Future Directions for Digital Twins

Professor Karen E. Willcox
Director, Oden Institute for Computational Engineering & Sciences
Professor, Aerospace Engineering & Engineering Mechanics
University of Texas at Austin

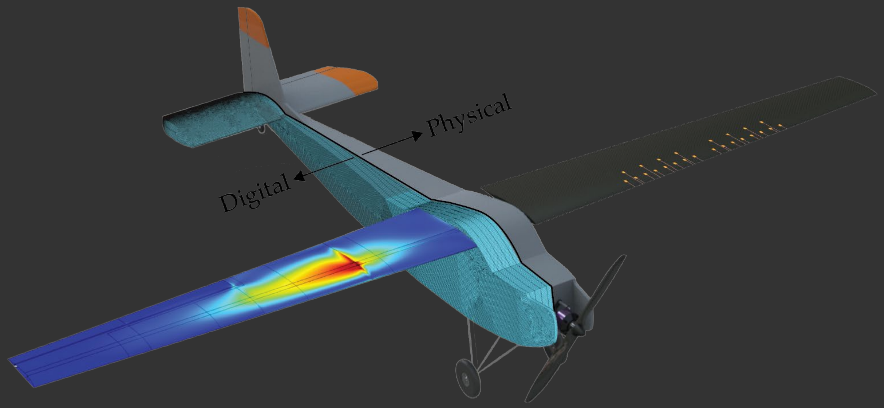
Aerospace Science and Engineering Board
National Academies
October 18, 2023

ODEN INSTITUTE
FOR COMPUTATIONAL ENGINEERING & SCIENCES

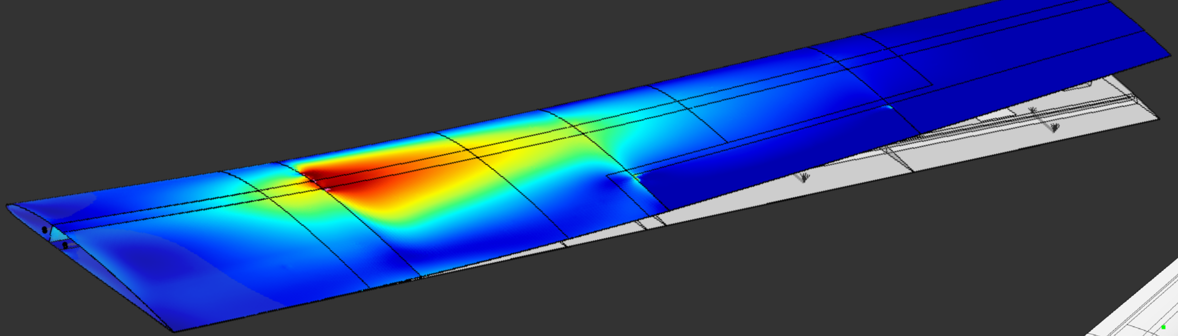
Concept — Design — Manufacturing — Operation — Post Life — Retirement

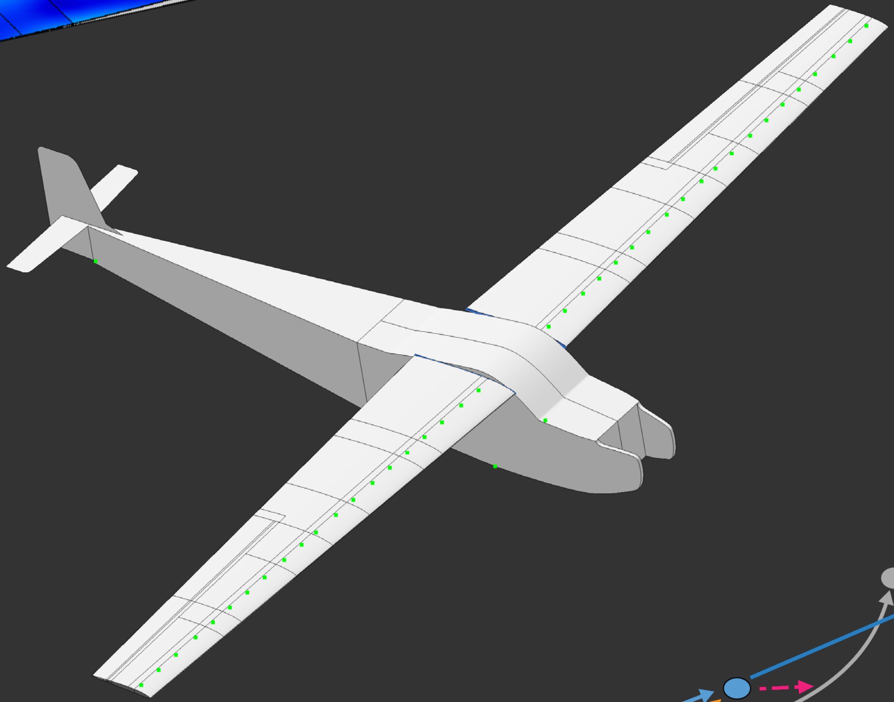
"A Digital Twin is a set of **virtual information constructs** that **mimics the structure, context, and behavior of an individual/unique physical asset**, is **dynamically updated** with data from its physical twin **throughout its lifecycle**, and **informs decisions that realize value**"

