

Promise and Opportunities of Digital Twins

Multiplex Thinking in the Age of Complexity

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Qatar University

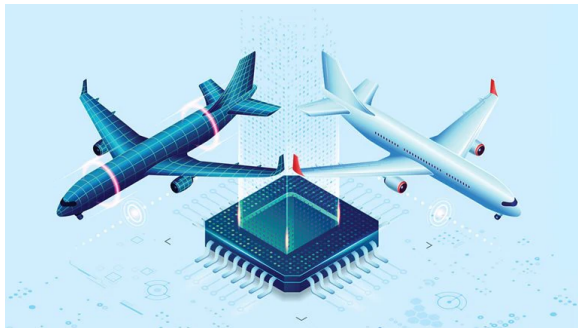


Keynote Talk,
2nd International Conference on Marine Engineering & Technology (ICMET),
6th November 2025.

What is a Digital Twin (DT)?

A virtual counterpart dynamically linked to its physical system

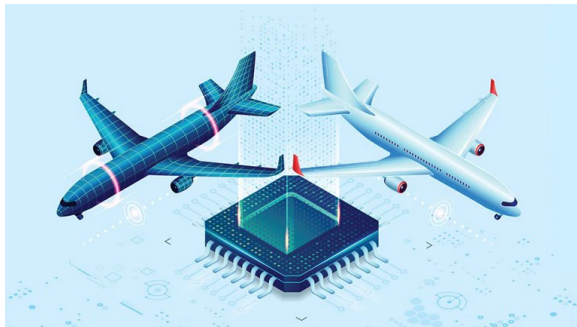
- ↔ Bidirectional feedback loop
- ↻ Continuously updates
- 📈 Predicts behavior
- ⚙️ Optimizes performance



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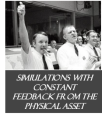
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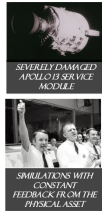
A DT connects the physical and digital worlds through live feedback — **representing**, **predicting**, **controlling**, and **prescribing** — to transform data into understanding and purposeful action.

From Apollo to Ocean: The Evolution of Digital Twins



1960s
Apollo 13
Simulators with
constant feedback

From Apollo to Ocean: The Evolution of Digital Twins

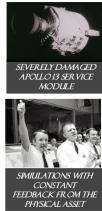


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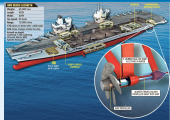
Today
Ocean & Beyond
Testing, design,
sustainability

Maritime Digital Twins: From Failure Prevention to Ocean Intelligence

Case Study: HMS *Queen Elizabeth*

A \$40M seal failure could have been **predicted** with a propulsion-system DT.

Shift: from *reaction* → *anticipation*.



Implications:

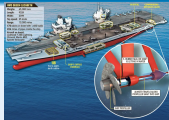
- Failures are costly and safety-critical.
- Context is harsh and variable.
- Therefore: DTs must pair VVUQ with data assimilation.

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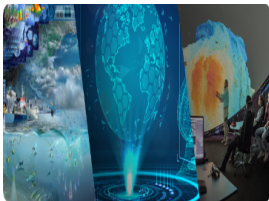
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Maritime DT Applications

