A Multidisciplinary Pilot Course on the Internet of Things: Curriculum Development Using Lean Startup Principles

Dr. Valerie Galluzzi, Rose-Hulman Institute of Technology

Valerie Galluzzi is an Assistant Professor in the Department of Computer Science and Software Engineering at Rose-Hulman Institute of Technology in Terre Haute, Indiana. Her research interests include wearable technology, machine learning, sensor networks, and the Internet of Things.

Dr. Carlotta A Berry, Rose-Hulman Institute of Technology

Dr. Carlotta A. Berry is an associate professor in the department of Electrical and Computer Engineering at Rose-Hulman Institute of Technology. She is the director of the multidisciplinary minor in robotics and co-director of the Rose building undergraduate diversity scholarship and professional development program. She has been the President of the Technical Editor Board for the ASEE Computers in Education Journal since 2012. She is a member of ASEE, IEEE, NSBE, and Eta Kappa Nu.

Prof. Yosi Shibberu, Rose-Hulman Institute of Technology

Dr. Yosi Shibberu is professor of mathematics at Rose-Hulman Institute of Technology. He has taught undergraduate courses on data mining, machine learning and bioinformatics and computational biology. Dr. Shibberu recently spent a year at Jimma University, Ethiopia, as a Fulbright Scholar and is the current endowed chair for innovation in science, engineering and mathematics education at Rose-Hulman Institute of Technology.

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Abstract

This paper will summarize the development and teaching of a multidisciplinary, project-based, pilot course on the Internet of Things using strategies inspired by the Lean Startup movement. The course was taught at Rose-Hulman Institute of Technology, a small teaching institution in the Midwest with an emphasis on engineering education. Eight students from four different majors: electrical engineering, computer science, computer engineering and mathematics, were selected to enroll in the course. Our basic approach was to first inspire student learning and then manage the learning. We used a just-in-time strategy to introduce core IoT concepts and principles. The course revolved around a project consisting of deploying sensors on treadmills in our university's sports and recreation center. The lean startup strategy we used was largely successful, dramatically reduced the lead time needed to develop and offer the course to only a few weeks. The multidisciplinary team of instructors greatly expanded the range of expertise available to the students and reduced the teaching burden on any individual faculty member. Students, however, significantly underestimated the amount of time and effort the faculty expected them to spend on the technical work and the final technical report that documented their achievements. This paper will present details and lessons learned from this pilot IoT course.

Introduction

The Internet of Things (IoT) refers to devices that have been equipped with electronics and sensors and connected to a network (usually the internet) to communicate with each other and/or with a central servers. The field of IoT has experienced massive growth recently. Advances in processors and batteries have made computing platforms inexpensive and small, enabling applications in realms which were previously only imagined (e.g., wearable technologies and smart cities). While demand is growing for those with expertise in IoT systems, courses exploring the IoT are in their nascence.

IoT has many challenges and opportunities. Challenges include managing ubiquitous information, remote control of devices in the physical world through a web service, and ensuring privacy and security in the physical web[25]. Many companies try to create products that incorporate IoT technology, but it remains difficult to find people who can effectively leverage the opportunities that IoT provides. In part, this is due to a dearth of expertise in the unique challenges of IoT. These challenges cross disciplinary boundaries. Software engineers interested in creating an app that utilizes IoT devices must ensure that their app behaves in a way that maximizes battery life and may need to use machine learning in order to make sense of the massive amounts of data that deployments can generate. Computer engineers interested in creating IoT devices must have an advanced understanding of firmware programming and radio communication to create smart devices that communicate with low power usage. Others (e.g., biologists, civil engineers, mechanical engineers) who want to use IoT for special projects they may have in mind need to understand the challenges and limitations of the technology and the wireless communication space in order to design systems accordingly. Currently, few courses on IoT are offered nationwide. There is a strong need for more.

