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What is the Internet of Things?

An Economic Perspective

Elgar Fleisch (ETH Zurich / University of St. Gallen)

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Elgar Fleisch

Professor of Information and Technology Management

ETH Zurich / University of St. Gallen

Contact:

Email: efleisch@ethz.ch

Website: www.autoidlabs.org

Business Processes & Applications

What is the Internet of Things - An Economic Perspective

I was always skeptical about the buzzword *Web 2.0* - at least, it seemed like nothing more than a buzzword to me, until I read the paper from O`Reilly titled *What is Web 2.0*? (O'Reilly, 2005). Until then, I thought of Web 2.0 as a collection of a few fuzzy concepts some people gave a new name, just to plant a new tree in an already crowded Internet garden in order to attract unjustified attention. However, after reading the paper and understanding the concepts of user participation and service orientation more deeply, I became a convert. To me, the term Web 2.0 now provides a natural and important bracket around the design patterns and business models of the next level in Internet technology and usage.

Many people may share the same feelings I once had for Web 2.0 for the term *Internet of Things (IOT)*. Is it just another skin around well-known concepts such as ubiquitous computing, pervasive computing, cyber physical systems, ambient intelligence, or technologies such as sensor networks and RFID? If not, what value does it add? And frankly, what is it really? What are its main building blocks?

In recent years, the usage of the IOT-idiom has grown considerably. It has become a leading theme in conferences, books, academic and professional journals, university courses, research summer schools, research programs of companies, universities, applied research organizations and government-funded research programs, as well as reports on global future developments and industry analysis. However, the relevance of the term IOT is still not comparable to, for instance, Web 2.0 when measured in usage (e.g., in Google searches and hits) or in global spread, which is still somewhat European centered.

With this paper, I first and foremost want to render an account of what I think the IOT is, what its constituting concepts are and which main impacts on society and economy we can see today and expect in the near future. Doing so, I want to provide my research team, students and, perhaps colleagues in academia and industry with a baseline and some directions for ongoing and future research and development endeavors. Thus, this paper is targeted towards students, practitioners and researchers who are interested in understanding and contributing to the ongoing merge of the physical world of things and the Internet.

The conclusions of this work are based on information compiled from three sources: on vast numbers of academic and industrial publications, on numerous interviews and talks with colleagues, and on the personal experience I was lucky enough to gain within the last eight years.

The paper is structured as follows: The first section identifies the differences between Internet applications and applications that would probably belong to a cloudy IOT. It is written to sharpen the understanding of what the unique characteristics of an IOT would be. The next section searches for patterns in the investigated IOT-applications. It does so by identifying the root causes that drive the value of IOT-application to users and companies. The resulting common theme, the reduction of the real world-virtual world transaction costs, provides the base line for the overall economic energy of the IOT, which is discussed in the subsequent section. The paper closes with a description of some less obvious and therefore juicy patterns of how companies approach the IOT, followed by a brief summary and outlook.

What is the IOT and how does it differ from the Internet?

The basic idea of the IOT is that virtually every physical thing in this world can also become a computer that is connected to the Internet (ITU, 2005). To be more accurate, things do not turn into computers, but they can feature tiny computers. When they do so, they are often called smart things, because they can act smarter than things that have not been tagged.

Of course, one could question whether things would really have to feature computers to become smart. For instance, a consumer good could be considered to be already smart, when tagged with a visual code such as a bar code or equipped with a time-temperature-indicator that, say, a mobile phone can use to derive and communicate the product's state of quality, dynamic carbon footprint, effect on diabetics, or origin. Certainly the boundary between smart things, which autonomously can derive and transform to different states and communicate these states seamlessly with their surroundings, and not so smart things, which only have a single status and are not very active in communicating it, is blurring (Meyer et al., 2009). For pragmatic reasons, however, I will focus in this paper on smart things that are smart because they feature tiny low-end computers.

The IOT-idea is not new[1]. However, it only recently became relevant to the practical world, mainly because of the progress made in hardware development in the last decade. The decline of size, cost and energy consumption, hardware dimensions that are closely linked to each other, now allows the manufacturing of extremely small and inexpensive low-end computers (Payne, MacDonald, 2004).

As mass adoption of these tiny networked computers becomes a real option, new questions surface. What, if anything, would discern the IOT from existing computing realities, in particular the Internet? What new values and risks would it generate? And what new infrastructure would it have to rely on? The following paragraphs describe the most important differences between the Internet and the IOT:

1. Invisible versus flashy hardware. First of all, the hardware in the IOT looks considerably different and serves a different purpose. Whereas the nerve ends of the Internet are full-blown computers, from high capacity work stations to mobile phones, that require regular access to the power grid, the nerve ends in the IOT are very small, in many cases even invisible, low-end and low energy consumption computers. They typically feature only a small fraction of the functions of their bigger Internet-siblings, often including sensing, storing and

[1] For early mentors of the IOT and similar concepts see (Gershenfeld, 1999), (Ferguson, 2002), (Kindberg et al., 2002), (Schoenberger, Upbin, 2002), (Wright, Steventon, 2004). For an overview of the history of the IOT see (Mattern, Flörkemeier, 2009).

communicating a limited amount of information. In most cases, they cannot interact directly with human beings.

2. Trillions versus billions of network nodes. Today, about five billion devices such as mobile phones (3.3 billion), personal computers (1.2 billion), MP3 players (220k), digital cameras (120k), web cams (100k), PDAs (85k), and data servers (27k)[2] serve a population of about 6.7 billion people, of whom only 1.5 billion are currently using the Internet[3]. These numbers seem huge, but in comparison to the number of things we constantly create on this earth, they are not. One can grasp an idea of the order of magnitude by estimating the number of consumer products that are produced every year. To do so, I divided the revenue of a leading consumer goods company by the estimated average product price, expanded the reported market share to 100%, and multiplied that result by the estimated lifespan. The resulting number (84 billion) only begins to hint at dimensions, as many of these products might never be equipped with minicomputers, and as consumer products only account for a fraction of the things we create each year. Sanjay Sarma even estimates 555 billion units in an Auto-ID Center-specific selection of supply chains (Sarma, 2001). However these figures may exactly look like, these estimates already suggest that there will be so many computer-enabled things around us that, firstly, people will not be willing and able to directly communicate with them, and secondly, a new network infrastructure, the IOT, might be required.

3. Last mile bottleneck versus highway. The last mile in a communications infrastructure refers to the communication link between the nerve endings, or the leaves in a local tree, and its next tier or layer. Driven by user demands, e.g., streaming videos, and technology progress, the speed of the last mile in the Internet has been increasing tremendously over recent years. Today, an average household in many countries can expect to have cable-based Internet access with a bandwidth of at least 1 MBit/s. With the implementation of emerging technologies such as fiber optics to the home, the bandwidth will soon become as high as 50 - 100 MBit/s. By contrast, the speed of the last mile towards an average low energy consuming radio frequency identification tag is only about 100 kBit/s.

