ahmad K. Shamsuri. “Thermal Analysis and Modeling of a Notebook Computer Battery.” Journal of Power Sources 115, no. 1 (2003): 131–36.

McLaughlin, Laurianne. “Analysis: Why Apple Picked Intel Over AMD.” Macworld, 15 September 2005. http://www.macworld.com/article/1046961/intelvsamd.html (accessed 21 September 2014).

Merced, Michael. “Battery Recall Exacts Steep Toll on Sony.” New York Times, 27 October 2006.

Mizushima, K., P.C. Jones, P.J. Wiseman, and J.B. Goodenough. “LixCoO2: A New Cathode Material for Batteries of High Energy Density.” Materials Research Bulletin 15, no. 6 (1980): 783–89.

Montfort, Nick, and Ian Bogost. Racing the Beam: The Atari Video Computer

System. Cambridge, MA: The MIT Press, 2009.

Motoyama, Yasuyuki. *Global Companies, Local Innovations: Why the Engineering Aspects of Innovation Making Require Co-Location*. Surrey, England: Ashgate, 2012.

Mudge, Trevor. “Power: A First-Class Architectural Design Constraint.” *Computer* 34, no. 4 (2001): 52–8.

Nishi, Yoshio. “Lithium Ion Secondary Batteries: Past 10 Years and the Future.” *Journal of Power Sources* 100, nos. 1–2 (2001): 101–06.

_____. “The Development of Lithium Ion Secondary Batteries.” *The Chemical Record* 1 (2001): 406–13.

_____. “Foreword: My Way to Lithium-Ion Batteries.” In *Lithium-Ion Batteries: Science and Technologies*, edited by Masaki Yoshio, Ralph J. Brodd, and Akiya Kozawa, v–vii. New York: Springer, 2009.

Nordhaus, William D. “Two Centuries of Productivity Growth in Computing.” *The Journal of Economic History* 67, no. 1 (2007): 128–59.

Nye, David E. *Technology Matters: Questions to Live With*. Cambridge, MA: The MIT Press, 2006.

Ozawa, Kazunori. “Lithium-Ion Rechargeable Batteries with LiCoO2 and Carbon Electrodes: The LiCoO2/C System.” *Solid State Ionics* 69, nos. 3–4 (1994): 212–21.

Pecht, Michael G. “Editorial: Re-Thinking Reliability.” *IEEE Transactions on Components and Packaging Technologies* 29, no. 4 (2006): 893–4.

Pillai, Padmanabhan, and Kang G. Shin. “Real-Time Dynamic Voltage Scaling for Low-Power Embedded Operating Systems.” In *Proceedings of the Eighteenth ACM Symposium on Operating Systems Principles* (2001): 89–102.

Pistoia, Gianfranco. “Nonaqueous Batteries Used In Industrial Applications.” In *Industrial Applications of Batteries: From Cars to Aerospace and Energy Storage*, edited by Michel Broussely and Gianfranco Pistoia, 1–49. Amsterdam: Elsevier, 2007.

Roberts, Paul F. “Dell, Sony Discussed Battery Problem 10 Months Ago.” *InfoWorld*, 18 August 2006. http://www.infoworld.com/article/2658394/computer-hardware/dell--sony-discussed-battery-problem-10-months-ago.html (accessed July 5 2013).

Rosier, Mathieu, and Bertjan Janzen. Reverse Logistics: How to Realize an Agile and Efficient Reverse Chain Within the Consumer Electronics Industry. London: PriceWaterhouseCoopers, 2008.

Schallenberg, Richard H. Bottled Energy: Electrical Engineering and the Evolution of Chemical Energy Storage. Philadelphia: American Philosophical Society, 1982.

Semiconductor Industry Association. The National Technology Roadmap For Semiconductors. Washington, DC: Semiconductor Industry Association, 1994.

