CHAPTER 12

Summary and Future Trends

In this chapter, we present a summary of the subject matter covered in previous chapters. We revisit the key influences that currently drive the development of sensor-based applications in the health, wellness and health-related environmental monitoring. We also look toward the future of sensing by examining some emerging trends, including those that suggest how sensors will become integral to many aspects of our daily lives. We discuss how the evolution of technology brought pervasive connectivity and computing, and how it will impact future sensor applications. We also examine how crowdsourcing empowers citizens, adding an innovative element to future sensor applications. Finally, we explore the sensing nexus that stems from the way sensors interconnect with information and communications technologies. New and innovative sensing solutions will enable us to develop fresh insights at a personalized level into how our behaviors, lifestyle choices, and other factors influence our health and wellbeing.

So Far

In this book we looked at many of the key drivers that are influencing sensor-based applications for monitoring health, wellness, and the environment. Global challenges such as aging, water constraints, and environmental pollution require innovative solutions. Sensors already play a key role in enabling innovation as we endeavor to make the world around us smarter—to improve our quality of lives, to better utilize our natural resources, and to reduce our impact on the planet. The role of sensors in enabling innovative solutions will continue to grow in the coming decades. The falling cost of sensor technologies is playing a key role in the rapid growth of their utilization. For example, the cost of MEMs accelerometers has fallen by 80-90 percent over the last five years (Manyika et al., 2013). Advances in sensor technologies will also be closely interleaved with progress in infrastructural technologies that support the aggregation, processing, transport, storage, and visualization of sensor data, as outlined in Chapters 4 and 5. The evolution of machine-to-machine (M2M) technologies and the Internet of Things (IOT) are examples of application domains where infrastructural technologies are utilizing sensors to advance the current state of the art. New revenue streams will emerge by fitting sensors to existing products and to new product ranges. The data can then be used to support improved client services and enhanced product development (Economist, 2013).

We have described a variety of sensing approaches that are commonly utilized. New approaches to sensing over the past 30 years, such as the development of biosensors and microelectromechanical systems (MEMS) technology, have significantly increased the breadth of available applications. We have witnessed a significant reduction in device costs and an increased prevalence of sensor-based solutions. These developments have coincided with the integration of information and communications technology (ICT) capabilities into sensors. The addition of computation, memory, and communications features to sensors ushered in the era of the smart sensor. And support for wireless communications set the stage for the development of wireless sensor networks with their promise of ubiquitous ambient sensing. More recently, the utilization of smartphones and tablets as sensor aggregators significantly influenced their adoption by the general public. Since the launch of the iPhone in 2007, growth in the sales of smartphones and tablets has increased sixfold (Manyika et al., 2013). IDC estimated that sales of smartphones will reach 1.7 billion units by 2017 (Llamas et al., 2013). Some 56 percent of people in the US already use smartphones for Internet access, while 31 percent use smartphones to collect and access health and medical information. This represents a 50-percent increase since 2008 (Jones, 2012). Similarly, growth in the adoption of tablets has seen current ownership rates among adults in the US reach 34 percent (Zickuhr, 2013) with global sales of tablets projected to reach 400 million units by 2017 (Mainelli, 2013). Smartphones and tablets provide an intuitive platform for users to digest and interact with sensor data and to collect data as the user requires. A technology that was relatively abstract or considered by many to be the preserve of specialized users can now deliver real meaning and have context for ordinary individuals.

Movements such as the quantified self have embraced ICT-based sensing capabilities—to track, to share, and to build knowledge about health and well-being. This form of sensing also underpins new thinking in medicine. This model moves away from reactive treatment toward proactive management of health. Sensors are used to identify the early warning signs of health issues so intervention can occur before a significant problem arises. Sensors also support the goals of personalized medicine, where treatments are tailored to our own unique biochemistry and DNA. This desire for personal understanding has now permeated our social and recreational activities. We have seen how many sensing technologies commonly used in healthcare are being utilized in sports and wellness applications to monitor performance. Interest is also growing in how the environment influences our health and well-being, leading to commercial products and platforms that let concerned citizens and technical enthusiasts monitor the air, water, ambient noise, and more.

