
Just how do those
little things
work anyway?

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The Magic of RFID

Many modern technologies give the impression they work by magic, particularly when they operate automatically and their mechanisms are invisible. A technology called RFID (radio frequency identification), which is relatively new to the mass market, has exactly this characteristic and for many people seems a lot like magic. RFID is an electronic tagging technology (see figure 1) that allows an object, place, or person to be automatically identified at a distance without a direct line-of-sight, using an electromagnetic challenge/response exchange. Typical applications include labeling products for rapid checkout at a point-of-sale terminal, inventory tracking, animal tagging, timing marathon runners, secure automobile keys, and access control for secure facilities.

In fact, various forms of crude RFID have been used since World War II. In the 1960s the technology became more practical, but the applications since then have resulted in relatively small tag deployments in narrow high-value areas without much public visibility. Also, given a tag's small size and ability to be hidden or molded into the casing of a product, some people may have encountered RFID without realizing it was present.

In the last couple of years many RFID stories have appeared in the popular press. Why is RFID making a splash now, given that the idea is at least 40 years old? Most technologies have a window of opportunity for deployment, which is related to the scope of the problem it solves, the maturity of the technology, and the cost of deployment. On all three of these points the world has changed over the past 40 years. Inventory tracking is now necessary on an unprecedented scale to support growing consumer markets at low operating costs and to remain price competitive despite the relatively high labor cost in the developed countries. Furthermore, the components

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used to build the tags and tag readers have become more sophisticated. Today, they provide greater functionality, reading range, and speed of data transfer. As a result, they support the ability to accurately read a large number of co-located tags at the same time. Standards also play a role—an important new standard created by the former Auto-ID Center (whose work is now being carried forward by the not-for-profit EPCglobal) has recently brought together a number of influential organizations such as Wal-Mart, Tesco (UK), and the U.S. Department of Defense (DoD), all of which recognize the opportunity RFID brings to improve operational efficiencies.

Lastly, the ultimate incentive for deployment of a technology is cost. When the benefits and cost savings brought about by the technology are greater than the deployment cost, the time is right. Since tags would most often be attached to large inventories of relatively inexpensive products, the tags need to be inexpensive. Some analysts say a tag must cost less than 5 cents (others below 1 cent) for the technology to be truly competitive. By comparison, existing tagging technologies such as bar-code systems involve little more than the very low cost of printing lines on packaging. At present, RFID tags are in the 50-cent range for small quantities, a number that could be reduced to the target price if their use were to grow as expected.

Initially, commercial deployment is likely to focus on pallet- or crate-level tracking in a warehouse, and depending on its success, may lead to item-level tracking in the future. RFID could improve the efficiency of warehouse management considerably. RFID tags would allow crate identities to be checked at a distance when entering or leaving the building, whether or not the tag is directly visible. A bar code used in the same application could well be facing the wrong direction, making it impossible to scan automatically. Once RFID has proved beneficial and has been well established, economies of scale such as mass production should help bring down the price. This would enable item-level tracking for high-value goods, and perhaps eventually, even tracking low-value items.

There is clearly risk involved in investing in the infrastructure before it is truly adopted on a national or global scale, but at the same time the costs will not decrease until that risk is taken. The previously mentioned organizations are engaging in serious trials, and other big chain stores can be expected to follow. These companies have enough presence in their market segments that they can make the opportunity a reality. Once their own warehouses adopt the technology, their suppliers will also be required to follow suit, accelerating the adoption process. These possibilities have drawn a lot of press attention, inspiring a flurry of articles and discussion on the Internet.

LOOKING INSIDE RFID

Before considering the issues raised by this technology, it is helpful to understand the basics of its operation. An RFID system is composed of readers and tags. *Readers* generate signals that are dual purpose: they provide power for a tag, and they create an interrogation signal. A *tag* captures the energy it receives from a reader to supply its own power and then executes commands sent by the reader. The simplest command results in the tag sending back a signal containing a unique digital ID (e.g., the EPC-96 standard uses 96 bits) that can be looked up in a database available to the reader to determine its identity, perhaps expressed as a name, manufacturer, SKU (stock keeping unit) number, and cost.