- AIAA Institute Position Paper, 2020



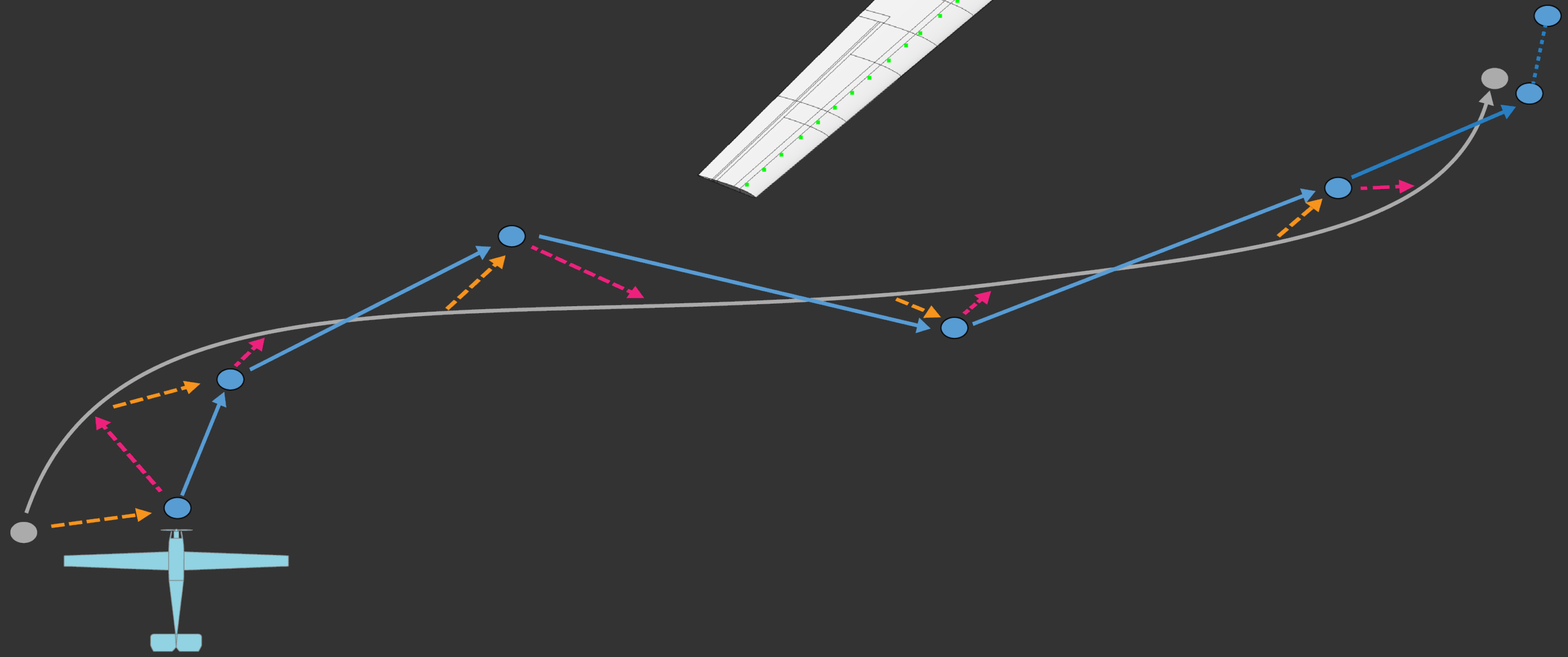
MODELS + DATA





DATA ASSIMILATION

PREDICTION



Paper for the 53rd Structures, Structural Dynamics, and Materials Conference:
Special Session on the Digital Twin

The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles

E. H. Glaessgen[*]
Durability and Damage Tolerance Branch
NASA Langley Research Center, Hampton, Virginia, 23681

D.S. Stargel[†]
Aerospace, Chemical, and Material Sciences
Air Force Office of Scientific Research, Arlington VA, 22203

Future generations of NASA and U.S. Air Force vehicles will require lighter mass while being subjected to higher loads and more extreme service conditions over longer time periods than the present generation. Current approaches for certification, fleet management and sustainment are largely based on statistical distributions of material properties, heuristic design philosophies, physical testing and assumed similitude between testing and operational conditions and will likely be unable to address these extreme requirements. To address the shortcomings of conventional approaches, a fundamental paradigm shift is needed. This paradigm shift, the Digital Twin, integrates ultra-high fidelity simulation with the vehicle's on-board integrated vehicle health management system, maintenance history and all available historical and fleet data to mirror the life of its flying twin and enable unprecedented levels of safety and reliability.