4. Babylon versus global identification and addressing. The low end hardware of the IOT is responsible for another difference: the identification and addressing of the nerve endings. In most cases, the Internet-based identification and addressing schemes require too much capacity to become part of low-end smart things. Therefore, academic and industrial communities are searching for alternative technologies and standards (e.g. EPC, ucode, IPv6, 6LoWPAN, Handle System, or Internet0) to number and address the smartening physical world. So far, most identifiers for smart things and technologies bridge the last mile based on local, technology vendor-specific closed-loop schemes. However, if the IOT would like to follow the successful path of the classical Internet, its architecture would have to make sure that any tagged object could in principle be accessed by any computer. For that, a global standard protocol, identification and addressing scheme for bridging the last mile from the Internet to the smart things would be required.

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[2] Data Source: Wired 7/2008

[3] Data Source: http://www.internetworldstats.com/stats.htm

5. Machine-centric versus user-centric. The characteristics of the Internet and the IOT define the range of services they support. The vast majority of Internet-based services are targeted towards human beings as users, e.g., the World Wide Web (WWW), email, file sharing, video, online chat, file transfer, telephony, shopping, or rating. The attributes of the IOT almost completely exclude humans from direct intervention. That is why Marc Weiser called for a paradigm shift towards human-out-of-the-loop-computing when he introduced the vision of ubiquitous computing. In most IOT-applications, the smart things communicate amongst each other and with computers in the Internet in a machine-to-machine way (Mattern, 2004). When users need to be involved, e.g., for decision making, they currently contribute via personal computers and mobile phones.

6. Focus on sensing versus on communication. The economic success story of the Internet started with the WWW, which allowed companies and individuals virtually for the first time to reach out to a global customer base at ridiculously low cost. Looking closely at the WWW's communication abilities (distribution and presentation of content), it seems no big surprise that the first economic success stories were made in the areas of advertising (Google) and shopping (e.g., eBay or Amazon). However, looking backwards has always been far simpler than forecasting.

The second boost of the Internet was largely driven by adding the ability to deal with user-generated content, i.e., data that is not only consumed by users but also provided by users. The success stories of these Web 2.0-based services include Facebook, YouTube, Twitter, and Wikipedia.

The IOT adds another data dimension. It allows the physical world, things and places, to generate data automatically. In fact, in my view, the IOT is all about sensing the physical world. It provides the infrastructure that for the first time enables us to measure the world, just as Gauss did around 200 years ago, but far more powerful. It is a cost-efficient means of growing a very finely granulated nerve system with trillions of new nerve endings. Linked together, they can provide humans with a measurement tool that opens the door to many new findings, applications, benefits, and risks.

Internet of Things, or Web of Things?

After reading through the differences, one can argue that the IOT is not on the same level as the Internet, that it is in fact "only" an application of the Internet, in very much the same way as many existing Internet-enabled services. Following that path, the term IOT would be an exaggeration, and should be renamed something like Web of Things.

On the other hand, one can easily argue that a Web of Things would require low level building blocks, e.g., for addressing the smart things, bridging the last mile and linking it with the Internet, that are peers with some Internet building blocks. As a consequence, the IOT may rightly be conceptualized as an extension of the Internet to reach out to the physical world of things and places that only can feature low-end computers (Gershenfeld et al., 2004).

In fact, often enough when we use the term IOT, we do not differentiate between the infrastructure and application levels. We use IOT as a bracket-term to refer to one or both at the same time.

On the *infrastructure level,* the IOT can be viewed as an extension to the Internet as we know it today. The IOT expands the technical Internet building blocks such as DNS, TCP, and IP with identification and addressing schemes, last mile communication technology, and an Internet gateway that matches the IOT requirements, foremost among them low energy consumption, low cost, and mobility (Sarma, 2004).

Identification and addressing scheme. In many applications, the identification and addressing of an IOT-leaf via IP numbers or MAC identifiers requires too much computing power to be handled by a minicomputer that can operate autonomously on a sustainable basis. Current developments in the areas of 6LoWPAN (IPv6 over Low Power Wireless Area Networks) (Hui, Culler, 2008), mini IPv6 standard stacks for sensor networks, energy-harvesting, energy-storage, and energy-consumption are likely to change this equation, but for the time being almost all up-and-running IOT-solutions use alternative ways to identify and address their sensors.

Last mile communication technology. Furthermore, the communication technology that bridges the air from a sensor to a regular node in the Internet has to bear up to the typical restrictions of a last mile in the IOT. It has to be wireless, robust, and, most of all, energy efficient. In some cases, the communication protocol must also enable security features, transport energy to run the sensor, or allow measurement of the distance (ranging) and localization. The proposed methods and standards for corresponding communication protocols are as manifold as the IOT application areas.

Gateway to Internet. And last but not least, once the identifier of a tag, along with other sensor information, has been successfully communicated to a node in the Internet -- a node that can operate based on Internet technology because, amongst other considerations, it regularly has access to the power grid -- it frequently has to be resolved against other resources in the Internet. For instance, in a very simple application, the gateway only has to find the digital proxy of a tagged thing. For this task, the identifier of the tag needs to look for a corresponding IP address, sometimes referred to as the “homepage” of the tagged thing, in much the same way as the Domain Name System (DNS) resolves a domain name into a corresponding IP address. A gateway based on the DNS, called the Object Name System (ONS), was proposed by the Auto-ID Labs.

In more complex and also more realistic scenarios, there will be more than a single “homepage” attached to a thing or place, and they will not really be homepages but web services. In an ideal open IOT-architecture, not only can every sensor be reached by every authorized computer or person, but in addition, every person and organization can set up their own services, link them with identifiers, and offer them to the public. For instance, a tag on a consumer good would not just provide a link to the product homepage provided by the producer (in the world of EPCglobal, which would be a pure ONS-based service). Rather, if brought close enough to an RFID reader, it would generate an additional list of alternative services provided by independent firms or not-for-profit organizations from which the user or the user's computer system can choose. This list could include services such as product rating, fair trade check, counterfeit check, proof-of-origin, replenishment alert, political shopping (do I, by buying the product, support labor in a foreign country or in my beloved home country?), or self check-out. The alternative services do not necessarily have to be in alignment with the interests of the consumer goods company. In the world of EPCglobal, the Discovery Service would generate the list of services that are available given an EPC.

On the *application level*, it can be observed that IOT-applications never work stand-alone, but always also use Internet-based services. So IOT-applications might simply be regarded as a special set of Internet applications that also leverage the IOT-infrastructure. They recently have been subsumed under the term "Web of Things," in retail environments "Web of Goods," or in closed-loop scenarios even "Intranet of Goods." In the "Web of Things," tagged items or spaces serve as additional triggers and actuators to re-invent classical web applications such as product rating, or to enable new services such as pet-tracking. As on the infrastructure layer, they extend classical Internet applications to the real world.

IOT-standards: One global one-size-fits-all?