Socializing data is a constant theme across our application domains, driven by our increasingly connected lifestyles. Mobile devices with ubiquitous connectivity, coupled with cloud-based, scalable computational and storage capabilities, enable sharing of data in real-time at the point of origin. The collective power of online communities is being applied to these data sources in order to make sense of them, to generate context, and to trigger actions as required. People will increasingly become mobile sensors, driving growth in crowd-sourced data sets. Initial applications have been focused on participatory sensing, where individuals actively participate in the sensing process. In the future, opportunistic sensing may become common, where individuals may not be aware of active sensing applications running on personal devices like smartphones. Changes in state, such as location, activity, and so forth, are automatically detected, which triggers the collection of sensor data based on the new context. The device owner is not required to play an active role in the sensing process beyond the initial setup (Lane et al., 2008). Of course, privacy must be carefully managed to protect participants. Urban sensing, particularly environmental applications, may utilize these approaches as the potential scale and density of sensing that can be delivered would be impossible to achieve otherwise. Both approaches leverage people-centric sensing to avoid the deployment of an expensive static infrastructure to create this new sensing paradigm (Kapadia et al., 2009). Similarly, as sensors are built into more and more devices, there is potentially an infinite number of "things" that can be sensed with a corresponding growth in data. The age of "big sensor data" has arrived, with huge opportunities for exciting innovations, but also with significant challenges. As frequency, volume, and diversity of sensor data increases, so does the importance of data visualization. Data visualization allows people to makes sense of the information by enabling knowledge discovery. Visualization also adds vibrancy to the data—a key element in stimulating and maintaining user engagement. Visualization will be a critical element in making the data actionable. Big data analytics will enable people to connect with their own data in meaningful ways, and will allow them to see how they can change their behaviors and lifestyles. As individuals, we ultimately want the sensor data to foster concrete, actionable suggestions.

Throughout the book we have been careful to ground the expectations of sensors in reality. Sensors are not a silver bullet for every problem that needs to be fixed. They can, however, enable innovative solutions if their operation characteristics are matched appropriately to the required use case. Some sensor technologies—particularly wireless sensors networks—have been overhyped to a certain extent. Networks comprising thousands or tens of thousands of nodes have yet to be realized. There are many technical and logistical barriers to achieving this goal. If we set aside the hype promoting pervasive wireless sensor networks as the solution to all of our problems, we find that they are being successfully utilized in small-scale, focused deployments, such as wellness monitoring of older adults. The reality may not live up to the hype for some time. For the foreseeable future, the value of these networks will be realized in more micro-level deployments with very targeted and specific use cases.

The potential to quantify our health and well-being on a continuous basis has significant implications at personal and societal levels. We have to be careful not to generate nations of "worried well" individuals who are paranoid about every decimal-place variation in their measurements. It is counterproductive for individuals to engage in self-stigmatization just because a sensor reading indicates that a particular health metric is not in the desired region. When used correctly and in the appropriate context, sensors can have an enormously positive impact on our lives that will grow into the future. So, what does the future of sensors hold for us?

