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How Inexpensive RFID Is Revolutionizing the Supply Chain

Innovations Case Narrative:
The Electronic Product Code

Like the electric, water, and information networks most of modern society relies on, there is another network, one far less visible, that makes modern life possible: the global supply chain. Almost every physical product that is grown, manufactured, or packaged arrives at a store or at our home through a series of transfers involving ships, planes, trains, and trucks. In between, products may be aggregated into pallets and containers; moved with cranes or forklifts; stored in ports, warehouses, or on shelves; kept secure in armored vehicles or vaults; kept fresh in refrigerated storage or "reefer" transportation units; and packaged, repackaged, or finished before they get into our hands. Supply-chain management, which involves everything from the sourcing and procurement of materials to logistics, is a major part of the U.S. economy. In 2011, U.S. business logistics costs totaled $1.28 trillion and accounted for 8.5 percent of the GDP.[1]

I am one of the developers of a new suite of technologies and standards for the supply chain that is based on low-cost, ubiquitous radio frequency identification (RFID). Our system, which is called the Electronic Product Code (EPC), consists of protocols for communication between readers and tags, and standards for storing and sharing data across companies. The project started at MIT in 1998, and by 2003, engineers from more than one hundred companies and faculty and students from five universities were collaborating to flesh out the system, build prototypes, and conduct field trials. About 2.5 billion EPC tags will be produced and deployed worldwide in 2012, and companies including Walmart, Airbus, JCPenney, and Inditex are in the midst of rollouts.

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A Primer on RFID

RFID systems consist of readers and tags. The reader puts out an RF signal and "illuminates" the tag, which consists of a chip and an antenna. A passive RFID tag doesn't have batteries; it absorbs some of the energy coming in from the RF signal to power up its chip and then reflects a signal back to the reader, in which its identity and other information are encoded. RFID systems can operate at different frequencies. National governments own the frequency spectrum in their territories and they license frequency bands to private and public customers, such as television stations, mobile phone companies, and military services. Each license specifies not just the frequency range but also the power or field strength the licensee can emit from its devices. Some frequency bands are kept "open" for general use, and RFID generally operates in these open bands. In 1998, most passive RFID was in the low-frequency (LF) and high-frequency (HF) bands. Performance at these bands is limited to a range of a few feet for a reasonably sized antenna. Ultra-high frequency offered the promise of a higher range, but the products available in 1998 did not provide the right price-to-performance ratio to take advantage of them.

When a reader starts reading tags, the tags must not respond all at once. The reader needs to space out the tags so it can hear each individually. This is called anti-collision, and it is a central factor not just in RFID but in all computer networking. Once a tag has been identified, the reader talks to each tag. The communication between reader and tags occurs by modulating the amplitude or frequency of the signal at the allocated frequency. The reader looks for these perturbations and extracts an encoded stream of bits—ones and zeros—to get data from the tag. The reader and tag need to have an agreed upon format for storing data: where the ID starts in the string, where it ends, what other data the tag may want to convey, etc. Together, the anti-collision scheme, the modulation scheme, the encoding scheme, and the data format are referred to as the protocol for communication between readers and tags.

THE SUPPLY CHAIN

Supply chains such as the caravans traveling the ancient Silk Road have spanned international borders for centuries. What has changed in recent history is the extent to which we depend on the global supply chain for everyday products such as toothpaste and clothes. This has been made possible by relatively low shipping costs, lower trade barriers, and the availability of low-cost labor in various parts of the world. The computation and sensors needed to manage modern logistics have barely managed to keep up with the increasing complexity of supply chains. Every day, billions of product barcodes are scanned, and trillions of pieces of information are keyed into computers manually to keep track of physical inventories.[2] Hundreds of thousands of scanners, cameras, optical character recognition systems, label printers, weighing machines, and GPS systems hum away, trying to tame the chaos of the movement of goods across the planet. Along the way, parts are ordered and delivered, purchases are made and money exchanged, regulations are met and customs duties are paid, and products are inspected for authenticity, quality, and regulatory compliance. This massive system is the engine of the modern economy.

Such a complex system cannot be flawless, and the range of possible errors is extensive. Every time products are packaged into cartons, there is the possibility that one less box, one more box, or the wrong box enters the expected mix. These possibilities are compounded exponentially if we consider all the physical aggregation, disaggregation, picking, sorting, and transfers that occur along the supply chain: building pallets, placing them in trucks, unloading the trucks at ports, placing goods in containers, loading the containers onto ships, unloading them at other ports, unloading containers, moving goods into warehouses, and so on. Meanwhile, there are limited ways to verify the correctness of a transfer. If a forklift operator can be persuaded to dismount, pick up a scanner, and find the label on a pallet, there is a chance he might discover that the wrong pallet has been placed in the truck. More often than not, however, errors go undetected, which leads to excess inventories or shortages.

Excess inventory causes headaches in several ways: holding costs increase, products become obsolete, products degrade, and pilferage increases. Stock-outs—that is, when there is no stock available to satisfy demand—are even more damaging because they interrupt commerce. In U.S. retail, for example, studies show that the average product is stocked out on shelves 8 percent of the time, which can lead to lost sales and dissatisfied consumers. Errors can lead to other problems as well, such as food spoilage and expired or damaged pharmaceuticals. The natural response to a fear of stock-outs is to increase inventory, which further compounds errors in the supply chain. This contributes significantly to the "bull-whip" effect:[3] factory orders can fluctuate greatly, leading to a type of boom-bust cycle that makes business planning difficult.