This paper describes a project-based, pilot IoT course that was offered to 8 students during the spring quarter of 2016. The demand for the course was actually much higher but the authors determined that limiting the enrollment for the pilot course was appropriate. The students were from 4 different majors: computer engineering, electrical engineering, computer science, and mathematics. The students were also at various academic levels: sophomore, junior, and senior. The strategy for teaching this course was to base the course upon a single IoT project. While students focused on the project, the faculty focused primarily on managing student learning. The course followed a student-learning curriculum framework rather than the more common course-content curriculum framework. A just-in-time strategy was used to introduce core IoT concepts and principles. The course project involved deploying sensors on treadmills in the university's Sports and Recreation Center (SRC). The students were tasked with designing the system for wireless communication between sensors. They were also responsible for identifying patterns in the data collected and using these patterns to determine whether a treadmill was in use and if so, the type of activity (walking or running).

IoT is a Challenging Subject to Teach

It is unclear when, where and in what context in the undergraduate curriculum IoT topics should be covered or even what these IoT topics should be[16]. Kortuem suggest that IoT will require a rethinking of how we educate engineers because IoT inherently involves democratic processes requiring a high degree of openness, transparency and collaboration[20]. IoT products and services will engage consumers at a more intimate level than current products and services making social and cultural norms even more relevant to engineering design. Compounding the challenging of teaching IoT is the fact that IoT requires a particularly broad set of skills ranging from sensor design and microcontroller programming to data mining and machine learning[24]. IoT instructors must negotiate a breadth vs depth challenge in teaching IoT[16].

IoT is also a rapidly evolving field and will require many user-centered innovations. Osipov claims that it is important to teach IoT students to be innovative[24]. IoT students should develop a holistic view of IoT ecosystems from sensor design to distributed processing of sensor data to creation of value-add products and services. User led innovation will also be key to future development of IoT applications[20].

An IoT course also provides an ideal opportunity for illustrating connections between disciplines. Abraham et. al use IoT as a tool to illustrate connections between electrical and computer engineering to students new to the major or pre-engineering students[14]. Topics covered included configuration of microcontrollers, data acquisition, building applications and discussing challenges related to data access, control, and security. Course activities included data acquisition with sensors on an Android phone. The students were required to plot the data, email data via a server, and create a web application that showed the location of the phone vibrating. The authors also created a project for higher level students that involved using a Raspberry Pi with a temperature and humidity sensor. The students were required to display the collected data and send out an email when the temperature and humidity exceeded some prescribed threshold.

Bogdanovic et. al designed an IoT course for business informatics students that included a teaching model that had three layers (device, service, app)[15]. The device layer was a cheap microcomputer (Raspberry Pi) or microcontroller (Arduino). The sensors were temperature or light. The sensor nodes communicated through a web service API. The students would then design apps to communicate to the equipment through the service layer. This was primarily a lab course that introduced technologies, scenarios, web services, web and mobile applications. The projects or contexts included a smart home, smart classroom, and smart library.

Dickerson discusses the redesign of a computer networking course to focus many of the topics on IoT technology[16]. The course does this by introducing students to wireless networks, radio communication, cellular networks, wireless computer network, active and passive RFID networks. There are also additional topics on microcontrollers, antenna design and RFID energy harvesting. Dickerson states that students should not have a narrow focus but rather a broad skillset. The format of this course is lecture based to teach students through the use of technologies. The course was successful but one area for improvement was making sure that the students are taught about the importance of considering power in the deployment of their system. In future offerings, the course will transition from a pen and paper format to a lab component.

There are several courses that have labs on teaching basic technical aspects of IoT but not the overall premise of IoT from soup to notes or inception to deployment[17, 19]. My Digital Life IoT Online Course is a course to help students understand and investigate their world. It includes algorithms, programming skill, distribution and collaboration, creative design, collaborative design, ethical issues, and concepts on a computing society. The course also used IoT to teach computer science principles. Stevens IT has modified the Software Engineering Curriculum to emphasize the technical competencies required for Cyber Physical systems and IoT software engineering[21].