Into the Future

To glimpse the future, sometimes it is useful to recall what has happened in the past. For example, the measurement of temperature can be traced back to ancient times. The works of Philo of Byzantium and Hero of Alexandria demonstrated an early thermoscope based on a closed tube that was partially filled with air. One end of the tube was placed into a vessel containing water. Expansion and contraction of the air due to temperature changes altered the position of the water and air interface along the tube. A number of European scientists in the 16th and 17th centuries, including Galileo, are credited with further developing the thermoscope. Sanctorio Sanctorius and/or Gianfrancesco Sagredo are said to have put a scale to the thermoscope, producing the first rudimentary air thermometer (Chew, 2008). The German physicist Daniel Gabriel Fahrenheit invented an alcohol thermometer in 1709, followed by the mercury thermometer in 1714. In 1724, he introduced the standardized Fahrenheit scale. In 1742, the Celsius scale was invented by the Swedish astronomer Anders Celsius. This scale is divided into 100 degrees between the freezing point (0°C) and boiling point (100°C) of water at sea-level air pressure. The Kelvin scale was invented by Lord Kelvin in 1848 and incorporates extremes of hot and cold. The Kelvin scales starts with 0K at absolute zero or –273°C degrees Celsius. In 1866, Sir Thomas Clifford Allbutt invented a clinical thermometer that could take a temperature reading in 5 minutes (Prater, 2008). This allowed clinicians to correlate the relationship between body temperature and a patient's state of health. From a rather slow beginning, then, the past few decades have seen a vast explosion in the variety of temperature sensors based on a diverse range of sensing modalities. Modern temperature sensors are now based on principles such as thermistors, thermocouples, non-contact sensors, and fiber optics with accuracies to 0.001 degrees Celsius, with highly integrated ICT capabilities. Significant progress has indeed been made from the early thermoscope. The same is true for many of the common sensing principles utilized in sensors today, which are based on decades or centuries of careful work to establish and validate their scientific operation. These painstaking efforts have laid a strong scientific foundation that is now being exploited, together with other technology developments, to deliver significant benefits across a wide range of application domains. Sensor technologies have now matured to a point where we are at the cusp of an explosion in the diversity of applications and their adoption.

There is significant momentum behind sensors and their application in healthcare, wellness, and environmental monitoring, as technology and the innovative solutions they can enable are growing steadily. Couple this momentum with advances in mobile and cloud computing and pervasive communications, and a clear inflection point is at hand. This inflection point represents a change in direction based on adoption of sensing and ICT that will allow us to start moving from the current reactive healthcare model to a wellness-preservation model. The next section examines some of the key areas that will influence the future of sensors in application domains of interest.

Pervasiveness

We are entering an era where sensors are becoming an integral feature in daily life. New types of sensors are emerging that can be distributed into the public environment, worn on the body, or integrated into the next generation of intelligent devices. Applications built using advanced sensing capabilities focus on improving the health and well-being of billions of people around the globe, and they are already distributed into ambient environments to passively monitor actions, behaviors, environmental conditions, and even vital signs unobtrusively. While technical challenges remain, the general trajectory of adoption and proliferation has been set. Environments will become smarter by initially announcing when they need adjustment to improve, for example, air quality, lighting levels, ambient noise levels, and so forth. In the longer term, as smart home technologies with integrated sensing become more prevalent, living environments will automatically adjust to maximize the health and well-being of the occupants. Research over the last decade, particularly with living laboratory experiments, has already demonstrated how this kind of sensing can be used in domestic environments. In the future, these environments will become more sophisticated in their ability to model normal patterns of behavior and to identify changes in these patterns that could indicate a potential health concern.

Sensors will be designed into objects people already use or carry on a daily basis. The reality of the sensor as an "everyday technology" has already emerged, with people routinely wearing activity monitors, fitness monitors, and so forth as outlined in Chapter 10. Sensors will reside in new devices that will become everyday objects in the near future, such as multisensing, health-monitoring smartphones or environmental-sensing smart clothing. These devices will increasingly feature desirable design aesthetics (Sarasohn-Kahn, 2013). This trend is already reflected in home environmental sensing products, such as the Netamo wireless weather station, which are designed to be seen and to become desirable lifestyle choices. Sensors will also be integrated into more and more everyday devices. In many cases, they will be invisible to users apart from the utility they deliver. A modern car, for example, may feature over 100 different sensor types. The car's owner doesn't necessarily know they are there, but the sensors enhance the driving experience and enable safer driving, with better fuel efficiency and less impact on the environment. Imagine a future where this is the case for health and wellness, with data collected actively and passively by sensors throughout the day. We will be able to access this data as we want or to be proactively notified of issues that need to be addressed at the earliest possible juncture, through a variety of personal devices. For example, visualize a world where you have a weekly health review on a windscreen heads-up display as you drive to work in a cloud-connected car.

