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Educating the Internet-of-Things Generation

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ABSTRACT

As highlighted by the articles in this special issue, the concept of the Internet of Things is becoming increasingly important and understanding both the technical underpinning and wider societal impacts of the Internet of Things (IoT) will be crucial for digital citizens of the future. Building on extensive experience in delivering large-scale distance learning, The Open University has redesigned its introductory computer science curriculum to place the Internet of Things at the centre of students' experience, in a course called *My Digital Life*. In this article we present the design of this module, including a learning infrastructure that allows complete novices to experiment with, and learn about, Internet of Things technologies. We also share our experience of having almost 2000 students participate in the first presentation of the course, engaging in a range of activities that include collaborative and collective programming of real-world sensing applications.

KEYWORDS

Internet of Things; Ubiquitous computing; Computer science education; Third Industrial Revolution

1 INTRODUCTION

Over the last decades the world of computing has changed dramatically. The continuing relevance of Moore's laws together with the near-zero cost of processing, networking and communication is giving rise to the Internet of Things, a new global computing infrastructure of trillions of connected devices that permeate the world we live in. The emergence of the Internet of Things will have a transformative effect on our society and requires us to rethink how to educate the coming generation of engineers and computer scientists. This important issue arises at a time when higher education is facing increasing pressures to transform itself to respond to critical changes in our society:

- *Emerging new jobs require new skills:* it has become clear that new developments in computing, energy and transportation will play a key role in what Jeremy Rifkin calls the 'Third Industrial Revolution' [1], the reconfiguration of industry towards renewable energies, smart grid technologies, and energy positive buildings. This revolution will create demand for engineering and science jobs, which will be strongly connected to the Internet of Things.
- *More people require and demand education:* over the last decades millions of people around the world have been raised from poverty to middle class and now require and demand access to higher education. Yet increasingly higher education institutions cannot accommodate the growing number of potential students.
- *Consumers are becoming producers:* The recent shift from consumer cultures to participatory cultures [2, 3] has reconfigured people's expectations about technology and their own role as producer and maker. Technology design increasingly needs to focus on democratic control, openness, social production and mass collaboration as much as on functional aspects and aesthetics.

These trends create a need for an education provision that can empower a new generation of digital citizen who can understand both the technologies that underpin the Internet of Things, as well as the societal impacts of widespread adoption of these technologies. Moreover, higher education programmes need to make sure that the next generation of engineers understand how to design and build technological systems that reflect our altered expectations of openness and participation. For computer science the challenge is to develop new forms of scalable education that are able to accommodate the large numbers of students around the world, that are attractive to potential students with various interests and that deliver an innovative curriculum that reflects the radical changes in computing technology.

In response to these challenges the Open University in the UK has embarked on a program to revamp its undergraduate computer science education and in Oct 2011 has started offering a new introductory course designed around Internet of Things concepts. Since then close to 6000 students have signed up for this 9-month course and about 4000 students have completed it. The key objective of this new course, called *My Digital Life*, is to place the Internet of Things at the core of the 1st year computing curriculum and to prime students from the very beginning for the coming changes in society and technology. Rather than narrowly defining the Internet of Things as a technical subject, this course is designed to help students view the Internet of Things as a tool to understand and interrogate their own

world, and recognize their own role in realising the potential of the Internet of Things. This is achieved through an educational model that focuses on concrete experiences, creative experimentation, active participation and collaborative learning – all factors associated with improved engagement and learning outcomes [9].

This article outlines our approach in designing this course, discusses an Internet of Things teaching infrastructure and explores to what extent the course has achieved its aims.

2 COLLABORATIVE LEARNING FOR THE ‘INTERNET OF THINGS’ ON A LARGE SCALE

The Open University (OU) was the world's first successful distance teaching university and has been offering open education programmes and distance education for over 40 years. With more than 250,000 active students it is Britain's largest university. There is a now growing worldwide trend towards online education, yet delivering successful online courses is a tremendous challenge. Massively open online courses (MOOC), a relatively recent form of online education, have garnered extensive attention due to initiatives of high-profile institutions like Stanford and MIT, and start-ups such as Coursera, Udacity, and 2tor. Yet unlike these open and free course offerings, OU students receive extensive, personalised support from tutors and – upon successful completion – get credits counting towards a BSc in Computing.