The massive integration of the supply chain also magnifies the impact of mistakes and illicit activities in production. We all are familiar with the periodic recall of food contaminated with salmonella, e-coli, or chemicals, which are examples of the global supply chain being a victim of its own success. Because goods can be transported so far so rapidly, mistakes can spread rapidly too. In 2011, for example, there were more than two hundred food recalls in the U.S. FDA registry. Illicit activities are even more pernicious. Counterfeit or diluted drugs in the global supply chain are a $50 billion business worldwide, which does not account for the immeasurable impact this has on human lives.

There are ad hoc measures for addressing each of these problems, but they tend to be manual and expensive. What is needed is a silent way to identify and count goods in the supply chain continuously and everywhere. Imagine a "toll pass" system that identifies goods in the supply chain, just as the E-ZPass system—which is an example of RFID—identifies cars at highway toll booths. In 1998,

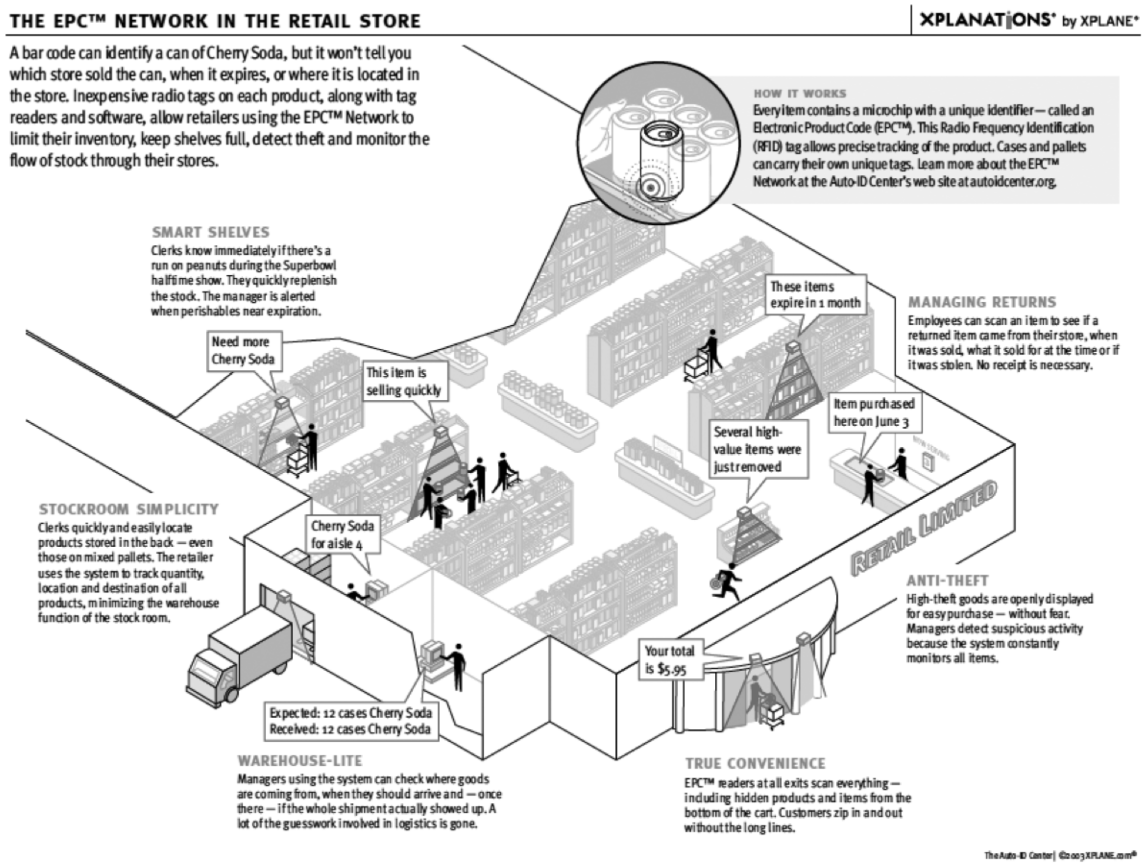

Figure 1. Drawing of the Auto-ID Center Vision by XPlane[4]

RFID technology was several orders of magnitude too expensive for the supply chain, so we set out to enable low-cost RFID tracking of goods—everything from frozen food to boxes of toothpaste.

THE FORMATION OF THE AUTO-ID CENTER

I first became excited about RFID because of my colleague Dr. David Brock, a roboticist at the Lab for Manufacturing and Productivity. David had an elegant concept in mind: why ask robots to laboriously recognize objects using computer vision and image processing when we could place a marker on the objects and have the robot simply read the marker? The marker he had in mind was an RFID tag. Unlike barcodes, which are read optically, RFID tags can be read without a line of sight—or, as we used to joke, telepathically. He further proposed putting an ID on the tag and putting the information needed on the Internet. The ID could then point to the location of the data, effectively increasing the data capacity of an RFID tag immeasurably.

