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Cyber-Physical Systems

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Autonomous cars. Robots at work, at play, at home. Intelligent, energy-efficient, earthquake-proof buildings. Physical infrastructure monitored and controlled by sensor nets. Embedded medical devices. Unobtrusive assistive technology. What is common to these systems? They have a computational core that interacts with the physical world. These *cyber-physical systems* are engineered systems that require tight conjoining of and coordination between the computational (discrete) and the physical (continuous). Cyber-physical systems are rapidly penetrating every aspect of our lives, with potential impact on sectors critical to U.S. security and competitiveness, including aerospace, automotive, chemical production, civil infrastructure, energy, finance, healthcare, manufacturing, materials, and transportation.

The trend in cyber-physical systems is to rely less and less on human intervention and decision-making and more and more on the intelligence as embodied in the computational core. In some cases, such as an automated brake system in a smart car, this computational core may be able to detect and respond faster than a human; in some cases, such as robotic surgery, this computational core can be more precise than a human and not prone to fatigue; and in some cases, such as a minefield, an icefield, or a volcano, we would rather risk the expense of a machine over the life of a human. In all cases, it will likely be the software that provides much of the intelligence of the computational core.

Our daily lives will depend more and more on these systems. Our lives, our money, our welfare. A challenge for our community then is "How can we design cyber-physical systems people can bet their lives on?"

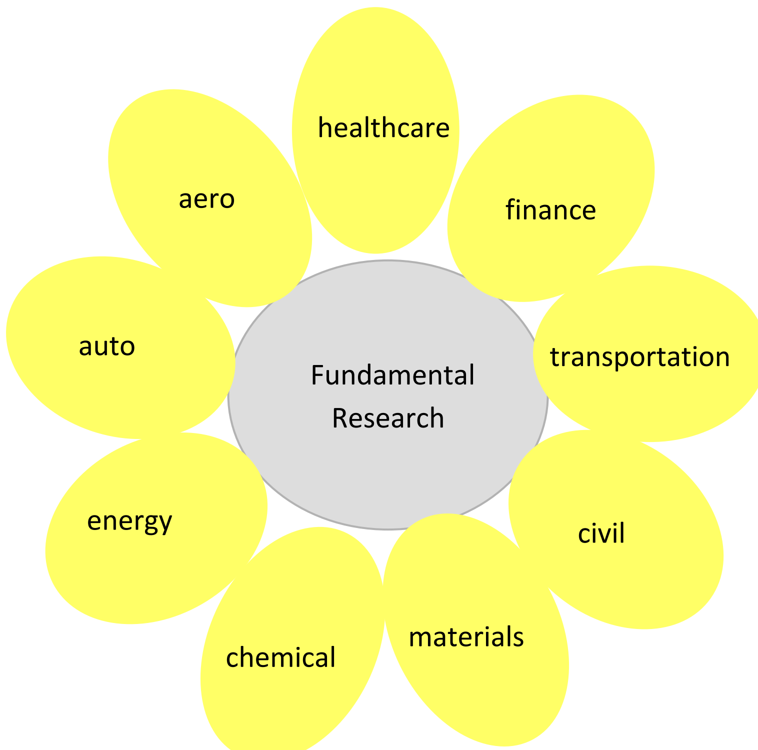
One technical challenge is how to deal with both the discrete and continuous worlds at the same time. Cyber-physical systems inherently operate under the presence of uncertainty, including disruptive events, in the physical world, where uncertainty may be due to Mother Nature or The Human (angelic or demonic). Intelligent cyber-physical systems will ideally not only be aware of and adaptable to a dynamic, unpredictable environment, but also do no harm. Perception, control, and coordination are essential to cyber-physical systems.

In computing, we rely on rich abstractions to compose hierarchically designed systems, where some abstractions even lend themselves to advanced verification techniques, especially as used to find subtle design bugs; however, we use these abstractions primarily to capture functional behavior and treat multiple competing influences in cyber-physical systems as "non-functional" requirements. Typically, we make overly simplifying assumptions about the environment and avoid explicit representation of time, space, energy, temperature, and other aspects of the physical world. Compositional reasoning, the ability to infer system behavior from component behavior, may be impossible for some of these requirements, especially when taken all together.

In engineering, we cautiously over-design our systems with wide margins to achieve physical fault separation and isolation; however, we tend to ignore intrinsic aspects of computing and communication, such as scheduling, resource management, network delays, and computational failures, since they are often regarded as secondary implementation issues. This "separation of concerns" principle, while crucial for tractability, often imposes an early architectural separation between the cyber and physical features of the system, thereby severely limiting our ability to assess the impact and tradeoffs among a full range of design alternatives.

Bridging the two worlds of the cyber and physical will be smart sensors, transponders, and actuators, likely in new and diverse form factors. Some applications will require new camera technologies to perceive and track moving objects, especially people.

The Cyber Physical Systems (CPS) Program (http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503286&org=CISE), spearheaded by NSF's Directorates for Computer and Information Science and Engineering (CISE) and Engineering (ENG), is providing an opportunity for the community to realize the vision of tomorrow's cyber-physical systems. The CPS Program seeks new scientific foundations and technologies to address the challenges of cyber-physical systems and to enable rapid deployment of applications across different sectors. We encourage different research communities to work together, bringing their different perspectives and expertise to the table. The goal is to usher in a new generation of cyber-physical systems whose functional performance far exceeds those of today in terms of adaptability, autonomy, efficiency, functionality, perception, reliability, safety, and usability.



To expedite progress, we hope to cultivate the "flower model" (see picture). Advances in fundamental research (center of flower) are inspired by problems from one or more domain sectors (petals of flower). Given a problem specific to one domain, a researcher might generalize the problem or generalize the solution (where both kinds of generalizations contribute to fundamental knowledge, the center), and then instantiate the solution to solve a similar problem in a different domain. Progress in one domain immediately benefits all other domains, avoiding duplication of effort or building point solutions that are not reusable. We hope that the virtual organization described in the CPS Program solicitation can facilitate the needed exchange both among different research communities and between industry and academia to effect this flower model.