The Internet of Things is a new topic for online education, and opinions about what the Internet of Things is, should be, or will be, differ greatly. The course team identified several concepts as fundamental for the Internet of Things and essential for this new course:

- the merging of the physical and digital realms;
- physical objects that become first class entities on the Internet;
- the huge increase in the number of internet-connected devices, objects, sensors and actuators;
- the huge increase in the amount and value of data;
- the emergence of novel embedded device platforms below the level of personal mobile devices;
- and novel applications in energy, transport, health, business and daily life.

Teaching Internet of Things concepts to first year students is a challenge, let alone teaching them online. Few students at home have access to embedded networked devices and very few solutions exist for teaching internet-scale programming of sensor applications. Most embedded device technologies require an understanding of hardware that cannot be expected of 1st year undergraduates – nor can we expect that large numbers of first-year students are willing to engage with hardware before moving on to other topics. Most importantly however, the significance of the Internet of Things lies not in its technology alone but in its implications for society – and in its impact on the computing discipline itself: we believe that the Internet of Things represents an ideal basis for a wide-ranging and rigorous introduction to computing, from algorithms to networks, from hardware architectures to big data. Using the Internet of Things as a foundation for teaching computer science also encourages a participative and collaborative pedagogic approach. The Internet of Things is an inherently democratic phenomenon, with many small parts, loosely coupled, each contributing as they can to a greater whole. By working with

this structure, we can encourage students to *learn with IOT technology*, rather than merely learning *about* the IOT. This is reflected in the topics and educational goals of the *My Digital Life* course¹:

Algorithms: students should acquire the ability to develop algorithms that operate on sensor data and create an output in the real world.

Programming skill: students should develop an understanding of the principles of programming, and demonstrate the ability to program networked systems embedded in the real world, including sensing and actuation.

Distribution and collaboration: students should develop an understanding of the importance of distributed and collaborative system architectures in computing, and demonstrate the ability to develop networked sensing applications.

Creative design: the course should enable students to become creative and apply the Do-it-Yourself philosophy to the Internet of Things, as suggested for example by [4,5,6]. This involves creating ideas for applications that manifest themselves in the physical world and transform these ideas into working prototypes

Collaborative design: students should develop the ability to work with other students to collaborate in the design of applications.

Ethical issues: students should develop an understanding of issues relating to privacy and security in the IoT, as well as the need for public involvement in the debate on the role of technology in society.

Computing in Society: students should understand how computing technology and the IoT underpin society and contribute to business and daily life, including historical context of the technological and intellectual developments that led to the Internet of Things.

Teaching an online course has significant challenges, for example related to student engagement and student evaluation. In order to ensure an exceptional student experience and avoid high dropout rates, our pedagogic approach is informed by experiential learning [7] and collaborative learning theories [8]. Experiential learning emphasises *concrete experience and active experimentation* while collaborative learning highlights a learning process where students capitalize on one another's skills and understandings, and actively support each other's learning. The course design has also been strongly influenced by the tradition of constructionism, which postulates that people are most likely to become engaged in an activity and learn things from it when they are active and creative participants [9]. Overall, the course is designed to support collective open engagement and experimentation by students².

¹ This list is a small selection of the topics touched upon in this course. This course is not solely focused on the Internet of Things, but considers the 'big picture', too. It gives students a conceptual framework for understanding and considering the profound technological, economic, political and ethical changes brought about by today's information technology.

² Given the diverse student population with varying expectations and experiences, and the fact that this is an introductory course, the overall course design is aimed at guided self-study where students and student teams can get personal support from dedicated teaching staff.