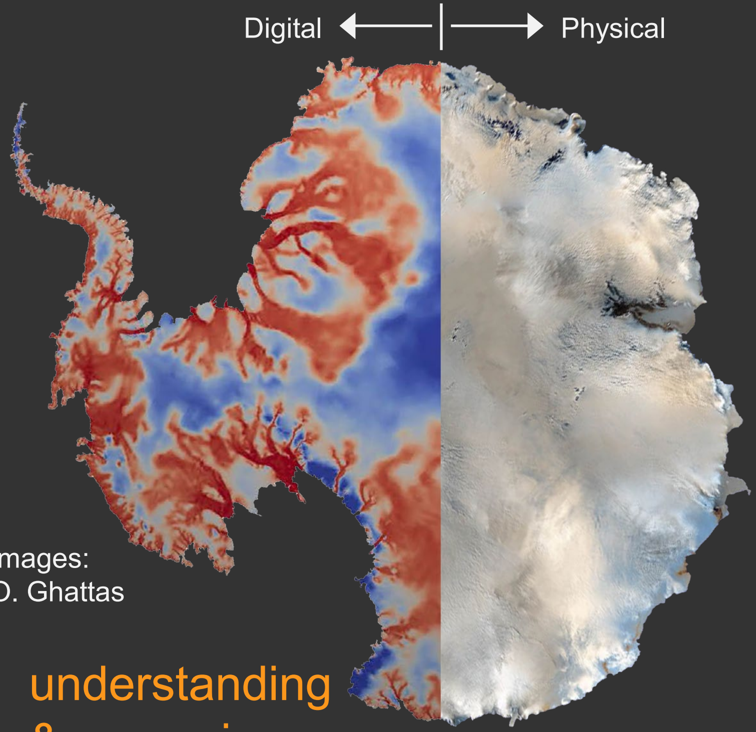
Introduction

Existing methodologies for vehicle certification, fleet management and sustainment are largely based on similitude and a heuristic understanding of the effects of operational and anomalous conditions on the structural health, safety and performance of a vehicle. A common manifestation of similitude and heuristics is in the form of the "factors-of-safety" used during design and certification. So-called factors-of-safety are rooted in a heuristic legacy wherein a factor of, say, 1.5 or 2.0 has "always" been sufficient to account for a particular class of unknown unknowns (e.g., loads, material properties). Often, the history and pedigree of such factors is uncertain.

Additionally, compounding of factors-of-safety is pervasive and may lead to unnecessarily heavy structures and reduced performance without necessarily improving the actual safety of the vehicle or the probability of mission success. Even current probabilistic or reliability methodologies are inadequate because they are based on assumed similitude between the circumstances in which the underlying statistics were obtained and the environment in which the vehicle operates. When similitude is violated, probabilistic methods break down as readily as those based on factors-of-safety. Although statistical assessments are important, they must be part of an overall best-physics approach that is relevant to each individual vehicle.

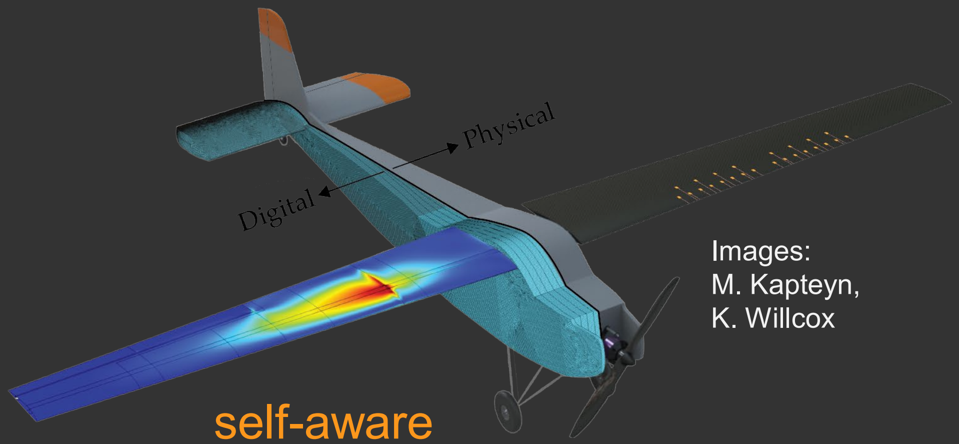
[*] Assistant Branch Head. Associate Fellow AIAA
[†] Program Manager. Senior Member AIAA

Digital twins have the potential to revolutionize **decision-making across science, technology & society**