I saw the problem from a completely different angle. RFID tags were very expensive at that time—around several dollars each. My angle was this: if we simplified RFID tags and protocols to the point where they were cost-competitive with barcodes, perhaps we could make RFID tags ubiquitous in the supply chain. Based on some back-of-the-envelope calculations, I proposed that the cost of tags could be brought down to 10 cents. David and I combined forces, and our effort was underway.

In early 1999 we met Kevin Ashton, a rising executive at Procter & Gamble (P&G) who was a brand manager for Oil of Olay and based in London. Kevin had been struggling with the problem of stock-outs of his products on shelves. He had done a great deal of business research on RFID and concluded that it would solve his problem—and a number of other problems in the supply chain as well. When he heard our pitch, he immediately pledged to introduce us to the senior management at P&G and Gillette.

Kevin also introduced us to Al Haberman, the venerable "father of the UPC barcode" (for Universal Product Code). Twenty-five years earlier, Al, then the CEO of a retail company, had lead the formation of the Uniform Code Council (now GS1 US), which had ushered in the use of the UPC barcode in retail worldwide. By 1999, five billion barcodes were being scanned daily. Al too had the feeling that a new technology was needed to enable the supply chain to make the next leap. We pitched more then 30 companies over the next several months, and by September 1999 we had signed up P&G, Gillette, and the Uniform Code Council as sponsors.

The formation of the Auto-ID Center (for Automatic Identification) was announced at the 25th anniversary celebration of the barcode, which was held at the Smithsonian Institute in Washington, D.C. The Auto-ID Center was established as a research consortium; Richard Cantwell, then a senior executive at Gillette who would serve as the long-term mentor for the center, became the first chairman of the sponsor board. We also recruited Sunny Siu, a network researcher at MIT, to become the center's research head because we felt that the load on the network would be a serious technical obstacle to our vision. As it turned out, the network was not our most serious obstacle. Sunny left MIT shortly after and I took over his role as research head of the center, and lured Kevin Ashton to become executive director. That move paid off. Kevin and I became close collaborators for the next four years and added over a hundred sponsors to our effort. Picking up on the Universal Product Code, David christened the unique number in our RFID tags the Electronic Product Code, and the Auto-ID Center was on its way.

THE JOURNEY

Little did we realize then how difficult the path was that lay ahead. We had taken on several major challenges: meeting complex technology expectations, attacking the semiconductor industry, joining the battle between retailers and suppliers, and, perhaps most importantly, confronting a general resistance to change among logistics professionals.

A Unifying Vision

In 1999, RFID was a very fragmented space, with several existing protocols at different frequencies. Many of the protocols were proprietary—in other words, owned by a single company and covered by patents. It took me several months to realize that the way "standards" worked in RFID often was to combine different, privately developed protocols into a single document and offer cross-licensing under terms referred to as RAND—reasonable and nondiscriminatory. The protocols also were commercially fragmented. For example, some RFID systems were designed for public transport. A city that used a particular proprietary protocol needed to work with the company it belonged to or with a licensee to install readers at all its turnstiles. This arrangement worked well in closed-loop systems and guaranteed a relatively healthy annuity to the contracting company. Furthermore, the cost of a tag in such applications wasn't critical—people tend to keep their commuter passes, so a $2 tag was acceptable. There was no incentive to simplify the protocols and make tags cheaper because there was no great advantage in doing so. Moreover, the semiconductor manufacturing facilities where high-end, cheaper RFID chips could be made were otherwise occupied at that time in the manufacture of more lucrative offerings, such as communications chips.

Our vision was entirely different—it was all or nothing. We wanted the EPC tag placed on a product in China to be readable on a ship in the Pacific, in a port in California, on a truck in the Midwest, in a warehouse in Illinois, and in the back room, display shelf, and checkout of a retailer in Chicago. Our system worked everywhere. For the 10-cent tag to take off, the protocol had to be as free of the shackles of intellectual property (IP) as possible and have a global reach. If the market would buy into it, there would be perhaps billions of RFID tags in a few years.

The Minimalist Tag

In order to achieve a read range of a few meters, we decided at the very beginning to concentrate on UHF RFID tags, which were needed for tracking inventory. Our approach to both cost and IP was to start from scratch instead of using existing protocols. In our early research, Sunny Siu and I had noticed that existing protocols were "heavy," in the sense of providing unnecessary functionality at the expense of performance, so we decided our approach would be to develop a minimalist, lightweight protocol that did just one thing very rapidly: identifying all the tags in a large population rapidly and reliably. By keeping the algorithm simple, we were sure we also would minimize the number of transistors needed to implement the protocol, and therefore minimize the area of the semiconductor chip. At that time, chip costs dominated the cost of the tags, and getting the price down to a couple of cents meant we only could afford a couple thousand transistors per chip. The argument made sense, and broke the vicious cycle of cost and performance that RFID had been trapped in, but it was a big bet. The bet was: we will make the tags lightweight and fast, and bet on the ability to read rapidly. Adoption will follow, driving costs down to commodity levels.

Our simulations were promising, but who would make the chip for us? Our initial brushes with large chipmakers were discouraging—their reactions ranged from disbelief to downright hostility. The risks were too great, we realized, and the rewards too far off to satisfy the ambitions of any up-and-coming executive doing a cozy business in bus passes. The innovation would have to be made by somebody else.

