Consensus Study Report

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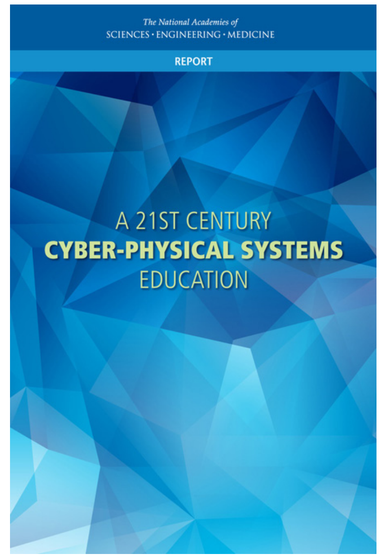
HIGHLIGHTS

A 21st Century Cyber-Physical Systems Education



A 21st Century Cyber-physical Systems Education examines the intellectual content of the emerging field of Cyber-physical systems (CPS) and its implications for engineering and computer science education. The report explores the need for CPS education, highlights essential knowledge needed by a CPS engineer, provides examples integrating these foundations into various curricula, and describes how such curricula might be developed and institutionalized.

CPS ENGINEERING AND THE CPS WORKFORCE

Defining Cyber-Physical Systems

Cyber-physical systems are "engineered systems that are built from, and depend upon, the seamless integration of computational algorithms and physical components." CPS can be small and closed like an artificial pancreas, or large and distributed like a regional energy grid. CPS engineering focuses on managing interdependencies and impacts of physical aspects on cyber aspects, and vice versa.

CPS support many critical tasks with significant economic and societal importance and raise safety and cybersecurity concerns. However, today's practice of CPS design and implementation is often ad hoc and unable to support the level of complexity, scalability, security, safety, and interoperability that will be required to meet future challenges. A workforce with the appropriate education, training, and skills is needed to create and manage the next generation of CPS solutions.

FINDING: CPS are emerging as an area of engineering with significant economic and societal implications. Major industrial sectors such as transportation, medicine, energy, defense, and information technology increasingly need a workforce capable of designing and engineering products and services that intimately combine cyber elements (computing hardware and software) and physical components and manage their interactions and impact on the physical environment.

FINDING: The future CPS workforce is likely to include a combination of (1) engineers trained in foundational fields (such as electrical and computing engi-

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neering, mechanical engineering, systems engineering, and computer science); (2) engineers trained in specific applied engineering fields (such as aerospace, and civil engineering); and (3) CPS engineers, who focus on the knowledge and skills spanning cyber technology and physical systems that operate in the physical world.

There will be multiple paths for attaining CPS knowledge and skills. One reason is that the workforce is likely to include both domain experts who are knowledgeable of CPS principles and a new type of engineer who is an expert at the intersection of cyber and physical issues. The educational backgrounds of the CPS workforce are determined by a mix of university programs that are influenced by available resources, institutional perspectives, and the demand from students and employers. As the field of CPS matures, education and employer demand will co-evolve.

FINDING: Given that most entry-level engineering and computer science positions are filled by undergraduates, it is important to incorporate CPS into the undergraduate engineering and computer science curricula.

RECOMMENDATION: NSF together with universities should support the creation and evolution of undergraduate education courses, programs, and pathways so that engineering and computer science graduates have more opportunities to gain knowledge and skills required to engineer CPS. The efforts should be complemented by initiatives to augment the skills of the existing workforce through continuing education and Master's degree programs.

DESIGNING CPS CURRICULA

The report identifies three broad areas that CPS education programs should cover: the principles of CPS, foundational skills, and system characteristics.

Principles of CPS - CPS curricula should define how physical and cyber features are *integrated* in areas like communication and networking, real-time operation, distributed and embedded systems, physical properties of hardware and the environment, and human interaction. CPS bridge engineering and physical world applications with the computer engineering and computer science cyber worlds. Basic principles of the physical world include physics, mathematical modeling, analysis, and algorithm and systems design and deals with their associated uncertainty and risk. Principles of the cyber worlds deal with embedded computation and communications hardware systems, software programming, and networking. Because sensors are a key hardware bridge between the physical and cyber worlds, it is also important to understand the properties of sensors and their real-world behavior, and techniques for processing the signals they produce. Control theory is an important tenet of CPS; relevant elements include stability, optimization, and how to control distributed, digital systems.

Foundational Skills - Drawing on the principles of CPS, CPS curricula should cover the following topics to give students a strong intellectual foundation:

1. ***Basic computing concepts*** beyond what is covered in introductory programming courses, such as embedded hardware, data structures, automata theory, and software engineering.

