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# Incommensurate technological paradigms? Quarreling in the RFID industry

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Dosi's work on technology paradigms and trajectories has emerged as an important idea in evolutionary approaches to the economics of innovation. This article explores these ideas using one particular case history. I examine how two technology paradigms clashed in the radio frequency identification (RFID) industry in the 2000–2002 period, a clash that manifested itself in a public quarrel that broke out between proponents of an incumbent paradigm and a challenger paradigm. These events present an excellent vantage point from which to observe a debate between two different technological perspectives within one industry to gain insights into the influence of technology paradigms.

## 1. Introduction

Dosi's (1982, 1984, 1988, 1997) work on technology paradigms and trajectories has emerged as an important idea in evolutionary approaches to the economics of innovation. According to Dosi (1988), "A technological paradigm is both an *exemplar*—an artifact to that is to be developed and improved (such as a car, an integrated circuit, a lathe...)—and a *set of heuristics* (e.g. Where do we go from here? Where should we search? What sort of knowledge should we draw on?)." One of the key ideas of technology paradigms and trajectories is that, once established, these technological guide posts have a "life of their own," that is technologies display a momentum of their own that is built upon the accumulated inputs of multiple actors. Paradigms define the "normal" problem-solving activity of technologists operating with the paradigm as defined by the know-how, equipment, knowledge, procedures, and experience which is accumulated by actors who make a living by dwelling in the paradigm, often over long periods of time (Molina, 1993). Based on the past triumphs of a paradigm, individuals working within a paradigm inhabit a particular "worldview" (Kuhn, 1962); and these worldviews are not just shared practices, but they are also often embedded in the structure and organization of firms and whole industrial sectors (Freeman and Perez, 1988; Henderson and Clark, 1990). Occasionally, "incommensurate" paradigms clash spectacularly within an industry as "normal" technology and "revolutionary" technology stake out incommensurate positions (Kuhn, 1962).

This article explores many of these ideas using one particular case history. The unique contribution of the article is to examine how two technology paradigms clashed in the radio frequency identification (RFID) industry in the period 2000–2002, a clash that manifested itself in a public quarrel that broke out between proponents of an incumbent paradigm and a challenger paradigm[1]. Such records of incommensurability are important because they may be interpreted as providing fairly strong evidence for the presence of technology paradigms, particularly when there is evidence of multiple actors sharing worldviews, as there is in this case. The clash of paradigms in the RFID industry presents an excellent vantage point from which to observe the details of two paradigms interacting in a contemporary setting based on records that are barely history. The data and analysis are based on recent public records of the quarrel between incumbents and challengers and are supplemented by interview data gathered directly from some of the participants close to the time.

This article builds on the work of prior scholars who have documented the back and forth of similar debates between industry participants. Balmer and Sharp (1993) investigated the case of conflicting scientific and technological paradigms among government institutions sponsoring the British biotechnology industry in the 1980s, concluding that the bitter quarrel that broke out offers important insights into prevailing paradigms of scientific and technical inquiry. Garud and Rappa (1994) documented the debate between proponents of different paradigms in the emerging cochlear implant industry, charting the co-evolution of factors that impacted the institutional and technological landscape of that industry. Garud and Karnoe (2003) addressed contrasting (paradigmatic) approaches to wind power innovation utilized by Danish and US firms and the process by which the Danish paradigm (premised on an accumulation of incremental innovations) prevailed over the US paradigm (premised on breakthrough innovations). However, I am not familiar with any article in the literature that addresses the issue of incommensurate technology paradigms at the level of detail discussed in this article. The recent unfolding events in the RFID industry

[1]The history of the RFID industry is quite rich and several different explanations can be offered in order to understand events within the industry. At least three different perspectives might be taken on events in the RFID industry: *technology paradigms* (as described in this article), *path dependent* (the David/Arthur model: see David, 1985; Arthur, 1989), and *strategic sponsorship* (institutional entrepreneurship: see Garud and Kumaraswamy, 1993 and Garud et al, 2002). Path-dependent explanations focus on market drivers of technological lock-in, such as technological complementarities and network effects, which have played a role in the dynamics of the RFID industry. Strategic sponsorship focuses on the activities of players to affect the institutional structure of the industry, through technical standards-setting activities for example. These activities have also had a role in the RFID industry (Dew, 2006). Both these perspectives run alongside and complement the exposition in this article, which focuses on the role of conflicting technological paradigms—a term Dosi (Dosi, 1982) has used to describe the underlying "research programs" driving innovative activity in certain technologies. Overall, the questions addressed by each of these perspectives are quite different, as are the research methods typically used. My thanks to an anonymous reviewer for drawing my attention to this important point.

present a unique opportunity to observe a debate between two different technological perspectives within one industry to evaluate the influence of technology paradigms.

The article proceeds as follows. In the next section, I briefly explain what RFID is and give a quick history of the technology and basic industry background. I then describe the emergence of a new initiative in the RFID industry—the Auto ID Center (AIDC) consortium—and recount the public quarrel that almost immediately emerged between existing industry players and the center. Section 3 briefly reviews the literature on scientific and technological paradigms. In section 4, I trace how technology paradigms help explain the quarreling in the RFID industry in the period 2000–2002, an analysis that illustrates some of the practical implications of "inhabiting a worldview" (Kuhn, 1962). The final section concludes the article.

## 2. Background

### *2.1 RFID history*

RFID tags are wireless bar codes. The underlying technology they are based on is "laughably" old (Booth-Thomas, 2003), sharing its roots with the set of fundamental scientific discoveries in radio waves that first saw commercialization by Marconi just after the turn of the twentieth century. RFID development was initially spawned by the invention of radar, which was decisive in the Allies victory in World War II. Large, powered RFID tags (also known as transponders) were placed on friendly aircraft. When interrogated by a radar signal, these transponders would give the appropriate response to identify the carrying aircraft as "friendly." This IFF (Identify: Friend or Foe) system was the first obvious use of RFID. Present-day aviation traffic control is still based on IFF concepts.

RFID has evolved through three technology generations. *First generation* RFID tags were built around circuit boards, making them as big as, or bigger than, a brick. The tag is "read" by a RFID reader that emits radio waves, normally in one of five ranges of the radio spectrum: 125–134 khz, 13.56 mhz, 870–930 mhz, 2.45 ghz, or 5.8 ghz (spectrum allocations vary by country and by use). Like several other significant technologies (high-performance avionics, integrated circuits, and computer software), much of the research and development for RFID was sponsored by the US military, and early applications of the technology were mainly for military uses or closely associated purposes, such as tracking railcars transporting nuclear waste. The research and development of RFID started in the 1950s, continued through the 1960s, and exploded in the 1970s (Landt, 2001). Researchers at the government-sponsored Los Alamos National Laboratory (LASL) were central in many of these developments, and later, in the 1990s, the Pacific Northwest National Lab (PNL) became instrumental in technical advances.