Proliferation and adoption of sensors will also be accelerated by the growing commercial availability of sensor solutions aimed at the consumer market. We are already witnessing how activity monitors and fitness devices have entered into public consciousness. All projections point toward a market that will witness significant growth in the coming decade. Already, established multinational brands have entered the fitness-sensing market as they recognize the growth opportunities. Expect to see more established technology players enter the market in the coming years with their own product offerings or in partnership with niche companies. In the short term, we will likely see a wave of new product offerings, but just as in most markets, this initial influx will see various winners and losers emerge as the market matures and consumer buying decisions adjudicate which products are the most compelling. As the concept of technology development through crowdsourced funding becomes more mainstream, new sensor solutions will emerge to address specific problems identified and funded by communities. These communities will also act as trusted advocates for the solutions that will positively influence adoption rates. The AirQuality Egg sensor described in Chapter 11 is one such community effort by designers, technologists, developers, architects, students, and artists. This community, devoid of vested interests, has the single goal of developing a sensor technology that allows the general public to participate and contribute to the conversation about air quality. Smartphones and tablets will continue to be enablers for personal sensor applications. The number of built-in sensors in these devices will grow and enable new usage models. The integration of dedicated sensor hubs in mobile platforms will also act as a key enabler by offering better performance, predictability, and extensibility.

The next stage of computing innovation is starting to take advantage of the various sensors packed into current and future handsets. Sensor technologies such as accelerometers, magnetometers, and ambient light sensors, together with supporting technologies such as GPS, wireless communications, and bandwidth awareness, are already common in modern mobile devices. The future will see even more types of sensors being integrated into smartphones, such as those for electrocardiography (ECG) monitoring. Opportunistic sensing with these devices will become more prevalent to reduce the requirement for conscious human action in the sensing process. The manner in which people interact with these devices will also provide rich data that can be used to gain insights into such areas as cognitive well-being and cognitive psychology (Lee et al., 2012) (Miller, 2012) Researchers are also looking at ways to use the data from smartphone sensors to provide context when modeling human behavior using classification techniques (Pei et al., 2013). While these types of applications are still in the research domain, their potential to scale, coupled with minimal infrastructural requirements, may well see their exploitation for mainstream clinical wellness monitoring in the near future.

Technology

Sensor technologies will continue to advance, both in terms of improvements to existing approaches and the development of new sensing modalities. That rate of advancement is likely to accelerate, driven in part by growing commercial demand. New consumer markets are emerging, driven by individuals' desires to proactively understand and manage personal health and well-being. The crossover from health sensing into sports and wellness sensing is growing—and generating new demands for sensor technologies.

New sensors will reach lower detection limits, have higher selectivity and sensitivity, and will have enhanced stability. Biosensors in particular have the potential to identify the early biochemical markers of disease. They can also rapidly identify both chemical and biological contaminants. In this regard, they have the potential to play a key role in environmental applications where there is a need, for example, to rapidly identify bacterial contamination of drinking water. A key step in realizing this goal will be the further development of lab-on-chip technologies. These nanoscale systems provide automated laboratory capabilities, such as sample preparation, fluid handling, analysis, and sensing/detection within the confines of a single microchip. Continued advances in MEMS technology and the rapid pace of evolution in semiconductor manufacturing techniques will enable production of these devices in large quantities, cost-effectively, and with the required reliability and stability. MEMs advancements will also undoubtedly enable the development of a new generation of sensors based on electrochemical, semiconductor, optical, and kinematic sensing principles.