RFID Tags in Various Shapes and Sizes

FIG 1

Source: Courtesy of Intel

An RFID tag is built from three components:

- Antenna
- Silicon chip
- Substrate or encapsulation material

These tags are generally referred to as *passive* because they require no batteries or maintenance. Tag operation varies according to the frequency at which the tag operates. Historically, four common ISM (industrial, scientific, medical) frequency bands have been used: 128 kilohertz, 13.56 megahertz, 915 megahertz, and 2.45 gigahertz (see figure 2).

When the early RFID tags were designed in the 1960s, building these systems was practical only at the lower frequencies. Modern RFID tags, however, are capable of operating at frequencies greater than 900 MHz, in the UHF band. This trend improves a tag reader's ability to read the identity of many co-located tags because the data transfer rate will be higher and the data from each tag will be transferred in a shorter interval of time, reducing its chance of colliding with another tag's data in a given read period (for example, in a shopping cart full of grocery items). To reduce the chance of two IDs being transmitted at the same time (a *collision)*, an anti-collision protocol is used to control the time window during which a tag will respond, derived from the tag's unique internal ID code.

OPERATING PRINCIPLES

Passive tags that operate at frequencies up to 100 MHz are usually powered by magnetic induction, the same principle that drives the operation of household transformers. An alternating current in the reader coil induces a current in the tag's antenna coil, allowing charge to be stored in a capacitor, which then can be used to power the tag electronics. Information in the tag is sent back to the reader by loading the tag's coil in a changing pattern over time, which affects the current being drawn by the reader coil—a process called *load modulation*. To recover the identity of the tag, the reader simply decodes the change in current as a varying potential developed across a series resistance.

Unlike a transformer, the coils of a reader and a tag are separated in space, and coupling between the coils can occur only where the magnetic field lines of the reader coil intersect with the tag coil, the *near field* region (see figure 3). Beyond this distance the energy breaks away from the antenna as propagating waves that we call a radio signal; this is known as the *far field* region. The boundary of the near field and far field is governed by the frequency of the alternating current and is approximately limited to a distance of $c/2\pi f$; for example, at 13.56 MHz used by the ISO 15693 and 14443 standards, this distance is 3.6 meters, but at 915 MHz, used by EPCglobal, the range of the reader if based on near field coupling would be limited to six centimeters, reducing its usefulness.

Note that even at the lower frequency it is not guaranteed a reader/tag pair will be able to exchange data up to the $c/2\pi f$ distance. Unfortunately, the magnetic field strength also falls off fairly rapidly, proportional to a $1/d^3$ factor, where *d* is the distance from the center of the reader coil to the tag. If the field strength is too weak at a given distance, it will not be possible to provide the tag with the energy it needs to switch on. This effect can be mitigated by increasing the size of the reader coil and the tag coil, but for handheld readers and tags attached to small objects, there are obvious limitations. In practice, at 13.56 MHz, most systems operate with a range between 1 and 30 cm, considerably shorter than the near field limit.

To circumvent the range problem at higher frequencies, a different principle is used to build tags operating at frequencies above 100 MHz—namely, electromagnetic capture. The technique involves the use of electromagnetic waves that propagate from the antenna in the far field region to power the tag.

A high-frequency tag operates much as an old-fashioned crystal-set radio, which requires no battery because it is able to capture enough energy from the received

Operating Principles of Two RFID Tag Designs

Near Field Coupling
13.56-MHz RFID system based on ISO15693

Far Field Coupling
915-MHz (UHF) RFID system conforming to the EPC-96 standards

FIG 2

Source: Courtesy of Intel

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signal. Because the tag is operating beyond the near field, however, data cannot be sent back to the reader using load modulation; instead, radio frequency *backscatter* must be used: the tag electronics changes the impedance of the antenna, reflecting back some of the incident RF energy to the reader (figure 4). The reader, using a sensitive receiver, decodes the ID of the tag from the pattern of reflections, expressed as a varying amplitude in the received signal. For far field communication, the energy delivered to the tag follows an inverse square law, and the return signal another inverse square law. Thus, the transmit power is attenuated by a $1/d^4$ law even before considering operational inefficiencies, where *d* is the separation of the tag and reader—a very rapid decline indeed, but the system can be made to work over a distance of three to four meters.