Mullett described an Internet of Everything course which addresses microprocessors, microcontrollers, hardware theory, software programming, operating systems and interfacing hardware and controllers to the real world[23]. This course was taught with the Arduino Uno microcontroller for interfacing to the sensors and the Raspberry Pi 2 microprocessor for web interface. The course was taught at a community college and influenced students to become makers and pursue STEM fields. Finally, Simic et. al describe a course as part of an e-Business curriculum at the University of Belgrade to create an IoT application for smart home automation[26]. Some of the challenges they faced included the level of technical ability needed as prerequisites.

It is evident from this brief literature review that the implementation of IoT courses is as varied as the field itself. This makes it difficult to not only model an IoT course after others but also to extract any standard learning objectives or specific required outcomes. This paper will describe the implementation of our pilot IoT course as well as how it might be improved and scaled at our and other institutions.

Lean Startup Strategy for Curriculum Development

Faced with many of the same challenges described in the previous section, for creating and teaching an IoT course, we chose to develop our pilot IoT course using a process inspired by the

Lean Startup movement. Specifically, we developed our pilot course to enable us to quickly enter a "build-measure-learn feedback loop" to learn what worked and what did not. The time from when we first came up with the idea for the pilot course to when it was first offered was a matter of only weeks, not the months or years of course development time that is more typical. Hansen states that curriculum design should not be too far removed from learners[1]. Using a lean startup strategy made it possible to involve students at a very early stage in our course development process.

The Lean Startup movement grew principally from lean manufacturing principles developed by Toyota Corporation in the 1980s and was widely referred to at the time as just-in-time manufacturing. Lean principles stress the importance of a holistic understanding of processes, careful consideration of process inter-dependencies, identification of stakeholders and their value propositions, identification of the root causes of problems, respect for people, continuous improvement and the systematic elimination of waste. Lean principles have been extended to management (Lean Management) and software development (Agile Software Development) and to education[2,3,4].

Lean Startup principles are an adaptation of lean principles to the special needs of entrepreneurs - the need to create new products and services under conditions of extreme uncertainty[5]. A key lean startup concept is that of a Minimum Viable Product (MVP). The main purpose of an MVP is to allow entrepreneurs to quickly enter a build-measure-learn development cycle used to validate the value proposition of a new product or service[5]. In Lean Startup thinking, the biggest possible waste is developing a product or service no one wants[6]. An MVP together with the build-measure-learn development cycle enables entrepreneurs to make scientifically justified decisions to either pivot or preserver with product development in a cost-effective manner. Ries compares traditional and Lean Startup develop process to the difference in launching a rocket and driving a car[5]. All too often, curriculum development is like launching a rocket, a lot of upfront development with few opportunities for major trajectory corrections after the rocket is launched. The Lean Startup approach is more like driving a car, a process of constant trajectory correction.

Two fundamentally different conceptual frameworks for curriculum development exist. The more traditional conceptual framework focuses on course content while the more modern conceptual framework focuses on the process of student learning. The course content framework is top-down and linear with content transmitted from teacher (the expert) to the student (the novice). The student learning framework is more dynamic and less well structured. Learning how to learn is an acceptable outcome. The student learning framework requires the teacher to have considerable autonomy in structuring the curriculum[1].

Froyd claims that course content based curriculum design results in students that are less able to translate knowledge into applications, students that are less skeptical in new situations and students that have a reduced ability to adapt to change[7]. On the other hand, student learning based curriculum design results in students who ask more questions in new situations, have a better ability to make connections between concepts and are generally more creative. Hansen states an excessive student reliance on a higher authority undermines student development[1]. For these reasons, we chose to follow the more modern student learning framework for developing and teaching our IoT course.

A Pilot Course on the Internet of Things

Our first planning meeting for our pilot course occurred only three weeks before the course registration period and eight weeks before the actual course was to be taught. Most of our subsequent discussions occurred by email. We agreed on the following guidelines for the pilot IoT course:

- It should be multidisciplinary with multiple majors enrolled.
- Enrollment should be limited to eight students and by invitation only. We wanted to make sure students were "early adopters" already committed to learning about IoT.
- The student work in the course would revolve around completing a single project.
- We would try not to duplicate content in existing courses.
- Hardware used should be off-the-shelf and ready to go.
- Machine learning and distributed computing should be important components of the course.
- Low power and low memory requirements should be important design criteria.
- Multiple sensors should be used.
- The project should be enhanced by communication between multiple sensors.

