A 21st Century Cyber-Physical Systems Education

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The rapid rate of change in the computing and engineering domains has our educational institutions on high alert. The authors explore how best to prepare graduates for a world in which cyber-physical systems are increasingly ubiquitous.

Using software to define capabilities in engineered systems provides extraordinary flexibility along with the promise of unprecedented growth in the economy, functionality, safety, and accuracy of control and operational decision-making. An exciting technological revolution is underway to engineer cyber-physical systems (CPS) that integrate computational and physical elements and manage the significant and intimate couplings between the two aspects. These complex systems increasingly operate in loosely supervised and complex environments, interact with the Internet and its services, operate with a high degree of autonomy, involve humans-in-the-loop, and, often, are safety critical. Such systems must address complications, such as systems-of-systems challenges and desired failure modes, if they are to achieve the desired levels of safety, security, and privacy. In this era of "smart things," virtually all industries are rapidly implementing CPS.

Interdisciplinary skillsets to invent, design, build, and deploy these systems are more necessary than ever before. The NSF recently sponsored a multiyear study by the National Academies of Sciences, Engineering, and Medicine to develop clearly articulated criteria for curricula to address effective CPS education.[1] The study found that all computing and engineering fields will make widespread use of CPS, and the workforce must have access to domain experts knowledgeable in CPS principles.

CPS AS AN ENGINEERING AND COMPUTING DOMAIN

In the course of the study, experts in a wide array of industrial sectors—including agriculture, transportation, and medical devices—reported the changing nature of their products and services as well as the corresponding

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challenges they face in recruiting engineers with the required skills. Thus, multiple paths to teaching CPS knowledge are required to meet labor demands. For example, CPS survey courses taught at the undergraduate level will provide students with a basic understanding of such systems and the key challenges to their design, which will be necessary in any engineering discipline, including aerospace, civil, or mechanical. In addition, engineering programs that include a CPS concentration or focus would accordingly provide a stronger, more deliberate foundation for CPS work. In addition, we posit the need for a new type of engineer—a CPS engineer—along with a corresponding bachelor's-level CPS engineering degree to create a cadre of engineers well versed in both the cyber and physical issues to meet growing industry needs for this expertise.

Although a handful of master's-level programs exist, they focus on embedded systems or CPS, with a chiefly electrical engineering or computer science slant. An MSc program in CPS for graduates of other engineering fields, such as mechanical or civil engineering, would also be valuable. If CPS follows the lead of other engineering disciplines, PhD programs will help educate tomorrow's CPS faculty, and PhD-level engineers will fill important technical leadership roles in industry.

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ESTABLISHING A CPS CURRICULUM

Depending on the particulars of each university or college, it's likely that a variety of approaches will be tried, reflecting existing department structures and curricula, faculty expertise, and available resources. Designing a CPS course or degree program is quite complex and involves, for example, a careful balancing of physical and cyber aspects and general CPS and application knowledge. Although CPS degree curricula are in their infancy, they'll evolve substantially as CPS classes and systems are more widely deployed. Moreover, like most engineering degree programs, those in CPS will face the challenge of prioritizing topics to fit in a manageable four-year program of study. To help guide those developing CPS curricula, the report includes model curricula from multiple perspectives.[1]

Given that the potential content for CPS programs is quite broad and rapidly evolving, the report focuses on principles and intellectual foundations rather than an array of specific techniques or facts. It identifies six overarching foundations for a CPS curriculum, as described in the following sections.

Foundation 1: Basic computing concepts

Expertise in CPS can't be achieved through only one or two programming classes, as it requires solid training in computing. The basic computing concepts listed below should be taught using case studies and examples from the physical domain. These concepts include embedded hardware; data structures and algorithms; models of computation, including automata theory (relevant to the finite state machines widely used in CPS) and discrete event systems; programming; software engineering and model-based design; real-time operating systems; and programming for networks.

Foundation 2: Computing for the physical world

There's a need for computing foundations to embrace physical-world properties and constraints. Real-world complexities often give rise to situations neither anticipated by the system designers nor addressed by the software, and thus often result in failure. System and software design and implementation must take into account the resource limitations of the platforms themselves, as well as conditions that the real world imposes on the platform. Students will need to thoroughly understand the following concepts: properties of sensors and analysis of signals; programming with sensors and actuators in open environments and with multiple modalities; real-time embedded systems; resource management and constraints such as time, memory size, and power; and techniques such as redundancy and fault-tolerance for managing unreliability in physical systems.