We are also likely to see advances in chemo-optical sensors in environmental applications, with improved reliability over existing methods. Water sensing and environmental sensing will feature greater autonomy for long-term independent operations in order to lower support costs. The sensor platforms will be smarter and form smart sensor networks. These smart sensor networks will have features such as automated and remote troubleshooting capabilities, with real-time telemetry, to ensure the fastest possible response times to issues as they arise. Data from various sources such as water quality monitors, geographic information systems, satellite imaging, and so forth will be used with data analytics to build predictive environmental models in order to facilitate real-time decision support. Sensing will play an increasing role in maintaining the stability, reliability, and predictability of environmental resources.

A key area for future sensor technology is non-contact physiological sensing. Any form of longitudinal sensing that requires direct human body contact is challenging. There are obvious issues with this kind of sensing, such as usability, biocompatibility, and behavior modification. Non-contact sensing offers a means to capture the necessary signal—for example, EKG/ECG—through integration with everyday devices such as laptops, smartphones, and tablets. Applications are now appearing that can use a smartphone's camera to measure heart rate. Another useful effort relates to driver drowsiness, a long-standing safety concern. First-generation systems are already emerging from companies such as Mercedes-Benz that use sensors to monitor driving style, and researchers are investigating next-generation non-contact sensing systems based on physiological signal monitoring, such as ECG, EEG, and respiration, to detect drowsiness. Smart clothing is another area where non-contact sensing will grow over the years, ranging from garments that monitor physiological processes to clothing that adapts its properties based on ambient environmental conditions. The development and success of non-contact sensing will be very much use case-specific and will target specific usability constraints.

As this book has shown, smartphones and tablets have already had a significant impact on sensing and related application utilization. The future is likely to see accelerated use of these platforms, and more sensing capabilities are likely to be built into these devices. They will also feature discrete sensor hubs that will overcome current limitations, such as non-deterministic sampling rates. Discrete consumer sensor applications will continue to be available, but they are likely to become specialized when integrating them into a smartphone or tablet is not possible because of limitations that include usability, sampling, and hygiene factors. Software interfaces—and in some cases physical interfaces, particularly with disposable sensors—will become more standardized. This integration will support greater interoperability between sensors and aggregation devices. Standardization of interfaces will ensure that users are no longer tied to a particular end-to-end solution from a manufacturer, but can select the sensor and software components that best fit their needs. The healthcare domain has already seen progress being made by the Continua Alliance, but much work remains. Data security on smartphones, particularly as they hold more personal health information, will become an increasing concern. This is particularly true of regulated healthcare applications. Solutions such as dual-profile smartphones are likely to emerge, with a healthcare profile featuring strong security features, such as local data encryption. Smartphone apps that make health claims will be under increased scrutiny by the FDA, following the publication of their mHealth regulations. A recent IMS report suggested that too many mobile health apps in the market appear to be of limited usefulness or have a questionable link to health and healthcare (Versel, 2013). Regulation will inevitably delay the release of future mHealth applications into the market. However, it will provide a level of quality and accountability lacking in mHealth applications until now.

From a systems perspective, the future will focus on tighter integration between the sensor and the ICT components in system on chip (SOC) designs. The systems will have improved computational power with lower energy usage and on-chip memory. More processing will take place locally, reducing the amount of network traffic. These systems also have a smaller physical footprint, which will enable smaller form factors. The Internet of Things will accelerate development of IP-addressable radio protocols, remote sensor manageability, and light-weight messaging protocols. Connecting sensors to cloud-based storage and services will become as intuitive as pairing a

Bluetooth headset to a smartphone. Such services will allow people to remotely manage how and when the services work. Low-power machine-to-machine devices and services will be a key enabler to manage the relationship between individual sensors and the cloud.

