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# Introducing Information Technology Students to Cyber-Physical Systems Using a Lab Experience

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## Abstract

Cyber-Physical Systems (CPS), or embedded computers, are not traditionally emphasized in Information Technology (IT) majors. However as these systems evolve they include more and more topics that are of fundamental interest to IT majors. Some key areas include networking, security and human-computer interaction. They are also evolving into large, heterogeneous distributed systems requiring significant integrative design skills to implement successfully; integration is another key area of interest to IT designers. In addition to including multiple aspects of interest to IT, CPS is rapidly growing to take ever-larger portions of the overall computing market.

A new combined class and lab experience has been designed for first-year IT students to introduce them to CPS concepts, with an emphasis on IT aspects of the field. This combined experience is taught as a single module, in a few hours, within a first year IT course. Two ideas were addressed by the experience. Firstly that CPS systems differ significantly from conventional computer systems and secondly that there are important design issues relating these systems to core IT topics. Lists of CPS concepts were developed and a subset of the concepts was included in the paired class-and-lab experience for the students. The lab experience uses a microcontroller system that interacts with the real world using analog and digital sensors and then communicates to the Internet through a webpage. The simple webpage is hosted by a web-server on the microcontroller, which illustrates both the capability and the limitations of a typical CPS system. Thus the students experience several aspects of CPS and are encouraged to develop cognitive relationships between CPS and IT. Details of the lab design are included in the paper. Pre- and post-assessment tests were carried out to evaluate the degree of student understanding of the lab concepts and their relationship between IT and CPS. Proposals and justification for including CPS as part of an IT curriculum are presented.


## Introduction

Embedded or Cyber-Physical computer systems are gaining increasing prominence in computing in general and research in this area is growing[1]. Small, embedded systems, based on microcontrollers, have outsold general-purpose desktops and laptops for many years. Now these smaller systems have acquired communication capabilities and are integrated and connected into a much wider world. Their connection to the Internet raises questions of security, software design, human-computer interaction and systems integration, all of which are of considerable interest to professionals within the IT domain.

Embedded computers are adopting the new title of Cyber-Physical Systems (CPS) This new title emphasizes their connection to the physical world, with its demands for reliability, real-time response and responsibility for human lives and equipment, while also addressing the connection to the world of computing. The word “system” in CPS is an indicator of the direction this discipline is rapidly heading  “Systemization” is apparent in two different (overlapping) aspects.

- Firstly many CPS have acquired networking capabilities. This is seen in microcontrollers, single-board computers and Compact Mobile Platforms IE smartphones, tablets etc. These systems manifest themselves in many products and larger systems, such as industrial control, consumer electronics, transportation networks, appliances, security systems, point-of-sale systems, health systems, and more. All of these systems are frequently connected to the Internet or to intranets.
- Secondly many CPS are becoming complex heterogeneous systems. For example within industrial control systems independent microcontroller devices or instruments link back to a centralized proprietary controller, which in turn is networked back to other controllers and linked upstream to MMI supervisory systems, and they in turn are linked through the Internet to corporate systems. Thus many different types of systems, each with their own operating system and their own communication and security capabilities all communicate and interact, leading to a complex and heterogeneous system.

The net result of all these effects is that designers are faced with a much more complex design challenge. It is no longer sufficient for cyber-physical systems to be designed by a vertical-market specialist technical designer, they now need to be designed with a more comprehensive systems viewpoint. Multiple researchers have explored the problems and importance of cyber-physical design[2-6]. These attempts at formal analysis of the problem point to the need for a more comprehensive design approach.

Part of the comprehensive design viewpoint needed should come from designers who address specific needs in the domain including integrative systems design, Human-Computer Interaction (HCI), Information Assurance and Security (IAS), reliability, networking, web interactions and much more. Since these skills are all part of the IT university curriculum IT professionals have a significant role to play in the design of these complex systems. In fact most of these skills are part of the pillars and central themes of IT education[7]. It is revealing that the respected annual survey sponsored by EE Times and others[8] indicate that over 50% of the projects include networking and more than 30% include wireless, but in this report the designers are classified as hardware, software or firmware engineers and their lists of design tasks do not include issues related IAS, HCI, or other IT-related issues.

Cyber-Physical Systems are not traditionally emphasized in IT programs. However the growth of non-traditional computing platforms and their interaction with traditional IT networks, servers is a strong indicator that IT programs should incorporate these systems into their curricula. A recent report[*] by IDC indicated that tablet computers will outship desktops this year. Tablet computers are one category of CPS and this trend is one more indicator that more diverse systems are intruding into the traditional IT space of desktops, laptops and network servers. IT professional and students need to consider that the future IT space will be a lot more diverse than that of the past. In the past IT systems were dominated by a couple of operating systems and the assumption of client and server systems with very predictable performance parameters. In the future the systems will be much more heterogeneous.