Images:
O. Ghattas

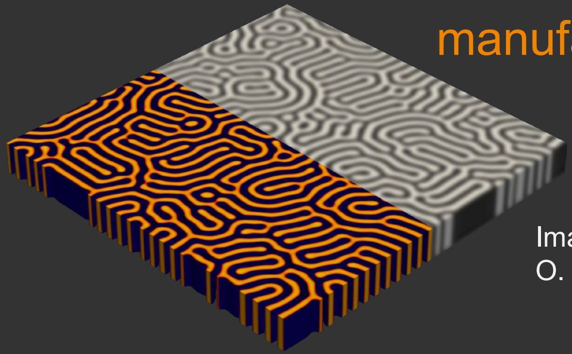
understanding
& managing
climate change



self-aware
aerospace
vehicles

Images:
M. Kapteyn,
K. Willcox

advanced
manufacturing



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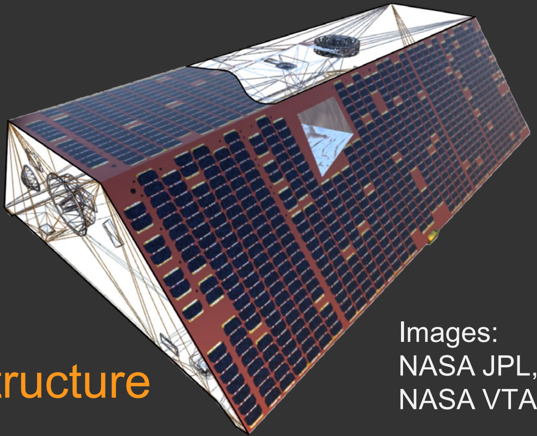
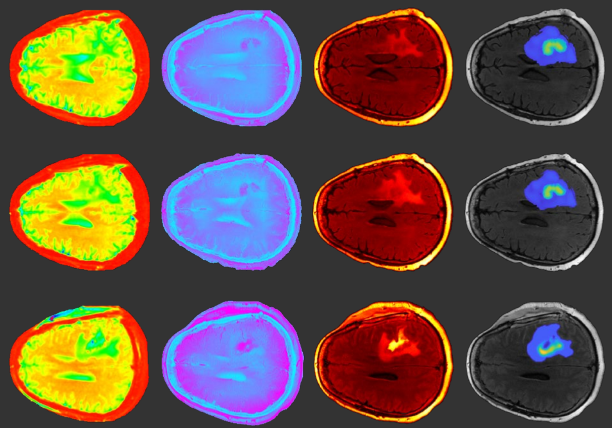
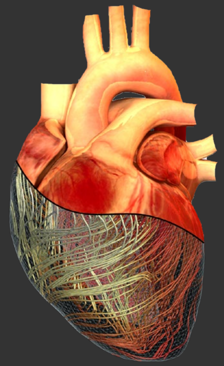
O. Ghattas



space
infrastructure

Images:
NASA JPL,
NASA VTAD





Images:
G. Foss, H. Liu, M. Sacks,
D. Hormuth, T. Yankeelov

patient-specific medicine

NATIONAL ACADEMIES Sciences Engineering Medicine

Foundational Research Gaps and Future Directions for Digital Twins

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.

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

NATIONAL ACADEMIES *Sciences Engineering Medicine*

Proceedings of a Workshop—in Brief

Opportunities and Challenges for Digital Twins in Atmospheric and Climate Sciences

Proceedings of a Workshop—in Brief

The digital twin is an emerging technology that builds on the convergence of computer science, mathematics, engineering, and the life sciences. Digital twins have the potential to revolutionize atmospheric and climate sciences in particular, as they could be used, for example, to create global-scale interactive models of Earth to predict future weather and climate conditions over longer timescales.

On February 1–2, 2023, the National Academies of Sciences, Engineering, and Medicine hosted a public, virtual workshop to discuss characterizations of digital twins within the context of atmospheric, climate, and sustainability sciences and to identify methods for their development and use. Workshop panelists presented varied definitions and taxonomies of digital twins and highlighted key challenges as well as opportunities to translate promising practices to other fields. The second in a three-part series, this evidence-gathering workshop will inform a National Academies consensus study on research gaps and future directions to advance the mathematical, statistical, and computational foundations of digital twins in applications across science, medicine, engineering, and society.[1]

PLENARY SESSION: DEFINITIONS OF AND VISIONS FOR THE DIGITAL TWIN

During the plenary session, workshop participants heard presentations on the challenges and opportunities for Earth system digital twins, the history of climate modeling and paths toward traceable model hierarchies, and the use of exascale systems for atmospheric digital twins.

Umberto Modigliani, European Centre for Medium-Range Weather Forecasts (ECMWF), the plenary session's first speaker, provided an overview of the European Union's Destination Earth (DestinE) initiative,[2] which aims to create higher-resolution simulations of the Earth system that are based on models that are more realistic than those in the past; better ways to combine observed and simulated information from the Earth system; and interactive and configurable access to data, models, and workflows. More realistic simulations at the global scale could translate to information at the regional scale that better supports decision-making for climate adaptation and mitigation through tight integration and interaction with impact sector models. Now in the first phase (2021–2024) of its 7- to 10-year program, DestinE is beginning

[1] To learn more about the study and to watch videos of the workshop presentations, see https://www.nationalacademies.org/our-work/foundational-research-gaps-and-future-directions-for-digital-twins, accessed February 10, 2023.

[2] The website for DestinE is https://digital-strategy.ec.europa.eu/en/policies/destination-earth, accessed March 9, 2023.