IoT is a multifaceted topic which requires the union of multiple specializations, hence our multidisciplinary focus. After some discussion, we came up with a list of concepts that are important in IoT but not covered heavily in other parts of our curriculum. These included:

- Need for wireless transfer of data. This leads to issues including loss of data/data corruption and potentially unlimited delay of data transfer. A real life system should be robust to these issues. In addition if the devices are spread over a large enough area one must think of ways to route information to the central server.
- Limited power. Most devices are battery powered and therefore we must think of ways to minimize power consumption by reducing sensor sampling, using lightweight computational algorithms on the device, and minimizing the amount of data transmission (which generally uses more power than doing calculations).
- Large amounts of real-time streaming sensor data. Generally we are interested in patterns that can be observed from raw sensor readings, not the readings themselves, and therefore need to perform machine learning to identify patterns of interest from the data. Note the extra complication that while we have lots of data within the system we may not want all of it to travel to a central server--instead of expending battery power and congesting the wireless space by sending raw sensor measurements we may want to do (at least some) processing on the device itself. This requires a good understanding of machine learning, feature selection, signal processing, and algorithms in order to ensure that we can make sense out of the sensor

data while at the same time minimizing the amount of data sent wirelessly.

- Distributed information. In many cases a device can improve its accuracy by understanding what other nearby devices are sensing. For example, in our eventual project of detecting running on a treadmill, we could benefit from understanding if devices on adjacent treadmills were strongly detecting running to determine whether our weak detection of running was a true detection or only the vibrations from an adjacent treadmill. Correctly leveraging this requires deep understanding of the characteristics of the system and the sensed value in order to determine the minimal amount of external information necessary to improve accuracy.

One of the most challenging parts of designing this course was finding a project that was broad enough that students would encounter many of these unique features of the IoT while at the same time being contained enough that an MVP could be created within the 10 week quarter. The MVP had to work with the hardware available on campus. Due to the time frames involved (only a few weeks to plan the course and a 10 week quarter in which to run the course) we did not have time for a project that required Institutional Review Board (IRB) approval as obtaining IRB approval could take several months.

Several projects were proposed by the faculty teaching team including placing sensors on treadmills or exercise machines with the goal of understanding exercise patterns on campus, placing a network of speed sensors on campus to understand travel patterns and parking lot usage, using robots in the hallways to detect the number of hallway occupants and examine traffic patterns, changing classroom bell sounds to sounds chosen by classroom occupants, and using decibel meters on phones to find areas on campus where sound limits exceed workplace safety guidelines. Each project was evaluated for suitability given the constraints/goals previously discussed. Table 1 provides a summary of the proposed project/need matrix.

Many projects were eliminated for various reasons--i.e., the speed sensors project was eliminated because we did not have existing speed sensor hardware, the hallway traffic pattern project was eliminated because we would need more than the three robots available to complete the project successfully, the classroom bell project was eliminated as we did not have hardware to change out classroom bells, and the cell phone project was eliminated due to privacy concerns. The project which placed sensors on treadmills or exercise machines was the only one which satisfied all of our constraints for project selection.

Project	Uses Existing Hardware	No IRB Approval	Wireless Data Transfer	Limited Power	Real-Time Data	Distributed Information
Exercise Machines	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Speed Sensors	No	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

Hallway Traffic	No	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Change Classroom Bells	No	**Yes**	**Yes**	**Yes**	No	No
Campus Noise Map	**Yes**	No	**Yes**	**Yes**	**Yes**	**Yes**

Table 1: Proposed Project/Need Matrix. Various projects were evaluated according to whether they satisfied our stated project goals. Note that the assessment of whether we would need IRB approval or not was tentative and was confirmed by the relevant department once the final project was selected. The only proposed project which met all goals was the exercise machines project, which proposed placing devices on exercise machines in the campus recreation center.