*Second generation* RFID tags are microchip-based. The relentless miniaturization of electronics which saw circuit boards reduced to microchips (Dosi, 1984) led to thumb-sized RFID tags consisting of a microchip (a silicon integrated circuit) with a copper radio antenna coiled around it that looks like the coil of an electric hot plate. These tags are passive, so-called because they require no battery; instead they get their power from the interrogation signal of the reader. The microchip revolution in RFID was spawned by the transfer, in 1977, of government-developed technology through LASL initially to two private firms: Amtech (now part of Transcore) and Identronix (now part of Escort Memory Systems). By 1984, RFID microchips were regularly being manufactured by several US and European companies and have since become high-volume/low-cost commodity items for larger companies such as Texas Instruments (TIRIS), Motorola (until recently, their Indala division), EM Microelectronics (EMS-Sokymat), and Phillips Semiconductors (Mikron).

In the United States, the mainstream adoption of RFID began with tollbooths, starting with the Dallas toll road in the 1980s and proceeding in other states, such as California and New Jersey's EZPass systems. In the same period, the Association of American Railroads (AAR) standardized on RFID as a means of tracking railcars after disastrous trials with bar coding. Before adopting RFID, "They'd lose railroad cars or whole trains." (Landt, personal communication). In the period 1991–1993, the major railway operators in North America spent $200 million to adopt RFID by installing 3 million tags (at $30 each) on 1.5 million cars and locomotives, and 3,000 readers (at $50,000 each, installed) in strategic locations all over North America (the United States, Canada, and Mexico). Much of the history of firms producing and installing RFID systems in this early period is something of a mystery: no database is known to exist (Landt, personal communication).

The use of microchips cheapened RFID tags significantly (eventually to a few dollars each) and, somewhat predictably, applications began to spring up in access systems for office buildings and keyless entry systems for cars (which made up approximately half of worldwide deliveries of RFID transponders in 2000). Other common uses are Exxon Mobil's Speedpass pay-at-the-pump system and animal identification (cattle, fish, household pets, and wildlife). In Europe, Sokymat (Switzerland) and Rafsec (Finland) led the way on assembling finished RFID-enabled items, such as keyless entry systems and reusable metro and bus passes. In the United States, the largest and most innovative player was undoubtedly Texas Instruments' TiRiS division, which sponsored many of the more innovative applications of RFID tagging, such as timekeeping by tagging runners in the 1996 Boston Marathon. In the 1990s, a large number of small and midsize RFID suppliers developed, including diversifying entrants from nearby industries (such as the bar code industry) that saw RFID as a complementary automatic identification technology. Estimates vary, but all suggest the RFID industry was worth substantially less than a billion dollars a year in the late 1990s (inclusive of tags, hardware, and services).

Two other important developments occurred in the 1990s. First, the US Department of Defense (DOD) began rolling-out several RFID-enabled systems. The spark that re-ignited DOD interest in RFID was the problem of tracking containers loaded with vital supplies bound for troops fighting the first Gulf War. Upon arrival in the Gulf, logisticians had to assign hundreds of personnel to opening each container to find out what was actually in it. After this, the DOD let three consecutive $25MM/year three-year contracts for an RFID system that tracks containers and their contents to a Californian firm, SAVI Technology (SAVI was founded on an idea that failed—the idea of tracking lost children after the founder lost his child at a park; this idea was unsuccessful, but the same idea applied to container parks was a big hit). Post 9–11, the SAVI container tracking system is fast morphing into a general container/maritime port security system under the auspices of Homeland Security and is now being rolled-out globally.

The DOD also developed RFID at small scale, investing in fundamental and applied research at PNL to track night vision goggles and M15 rifles, create electronic dog tags, and monitor aircraft brakes and solid rocket fuel, several classified projects run by three-letter agencies, and some involving the use of RFID-equipped insects (bumblebees to find land mines and remote-controlled cockroaches as carriers of listening and image collection devices). In 2002 Defense Advanced Research Projects Agency (DARPA) and the Defense Micro Electronics Agency (DMEA) awarded a four-year $120MM research and development contract to Alien Technology Inc., North Dakota State University, and the University of Alaska at Fairbanks to develop RFID technology as a battlefield communication system based on the idea of developing sensors that are so small that they can be disguised as pebbles and seeds dropped by the tens of thousands over battlefields. These sensors would be able to detect vibrations caused by enemy convoys, chemical or biological agents, or even just the sound of enemy soldiers breathing.

The second important development of the 1990s was standardization efforts. Like the first generation of RFID tags, second generation RFID systems are based on manufacturers' proprietary technology. Under the International Standards Organization (ISO), there were ongoing and serious attempts to create standards for RFID. In addition, the Uniform Code Council (UCC, which runs the bar-coding system) sponsored the global tag (GTAG) initiative which, in effect, was a RFID tag that carried a bar code.

### *2.2 The emergence of the AIDC*

In the late 1990s, several organizations began to consider a successor technology to the bar code including Wal*Mart, which experienced tremendous success with bar coding and continuously prodded its major suppliers for new initiatives (Dunlop and Rivkin, 1997; Eberhardt, personal communication), and the UCC, which developed and administers the bar code system (Brown, 1997; Haberman, 2001). This resulted in the launch of the AIDC at Massachusetts Institute of Technology (MIT), which aspired to develop a *third generation* of RFID tags. The AIDC was symbolically launched at the Smithsonian museum in Washington D.C. on the 25th anniversary celebration of the bar code, where it was described as "[T]he beginning of a new journey: the journey to discover what will follow the bar code." (Rittenhouse and David, 1999). Funding for the center was provided by charging members a joining fee of $300,000, with initial funding provided by Proctor and Gamble (P&G), Gillette, the UCC, the European Article Numbering association (EAN), and the MIT. The center subsequently developed into a consortium of 100 major organizations. The AIDC had a triple role:

- A *research* consortium focused on inventing and innovating with RFID technology. The AIDC proposed a radical change to the basic architecture of RFID technology. In the proposed system, RFID tags hold a 96-digit identifying number called an electronic product code (EPC) that can be used to uniquely identify any object.
- A *standards* consortium focused on creating technical standards for the EPC, by consensus among the membership. A key role of the AIDC was the development of "open" standards for RFID central to which would be a *free* open software system that the center would research and design. The system would be designed to work with any kind of RFID tag carrying an EPC.
- A *facilitator* for the adoption of the EPC. The center promoted the adoption of the EPC in industry through an extensive education program. The aim of this program was to encourage widespread diffusion of the EPC to drive up tag volumes and drive down tag costs.

