

Living Digital: *Multiplex AI-Driven Twins for Smarter Health Management*

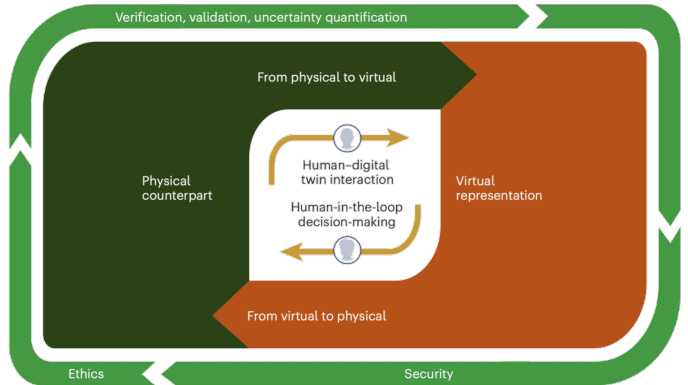
Junaid Qadir

Professor of Computer Engineering
Qatar University

What is a Digital Twin (DT)?

**A virtual counterpart
dynamically linked to its
physical system**

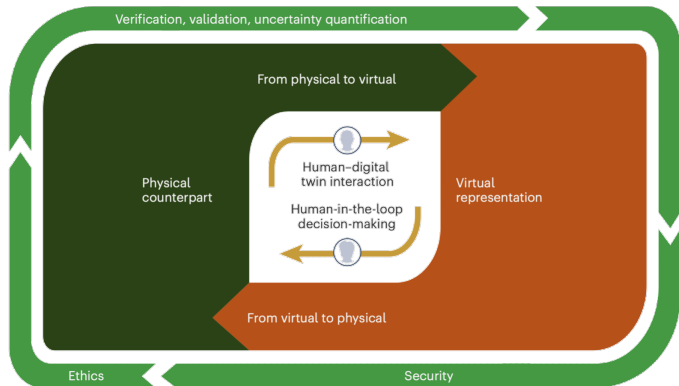
- ↔ Bidirectional feedback loop
- ↻ Continuously updates
- 📈 Predicts behavior
- ⚙️ Optimizes performance



What is a Digital Twin (DT)?

A virtual counterpart dynamically linked to its physical system

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



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

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 (patient, organ, hospital)
- ③ **Physical → Virtual Flow** — Data collection & personalization
- ④ **Virtual → Physical Flow** — Predictions driving clinical actions
- ⑤ **Cross-Cutting** — VVUQ, security, ethics, human-in-the-loop

VVUQ: Building Trust in Healthcare Digital Twins

Verification

Are we building it right?

Checking computational implementation

Validation

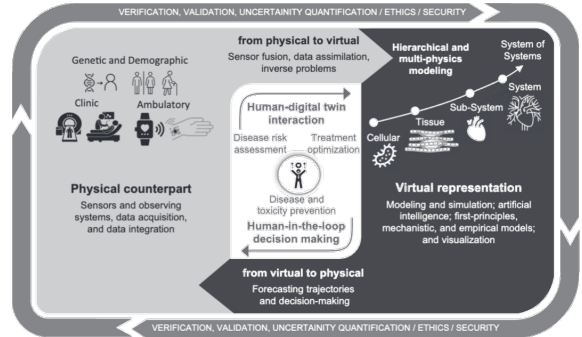
Are we building the right thing?

Comparing with clinical outcomes

Uncertainty Quantification

How confident are predictions?

Quantifying model & data uncertainty



VVUQ: Building Trust in Healthcare Digital Twins

Verification

Are we building it right?

Checking computational implementation

Validation

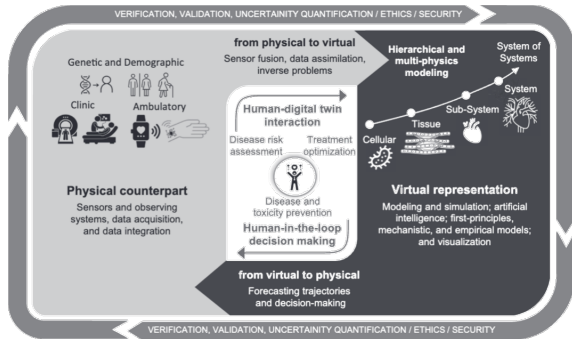
Are we building the right thing?

Comparing with clinical outcomes

Uncertainty Quantification

How confident are predictions?