Foundation 3: Discrete and continuous mathematics

Both discrete and continuous mathematics are foundational skills for all CPS engineers. CPS deals with both continuous and discrete systems; thus it is critical for students to learn how to deal with that integration. Concepts students will need to understand include graph theory and combinatorics; probability, statistics, and stochastic processes; logic; linear algebra; and calculus and differential equations.

Foundation 4: Cross-cutting application of sensing, actuation, control, communication, and computing

This foundation is essential due to the cross-cutting nature of CPS, as well as control over communication networks and sensing, signal processing, and actuation with real-time constraints. The interdisciplinary nature of the topic must be intrinsic to all aspects of the curriculum. Knowledge of control, signal processing, and embedded software design and implementation are at the core of this foundational principle. To ensure adequate coverage of this concept, curricula will cover

- Control principles including linear and nonlinear systems, stochastic systems, adaptive control, system identification, and hybrid control;
- Optimization and optimal control of dynamic systems;
- Networking concepts including wireless communications, synchronous and asynchronous communications, and ad hoc networking;
- Real-time analysis including task models describing real-world information sources, time-triggered or event-triggered control, and decision-making with noisy data;
- Signal processing using control, computation, and communication models;
- Safety, reliability, and dependability;
- Security and privacy;
- Impact of physical properties on software requirements;
- Human factors related to humans-in-the-loop as well as behavioral aspects; and
- Networked control.

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Foundation 5: Modeling heterogeneous and dynamic systems and integrating control, computing, and communication

CPS modeling requires a complete picture of control, communications, and computing—with emphasis on representing and accounting for modularity, abstraction, uncertainty, and heterogeneity. Relevant techniques include linear and nonlinear models, stochastic models, and discrete-event and hybrid models, and associated design methodologies based on optimization, probability theory, and dynamic programming are needed. Key concepts of this foundation include properties of the physical world, including uncertainty and risk; properties of computational devices, including computational and power limits; properties of communication systems, including limitations of wireless communications; error detection and correction; merging physical and computational modeling; and commonalities between signals and systems and finite-state automata.

Foundation 6: CPS system development

CPS development, from determining initial requirements to certification—with emphasis on safety-critical systems, high confidence, and resiliency—requires a life-cycle view that parallels traditional systems engineering. Students should master the following key concepts that transcend the entire life cycle: safety, resilience, security, and privacy; requirement development; assurance cases and hazard analysis; formal verification and validation; model-based design and tools; system design, including design for system evolution and life-cycle certification; platforms such as the Internet of Things or cloud computing; and testing CPS in the laboratory and in their intended environment.

BEYOND FOUNDATIONS

Beyond these intellectual foundations, the report brings to light highlights several other important elements of a CPS curriculum. Successful development of CPS requires attention to system characteristics, including security and privacy, interoperability, reliability and dependability, power and energy management, safety, stability and performance of dynamic and stochastic systems, as well as human factors and usability. The study observes that, in keeping with the best practices in engineering, these topics are best introduced early and infused throughout CPS coursework and projects.

Broader trends in engineering education, including the observation that rapid change and preparation for continual reeducation is particularly important for an emerging and rapidly changing area like CPS, are also covered in the report. Likewise, the inherently interdisciplinary nature of CPS and the growing complexity and scale of engineered systems place a premium on those able to work well in teams and communicate effectively with both technical and public audiences.

Of course, no discussion of curriculum development is complete without some discussion of the challenges inherent in tackling a new field of engineering. The report emphasizes building awareness of CPS opportunities among students in K–12 and incoming college freshmen. In addition, it describes how educational institutions must invest to develop, recruit, and retain the faculty needed to provide an up-to-date CPS education. Add to this the need for new instructional materials, laboratory facilities, and testbeds to effectively support CPS courses and programs. In addition to federal agencies that support STEM education, contributions from industry, professional societies, and colleges and universities can all play important roles in building such resources and capabilities.

Success in these endeavors will have significant payoffs. An engineering workforce with high proficiency in CPS skills will help realize the full potential to engineer increasingly capable, adaptable, and trustworthy systems.

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