### *2.3 A public quarrel erupts*

Within a few months of its founding, the AIDC found itself in conflict with key elements of the existing RFID industry. The opening salvo was fired by *Supply Chain Systems*, a popular industry trade magazine servicing the logistics industry (at the time, it was known as *ID Systems*). It published an editorial comment which it carried in its weekly online newsletter Newslink, entitled "ADC's Future Is Out of Sight" (ADC referred to AIDC). In the article, commentator Paul Quinn reflected the general tone of skepticism with which RFID industry incumbents greeted the AIDC. Referring to MIT, Gillette, P&G, and the UCC, Quinn equivocally remarked, "Were the founders of a major new research lab of less stature, it would be easier to ignore their mission." (Quinn, 2000a). The article quoted part of an interview conducted by Quinn with Kevin Ashton, the executive director of the AIDC, where Ashton circulated the idea that the center would research and develop a five-cent RFID tag (this was approximately a 10-times reduction in cost, based on typical RFID industry metrics in 2000). Quinn then followed:

> All of which is way cool. But nagging questions remain:
>
> - What's going to be the *real* cost of a tag, and will this cost be justified in terms of streamlining the supply chain?
> - Can the problem of interference from metal, including containers and equipment, be overcome?
> - How much read range is enough, and can this arbitrary range be achieved at acceptable costs?

- What's going to happen to end users' existing investment in bar code equipment?
- Is the fundamental problem of reading many tags at the same time going to be licked?
- Is it *realistic* to hope for a true universal standard?

> Meanwhile, back at warehouse (and the factory, and every other station in the supply chain), efficiency rules. And although today's state-of-the-art ADC solution may be overshadowed by something better a few years down the road, it will be a long time before it becomes obsolete. (emphasis added) (Quinn, 2000a)

The "way cool" comment, which was industry vernacular for "unrealistic," prompted a debate which was published by *ID Systems* later that year. In November 2000 Quinn wrote again, this time under the title, "Can an RFID Tag Turn on a Dime?" (Quinn, 2000b). This time Quinn carried a letter by James Heurich, president of RFID Inc., a well-established privately-held producer of RFID tags and readers, together with a reply by Kevin Ashton. These two letters expressed conflicting views about the prospects for cheap tags in the RFID industry and sharp differences of opinion about both the prospects of RFID tagging substituting bar codes and the virtues of getting users excited about such a prospect. Heurich represented the views of the established incumbent industry players. Ashton represented the views of a challenger group of firms assembling in the AIDC consortium. According to Heurich:

> The primary reason *a 10-cent Tag is simply not achievable* is an evaluation of costs. These are no secrets, everyone, EVERYONE, who owns or produces their own silicon knows it costs an average of 7 to 12 cents to produce a die as it sits on a wafer. The wafer must then be sliced and diced, then picked and placed...picking and placing adds around 10 cents, and additional components like the antenna/adhesive package or sometimes a necessary external capacitor can add 5 cents. Not figured into these estimates are the costs of competent employees handling the materials, shipping, fallout, etc. And these estimates are for quantities in the hundreds of millions. Quantities of only 1 million would easily triple or quadruple the variable costs. (emphasis added) (Quinn, 2000b)

In other words, component costs alone amount to 22–27 cents for an RFID tag of the most primitive kind. Heurich went on to chastise Ashton for expressing the idea that a dime tag was possible, let alone a nickel tag, by making a reference to science fiction (Star Trek): "Those who claim that a marketable 10-cent RF tag...are wholly irresponsible. *Are the claims possible? Yes, as is the ability some day of Scotty beaming us up* (emphasis added)." Heurich went on to point out that the AIDC had no real solution and did not actually compete in the RFID market:

> Perhaps companies that have no real solution to compete in the smart label market would prefer the market remain confused and misinformed? Several times per week we receive sales lead asking for...[a tag that]...should cost 10 cents. Our sales staff makes a point of first attempting to inform the inquirer that *no such RF Tags exist* and if they persist we refer them directly and by name to those competitors responsible for misinforming the market. If they claim it, let them burden the costs to service it. (emphasis added) (Quinn, 2000b)

In a final salvo, Heurich referred to a memorandum that RFID Inc. had sponsored at the Automatic Identification Manufacturers (AIM) association: "Please reference the AIM referendum initiated by RFID, inc. and signed by many RFID companies calling for self regulated constraints on claims and the need to not mis-educate the public."

In his editorial, Quinn broadly supported Heurich's letter that generally expressed the views and frustrations of incumbent producers in the RFID industry. He pressed home the point that the AIDC's pursuit of the five-cent tag was unrealistic and bordering on science fiction by pointing to the "hard evidence to date":

> Mr. Ashton is evangelistic about ultra-low-cost, ubiquitous RFID—wireless U.P.C., as it were. And some very big organizations have put up serious money to help develop the concept. But for this technology, the journey from lab to practical application promises to be a long one, judging by the hard evidence to date. (Quinn, 2000b)

However, Quinn did publish Ashton's reply to Heurich. Ashton initially expressed a conciliatory tone by acknowledging that "Most currently available technology for all the reasons that Mr. Heurich has outlined in his letter don't scale down to the costs that we're looking at; (he's) completely right." But the reply was notable for three comments that underlined how diametrically opposed Ashton's views were compared with RFID industry incumbents, such as Heurich. According to Ashton:

> The question is, Is today's technology as good as it gets? Or are there new ways of approaching the problem? Our view at MIT is that there are new ways of approaching the problem. We think there are ways to get these costs down (and) we're working on it...This is a new problem, certainly for the semiconductor industry, which has historically focused on "more power." There's never really been a need for a very-low-cost, lightweight IC, so it's not something that's had as much R&D put against it as has (the challenge of creating) more power, more features. (Quinn, 2000b)

Second, to underline his point, Ashton quoted a famous example in the history of invention:

> [W]e shouldn't close our minds to the possibility that there are other ways of doing things...When the Wright brothers said that they could fly, for

> example, Lord Kelvin, who was then chair of the Royal Society in Great Britain, and was probably one of the world's leading scientists, said it was impossible. (Quinn, 2000b)

This led Ashton to state that "The idea that at the start of the next millennium it will be impossible to make an RFID-like piece of technology cheaply is, to me, absurd."