Skilton, Paul F., and Jessica L. Robinson. “Traceability and Normal Accident Theory: How Does Supply Network Complexity Influence the Traceability of Adverse Events?” Journal of Supply Chain Management 45, no. 3 (2009): 40–53.

Smalley, Tim. “Performance per What?” Bit Tech, 20 May 2007. http://www.bit-tech.net/columns/2007/05/20/performance_per_what/1 (accessed 15 September 2014).

Smith, Tony. “Megahertz Myth: There Is More To a PC’s Virility Than Clock Speed.” The Guardian, 27 February 2002.

Sony Corporation. “Sony to Initiate Global Replacement Program for Notebook Computer Battery Packs.” 28 September 2006. http://www.sony.net/SonyInfo/News/Press/200609/06-090E/index.html (accessed 6 July 2014).

_____. “Product and Technology Milestones: Personal Computer.” Sony Corporate Info. http://www.sony.net/SonyInfo/CorporateInfo/History/sonyhistory-h.html (accessed 26 August 2014).

Sumner, James. “Standards and Compatibility: The Rise of the PC Computing Platform.” In History of Technology Volume 28: By Whose Standards? Standardization, Stability and Uniformity in the History of Information and Electrical Technologies, edited by James Sumner and Graeme J.N. Gooday, 101–127. London: Continuum, 2008.

Tang, Christopher S. “Making Products Safe: Process and Challenges.” International Commerce Review 8, no. 1 (2008): 48–55.

Tassey, Gregory. “Rationales and Mechanisms for Revitalizing US Manufacturing R&D Strategies.” Journal of Technology Transfer 35, no. 3 (2010): 283–333.

Thomke, Stefan, Vish V. Krishnan, and Ashok Nimgade. Product Development at Dell Computer Corporation. Boston: Harvard Business School Publishing, 1998.

Westbrook, Michael H. The Electric Car: Development and Future of Battery, Hybrid and Fuel-Cell Cars. London: The Institution of Electrical Engineers, 2001.

Whittingham, M. Stanley. “Electrical Energy Storage and Intercalation Chemistry.” Science (New Series) 192, no. 4244 (1976): 1126–27.

_____. “Lithium Batteries and Cathode Materials.” Chemical Reviews 104, no. 10 (2004): 4271–4301.

Wowak, Kaitlin D., and Christopher A. Boone. “So Many Recalls, So Little Research: A Review of the Literature and Road Map for Future Research.” Journal of Supply Chain Management 51, no. 4 (2015): 54–72.

Young, Jeffrey S., and William L. Simon. iCon: Steve Jobs, the Greatest Second Act in the History of Business. New York: Wiley, 2005.

Zhang, Zhengming, and Premanand Ramadass. “Lithium-Ion Battery Separators.” In Lithium-Ion Batteries: Science and Technologies, edited by Masaki Yoshio, Ralph J. Brodd, and Akiya Kozawa, 367–412. New York: Springer, 2009.

Zu, Chen-Xi, and Hong Li. “Thermodynamic Analysis on Energy Densities of Batteries.” Energy and Environmental Science 4 (2011): 2614–24.

<footnotes>

{1} See, for example, Damon Darlin, “Apple Joins in a Recall of Batteries”; Yukari Iwatani Kane, “Sony Apologizes for Battery Recall”; Michael Merced, “Battery Recall Exacts Steep Toll on Sony”; and Paul F. Roberts, “Dell, Sony Discussed Battery Problem

10 Months Ago.”

{2} Richard H. Schallenberg expressed this point in his pioneering study of battery technology; see *Bottled Energy*.

{3} Thomas P. Hughes, *Networks of Power*.

{4} Hughes, “The Evolution of Large Technological Systems.”

{5} See, for example, the twelve-year study conducted by Clair Brown and Greg Linden, “Offshoring in the Semiconductor Industry”; and the Committee on the Offshoring of Engineering, *The Offshoring of Engineering*.