Eventually it was startup companies that came to our rescue. The first was Alien, a California-based company founded by Dr. Steven Smith, a UC Berkeley researcher. Jeff Jacobsen, who was CEO of Alien at the time, immediately understood our vision and jumped in with both feet. Startups, after all, have little to lose and are formed precisely to address the risky challenges that large companies balk at. Roger Stewart of Alien and Dan Engels, Matt Reynolds, and I from MIT started to design an aggressive minimalist protocol. Later, Curt Carrender and John Price of Alien joined the team and advocated a more conservative approach. The outcome of this process was the Gen 1 Class I EPC protocol. Alien agreed to produce chips according to this protocol, and we were off and running.

Later, another startup company, Matrix RFID, joined the mix. Founded independently to develop a proprietary protocol that had the same elements of minimalism as our design, Matrix had a successful product that many of our sponsor companies found attractive. Matrix agreed to make their protocol "open" if we would "bless" it as a standard. This was a big compromise of our mantra of having a single global protocol, but in the end we did make the compromise, for three reasons: first, we realized it would unify the community; second, the Matrix protocol was in line with our principles of minimalism; third, we realized that one reader could read tags from either protocol.

The RFID reader was another problem we tackled directly. Kevin Ashton and I were adamant that a single reader should be able to read all tags at all frequencies in the UHF range, and possibly in the HF range too. At the time, RFID readers were relatively expensive—several thousand dollars—and we were convinced that the electronics in a reader cost only a couple of hundred dollars. We commissioned yet another startup, Thing Magic, to develop an open-sourced reader, which we placed on our public website. This too was an eye-opener to end users who had been conditioned to pay high prices for readers.

Going Global

Since by definition our vision was global, we decided to make our enterprise global. The Auto-ID Center was located at MIT, so what would "global" actually mean? Our answer lay in reaching out to university partners around the world. We first reached out to our old friends in the other Cambridge, at Cambridge University in the UK. Professor Duncan MacFarlane joined the center in 2000 and founded an Auto-ID Center in Cambridge, UK. The focus of this center was manufacturing. We next reached out to continental Europe. Professor Elgar Fleisch of ETH Zurich founded a Swiss center that had locations in Zurich and at the University of St. Gallen. A number of European companies, both suppliers such as Unilever and Nestle and retailers such as Tesco and Metro, also joined the center. The European research presence gave us three advantages: excellent research talent, local credibility, and a deep understanding of local issues such as privacy, which I address later.

After Europe, we turned our attention to Asia. We already had received a great deal of interest from Japanese, Chinese, and Taiwanese manufacturers. Kevin made a scouting trip to Japan and met Professor Jun Murai of Keio University, an icon in the Japanese academic world who had played a major part in bringing the Internet to Japan. Jun loved our vision and agreed to join the center. He gave us instant credibility and reach in Japan. In the end, we had over 10 Japanese sponsors.

We encountered a problem with UHF frequency band availability in several major countries, including in the EU region, India, and Japan. In some ways, RFID bands are like highways, and the wider the highway, the more traffic—or read rates—you can squeeze through. Through our collective lobbying, we were able to open up bands in each region that was generous enough to permit good performance of our standards. The regional Auto-ID Centers played a critical part in this effort. For example, Jun Murai played a key role in persuading the Japanese government to open up a UHF band in the 950 MHz band.[5] Our vision of a single universal reader paid off: the Japanese band was accessible to our readers, and many commercial vendors were able to build readers and tags that could operate at all the UHF frequencies around the world.

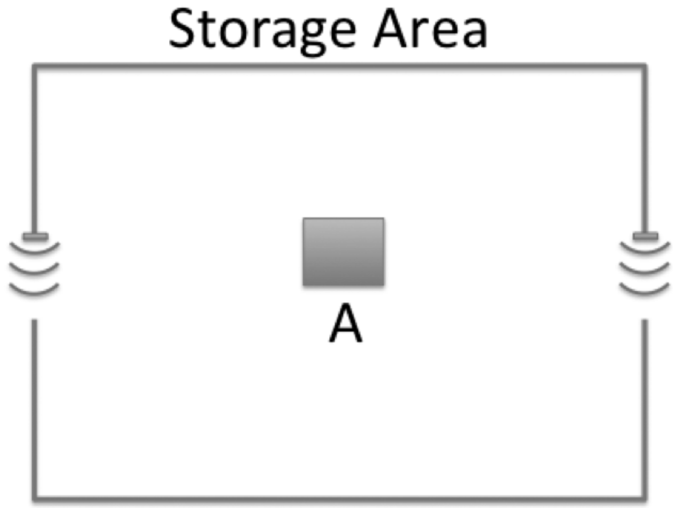

Figure 2. Storage Area with Readers at Left and Right Gates

SOFTWARE

By definition, RFID data is real time and requires real-time action and reaction. However, the natural tendency of IT professionals was to think of RFID as a barcode replacement, and they initially thought RFID readers could simply be plugged into existing barcode software. We made a significant effort to persuade companies that this would not work. Large software vendors, whose existing relationships with big corporations were threatened by this paradigm change, were our biggest challenge.

There are several subtle ways in which RFID and barcodes are different. First, unlike barcode readers, RFID readers read data all the time. Much of the data collected from an RFID scanner is repetitive and must be discarded. When meaningful reads do occur, they must be recognized and inferences must be made. This processing must occur all the time in the background.