This very public war of words raged on into 2001. In July 2001 *ID Systems* carried a large article called "RFID Feeds the Supply Chain," where Deb Navas, Editor-at-large, devoted space to the problems caused in the RFID industry by "extravagant claims" of soon-to-arrive cheap RFID tags which were, according to her, damaging the industry's growth prospects:

> Cost remains another big issue for RFID vendors and potential customers. Extravagant claims of "imminent price breakthroughs" have plagued the industry since the mid-1990s, when RFID was hyped as the up-and-coming replacement for U.P.C. labeling in grocery applications. According to many industry experts, such statements are blatant misrepresentations, dampening potential user enthusiasm for implementing the technology in applications for which it is ideally suited, or in which the technology's advantages would clearly outweigh higher system costs. (Navas, 2001)

This opinion was shared by many industry players who had long and illustrious careers in RFID development. For instance, Jerry Landt, who had worked at LASL and for one of the original industry pioneers, Amtech, and subsequently became the research director at Transcore (sole supplier to the ARA and many tollbooth systems) countenanced that:

> To really be honest this is an industry that seems to attract a lot of interest. Over the years I have noticed that people always like to quote real low prices just to try to get interest in the technology and their product. Real low prices, real elaborate claims on performance and these kinds of things and it's actually, I think, slowed the development of the industry down because the potential consumers get very confused. If they are looking at one system from a vendor and they are about ready to buy and they say this is going to save us money and all that and then somebody comes out and says, "Just wait a minute, next year I can provide that same functionality for half the price", well, they are going to wait. And if that doesn't happen the whole thing just slows down. You have seen that happen over the years. (Landt, personal communication)

In their July 2001 report, *ID Systems* upped the stakes in the debate by providing data on RFID tag costs to illustrate that the industry had reached a dead end with a floor price of a little over 30 cents each for an RFID tag (excluding any packaging costs). This price compared with a fully built-up cost (including handling costs) of 5–7 cents for a bar code, thus providing evidence for incumbents' beliefs that RFID tagging would not replace bar codes anytime soon (Table 1).

In the same article, Heurich was quoted again, this time saying that: "I don't see prices coming down. If someone comes up with even a ten-cent tag within the next few years, it's going to be another technology. People expect an integrated circuit tested and attached to an attenuating antenna for that price?" Then he criticized the AIDC advocates again, this time saying that:

> The industry has worked hard to dispel myths about RFID, but then another outlandish claim comes along, like that in a recent article proclaiming that the five-cent tag is coming to market...It causes customers to postpone implementations, waiting for *something that doesn't exist*. (emphasis added) (Navas, 2001)

The rhetoric underlined the fact that not only did industry incumbents believe they were right, but they also felt confident enough about their beliefs to openly chastise those that disagreed with them.

Although existing industry players insisted tag prices below 35 cents were impossible, the AIDC continued to speculate on 25-, 10-, 5-, or even 1-cent tag prices—precisely the kind of speculation that was infuriating industry incumbents. In September 2001, Ashton gave a keynote address at an international "smart labels" conference in Cambridge, UK (Ashton, personal communication). In his address, he told the assembled audience of technologists that the AIDC was endeavoring to re-write the rule book of the RFID industry rather than play by it. Ashton referred to Sanjay Sarma, the research director at the AIDC: "As my friend and colleague Prof Sanjay Sarma is fond of saying, the "rules" about silicon that everybody knows were made at places like MIT, Berkeley and Stanford...And if we don't like the rules, we can change them." He continued with:

> The solution is to build new roads: to change the rules. Making chips too expensive? Make it cheaper. Handling is impossible? Make it possible.

**Table 1** Manufacturing costs for 13.56-mhz radio frequency identification (RFID) tags reported in ID Systems (2001)

| | |
|---|---|
| Silicon die (depends on size) | 6–8 cents |
| Slice/dice | 2 cents |
| Test | 2 cents |
| Pick-and-place chip onto antenna | 10 cents |
| Printed antenna | 10 cents |
| Total cost | 30–32 cents |
| Packaging (varies) | $0.30–$10.00 |

Information courtesy of RFID Inc.

> Testing too costly? Find another way to test. These "rules" are not laws of physics or God. They are just technology boundaries—boundaries that until recently hadn't been explored because there was no call for smaller, cheaper, simpler silicon chips...The claim that silicon can never be cheap enough simply isn't true. (Ashton, personal communication)

Two months later, in November 2001, the AIDC confidentially circulated a "white paper" report to its members entitled: "Towards the 5c Tag" (Sarma, 2001). In it, the center laid out the economics of very high volume tag production, concluding that "the goal of the 5c tag is difficult but achievable." According to the center, cheap RFID tags could be mass-produced using both conventional manufacturing technology and new manufacturing methods such as Fludic Self-Assembly (FSA). This affirmed that in the center's view, RFID tagging might one day compete with bar coding as the technology of choice in many logistics applications, based on comparable fully built-up costs. This provided evidence for the challengers' beliefs that the incumbents were wrong about the future prospects for the RFID industry.

As the debate rolled into 2002, there was still no resolution. In June *SCAN: The Data Capture Report*, a popular trade magazine that had catered to the logistics industry since 1977, ran an editorial "explaining why major end users are frustrated with the RFID industry for hyping its products. Basically, they are tired of hearing about five-cent tags that don't exist..." (Morgan, 2002). In July, a response came in, this time from Alien Technology, an up-and-coming tag manufacturer which was part of the AIDC. Jeff Jacobsen, Alien's CEO, and Tom Pounds (Alien's VP of Marketing and Business Development) laid out the economics of disposable RFID tags in great detail, based on Alien's proprietary FSA manufacturing process, asserting that the AIDC's claims that the nickel tag was coming were indeed correct. According to Pounds:

> I see SCAN/DCR from time to time and generally appreciate the quality of your insights into the AIDC marketplace. [However,] your most recent editorial expressing skepticism regarding low-cost RFID may put your bar code-oriented audience too much at ease. Low-cost AutoID is coming within the next three years, and it will have a major effect on many industries and applications. (Morgan, 2002)

Based on the information Pounds and Jacobsen gave to *SCAN/DCR* about low-cost RFID, Table 2 summarizes Alien's views on the prospective costs of RFID (which were broadly shared by researchers at the AIDC). This analysis suggests that challengers might be justified in claiming that RFID would substitute bar coding in many applications over a medium term (2–5 years) time horizon.

*SCAN/DCR* also published responses to Jacobsen/Pounds, including a summary of the responses of four major RFID vendors: "The gist of what we heard from those who had no stake in Alien was, 'Don't believe everything you hear.' " (Morgan, 2002).

**Table 2** Differences in radio frequency identification (RFID) tag manufacturing costs, comparing conventional pick-and-place robots with fludic self-assembly (FSA) reported in SCAN/DCR (2002)

| | Pick-and-place robots | FSA |
|---|---|---|
| Tags per day | 50 million | 50 million |
| Capital investment required | $200 million | $2.5 million |
| Staffing | 200 + staff | Average 1 operator |
| IC dimensions | 1300 microns (1.3 mm) | Test chips: 850 microns;<br>Production: 390 microns;<br>Possible: 30 microns |
| IC area | 1,690,000 microns sq. | 152,100 microns sq. |
| Sawing alley between Ics | 70–150 microns | 10 microns |
| ICs per 8-inch wafer | 15,000 | 250,000 |
| IC cost | 7–12 cents | 1 cent |
| RFID tag cost | 35 cents | 5 cents |

Information courtesy of Alien Technology, Inc.

In summary, RFID industry incumbents and challengers had staked-out incompatible positions on the future prospects of the industry. Incumbents claimed low-cost RFID was impossible and that RFID would not substitute bar coding; challengers claimed they already had the solutions in sight that would make low-cost RFID a reality and that RFID would start to substitute bar coding within a few years. How could people working in the same industry come to have such divergent opinions?