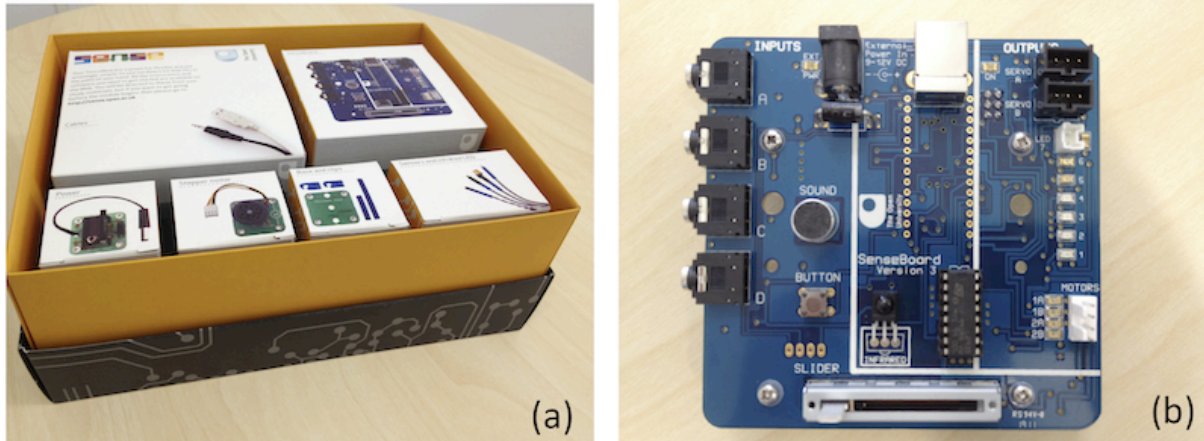


Figure 1: SenseBoard - (a) Students receive the SenseBoard in a custom-designed package that makes it easy to identify the different types of component; (b) The layout of the SenseBoard is organised with inputs and outputs in clearly labeled groups. Also, different types of sockets are used for analogue sensor inputs, LED output and stepper motor output, making it easier for novice students correctly configure the hardware components.

3 INTERNET OF THINGS TEACHING INFRASTRUCTURE

A key goal of My Digital Life is to use the Internet of Things as way to teach computing principles and key skills, such as programming, to students with no prior experience in computing. Achieving this goal for a large-scale online course required us to develop a completely new IoT teaching infrastructure, which consists of:

- The *SenseBoard*, an embedded networked sensor device that has been custom-designed for this course. The SenseBoard (Figure 1a) is based upon the Arduino microcontroller and has a number of input/output devices on board, including a slider, a pushbutton switch, a bank of 6 LEDs, and analogue inputs for additional sensors. It comes bundled in a box (Figure 1b) with sensors (a thermistor, a phototransistor and a motion detector), a stepper motor and a USB cable. The cost of the hardware is covered by the tuition (the Open University provides open education, but charges tuition). An early design of this board is described in [10].
- *Sense* (<http://sense.open.ac.uk>), a newly developed visual programming language and programming environment that allows students to ramp up their learning quickly and to develop working programs that interact with the SenseBoard from the beginning of their studies. Sense is an extension MIT's Scratch language [12] with special features for embedded device programming and has been described in [11]. As with Scratch, students develop Sense programs by assembling visual program blocks (e.g. if-else statements, logical operators and variables), whereby the programming environment (Figure 2) ensures that blocks are only assembled in syntactically correct ways (which are not necessarily semantically correct). Sense currently supports Windows, Mac and Linux and is available for public use at <http://tinyurl.com/OUSense>.

- A cloud infrastructure that connects the SenseBoards of all students together. This enables novice students to build Internet-wide collaborative sensing and actuation applications, a capability that did not exist in comparable toolkits (e.g., Phidgets [13]) at the time My Digital Life was being produced. The value of such connectivity is apparent from the examples of connected devices for IoT supported by the more recent .NET Gadgeteer platform described elsewhere in this special issue [20]. In order to support this key requirement we developed a cloud-based solution, hosted on University servers, that enables SenseBoards to exchange data with each other. Students can use the Sense programming language to pipe data into named data channels, which can be read back as an RSS feed by the same device or any other SenseBoard. This allows students to store data 'in the cloud' for later use, but also to build applications that collect and use sensor data from multiple devices. Students can create their own sensor feeds and share them selectively with other students. A limitation of our current implementation is that only asynchronous communication is supported.

