

Architecting the Future of Software Engineering: A Research and Development Roadmap
by Anita Carleton, John Robert, Mark Klein, Dr. Doug Schmidt, Dr. Forrest Shull, John Foreman,
Dr. Charlie Holland, Dr. Jeff Boleng, Erin Harper

Software is vital to our country’s global competitiveness, innovation, and national security. It also ensures our modern standing of living and enables continued advances in defense, infrastructure, healthcare, commerce, education, and entertainment. As the DoD’s federally funded research and development center (FFRDC) focused on improving the practice of software engineering, the Carnegie Mellon University (CMU) Software Engineering Institute (SEI) is leading the community in creating a multi-year research and development vision and roadmap for engineering next-generation software-reliant systems. This article motivates and describes that effort.

Software Engineering as Strategic Advantage

In a [2020 National Academy of Science Study on Air Force software sustainment](#), the U.S. Air Force recognized that “to continue to be a world-class fighting force, it needs to be a world-class software developer.” This concept clearly applies far beyond the Department of Defense. Software systems enable world-class healthcare, commerce, education, energy generation, and more. These systems that run our world are rapidly becoming more data intensive and interconnected, increasingly utilize AI, require larger-scale integration, and must be considerably more resilient. Consequently, significant investments in software engineering R&D is needed now to enable and ensure future capability.

Goals of This Work

The SEI is leveraging its connections with academic institutions and communities, DoD leaders and members of the [Defense Industrial Base](#), and industry innovators and research organizations to:

- identify future challenges in engineering software-reliant and intelligent systems in emerging, national-priority technical domains, including gaps between current engineering techniques and future domains that will be more reliant on autonomy and AI
- develop a research roadmap that will drive advances in foundational software engineering principles across a range of system types, such as intelligent, autonomous, safety-critical, and data-intensive systems
- raise the visibility of software to the point where it receives the sustained recognition commensurate with its importance to national security and competitiveness
- enable strategic partnerships and collaborations to drive innovation among industry, academia, and government.

Guided by an Advisory Board of U.S. Visionaries and Senior Thought Leaders

To succeed in developing our vision and roadmap for software engineering research and development, it is vital to coordinate the academic, defense, and commercial communities to define an effective agenda and implement impactful results. To help represent the views of all these software engineering constituencies, the SEI formed an advisory board from DoD, industry, academia, research labs, and technology companies to offer guidance. Members of this advisory board include the following:

Carnegie Mellon University

Software Engineering Institute

- **Dr. Deb Frincke**, *Advisory Board Chair, Associate Laboratory Director for National Security Sciences, Oak Ridge National Laboratory*
- **Dr. Michael McQuade**, *Vice President for Research, Carnegie Mellon University*
- **Dr. Vint Cerf**, *Vice President and Chief Internet Evangelist, Google*
- **Ms. Penny Compton**, *Vice President for Software Systems, Cyber, and Operations, Lockheed Martin Space*
- **Mr. Tim Dare**, *Deputy Director for Prototyping and Software, Office of the Under Secretary of Defense for Research and Engineering (previous position)*
- **Ms. Sara Manning Dawson**, *Chief Technology Officer Enterprise Security, Microsoft*
- **Mr. Jeff Dexter**, *Senior Director of Flight Software & Cybersecurity, SpaceX*
- **Dr. Yolanda Gil**, *President, Association for the Advancement of Artificial Intelligence (AAAI); Director of Knowledge Technologies, Information Sciences Institute at University of Southern California*
- **Mr. Tim McBride**, *President, Zoic Studios*
- **Ms. Nancy Pendleton**, *Vice President and Senior Chief Engineer for Mission Systems, Payloads and Sensors, Boeing Defense, Space and Security*
- **Dr. William Scherlis**, *Director Information Innovation Office, DARPA*

In June 2020, the SEI assembled this board to leverage their diverse perspectives and provide strategic advice, influence stakeholders, develop connections, assist in executing the roadmap, and advocate for the use of our results.

Future Systems and Fundamental Shifts in Software Engineering Require New Research Focus

Rapidly deploying software with confidence requires fundamental shifts in software engineering. New types of systems will continue to push beyond the bounds of what current software engineering theories, tools, and practices can support, for example:

- Systems that fuse data at a huge scale, whether for news, entertainment, or intelligence: We will need to continuously mine vast amounts of open-source data streams (e.g., YouTube videos) for important information that will in turn drive decision making. This vast stream of data will also drive new ways of constructing systems.
- Highly engineering smart cities, buildings, roads, cars, and transport: How will these highly connected systems work together seamlessly? How will we enable safe and affordable transportation and living?
- Personal digital assistants: How will these assistants learn, adapt, and engage in home and business workflows?
- Dynamically integrated healthcare: Data from your personal device will be combined with hospital data. How do we meet stringent safety and privacy requirements? How do we evaluate assurance in a highly data-driven environment?
- Mission-level adaptation for DoD systems: DoD systems will feature mission-level construction of new integrated systems that combine a range of capabilities, such as intel, weapons, and human/machine teaming. The DoD is already moving in this direction, but how can we increase confidence that there will be no unintended consequences?