The speed and accuracy of sensor systems will evolve to deliver improved reliability, sensitivity, and selectivity. Calibration of sensors will become a more standardized feature that exists for the lifetime of a sensor, in a manner that is highly automated and, ideally, with little or no human interaction required. Many of the current consumer-oriented sensors have limited calibration (such as a single factory calibration) before shipping. As reliance on sensor data in daily life grows, poor-quality data as a result of inadequate calibration will not be acceptable. Ultimately, the goal is to have sensors that do not require calibration. Approaches such as coulometric sensing (see Chapter 2), which in principle does not require calibration, offers an interesting glimpse of what the future might hold for at least some applications.

Current manufacturing approaches to sensor production have limitations in terms of cost, integration, and scalability. Printable sensors are an area of growing research activity to address these limitations. Existing printable technologies coupled with new materials based on advances in nanotechnology have the potential to deliver large-scale sensor production at ultra-low costs. The flexibility of the technology also has the potential to allow the printing of sensors on everyday items such as clothing. For example, the EU project 3PLAST (an acronym for printable pyroelectrical and piezoelectrical large area sensor technology) is researching methods to produce pressure and temperature sensors that can be printed onto a plastic film. The film can then be affixed to objects such as electronic equipment. The approach is based on pyroelectrical and piezoelectrical polymers that can be screen-printed in large volumes. The sensor is also combined with an organic transistor to improve its signal quality (Printed Electronics World, 2010). Similarly researchers at the University of California have successfully demonstrated printing electrochemical sensors directly onto neoprene wetsuit material (Phys.org, 2011). The sensor features two LEDs: A green LED is illuminated when the water is safe, and a red LED is illuminated when phenols are detected in water. For safety-critical applications, researchers are investigating the potential use of heat flux sensors and motion sensors that can be printed directly onto the protective clothing worn by firefighter to detect when they are in danger (Navone et al., 2013, Wei et al., 2012). We are likely to see many more applications emerge over the coming years that initially focus on specialized use cases. However, given the potential opportunities for innovative product offerings, rapid adoption of these sensing technologies in the consumer market is likely to follow.

The application of screen printing to the fabrication of disposable biosensors is an area of active research. Sensors have been produced via screen-printing for the detection of a variety of analytes, including organophosphates (pesticides) (Crew et al., 2011), Ochratoxin A (a mycotoxin produced by *Aspergillus ochraceus* and a number of other molds) (Alonso-Lomillo et al., 2010), and uric acid (elevated levels associated with gout, diabetes, and kidney stones) in human blood serum (Piermarini et al., 2013). Bio-tattoos (or biostamps) are a form of printable sensor that, while at an early stage of development, is already generating significant interest. For example, MC10 has demonstrated a bio-tattoo that stretches with the skin and monitors temperature, hydration, and strain. These tattoos are protected using a spray-on bandage to make them more durable and waterproof. The sensors can lasts up to two weeks before natural skin exfoliation results in their removal. The next phase of development will focus on the integration of wireless power and communications to enable connectivity to a smartphone (Etherington, 2013). The scalability and cost-effectiveness of such an approach will enable the greater proliferation of disposable sensors, making them accessible for in-situ use to mass markets in the future.

Wireless sensor networks—and their potential for application innovation—have received significant attention and interest over the last 20 years. What is unclear is whether large-scale WSNs can live up to the hype that has surrounded them. Small-scale networks with low numbers of sensors have successfully moved beyond the research domain into the commercial reality. Although some technical challenges remain, commercial exploitation will continue to accelerate. However, for applications that require hundreds or thousands of sensor nodes, the path forward is unclear. The largest deployments achieved to date are in the low hundreds. No one has demonstrated truly large-scale deployments over large geographical areas in either urban or rural environments. Without such deployments, the “practical issues around scale are yet to be fully explored” (Corke et al., 2010). Therefore, questions around the true cost of deployments and whether they are economically viable remain unanswered. Other technical issues, such as reliable outdoor communications in variable environmental conditions, require further research (Zhu et al., 2012). Sensor nodes in WSNs, such as those used for environmental applications, are also likely to feature more sophisticated sensors and multiple sensors on the node. This will generate new challenges, such as multisensor data fusion, multiple calibration strategies, and so on. However, the ability to fuse sensor streams will enable situational awareness—a key element in providing a context for sensor measurements. This information is critical, particularly for remotely deployed sensors nodes, as it helps us to really understand what the data is telling us. The concept of the multi-purpose sensor platform may also emerge, where the sensors and their data from one deployment can be shared among a number of applications. This can decouple the sensing infrastructure from the application (Leontiadis et al., 2012). This approach is analogous in many ways to the development of cloud computing in the IT domain, where applications are decoupled from their computing, storage and networking requirements.