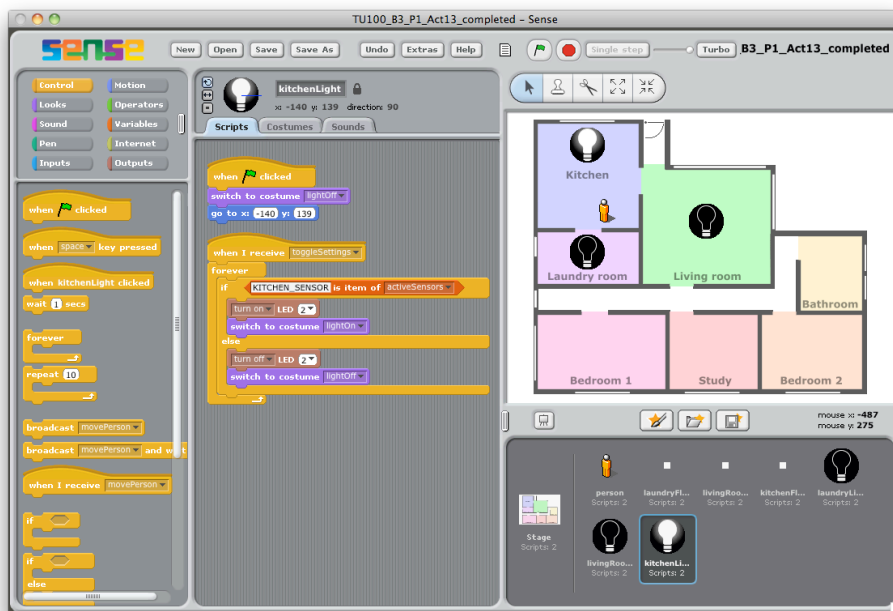


Figure 2: Sense Programming Environment. Students construct programs by dragging visual program elements (control structures, etc.) from the block palette (left-hand panel) and dropping them into the script editor (middle panel). The stage (right panel) is used for graphical input-output.

This IoT learning infrastructure directly supports the underlying pedagogical approach: The Senseboard supports active learning and experimentation with sensing, actuation and networking by students at home. The cloud infrastructure that links students' SenseBoards supports collaborative learning by enabling a group of students to share sensor data and to build applications with distributed sensing and actuation. Student collaboration and peer-to-peer learning is also supported through an extensive web-based infrastructure with discussion forums, social networks, and wikis.

4 EXPERIENCES AND LESSONS LEARNED

This new course was delivered for the first time from October 2011 to March 2012 with a cohort of 1967 students. In this section we discuss experiences and lessons learned during this first delivery of the course.

4.1 Methodology

In order to understand how well students receive the new course, and which issues the students are grappling with we qualitatively analysed the postings made by students in the online support forums. We filtered the postings and identified those that indicated issues related to the use of the SenseBoard and Sense programming environment. In addition we looked at student comments reported in an end-of-module survey that was sent to 688 students (34% of the cohort) and received 221 responses. Finally, we compared grade statistics of this new course with an older traditional introductory computer science module.

4.2 Student Experience

4.2.1 Student cohort profile

More than 70% of the students were adult learners (aged 25-49 years old) and the Male-Female ratio was ~3:1. As is common with many entry-level Open University courses, a sizeable proportion of students in this cohort (~40%) have no prior qualifications beyond a secondary school education. Additionally, it should be noted that 15% of the cohort indicated that they had some form of disability, requiring different accessibility technologies in order to engage with the learning materials.

4.2.2 Fast Ramp Up Time and Understanding of Programming Principles

A key goal of this course is to empower novices and to make IoT technologies accessible to students with no prior programming skills. In this respect the outcome has been reliably and overwhelmingly positive. Evidence from programming assignments, online students and tests with groups of prospective users during the design stage have shown that new users are able to produce a working program during their first session with the SenseBoard and Sense in under 20 minutes. Starting from the smallest possible program students are able to scale up rapidly to programs that transform sensors data into output, and make use of network capabilities of Sense. After a few sessions, novices with no exposure to programming before entering the course are able to understand and modify given programs and develop new ones on their own. More importantly, results from assignments and online discussions show that students develop a good understanding of key programming principles such as variable assignment, control structure, and program execution – even though the initial teaching does not particularly focus on these aspects. The positive experience of students is reflected in the end-of-module survey comments, which included statements like “I enjoyed the sense activities and the sense board ... it added an extra dimension to the course which was unique and interesting”. Many students identified experience of learning with Sense and the SenseBoard as the most value aspect of the module.