Research Focus Areas

These fundamental shifts in software engineering outlined above will require new research focus areas. The following research focus areas have been identified to date by the SEI and its partners in this effort:

- **AI-Augmented Software Development:** Each stage of the software journey will be augmented by AI. We must leverage advances in deep learning and search-based algorithms for next generation software design, evolution, and conformance tools, to enable routine use of sound software engineering principles.
- **Software Construction through Compositional Correctness:** This research area focuses on the development of software-reliant systems (and systems of systems) constructed from modular and assurable components, where behaviors and attributes of the compositions are provably more robust and resilient than the component parts in isolation.
- **Assuring Continuously Evolving Systems:** This research area focuses on providing evidence-based assurance arguments that a system will behave as intended, considering both desired functionality and quality attributes, as it evolves continuously to incorporate new capabilities and dynamically self-adapts its operating configuration(s) at runtime in response to changing mission demands and environmental conditions.
- **Engineering Socio-Technical Systems:** Societal-scale systems will define foundational approaches that account for human behavior at scale with self-reflection and correction of continuously evolving socio-technical ecosystems. This research area is about building and evolving societal-scale software systems that enable the benefits of large-scale societal interactions while mitigating ethical risks associated with privacy, bias, trust, concealed influence, or unrestrained social manipulation.
- **Engineering AI-enabled Software Systems:** Repeatable and scalable practices, techniques, and automation are needed to engineer reliable software and AI-enabled systems that meet their business and mission goals within their resource constraints. This area will focus on applying and creating engineering practices for software and AI-enabled systems and applying automation using AI that can improve quality and efficiency.
- **Engineering Quantum Computing Systems:** Advances in software and software engineering will be needed to implement quantum computing systems. This research area will focus on categories such as quantum algorithms, development tools and languages, computing platforms, and testbeds.

Help Shape Our National Software Research Agenda

Along with the advisory board, our research team has thus far examined future trends in the computing landscape and emerging technologies; conducted a series of expert interviews; and convened multiple workshops for broad engagement and diverse perspectives, including a workshop on Software Engineering Grand Challenges and Future Visions co-hosted with the [Defense Advanced Research Projects Agency \(DARPA\)](#). This workshop informed the SEI's software engineering research agenda and brought together leaders in the software engineering research and development community to describe (1) important classes of future software-reliant systems and their associated software engineering challenges, and (2) research methods, tools, and practices that are needed to make those systems feasible.

Your feedback would be appreciated on the software engineering challenges and proposed research focus areas to help inform the National Agenda for Software Engineering Study. Please email sei-nas@sei.cmu.edu to send your thoughts and comments on the software engineering study & research roadmap or to volunteer as a potential reviewer of study drafts. Thank you.

Carnegie Mellon University
Software Engineering Institute

Copyright 2021 Carnegie Mellon University.

This material is based upon work funded and supported by the Department of Defense under Contract No. FA8702-15-D-0002 with Carnegie Mellon University for the operation of the Software Engineering Institute, a federally funded research and development center.

The view, opinions, and/or findings contained in this material are those of the author(s) and should not be construed as an official Government position, policy, or decision, unless designated by other documentation.

NO WARRANTY. THIS CARNEGIE MELLON UNIVERSITY AND SOFTWARE ENGINEERING INSTITUTE MATERIAL IS FURNISHED ON AN "AS-IS" BASIS. CARNEGIE MELLON UNIVERSITY MAKES NO WARRANTIES OF ANY KIND, EITHER EXPRESSED OR IMPLIED, AS TO ANY MATTER INCLUDING, BUT NOT LIMITED TO, WARRANTY OF FITNESS FOR PURPOSE OR MERCHANTABILITY, EXCLUSIVITY, OR RESULTS OBTAINED FROM USE OF THE MATERIAL. CARNEGIE MELLON UNIVERSITY DOES NOT MAKE ANY WARRANTY OF ANY KIND WITH RESPECT TO FREEDOM FROM PATENT, TRADEMARK, OR COPYRIGHT INFRINGEMENT.

[DISTRIBUTION STATEMENT A] This material has been approved for public release and unlimited distribution. Please see Copyright notice for non-US Government use and distribution.

Internal use:* Permission to reproduce this material and to prepare derivative works from this material for internal use is granted, provided the copyright and "No Warranty" statements are included with all reproductions and derivative works.

External use:* This material may be reproduced in its entirety, without modification, and freely distributed in written or electronic form without requesting formal permission. Permission is required for any other external and/or commercial use. Requests for permission should be directed to the Software Engineering Institute at permission@sei.cmu.edu.

* These restrictions do not apply to U.S. government entities.

DM21-0333