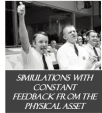
Quantifying model & data uncertainty



Developing Trustworthy Clinical DTs (NASEM Consensus Report)

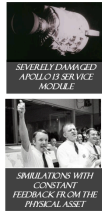
VVUQ must be **continually embedded** from the beginning, not added at the end.
Healthcare DTs require **dynamic validation** as patient conditions evolve
and **rigorous VVUQ for AI/ML** components.

DTs Through Time: From NASA Origins to Patient-Centered Care



1960s
Apollo 13
Simulators with
constant feedback

DTs Through Time: From NASA Origins to Patient-Centered Care

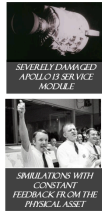


1960s
Apollo 13
Simulators with
constant feedback



2000s
Product
Lifecycle
Grieves
formalized
the concept

DTs Through Time: From NASA Origins to Patient-Centered Care



TESTING AND DESIGN

1960s
Apollo 13
Simulators with
constant feedback

2000s
Product
Lifecycle
Grieves
formalized
the concept

Today
Healthcare &
Beyond
Personalized
medicine,
precision health

Toward Predictive, Personalized, and Proactive Care

REAL WORLD PATIENT

The patient and the tumor form which data is gathered using various clinical assessments to inform the digital twin.

VVUQ

Validation, verification, and uncertainty quantification

As the patient and tumor are concurrently evolving and the data collection can also change over time, VVUQ must occur continually for digital twins.

Uncertainty quantification needs to be addressed for all aspects of the digital twin, including the patient's data, modeling and simulation, and decision making.

DIGITAL TWIN

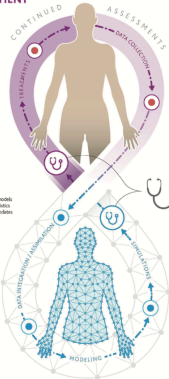
The virtual representation comprised of models describing temporal and spatial characteristics of the patient and tumor with dynamic updates using data from the real world patient.



Modeling

Models spanning a range of fidelities and resolutions may be utilized and potentially integrated together.

As new observed data are acquired, the data are assimilated and the models are calibrated, updated, and extended.



Clinical assessments

Data are collected in many ways



Human and digital twin interaction

Utilizing the simulated predictions and related uncertainties, the clinician and patient can make informed clinical decisions around treatment and also the clinical assessments, which affect the data informing the digital twin.



Simulations & predictions

Simulations of potential treatments can generate predictions of outcome and in turn can be optimized to determine the most favorable treatment options.

Healthcare DT Applications

- Personalized Diagnostics** – Physics-informed models for early detection
- Treatment Optimization** – *In silico* pharmacokinetic trials for dosing precision
- Hospital Operations** – Discrete-event simulation for patient flow and capacity
- Precision Medicine** – Genomic–phenotypic fusion for targeted interventions

Example of a digital twin of a cancer patient and tumor

Credit: NASEM DT Report.

Toward Predictive, Personalized, and Proactive Care

REAL WORLD PATIENT

The patient and the tumor from which data is gathered using various clinical assessments to inform the digital twin.

VVUQ

Verification, validation, and uncertainty quantification

As the patient and tumor are constantly evolving and the data collection can also change over time, VVUQ must occur continually for digital twins.

Uncertainty quantification needs to be addressed for all aspects of the digital twin, including the patient's data, modeling and simulation, and decision making.

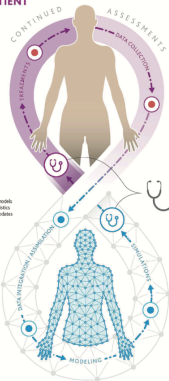
DIGITAL TWIN

The virtual representation comprised of models describing temporal and spatial characteristics of the patient and tumor with dynamic updates using data from the real-world patient.



Modeling

Models spanning a range of fidelities and resolutions may be utilized and potentially integrated together. As new observed data are acquired, the data are assimilated and the models are calibrated, updated, and reestimated.



Clinical assessments

Data are collected in many ways



Human and digital twin interaction

Utilizing the simulated predictions and related uncertainties, the clinician and patient can make informed clinical decisions around treatment and also the clinical assessments, which affect the data informing the digital twin.



Simulations & predictions

Simulations of potential treatments can generate predictions of outcomes and in turn can be optimized to determine the most favorable treatment options.

