Chapter 3

A HISTORY OF THE EPC

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Introduction

Although the concept of radio frequency identification (RFID) is not new, the term RFID has been in use for only a couple of decades.[2] In the 1980s and 1990s, long after the early use of RFID during World War II, innovations in RF circuitry enabled passive RFID tags (tags without batteries, which scavenge power from the reader's field) to provide enough range to become viable. Today, RFID tags are seemingly everywhere: in toll passes, card-keys, automobile keys, payment systems (like the Mobil Speedpass system), and animal identification.

What has changed is the emergence of the Electronic Product Code (EPC) system, which is a suite of standards and technologies that weaves basic RFID into a standardized scheme for keeping track of material in the supply chain. The EPC was created at MIT by a few researchers involved in a research project called the Distributed Intelligent Systems Center (DISC). Later, this research effort morphed to fulfill a growing need in the retail supply chain and became the Auto-ID Center. This chapter presents a brief history of the Auto-ID Center, talking mostly about the technology, the industry, and the adoption of the EPC system.

The Beginning

My own first, forgettable, brush with RFID occurred in the early 1990s when I was a graduate student at Berkeley. At that time, I was interested in identifying

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2. For additional information, see Landt, J. "Shrouds of Time: The History of RFID." www.aimglobal.org/technologies/rfid/resources/shrouds_of_time.pdf.

and locating work-pieces for manufacturing automation. I had looked at RFID as a possible positioning device in automation and rejected it as being far too imprecise and expensive. Little did I realize then that our paths would cross again!

The Distributed Intelligent Systems Center

A colleague at MIT, David Brock, reintroduced me to RFID. At the Artificial Intelligence (AI) Labs, David had spent a great deal of time thinking about the problem of artificial perception in robotics. He wrote a white paper at the AI lab wondering why an RFID tag couldn't be used as a marker to identify objects rather than recognize the object from scratch. He suggested using a unique number to identify the object and using the network to download an almost unlimited amount of information about the object.

David charged into my office one day in the beginning of 1998 and described this idea to me. As a roboticist myself, I found it aesthetically appealing. However, my earlier worries persisted. For true ubiquity, cost would be the barrier. Yet I was intrigued enough that I invited David to join my group, and we founded the DISC.

The bug that David infected me with was the idea of ubiquitous RFID—*let's put it everywhere*. We could use it in the supply chain, we could use it in robots and machines to replace computer vision, and we could use it to track food, drugs, and cattle. But in all these applications, the high costs of tags were a huge stumbling block. High costs initiated a vicious cycle: The higher the costs, the lower the adoption; the lower the adoption, the higher the costs. Over the next several months, we met several times to talk about the idea and co-opted another colleague, Sunny Siu, to join us in our brainstorming sessions. We became aware of similar thinking that had been going on in the Media Lab at MIT and by Nick Negraponte in the early 1990s.

The seeding idea was a numbering scheme. Over time, we decided the structure of the number, and we named it the EPC. The EPC would have four fields:

- Version number
- Manufacturer number
- Product number
- Serial number

The EPC was to point to a database. The obvious thing to do was to use XML to represent the data about an object. We called this language Physical Markup Language (PML). Dan Engels was finishing a Ph.D. in the Department of Electrical Engineering and Computer Science at that time, and David, Dan, and I spent a great deal of time looking at a number of approaches for describing physical objects and distributing the information, including many emerging representations and schemes like the Resource Description Framework (RDF) and Information and Content Exchange (ICE).

The missing piece was how to map the EPC to the IP address of the database. In our brainstorming sessions, a student, Eric Nygren, suggested simply co-opting the Domain Name System (DNS). We called this new system the Object Name System (ONS), and Joe Foley, another student, implemented the first prototype. Then we hacked into the controls of an old microwave oven and installed an RFID reader in it. We then attached RFID tags to a few microwave-ready meals. Joe and I created a Web page to provide cooking instructions in the form of Physical Markup Language (PML). When a food packet was inserted into the microwave oven, the oven would read the tag, locate the server using ONS, download PML cooking instructions, and automatically cook the food. This would be our first and most enduring demonstration. Seeing this, the head of the Department of Mechanical Engineering at MIT, Professor Nam Suh, contributed $100,000 from the department to support this fledgling effort. This gave us the breathing room to incubate our effort.

In early 1999, it occurred to me that the way to get the RFID industry out of its vicious cycle would be to inject it with minimalism. This would become the overriding theme that would drive the progress of the Auto-ID Center. In time we would develop low-cost tags by making the chip extremely small, making the protocols extremely simple, developing simple network ideas built on existing standards, developing new ways to package extremely small chips, developing minimalist data standards on the chip, and so on. That theme of minimalism would be a harder vision to sell than I had expected. Sell it we did, though, and it has led to the creation of the EPC network.

