NATIONAL ACADEMIES Sciences Engineering Medicine

Foundational Research Gaps and Future Directions for Digital Twins

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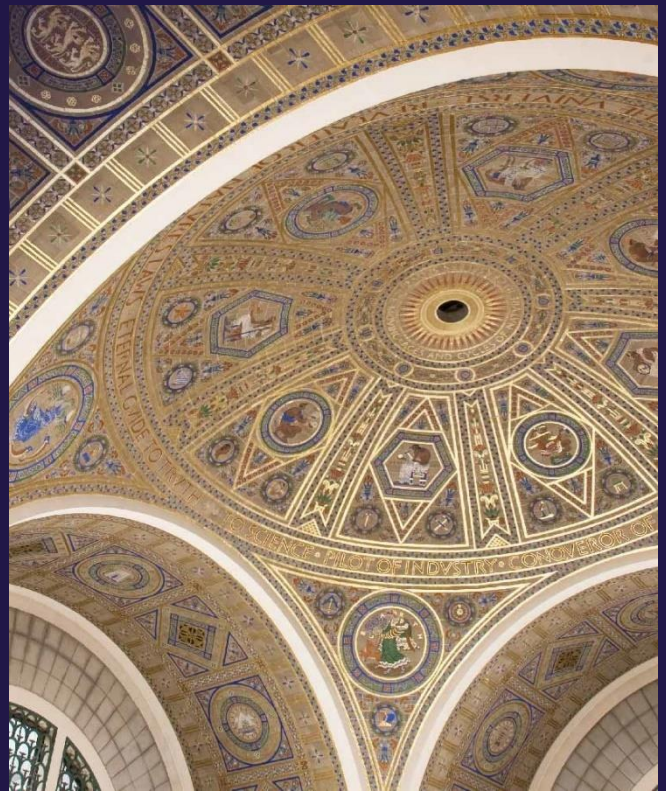
Director, Board on Mathematical Sciences and Analytics

The National Academies



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FOUNDED IN 1863

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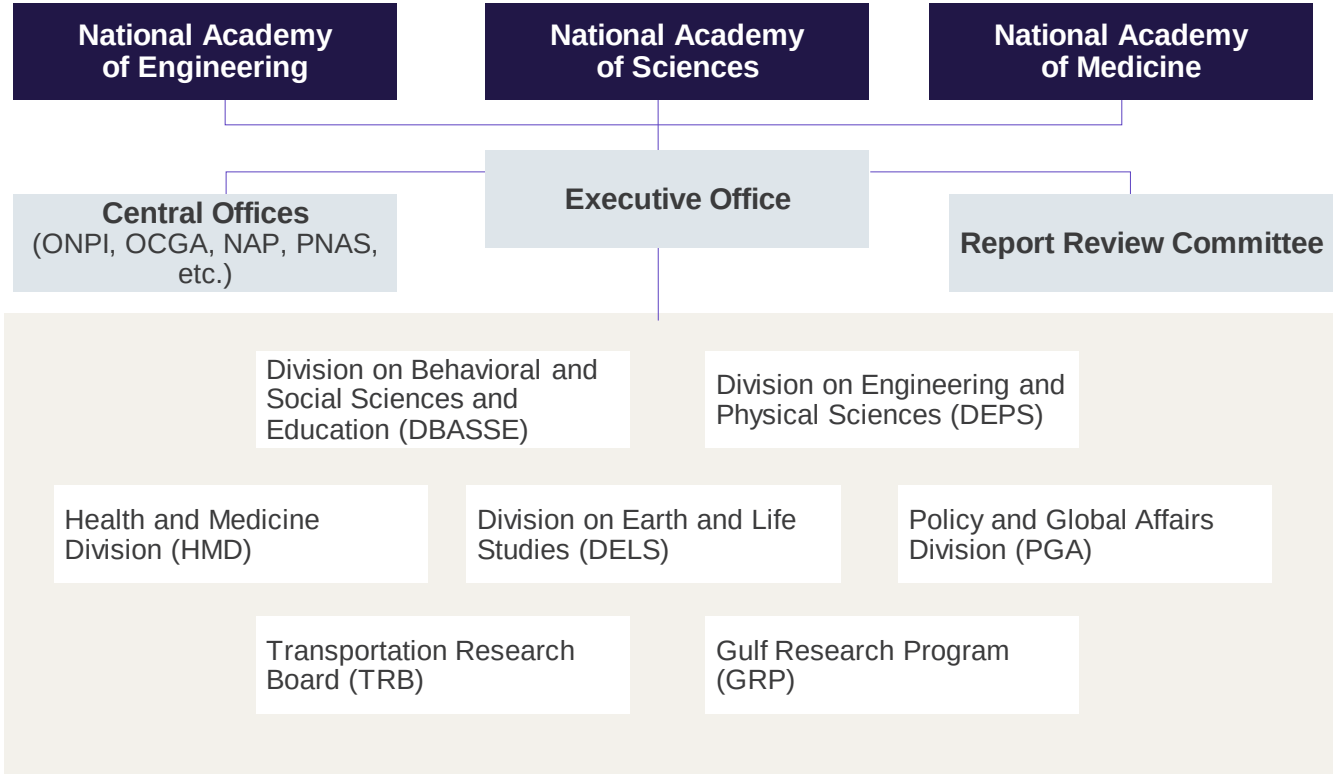
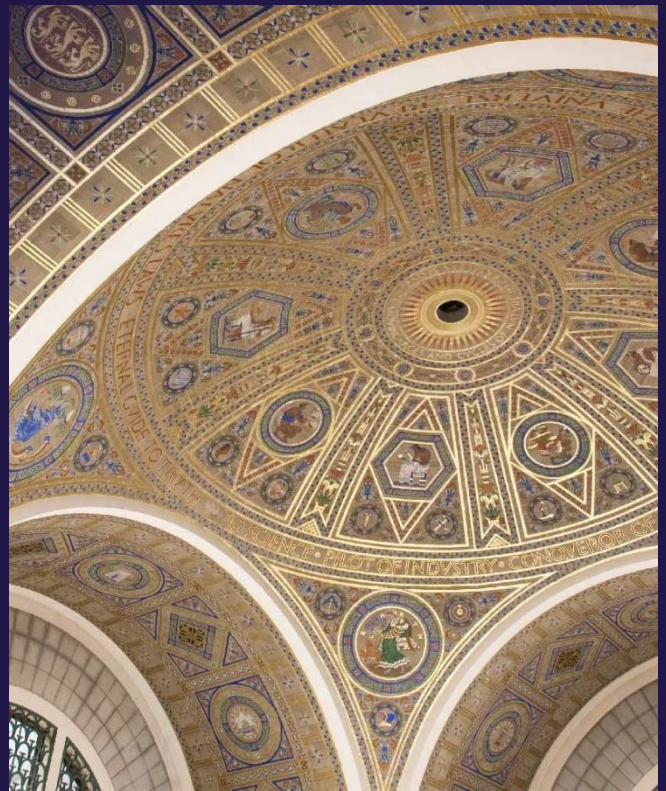
Program Units within the Academies