Personal Health

There will be a gradual transformation of healthcare into the digital domain through digital medical records and the widescale adoption of biomedical sensing devices beyond the confines of hospitals. This will help facilitate the realization of Leroy Hood's vision of predictive, preventive, personalized, and participatory (P4) medicine (P4 Medicine Institute, 2012). Members of the current quantified-self movement (individuals who are interested in using technologies such as sensors and mobile computing to collect data about aspects of their own daily life, including physical and mental performance levels, health, food intake, personal environment, and so on), are the first early adopters of this vision. How this form of monitoring translates to the general public is a topic of debate. While members of the quantified-self movement are highly motivated individuals with a real interest in viewing and trying to understand what the data is telling them, many will argue that the general public will be less motivated, if not apathetic. Clearly, engendering a desire among citizens to view their data is going to be important. Providing the public with the necessary motivations and incentives is full of potential minefields. People might argue that it has connotations of the "nanny state," which provokes a strong negative reaction in many. However, possible changes in how insurance companies price premiums, or monitoring of adherence to therapeutic regimes or general lifestyle risk assessments, may provide the necessary impetus to motivate individuals. For example, Professor Larry Smarr at the University of California, San Diego, has been a devotee of the quantified-self practice for many years. He has been tracking over 150 variables related to his health for the last ten years using sensors, self-test kits, and laboratory analysis. Using the data on a longitudinal basis, he was able to identify changes in his levels of complex reactive protein (a biomarker for detecting the presence of inflammation) in his blood that peaked at 27 times above normal levels. Subsequently he identified that lactoferrin (a multifunctional protein that, among other functions, is a sensitive and specific biomarker for inflammatory bowel disease (IDB)) in his stool samples peaked at 124 times above normal levels. Smarr then used the data, along with research in the scientific literature, to self-diagnose Crohn's disease. Smarr also makes extensive use of body-worn sensing as part of his continuous monitoring program. He uses a FitBit to track his activity levels, and at night he uses a Zeo sensor to monitor his sleep quality. He also uses smartphones apps such as Instant Heart Rate to measure his pulse rate via the phone's camera and another app to monitor his stress levels (Landau, 2012).

Although current self-monitoring activities are still in their infancy and are a little cumbersome, they provide insight into the future of self-sensing that over time will undoubtedly lead to a shift within healthcare. This transition is not without significant challenges that extend beyond sensing. Firing data at your doctor from a home-sensing regime that wasn't prescribed by him or her in the first place may receive a frosty reception or be completely ignored. It will take time, as physicians and other healthcare professionals wrestle with these new sources of data. Making sense of the data will be critical and challenging for individuals and their physicians and will require behavioral changes across the clinical ecosystem to fully exploit the value of the data.