Meanwhile, at Procter & Gamble

The EPC revolution would not have taken off had a fateful meeting not taken place in early 1999, when Dave and I met Kevin Ashton, then a brand manager for Oil of Olay with Procter & Gamble in London. Before we met Kevin, I expected that ubiquitous RFID tags would first find application in the front end of the supply chain, which consists of factories and automation systems. Here I was wrong. For a few years, Kevin had been struggling with a problem that plagues the retail industry: out-of-stocks. It turns out that fast-selling items are out of stock about 10 percent of the time in a typical retail store. This problem can mean billions of dollars of lost revenue, not to mention dissatisfied customers who could switch brands and stores. Kevin's idea was simple: tags on all retail items, readers on all retail shelves, and a system that would proactively inform the retailer and the manufacturer of shrinkage and stock-outs. Kevin had spent the last year trying to get the RFID industry interested in low-cost tags. Unfortunately, instead of receiving support from RFID vendors, Kevin, like David and me, had been given a list of reasons why his approach simply would not work. At our first meeting, in 1999, we knew that there was a resonance of vision. Kevin's passion for the possibilities of RFID in the retail supply chain sealed the deal; we had a new application area. The Auto-ID Center was therefore, the confluence of two independent streams: DISC technology and Procter & Gamble's and Gillette's struggles with retail.

A Mini-Lecture: The Supply Chain

To understand the growth of the EPC, it is important to understand the problems of the supply chain. The *extended supply chain* starts in a mine or on a farm, and it ends in either a recycling plant or in a trash can. In between, material is transported from stage to stage, it is combined or separated, it is modified or processed, and it changes hands from one owner to another. When material changes hands heading downstream, money goes upstream, and each entity makes a profit for adding value to the evolving work piece.

The term *logistics* usually refers to the handling of material and the aggregation and deaggregation into and from bulk for transportation. The term *supply chain* (as opposed to extended supply chain) usually refers to the management of materials in the chain from the factory to the consumers' hands. The retail industry is analogous to routers in the Internet. Retailers route material as efficiently as possible from the suppliers to customers in stores. Their efficiency determines the cost to the customer, the profitability of the retailer, and the sales of the supplier.

At each stage in the chain, uncertainties, losses, and errors of estimation cause inefficiencies. Carrying too much inventory is bad because it results in billions of dollars of locked-up capital, high carrying costs, obsolescence, problems with quality and freshness, and theft. Having too little inventory results in empty store shelves, a problem that plagues the retail industry worldwide to the tune of billions of dollars. Unfortunately, difficulties in counting inventory cause the pendulum to swing precipitously between too much inventory and too little inventory in a phenomenon called the bullwhip effect. First described by Forrester, an MIT professor who also invented key components of early computers, the bullwhip effect is inevitable in any dynamic chain like the supply chain. Simply put, even if demand at the end of the chain is nearly constant, small ripples multiply upstream and create tremendous variations in demand.

The secret to walking the tightrope between these two problems is accurate measurement of inventory. Bar codes were conceived as a way to measure inventory, and to a large extent, they did help. However, bar codes are essentially line-of-sight in their operation and require manual manipulation. The result is that every scan of a bar code has a hidden cost associated with it; in fact, UPC bar codes are often scanned only once in their life-times, at checkout. To a large extent, inventory is still guessed at, often incorrectly. In a study of a retailer by a Harvard group, up to 65 percent of all inventory records were inaccurate. This is where RFID tags come in. RFID tags permit one to count inventory without line-of-sight. The tags permit better, faster, cheaper, and more frequent inventory measurement. This measurement, in turn, enables more efficient change of hands between commercial entities, better traceability of goods, better protection from theft and other malfeasance, and most important, a more stable tightrope walk between the two ills of the supply chain: too much inventory and too little inventory. Together, these benefits are worth, potentially, billions of dollars to companies and to society.

As our research into RFID began, I wanted to be sure that this was the case. We had already been introduced to the problems of stock-outs. Was that the tip of the iceberg? In 2000, my student Yogesh Joshi and I studied the bullwhip effect and the effect of inventory visibility on this debilitating phenomenon.[3] What we found was startling. By making inventory visible to trading partners across the supply chain by using RFID, we could, at least in theory, almost completely eliminate the bullwhip effect. Armed with this profound insight, we plunged into the RFID world in search of our elusive goal of ubiquitous, inexpensive RFID tagging. We knew there was value there.

The Auto-ID Center

In 1999, David, Sunny, and I met Alan Haberman, who is frequently called the "father of the bar code." Alan was on the original CEO committee that took bar code technology and made it the ubiquitous, standardized symbol of retail commerce that it is today. In the process, that committee created the Uniform Code Council (UCC), which administers the UPC bar code in the United States. Its sister organization, EAN International, administers the bar code for the rest of the world.

Back in the 1970s, MIT Chairman Howard Johnson had put together a cross-disciplinary group of young professors to evaluate the Symbol Selection

3. Joshi, Y. "Information Visibility and Its Effect on Supply Chain Dynamics," M.S. Thesis, Department of Mechanical Engineering, MIT. June 2000.

committee's bar code choices.[4] They had agreed with the process and the final selection and suggested that the chosen technology would stand for 25 years but had expected that the bar code would then be overtaken by a new technology. And so it was coming to pass!