Modern high-frequency tags, like the microprocessors in PCs, are beneficiaries of Moore's law. The laws of physics dictate the amount of energy that a reader can transmit to an RFID tag. The amount of energy required to power a digital circuit clocking at a particular frequency, however, has been falling annually as a result of advances in silicon technology that have led to the regular reduction in the size of lithographic features in integrated circuits. This is the same reason that a modern PDA can be operated by a battery, even though it has the same computing power as a mid-80s PC. Thus, every few years, RFID systems can be designed with greater read range, since the tags consume less power when clocked at the same frequency.

In recent years, RFID tag functionality has also become more sophisticated. Today's tags can accommodate a larger number of bits in the ID code than earlier models could, enabling the creation of billions of tags with unique IDs (EPCglobal specifies tags with 96-bit codes representing 79 billion billon billion (octillion) numbers (although some are redundant because of the inclusion of a checksum code). RFID readers have also been improved by the development of inexpensive receivers that are capable of detecting the tiny signals a battery-less UHF tag can return, which at distances of three meters registers power levels on the order of a billionth of a milliwatt.

EXTENDING RFID APPLICATIONS: SENSORS, SECURITY, AND MEMORY

RFID provides a data transport mechanism between a tag and a reader, which can be extended to provide greater utility than returning a simple identification number. The three important extensions of electronic tagging are: sensing the environment, security, and electronic memory.

SENSORS

The addition of a physical sensor to a tag has been an important development, providing the capability for a storeowner to learn something about the conditions

Near Field Coupling for RFID Tags Operating <100 MHz

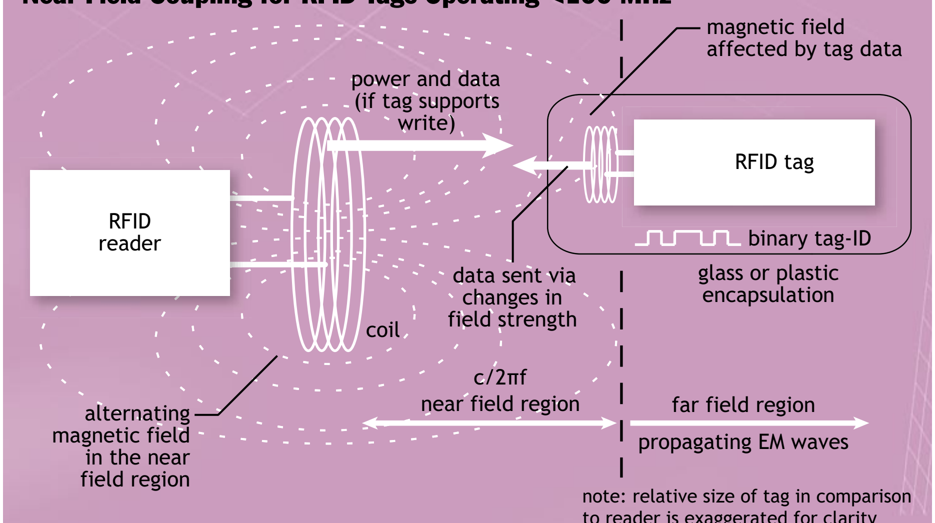

FIG 3

Source: Courtesy of Intel

a product has experienced in the past, at the time its tag is interrogated. Consider a frozen chicken that is being transported to a store. If the refrigeration of the transporter truck fails on the road, the chicken may well begin to defrost and potentially be contaminated by bacterial growth. By incorporating a temperature-sensitive material into the tag, and electronics that can detect a change in its state (e.g., its electrical resistance might permanently increase), it is possible to determine which of the chickens could be contaminated. Not only is the customer protected in this situation, but some of the product might also be saved if the sensors show critical temperatures were not exceeded, perhaps in a more insulated part of the truck. In this case, it is also a win for the meat company and the retail stores. KSW-Microtec in Germany produces an RFID tag called TempSens (see figure 5) that is based on these principles and is being trialed by a European pharmaceutical company.

SECURITY

Packaging of modern products is frequently associated with tamper-protecting mechanisms to alert a customer if a product has been opened between the factory and time of purchase. In this way, consumers can be warned that something may have been removed from the package, or more seriously, that the product may have been deliberately contaminated. By combining RFID with a switch—perhaps a simple wire attached to the tag and the packaging that is broken when the product is opened—a tag can indicate the suspicious conditions when read at the time of purchase. If the same tagged product has been interrogated earlier by other readers, the read times can be used to determine roughly when the product was tampered with, perhaps leading to the apprehension of the perpetrator. The U.S. Food and Drug Administration has recommended that RFID be considered for the protection of pharmaceutical products.