Establishing the relationship between sensor measurements, coupled with their variation over time and their relationship to disease state, will be enormously challenging. However, tools such as high performance computing (HPC), cloud computing, big data analytics, and so on are providing key tools to make those breakthroughs possible. Medicine is slowly moving into the digital age. Eric Topol, an evangelist for the use of technology in healthcare, has said: "Medicine today is all about averages, medians, population, and mass screenings … unacceptable and antiquated!" Topol has been a long-standing proponent of a future in which doctors will prescribe sensors and apps running on smartphones to achieve an effective diagnosis, as opposed to prescribing a collection of pills and seeing how the patient responds (Robbins, 2012). Clearly, this vision for the future of healthcare will take time to materialize. Early pioneers such as Topol are forging new territories that will act over time as catalysts to advance sensors and associated technologies in healthcare. Speculating how long these changes will take is challenging. But it is fair to say that change will occur at a slower pace than many predict or would like it to happen at. Ultimately, the magnitude of the problems facing healthcare systems will force radical change, but not before teetering at the brink for a while.

Crowdsourcing

Crowdsourcing, or "participatory sensing" applications, are becoming increasingly common. There is the obvious attraction of using citizens as sensors due to their mobility and their ability to react dynamically to situations or their environment. The growth in crowdsourcing's popularity has been driven by access to low-cost sensors and the availability of Internet-enabled mobile devices such as smartphones. As Chapter 11 shows, environmental sensing among individuals is emerging as an application domain. It is likely that these types of applications will continue to grow in popularity, particularly as more commercial sensor platforms appear to meet demand and interest.

A number of questions will need to be addressed once the initial enthusiasm abates. The quality of the sensing is often problematic. Low-cost sensors are often used to deliver a product within a certain price range, to the detriment of data quality. Therefore, the sensitivity and selectivity of sensors for the targets of interest may not be sufficient. Moreover, the sensors may not have field-calibration features, resulting in drift and erroneous data. Collectively, these limitations can result in data-quality issues for any crowdsourced observations. These issues create a considerable challenge: how do we differentiate between readings from sensors that are accurate and inaccurate? Other issues that need to be addressed in the future include information overload, "noise," malicious misinformation, bias, and trust. These will be areas of significant research in the future as the crowdsourcing domain matures.

As various technology-driven paradigms continue to evolve, such as Web 2.0, cloud computing, mobile computing, and so on, they will enable crowdsourced sensing to play a greater role in creating collective intelligence models. Building these models will require generating shared insights into issues that affect health, such as air and water quality. Crowdsourced sensing will be able to quickly establish the geographic boundaries of issues and to follow these boundaries dynamically. The ability of crowdsourced sensing to empower individuals and to provide a form of data democratization will continue to make it attractive, despite the concerns about data quality and the ability to interpret the data correctly. Finding robust solutions to issues such as data integrity, quality, and reliability will be critical to its success and determine how extensively crowdsourced sensing is ultimately adopted.

In addition to participatory sensing, opportunistic sensing may have a key role to play, particularly in the environmental domain, in future sensor applications such as those that monitor ambient noise pollution, urban air quality, and so forth. Opportunistic sensing has the potential to provide data on a much larger scale in comparison with participatory sensing, which currently predominates. However, as we have discussed previously, there are serious concerns with respect to privacy and security that require adequate protections being in place before such applications can be rolled out on a large scale.

The Sensing Nexus

Many of the factors that influence health and well-being have been well established. As individuals, though, we haven't had the necessary tools to measure, track, visualize, and interpret this data. The sensing nexus that is now emerging, supported by developments in ICT technologies, is giving us the tools for the first time to better understand and take control of our health and well-being, and to understand the environment around us. We are on the cusp of a major paradigm shift where sensors, for the reasons discussed throughout this book, will become more pervasively distributed into our lives. They will allow us to detect health issues earlier, when intervention can be more effective. Even more important, they will enable insight into how behaviors, lifestyle choices, environments, and even emotional states influence health and well-being. The future will be about making informed, proactive choices that focus on us being well and maintaining that state for as long as possible. Sensing and ICT technologies are making this a more accessible goal that will be within the reach of most individuals. These technologies give us tools and capabilities to think about and take ownership of our own health destinies. As the renowned Irish writer Oscar Wilde once said, "A man who does not think for himself does not think at all."

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