Alan, then a member of the UCC Board of Governors (BoG) , was in the middle of a search for the proper research organization to for a successor technology to bar code ID techniques. The search was on behalf of the UCC's current CEO Tom Rittenhouse and the Board of Governors, Ironically, it was just shy of 25 years since the first bar code scan across a checkout. During that time bar codes had truly become ubiquitous: today more than five billion bar codes are scanned daily around the world, according to informed estimates.

Alan was also the chairman of an ISO committee on RFID standards, and he was interested in our starting a research effort to enable low-cost, ubiquitous RFID tagging. He, like us, was frustrated by the high costs of RFID tags and the lack of technical progress. During a one-hour lunch, our group struck an agreement: We would morph DISC into a new center based at MIT with funding from the UCC. Alan, David Brock, Sunny Siu, and I then had a series of conversations with MIT staff. Two people on the staff, Fritz Kokesh and Carol Carr, played a major role in laying out the financial and organizational structure of the new center. The center would be driven by end users rather than vendors, and its mission would be to enable the proliferation of low-cost passive RFID tags in the supply chain. All we needed now was money! So we then evangelized a number of companies, Procter & Gamble and Gillette being the first targets of our campaign.

The Auto-ID Center was launched on September 30, 1999, during the twenty-fifth anniversary celebration for the bar code at the Smithsonian Museum in Washington, D.C. In addition to the UCC, we had support from two founding sponsors: Gillette and Procter & Gamble. Steve David, the CIO of P&G, Allan Boath of Gillette, and Tom Rittenhouse of the UCC presented checks to Professor Nam Suh. The organization of the lab gradually fell into place. Alan Haberman would be the chairman of the board of end-user sponsors. (About a year later, Alan stepped down as chairman and Dick Cantwell of Gillette took over. Dick would play a very important role in the coming years.) Sunny Siu became research director of the lab because it was very important for us to emphasize the centrality of the Internet in this effort. (Sunny left MIT in 2001, and I took over as Research Director. I became the chairman of research a year later as the center grew.) Kevin Ashton became executive director to operate the lab. P&G graciously offered to cover Kevin's

4. Haberman, A. (ed.) *25 Years Behind Bars*. Harvard University Wertheim Publications Committee. Cambridge: Harvard University Press, 2001.

salary in this role. Kevin and I would work closely to hold the effort together as we navigated difficult, sometimes hostile waters. We received a great deal of support from Alan and Dick in overcoming fundamental technical and industrial barriers that would appear in our way.

The first order of business was enabling inexpensive RFID tagging. This was no minor challenge—tags cost more than a dollar at the time, and we were already being ridiculed for our assertions. The entire RFID industry was locked in a high-margin, low-volume cycle. Our objective was to break that cycle. No one even thought low-cost tags possible, with the exception of Noel Eberhardt of Indala, a division of Motorola Corporation. Noel had invented Bistatix electrostatic tags. Bistatix tags used a cheap antenna, and the chips were very small. Noel believed that they could be manufactured for about a nickel.

The Cheap Tag

It would become clear in the months after we met Noel that Bistatix tags would not provide us the read range necessary to meet the requirements of the supply chain. Yet Noel had given us a glimmer of hope. Other attractive possibilities at that time included nonsilicon tags using polymer circuits and an innovative chipless RFID technology developed by Rich Fletcher and Neil Gershenfeld at the MIT Media Lab. Over the six months following my first meeting with Noel, I plunged myself into an in-depth analysis of the manufacturing of RFID tags. I looked at the circuitry on the chip, the manufacturing issues related to the digital and analog portions, the separation of the chip from the wafer, the thinning of the wafer, the handling of the dies, the attachment of the die to the antenna, the manufacture of the antenna, and the attachment of the assembly to a package. I even attended a two-day course on paper manufacturing in Canada! My conclusion was that Bistatix, polymer tags, and chipless tags were not likely to solve the RFID problem in the near term. Instead, I felt that it would be better to return to silicon electromagnetic tags and find a way to make them work. I developed a two-pronged strategy to address this challenge.

First, I recognized that the primary and most rigid component of tag cost was chip cost, which in turn is largely proportional to chip area. We would therefore have to spend a great deal of effort minimizing the complexity of the state machine and the memory required on the chip. We would do this, ironically, by developing simpler, lower-weight protocols that, while reducing cost, were also applicable to a larger range of applications.[5] For example, earlier versions of RFID tags used complex anticollision techniques, supported large, complex

5. Swamy, G. and Sarma, S. "Manufacturing Cost Simulations for Low Cost RFID Systems." 2003. www.autoidlabs.org/whitepapers/mit-autoid-wh017.pdf.

memory structures, and included encryption. By contrast, we insisted on reducing the memory on the tag to a simple license plate, and we simplified the anticollision to simpler tree-walking or Aloha-like variants. We eliminated encryption from the simplest tags because there was no memory to protect! In doing so, we had to address a number of issues ranging from digital signal processing to semiconductor manufacturing issues. This minimalist approach succeeded in reducing the size of the chip, and since cost is roughly proportional to size, it permitted us to reduce cost. Minimalist chips also had additional benefits that propelled the EPC movement. Smaller chips consume less power, increasing the possible range of the tag. A minimalist approach also enabled easier, lower-level standards that could be used by more applications.