Unlike in the Internet, there is currently no single global set of standards for the IOT, and in all likelihood, there never will be. The most important reason is that the IOT leaves the clean, closed, logically consistent and self-sufficient digital world. IOT projects suddenly have to deal with physical properties such as distance (should a tag ideally be readable within a few hundred meters, a few meters, or a few millimeters?) and characteristics of neighborhoods (e.g., materials that absorb or reflect radio waves).[4]. These properties depend on concrete applications, and these applications are almost as manifold as the physical world itself, resulting in a rich variety of technological forms of appearances.

In some industries, however, de facto standards emerge. For instance, mainly due to the mandates of Walmart, Metro, and other large retailers, the EPCglobal standard stack is the de facto standard in the retail and consumer goods industries (Thiesse et al., 2009). And since retailers do not only sell consumer goods, the EPC standard likely expands to other related industries, such as the textile or the pharmaceutical industry. Once a standard drives large quantities, and the EPCglobal standard stack certainly does that, the cost of standard-compliant technology declines dramatically (after all, size matters) and is likely to draw additional industries to join in, which will be further propelled by the availability of open source implementations of the EPC stack (Flörkemeier et al., 2007).

[4] In classical IT projects "only" two general types of skills have to cooperate to create a working solution: the people who understand the business or user side of an application, and the IT guys. In an IOT-project, at least for the time being, an additional party who can deal with the physical challenges, typically electrical engineering technicians, is needed (Henzinger, Sifakis, 2007).

When things add value - IOT value drivers

Another approach to isolating the essence of the IOT is to look at the value that its applications add for both businesses and consumers[5]. I learned quickly that trying to structure IOT applications is as impossible as modeling the entire world, because essentially every business process in essentially every industry on this globe is embedded in the physical world. Thus, the IOT is potentially relevant for every step in every value chain. So I switched to searching for the origins of the value an IOT application would provide to its milieu. To do so, I took a list of about a hundred existing and emerging applications that leverage the IOT concept. It turned out that every investigated application sports one or more of the seven main value drivers identified below. The first four drivers are dedicated to root causes based on machine-to-machine communication, while the latter three show root causes based on the integration of users.

1. Simplified manual proximity trigger. The first driver in the proposed value driver stack is very basic and is part of numerous applications such as self check-out and stock-taking in libraries, access control in buildings and sporting facilities, basic payment procedures, even pet tagging. Its business value stems from the fact that some smart things can communicate their name, i.e., their unique identification number, in a very robust, fast and convenient way when they are manually (and usually consciously) moved into the roaming space of a proximity sensor such as an antenna or a camera that sits and waits for something to pass by. As soon as the smart thing is close enough to the hot spot, a transaction, e.g., a payment procedure, a validity check or the creation of an entry record, is automatically triggered.

Businesses include this value driver in their applications because it makes the life of their employees more convenient (e.g., moving an RFID-loaded access card across a hot spot is far more convenient than entering a six digit personal security number), enables customer self service (i.e., outsourcing of costly tasks such as check out to customers) and as a consequence reduces labor costs. Consumers value this driver for some of the same reasons. It helps them to save time, to gain independence via self-serving, and finally to increase their perceived convenience.

2. Automatic proximity trigger. This value driver adds a single but important feature to the previous one: it triggers a transaction *automatically* when the physical distance of two things, let us say a pair of Levi's jeans and a gate in a department store, drops below a threshold, e.g., when a consumer steps out of a store with a purchase he forgot to pay for. Many business applications in production and the supply chain management sport this value driver, from asset management to inventory management. Whenever a smart thing such as a tagged truck, forklift, pallet, carton, work-in-progress bin, or consumer product does not remain at a distance from some other smart thing or place that can sense it, a transaction

[5] In the European Union it recently became common to replace the term “consumer” with “citizen”, possibly to stress the fact that the concept of men is richer than that of consumer, and that new technology development should address human beings as a whole. In this paper, I deliberately use all such terms synonymously to convey that I never saw humans as pure shopping mammals.

such as an update of a bookkeeping record, the initiation of a replenishment task, or the ring of an alarm bell is triggered. In other words, IOT applications using this value driver leverage the powerful qualities of physical neighborhoods to build new and better business processes. In the pure digital world of classical supply chain management systems, production planning systems, or enterprise resource planning systems, this was, of course, simply impossible (Bullinger, Ten Hompel, 2008), (Vitzthum, Konsynski, 2008).

The implementation of this value driver leads to an increase in speed, accuracy, and convenience that allows companies to reduce their labor costs, process failure costs and costs of fraud[6]. In addition, it delivers massive new data that can be used to improve processes constantly over the time. Consumers may directly profit from physical self triggers via an additional level of convenience, for instance, when a new BMW car opens its doors on its own as the bearer of the car key approaches. Further, several manufacturers in the automotive, aircraft and computer assembly sector are developing systems to link the informatory with the physical world on the shop floor by means of augmented reality applications (Ong et al., 2008), (Regenbrecht et al., 2005). Proximity triggers are applied to support workers with work instructions, assembly plans and other information they just require to fulfill their current task. Assembly steps can even be documented automatically, which may eliminate almost any manual information processing on the shop floor.

3. Automatic sensor triggering. Value drivers one and two create benefits by manually and automatically sensing and communicating the name of a thing. Value driver three expands the ID by any data a smart thing could collect via any sensor. Examples for sensor data include temperature, acceleration, localization, orientation, vibration, brightness, humidity, noise, smell, vision, chemical composition, and life signals. This driver allows a smart thing to constantly sense its condition and environment for relevant movements and initiate actions based on preprogrammed rules. For instance, it would allow a smart olive tree to constantly check temperature, brightness, and humidity (of soil and air) to adjust the optimal water feed. Automatic sensors enable local (therefore individual) and prompt (therefore event-based) decision making. They rapidly increase the quality of processes, which results in more efficient (better input/output relation) and more effective (better output) ways of doing things. In the case of the olive farm, so-called Precision Agriculture would translate into better, or at least bigger, olives since the watering over time would be closer to a theoretical optimum (Wark et al., 2007). It would probably also lead to a more environmentally friendly usage of water, since the tight process control would eliminate unnecessary irrigation.

The fields of application are manifold. They reach from condition monitoring throughout the entire supply chain to networked smoke detectors in private homes, from the management of perishable goods to the production of sweet wine, from the monitoring of manmade construction to early-warning systems for forest fires or earthquakes, from smart meters to increase the efficiency of the electric grid to the monitoring of life signals of patients in hospitals and at home. This value driver represents the options that develop when computers, the IOT, can measure the world in detail at reasonable cost. Then, the IOT serves as a network of sensors for far more senses than those of human beings. And it can do so continually, at a ridiculously high resolution, and across the globe.