Digital Twin Study



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What is a “Digital Twin?”

“[A] set of virtual information constructs that mimics the structure, context and behavior of an individual/unique physical asset, or a group of physical assets, is dynamically updated with data from its physical twin throughout its life cycle and informs decisions that realize value”

American Institute of Aeronautics and Astronautics Digital Engineering Integration Committee. 2020. “Digital Twin: Definition & Value.” AIAA and AIA Position Paper, AIAA, Reston, VA.

Statement of Task

A National Academies of Sciences, Engineering, and Medicine-appointed ad hoc committee will identify needs and opportunities to advance the mathematical, statistical, and computational foundations of digital twins in applications across science, medicine, engineering, and society. In so doing, the committee will address the following questions:

- How are digital twins defined across communities?
- What foundational gaps or opportunities vary across application domains?
- What best or promising practices for digital twins are emerging within and across application domains?
- What opportunities exist for translation of best practices across domains?
- What use cases could advance awareness of and confidence in digital twins?
- What are the key challenges and opportunities in the research, development, and application of advancements in digital twins?

Sponsors

- Department of Energy
  - Advanced Scientific Computing Research
  - Biological and Environmental Research
- National Institutes of Health
  - National Cancer Institute
  - Office of Data Science Strategy
  - National Institute of Biomedical Imaging and Bioengineering
- National Science Foundation
  - Engineering Directorate
  - Mathematical and Physical Sciences Directorate
- Department of Defense
  - Air Force Office of Scientific Research
  - Defense Advanced Research Projects Agency

Collaborative Divisions and Boards

This project is being conducted under the auspices of the Board on Mathematical Sciences and Analytics (DEPS/BMSA) in collaboration with the:

- **Division on Engineering and Physical Sciences**
  - Computer Science and Telecommunications Board
- **Division on Earth and Life Sciences**
  - Board on Atmospheric Sciences and Climate
  - Board on Life Sciences
- **National Academy of Engineering**