The Sense programming language with its graphical representation of control structures and blocks clearly helps students and especially novices quickly develop an understanding of the principles of

programming simple IoT applications. This is in contrast to similar toolkits like Phidgets and various Arduino-based platforms that have a longer ramp-up time and require, rather than develop, a conceptual understanding of programming.

4.2.3 Creativity and Tinkering

After initial success with simple programs many students rapidly carry on and develop their own projects. When students realize that the input from the sensors on their board can be aggregated with that from other students via the internet – wherever those students may be – they are struck by possibility: “Oh, so that means that I could...”. Although we provide introductory activities, many students are designing, creating and sharing their own projects. A not insignificant number of students jump ahead in the course material and start working on their own projects even before any formal Sense teaching has taken place. For example, during the first course offering in 2011 more than 200 projects had been announced on the student forums before Sense had been officially introduced.

The most common projects were recreations of early arcade video games, perhaps reflecting the age of our students and the rich multimedia potential of Sense. Students made use of the slider on the SenseBoard and multiple sensors to build various types of experimental video game controllers. Exposure to Sense lead students to request advice about all aspects of game programming, and led to discussions of complex mathematics and how to increase performance – activities that are clear indication of a successful self-directed learning process. Students also build applications that directly relate to their personal life at home, such as baby monitors.

Another type of student projects includes applications that turn sensor data into physical actions. For example students have developed a number of music-related projects, such as music equalizers with graphical user interface and LED output, or apps that visualize volume via light and movement. Perhaps owing to the English habit of talking about the weather there is a proliferation of online weather stations – some use public RSS feeds, some sense the local conditions (very crudely), and some share data across the Internet. Other examples include food related projects (for example sound-controlled tea makers) and even one application for detecting paranormal activity (making use of undisclosed methods of combining sensor data). The range of project ideas demonstrates that our IoT-focused approach of introducing students to computing helps students to develop a broad view of what computing is and can be. We believe that students’ ability to see computing as part of the physical world – as opposed to something that takes place inside a box – is a key differentiator of our course compared to traditional undergraduate computer science courses.

4.2.4 Sharing and Collaboration

Sharing and collaboration among students takes place on many levels. Students engage in frequent sharing of ideas and advice on the discussion forums, indicating that collaborative learning is routine among students and that many. There is also evidence for an emerging open-source ecosystem for Sense applications. Students often make the code of their own projects available on the student forums, for other students to download. While this remix culture is a potential problem from a traditional academic point of view – sharing code could be interpreted as contributing to plagiarism and cheating – in our view it is a powerful way to foster learning and engagement. With this in mind, activities involving Sense and the SenseBoard were designed to be exploratory investigations of both the Internet

of Things and programming concepts, allowing students to share results and discuss them. Graded assignments on the other hand required students to demonstrate their understanding of underlying concepts, e.g., by engaging in peer review of project work, rather than simply delivering a completed program. Some students also video their projects and share them on youtube. One example is a project that uses the SenseBoard to develop a remote controlled laser display for visualizing the rhythm and volume of music, as well as sensor data received over the network (<http://www.youtube.com/watch?v=g-m3O5vhMss>).

There are also examples of distributed sensing and actuation applications, albeit fewer than we had hoped for. One such example is social presence and status indicator that uses LED arrays on students SenseBoards to indicate the whether members of a student group are at home or not (each LED indicating the presence of one specific student). Here, shared data feeds are used to communicate the status of students; the status is either set manually or determined from sensor information.

4.2.5 Attainment

Over 85% of students attempted programming - many for the first time. This is a high number given the student population and fact that this is an open course that requires minimal prior educational attainments. Around 75% of students developed sufficient expertise with Sense and the SenseBoard to pass those parts of the final project. (It is possible, though harder, to pass the module without engaging in the programming section of the final project.)

Overall student success rate and dropout rate for this course is on the same level as with the previous traditional introductory course that it replaced. This is a slight disappointment as it was hoped that this new course would ultimately deliver better student results. However, it is not entirely unexpected since first presentations are always affected by discovery of errors in learning materials and issues that arise due to tutors' lack of familiarity with the teaching process. There are indications that outcomes can be improved if we fine tune how we deliver the course, for example by changing the overall pacing and by providing options for stronger students to receive credits for their independent work.