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[6] See (Lee, Oezer, 2007) and (Sellitto et al., 2007) for a review of RFID-related value drivers

4. Automatic product security. Another value driver that is part of many applications such as proof-of-origin, anti-counterfeiting, product pedigree, and access control is product-related security. The thing to be secured can bear a minicomputer that is equipped with some security technology such as cryptography. The space or user confronted with such a smart thing can check the validity of it by walking through the implemented method, for example, a challenge-response operation. These methods are well established and well understood. For instance, they are building blocks of every ATM card or car key. However, they require expensive and power-intensive computing resources. In addition, they often demand costly handling of digital keys. That is why this method is limited to applications where high values and risks are at stake.

For inexpensive mass-produced products, another method surfaces: smart things can provide some level of derived security based on the interplay between a smart thing and its digital proxy. Imagine that every smart thing has its own homepage (the digital proxy) that is constantly updated whenever a physical artifact has triggered some action as described above. This homepage, which looks very much like a curriculum vitae or a pedigree, can be used to derive with some level of confidence whether the thing under investigation is the rightful owner of the homepage or not. For instance, if two products point to the same homepage, one must be a fake (Staake et al., 2008).

In both cases, computers can check the validity of a product automatically, without human intervention. Whereas the first method works with costly high-end security features built into the hardware of the nerve endings of the IOT, the second method approaches the security problem by leveraging the network, i.e., it constantly collects and updates data from the IOT and then, upon request, uses software to calculate the likelihood of a product being counterfeit. The network-based method is fuzzier than the hardware-based one, but it is so inexpensive that it can be applied to every good, and that checks can be carried out on a constant basis. This, in the end, leads to a new level of security. If every truck, shelf, sales rep, and consumer checks every drug (because it is simple), the business of counterfeit producers breaks. With enough eyeballs, all fakes are shallow.[7]

5. Simple and direct user feedback. Although the IOT nerve endings are usually very small, usually even invisible, sometimes smart things feature simple (which translates in this context to small and energy-efficient) mechanisms to give feedback to the humans who interact with them at the point and time of action. Often they give feedback to reassure, for instance, an employee that the manual or automatic proximity trigger actually worked. They do so by producing an audio signal such as a beep (e.g., when a pallet was properly identified by a gate), or a visual signal such as a flashing LED (e.g., when a virtual Kanban-card was sent and received wirelessly). In more entertaining consumer-oriented applications, the feedback may even produce funny sounds (look for Friedemann Mattern's Knight's castle in (Lampe, Hinske, 2007)), haptic effects such as those we know from playing Wii, or even smell. In applications that deal with perishable goods, a simple automatic sensor trigger can show its finding on tiny traffic signal-like displays that tell a consumer whether the product is

[7] Eric Raymond once said, on the quality of open source software, that "with enough eyeballs, all bugs are shallow." His statement is often cited when the quality of user-generated content, e.g., in Wikipedia, is discussed.

still worth its not so dynamic price. Advanced car keys can sense *where* their car is and indicate the direction to the driver. In production environments, for instance at the production facilities of Infineon and ST Microelectronics, smart assets even feature a low-energy-consumption display that tells the operator, amongst other useful information, the next destination, a machine tool or a shelf, they are to be brought to. This feature, in combination with identification, localization, and connection to the production execution system, allows a new level of nearly error-free production of logic chips that is also flexible and cost efficient.

6. Extensive user feedback. This value driver extends the output from simple user feedback to rich services. To cope with the limitations of the last mile of the IOT, a user friendly computer, most often a mobile phone, has to serve as a gateway that links the smart thing with its homepage or any other resource in the Internet that is relevant to the user and the thing in context. Applications that leverage this value driver are manifold. One could easily imagine a service that augments product information on physical products, such as a bottle of wine, with additional information, for instance, from the producer, the dealer, the Wine Spectator, the Johnson wine guide, or consumer forums (van der Heijden, 2006), (Keegan et al., 2008). Other consumer product-related service ideas, some already implemented, include on-the-spot price comparisons (should I buy the product here in this retail store, when I can get it for a two-dollar discount three blocks down the road or a four-dollar discount at Amazon?), political shopping advice (which country's labor produced this product?), allergy and health warnings (will this product harm me if I have, say, an hazelnut allergy, or if I suffer from a particular type of diabetes?), or product rating (How did my friends like this wine? Would they be happy to drink it this evening?) (von Reischach et al., 2009).

The augmentation application is also being used to create new tourist services in cities and museums, where artwork and points of interest are tagged to link mobile phones that pass by with audio and video streams that explain the foreign world in the language and at the individual level of detail and expertise selected by the interested connoisseur. It also is helpful for linking products such as coffee machines and machine tools that are already in operation with their operation and repair manuals or individual maintenance records.

In all applications, the mobile phone is the primary means for providing the window to thing-specific content and services that run on the web. For this and other reasons (simplicity, mobility, computing power, sensor richness, security level, network infrastructure, adoption rate, etc.), many, including myself, believe that the mobile phone is bound to be the mass computer of the future. The recent investments of high tech companies that had historically been focusing on the personal computer market, e.g., Apple, Google, and Microsoft, in the mobile phones market may provide additional evidence for this trend.

Businesses profit from this value driver by establishing a new channel to maintain contact with consumers, offer new services, and gain consumer attention (Allmendinger, Lombreglia, 2005). Services such as product rating and price comparison are nothing but packaged advertisement. This explains why Google has to be bold regarding Android, its mobile phone computing platform. Consumers profit from the fact that they can access personalized (the mobile phone likely knows who they are) services in a very simple and fast way (no need to start up the computer, the browser, search for a producer's homepage, drill down to the information they are looking for) right at the place (on the spot, e.g., in a CVS store) and time (now!) they need to act.

7. Mind-changing feedback. This value driver is at odds with the drivers explained above and is not based on new technical features of the IOT. Its motivation stems from the concern that the combination of real world and virtual world computing might generate a new level of manipulating people. Most humans still spend most of their lives in a physical world. In light of the how many people spend their leisure time in front of TV sets, gaming consoles, or the Internet trying to kill a monster or find a second life, one could doubt that. However, I believe that the physical world is still by far the greatest location for joie de vivre. Physical experiences such as touching well-designed objects (and humans) or staying in bleak buildings does something to us emotionally. Now, as computing becomes physical, e.g., when computers and the Internet grow a physical nerve endings, some of that power is accessible in IOT applications and will hopefully be used for good.

Examples of such applications include a toothbrush that interacts with a comic figure on the bathroom mirror to motivate children and grownups to seriously take care of their teeth, or smart meter-based applications that show a consumer how much electric power and water he is consuming, how much peers consume, and what he could do about his resource consumption not only to increase the cash in his wallet, but also to satisfy his ecological conscience. Companies, from the utility and insurance industries can use this driver to design new products and services that align their business goals with consumers who want to improve their lives and act more responsibly.

In another insurance application, a consumer gets a discount on his car insurance when he equips his car with a crash recorder that acts like a flight recorder in an airplane. In case of an accident, the crash recorder can help the insurance company reconstruct the exact course of events. This fact generates two benefits on the insurance company's side: First, it helps insurance companies to attract risk-averse customers, who usually generate above-average margins. So far in their self-perception unjustifiably unrecognized race drivers certainly would not sign a contract like that. Secondly, it would help to maintain the risk-averse driving style because incorruptible, honest crash recorder data would not be able to spin their content in either direction[8].