Second, we took the earlier work of the DISC and turned it to an advantage for lower-costs tags. In DISC, we had in effect proposed putting much of the data and intelligence associated with tagged items, which had hitherto resided on the RFID tags themselves, on the network instead. In much the same way as a license plate on a car can be used to find the traffic tickets associated with that car, the EPC made it possible to refer to data associated with that tag without burdening the tag with extra memory. The ONS would be used to find the authoritative owner of the original data associated with an EPC tag. PML would store data about the tag on a server called the PML Server.

By February 2000, this two-pronged strategy had become more solid. I presented it at the Second Auto-ID Sponsor Meeting and called it the "cheap chip manifesto." The strategy was clear, but a lot of questions remained:

- Who would design the protocol?
- How would small chips be packaged?
- Who would make these chips?
- Who would make the tags?
- How would we drive adoption?

Yet our sponsors had faith in us, and the die was cast. If this strategy didn't work, we would go bust. My career was certainly on the line. From here on, we were on a mission to flesh out the strategy and bring about broad adoption.

"Low-Cost" RFID Protocols

By 2000, it was becoming clear to us that the RF protocols used to communicate between readers and tags were somewhat bloated. The bloat occurred in part because there was no incentive for making the chip small until we made that a popular idea. Also, others hadn't tried to leverage the network or take advantage of recent advances in chip design or communication theory. In 2000, Sunny Siu and his student Ching Law published a paper describing a series of ultra-simple tree-walking protocols that permitted the fast and efficient inventorying of a field of tags. These protocols were so simple and so efficient that we wondered why they weren't being used. We would find out later that others were thinking along similar lines. However, we were completely unsuccessful in persuading bigger tag manufacturers to adopt these approaches. A few tag companies did join the Auto-ID Center, but although the engineers who attended our meetings were intrigued, they were unable to persuade their companies to take the plunge.

At the end of 2000, I met Jeff Jacobsen and Roger Stewart of Alien Technology, a startup company based in California. Jeff and Roger immediately saw the value of what we were saying, having independently come to the same conclusions we had. They committed to developing a new protocol based entirely on a minimalist approach—the smaller the better—and what followed was a period of fruitful and enjoyable brainstorming. Roger, along with his colleagues Kurt Carrender, John Price, Dr. Stephen Smith, and John Rollins of Alien, spent a great deal of time with Dan Engels, Matt Reynolds of MIT, and me, developing what would eventually become the Class I UHF protocol published by the Auto-ID Center. We were also helped by a number of people from other companies, like Leigh Turner of Rafsec. Alien committed to making chips to this protocol and continues to manufacture them to this date. Later, Dan, Professor Peter Cole of Adelaide, Australia, and researchers from Philips created the Class I HF protocol. In 2002, Matrics, a startup company that had independently created a very efficient tree-walking protocol, worked with the center to create a more secure, more efficient version of its old protocol, which we published as the Class 0 UHF protocol. Matrics also committed to manufacturing chips to this protocol, which it continues to sell today.

As we developed tag protocols, we simultaneously needed to consider the various frequencies involved in different countries and the different protocols that we needed to read. Which protocol should people buy readers for? Which frequency? These questions were proving surprisingly paralyzing to early adopters. Our view was that we should support all frequencies and all protocols. The best way to solve the problem was by building a single reader that could handle all the protocols and frequencies. At that time, *software-defined radio* had begun to gain acceptance as an alternative to hardware radio. CPU speeds were beginning to make this, the ultimate in flexibility, a reality. Kevin knew the engineers of a small MIT spinoff called ThingMagic, one of whom was Matt Reynolds, who had just graduated. We contracted ThingMagic to build a single "agile reader" that could put all the uncertainty to rest. ThingMagic published a design for an agile reader that also had a bill of materials of less than one hundred dollars. With one fell swoop, we were able to quiet all the uncertainty about reader hardware and frequencies. Now, it was possible to invest in fixed infrastructure that would absorb any future changes in protocols.

"Low-Cost" Manufacturing

One of the challenges we faced with our approach was this: We could make the chips smaller to save silicon cost, but smaller chips are much more difficult to pick up and handle. In fact, when chips become smaller than about $1mm^2$, electrostatic forces become so significant, and precision requirements so high, that the traditional robots used to pick and place these chips in their packaging become uneconomical. In other words, what we might save in silicon costs we would more than expend in expensive manufacturing processes. Manufacturing challenges like these were major roadblocks in the strategy we stated in February 2000. Others questions that were plaguing us were:

- How would we test 100,000 chips per wafer?
- How would these chips be separated from each other on the wafer without wasting a great deal of silicon in the gaps (streets) required to saw the chips from the wafer?
- How would these chips be attached to the antennae?

Over the course of 2000, we came up with what we thought were feasible answers to these questions. First, we said that in the future, small chips would be packaged not by robotics, but by massive parallel assembly. At that time, I speculated that a process in which chips would be "vibrated into place" would be the way of the future. I said that RFID tags need not be tested in the wafer because they could always be tested wirelessly. I said that chips could be separated by etching and thinning rather than by sawing to make the streets an order of magnitude thinner. I summarized these thoughts in a whitepaper that was received with a bit of pessimism and even hostility. While these ideas were seemingly sensible, how were we to get them to reality? We were, after all, at an academic institute.