⚙️ Intelligent Design & Ops

Virtual prototyping to reduce cost and risk

🌿 Sustainable Operations

Multi-scale twins for predictive maintenance, fuel optimization

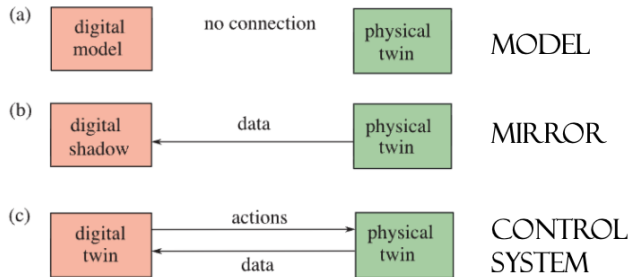
🌊 Ocean Intelligence

Connect ship-port-ocean twins; integrate sparse data

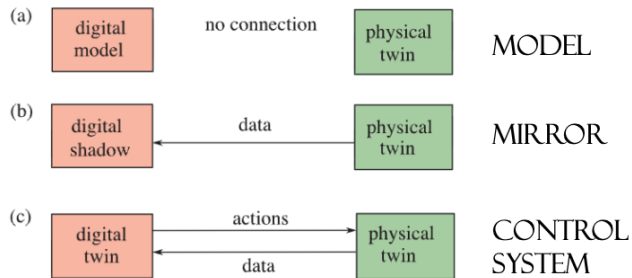
🚀 Strategic Edge

Build interdisciplinary capability: naval + modeling + AI

Beyond Simple Models: The DT Difference

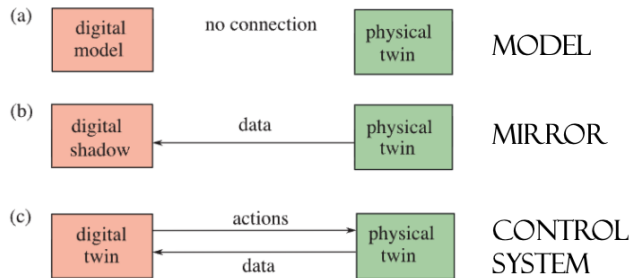


Beyond Simple Models: The DT Difference



In DTs, the model is in the loop with reality. DTs create a living dialogue between physical and virtual realms that transforms observation into action—enabling interactive “what-if” exploration of interventions, policies, and scenarios

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Key Insight

Bidirectional feedback enables:

- 1 Dynamic data-driven model updating
- 2 Optimal decision-making and control

The DT Consensus Definition (US NASEM)

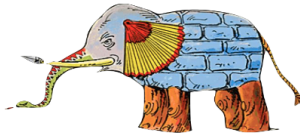
National Academies of Sciences, Engineering, and Medicine (NASEM, 2024)

A DT is a set of **virtual information constructs** that mimics the structure, context, and behavior of a natural, engineered, or social system, is **dynamically updated** with data from its physical twin, has a **predictive capability**, and **informs decisions** that realize value.

The Five Essential Elements:

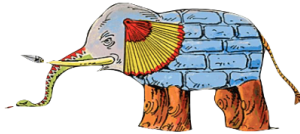
- ① **Virtual Representation** — Models (physics, ML, statistical)
- ② **Physical Counterpart** — The actual system
- ③ **Physical → Virtual Flow** — Data collection & personalization
- ④ **Virtual → Physical Flow** — Predictions driving actions
- ⑤ **Cross-Cutting** — VVUQ, security, ethics, human-in-the-loop

The Problem of Reductionism and Either-Or Thinking



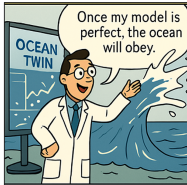
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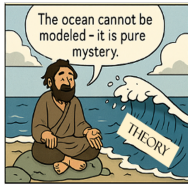


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TECHNOLOGY OPTIMIST

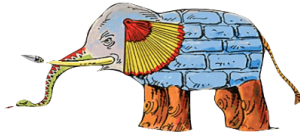


TECHNOLOGY SKEPTIC



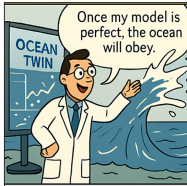
Reductionist (Either-Or) Thinking)

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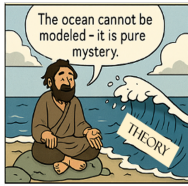


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These protagonists are not entirely wrong—but their either-or view is incomplete. We need a dynamic balance and synthesis.

Reductionist (Either-Or) Thinking)

Multiplex Both-And View of Complex Systems

Convergent Problems

- Well-defined, stable
- One correct answer
- Optimization mindset
- *Example: Engine performance*

DT Role: Simulate, predict, and optimize performance

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DT Role: Explore scenarios and inform stakeholder decisions

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A MULTIPLEX BOTH-AND VIEW OF COMPLEX SYSTEMS

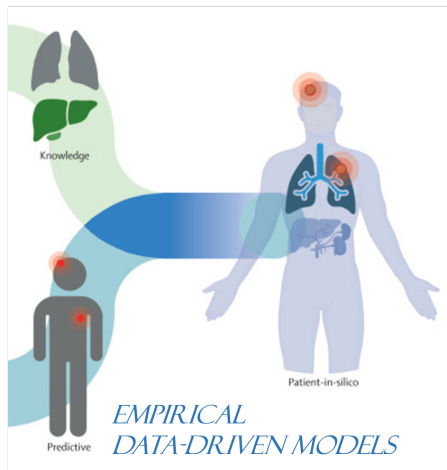


*Embrace the endless possibilities within the whitewater world—
John Seely Brown*

the coexistence of turbulence and order

Combining Mechanistic and Empirical Models for Personalized Healthcare

MECHANISTIC MODELS

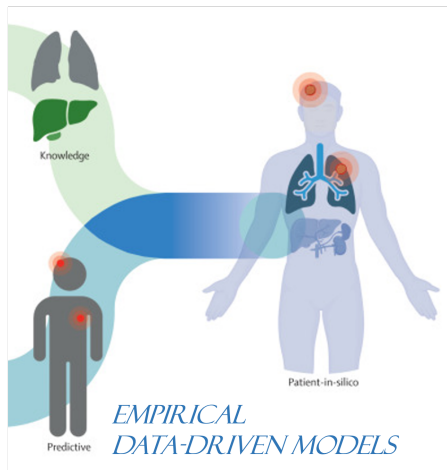


Building the Virtual You

Combining mechanistic models with empirical data for personalized medicine

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Applications:

- ♥ Patient-specific modeling
- 💊 Treatment optimization
- 🧪 In-silico clinical trials
- 🧬 Genomic integration

VVUQ: Building Trust in Digital Twins

Verification

Are we building it right?