Second, RFID data merely indicates an item's proximity to a reader. For example, consider Figure 2, which shows two readers, one at the left entrance of a storage area and one at the right entrance. Enterprise software needs to know if the tagged object is in the room, but RFID merely indicates that a reader read the tag. To be sure that the tagged object is in the room, the object must have passed through only one of the readers. This type of logic is specific to layout and implementation.

Third, RFID data is a feedback mechanism, which means that it reports what is happening on the ground, whereas existing enterprise software was largely one way. Operators were given instructions and they were expected to follow them—the real world wasn't expected to "talk back." For example, say that a pallet is being loaded with packages coming off a conveyor. With RFID, the real world might report back and say that the wrong package had been loaded and shrink-wrapped onto the pallet, whereas enterprise software was largely incapable of accommodating this kind of feedback.

These issues were a sticking point with potential users of our new system in the early 2000s. IT vendors have a strong hold over companies that depend on their products for day-to-day operations, and IT innovations are becoming difficult to implement without first convincing these gatekeepers—the large vendors. Today, an implementation of SAP or Oracle or IBM is supposed to automate a company's business processes. However, software implementations can be expensive and surprisingly inflexible. Changing business processes can be difficult and expensive. We ran into this problem with RFID. However, new cloud software models, rapid software development methodologies, and mobile phones are enabling a newer, nimbler approach to software development. Not only are these approaches often better and cheaper for companies, they also accelerate other innovations that are today held back by monolithic software implementations.

Sun Microsystems was one of the first companies to become a sponsor of the Auto-ID Center. As head of a company that thrived on data, the vision was immediately clear to CEO Scott McNealy. With Sun backing us, startup companies again proved to be our allies. Several startup companies, such as ConnecTerra, Globe Ranger, and OATSystems, also joined the center. My initial vision for the software architecture consisted of a series of software routers that processed RFID data in flow mode rather than in batch mode. I also wanted to make the software open source. OATSystems implemented its open-source software on contract, and we released it to the community.[6] However, in the end, companies preferred a different approach: open interface standards and proprietary software. Nevertheless, our functional vision became dominant. RFID "middleware" was born and became a new category in the software world.

STANDARDS

By about 2002, the Auto-ID Center had gathered over 70 sponsors into a research consortium that involved five universities and over one hundred participating engineers and executives. We launched a field trial to test the concept of RFID in the supply chain. We tagged pallets from distribution centers belonging to Johnson & Johnson, Kraft, P&G, and Gillette, and tracked them to Walmart and Sam's Club DC's in Tulsa, Oklahoma. The field test provided a vivid demonstration of what was possible with RFID. Momentum was building, and the demand for commercialization—as distinct from our experimental phase—was around the corner.

Meanwhile, questions began to arise about the standards process. For example, were the Auto-ID labs, a loose affiliation of university researchers and company engineers, a standards governing body? In order to answer such questions, I researched the way the World Wide Consortium and Institute of Electrical and Electronics Engineers promulgate standards, and then created a similarly democratic standards-development body within our research community. The first committee I created was the Hardware Action Group (HAG), which would work on the EPC and RFID protocols. Loek d'Hont of Matrix and Chris Diorio of yet another startup, Impinj, joined the other key players in the HAG. I also created a committee called the Software Action Group (SAG), which would work on software interfaces. Ken Traub, the chief technology officer of ConnecTerra, led the SAG along with another MIT alum, Bruce Delagi of Sun Microsystems. Ken would play a major role in the subsequent development of standards in the EPC world and would be a coauthor of virtually every major standards document now used in the field.

Creating the HAG and SAG was a milestone because it formalized the standards formation process for RFID hardware and software. We also created an IP policy so that participants in the standard-setting process would have clear expectations of how their contributions would be protected. This also laid the groundwork for the commercialization of EPC.

By the end of 2002, companies were asking us to issue them EPC numbers. We did, but we did not have a mechanism to charge them a fee. Kevin and I started brainstorming about spinning off a not-for-profit entity. The bodies around the world that issued barcodes had recently coordinated their efforts and formed a loose worldwide standards body called GS1. GS1 US, formerly the Uniform Code Council, had been a sponsor of the Auto-ID Center. However, there was some tension between the EPC and GS1 communities, perhaps based on the fear that RFID would replace barcodes. Kevin and I, meanwhile, feared that GS1 was an old-fashioned organization without the expertise to manage this new *enfant terrible,* the EPC. The ice was broken when the leadership of GS1 changed. In June 2002, the new CEO of GS1 sent his chief technology officer, Bernie Hogan, to discuss the possibility of transferring the commercialization of the EPC to GS1. After a number of discussions in which Kevin and I insisted that EPC be handled differently, GS1 agreed to form a new organization called EPCglobal as a subsidiary of GS1. I met with MIT's dean of engineering, Tom Magnanti, and head of the Technology Licensing Office, Lita Nelsen, to propose that we give our intellectual property rights away to EPCglobal for nominal licensing fees. I was pleasantly surprised by their positive reaction. Tom's words were, "If it's good for the world, we will give it away." EPCglobal was formed in early 2003, and the transfer occurred in the summer of 2003.