The selected project involved placing Shimmer3 IMU sensors, which include a gyroscope, on treadmills. We verified that as long as sensors were placed on equipment in the SRC (rather than students) the sensors would record no identifying information and we would then not need IRB approval.

Our pilot IoT course was offered in the spring of 2016 as a special topics course on the Internet of Things. The course was cross-listed by the Computer Science & Software Engineering Department, the Electrical & Computer Engineering Department and the Mathematics Department. Enrollment was limited to eight students over the three sections. The eight students were selected based on their qualifications and interest and enthusiasm for taking the IoT course. We split students into a hardware team (those enrolled in electrical engineering) and software team (those enrolled in computer science and mathematics). Every week students attended four meetings: two team meetings which only included members of their respective team and two larger group meetings which included all students in the course.

The hardware team was focused on exploring low level aspects of IoT. The hardware team investigated radio communication and compressed sensing. Compressed sensing is an advanced topic in signal processing. Compressed sensing allows a device to sample the environment at much lower sampling rate. The software team was focused on exploring high level aspects of IoT. The software team investigated Bluetooth communication and machine learning.

Each team was given several options for aspects of the project topic that they could examine. These are listed below.

- Hardware Team
    - Examine routing protocols for data in sensor networks. The goal of this would be to first simulate and then implement several routing protocols on the Shimmer3

sensors and compare their performance. In order to attempt this, it would be necessary to add a radio to the Shimmer3 sensors as they only come with bluetooth by default.

  - Investigate and apply the technique of compressive sensing. The goal would be to first simulate the effect of compressive sensing on the data and then eventually implement a compressive sensing method on the Shimmer3 sensors.

- Software Team
  - Utilize machine learning to recognize the activity occurring on instrumented treadmills. The goal would be to create an application that determines the activity in real time and reports it to the user (with additional applications including reporting which treadmills are in use and recommending the best time to go exercise).

Both hardware and software teams were required to coordinate their work. For example, the hardware team worked on finding alternate radios for the shimmer sensors and, when that failed, learned about compressive sensing and simulated using it for the shimmer sensor deployment using the data set collected by the software team. At each class meeting students reported their progress and were assigned project work to complete before the next meeting.

Results

The students were for the most part excited to be in the IoT course. The selection of students allowed to enroll in the pilot IoT course almost certainly played a significant role in the positive attitudes of the students in a course that at times was frustrating due to unexpected difficulties involving both hardware and software and confusion with what the faculty expected from the students.

At the beginning of the course, students were quickly introduced to the Shimmer IoT device and left to begin collecting their own data sets. Once enough data was collected, students were tasked with exploring the potential of various data features (feature engineering) to predict treadmill activity. Data features the students selected were: the mean, maximum, and standard deviation of the three axis accelerometer and magnetometer sensor readings as well as of both the frequency and power spectra of these sensor readings. Students concluded that the other sensors available on the Shimmer, gyroscope, ambient temperature, ambient pressure and battery voltage, were not useful for the project.

Once a sufficiently rich set of features had been explored, students were introduced to machine learning classifiers and the concept of cross-validation. After testing a wide range of classifiers, the students selected a random forest classifier as the most accurate and reliable classifier. They were able to classify treadmill activity as no activity, walking, or running with true positive rate 0.981, false positive rate 0.086, precision 0.980 and recall 0.981. By the end of the course, the students were able to demonstrate a functioning prototype that could distinguish between no activity, walking and running on the treadmill in real time.

The students had to overcome a number of obstacles and they learned several key lessons along the way.

- Importance of Power Consumption:

  It quickly became apparent to the students that a major challenge of the project was keeping the Shimmer devices charged. A permanent installation would have required a weekly trip to the sports center to recharge batteries. Efforts quickly turned to how to minimize power consumption. How much preprocessing and compression of the data should be done to minimize power consumption? Was it energy efficient to wirelessly transmit the raw data for processing off-line? Students spent some time investigating the topic of compressed sensing, but ran out of time before they could implement any algorithms.