MEMORY

Stable storage, in the form of a read/write memory based on EEPROM (electrically erasable programmable read-only memory), is a relatively straightforward addition to an electronic tag, without any need to modify its encapsulation. Sensor tags, by contrast, require additional components that are not easily integrated, and the encapsulation needs to be carefully redesigned to accommodate them. Adding user-programmable memory to a tag opens up many new possibilities for its use. It can be used to store information that remains associated with a tagged product without the need for factories, shipping companies, retail stores, and customers to share a common database to find information about its history. For example, if a car's VIN (vehicle identification number) were stored in an RFID tag, the name of each owner of the car could be stored alongside it, providing an ownership record over the lifetime of the car; it remains with the car and cannot easily be lost. Service information could be stored in a similar way, and independent garages would be able to find out about any prior service history to help guide their work. Read/write RFID tags are available from many companies including Philips, Texas Instruments TIRIS, and Gemplus;

Far Field Communication for RFID Tags Operating >100 MHz

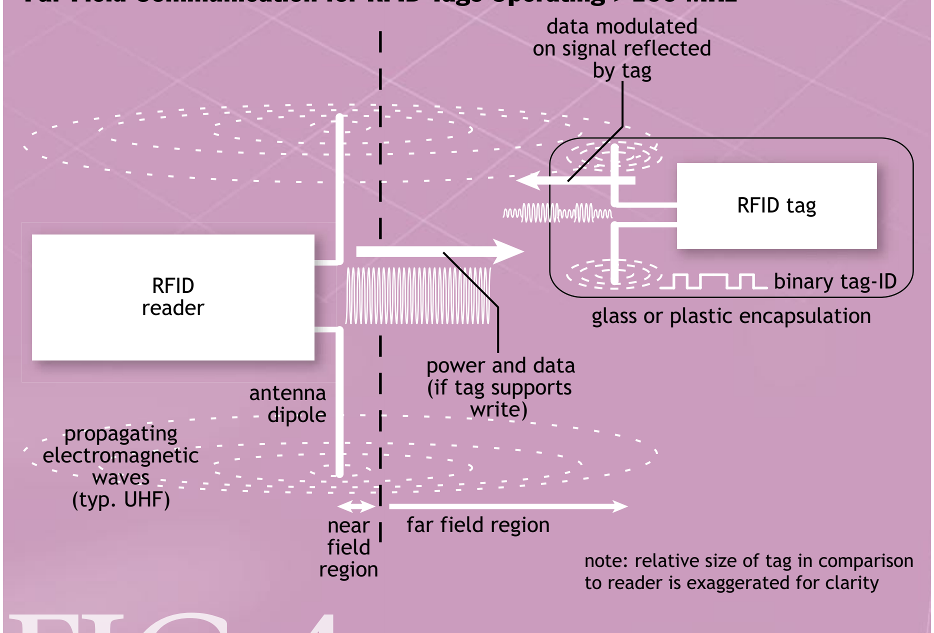

FIG 4

Source: Courtesy of Intel

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however, there are no standards in place that advise a customer how this memory should be used.

ISSUES TO BE RESOLVED WITH RFID

Given everything you have read so far, you may have been led to believe that apart from cost, the remaining technical issues for RFID are all solved. A number of issues, however, still present a challenge: tag orientation, reader coordination, multiple standards, stored data, range, cost, and customer concerns.

ORIENTATION

Although RFID does not require line of sight to operate, the reader cannot communicate effectively with a tag that is oriented perpendicular to the reader antenna. This is similar to the problem that we have all experienced when trying to receive a weak radio station on a portable radio. The reception can be improved dramatically by rotating the radio, but in some orientations it is hardly able to receive the station at all. If a number of products are placed in a random orientation inside a shopping basket, some will be oriented in a direction that makes them invisible to the reader.