4.3 Internet of Things Teaching Infrastructure

Overall the technical infrastructure has held up remarkably well and allowed for a positive student experience. Both the custom-designed hardware board and the cloud computing platform did not cause significant problems.

In order to gain an understanding of some of the common issues experienced by students, we conducted a preliminary analysis of the activity in the Tech Help forum. Overall there were 7208 postings to this forum, distributed across 883 discussion threads. By using simple keyword searches to identify the topics associated with different posts it was found that only 271 posts were directly related to problems with the Sense Board or Sense software. Given this represents less than 5% of all the posts to the forum, it would appear that the hardware and software provided for experimenting with the Internet of Things did not cause any significant problems for the students. However, the end-of-module survey shows that the impact on those students who did have problems was significant enough to make them comment on it as a particularly negative aspect of their study experience. Looking more closely at the problems that did arise with the experiment kit, it is possible to broadly classify them into the following categories:

Cloud (RSS) service problems: It was found that some students were having difficulties with reading and writing values to/from the OU hosted RSS server due to an authentication problem. Searching for the keyword 'RSS' in the forum resulted in 208 posts about this problem.

Sensor Board connection problems: A number of students experienced problems getting Sense to correctly connect with the Sense Board. Searching the forum using the keywords 'Board' and 'Connection' identified 24 posts relating to this issue.

Sensor problems: Some students had problems using the sensors and actuators provided with the Sense Board kit. This included problems such as faulty sensors or difficulties in interpreting the values reported by a particular sensor. This issue accounted for 39 posts, which were identified using the keywords "sensor problem" or "sensor not working" in the forum.

4.4 Outcomes and Next Steps

In summary, we found that our approach of teaching computer science principles using the Internet of Things worked. Students quickly developed skills in developing SenseBoard applications that either took in physical input from sensors or created an effect in the physical world. Similarly, students were able to develop networked applications, but perhaps not to the extent expected. The Internet of Things teaching infrastructure resulted in a very small number of issues being raised by students and was key for the overall success. This demonstrates that the design of these tools has been successful in providing a robust and usable instructional toolkit for teaching the foundations of the Internet of Things.

Our future plans for the development of the toolkit and associated learning materials will focus on several issues:

First, we are investigating how learning analytics can be integrated into our infrastructure. We need to have a better understanding of how our students engage with the materials and how they use the hardware and software toolkit. Automated tools for tracking the use of sensors, networking capabilities, software constructs etc. would allow us to correlate student attainment with how often and in which way students used the IoT tools. We believe that analytics aspects will be an emerging issue for the Internet of Things in general and we plan to investigate this area from a HCI, software and educational point of view.

Second, we plan to extend the capabilities of the SenseBoard to support an RFID reader, thus allowing students to explore another enabling technology associated with the Internet of Things.

Finally, we are currently looking at enhancing the SenseBoard to better support the ~15%-20% of students who have a disability by designing a screen-reader compatible software simulator, as well as a number of add-on components that could provide auditory and vibro-tactile outputs.

5 EDUCATION AND THE INTERNET OF THINGS

The Internet of Things is gaining global significance. China for example has initiated a strategic program to push the development of core technologies and applications in the Internet of Things area with a special focus on agriculture, logistics, transport, electricity, public health and other key areas [15]. Companies like CISCO, IBM, Alcatel-Lucent and Intel already have been heavily engaged in Internet of

Things related research and projects. Intel recently announced plans for a joint Internet of Things research lab in partnership with the Beijing Municipal Government and the Institute of Automation of Chinese Academy of Sciences. With so many players seeing the Internet of Things as a significant part of the future it is not surprising that educational issues are receiving more and more attention. The NMC Horizon Report on Higher Education [16], a yearly survey of the impact of current and future technologies on education, mentioned the Internet of Things for the first time in its 2012 edition and predicts its likely adoption by 2016/17.