NATIONAL ACADEMIES *Sciences Engineering Medicine*

Proceedings of a Workshop—in Brief

Opportunities and Challenges for Digital Twins in Engineering

Proceedings of a Workshop—in Brief

The digital twin is an emerging technology that builds on the convergence of computer science, mathematics, engineering, and the life sciences. Digital twins have potential across engineering domains, from aeronautics to renewable energy. On February 7 and 9, 2023, the National Academies of Sciences, Engineering, and Medicine hosted a public, virtual workshop to discuss characterizations of digital twins within the context of engineering and to identify methods for their development and use. Panelists highlighted key technical challenges and opportunities across use cases, as well as areas ripe for research and development (R&D) and investment. The third in a three-part series, this evidence-gathering workshop will inform a National Academies consensus study on research gaps and future directions to advance the mathematical, statistical, and computational foundations of digital twins in applications across science, medicine, engineering, and society.[1]

PLENARY SESSION 1: DIGITAL TWINS IN STRUCTURAL ENGINEERING

Charles Farrar, Los Alamos National Laboratory (LANL), explained that many digital twins are computer-based digital models of physical systems that interface with data. A ban on system-level nuclear testing[2] as well as increased investments in high-performance computing hardware, code development, and verification and validation methods and experiments enabled initial advances in "digital twin technology" at LANL beginning in 1992. He emphasized that a digital twin is shaped by questions; as those questions evolve, the digital twin evolves to incorporate more detailed physical phenomena, geometry, and data and to account for more sources of uncertainty.

Farrar underscored that validation data are often difficult and costly to obtain and replicating actual loading environments is challenging. All real-world structures have variable properties, and incorporating this variability into modeling is particularly difficult. Most structural models are deterministic but their inputs are often probabilistic. Therefore, he said, uncertainty could be incorporated by varying model parameters based on known or assumed probability distributions.

Farrar indicated that digital twins could include physics-based (e.g., finite element), data-driven (e.g., machine

[1] To learn more about the study and to watch videos of the workshop presentations, see https://www.nationalacademies.org/our-work/foundational-research-gaps-and-future-directions-for-digital-twins, accessed February 23, 2023.

[2] In September 1992, the Senate passed the Hatfield-Exon-Mitchell Amendment, a 9-month moratorium on nuclear testing that preceded the Comprehensive Nuclear-Test-Ban Treaty of 1996.

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NATIONAL ACADEMIES *Sciences Engineering Medicine*

Proceedings of a Workshop—in Brief

Opportunities and Challenges for Digital Twins in Biomedical Research

Proceedings of a Workshop—in Brief

The digital twin (DT) is an emerging technology that builds on the convergence of computer science, mathematics, engineering, and the life sciences. Given the multiscale nature of biological structures and their environment, biomedical DTs can represent molecules, cells, tissues, organs, systems, patients, and populations and can include aspects from across the modeling and simulation ecosystem. DTs have the potential advance biomedical research with applications for personalized medicine, pharmaceutical development, and clinical trials.

On January 30, 2023, the National Academies of Sciences, Engineering, and Medicine hosted a public, virtual workshop to discuss the definitions and taxonomy of DTs within the biomedical field, current methods and promising practices for DT development and use as various levels of complexity, key technical challenges and opportunities in the near and long term for DT development and use, and opportunities for translation of promising practices from other field and domains. Workshop panelists highlighted key challenges and opportunities for medical DTs at varying scales, including the varied visions and challenges for DTs, the trade-offs between embracing or simplifying complexity in DTs, the unique spatial and temporal considerations that arise, the diversity of models and data being used in DTs, the challenges with connecting data and models across scales, and implementation issues surrounding data privacy in DTs. The first in a three-part series, this information-gathering workshop will inform a National Academies consensus study on research gaps and future directions to advance the mathematical, statistical, and computational foundations of DTs in applications across science, medicine, engineering, and society.[1]

VISIONS AND CHALLENGES FOR DIGITAL TWINS

Reinhard Laubenbacher, University of Florida, the plenary session's first speaker, described the DT as a computational model that represents a physical system; a data stream between the system and the model is used to recalibrate the model periodically so that it continues to represent the system as it changes over the lifespan of its operation. He stated that DTs are revolutionizing industry (e.g., aeronautics) with applications including forecasting and preventative maintenance. He proposed that this notion of preventive maintenance could be reflected in medical DTs, with the potential for patients to avoid unscheduled visits to the doctor. Medical DTs

[1] To learn more about the study and to watch videos of the workshop presentations, see https://www.nationalacademies.org/our-work/foundational-research-gaps-and-future-directions-for-digital-twins, accessed February 10, 2023.