All these applications leverage effects that are currently being studied by a discipline called behavioral economics, which operates on the premise that humans act in every way but rationally. However, as Dan Ariely shows, they act predictably irrationally (Ariely, 2008).

[8] For further information on usage-based insurance models see (Filipova, Welzel, 2005), (Coroama, 2006).

Value driver	Value root	Business value	Consumer value	Example applications
1. Simplified manual proximity trigger	Self-talking ID eases the triggering of a transaction and leads to increase in transaction speed, accuracy & convenience	Increased job satisfaction, enables consumer self-service & reduces labor costs; increases data accuracy	Increase in self-service, speed, and convenience	Self check out in libraries, stock-taking in libraries, Access control in buildings, sporting facilities and such, Pet tagging
2. Automatic proximity trigger	Self-talking ID automatically triggers a transaction when in a roaming area; Leads to additional speed, accuracy & convenience	Reduced fraud-related costs, process failure costs, and labor costs; New high-granularity data for process improvement	Increase in convenience	Asset tracking; Robot stock-taking in libraries Theft prevention in stock-taking; Car keys
3. Automatic sensors trigger	Smart thing monitors its local surroundings, applies sensor data to process rules and self-triggers actions if required; Enables event-based actions based on local data; increases process quality	Individual and prompt process control increases process efficiency and effectiveness; Additional level of data granularity for further process improvement	Leap in quality of products and services	Olive oil production, condition monitoring, networked smoke detectors, management of perishable goods, compliance monitoring, smart meters
4. Automatic product security	Built-in cryptography and interplay between physical things and their digital representations enables new level of security of things	Reduction of cost of process failure due to fraud; reduction of process security cost Increase in consumer trust	New trust-related services	Anti-counterfeiting, proof of origin, pedigree, access control
5. Simple direct user feedback	Smart things provide direct feedback to users to increase confidence and local process control	Processes become more accurate, more flexible, and faster	Increase in convenience and entertainment value	Production lot that shows next job, perishable good that tells its quality status, feedback gate, digital enhanced games, direction indicating car keys
6. Extensive user	Real-world object	New customer	Increases	Deep product

feedback	serves as a link to a broad range of services relevant to user and object; User handles services, typically via mobile phone	contact, new advertisement opportunity, additional service revenues	convenience because individualized information is at hand exactly at the point of decision	information, price comparison, political shopping, allergy test, product rating, audio tagging, city and museum guide, mobile operation and repair manual, maintenance record
7. Mind changing feedback	Technology that is targeted to influence the behavior of users, hopefully for the good	Enables new emotional product features and new services; enables active selection of attractive customer segments; helps to align business goals with green goals	Helps to improve life and act responsible in many different ways	Improve health, e.g., via smart toothbrush, avoid risks, e.g., via crash recorders or pay-as-you-drive models, save energy via smart meter apps, save water via water metering

Table 1: Summary of IOT value drivers

The economic energy of the IOT

The value drivers are a result of a fundamental economical principle of the IOT: The IOT, with its technologies to automate the bridging of the last mile between the Internet and the physical world, dissolves the transaction costs that are caused by real world-virtual world media breaks. A real world-virtual world media break occurs when a piece of information is transferred from one carrier medium, e.g., a bar code, to another, e.g., a database that serves a warehouse management system. When things become computers, these media breaks, along with their attached costs, fade away (Figure 1).

Dissolving real world-virtual world transaction costs - The power of avoiding media breaks

Making media breaks disappear might seem to be a small thing, but it is not. In fact, one could characterize the entire computerization of business and society that has happened in the last 60+ years as a consequence of the ongoing avoidance of media breaks. With every new generation of information systems, a set of media breaks vanished. For example, with the introduction of department-wide information systems, e.g., in accounting, all accounting-relevant data only needed to be entered into an accounting system once, resulting in one media break per digitalization. After that, the accounting system could use the data as often as required without another media break. Before the introduction of accounting systems, every calculation resulted in several media breaks because an accounting clerk had to transfer information from a piece of paper into his electronic calculator and then the outcome back to another, usually paper-based, medium.

With the introduction of company-wide enterprise resource planning systems (enabled, among other things, by the Ethernet), again millions of company-internal media breaks vanished. With cross-company information systems (enabled by the Internet) such as supply chain management systems, another large set of media breaks faded away. The same held true when content management systems enabled the integration of weakly structured information such as text, presentations, and videos, or when Internet-enabled information systems started to integrate not only business partners but also consumers.

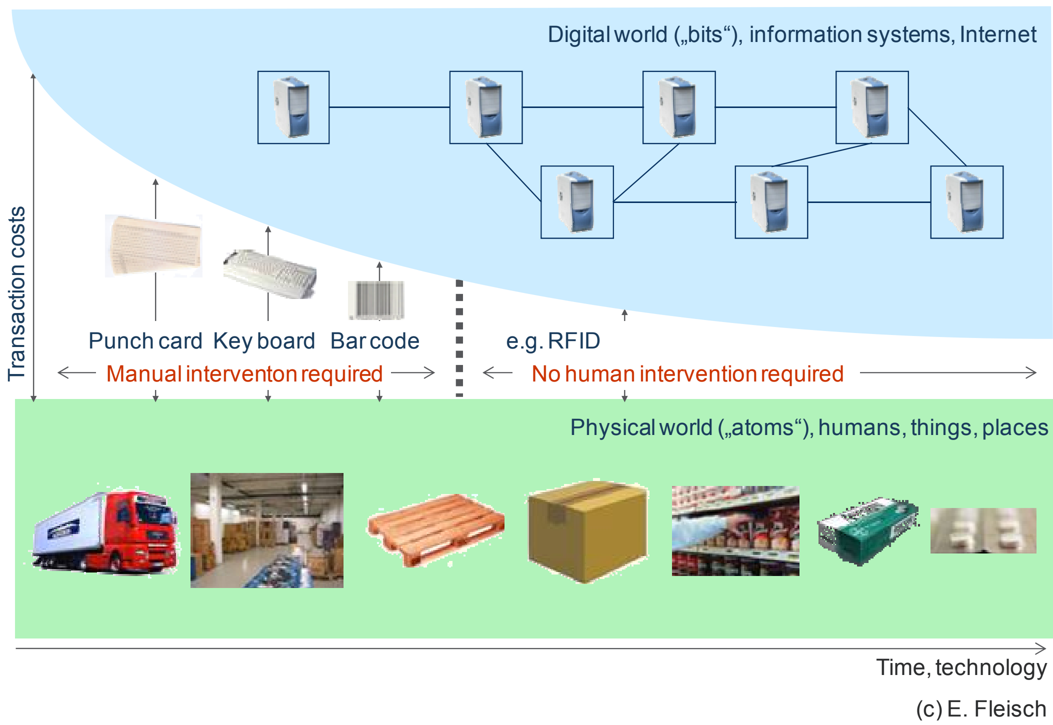

Figure 1: Merging Worlds

Of course, there is a reason that dissolving media breaks are a constant in the history of business computing: media breaks usually require humans to be resolved. While humans are the reason for living in general, they are not very good at dealing with media breaks, which results in error-prone, slow and costly procedures. Error-prone, because men are not built for replicating simple, boring and tiring tasks, such as keying in data, thousand times a day. So they are bound to make errors, which may sum up to an average master data accuracy of about 70% (!) (DeHoratius, Raman, 2008). Slow, because our abilities to do parallel processing are very limited. And costly, either because labor is in many countries for some reason taxed more than capital, or because we are biologically overqualified for replicating tasks simple machines could do for us.