Committee Members

- Karen Willcox (NAE; chair), UT Austin
- Derek Bingham, Simon Fraser University
- Caroline Chung, MD Anderson
- Julianne Chung, Emory
- Carolina Cruz-Neira (NAE), UCF
- Conrad Grant, JHUAPL
- Jim Kinter, George Mason
- Ruby Leung (NAE), PNNL
- Parviz Moin (NAS/NAE), Stanford
- Lucila Ohno-Machodo (NAM), Yale
- Colin Parris (NAE), GE
- Irene Qualters, LANL
- Ines Thiele, Univ. of Galway
- Conrad Tucker, CMU
- Rebecca Willett, Univ. of Chicago
- Xinyue Ye, Texas A&M

Consensus Report Progress

- Committee has met on a weekly basis since Oct 2022, including 3 large public workshops
- Focus of the report is on the foundational methods and gaps within the context of digital twins
- Primary Audience: The scientific community & federal funding organizations who support DT research
- Report is being finalized in response to peer review
- Release is anticipated this Fall

Workshops

Held three public workshops to address definitions and taxonomy, current methods and promising practices, key technical challenges and opportunities, and opportunities for translation in the:

- **Biomedical Sciences (Jan 30, 2023)**
- **Atmospheric, Climate, and Sustainability Sciences (Feb 1-2, 2023)**
- **Engineering Domains (Feb 7 & 9, 2023)**

Recordings and summaries are available at the study webpage:

https://www.nationalacademies.org/our-work/foundational-research-gaps-and-future-directions-for-digital-twins

Workshop #1: Digital Twins in Biomedical Sciences

Discussion Topics:

- Digital Twin Definitions
- Digital Twins at the Cellular and Molecular Scale
- Digital Twins at the Organ, Tumor, and Microenvironment Scale
- Digital Twins at the Whole Human, Multisystem, and Population Scale
- Connecting Across Scales
- Privacy, Ethics, and Data Issues
- Opportunities for Convergence

Workshop #1: Digital Twins in Biomedical Sciences

Opportunities:

- Develop a dynamic interaction between real world patients and digital twins to inform clinical decisions regarding interventions including treatments and clinical assessments
- Conduct virtual clinical trials

Gaps:

- Improve modeling, computation, and data — combined data-driven and mechanistic models can be useful but are limited due to complexities and understanding of the biological processes
- Managing data heterogeneity and integrating disparate multimodal data, collected across different time and size scales
- Accounting for and communicating uncertainty
- Developing trust with patients and clinicians — requires education and transparency
- Addressing ethical, privacy, and security concerns — including bias in data, models, and clinical processes
- Improving data-sharing mechanisms, especially considering data identifiability

Workshop #2: Digital Twins in Atmospheric, Climate, and Sustainability Sciences

Discussion Topics:

- Digital Twin Definitions
- Current Methods and Practices
- Key Technical Challenges and Opportunities
- Translation of Promising Practices to Other Fields
- Transparency, Societal Benefit, and Equity

Workshop #2: Digital Twins in Atmospheric, Climate, and Sustainability Sciences

Opportunities:

- Interactive simulations of Earth systems with improved prediction capabilities, support for policy decisions, and mechanisms for the community to engage with the data
- More realistic and higher resolution models, incorporating both real and synthetic data, with the potential to include more community-centric metrics

Gaps:

- Increasing observational abilities, computational capacity, mechanisms for large-scale data handling, and federated resource management
- Expanding research on parametric sparsity and generalizing observational data
- Increasing generation of training data and computation for highest possible resolution
- Improving uncertainty quantification and calibration based on both observational and synthetic data — Bayesian approaches, reduced-order and surrogate models, fast sampling, and increased user access to data could help

Workshop #3: Digital Twins in Engineering

Discussion Topics:

- Digital Twin Definitions
- Perspectives from Stakeholders (e.g., automotive, aviation, academic research)
- Current Methods and Practices
- Key Technical Challenges and Opportunities
- Digital Twin R&D Needs and Investment

Workshop #3: Digital Twins in Engineering

Opportunities:

- Provide timely and actionable information to improve asset management
- Enhance asset reliability, plan maintenance, reduce maintenance and inspection burden, and improve efficiency
- Test, design, and prototype processes and exercise virtual prototypes

Gaps:

- Connecting the simulations across length scales and physical phenomena
- Advancing experimental design as well as sensor placement and scheduling
- Capturing the sources of manufacturing, operational, and environmental variation
- Managing uncertainty propagation and quantification
- Integrating data science and domain knowledge to enable decision-making
- Managing massive amounts of data and applying advanced analytics
- Developing ontologies and harmonization among the digital twin user community

Final Report Expected this Fall

Will address:

- Digital twin definition(s) and use cases
- Cross-cutting foundational research gaps, challenges, and opportunities – e.g., modeling, simulation, uncertainty quantification, multimodal data
- Promising practices for digital twin development and use
- Opportunities for translation of best practices across domains

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Thoughts and questions?

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