[*] http://mashable.com/2013/03/26/tablets-outsell-desktops/

In order to introduce these ideas to a class of first-year IT students a combined class and laboratory experience was designed for the students to interact with CPS, but in such a way that they were able to make the connection between CPS and IT.

In other classes in the IT major students emphasize web systems, networking and other topics of the IT fundamentals. This experience focuses on the physical world interface and links it to the integrated systems that are part of the IT domain. Specifically the relationship between cyber-physical systems and networks and the web is exposed. Since this lab experience is a single, first-year class and lab (two hours total) many of the details of CPS are not discussed in depth. The purpose of this class and lab experience is to illustrate the opportunities and need for IT to become involved in the growing field of CPS.

**Objectives of the class/lab**

This class/lab module is a single module in an introductory IT class. The class introduces IT students to a variety of IT topics and tries to ensure they have a minimal set of skills that will be expanded in later classes. Each topic in the class is as a single module as part of the overall class.

The overarching objective is to design a student experience so that early students in an IT program understand some basic principles of CPS and realize and accept the importance of the relationship between CPS and IT. The aspects of CPS that are addressed are the real-world interface (sensors and actuators), development issues, cost and computing power issues. In this simple lab other important aspects such as real-time systems and user-interface design are only addressed lightly.

Thus the specific goals of the lab design were as follows

- Incorporate CPS principles
    - Use a small, non-desktop system interacting with the real world through sensors/actuators. Include both digital and analog sensed variables.
    - The CPS system will be developed using a CPS SDK environment IE a separate development computer and a target computer. Students should realize that the target computer does not have the capability to act as a development machine and that the development computer does not have the capability to act as an interaction system.
- Incorporate system and networking principles
    - The system needs to delegate part of its functionality to a different system, to which it is connected by a networked link. Students should see the possibility of a CPS system being linked to the broader world (Internet). The system should use a web browser interface for some of its functionality to demonstrate the link between the Internet and the physical world.

There are also pedagogical and practical goals

- Engaging: The lab should be engaging and memorable to raise the students' awareness and enthusiasm and thus to encourage learning.
- Experiential and Creative: The students should have the opportunity to design and implement part of the system, in keeping with the experiential nature of the learning

model favored by technology disciplines. The creative aspect will move the learning experience further up the scale in Bloom's taxonomy[9].

There are a number of constraints affecting the design of the experience.

- Available time is limited. This experience is one module of a class and is allocated a single class period (90 minutes) plus a single lab experience (60 minutes).
- Students have diverse backgrounds. The class is nominally a first year class, however IT students most often transfer in from other majors. About 70% of the students each year are distributed between the second and fourth year students (measured by credit-hours completed). Students' programming backgrounds vary from none to paid programmers.
- Lab equipment is limited. The class is large enough to require 15 identical lab stations. Therefore the system had to be designed so that the cost, multiplied by 15, was reasonable. Even with 15 stations students work in pairs, and two or three lab sections are required.

## Measurement of effectiveness of the student experience

In line with the research goals of the lab experience measurements will be made of:

1. Students' understanding of CPS
2. Students' understanding of the pillars of IT relevant to this experience.
3. Students' evaluation (opinion) of the relationship between CPS and IT.

These measurements will be made with pre- and post- surveys of the students and observations by the developers during the class and lab.

This experience is not primarily intended to educate students into the skills of CPS. Rather it is intended to make them aware of the field of CPS and its potential relationship to IT. Therefore the measurements taken relate more to attitudes rather than specific skills, thus opinion surveys are used. Their achievement of the basic programming skills required is simply measured by their completion and demonstration of their working system. All of the students achieve this, although some of them require more help from the teaching assistants in the lab than others.

## Design of the learning experience

The course that this class and lab are part of is an introductory course for first-year students to teach them the fundamentals of the IT profession. The class is divided into modules, each addressing one topic. This module, consisting of one class period and a one-hour lab period, addresses the concepts of cyber-physical systems and how they relate to the profession of IT.

The concepts of cyber-physical systems are introduced to the students in the class period. These concepts have been analyzed elsewhere[10-13]. A summary of some of the key concepts includes: heterogeneous integrated systems; narrow application focus; separate development and target systems; sensors and actuator physical interface; non-traditional HCI design (through sensors and actuators); non-traditional IAS issues; real-time; mobile; constrained compute capability.