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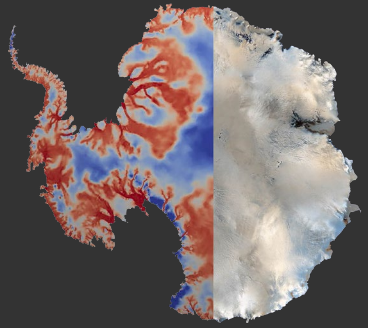
Physical System

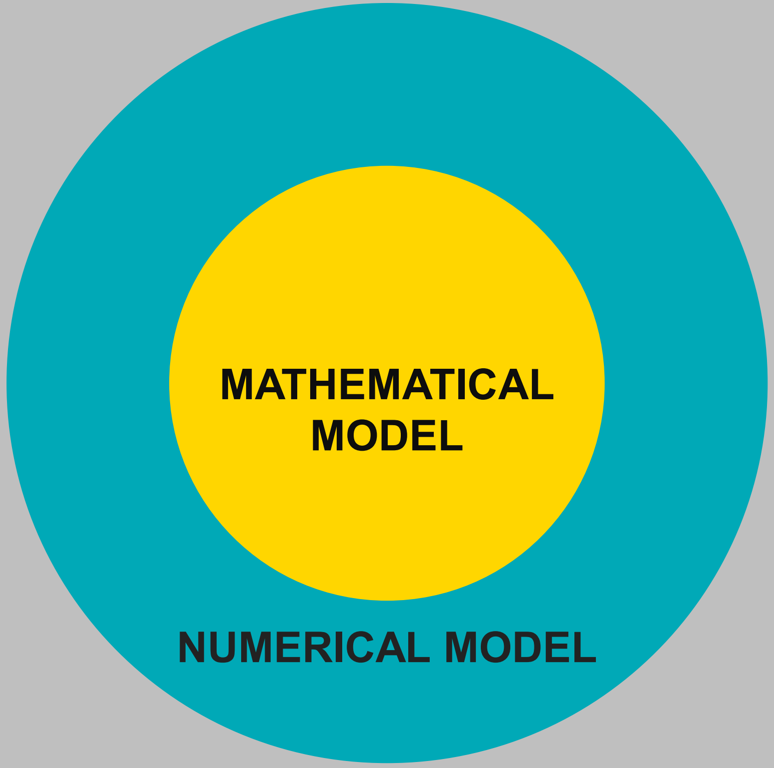


From Physical to Virtual
inverse problems, data assimilation, sensor fusion, model adaptation

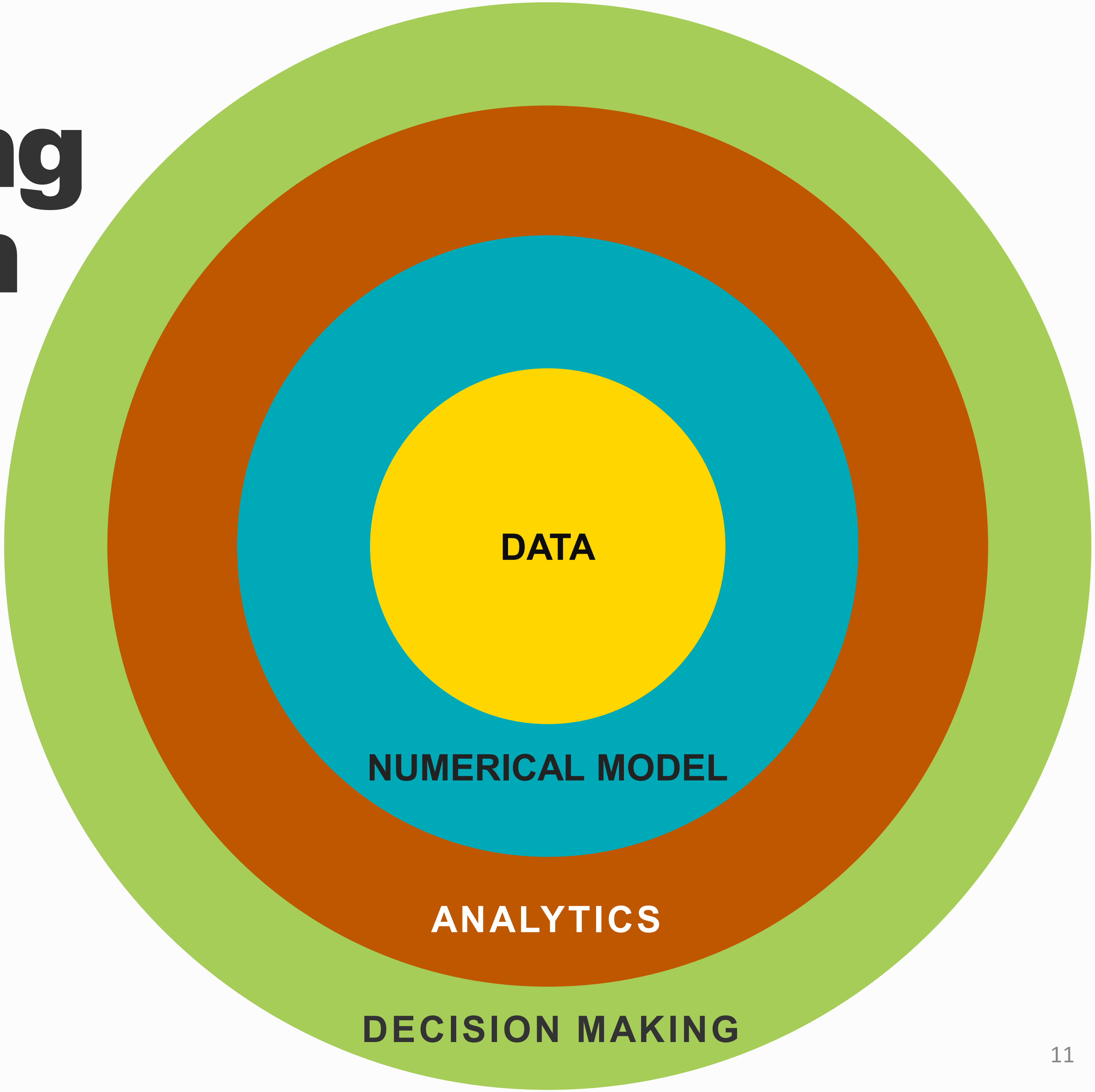
Validation, Verification, Uncertainty Quantification