Since the tagged product cannot be re-oriented, the solution to this problem is to vary the position of the reader or build advanced antennas that are less sensitive to orientation. One approach is to use many readers that have a diversity of orientations relative to the read area and to sequence through them performing multiple scans from different directions. The read results can then be merged, providing a much greater chance of identifying all of the tags present. Another solution employs antenna diversity by using a single reader with several switchable antennas that can be sequentially connected to the reader. This is likely to be a more cost-effective solution because it would reduce the number of relatively expensive radio and processing components needed to build the system.

READER COORDINATION AND SIGNAL PROCESSING

Most RFID readers are not designed to operate in the presence of another reader that is also scanning for tags. To date, this has not been a significant problem, as RFID has been in limited deployment without much opportunity for readers to interfere with each other. As electronic tags become more common, however, readers will be deployed on a larger scale, effectively garbling the data for systems in proximity to each other. This problem will become particularly serious if many mobile hand-readers are in use within close range of each other. Standards will be needed to define a protocol to allow these systems to share the available bandwidth, perhaps based on a wireless CSMA (carrier sense multiple access) protocol. ISO is addressing these issues, but details are beyond the scope of this article.

Further, improvements can be made when interpreting the tag signals received at the reader, intelligently filtering out noise. Application of advanced data-coding techniques in the tag electronics may also improve noise immunity and allow some multitag signal collisions to be separated and interpreted correctly. This may require more costly signal processing in the reader, but the benefits of greater accuracy will eventually lead to acceptance by a larger market and will drive the cost back down again.

Temperature-sensing RFID Tag

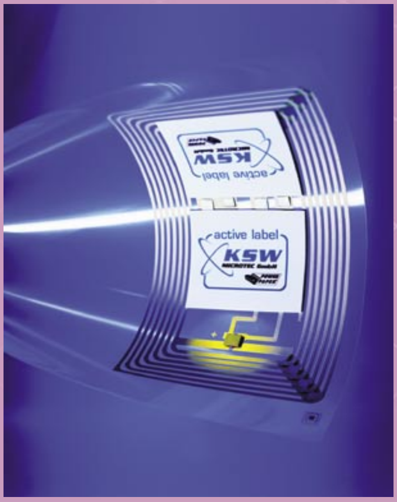

FIG 5 Source: Courtesy of KSW-Microtec

PRODUCT PACKAGING INDEPENDENCE

In contrast to RFID, bar codes can be printed on a label and still be readable independent of the contents of the product or packaging. RFID, on the other hand, can be disrupted by materials in the product itself. Because tags use tuned RF circuits to receive interrogation signals, it is possible to detune or attenuate the signals if placed next to certain types of packaging. Ferrous metals are some of the worst offenders—RFID and canned foods are not a good combination. This problem is a challenging one, as the most obvious solution is to change the packaging material, but clearly some products do not have economic alternatives to metal, or metallized packaging, particularly where robustness and airtight storage is required. It will be interesting to see if the popular use of RFID eventually has an effect on the materials used for industrial packaging, or if material science can provide a material to isolate the effect of a product on a tag.

MULTIPLE STANDARDS

As noted earlier, several frequencies and standards have been used for RFID tagging solutions—for example, the popular ISO 14443 standard that operates at 13.56 MHz, the EPCglobal (96-bit) 915-MHz standard, and several others. In an ideal world, industry would adopt one standard; however, there are cost trade-offs, national frequency use restrictions, and politics that keep several of these active in their own commercial domain. For example, while Wal-Mart is considering adoption of the EPCglobal standard, Nokia (the largest cellphone manufacturer in the world) is about to release a cellphone that incorporates an RFID reader based on the ISO 14443 standard. The combination allows callers to scan posters and stickers that contain an embedded tag and buy the depicted products with the charge appearing automatically on their next phone bill. A solution to this standardization problem is to build readers that can operate using multiple standards, perhaps automatically searching for tags across a number of frequency bands using a suite of protocols, and be programmable, allowing them to adjust to national frequency restrictions.

DATA FORMATS

Although the data format returned by read-only tags is defined by standards, the writable tags provide flash memory that customers can use in a proprietary way. There are potential benefits to standardizing the way data is represented here, perhaps allowing information to be shared or passed among independent organizations as it moves through a supply chain. For example, a product might move from the factory by road, air, and then road again to a warehouse in a foreign country, and finally a retail store, each operating with its own computerized inventory system. Damage might occur in transport as a result of negligence by any of the intermediate handlers.