Checking computational implementation

Validation

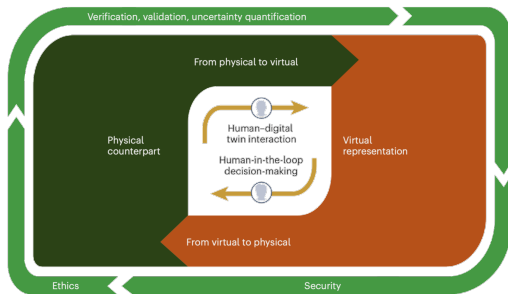
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How confident are predictions?

Quantifying model & data uncertainty



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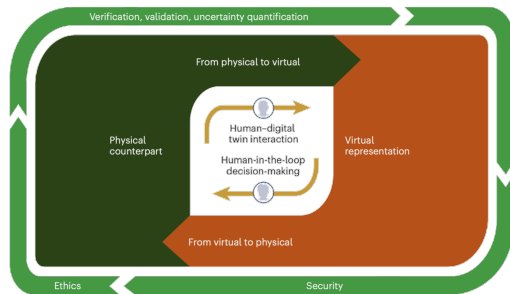
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Developing Trustworthy Credible DTs (NASEM Consensus Report Recommendation)

VVUQ must be **continually embedded** from the beginning, not added at the end.
DTs require **dynamic validation** as physical systems evolve and **rigorous VVUQ for AI/ML** components comparable to physics-based models.

UN Ocean Decade (2021-2030): DTs for Sustainability

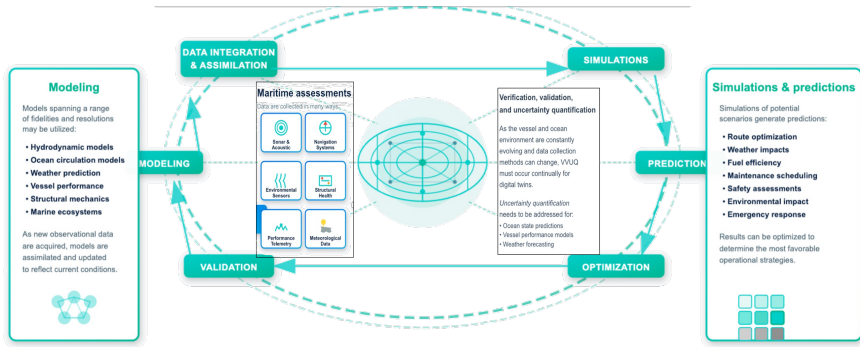
Vision: “The science we need for the ocean we want” (<https://oceandecade.org/>)

Leveraging DT technology to transform ocean science and enable sustainable ocean management—addressing climate change impacts, optimizing human activities for sustainability, enabling citizen science and policy making, and reversing biodiversity decline.

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Key Research Techniques and Issues

Virtual Representation

- Physics-informed ML
- Multi-scale modeling
- Surrogate models

Physical Counterpart

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- System-of-systems complexity
- Integration & interoperability

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- Digital twin sustainability
- Cross-domain translation and Continuous VVUQ
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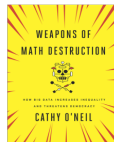
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Privacy & ethics



THERE ARE ETHICAL
CHOICES IN EVERY SINGLE
ALGORITHM WE BUILD

DTs pose various novel ethical challenges



Further Reading and Our Ongoing Work

National Academies of Sciences, Engineering, and Medicine (NASEM) DT Study

Commissioned by: DOE, NSF, NIH, DoD **Output:** 8 Recs, 19 Conclusions, 22 Findings, 48 Tech Gaps



Access the full report: <https://tinyurl.com/NASEMDTReport>

The National Academies' year-long multi-agency study (DOE, NSF, NIH, DoD) identified foundational research gaps and strategic directions for advancing trustworthy and interoperable DTs across disciplines.

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Our research focus: advancing **Multiplex Digital Twins** that use *both—and modeling*—combining mechanistic, empirical, AI, and statistical approaches—to create holistic, ethical solutions in **healthcare, education, and sustainability**.

Thank You!

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Questions?