TECHNOLOGY AND PUBLIC POLICY

Since the early days of developing RFID, MIT researcher Dan Engels and I had been writing academic papers on the technical problems that would become important in RFID in the years ahead. For example, we wrote a series of papers on interference between readers—a problem that was eventually tackled in a later version of the EPC air protocol.[7] One problem we addressed early on was privacy. Because RFID tags can be read without line of sight, it is conceivable that someone could read the contents of another person's shopping bag. Dan and I and two colleagues wrote a series of papers on this topic in 2002 and 2003.[8] Meanwhile, Kevin Ashton formed an advisory group to consider public policy issues. Elliot Maxwell, who is now a Fellow of the Communications Program at Johns Hopkins University, chaired the group, which gave us wise counsel on protecting privacy—guidance that has made it into every EPC tag since, including the ability to kill a tag.

This did not stop a storm of controversy from erupting, driven in part by a misunderstanding of the technology. For example, some articles indicated that RFID tags used indoors could be read from the street. Kevin, Dick Cantwell, and I spent hundreds of hours fielding calls on the topic, writing articles, and doing interviews. In later years, I would testify before U.S. congressional committees and to various privacy czars in Europe. While I don't think such concerns derailed committed EPC users, in the end they did deter companies that were on the fence. In many ways, EPC became a lightning rod for privacy fears about technology in general—GPS, mobile phones, loyalty cards, and so on. While emotions were running high at the time and fears were overstated, I believe the tension of the controversy raised the game of the technology community. Ten years on, the upcoming version of the EPC standard has very advanced methods for hiding the identity of tags.

COMMERCIALIZATION AND EPCGLOBAL

Two major events occurred in 2003 that shook the RFID world. First, Gillette ordered 500 million EPC tags from Alien Technology. This was, as far I can tell, the largest single order in the history of RFID, and any lingering doubts about the viability of the upstart new system were put to rest. Second, Walmart announced a compliance mandate that would require its top suppliers to tag products that they shipped to its facilities. Given Walmart's heft in the retail world, this was a major move in the industry. The drums of commercialization were beating fast.

The Auto-ID Center had its last meeting in the summer of 2003 in Zurich. It was a bittersweet moment, as many of us had been close collaborators and had become friends. I was very keen, though, that the center be closed, as its work was done and the commercial phase of our operation needed to begin through EPCglobal.[9]

From 2004 onward, other retailers started announcing tagging requirements, and the U.S. Department of Defense (DoD) also announced an EPC tagging effort.

Over a dozen startup companies were launched, and existing companies raised more than $300 million in venture capital. The industry was abuzz with news and excitement, and the EPC movement made it into the *New York Times* and *Time* magazine. Little did we know that this was the beginning of another seesaw battle.

EARLY EPCGLOBAL

Two immediate priorities faced EPCglobal in its infancy. The first was the development of a standard for the next EPC version. The other was dealing with intellectual property on a commercial scale.

I am a believer in Schumpeter's views of creative destruction. The first versions of the EPC protocols, the EPC Gen 1 protocols, worked well, but few designers get it exactly right the first time so, much to the chagrin of many of the vendors who were developing healthy expectations for the Gen 1 protocols, I commissioned the development of a Gen 2 protocol. I felt that we had left out some important features from Gen 1, and that the new protocol could be better and faster. This was my last executive action before the formation of EPCglobal. I persuaded Chris Diorio of Impinj to lead the development of Gen 2. In the years ahead, he and Stephen Smith of Alien would combine innovations and create a masterful new protocol that has become a staple in the RFID world today: Gen 2. In the run up to this, Dan Engels and I wrote papers summarizing the different classes of protocols and describing how mixed populations of tags—Gen 1 and Gen 2—could be read by the same reader.[10] In this manner we assured end users that they could make the transition to Gen 2 without worrying about their inventories being contaminated with Gen 1 populations. Gen 2 had several new features, including an improved ability to deal with reader interference, better control over tags, and better reading performance.

The second major initiative EPCglobal had to undertake was clearing the field for intellectual property. While we had added certain IP safeguards in 2001, the issues that came up during commercialization had become much more complex. The Auto-ID Center itself had over one hundred sponsors by then, including several large companies. Each had its own IP portfolio, and a great deal of jockeying ensued. The issues ranged from offense to defense. If a company had IP from which it thought it could make a fraction of a cent per EPC tag, it wanted to protect it. If, on the other hand, it felt its own IP was compromised, it considered itself at risk. In the end, while we thought our protocol did not violate any of the IP, some companies felt they had IP on device and manufacturing tricks that would be needed to implement the actual chip. In the end we managed to thread the needle, and the protocol itself was considered to be free of external IP encumberment. This was a major milestone in the commercialization of the EPC. Eventually we would take the EPC and other related standards to the International Standards Organization with success: a version of the original Gen 2 standard is now an ISO standard.[11]

THE LONG ROAD TO COMMERCIAL SUCCESS

By 2005, it became clear that there were other twists and turns ahead in the EPC journey. In retrospect, there were three reasons for the length and tortuousness of the journey:

1. Changing business processes is difficult. The first industry that the EPC industry targeted was retail. Other industries, such as aerospace and defense, have since adopted EPC, but retail remains a mainstay. Retail, however, also would prove the most challenging, primarily due to the dynamics of the industry. First, the retail industry is based on mass-scale business processes. Walmart, for example, has more than four thousand stores worldwide. To install readers in all these stores and to get all the store associates to change their business practices is a massive challenge. That Walmart has achieved this 10 years after its first use of RFID is a testament to their perseverance. Second, the mandate approach created tension between retailers and suppliers. Suppliers felt they were being burdened with the cost of the tags while the retailers reaped all the benefits. RFID got caught up in these negotiations.