In the class the students are introduced to several specific CPS characteristics such as physical world interconnections, the benefit of small separate, low-power, low-cost computing devices, such as microcontrollers, and the enhanced benefit of linking these devices together and connecting them to the Internet. Once these devices are connected to the Internet basic IT concepts such as networking, security, HCI design and databases become immediately relevant. The concepts of the "Internet of Things"[14] is introduced. This provides the students with a basic background that enables them to appreciate the lab experience.

While all these topics are addressed in the class, with supporting data, and examples, the lab only addresses a subset of these concepts.

The lab is designed around the idea of the time-machine in the movie "Back to the Future". A small microcontroller is connected to two analog input devices—representing the brake and accelerator of the DeLorean Sports car/time machine used in the movie. The microcontroller includes web server hardware and software and it serves up a dynamic web page. The speedometer of the DeLorean is displayed on a web page both as an analog speedometer dial and as a digital display.

There was some concern that since the movie trilogy was released in the 1980's, that many of the students would be unfamiliar with it, since most of the students were born after the movies were released. This was addressed by showing the students a short clip from then movie, including the catch-phrase "88 miles per hour" and images of the sports-car and time-traveling "flux capacitor". In any case, an informal survey (show of hands) revealed that the vast majority of the students (~90%) had seen the movies. Students interest was further piqued by showing them that they could buy a "flux capacitor" on eBay. Finally the students are shown a working version of the lab developed by one of the authors. These decorative aspects of the lab are intended to engage the students' interest and help motivate them to complete the more serious learning experiences.

As indicated in the objectives section above, each lab station consists of a single microcontroller (details below) with analog and digital sensors connected to it and LED and sound outputs. The microcontroller is also connected to a desktop computer by a USB link, which demonstrates the need for a separate programming environment. The microcontroller is further connected to a computer running a browser via an Ethernet cable. Students are informed that the microcontroller is running a web server and that the microcontroller browser is dynamically displaying the graphic speedometer on the browser. A clickable link on the browser window re-calibrates the analog inputs; the effect is visible on the browser display. All the source code is provided so that advanced students have the option of exploring the details of the configuration and set up. Thus the students are exposed to, and instructed in several key concepts

- Development of CPS software is done on a separate machine from the CPS target machine
- The CPS interacts with real world through analog and digital inputs and outputs
- CPS can be connected to familiar network destinations such as a browser, and by implication (and discussion) to the entire Internet.
- Communication through the browser is bi-directional and can affect real-world systems.
- Interaction design (HCI) is directly related to real-world signals and is impacted by the limited processing capability of the microcontroller (the browser runs in tens of kilobytes of memory)

As indicated previously the lab is constrained to a one-hour experience. Due to this time constraint the basic structure of the software is pre-written. Without writing any code the students are able to control the car speed by manipulating the accelerator and brake and when it reaches the magical "88 miles per hour" necessary to activate the time machine they can press a button to activate the "flux capacitor", as described in the movie. However the "flux capacitor doesn't do anything except indicate with a single LED that it has been activated.

The students' programming task is to create a suitable light and sound display by writing C-language code for a set of LEDs and a speaker to represent the "flux capacitor". Experience with previous versions of this lab have shown that first-year students, some of whom have never programmed before, can learn to program and control a set of LEDs and a speaker within the one hour allocated for the lab experience. The open-ended nature of the assignment means that students with previous programming experience can build fairly sophisticated synchronized light-sound displays while less experienced students can achieve flashing LEDs and a few beeps. Teaching assistants circulate through the lab and challenge the more advanced students to complete more sophisticated sound/light displays. The best of these are shared with the rest of the group as they are completed. Thus the lab addresses the needs of students with different backgrounds.

**Lab Workstation**

The lab equipment for each workstation consisted of an Arduino-compatible development platform (Microchip 32-bit microcontroller; Cerebot MX7CK) from Digilent Corporation (www.Digilentinc.com), combined with a small, custom-designed breadboard with the sensors and sound actuator on it. The microcontroller board included a webserver which is linked to a lab computer and serves up a webpage, to demonstrate the linkage to the Internet. The system was deliberately designed with a physical separation between the computer and the sensor/actuator board to visually emphasize the physical world linkage. The setup for each pair of students was less than $200. The lab computer was loaded with the necessary development software for programming the target microcontroller.

**Measuring Student Response**

The student response to the lab was measured by pre- and post-surveys [15] evaluating the students' understanding of some of the basic CPS concepts and their opinions of the relevance of CPS to IT. 39 students completed the pre-survey and 35 completed the post survey. The surveys addressed the students' current understanding of computing in general and of CPS-related topics in particular. They were specifically asked whether they were familiar with either CPS or Embedded systems. The pre-survey was given before any instruction in the topic area was provided. The results of a few selected survey questions are summarized below.