{6} See, for example, Nathan Ensmenger, “Rethinking Computers,” *The Computer Boys Take Over*, 4; Michael Sean Mahoney, *Histories of Computing*, 31.

{7} James Sumner has provided perhaps the most lucid definition of the platform concept, from which I have here drawn; see “Standards and Compatibility,” 107.

{8} Four of the seven titles in The MIT Press Platform Series as of October 2015 are rooted in the classic desktop/console era; see Nick Montfort and Ian Bogost, *Racing the Beam*; Jimmy Maher, *The Future Was Here*; Nathan Altice, *I Am Error*; and Alison Gazzard, *Now the Chips are Down*.

{9} For a representative sample, see Paul E. Ceruzzi, *Computing: A Concise History* and *A History of Modern Computing*; Paul Freiberger and Michael Swaine, *Fire In The Valley*; Martin Campbell-Kelly, William Aspray, Nathan Ensmenger, and Jeffrey R. Yost, *Computer*; James W. Cortada, “How New Technologies Spread,” *The Digital Flood*, and *The Digital Hand*.

{10} Sumner, “Standards and Compatibility,” 107; Thomas Haigh, “The IBM PC,” 36.

{11} See, for example, Aspray, ed., *Chasing Moore’s Law*; Dale W. Jorgenson and Charles W. Wessner, “Preface,” xiv, and “Introduction,” 11.

{12} William D. Nordhaus, “Two Centuries of Productivity Growth.”

{13} Trevor Mudge, “Power.”

{14} See, for example, Semiconductor Industry Association, The National Technology Roadmap, 14.

{15} Shekhar Borkar, “Design Challenges of Technology Scaling.”

{16} Randall D. Isaac, “Semiconductor Productivity and Computers,” 51–5.

{17} Jonathan G. Koomey, Stephen Berard, Marla Sanchez, and Henry Wong, “Implications of Historical Trends,” 50.

{18} Tim Smalley, “Performance per What?”

{19} Padmanabhan Pillai and Kang G. Shin, “Real-Time Dynamic Voltage Scaling”; Mudge, “Power,” 55; Grigorios Magklis, Greg Semeraro, David H. Albonesi, Steven G. Dropsho, Sandhya Dwarkadas, and Michael L. Scott, “Dynamic Frequency and Voltage Scaling.”

{20} See Koomey, Berard, Sanchez, and Wong, “Implications of Historical Trends,” 50.

{21} Chen-Xi Zu and Hong Li, “Thermodynamic Analysis.”

{22} David E. Nye, Technology Matters, 2.

{23} Yoshio Nishi, “Foreword,” vi; Kazunori Ozawa, “Lithium-Ion Rechargeable Batteries,” 212.

{24} Schallenberg, Bottled Energy, 391–392.

{25} See M. Stanley Whittingham, “Lithium Batteries and Cathode Materials,” 4274; Hervé Arribart and Bernadette Bensaude-Vincent, “Beta-Alumina,” February 16, 2001, Caltech Library, available at http://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/materials/public/Beta-alumina.htm (accessed 12 August 2013). The expression “advanced power source” generally refers to devices that are rechargeable, powerful (defined as the rate of energy flow per unit of volume), and energetic (defined as the amount of stored energy per unit of volume or mass). Batteries are often considered “advanced” if they have energy densities of greater than 30–40 watt hours per kilogram, the contemporary limit of classical batteries such as the lead-acid and nickel-cadmium systems. Notable advanced power sources include sodium-sulfur, lithium titanium disulfide, sodium metal chloride, and lithium aluminum-metal sulfide batteries, as well as a range of fuel cells; see Zu and Li, “Thermodynamic Analysis,” 2615.

{26} Michael H. Westbrook, The Electric Car, 24–25.

{27} Ralph J. Brodd, Factors Affecting US Production; Gianfranco Pistoia, “Nonaqueous Batteries,” 1; T.R. Crompton, “Preface,” ix.