## 3. That is a nice story, so what?

Superficially, it might appear that the battle between incumbents and challengers in the RFID industry was simply a matter of "cheap talk" (Farrell and Rabin, 1996). Yet the intensity of the debate and the stakes involved seen to indicate deeper commitments were at work. A Kuhnian/Dosian perspective suggests that incumbents and challengers talked across one another because they were practicing their trades according to different worldviews, that is according to different paradigms.

Technological paradigms embody the accumulated body of knowledge of a technology but also encompass an *outlook* on the technology that includes definitions of its capabilities, relevant problems to be solved to yield improvements in the technology, and the specific practices for acquiring new knowledge about the technology. Dosi (1988: 1534) has stressed that technology paradigms determine the notional opportunities for future advancement of the technology. Similarly, Rosenberg (1976) has highlighted the importance of what he called "focusing devices," that is technologists focus their search activities on prototypical problems, opportunities, and targets. These focusing properties of paradigms can be thought of as partitioning the notion search space attainable at any one time into specific regions on the grounds of the available paradigmatic knowledge (Dosi, 1988: 1535). In other words, each technology paradigm involves a specific technology of technical change (Dosi, 1988). The essential point is that well-established paradigms are knowledge bases that heavily influence the direction and intensity of efforts to improve a technology. Moreover, and perhaps more importantly, paradigms also define what does *not* get searched for because it is thought impractical, impossible, or not worth trying. In Dosi's (1982) words, a technology paradigm "embodies strong prescriptions on the *directions* of technical change to pursue and those to neglect" (italics in original). Several notions including competency traps (Levitt and March, 1988), core rigidities (Leonard-Barton, 1994), and absorbative capacity (Cohen and Levinthal, 1990) all point to the idea that the existing know-how of technologists colors what information they recognize as valuable (Cohen and Levinthal, 1994).

Because technology paradigms define the notional "opportunity space" available for improving a technology, it is sometimes useful to think of technologies progressing along the fairly ordered "trajectories." Technology trajectories can be thought of as the progression "along the economic and technological trade-offs defined by a paradigm" (Dosi, 1988: 1128). An excellent example is Moore's Law in microelectronics. According to Moore's Law, improvements in the performance of semiconductor devices follow from increasing the density of transistors on a given area chip space. Moore predicted density would double every 18 months, a prediction that held rather well throughout the 1980s and 1990s. Increasing chip speed by increasing the density of transistors on the chip thus defined "normal" problem solving in semiconductor research for many years. Research victories in semiconductors were accumulated precisely by limiting the exploration activities according to the way Moore had defined the problem of semiconductor research, and these strategies had proven to be extremely successful. According to Dosi, although there is no *a priori* reason why one should observe the relatively ordered accumulation of a technological trajectory, the evidence suggests straightforwardly that technologists' explorations *are* limited by paradigms such as Moore's Law. Because these knowledge bases constrain the directions of innovative search by determining the notional opportunities of future technical advance, they produce fairly orderly patterns of innovation. Therefore, the way in which we observe technological change in industries is often as an orderly trajectory of improvement (Dosi, 1988: 1129).

One important consequence of paradigms is *incommensurability* (Kuhn, 1962), which means that paradigms can be sharply discontinuous—or "out of line"—with one another. When rival technological paradigms compete for dominance in an industry, each body of knowledge specific to each technology determines the perceived opportunities for improving the technology (Dosi, 1997: 1534). Heterogeneous paradigms therefore result in heterogeneous views about the prospects for technological improvement in an industry. Different technology paradigms have their *own* solutions to a particular problem and attempt to suppress each other's novelties:

> Technology paradigms have a powerful *exclusion effect*: the efforts and the technological imagination of engineers and of the organizations they are in are focused in rather precise directions while they are, so to speak, "blind" with respect to other technological possibilities. (Dosi, 1982: 53, italics in original)

Hence, technologists can have views that are *persistently* incommensurate with one another. In Kuhn's view, schools guided by different paradigms "are always slightly at cross purposes" (Kuhn, 1962: 112). Moreover, given bounded rationality and uncertainty (i.e. limited knowledge), there is no reason to suppose there is any way of adjudicating between different schools of thought (Dosi, 1982: 159) and therefore no reason to believe that the powerful exclusion effects of paradigms might be ameliorated, or even that amelioration is necessarily desirable. Such incommensurability can occur in weaker and stronger forms. Stronger forms of incommensurability can occur when technologists working in different paradigms share so little of their practices, procedures, and thinking that they barely comprehend one another (imagine a conversation between organic and synthetic dye manufacturers in the 1870s). Weaker forms of incommensurability mean that technologists basically understand each others' principles and practices, but differences in their customs and behaviors still lead them to hold divergent beliefs about a technology. As Kuhn seems to suggest when he wrote that different paradigms are always *slightly* at cross-purposes, the affects of different worldviews on the outlook of different individuals and communities are often quite subtle. But even fairly subtle differences can result in industry participants talking across one another, very much in the fashion witnessed in the RFID industry.

## 4. Why the bitter quarrel?

Technology paradigms help us understand why the notion that RFID tags might be produced for a nickel, as the AIDC suggested, was completely alien to the worldview inhabited by incumbents in the RFID industry. Normal business in an industry, such as normal science, rests on the assumption that business people know what the technology and market are really like, and those who share a worldview attempt to suppress novelties that subvert their basic commitments (Kuhn, 1962: 5). The RFID industry functioned based on certain premises about the nature of RFID technology. Given these premises, vendors sought out niche application markets for relatively high-priced tags and readers and often used distribution channels that included value-added resellers who tailored products to very specialized applications. These business practices were aligned with incumbents' basic conceptions of, and commitments to, what they believed was technically and economically viable with RFID. The AIDC saw different innovative opportunities for RFID. Their views involved ideas that were very much at odds with the existing industry. This section of the article traces the paradigmatic roots of these differences and disagreements between incumbents and challengers.

### *4.1 Understanding the incumbent paradigm*

Understanding the incumbent paradigm in the RFID industry requires an understanding of three elements of RFID systems in 2000: (i) the basics of RFID tag fabrication; (ii) the dynamics of semiconductor innovation; (iii) the business model used by RFID vendors. First of all, in RFID tag fabrication there were three key processes that were generally performed by different firms:

- Semiconductor fabrication: RFID dies (ICs) were typically made from 8-inch diameter silicon wafers. Thousands of identical ICs each as small as 1.3 mm (1300 microns) on each edge (~1.7-mm squared) were laid down on one wafer. These ICs were then tested and cingulated (cut) from the wafer using a diamond saw. Five major semiconductor producers shipped 98% of RFID microchips in 1999. Because the demand for RFID dies was relatively small and the capital costs incurred in semiconductor manufacturing was high, these firms produced dies using equipment and processes that were also used to produce more complex and higher volume chips.
- Inlet manufacturing: This process involves handling the tiny die by picking it and placing it (using a robot) onto a substrate and attaching an antenna (normally copper) to produce an unpackaged RFID inlet.
- Tag assembly: This involves packaging of the inlet into a finished product of some kind. Examples include adhesive "smart labels" (a wireless bar code) and identification cards used for keyless access to a building, etc. In the United States, around 500 firms were actively supplying finished tags in 2000; many focused on specific niche markets.