Adding the rebound effect: high-resolution data becomes economical

The IOT technologies are not the first attempt to reduce the cost of the last mile. In fact, every data entry method, from punch card to keyboard to barcode, has pursued the goal of reducing real world-virtual world transaction costs. However, when things and places also sport minicomputers, the variable transaction costs[9] converge toward zero. And that produces a rebound effect[10]: as the price of a sensing event declines, it becomes more attractive to sense more often (Figure 2).

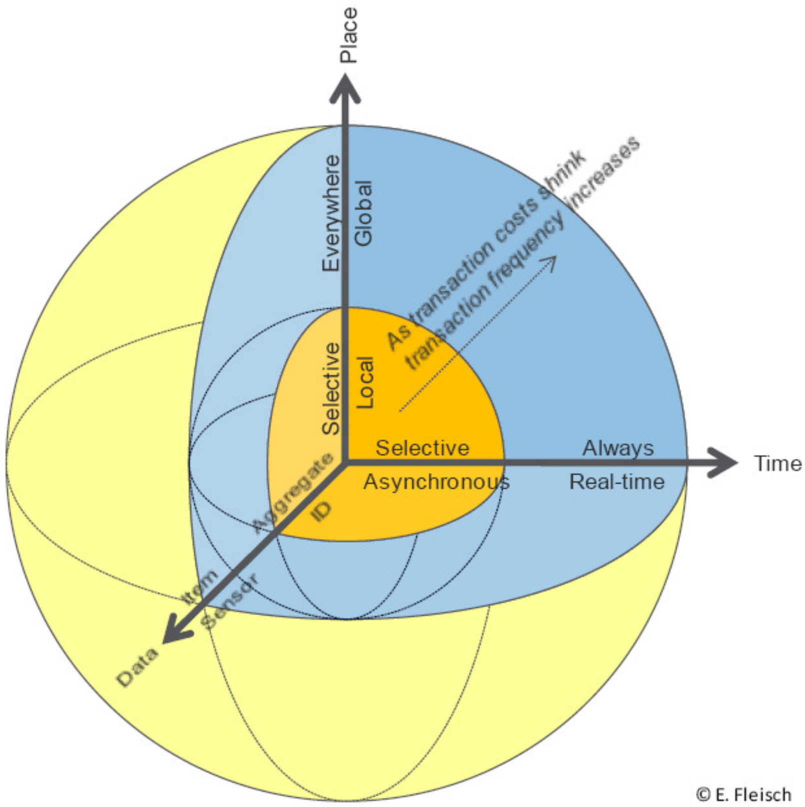

Figure 2: Towards real world high resolution data

In different applications, one can study the movement from low-resolution sensing to high-resolution sensing along three axes. First of all, when the transaction costs of real world sensing are high, companies tend to sense only when it is inevitable to do so. For instance, they check their inventory only once a year or when something unusual with high financial

[9] Variable transaction costs as opposed to fixed transaction costs refer to the marginal cost of one reading event, not including the one-time cost of hardware, software and such.

[10] We probably all know the rebound effect shrinking telephone charges cause: as it becomes cheaper for us to place a call, or surf on the Internet, we check our mail and make long distance calls more often. As a consequence, the monthly phone bill is likely to increase instead of decrease.

consequences happens. However, when sensing is free, they might want to sense all the time. Why? Because it allows processes to react in real-time, and that is often a precondition to achieving optimal process efficiency. Second, with low sensing costs, it becomes economical to check real world status not only within the business's own four walls at a few gates (e.g., asset tracking in a closed-loop bar code-based application), but throughout the entire supply chain via an infrastructure that works everywhere (e.g., asset tracking by leveraging GPS/GSM-technology). And finally, with sensing costs fading, companies start to increase the richness of the data they sense, from simple automatic reading of identification numbers of large things such as containers to any status of a single item or its surroundings that new sensing technology can measure.

“Trusted” data

Machine sensing not only leads to a new level of data resolution, it also produces “trusted,” or as Pentland calls it in a slightly different context, “honest” data. Trusted data is data that is difficult to influence because it is quietly and continuously collected by machines all the time; employees and users cannot deliberately choose the time and place of sensing events, as these happen silently as business processes are executed, e.g., when a work-in-progress asset on a shop floor is moved to the next machine tool, or when an express mail package is delivered. The price of this silent monitoring is, of course, loss of privacy[11]. However, this loss of informational self-determination (which is another definition of privacy) also has a somewhat positive aspect: it generates data that is more trustworthy. For instance, a retailer might trust sensor-collected delivery data of its logistic partner far more than questionnaire-based data that only collects statements from truck drivers whether they have been on time or not. In fact, the power of trusted data may even modify the business relationship between the retailer and its logistic partner towards sensor data-based quality control, and in consequence, remuneration.

The magic of measure and manage - generating the MRI for business administration?

You can manage only what you can measure. This statement is credited to Peter Drucker, one of the most influential management thinkers to date. It states the fact that measuring the effects of a system is a condition of being able to understand and improve it. It serves as a basic principle in the management of any type of man-made organization. For instance, it is impossible to effectively guide a legion of firemen to fight a forest fire without knowing where the teams and the fire sources are, or to steer an army of sales representatives without methods to measure their achievements.

[11] See (Langheinrich et al., 2005), (Thiesse, 2007) for privacy issues in the context of the IOT.

The truth of Drucker's statement is not limited to the management domain. It also holds true for disciplines such as physics and medicine, and it explains why many Nobel prizes have been awarded to people who invented new breakthrough measuring instruments: with new means of measurement, e.g., the X-ray apparatus of Wilhelm Conrad Röntgen, the magnetic resonance imaging (MRI)-technology of Paul Lauterbur and Peter Mansfield, and the scanning tunneling microscope of Heinrich Rohrer and Gerd Binnig, phenomena could be seen that were invisible before, new connections could be made, new diagnoses derived, new therapies tried out, etc.