Here too, we found excellent partners in companies like Alien Technology. Alien had developed a process for delivering chips using fluidic flow rather than vibration as I had suggested, which nevertheless enabled massively parallel, inexpensive assembly of ultrasmall chips into RFID packaging. Alien was also the first company to support us in our claim that low-cost tags were possible with volume.

Other companies like Rafsec Corporation also played a big part in the gelling of this approach. Rafsec had developed an inexpensive technology for manufacturing antennae, and it announced a relationship with Alien. Now, we had the prospects of a complete tag. Later, Philips confirmed my view that vibration too was a viable technology and said it had discovered that Philips itself had used vibrational techniques in other component assembly. My student Kashif Khan wrote his Ph.D. on vibration-based techniques and published it in 2003.

The Software and the Network

Handling the hardware questions was just one aspect of the EPC challenge. The other was software. Our goal was to remove data from the tag and manipulate the data on the network. As I mentioned before, the first version of the ONS was written by my student Joe Foley in the late 1990s.

Around that time, it also became obvious to me that we needed a software-architecture to handle RFID data in a scalable, sensible way. RFID data comes fast and furious and needs to be absorbed, filtered, and interpreted for local action. At the same time, the readers themselves interfere with each other, and this interference needs to be controlled. Dan Engels and I had written many papers about this problem, which we had predicted to be one of the major challenges in RFID. My student Jim Waldrop spent a great deal of time thinking about this problem, and we came up with a concept similar to the neuron and nervous system. We called our version the Savant. The Savant would get data as input, then filter, smooth, and interpret it and pass on a digested form of the data to a higher-level Savant. There would be a layer of Savants talking to readers at the edge, a layer of Savants one level up, aggregating from lower-level Savants, and perhaps the highest-level Savant aggregating all this information. Each Savant would be equipped with rules to deal with information as appropriate for its level.

Embedded in this design is the principle of *locality of reference*. The basic idea is that the closer you are to an event in space and time, the more the information is useful to you. Consider news of a theft in a company. It is of limited value to the CEO because the CEO is too far away, geographically and organizationally, to act on it. It is of use to the store clerk, though, perhaps because the clerk can apprehend the thief. Similarly, the same news is useless to the store clerk if it comes a day late. For these reasons, a centralized approach to RFID data would just not work. The Savant hierarchy decentralizes the decision process. It permits immediate decisions to be made at lower levels and presents digested information to higher levels at a stage of abstraction that is useful there.

With the launch of the field trial, which I will describe later, it became obvious that student-written software would not scale. Instead, we needed to develop a body of freeware that could be used and improved and adopted by number of people to get the RFID adoption off the ground. But who would do this?

Larger companies weren't willing to invest in this concept, and the field trial was moving ahead. At this point, I hired OATSystems, a tiny consulting company consisting of MIT graduates, to write the industrial versions of the ONS and Savant freeware and standards and to deploy them in the field trial. These efforts turned out to be surprisingly successful. Prasad Putta, Sridhar Ramachandran, and Gabriel Nasser played key roles. ONS and Savant were downloaded from our Web site hundreds of times, and more important, they were very successful in driving the field trial and early adoption. The invention of an RFID foundation proved to be critical—there was a prevailing, and completely incorrect, perception that RFID systems could be managed exactly like bar code systems. We were able to seed the creation of a whole new and entirely necessary industry by creating the Savant System. Another company that was supportive and generous in the development of this new way of thinking was Sun Microsystems, which provided not only moral support and technical guidance but also the voice of its senior executives. Scott McNealy, the CEO of Sun, was a vocal supporter of the Auto-ID Center.

Privacy

RFID is one of those technologies that naturally raise privacy concerns. The fear is justified to some extent. For one thing, passive RFID tags are often confused with Hollywood staples like global positioning system (GPS)-based tracking devices, wireless sensors, and electronic recorders, which have been the bane of many secret agents in movies. Of course, today, passive tags have such poor communication performance and such severe cost pressures that they are a poor choice for an antagonist seeking to invade one's privacy. The cell phone in your pocket and the toll pass in your car offer better opportunities to invade your privacy. Yet, if one assumes that tags have long range, privacy fears are understandable. What if someone could read the contents of your pocket and conclude that you are on a particular medication? What if this happened during an interview?

Fortunately, privacy concerns were very much on our minds from the beginning. Kevin did the community a great service by talking about privacy as early as 2000. Even in 1999, David Brock, Joe Foley, Sunny Siu, and I talked about turning pieces of the EPC off to protect privacy. In those meetings, which were held in the Given Lounge of the Lab for Manufacturing and Productivity at MIT, we also discussed ways to modify the ONS to provide more anonymity. In 2001, a major retailer surprised us all by insisting that we provided an electronic means for turning the EPC tag off within the protocol. Essentially, burning a fuse within the circuit could do this. By and large, the companies I have worked with have surprised me pleasantly with their proactive support for our research in the area of privacy.