2. There are hidden costs in technology implementation. While the Auto-ID Center and EPCglobal had successfully shown how to reduce the cost of readers and tags, other costs would add up when the business cases for RFID were drawn. For example, reader installation costs—power, Ethernet, etc.—would in many cases exceed the cost of the readers. Perhaps even more painful were IT integration costs. IT architecture in many companies are layer upon layer of legacy implementation going back several decades. It is hard to take a new real-time information source and integrate it with a complex, often antiquated stack of software.

3. It is easier to sell a painkiller than a vitamin. Or so the old business maxim goes, and we discovered the truth of it the hard way. While the business case for RFID was positive, retailers and suppliers were satisfied with their businesses in the mid 2000s. Business was strong, and there was no real reason to invest in change. At that point, regular retail's greatest threat was from online retail. RFID was attractive, but it was third or fourth on businesses' priority list. The 2008 crash spelled doom for any new technology initiative, at least temporarily, as businesses were suddenly cash strapped and discretionary spending plummeted. A number of RFID startup companies went out of business or were sold for assets in that period.

The 2008 crash, strangely, also provided precisely the pain that was needed to trigger renewed interest in RFID. Figure 3 shows the ratio of inventories to sales for U.S. manufacturing and trade industries.[12] Following the crash, companies with high inventories were doubly penalized; not only were sales down, but now they had inventory they could not get rid off. Many retailers—and many businesses in general—went through a very tough period. The lesson had been learned. It can be seen in the figure that inventories have been lower in subsequent years.

The apparel retail industry was particularly hard hit, and it is now the industry leading a massive move to RFID. Walmart, Macy's, JCPenney, Inditex, Gerry

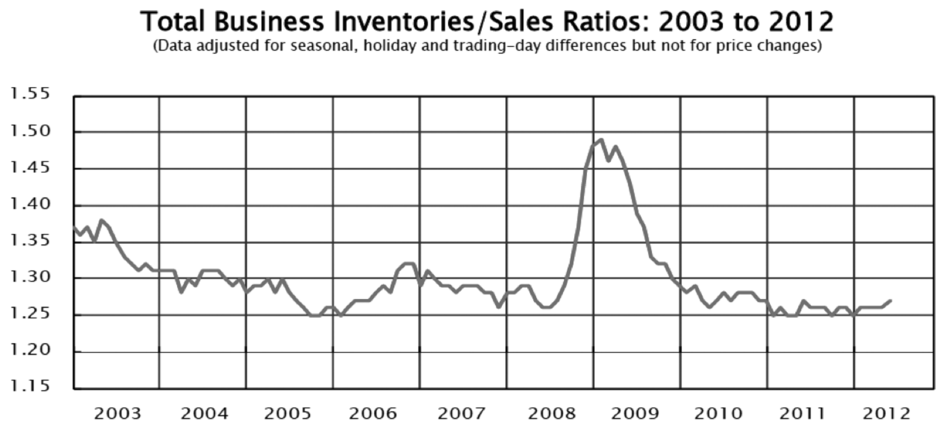

Figure 3. The 2008 crash starkly illustrated the risks of carrying too much inventory.

Weber, and many other retailers have announced plans to tag much if not all of their apparel. The EPC industry is now in a major upswing, and investments in EPC technologies are once again increasing. The last two years have been relatively healthy for RFID, and 14 years after the launch of our research, EPC is now truly a sustaining industry.

CURRENT STATE OF THE EPC INDUSTRY

Over the years there has been a lot of consolidation in the EPC industry. Matrix was acquired by Symbol (now Motorola), ConnecTerra was acquired by BEA Systems, Vue Technology was acquired by Tyco, and OATSystems was acquired by Checkpoint Systems. Impinj has filed for a public offering. Over 2.5 billion RFID tags will be sold in 2012, and the number is projected to increase significantly in the years ahead. EPC is certainly at the top of the list for technologies to consider in retail.

The apparel industry is currently the most exciting sector for EPC tags. The fundamental problem in apparel is the difficulty of counting inventory. For example, all the items in a stack of jeans look the same to a store associate, but they are of many different sizes. If a customer can't find her size, a sale is lost. The process of monitoring apparel inventory is cumbersome, and retailers consistently dump end-of-season inventory to secondary resellers and liquidators, a very inefficient practice. Having EPC tags on clothing enables store associates to assess inventory rapidly. Handheld readers have proven to be an effective technology for this purpose. Handheld performance has improved significantly in recent years because of improvements in battery life and read range. Handheld readers are also relatively easy to deploy, as they communicate wirelessly and thus do not require power lines.

LESSONS LEARNED

We learned many lesson during this journey, and I summarize them here.

Systems Technology Is Different

Universities and research institutions commercialize thousands of innovations every year, primarily component technologies. Electronic Product Code is a systems innovation, and there have been fewer attempts to commercialize systems technologies. Systems consist of not one or two but several components and standards and they require a user community to reach the point of self-sustainability and value. The Internet and the World Wide Web are two notable examples.