In China the impact is expected much sooner and academics are investigating the potential of the Internet of Things for reforming vocational education [17] and University education [18]. The main focus here is not on pedagogy but on the application of Internet of Things technologies (such as RFID and sensor networks) to improve the teaching system – i.e. the campus environment and the management and organisation of educational institutes [19].

In Europe, Queen Mary (University of London), offers a four-year BSc(Eng) in Internet of Things Engineering³. This course pulls together a number of highly relevant topics related to the Internet of Things and approaches the Internet of Things primarily from a telecommunications and network engineering angle with heavy focus on wireless communications, sensors, and IPv6. The ETH Zurich, in contrast, has for several years offered a MSc-level seminar on "Business Aspects of the Internet of Things"⁴ while basic IoT-related skills and technologies are taught embedded in traditional BSc and MSc programmes.

In the US, where the term Internet of Things has not yet reached the prominence it has elsewhere, the Internet of Things is nevertheless an important topic for education, albeit under different names. New York University's ITP program has for many years run a Sensitive Buildings Class⁵ where students create smart habitats for city dwellers. Students learn how sensor management systems work and create their own prototypes. However, there are also many examples of Universities of using Internet of Things technologies as part of education management systems, for example Northern Arizona University is using student cards that are embedded with RFID tags to track their class attendance⁶ and The El Paso Health Sciences Center at Texas Tech University has adopted a campus-wide RFID system to track the location of science lab equipment and resources⁷.

Some of the most interesting ideas in the IoT space currently emerge from "innovation communities" of artists, designers, hobbyists, researchers, and small technology firms dedicated to creating and freely disseminating innovations. An important aspect of this global community is the development of open source hardware and software platforms for unrestricted prototyping and experimentation. The most prominent example of this category is the Arduino open-hardware platform⁸. However, the cooperative,

³ <http://www.qmul.ac.uk/undergraduate/jointprogs/internetofthings/index.html>

⁴ http://www.im.ethz.ch/education/FS12/iot_lec

⁵ <http://www.idigi.com/blog/community/nyu-sensitive-buildings-class>

⁶ <http://www.rfidjournal.com/article/view/7628>

⁷ <http://www.radiantrfid.com/rfid-asset-tracking-texas-tech-health-sciences-el-paso.html>

⁸ <http://www.arduino.cc>

community-minded spirit of open source projects is also extending to data aspects of the IoT⁹. Indeed, hardware and software toolkits that enable experimentation with ubiquitous computing and IoT technologies are not new and have for a long time been used in University education. During the development of the My Digital Life course, the design team evaluated a range of hardware platforms including Arduino, d.tools [21], Phidgets [13], PicoBoard¹⁰, LilyPad Arduino [23], the MAKE Controller Kit¹¹, and software platforms such as iStuff¹², LabVIEW¹³ and Pachube¹⁴. An extensive comparison of such toolkits is presented in [4]. As highlighted by Hodges et al. [14], these systems offer a low barrier to entry and a higher ceiling of capability. The latter point is exemplified by Microsoft's .NET Gadgeteer platform (<http://www.netmf.com/gadgeteer/>), which allows users to develop quite sophisticated devices that include digital cameras and user interaction through a touch screen display [20]. In most cases the claims of low barriers to entry mainly refer to the ease with which the electronic components can be reconfigured, and assume that users are able to easily use industrial programming languages such as C/C++, C# or Java to develop software for the IoT devices they design.

We discovered that existing hardware and software toolkits do not satisfy our unique requirements, which include:

- Low cost: As our intention was that every one of our students receives a complete "Internet of Things in a box" we needed to lower hardware costs as much as possible
- Scalable manufacturing: As our course attracts several thousand students we needed to be able to manufacture hardware in large quantities on a reliable, regular schedule.
- Extremely simple tool chains: In online education, where students use the hardware and software at home, slight variations in students' setups and minor technical problems can be very time consuming to diagnose and fix, and hence expensive to support.
- Long-term future: The Sense Board and Sense programming environment is designed to be used in education for several more years. It was thus paramount that we can ensure that we will be able to manufacture - and redesign - the toolkit for as long as we deem necessary. We thus had to reduce our reliance on external platforms. For example, even though Pachube provides a very useful cloud computing platform the uncertain future of the company (or any other IoT startup for that matter) made it impossible for us to rely on their service (indeed Pachube has been sold since we started this project with unknown long-term consequences for their platform).