2. ***Computing for the physical world***, which involves understanding physical world properties, real-time embedded systems, and computing resource constraints such as power and memory size.

3. ***Discrete and continuous mathematics*** beyond calculus, such as differential equations, probability and stochastic processes, and linear algebra.

4. ***Crosscutting applications for sensing, actuation, control, and communication*** including the central role of interactions between physical and cyber aspects and how to control communication networks, sensing, signal processing, and actuation with real-time constraints.

5. ***Modeling of heterogeneous and dynamic systems integrating control, computing, and communications*** with emphasis on uncertainty and system heterogeneity, including techniques such as linear and nonlinear models, stochastic models, discrete-event and hybrid models, and associated design methodologies based on optimization, probability theory, and dynamic programming.

6. ***CPS development***, especially for safety-critical, high-confidence, and resilient systems, requires a life-cycle view from initial requirements to testing, certification, and in-service use. This should include formal verification and validation procedures and adaptable designs that can accommodate system evolution.

System Characteristics - Many CPS are large, complex, and/or safety-critical. CPS curricula should focus on the key characteristics required for the successful development of CPS including security and privacy, interoperability and reliability, safety, power and energy management, stability and performance, and human factors and usability. These topics are best introduced early and infused throughout in CPS coursework and projects.

OPPORTUNITIES AND OBSTACLES FOR INSTITUTIONALIZING CPS CURRICULA

The nature of CPS makes it difficult to develop and teach CPS-focused curricula. Challenges include:

Drawing students to CPS. Although students may be interested in CPS technologies or in the applications that CPS enable, they may not realize that they ought to seek out courses or a program that emphasizes CPS knowledge and skills. At the undergraduate level, it is important to expose STEM-oriented students to the field and the potential benefits of studying CPS. CPS engineering courses and programs should consider leveraging student interest in areas such as robotics, Internet of things, health care, and smart cities when advertising their programs and when selecting examples to use for courses and projects.

Recruiting, retaining, and developing faculty. Few mechanisms exist to support extensive faculty commitment to a new interdisciplinary field, which makes it hard to develop, recruit, and retain the faculty needed to provide an up-to-date CPS education for undergraduate students. Both research funding and opportunities for academic advancement are needed to develop a pool of faculty. NSF's Cyber-Physical Systems program has helped build an academic community around CPS and foster links between academia and industry.

Developing needed courses and instructional material. The number of textbooks, curricular materials, and laboratory facilities that exist to support CPS remains limited. Just as merely regrouping current classes will not yield a CPS curriculum, current texts may not fully incorporate the effects of the physical system on cyber technology, and vice-versa. Furthermore, often the complexity of CPS demands that students gain a full understanding of how the physical environment impacts these systems. Realistic models can provide some of this knowledge, but testbeds will be needed for students to fully recognize the constraints the physical environment can create.

Paths to CPS Knowledge

Exposure to CPS in K-12. Incorporating some knowledge into K-12 courses such as basic calculus, physics, programming, or robotics could relieve some of the pressure on an already-crowded undergraduate curriculum and would help ensure that students arrive ready to embark on a CPS-focused curriculum when they begin their undergraduate studies.

Vocational and community college programs. Adding CPS skills to community college programs would not only create paths to 4-year CPS degrees but would also train the workforce that will be needed to operate and maintain increasingly complex CPS. Mid-career engineers may also need to bolster their skills and knowledge as their jobs increasingly involve CPS.

Inclusion of CPS in introductory engineering and computer science courses. The majority of engineers will need a basic understanding in the complexities of building and maintaining CPS.

One or more CPS survey courses taught at the undergraduate level. Survey courses provide students with a basic understanding of CPS and the key design challenges, both of which are especially important for domain experts from the individual engineering disciplines.

Engineering programs that include a CPS concentration or focus. Although several engineering fields, such as mechanical and aerospace engineering, have begun incorporating some CPS principles, they may also benefit from a more deliberate approach to teaching CPS foundations.

A (new) bachelor's-level CPS engineering degree. The committee believes that the creation of a new type of engineer—a CPS engineer who is an expert at the intersection of the cyber and physical issues—will be needed to meet workforce needs.

A master's-level CPS degree. A handful of graduate degree programs that focus on embedded systems or CPS exist, chiefly with an electrical engineering or computer science slant. An M.Sc. program aimed at graduates from other engineering fields, such as mechanical or civil engineering, would also be valuable.

Ph.D. programs in CPS. The educational content in master's-level programs may suffice for some or all of the training of future faculty, but demand for CPS faculty, combined with industry demand for Ph.D. training and sustained research funding, is likely to spur institutions to establish Ph.D. programs.

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