Table 1. Pre-class survey. Student technical background (1 to 5 scale with 5 being best)

| Topic/Question | Response |
|---|---|
| General IT-related experience (summary of 5 questions) | 2.43 |
| CPS-content related questions (summary of 5 questions) | 1.17 |
| Level of familiarity with CPS | 1.87 |

| | |
|---|---|
| Design experience with CPS | 1.13 |

A brief description of CPS (one paragraph) was then given and two further questions were asked in the pre-survey. The responses were a Likert-scale, coded as 1 (Much Less, Irrelevant) to 5 (Much more, All IT need to be involved)

Table 2. Pre-class survey. Student CPS background and attitude

| **Topic/Question** | **Response** |
|---|---|
| Estimate number of CPS systems in the world compared to conventional computer systems | 4.49 |
| How important is understanding and design of CPS for IT professionals | 3.87 |

After the students completed the class and lab a post-survey was administered. This was also a Likert-scale, coded as 1 to 5.

Table 3. Post-class survey. Student learning and CPS attitude

| **Topic/Question** | **Response** |
|---|---|
| Familiarity with CPS before doing lab | 1.71 |
| How much did you learn about CPS by doing this class/lab | 3.94 |
| How important is understanding and design of CPS for IT professionals? | 4.20 |

Several interesting points arise from the above data. Firstly these first-year students were moderately confident of their computing abilities (2.43 on a 1-to-5 scale) and are much less informed about CPS-related topics, such as sensors, actuators, microcontrollers etc. than they are about general computing topics, such as system administration, databases, computer security etc. (2.43 vs. 1.17). This is not surprising but worth confirming. Secondly their general opinion of their understanding of CPS, prior to the class presentation is higher than their understanding of components of CPS (1.87 vs. 1.17), furthermore when asked the same question after the class/lab their self-estimate of their general CPS understanding dropped to 1.71 (but still higher than their understanding of several CPS component skills). This probably indicates that they realized that CPS is more complex than they first assumed it was.

Prior to the class presentation the students were already aware that CPS systems outnumber conventional computing systems, but their estimate was still significantly low, compared to the actual numbers.

Prior to completing the class/lab the students felt that CPS was relatively important as a topic within the IT domain (score of 3.87, falling between "many-" and "most IT persons should be involved". After completing the experience the score rose to 4.20, falling between "most-" and "All IT should be involved". Students felt the lab was a good learning experience with an average score of 3.9 (corresponding to "Learned much").

The 24 optional open comments were almost all positive or very positive. They ranged from simple endorsements like, "Awesome!" and "I really enjoyed the lab and learned a lot", to more thoughtful comments like, "I always wanted to know more about CPS" and "I learned a lot and the lab really peeked [sic] my interest in this field". Only two comments were mildly critical. One pointed out a typographical error and the other indicated a desire for more instruction on the hardware.

**Conclusions**

There is a real need to include CPS material in IT courses. Students are aware of CPS and feel it is an important part of IT. Exposing IT students to a CPS lab experience is both positive for the students and increases their desire to have more of this material available within the IT curriculum. This is supported by the growing evolution of CPS systems into the IT field. Not only is this a topic that students want to see included, it is a topic that is already significantly present within IT and is growing to take an ever-larger role within the discipline.

A lab and class experience was successfully designed and used within a first-year class environment. The experience was both popular with the students, demonstrated their existing interest in the field of CPS related to IT and increased their expectation of seeing more of this relationship in the future. It is possible to use very low-cost systems to demonstrate the principles of CPS and also to demonstrate their relationship to the wider world of IT through networking.

Future development in this area needs to make the relationship between CPS and IT more apparent and to demonstrate other aspects of IT and CPS. Some developments that are being pursued for future variants of this design include human-computer interactions for non keyboard/-screen systems, systems integration of heterogeneous systems including multiple types of CPS and conventional computer systems and also security aspects of CPS when tied into IT. A newer version of this lab, currently under development, includes a Wi-Fi link and will allow students to attack the connection by simply using their smartphone. This will demonstrate IAS vulnerabilities in systems of this type.

In a more general sense IT program designers need to become more aware of the impact that CPS will have on IT in the future and continue to design classes that address how IT professionals will contribute to this domain. IT professionals need to recognize the future penetration of CPS into traditional IT areas and should thus start to proactively take a role in helping to design systems that will integrate smoothly and effectively. Furthermore CPS provides exciting new development opportunities for IT students and professionals.

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