A large part of the cost of a finished RFID tag was attributable to the semiconductor. As Dosi (1984) has documented, semiconductor manufacturing is in many ways a quintessential example of technology paradigm and trajectory. The trajectory of semiconductor fabrication led to ever smaller, cheaper, better functioning microchips. RFID vendors adapted their business model to the dynamics and boundaries created by the semiconductor technology trajectory. Moore's Law made it possible to add more and more functionality to an RFID tag, and RFID vendors responded by marketing more and more functionality to users. Research and development activity in the RFID industry focused on leveraging the innovation opportunities enabled by Moore's Law, such as adding encryption functions and increasing the memory space on tags. In Dosi's terms, the direction of innovative search was focused on a particular cluster of technological characteristics; explorations of the notional characteristics space were limited to a small subset of possible explorations. In a whole host of niche applications, adding functionality to the tag provided a competitive advantage for RFID vendors who sought better margins by providing customers with better functionality (Christensen and Bower, 1996). A short example of an innovative RFID application illustrates this point.

Beer kegs are used by brewers to deliver beer from the brewery to its point of sale. After use, they are returned to the brewery where they are washed, repaired (if necessary), and refilled ready for the next delivery. For many years, kegs have been tracked by bar coding. However, 2%–5% of bar codes do not "read," a new label is required for every trip, and labels are abused along the supply chain by defacing/peeling off, resulting in a typical brewery losing 4% of its kegs to theft every year. RFID tags provided a solution. Encapsulated in plastic, a tag is more robust than a bar code, can be used for multiple trips, and "reads" almost 100%. With their high memory facility, RFID tags can have encrypted information written to them by an RFID reader, enabling beer companies to track the history of a single beer keg over its lifetime. This resulted in several benefits. Brewers had less kegs stolen and increased their sales by better controlling "unofficial" fake beer going into the distribution chain. By storing the precise weight of each keg on the tag, brewers paid less duties because they can precisely record the amount of beer they recover from the bottom of each keg on its return. They also saved on maintenance because cleaning data are written to the tag on each keg, so the brewers could schedule keg servicing.

The brewery example is an illustrative example of the pushes and pulls that created a particular trajectory of innovative activity in the RFID industry. One of the strengths of the RFID industry was its strong engineering approach and its accumulation of tacit knowledge by learning-by-doing. This was important because much of the finer science of RFID tagging is still not very well understood (e.g. antenna design), so the industry relied on knowledge accumulated by experimenting with the technology. This resulted in a lot of customized solutions, with different vendors producing tags to different technology standards. The RFID industry thus developed a mishmash of different standards for different applications, and vendors' business models were frequently based on locking customers into incompatible technology. RFID vendors mainly competed by offering RFID tagging solutions that were based on increasing the functionality of the technology. In Dosi's (1988: 1128) words: "It quite often happens that prototypical problem-solving models, rules on how to search and on what targets to focus, and beliefs as to 'what the market wants' become the shared view of the engineering community." Elsewhere, scholars have pointed out that this results in "industry recipes" (Spender, 1989), that is a general consensus in an industry on how business is done, what customers want, what the purpose of R&D is, and how firms make money. Using this model, RFID vendors were collectively successful in increasing the diffusion of RFID throughout the 1990s. They premised their future activities on continuing to do business in a paradigm that had proved it worked. All of these efforts were directed at making RFID valuable in certain applications but were far from seeing RFID as a "disposable" technology, that is five-cent throwaway tags.

### 4.2 *Understanding the challenger paradigm*

The AIDC's approach to RFID represented a different paradigm in RFID tagging. It called its design the EPC Network. The origin of the EPC Network lays with an MIT computer scientist, Dr. David Brock, who had a research interest in what is sometimes known as the "perception" problem or "object computer interface" problem in robotics, that is how should a computer perceive its environment? The easiest way to understand why the EPC Network was a different approach RFID tagging is to understand these origins. Brock developed a novel way to think about how robots might handle objects by pointing-and-clicking at an RFID tag on the object, the same way people point-and-click on hypertext on the Internet. Brock imagined every object being embedded with an RFID tag that held a unique identification number (an EPC) that robots would "click" on the tag using their RFID reader and that the click would take the robot to a webpage where it can retrieve an infinite array of information about the object that the tag is attached to: what the object is, how to pick it up, etc. The EPC Network evolved out of this idea.

Brock's innovation was explicitly *architectural* in nature (Henderson and Clark, 1990). The EPC Network owed more to the system architectures of the bar code and the Internet than it did to the traditional practices of the RFID industry. Consistent with theory and evidence in the history of technology (Reinganum, 1983), this challenger technology was not a product of the existing industry but a contribution of an outsider whose ideas were grounded primarily in the normative practices of computer science, not RFID. Brock's innovation was not in fact a radical departure from established practices in these other industries, although it was a radical departure in the RFID industry. The EPC Network in fact combined three technologies that already existed: product codes, RFID, and the Internet. Per Henderson and Clark (1990), the essence of this architectural innovation was to recombine existing technologies in a new way. Each of these technologies had its own distinct history up until that time. Brock's innovation did not leave the system components untouched, but it did leave the core design principles associated with each of the components intact.

The EPC Network involved distinctly different trade-offs than the ones that were traditional in the RFID industry. These differences in trade-offs meant the EPC Network was a different paradigm to the incumbent RFID paradigm. First, the EPC Network was conceived as a truly "open" system designed so that all manufacturer's tags and readers would be interoperable. Second, the EPC Network dramatically simplified RFID tags by putting very little data on a tag: just a product code. Third, the product code on the tag was linked to a databasing system via the Internet (or an equivalent data interchange system), and all information related to the product code was held remotely on databases. This removed all the complexity from RFID tag to minimize the cost of tags (low variable cost) but increased the infrastructure requirements to support RFID tagging (high fixed costs). This design was an inversion of the basic principles used in the incumbent RFID technology paradigm, where there were a mishmash of standards (including several *de facto* manufacturers' standards in particular applications, such as ocean-going containers [Savi] and railroads [Amtech]), tags were relatively complex (high variable cost), but the system requirements were minimal (low fixed costs). For applications involving relatively few RFID tags, the incumbent paradigm was cost-effective. But for applications such as mass retailing and fast moving consumer goods where billions of RFID tags might be required, the EPC Network promised lower costs because the variable costs of tags were minimized, the higher fixed costs could be spread over billions of items, and open standards facilitated data transfer between producers, distributors, and retailers.