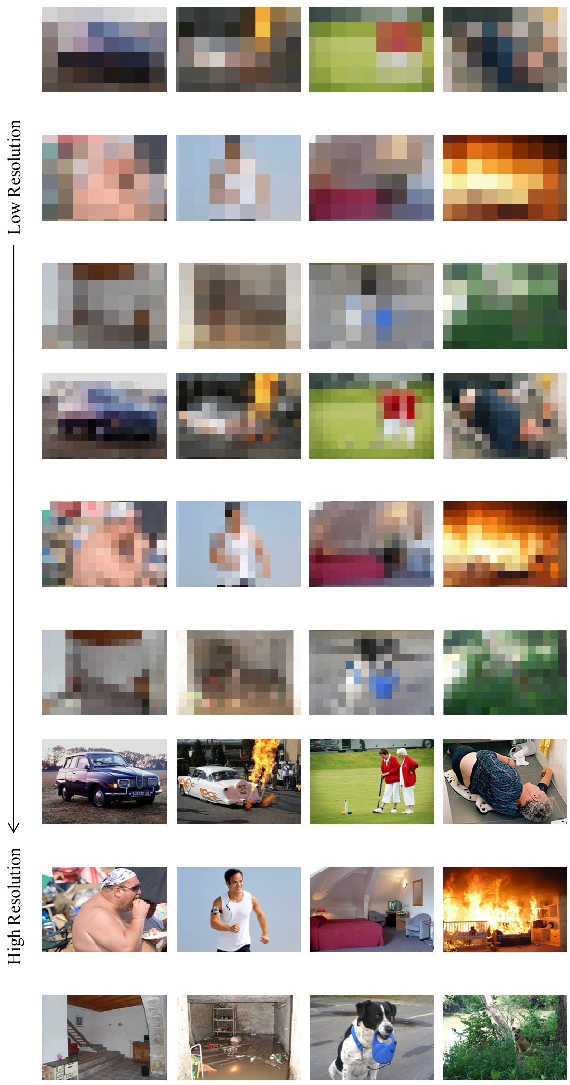

Figure 3: Low resolution versus high resolution management

These new measuring technologies had one thing in common: they advanced their disciplines. Now the question is whether the IOT, this giant global network of sensors, plays in the same league, whether it truly has the power to advance business administration, economy, especially the behavioral part of it, or any other disciplines that are linked to the management of man-made organizations.

Things cannot not communicate – leveraging the power of the physical world

Paul Watzlawick once famously stated that humans cannot not communicate. They communicate constantly on a functional (e.g., talking) and/or emotional (e.g., blank glance or knowing smile) level. Now, let us assume that goods also cannot not communicate. On the functional level, the bottle of water on my desk, for instance, communicates via its label its name, origin, exact ingredients, capacity, expiration date, EAN-code, etc. The design of the bottle, including the label, carries emotional values such as “I am from the mountains,” “I am healthy, fresh, and I taste great,” “Touch me, buy me, open me, drink me.” That is what product designers are paid for.

IOT-technology can increase both the functional and the emotional communication capabilities of things and places. For instance, on the functional level, it can generate new information on product quality (was the cool chain broken?), authenticity (is it a fake?), rating (do my friends like it?), and price (is it cheaper next door?). On the design level, a smart bottle could, for instance, show its newest commercial, or change its color with its temperature, when it is opened, or when it is touched. And most importantly, it could do so in a relatively unobtrusive way: the bottle still could sport a lean design because most of the additional functionality is only brought to life at the will of a user, man or machine, via a wand such as a mobile phone.

Smart things enable rich but hidden functionality that can be built to serve all parties in their value chain, including producer, consumer, transportation, customs, repair centers, and financial service providers. As things become smart, they turn into physical anchors for various services. At the same time, they maintain or even increase the emotional attractiveness only physical things can offer.

How companies make use of the IOT

This section summarizes some intriguing observations my colleagues and I made when shadowing companies as they started to introduce IOT-technologies. We subsume the findings under the term High Resolution Management (HRM), which stands for a management that consequently leverages the power of sensor data to increase visibility and exploit it for business excellence[12].

Go for complex problems – nuts do not require a sledgehammer

The first question every organization that is aware of a new tool has to ask itself is: where would it make sense, if at all, to utilize the power of the tool?[13] Which criteria must a problem satisfy to be eased by the new tool? In the case of HRM, the answer is: do not go for simple challenges, go for complex ones. You do not use MRI to diagnose a scratch.

A problem is simple when, thinking in terms of a socio-technical system, it only involves a few nodes with a few states, which behave deterministically. An example would be a mass-production facility that runs only a few stable machine tools, linked by a fully automated conveyor belt. In this case, simple rules and management tools are the most cost-efficient means to control the problem.

[12] see (Fleisch, Müller-Stewens, 2009) for an introduction to High Resolution Management.

[13] Yes, it is true: in many cases the problem not only triggers the search for a solution, but also the availability of the potential cure.

However, if the number of nodes (and thus edges) in a problem is high, and the nodes behave non-deterministically, the complexity of the entire system explodes.[14] It is easy to find complex problems in every industry. One example is the management of a textile retail chain where every day in every store, a dozen or so sales assistants serve hundreds of customers and move around thousands of articles of clothing. Without a strong organizing power, a retail chain would end in chaos within a few days, simply because it is bound to the same forces of entropy that seem to turn your children's rooms into a mess without anybody even entering them.

The first thing companies try to do is to avoid complexity, e.g., by reducing the number of product variants[15]. Whenever that is not possible, e.g., for competitive reasons when a company wants to offer a rich set of individualized products, services, or experiences, the managing organization has to increase its management capability until the power of the solution matches the power of the problem. One way to increase the management capability is to leverage sensor-based data, because they increase the number of potential states in the management system dramatically. Thus, they help the management system to absorb the complexity of the managed system[16] and, as a consequence, lead to more efficient and effective results.

This explains why the most discussed applications of the IOT deal with complex problems, e.g., the management of large numbers of assets in a supply chain, and are hard to implement. It also explains why it seems not to be wise to use IOT-technologies to solve simple problems that have already been worked out with simpler means.

Search for blind spots

Companies using IOT-technologies often experience an effect that physicians might have learned when they used MRI for the first time: they identify problems they were not looking for but that just became visible because of the newly available high-resolution data. For instance, when a car manufacturer tagged his work-in-progress automobiles to better control the just-in-time deliveries during the assembly process, he was extremely surprised to see that problem-cars, cars that generated more challenges than usual during assembly, were regularly put on a holding track. The assembly teams did so to push off the problem-car to the next shift so they could manage their performance metrics, e.g., how many cars they assemble in a shift. This approach was not only unfair to the subsequent assembly teams, who, by the way, did the same. It also generated a costly and ever-growing mismatch between the order of the highly individual cars on the assembly line and the order of the just-in-time delivered parts such as doors or windows to be mounted. A logistics company was

[14] The number of potential system states is a measurement for the complexity of a system in systems theory.

[15] Check the number of product variants Toyota and, say, Daimler or BMW offer. And then compare the profitability of both companies.