- Challenge of Establishing a Ground Truth Data Set:

  The students devoted one early Saturday morning, when no one was in the sports center, to record a ground truth data set. In addition to recording sensor measurements in various controlled settings, the student made a video recording of each activity on the treadmills. Labeling each activity on the treadmill as either no activity, walking or running, proved to be labor intensive and a limiting factor in determining the amount of training data they could use to train their classifiers.

- Danger of Overfitting Data:

  Students were initially too confident in their ability to distinguish no activity, walking and running on the treadmill from sensor measurements. Their initial classifier performed poorly largely because of overtraining. This overtraining provided the instructors an opportunity to introduce students to the concept of cross-validation. Cross-validation significantly improved their classification accuracy in subsequent tests.

The students used the machine learning package WEKA. This proved to be a good choice because of both ease of use for novice users and the variety of machine learning classifiers and preprocessing tools contained in the package. WEKA is a free package. One challenge students had to overcome was establishing a common data format. Subsequently, one of the students wrote a Python script that facilitated data exchange from .csv file format provided by the Shimmer devices to the .arff format needed by WEKA.

The Shimmer devices were fairly easy to use, but students did need to spend a significant amount of time familiarizing themselves with how to operate the devices to record and save data and had to frequently refer to documentation and conduct web searches on various device features.

Students were required to devote the last two weeks of the 10 week quarter to writing a technical report on their IoT project for online publication in the our university's technical report series. These last two weeks proved to be the most challenging for the instructors as student expectations did not match the instructors' expectations as to what constituted a technical report. Students (and instructors) had to endure many rounds of rewrites. During the last two weeks, students and instructors also discussed additional IoT related topics which included: (i) the importance of adhering to federal guidelines for human subject research (ii) the sharing of data and intellectual property and open source licensing (iii) the importance of security in IoT applications.

Since content was presented in a just-in-time manner, students from different majors and academic levels had many opportunities to share their expertise with each other during scheduled class meetings and outside of class as they worked on the project. We view this as a strength of the course. However, assessing the technical content that each student learned in the course is more difficult in such a course since the technical content can vary depending on the project selected for the course and the particular strategies used by the students.

How might the pilot IoT course be scaled to larger class sizes? If all students in a large class are required to complete the same project in small groups, economies of scale could be achieved. One method for achieving economies of scale is for the multidisciplinary team of instructors to meet with each small group of students on different aspects of the common project and then share "lessons learned" using video recordings with the rest of the class. However, the overhead of establishing a rapport with the students should not be underestimated.

Conclusions

The Lean Startup strategy used to develop this IoT course was largely a success. The course was offered and taught with a minimum of preparation (only a few weeks) compared to the more typical summer months or even years of planning for a new course. Both students and instructors learned a great deal during the course both about IoT and how to improve how IoT is taught. Team teaching the course reduced the burden on any individual faculty member and allowed the students to gain a multidisciplinary perspective as well as provide students with a wide range of expertise to consult with.

While this pilot version of the course was well received by both students and faculty, there is still much room for improvements. For example, creating a more stringent framework for student expectations, reporting activities and results, and creating a detailed assessment plan would strengthen the course. This is challenging in a problem based-learning course since the content delivery is dictated by the selected problem and student performance/needs which can vary from quarter to quarter. Good ways for achieving additional structure in a problem-based course are (1) require students to submit weekly progress memos and a time log of activities (2) require a literature review of relevant sources and (3) require documentation of communications between the various sub-teams (hardware, software, data). The faculty instructors did require submission of some of these items but the grading criteria and rubric should have been much more stringent.

Additional topics such as data and device security and privacy should also be introduced in the course. Including the "voice of the customer" (consumer feedback) as part of this pilot course was judged too ambitious for a one quarter project, but should be a component of IoT projects spanning multiple quarters. Invited lectures from members of the community will enhance student excitement about IoT and IoT courses and further reduce faculty burden in developing and teaching new IoT courses. In conclusion, the authors feel that the speed and flexibility with which this pilot IoT course was developed and deployed makes it model for possible replicated at other institutions.

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