"Big Idea" Systems Development Is Critical but Losing Its Cachet

Systems require long periods of incubation before they can be commercialized. The Internet benefited from years of support from the DoD's Advanced Research Projects Agency (ARPA, later DARPA.) The World Wide Web was invented and developed at CERN, the European Organization for Nuclear Research, and then incubated at MIT with the formation of the World Wide Web Consortium in 1994. Again, DARPA was a sponsor. The EPC may not yet have achieved the same scale, but it was founded as a more industry-oriented partnership. Its eventual success was due in large part to the staying power of the community that built it—researchers, engineers, business executives, and companies such as Walmart. For me, Kevin, and David Brock, the venture carried career-ending risks. I did not have tenure when I founded the center, although I was fortunate to receive it in 2003.

The Auto-ID Center did receive $300,000 of funding from the DoD, but it did not receive funding from other federal agencies, such as the National Science Foundation. In fact, I believe funding agencies in the U.S. are gradually losing their ability and willingness to sponsor the type of game-changing systems efforts the nation has thrived on. I worry that there are few "big idea" projects on the radar today. The difficulty may lie in the silos in funding agencies, which are essentially built around component areas rather than systems. DARPA has been effective in funding big systems, but its defense-oriented mandate limits its applicability in general areas. Still, DARPA, was and remains our one big government supporter.

Systems Are Cross-Cutting

Component technologies fit neatly into traditional engineering departments, but systems know no boundaries. Our project spanned several areas: mechanical engineering (my home department), electrical engineering, computer science, engineering systems, management, marketing, operations, law, and political science. I was lucky to be at MIT, which has an open culture, but crossing territorial boundaries generally is difficult. Furthermore, it is said of systems that "the sum is greater than the parts," which has key implications academically. Writing papers on individual topics was a challenge early in the process, because conferences and journals in any area would only see a small facet of the larger puzzle being addressed and often consider the contribution it made trivial. Therefore, the natural tendency of an author is to over intellectualize a solution to gain acceptance. This works against systems thinking, where Occam's razor is important—the simplest solution, which may not be worthy of an academic paper, is often the best solution. Successful system designs abhor unnecessary complications, but I have observed that real-world problems eventually do lead to deep intellectual challenges that merit high-quality scholarship. RFID security, for example has become a vibrant field, and our first paper on the topic now has over one thousand citations. However, the compartmentalized nature of academic publishing, and academic publish-or-perish timelines, are not conducive to thoughtful system design.

Systems Require an Ecosystem

Despite the challenges described above, academe is the ideal place to build and implement ground-breaking systems technologies. Other large systems such as GSM standards for mobile phones and Wi-Fi for wireless networking, which are primarily standards efforts, have been developed entirely in industry consortia with little academic involvement. However, the primary task in these efforts was standards development; the capability of technology was never in question. When it comes to leaps forward in technology, universities offer ideal, neutral platforms for putting together the ecosystem required for a system to be developed. There clearly are ways universities and funding agencies can further facilitate the process, but there are no other venues for big-idea projects and cross-cutting research. The ecosystem is critical in launching these systems. Hardware, software, businesses, regulations, and standards do need to come together to enable the system, and field trials, industry roadmaps, and cooperative commitments from companies are necessary for the system to become self-sustaining.

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1. See http://cdljobs.typepad.com/trucking_news/2012/06/us-supply-chain-and-logistics-industry-continues-slow-rebound-led-by-rail-and-trucking.html.
2. Stephen Brown, *Revolution at the Checkout Counter: The Explosion of the Bar Code*. Cambridge, MA: Wertheim Publications in Industrial Relations, 1997.
3. H. L. Lee, V. Padmanabhan, and S. Whang, "Information Distortion in a Supply Chain: The Bullwhip Effect," *Management Science* 43, no. 4 (1997): 546-558.
4. This image belongs to my center and was created on contract. The pdf is available at http://www.rfidfactory.com/pdfs/XPLANE-InTheRetailStore.pdf.
5. In July 2012, the Japanese government moved RFID down to a more U.S.-compatible 920 MHz UHF band.
6. I would subsequently join OATSystems as a board member, and then take a leave of absence to become the CTO of the company. OATSystems was acquired by Checkpoints Systems (NYSE: CKP) in 2008.
7. D. W. Engels and S. E. Sarma, "The Reader Collision Problem," proceedings of IEEE International Conference on Systems, Man and Cybernetics, Hammamet, Tunisia, October 2002.
8. D. W. Engels, R. L. Rivest, S. E. Sarma, and S. A. Weis, "Security and Privacy Aspects of Low-Cost Radio Frequency Identification Systems," First International Conference on Security in Pervasive Computing, March 12-14, 2003.

9. I joined the board of EPCglobal and remain on the board to this day. Dick Cantwell became chairman and stayed in that role for nine years.
10. E. Sarma and D. Engels, "On the Future of RFID Tags and Protocols," Auto-ID Labs Technical Report, MIT-Auto-ID-TR-018, 2013.
11. M. O'Conner, "Gen 2 EPC Protocol Approved as ISO 18000-6C," *RFID Journal*. Available at http://www.rfidjournal.com/article/view/2481.
12. *U.S. Census Bureau News*, July 16, 2012. Available at http://www.census.gov/mtis/www/data/pdf/mtis_current.pdf.