Through 2001, Dan Engels, Peter Cole, and I spent a great deal of time thinking about the technical issues around privacy. Turning the chip off gave the consumer control and choice, but it also eliminated possible downstream benefits like recycling. Was there a better way? Our thinking was solidified further by some work we did with Professor Ronald Rivest and his student Steve Weis. We published a couple of papers, listed all the scenarios that we could think of by which RFID tags could be misused (assuming conservatively that tags could be read from a far greater range than they can now), and came up with several ways to address these problems.[6] Unfortunately, many of these solutions come at a higher cost. However, I feel confident that giving consumers the choice to kill tags protects them in every scenario I can think of.

Separately, Kevin established a distinguished panel of independent public policy experts to advise on matters related to privacy and social impacts of RFID tags. This panel, led by Elliot Maxwell, studied the problem from a number of angles and gave us invaluable guidance not only on where tags were today but also on where they could be in the future. One member of this panel was Simson Garfinkel, an MIT student who published the RFID "Bill of Rights" (Appendix D).

Ironically, questions about privacy started hitting the press after we had completed most of this analysis. While much of the writing was balanced, some of it was based on technically infeasible propositions. The stories sometimes did not recognize the physical limits of RFID tags, the technical issues we had studied, the scenarios we had analyzed, and the policies we had *already* published. Instead, they speculated on somewhat unrealistic scenarios like someone reading the contents of a home from a satellite or an RFID reader keeping track of a person's whereabouts. It is certainly the case that RF technology can be misused—indeed, any technology can. However, the EPC effort must not be painted with the same brush; it is defined to be inexpensive and therefore destined to be of minimal performance. In fact, the long ranges speculated upon would be a curse for the supply chain. Imagine if, when you tried to read a pallet in front of you, you heard the voices of all the tags within a radius of a mile. Fortunately, the balanced view seems to have won; privacy is important, and the EPC has safeguards to protect the consumer.

I have always felt that one unfortunate result of the trajectory of these privacy discussions was that many real privacy issues in RFID were never discussed.

6. Sarma, S.E., Weis, S.A., and Engels, D.W. "Low-Cost RFID and the Electronic Product Code," Workshop on Cryptographic Hardware and Embedded Systems (CHES 2002), San Francisco, CA, August 12–15, 2002.

Engels, D.W., Rivest, R.L., Sarma, S.E., and Weis, S.A. "Security and Privacy Aspects of Low-Cost Radio Frequency Identification Systems," accepted for publication to the First International Conference on Security in Pervasive Computing (SPC 2003), March 12–14, 2003.

EPC has survived the trial by fire, and is better for it. However, not all RFID is EPC. Consider toll passes for cars, a prime example of privacy violation. The diminishing availability of coin lanes on highways is putting greater and greater pressure on people who don't have toll passes to get them. Yet toll passes have all the characteristics that EPC tags don't: They have long range, and they can't be turned off (I put mine inside the dash to protect myself). Our defense of EPC should not be construed as a defense of all RFID. All remote sensing technology needs to be examined carefully.

Summary: The Ultimate Systems Problem

There is a great deal of interest in *systems* research in academe today. In fact, MIT now has a new Engineering Systems Division. If there was ever any doubt about the relevance or the intellectual satisfaction of this hard-to-define topic, the Auto-ID Center should put it to rest. Under one research roof, our project touched topics as diverse as communication theory, circuit design, silicon manufacturing, manufacturing automation, paper manufacturing, cryptography, networking, software engineering, control theory, databases, distributed systems, public policy, the supply chain, logistics, and business modeling. Professors, students, technology companies, and user companies from around the world coordinated their work in this multifaceted effort to solve a pressing problem in industry. The impact was real, and the investments today are real. I believe that we have barely scratched the surface though; a great deal of research remains to be done on this exciting topic and in the related field of sensor networks.

RFID also is an excellent theme on which to base a course on system design. In fact, we taught our first graduate class on RFID in 2004, and I have rarely derived as much intellectual satisfaction from a teaching assignment.

Harnessing the Juggernaut

From 1999 to 2003, the Auto-ID Center grew from one lab to six, from three sponsors to more than a hundred, and from a gleam in our eyes to today's rollouts. This incredible growth occurred first, of course, because RFID solved fundamental problems in the supply chain. In addition, we—the researchers and the participating sponsors in the Auto-ID Center—were able to overcome some fundamental technology challenges and evangelize the concept very effectively.

The Six Auto-ID Labs

In 2000, it became clear that although we were making great progress within MIT, we needed help from other labs for several reasons. First, there was focus: Other labs with expertise in areas of RFID technology and RFID applications that we were not looking at could help us expand our horizons. Second, there are geographical differences in the use of RFID. For example, the regulatory environments in North America, Europe, and Asia are different, as are the supply chains. Even the way recycling is done is different. It was with these thoughts in mind that we set out to bring other distinguished research universities into the Auto-ID orbit. The mandate to expand the universities came from the Auto-ID sponsors, and we spent the next few years growing the family.