[16] The thinking of this paragraph is based on Ashby's law that states the "only variety can absorb variety".

flabbergasted when they learned the trusted numbers and reasons for their far higher than expected rate of delayed deliveries: one of their truck drivers did not like to drive west into the sunset, so he regularly took a lengthy and costly detour north and only turned west (and back south) when it was dark. A consumer goods company was surprised to learn that only 20% of the promotion displays they shipped to one of their retailer's stores were treated as negotiated and planned.

Diagnose and improve

This blind spot phenomenon is also responsible for some of the difficulties when compiling a business case: it is simply impossible to calculate the return of an investment when the problems that are to be solved are partly unknown. That is why some companies utilize IOT-technology in a first step simply as a diagnostic tool, i.e., to generate a trusted picture of the reality of their practiced routines. They then use the resulting extensive sets of sensor data to improve their processes. For instance, one retail company measured the impact of different types of merchandise presentation on sales and, for example, found out that some trousers sold better when they were presented hanging on racks than when they were lying on shelves (Thiesse et al., 2009). After learning a lesson like that, the retailer only needs to change his routine. He does not need to keep the IOT-system running to gain the benefit.

Automate low level management

In many cases, companies use IOT-technology as a tool for the next step in industrialization: they automate simple manual tasks such as signing in cargo, updating stock keeping records, initiating replenishment processes, detecting failures, and sending notifications. Thus they eliminate very low-level coordination work that was previously executed by humans.

At the core of the matter, IOT-technology drastically reduces the cycle time of an operational management cycle with the three steps "do" (perform a task), "check" (compare the results of the task with the expected values) and "act" (introduce a correction if needed) by automating the "check"-step (e.g., measuring a tire pressure) and often also the "act"-step (e.g., sending a notification). This allows a continuous comparison of actual with expected values and enables, as a consequence, the early detection of deviations, which is key in keeping the impact of an error as small as possible (as the impact of an error often grows exponentially over the time it remains undetected).

Constant sensor-based checks eventually enable information systems to automatically detect relevant real-world events and build the basis for an operational management by exception, in which the installed information systems and routines deal on their own in all foreseen situations. They only call human managers for help when they detect an unknown state of affairs.

Measure, manage, and innovate

Of course, companies use IOT-technology for more than just diagnosis and low-level automation. When we define using IOT-technology as a diagnostic tool as business innovation level 0, then purely automating but not changing business processes would be level 1.

The next level, level 2, includes the IOT-enabled modification of business routines, e.g., changing from a clerk-operated check-out process to an RFID-enabled self-check-out in a library. In level 3 business innovations, companies integrate IOT value drivers into their product or service offerings. For instance, a toothbrush company turns some of its products into smart products by equipping the shafts and brushes of its electric produces with tiny computers. These computers align the shaft's movements with the shape of the brush, to measure how often and how persistently each family member (each of whom is using the same expensive shaft but his own plug-in brush) cleans his teeth, to encourage both children and grownups to keep on brushing by interacting with a brushing Mickey Mouse in the smart bathroom mirror, and to prevent customers from using cheaper brushes.

On level 4, in terms of change, the highest level of business innovation, companies use IOT to transform their business model. Once a company has absolute visibility (think of it as a real-time video stream, in contrast to weekly black and white photos) of its most important objects, such as beer kegs in the case of a logistics provider for breweries, cars in case of an insurance company, or drilling machines in case of a machine tool company, it can, for instance, switch from selling its products to renting them to its customers on a pay-per-use basis with a huge impact for both vendor, and customer.

Summary

In this paper, I tried to answer the question "What is the Internet of Things?" I did so by digesting a careful study of hundreds of applications that automatically or semi-automatically integrate real-world objects and places with the Internet. In the first step, I looked at the differences between Internet applications and applications that probably belong in the category of the IOT, mainly to sharpen my own understanding of what the unique features of an IOT would be and where IOT-specific challenges could be found. I identified six characteristics that suggest that integrating the real world with the Internet requires a new set of infrastructure building blocks.

In the next part, I tried to group the IOT-applications to derive some common design-schemes. After several unsuccessful attempts, I started to look at the value drivers of each application, i.e., for each application I searched for the IOT-related root-cause of a benefit for businesses and users. I identified seven value drivers. Each investigated application used one or more of these value drivers.

All value drivers were related to the reduction of the real world-virtual world transaction cost. Taking that as a starting point, I looked for the main economic energy of the IOT. The result of this endeavor suggests that the IOT will eventually provide management systems with low-cost, high-resolution data about the real world. The IOT therefore has the potential to become an MRI-technology for businesses and society, with all its attached advantages and drawbacks: it might become a tool that advances the entire discipline of how to manage organizations and complex systems.

In the last section, I looked at some patterns in how companies make use of IOT and found some intriguing observations that will hopefully help readers to shorten the learning curve of their organization.

Limitations

Although I studied many IOT-applications, I almost certainly left out entire sets of applications and technologies that could potentially influence the derived results, i.e., the value drivers and the building blocks. Future work with access to additional scenarios will test the robustness of the proposed frameworks.

In this paper, I focused very heavily on the questions of how and where the IOT could add value to users and organizations. I deliberately did not analyze where the real-world MRI would add risks, although the potential negative aspects are obvious. Since Pandora opened the box, we all know that every technology hat two sides. Given the proposed momentousness of the IOT, an in-depth investigation of the consequences that must end in concrete applicable concepts[17] seems to be inevitable.

Outlook

If the comparison with MRI holds true, the IOT will feed legions of academic and industrial researchers and developers with challenging and fascinating questions for many years. Example questions across all layers include: How can organizations efficiently derive insights from massive sensor data to improve their offerings and operations (the key phrase here is "real-world mining")? How can I protect myself from being scanned all day long? How can society leverage the power of this new insight to change the world for good, e.g., by developing mind-changing applications to help consumers to use scarce resources such as water and electrical power in a responsible way? What if robots join the IOT and things not only become massive sensors but also actuators? How can we build even more energy-efficient and autonomous minicomputers? The race is certainly on.

[17] Pentland, for instance, suggests in his "new deal on data" to treat data like money (Pentland, 2009).

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About the Author

Dr. Elgar Fleisch, professor of information and technology management, ETH Zurich and University of St. Gallen (HSG)

The research of Prof. Fleisch focuses on the economic impacts and infrastructures of ubiquitous computing. In the Auto-ID Lab, he and his team develop, in concert with a global network of universities, an infrastructure for the Internet of Things. In the Bits-to-Energy Lab, which he co-chairs with Prof. Mattern of ETH Zurich, he investigates and designs technologies and applications to save electrical power, and in the Insurance Lab, Elgar Fleisch, together with Prof. Ackermann of HSG, drives forward technology-based innovation in the insurance industry. All research projects are joint efforts of industry and academia; their results have been published in more than 200 scientific journals and books.

Elgar Fleisch is a co-founder of several university spin-offs, e.g., Intellion, Synesix, Coguan, Dacuda and Amphiro, and he serves as a member of multiple management boards and academic steering committees.

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