From Virtual to Physical
automated control, decision making, sensor steering, experimental design

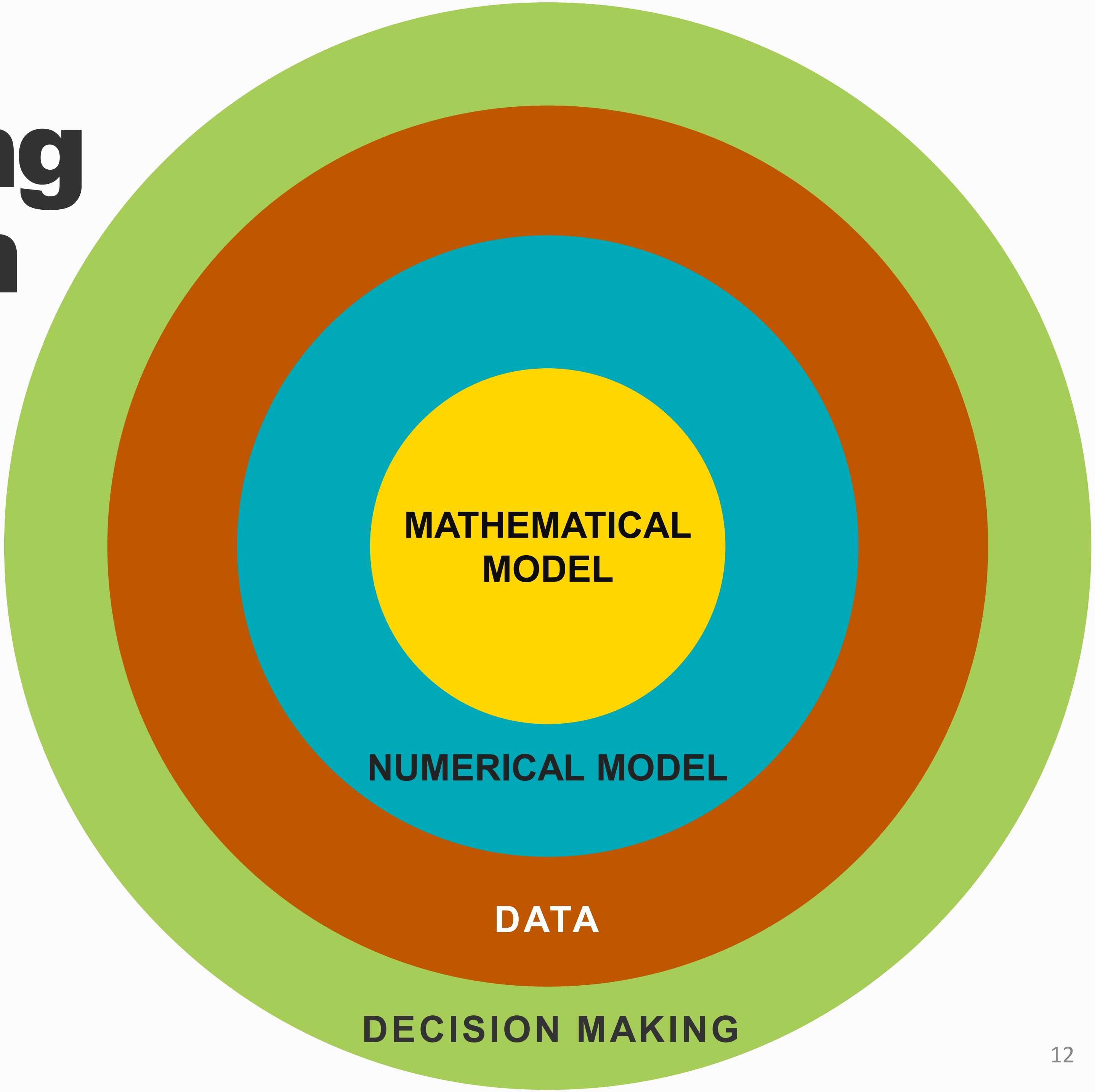
Virtual Representation



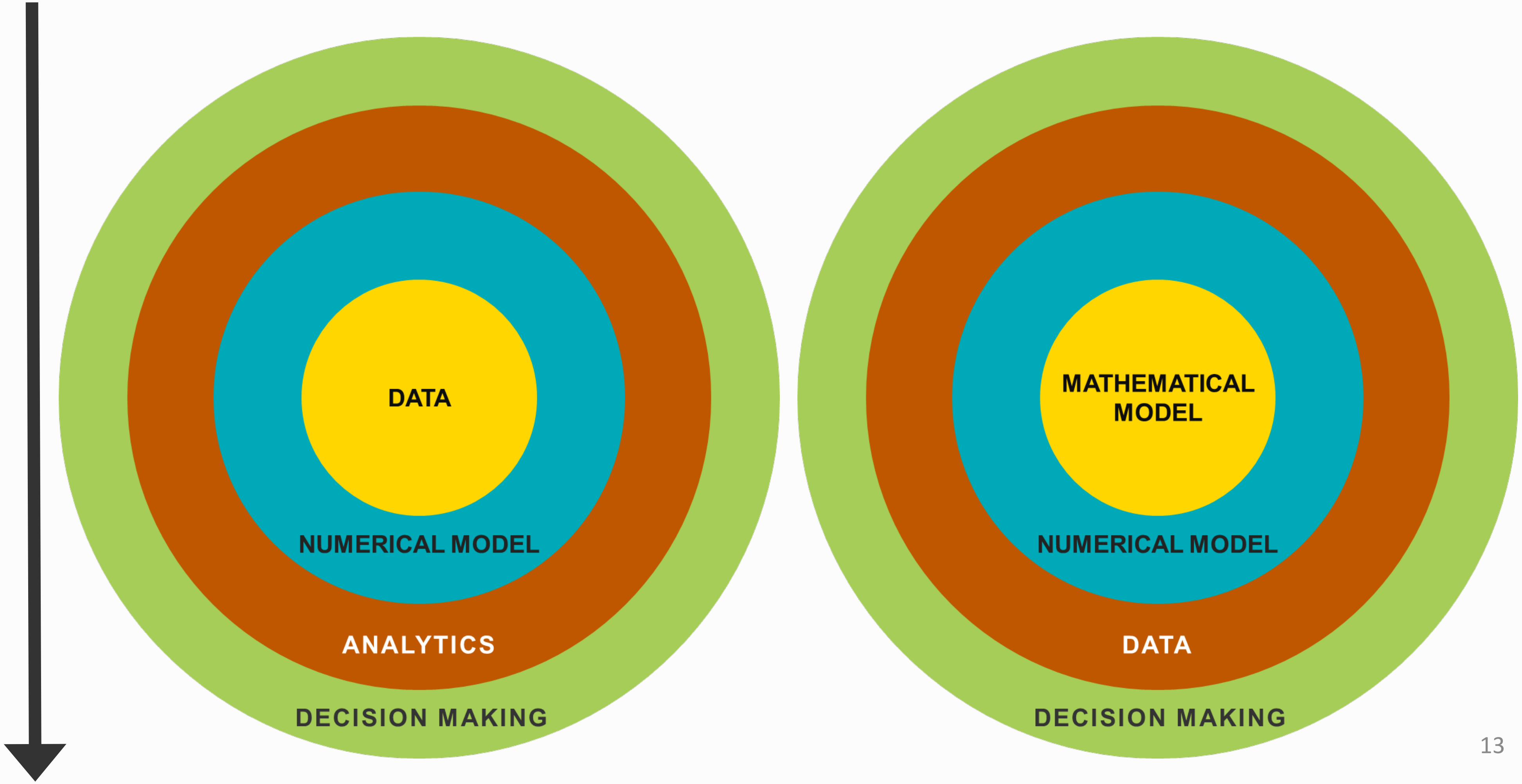
Conceptualizing a Digital Twin



Conceptualizing a Digital Twin



Conceptualizing a Digital Twin



The mathematical & computational challenges of Digital Twins

Complex physical phenomena
multiscale, multiphysics

High dimensionality
of parameter spaces, state spaces & decision spaces

Computational constraints
rapid / real-time assimilation & predictions, security, privacy

Limited data
observations are noisy, indirect, & expensive/intrusive to acquire

Verification, validation & uncertainty quantification
with dynamically evolving assets & models

DOMAIN KNOWLEDGE

PREDICTIVE PHYSICS-BASED MODELING & SIMULATION

HUMAN-COMPUTER INTERACTIONS

OPTIMIZATION & CONTROL

HIGH-PERFORMANCE COMPUTING

EDGE COMPUTING

DATA ASSIMILATION

SURROGATE MODELING

UNCERTAINTY QUANTIFICATION

ARTIFICIAL INTELLIGENCE

MACHINE LEARNING

Digital Twins

Next-generation digital tools that move

Beyond Forward Simulation