{28} John B. Goodenough, interview by Matthew N. Eisler, July 11, 2013, Austin, Texas.

{29} Goodenough, “Rechargeable Batteries,” 2022; Goodenough and Youngsik Kim, “Challenges for Rechargeable Li Batteries,” 592; Whittingham, “Electrical Energy Storage,” 1126–27.

{30} Long used successfully as the anode in primary (non-rechargeable) cells, metallic lithium was attractive for its high voltage and energy density. In a secondary or rechargeable cell, however, this material was hazardous because it interacted with the electrolyte in such a way as to cause lithium to plate unevenly on the anode on repeated cycling at high voltage. Over time, recharging created a dendrite, a growth that could bridge the electrodes, trigger a short circuit, and ignite the electrolyte.

{31} K. Mizushima, P.C. Jones, P.J. Wiseman, and Goodenough, “LixCoO2: A New Cathode Material”; see also Goodenough, Mizushima, and T. Takeda, “Solid-Solution Oxides.”

{32} Goodenough, interview with Eisler.

{33} Goodenough, “Rechargeable Batteries”; Nishi, “Lithium Ion Secondary Batteries,” 102.

{34} Nishi, “My Way to Lithium-Ion Batteries,” vi.

{35} Nishi, “The Development of Lithium Ion Secondary Batteries,” 411–12.

{36} Hossein Maleki and Ahmad K. Shamsuri, “Thermal Analysis and Modeling,” 131.

{37} Zhengming Zhang and Premanand Ramadass, “Lithium-Ion Battery Separators,” 367–68.

{38} Charles Stone, First Annual Society of Chemical Industry-Chemical Heritage Foundation Innovation Day, September 14, 2004, Philadelphia. [Author, what kind of source is this? Printed? Oral? Archival?]

{39} Sea-Jin Chang, Sony vs. Samsung, 13, 30.

{40} Yasuyuki Motoyama, Global Companies, Local Innovations, 28–29; Sony Corp., “Product and Technology Milestones.”

{41} In a 1998 interview, Dell derided the “engineering-centric” approach of his component-manufacturing competitors as a form of machismo, a “rite of passage” antithetical to business principles; see Joan Magretta, “The Power of Virtual Integration,” 74.

{42} Kathryn Jones, “Dell Recalls Thousands of Notebook Computers.”

{43} Steve Lohr, “Dell’s Second Stab at Portables.”

{44} This was defined as a 2.5–3 percent market share; see Stefan Thomke, Vish V. Krishnan, and Ashok Nimgade, Product Development at Dell.

{45} Magretta, “The Power of Virtual Integration.”

{46} Thomke, Krishnan, and Nimgade, Product Development at Dell, 10.

{47} Motoyama, Global Companies, Local Innovations, 38.

{48} Brodd, Factors Affecting US Production Decisions, 18, 24–29.

{49} Ibid.

{50} Michael Kanellos, “Can Anything Tame the Battery Flames?”

{51} Donald MacArthur, George Blomgren, and Robert A. Powers, Lithium and Lithium Ion Batteries, 17–8; MacArthur, Blomgren, and Powers claimed that Sony saw the lithium ion battery not as a profitable stand-alone segment but as a way to promote its electronics business.

{52} Catherine Greenman, “Laptop Batteries Are Linked to Fire Risk.”

{53} CPSC, “CPSC, Dell Announce Recall of Batteries for Notebook-Computers.”

{54} CPSC, “CPSC, Dell Computer Corp Announce Recall of Notebook Computer Batteries.”

{55} CPSC, “CPSC, Compaq Announce Recall of Notebook Computer Battery Packs.”

{56} CPSC, “CPSC, Apple Announce Recall of PowerBook Computer Batteries”; “CPSC, Apple Announce Recall of iBook and PowerBook Computer Batteries.”