These different trade-offs led incumbents and challengers to see the innovation opportunities and imperatives in RFID quite differently. Sanjay Sarma, the AIDC's research director, calculated that in principle the EPC Network could reduce RFID chip sizes significantly and therefore drive the cost of an RFID microchip down from 7–12 cents to perhaps 1 cent. However, as chips started to get extremely small, a key constraint in RFID chip costs emerged. Chips started to get smaller than conventional robots could economically handle them. This meant that conventional IC fabrication techniques resulted in a floor in the size of RFID dies, at around 1.7-mm squared. Below this point, chips got smarter but they did not get any cheaper. This problem was well known in the silicon industry as the "packaging problem." RFID incumbents had adapted their business model to avoid this technology barrier. But the EPC Network made trade-offs that demanded that microchips must be very tiny to be cheap. Instead of adapting to the constraint, the AIDC had to attack this constraint head-on: "This handling curve is a product of current manufacturing technology and it's never before been necessary to really make handling cheap...but this is one case where you actually need to take that handling bull by the horns. You have to solve that problem." (Sarma, personal communication). Very cheap RFID tags were essential to the proposed EPC Network, so Brock's innovation acted as a focusing device that directed problem-solving search at the microchip packaging problem (Mowery and Rosenberg, 1979: 125). Accordingly, the AIDC was informed by a technology paradigm that led to a different *intensity* of search for ways to produce very cheap, disposable RFID tags than the incumbent RFID paradigm (Dosi, 1997: 1535). Its paradigmatic commitments meant that the ways the AIDC approached the innovative opportunities available in RFID was different from incumbents. This inclination was further reinforced by the founding members of the AIDC such as Kevin Ashton (who came to the center from P&G, which had widespread experience in mass producing low cost consumer goods), Alan Haberman (who was a pioneer of the bar code which, in its initial stages, faced similar criticisms to the ones the EPC faced), and Sanjay Sarma (who was a manufacturing operations researcher at MIT).

### *4.3 Were these two RFID paradigms really incommensurate?*

Returning to Dosi's description of technical paradigms as exemplar artifacts *and* a set of heuristics, we see a number of important elements define key differences between the incumbent RFID paradigm and the challenger paradigm. First, the basic ideas underlying the architecture of the two systems were different. Incumbents had one conception of the industry: relatively sophisticated tags (increasing owing to Moore's Law) applied to niche applications supported by a mishmash of local, application-specific standards (customized solutions with barriers to switching). Brock's ideas presented an alternative conception: dumb tags (lowest possible cost) for mass market applications supported by universal standards (any tag works with any reader, including across multiple frequencies). These two conceptions sat uneasily with each other. Second, the core problems that required search and solution were defined differently by each paradigm. Incumbents primarily targeted their problem solving toward better tag and reader performance so that RFID could be of value in a wider range of applications (i.e. across a broader set of market niches). This strategy had proven itself as a viable model for diffusing RFID technology and had led to a steady expansion of the industry. By contrast, the AIDC defined its focal problems as developing ways of packaging very small microchips and developing the technical standards and infrastructure for an open EPC Network. The strategy was to achieve a breakthrough in tag costs. Third, each paradigm publicly undermined and diminished the achievements of the other side. Clearly at cross-purposes, they talked across one another. For instance, the AIDC's research director, Sanjay Sarma (personal communication), remarked that when he began working on a way to handle very small microchips "people were laughing at me."[2]

Perhaps the most conclusive evidence on the role of technology paradigms appears in the thinking of the direct participants themselves. Kevin Ashton, the executive director of the AIDC, was particularly perceptive in this regard. According to Ashton:

> If you find anybody who is involved in RFID who is not a sponsor of the AIDC then the chances are by now that they will be a skeptic. Talk to the Automatic Identification Manufacturers Association, talk to some of the RFID related companies that aren't involved in this project...There are plenty of people on the technology side who think it can't be done...
>
> One of the interesting things to me is a lot of the theory about how innovation happens is playing out before my eyes right now, particularly with the attitude of incompetent players who...actually find it very difficult to

[2]As of 2006 tag costs in the RFID industry had declined substantially from the figures touted by incumbents in 2000–2001, though not to 5 cents. As indicated in Table 1, basic inlays were estimated to cost 30–32 cents in 2001. According to Read (2005), by October 2005, Avery Dennison was offering inlays for \$0.079 for orders in excess of one million, and Smart Code was offering inlays for \$0.075 for order quantities that exceed one million units and for \$0.072 for orders of 10 million or more (notably, both of these firms were new entrants in the RFID industry). At the time, it cost approximately 2 cents to convert an inlay into a non-printable, pressure-sensitive label (in large volumes), giving a net figure of around 10 cents per finished tag. These figures were prices openly touted in the market and were generally thought to be slightly below production costs.

> understand new ways of doing things because they are so locked into the way they have always done it...
>
> *Thomas Kuhn*...talks about...partial communication...[O]ne of his observations is that people schooled in the old theory find it very hard to communicate with people who are thinking in terms of the new theory and the other way around. That's partial communication: you think you understand but you don't really...We see that a lot. So you will find many of the naysayers incredibly convincing because they themselves are convinced...
>
> There are some concepts that we could probably explain to you as someone whose RFID knowledge is pretty much a clean sheet of paper and you would understand in 30 seconds. An expert from the twentieth century would never understand them because they are so ingrained or so trained to think about things in a different way...[T]he degree of misunderstanding among the people you would probably expect most to understand is remarkable. (emphasis added) (Ashton, personal communication)

What is quite clear from Ashton's remarks is that at least some of the key players in the quarrel between incumbents and challengers directly *experienced* the old and new paradigms as incommensurate, that is were cognizant of misunderstandings. People schooled in the "new theory" found it very hard to communicate in any comprehensive fashion with people schooled in the "old theory" and *vice versa*. According to Ashton, incumbents and challengers might think they are communicating with each other, but in fact they do not quite understand each other. And so they talked past one another, as Kuhn often emphasized. All of which seems to underline the fact that when technologists inhabit different worldviews they literally seem to practice their trades in different worlds.

### *4.4 Bringing the RFID story up to date: the role of users and technology standards*

One reason why incumbents and challengers talked past one another was the nature of the organizations that discovered Brock's research and decided to sponsor it. The AIDC was a user-driven organization. Initially it was set up exclusively by and for users; later vendors and other organizations were admitted as members and made up approximately half the membership; but only users could sit on the main board which controlled the activities of the center. The users that ran the center included Wal*Mart, Target, CVS, the DOD, USPS, UPS, Johnson and Johnson, Pfizer, Kellogg's, and Kodak. For many firms, pre-existing capabilities developed with bar coding and electronic data interchange (EDI) made the EPC Network attractive. The AIDC quickly built critical mass after Wal*Mart joined in December 2000. Thereafter, new members joined the AIDC at five times the rate they had done previously. The bar code had evolved out of a similar project initiated by a user-driven consortium in the early 1970s.