The Sense Board and Sense programming environment was designed to overcome these problems. Although it doesn't have as high a capability ceiling as solutions like the .NET Gadgeteer, it does significantly lower the barriers to entry, and has been successfully deployed to enable novice users to build their own IoT devices and program them.

⁹ <http://opensourceensing.org>

¹⁰ <http://www.picocricket.com/picoboard.html>

¹¹ <http://makezine.com/controller/>

¹² <http://hci.rwth-aachen.de/istuff/>

¹³ <http://www.ni.com/labview/>

¹⁴ <http://www.pachube.com>

Placing the Internet of Things at the core of the 1st year computing curriculum and opening up the curriculum for collaborative experimentation is a radical departure from a traditional computer science curriculum. Most if not all educational initiatives described above focus on graduate education and thus assume a level of understanding and skills that cannot be expected of 1st year undergraduates. Traditional undergraduate education in computer science typically starts with first principles and only gradually opens up to allow for experimentation and collaborative learning. Current online educational offers focus on topics that can easily be learned at home via self-study, which excludes the Internet of Things. The removing all these restrictions the *My Digital Life* course breaks new ground and provides a new model for undergraduate computer science education.

6 IMPLICATION AND CONCLUSIONS

Rising demand for education and fundamental changes in the technology landscape require new approaches to computer science education. We believe that the positive results from our efforts of reshaping undergraduate computer science according to Internet of Things principles has far reaching implications:

Implications for Computer Science Education. We have demonstrated that the Internet of Things is a viable vehicle for teaching computer science principles. Traditionally teaching of embedded systems programming, sensors networks and similar topics is deferred to higher-level courses, while introductory courses focus either on more fundamental topics or computing technologies that are ‘closer to home’ such as PCs and web programming. In contrast we have developed a course that, from the outset, uses the technologies that are at the forefront today and will be essential for the foreseeable future. Even though the concept of the Internet of Things is not well-defined and in flux, it is possible (and necessary) to incorporate the Internet of Things early on in computer science education because it orients students towards the future of computing and society. Additionally, the physical computing aspects draws in students who would never have considered a traditional computer science course (according to direct testimony from our students and public discussions on Facebook etc).

Implications for Online Education. Even though there is a tremendous excitement about online education and massively open online courses, most course offerings are limited to subjects that can easily be taught online. For computer science this means that courses focus on topics that can be studied with commodity technology, such as desktops and laptops. Our experiences with almost 2000 students per cohort demonstrate that it is feasible to teach subjects that require specialised equipment. We believe that it is time to investigate large-scale and scalable online teaching infrastructures for computer science education, ranging from cloud computing to the Internet of Things. For individual Universities it is often difficult to develop the infrastructure in-house. Our new Internet of Things course required a multi-year effort by a large group of dedicated educators and a significant investment in people and technology by the Open University. Particularly noteworthy is the fact that we designed a networked sensor board from scratch, and that we now manufacture and distribute the board to all our students. Similarly noteworthy is the cloud infrastructure without which the delivery of the course would not be possible.

Implications for Internet of Things Research and Industry. The Internet of Things is seen as the next revolution in IT. Emerging originally out of an industrial context, in the public view the Internet of Things is still primarily associated with the interests of large industrial players. However, unless we willfully expand the discussion and assign the needs, desires and fears of ordinary citizens as much importance as the requirements of industrial players, there is the danger that the Internet of Things falls short of its potential. According to the Open Source Sensing Foundation (<http://www.opensourcesensing.org/>) “a long and expensive battle is looming” over privacy, accuracy, ownership and sovereignty “between those using sensors to collect data and those whose data is being collected”. The best way of alleviating these fears is by engaging with citizens and users in a deeper and more meaningful way. As our course has shown there is a tremendous as of yet untapped source of creativity and excitement around Internet of Things technologies and concepts. We believe that user-led innovation will play a significant role in the future development of the Internet of Things [4,5,6]. How to ensure that the emerging Internet of Things supports user-led innovation and empowers ordinary people and citizens will be a critical question for the coming years.

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