The first university we brought in was the University of Cambridge. For some time, I had known Dr. Duncan McFarlane there as an expert on manufacturing systems. Ironically, although manufacturing automation was where we started our research into RFID, it was the one process we were *not* doing. Duncan and his staff were the ideal group to take on the task of expanding research in the impact of RFID on manufacturing. Next, I met Professor Peter Cole of the University of Adelaide, Australia. Peter is an icon in the radio frequency systems and one of the leading lights of RFID hardware. He was also a founder of ISD (now known as Tagsys), a well-known company in the RFID space. We established both these labs by 2001. In 2002, Kevin Ashton and Dick Cantwell spent a month in Japan and met Professor Jun Murai of Keio University. Jun, who is also called the father of the Internet in Japan (the first network there was called Jun-net), established an Auto-ID Center at Keio. He brought not only a great deal of credibility but also an extraordinary knowledge of DNS and security to the group. Jun was in fact instrumental in the establishment of the 950–956MHz band in Japan for RFID. Kevin also met Professor Hao Min, a leading expert in Fudan University, China. Shanghai, where Fudan is located, is rapidly becoming the silicon fab capital of the world. With his deep knowledge of this space, Hao was another excellent addition to the Auto-ID team. Finally, in the beginning of 2003, we invited an old friend, Professor Elgar Fleisch of the University of St. Gallen, Switzerland, to the Center. The lab, which was jointly hosted by the University of St. Gallen and ETH Zurich (Einstein's alma mater), did a great deal of work not only on PML but also on the initial RFID value-calculator along with Cambridge. One of the more successful outreach efforts of the Center was a value calculator written by the University of Cambridge and offered on the Auto-ID Center Web site (with help from Mark Ferguson of Cambridge).

The Evolution of the Industry

The Center tripled its sponsorship every three years for four years. Much of this increase can be attributed to the relentless evangelizing of our staff and our existing sponsors. The vision was, after all, a seductive one. As the sponsorship grew, the organization of the labs evolved. In 2000, Dick Cantwell had taken over from Alan Haberman as chairman of the board of end-user sponsors (though Alan remains a close friend and advisor of the entire effort to this day). Around the same time, the board of vendor sponsors, which we dubbed the Technology Board, was growing bigger and contributing actively to the effort. Dirk Heyman of Sun became the chairman of the Technology Board. (Dirk later moved to Gillette, where he continues to work on RFID.)

In 2001, Wal-Mart joined the Auto-ID Center, and this move would prove to be a very important event. For a company renown for its innovative but grounded attitude to join a research effort meant that the research was getting close to practicality.

A second turning point was the field trial, which was the brainchild of Steve David of Procter & Gamble. Although I had misgivings about the organizational challenges of running such a large effort from a university, Steve's idea turned out to be a masterstroke. Wal-Mart chaired this self-organized effort, and through it, we learned the practicalities of RFID hardware and RFID software, the impact on logistics, and the impact on the economics of the supply chain. In the end, the field trial lasted two years and spanned eight states, ten cities, and 40 companies. The trial gave our emerging research a strong veneer of realism—something other research projects can only dream about. Much of the credit for the successful operation of the field trial goes to Silvio Albano, who was loaned to the Center by the Gillette Corporation to operate the field trial, and to Dan Engels, who was the technical lead. Kevin Ashton pushed for the eventual goal of item-level tagging, which we managed to get to in the field trial.

The third important event related to adoption was Gillette's order for 500 million tags placed in November 2002. The vendor that received this order was Alien Technology. Dick Cantwell, who was at that time also the chairman of the end-user sponsors' board at the Auto-ID Center, announced this order to a packed group of sponsors at our sponsors meetings. After taking over the Gillette effort from Allan Boath in 2000, Dick had passionately argued the benefits of EPC in reducing shrinkage and stock-outs in the supply chain. By placing this order, Dick was announcing three things:

- EPC technology had arrived in the real world.
- Gillette was willing to place a bet on its value.
- The race for extracting value from RFID was now on.

Executives like Dick Cantwell and Steve David play an unheralded role in moving American Corporations forward.

The final, and perhaps most powerful, step in the gathering momentum behind RFID was the Wal-Mart "mandate" announced in the middle of 2003. Linda Dillman, CIO of Wal-Mart, announced that starting in 2005, the retailer would require its top 100 suppliers to ship all cases and pallets of a few SKUs to a distribution center in Texas. Starting there from there, the expansion would encompass the entire supply chain. Nothing riveted attention more than the largest corporation on the planet making an announcement of this magnitude. (For additional information on this topic, see Appendix F.) To clarify matters even more, the Department of Defense (DoD) then followed suit, announcing a mandate of its own. Today, similar announcements from Target, Tesco, Metro, and other retailers around the world are further underlining the inevitability of the EPC.

The Creation of EPCglobal

By January 2002, the Auto-ID Center was outgrowing the confines of universities. The research was becoming more applied, and the commercial demands, like the sale of EPC numbers, were exceeding the capacity of universities. Despite the success that we were having in drawing in more companies, the need for a spin-off was apparent. In January 2002, I met Carol Carr and Tom Henneberry of the Office of Sponsored Programs at MIT to consider a number of alternatives. Should we create a new not-for-profit entity? A for-profit one? Would MIT invest and try to make money? Subsequent meetings with Professor Rohan Abeyaratne, the new head of the Mechanical Engineering Department; Dean Tom Magnanti; and Lita Nelson, the head of MIT's Technology Licensing Office made it clear to me that MIT was willing to take, and even insistent about taking, an extraordinarily generous approach to this spin-off. It wanted to create a not-for-profit organization to further EPC technology in the interests of society and the world.