The AIDC accelerated the evolution of technical standards for RFID by establishing a critical mass of prospective adopters who were committed to universal open standards similar to the bar code. Consortium members thought it was strongly in their interests to establish open technical standards for RFID (Haberman, personal communication). They thought it was suicidal to have multiple standards for RFID and believed the standards vacuum in RFID was a major roadblock to the diffusion of the technology. According to a recent review of the standards literature by Tassey (2000), standards are ubiquitous in technologies such as the EPC Network that inherently have a systems character and are necessity for successful adoption. Tassey defines standards as collective choices struck between users, producers, and government: "An industry standard is a set of specifications to which all elements of products, processes, formats, or procedures under its jurisdiction must conform." (p. 588). Tassey points out that because standards have an infrastructure quality to them they have a "public goods" nature, and hence underinvestment in standards is common. This was a key motivation for the AIDC, which involved collective action by members who invested in research and development to innovate within the challenger technology paradigm, and in universal open standards for RFID.

In fact standards of various kinds were involved in both the challenger and the incumbent paradigms, which suggests that standards were necessary but were insufficient on their own to change the RFID industry. There had been various efforts by RFID vendors to develop technical standards. In 1999 American National Standards Institute (ANSI) published a standard in 1999 for 13.56 mhz and 915 mhz tags which covered the air-interface protocol, which was regarded as key because it determined how the tag and reader communicated. The UCC (which runs the bar-coding system) sponsored the GTAG initiative which, in effect, was a RFID tag that carried a bar code. ISO subsequently built on the ANSI standards during 2000–2003 with ISO 18000–1 through 6. The ISO standards were widely supported by RFID manufacturers and were truly international standards because they met various county requirements. Despite progressing at a painfully slow pace, they passed through a rigorous six-stage process of consensus building and voting by members and were well supported in Europe, Japan, and China, where authorities shuffled their spectrum allocations and power restrictions to enable a global allocation for UHF RFID (which fell under ISO 18000–6).

However, the emphasis placed on standards by the competing paradigms and the process of their pursuit were completely different. The difference in emphasis was captured by one AIDC advocate who described the situation in the RFID industry in 2002 as follows:

> [T]his whole thing doesn't work unless there's a standard. You can't have five different groups of people who are all out there waving their flag that they're standard. That's part of the problem. Two major problems existed before we got into our RFID. One, there was no global standard. Secondly the IC manufacturers all had their own internal developed standard...The Auto ID Center takes it to "English" (Jacobsen, personal communication)

The process through which standards were pursued was also different. RFID standards at ISO were sponsored by technology vendors, not end users, and this made conflicts of interest inevitable (Farrell and Saloner, 1988). This made the ISO standards-setting process tortuously slow. Manufacturers had incentives to "game" the standards-setting process to increase the chance that a technology was selected that they sponsored and had invested in. By contrast, the AIDC was a consortium run by users who cared much more about establishing a workable standard rather than exactly which standard it was. For users, there was an obvious cost to a long period of no standard, with no compensating gains. Therefore, the goal of end users sponsoring the challenger paradigm was to do an end run round the standards-setting processes pursued by vendors of RFID equipment, by establishing the EPC as a *de facto* standard. Importantly, users could credibly commit to adopting the technology, whereas producers could never credibly commit to end user adoption, only to designing and attempting to sell product based on the standard. For instance, Wal*Mart simply refused to adopt any technology that was proprietary (Roberti, 2003a), and others, such as the US DOD, refused to adopt anything that was not both non-proprietary and also ISO compliant. Wal*Mart told its top 100 suppliers in November 2003 that it was driving for one open globally accepted RFID standard that it would require all its suppliers to use on pallets and cases of goods delivered to Wal*Mart warehouses starting in January 2005 (Roberti, 2003b). The DOD followed with similar requirements for its suppliers. Therefore, introducing a critical mass of users into the RFID industry changed the dynamics around standards. Users coordinated and collaborated on the adoption of the EPC. These actions did an end run around the standards-setting processes among RFID vendors and made ISO 18000–6 actually worth something by getting it widely accepted among end users.

## 5. Conclusions

To conclude, let me briefly restate the quarrel in the RFID industry as I understand it, and then assess how well it conforms with the theory of technology paradigms articulated by Dosi.

The story I have laid out here takes as its starting point the evolution of the RFID industry since the 1970s along a fairly well-defined technology trajectory that was fed both by developments in the silicon industry and by research and learning-by-doing in applied RFID settings. Like most innovations, RFID experienced a long, tortuous development path before it began diffusing in the 1980s. During the 1990s the technology continued to diffuse in many small market niches, with close collaboration and feedback from users being a very important part of this process (particularly in the military context). Vendors in the RFID industry adapted their business models to the benefits and constraints to be found both in RFID itself and in the development and production of integrated circuits.

However, the technology never found its "killer application" (Eberhardt, personal communication) and thus stopped short of becoming a mainstream technology. Then, in 1999, an initially small group of firms launched the AIDC, which proposed a challenger paradigm for RFID called the EPC Network. It turned the basic principles of the existing RFID industry on its head with an architectural reshuffle. This new paradigm proposed fundamentally different trade-offs than the incumbent RFID paradigm, and a new research program aimed at innovating on a few key dimensions of RFID development, including microchip packaging and universal technical standards. The goal, one might say, was to develop a "dominant design" in the RFID industry around the notion of making RFID into a wireless bar code (Utterback, 1994). Subsequently, incumbents and challengers publicly argued over the technical possibilities for RFID, with both sides talking past each other. The two paradigms were incommensurate.

How well does this story mesh with Dosi's theory? According to Dosi (1982: 161), we should be able to identify key paradigms, define the trade-offs and puzzles the paradigms solve, separate periods of normal technological progress from revolutionary periods, and understand the transitions between paradigms, that is how an industry re-stabilizes after a paradigmatic clash. The evidence on incommensurate technology paradigms in the RFID industry resonates with the theory. While it is too early to present findings on the transition between paradigms (or even if there has been/will be a transition), this study has dwelled on the other elements of technology paradigms at length. Technological paradigms are indeed alive and well in the RFID industry, just as Dosi would have us to believe. Other scholars have reached similar conclusions based on their analyses of different industries. Usselman (1993: 32) suggests that one could extend the analysis of paradigms to whole industries and, after a comprehensive in-depth study, Mokyr (1990) appears to have come to much the same set of conclusions about the influence of paradigmatic bodies of knowledge in the long-term history of technical change. However, inasmuch as paradigms are "invisible colleges" (Kuhn, 1962), it requires some sensitivity on the part of researchers to uncover evidence of the broad bodies of shared knowledge underlie technology paradigms. This evidence arises in inter-organizational interactions, because paradigmatic bodies of knowledge transcend individual firms. The recent history of the RFID industry presented in this article is one valuable opportunity to observe the details of incommensurate paradigms interacting in a very contemporary setting.

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