{57} CPSC, “CPSC, Hewlett-Packard Company Announce Recall of Notebook Computer Batteries.”

{58} CPSC, “Dell Announces Recall of Notebook Computer Batteries Due to Fire Hazard.”

{59} Damon Darlin, “Dell Will Recall Batteries in PCs.”

{60} Roberts, “Dell, Sony Discussed Battery Problem 10 Months Ago.”

{61} Darlin, “Dell Will Recall Batteries in PCs.”

{62} Roberts, “Dell, Sony Discussed Battery Problem 10 Months Ago.”

{63} Darlin, “Dell Will Recall Batteries in PCs”; Roberts, “Dell, Sony Discussed Battery Problem 10 Months Ago”; Tom Krazit and Michael Kanellos, “Dell to Recall 4 Million Batteries.”

{64} Darlin, “Apple Joins in a Recall of Batteries.”

{65} Sony Corp., “Sony to Initiate Global Replacement Program for Notebook Computer Battery Packs.”

{66} CPSC, “Lenovo and IBM Announce Recall of Thinkpad Notebook Computer Batteries Due to Fire Hazard.”

{67} Candace Lombardi, “Sony Plans Its Own Battery Recall.”

{68} CPSC, “Sony Recalls Notebook Computer Batteries Due to Previous Fires.”

{69} Kane, “Sony Apologizes for Battery Recall”; Yuri Kageyama, “Sony

Apologizes for Battery Recall." Sony's sense of responsibility, opined Kageyama, could be gauged from the fact the apology had been delivered by seated executives making shallow bows, a relatively mild public display of corporate contrition.

{70} Goodenough, interview with Eisler.

{71} CPSC, "Sony Recalls VAIO Flip PC Laptops Due to Fire and Burn Hazards."

{72} CPSC, "Hewlett-Packard Agrees to $425,000 Civil Penalty for Failure to Immediately Report Lithium Ion Battery Packs."

{73} Jason Dedrick and Kenneth L. Kraemer, "Impact of Globalization and Offshoring," 127–8.

{74} Michael G. Pecht, "Editorial: Re-Thinking Reliability"; see also Robert X. Cringely, "Safety Last"; Darlin and Barnaby J. Feder, "We Ask So Much of Our Batteries."

{75} See, for example, Lars-Erik Gadde, "Moving Corporate Boundaries"; Paul F. Skilton and Jessica L. Robinson, "Traceability and Normal Accident Theory"; and Mathieu Rosier and Bertjan Janzen, Reverse Logistics, 27.

{76} See, for example, the reports of the Committee on Materials Science and Engineering, Materials Science and Engineering for the 1990s; Committee on Condensed-Matter and Materials Physics, The Physics of Materials; and the Committee on Condensed-Matter and Materials Physics 2010, Condensed-Matter and Materials Physics. In 2010, the senior economist of the National Institute of Standards and Technology warned that vertical disintegration inhibited innovation and called for state intervention in enabling "co-location synergies"; see Gregory Tassey, "Rationales and Mechanisms for Revitalizing US Manufacturing," 31.

{77} The question of user experience and agency has been addressed by, among others, Langdon Winner, Ruth Schwartz Cowan, Steven Epstein, Trevor Pinch, and Ronald Kline.

{78} See Tony Smith, "Megahertz Myth"; and Laurianne McLaughlin, "Analysis."

{79} See, for example, Kartik Kalaignanam, Tarun Kushwaha, and A. Meike Eilert, “The Impact of Product Recalls”; and Pamela R. Haunschild and Mooweon Rhee, “The Role of Volition.”

{80} See, for example, Kaitlin D. Wowak and Christopher A. Boone, “So Many Recalls, So Little Research”; David J. Ketchen, Jr., Kaitlin D. Wowak, and Christopher W. Craighead, “Resource Gaps and Resource Orchestration”; and Christopher S. Tang, “Making Products Safe.”