Later that year, Mike DiYeso, Steve Brown, and Bernie Hogan of the Uniform Code Council traveled to MIT for a series of meetings with Kevin, Carol Carr, Tom Henneberry, Lita Nelson, and me. The UCC offered to run the EPC Network and to create a new not-for-profit group to do so. This was an ideal outcome, given that the UCC was an early sponsor of the Center and a successful not-for-profit standards body. We worked out a licensing agreement from MIT to this new entity, which we named EPCglobal. EPCglobal was a joint venture of the UCC and its sister organization, EAN. (UCC and EAN have now formally merged to form GS1.) Lita hammered out these agreements, and MIT licensed its technology free. Kevin and Lita had the excellent idea of putting a provision in the licensing agreement that the technology would not be used to tag human beings except in two scenarios: defense and hospitals. EPCglobal and the Auto-ID Center also agreed to continue a relationship wherein the center would be funded in exchange for ongoing research.

To prepare for the transition, I had already packaged the standards development process into two self-administered groups called the Hardware Action Group and the Software Action Group. Dan Engels led the Hardware Action Group, and Bruce Delagi of Sun headed up the Software Action Group. I had written an early document describing how the standards process might work, based on the W3C process. EPCglobal also created a public policy group of its own and took on the policy created by the Center. To aid the new organization, Tom Scharfeld at MIT wrote a white paper on certification, and Kevin wrote a paper on public policy. The last Auto-ID Center board meeting was held in November 2003. After that meeting, all activities other than research were transitioned to EPCglobal. A Board of Governors was created for EPCglobal, and Dick Cantwell of Gillette took over as chairman of that board. The research was to remain in the now-renamed Auto-ID Labs. Professors Elgar Fleisch and Jun Murai became the joint chairs of the new Auto-ID Labs. Dan Engels became director of research at MIT. I stepped aside as chairman of research and Kevin stepped aside as executive director of Auto-ID Center.

No transition, especially one of this magnitude, can be made without bumps in the road. The major sticking point in the transition from the Center to EPCglobal proved to be intellectual policy: EPCglobal has a unique mandate to offer royalty-free standards. We had always known that IP would be a challenge in this new space. In fact, we did a fair bit of research on intellectual policy, which Kevin summarized in a paper.[7] We had done as much as we could to avoid the minefield of intellectual policy that RFID faces. Many companies found the policy difficult to adopt, but after much negotiation, this and other similar problems seem to have been overcome. EPCglobal now has over 400 members and offices in several countries. The most recent EPCglobal meeting in Baltimore, Maryland, which was held in September 2004, had over 1,200 participants.

Conclusions

In 1999 and 2000, Kevin and I spent many evenings pondering the future and all possible outcomes for our EPC crusade. Looking back, though, I realize the

7. Ashton, K. "Towards an Approach to 'Intellectual Property.'" 2002. www.autoidlabs.org/whitepapers/MIT-AUTOID-EB-004.pdf.

Auto-ID Center exceeded most of my expectations. We had hit on the right formula for success: industry and academia working together. We had extremely supportive sponsors from the user and technology communities, like Gillette, Procter & Gamble, and Alien Technology. We even had, in the UCC, a respected industry body. This base gave us a great deal of license to invent and to be iconoclastic.

While many of our assertions and predictions were based on analysis and research, some were based on gut reactions. They turned into self-fulfilling prophecies because the researchers, the sponsors, and the entire community were intensely committed to them. We could ignore distractions and blind ourselves to naysayers, sometimes recklessly. Many of our predictions have come true. Some are still in progress. Others failed. For example, the mantra of minimalism and the use of the network, so difficult to convey only four years ago, are widely accepted today. We predicted that tags could be manufactured for less than five cents, which I still believe, perhaps even more confidently than before. Yet volumes are not where they need to be, and tags still cost about 20 cents. I still see this as a big step forward, given that UHF tags cost more than a dollar when we started. Where we were wrong was in assuming that item tagging was imminent. Case and pallet tagging are taking off, but the economics of item tagging are still not generally feasible.

On the other hand, RFID, and specifically the EPC form of RFID, is here to stay. It is very important to contrast RFID and the EPC and that the EPC is one way to use RFID technology—and, I will assert, a responsible and economical way. The value of the EPC to retailers is undeniable. The value to manufacturers too, in my analysis, is significant. The challenge will be in modifying business processes to extract this value.

The EPC will affect a number of industries. It will make baggage tracking in airlines more efficient and safe, it will make pharmaceuticals more difficult to counterfeit, it will enable the delivery of fresher food, and it will enable better management of spare parts in the automotive and aerospace industries. Semi-passive and active tags will open up newer and even more exciting applications but will bring with them the very policy concerns that were mistakenly directed toward passive RFID tags. Either way, technology will continue to evolve, and as a society, we must ensure that we continue to extract the best of new technology to improve our standard of life.