If each transport company recorded the state of the package in the tag at the point the company received the package, the manufacturers and retailers could locate where the problems in the supply chain were occurring. This requires that the data be written to the tag in a form that can be interpreted by all parties. Eventually an XML-based format might be adopted for this purpose. However, the memory available in current tags (typically 2 kilobits) will probably be too small for an efficient representation in XML; a more compact notation would need to be standardized. While Moore's law continues to increase the memory capacity potential of RFID tags possible at reasonable cost, XML may well be used for this purpose in the future.

LONGER RANGE

In practice most of the lower-frequency RFID systems can read tags at a maximum distance of about a meter, and the UHF systems extend that to three to four meters. Some companies are now claiming that more than five meters is possible, although this may be under very ideal conditions, high sensitivity to orientation, and possibly with a tag battery assist or energy harvesting. As the power requirements of the silicon in a tag drop and the semiconductor industry designs more sensitive receivers at reasonable cost, reliable longer-range systems should become possible and expand the usefulness of RFID in warehouses and other voluminous environments.

LOWERING MANUFACTURING COSTS

Lowering tag and system costs would likely further the adoption of RFID, particularly for item-level tagging. There is little incentive to put an RFID tag on a 50-cent candy bar if the tag also costs 50 cents. Although, as described earlier, tag volumes driven by RFID adoption in large corporations will play a role in this process, technological innovations can also help. Two ideas have recently become practical:

- A unique tag fluidic self-assembly process allowing the active silicon component to float around and bond to the antenna assembly in a liquid medium. The silicon device is exactly the right shape to lock into its target when it floats into place. Hundreds of devices can be in the solution at once during the bonding process, thus reducing assembly costs.
- An entirely plastic RFID tag, built from plastic transis-

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tors on a flexible substrate. This design would allow all parts of the tag to be created at the same time, simplifying the assembly process, and may even employ an inexpensive ink-jet printing technology to build the circuits—all effectively reducing costs.

Both of these solutions are still experimental and will take time before they have proven their worth. In the meantime, the more traditional approaches may win out by streamlining the existing engineering processes.

PRIVACY AND CUSTOMER PUSHBACK

Many companies in this business were surprised by recent social reaction to a trial deployment of RFID tags in retail stores. Privacy groups claimed that RFID embedded in clothes could be used to provide directed marketing targeted at people as they walked through a store. Retailers say they simply want to stop theft from stores, make checkout more efficient, and perform store-level stock checks quickly and inexpensively. Stock checks are especially difficult for clothing stores, where the apparel is often moved among aisles as customers try on a variety of items.

Some privacy groups also worry that the tags could be read at great distances unbeknownst to the wearer. Some even fear that tags in peoples' homes might be read by a passing car. Based on the earlier technical description in this article, it should be clear that these scenarios are either impossible or very hard to achieve because of the near field limit, orientation, absorption by building materials, and the attenuation of the far field signals with distance.

Fear of a technology can be very real, however, and if early adopters do not address these issues successfully, they may well face customer pushback and loss of sales. The EPCglobal standard has predicted some of these issues and defines the use of a built-in switch (a "kill-switch") that can disable a tag at the point of sale. This kind of information needs to be made readily available to help allay consumer fears.

CONCLUSION

RFID is a technology that can provide considerable value in a world in which operating costs are often dominated by labor time. The technical issues associated with RFID are likely to be resolved as further investments are made in the technology. Enough progress has been made at this time that trials for the first truly large-scale roll-outs of RFID are beginning.

The next major hurdle is not directly related to the technology, but the software systems that will be needed to manage RFID-based inventory control. The extensive use of an electronic tagging technology will generate a flow of product information that will be several orders of magnitude greater than it is now. Database management software in the future will need to deal with item-level references, track product sales in the event of a recall, respond to data recovered from a tag's writable memory, and make automatic decisions about reordering items as buying trends develop. Many of these processes will need to operate in realtime because tag tracking is automatic and continuous, and the data flow will be derived from products shipped globally across all time zones. Systems that encompass all of these capabilities do not exist today, but as they are built they will need to be integrated into less-capable legacy inventory management systems, a task that will challenge commercial software system developers.

All of these efforts will promote the expanded use of tagging technology on a global scale so that one day every manufactured item might include an RFID tag, bringing consumers and vendors alike the many advantages outlined here. Q

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