Healthcare DT Applications

- Personalized Diagnostics** – Physics-informed models for early detection
- Treatment Optimization** – *In silico* pharmacokinetic trials for dosing precision
- Hospital Operations** – Discrete-event simulation for patient flow and capacity
- Precision Medicine** – Genomic–phenotypic fusion for targeted interventions

Case Study: Oncology Digital Twin

Patient-specific tumor DTs integrate **imaging data**, **genomic profiles**, and **microenvironment dynamics** to simulate tumor progression and predict treatment response **before therapy**.

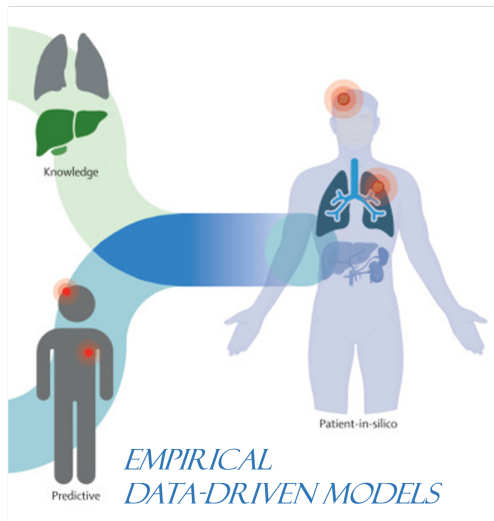
From educated guessing with *Empirical dosing* to
→ **Personalized precision oncotherapy**

Example of a digital twin of a cancer patient and tumor

Credit: NASEM DT Report.

Mechanistic OR Empirical Models for Personalized Healthcare?

MECHANISTIC MODELS



Multiplex Both-And View of Complex Health Systems

Convergent Problems

- Well-defined, stable
- One correct answer
- Optimization mindset
- *Example: Drug dosing*

DT Role: Simulate, predict, and optimize treatment

Multiplex Both-And View of Complex Health Systems

Convergent Problems

- Well-defined, stable
- One correct answer
- Optimization mindset
- *Example: Drug dosing*

DT Role: Simulate, predict, and optimize treatment

Divergent Problems

- Dynamic, evolving
- Multiple perspectives
- Judgment required
- *Example: Care pathways*

DT Role: Explore scenarios and inform clinical decisions

Multiplex Both-And View of Complex Health Systems

Convergent Problems

- Well-defined, stable
- One correct answer
- Optimization mindset
- *Example: Drug dosing*

DT Role: Simulate, predict, and optimize treatment

Divergent Problems

- Dynamic, evolving
- Multiple perspectives
- Judgment required
- *Example: Care pathways*

DT Role: Explore scenarios and inform clinical decisions

**BOTH-AND
MULTIPLEX
APPROACH:**



*The either-or view is partially correct but incomplete.
We need a dynamic balance & systemic synthesis.*

*We need Either-Or Thinking
With (Not Or) Both-And Thinking*

*We need Either-Or Thinking
With (Not Or) Both-And Thinking*



Procrustean Fallacy
Stretching or Constricting Reality
to Fit the Model

Healthcare DTs: Use Cases Across the Care Continuum

Organ-Level Twins

- Cardiac twins for arrhythmia prediction
- Liver twins for drug metabolism
- Brain twins for neurological disorders

Hospital Twins

- Patient flow optimization
- Resource allocation
- Emergency response planning

Surgical Planning

- Virtual surgical rehearsal
- Patient-specific implant design
- Outcome prediction

Population Health

- Epidemic modeling
- Health system planning
- Policy simulation

Healthcare DTs: Use Cases Across the Care Continuum

Organ-Level Twins

- Cardiac twins for arrhythmia prediction
- Liver twins for drug metabolism
- Brain twins for neurological disorders

Hospital Twins

- Patient flow optimization
- Resource allocation
- Emergency response planning

Surgical Planning

- Virtual surgical rehearsal
- Patient-specific implant design
- Outcome prediction

Population Health

- Epidemic modeling
- Health system planning
- Policy simulation

Idiographic

idios (Greek: “one’s own”)

Particularizing

Understanding the unique individual

vs.

Nomothetic

nomos (Greek: “law”)

Generalizing

Discovering universal patterns

Healthcare DTs: Key Research Techniques and Issues

Virtual Representation

- Physics-informed ML
- Multi-scale physiological modeling
- Surrogate models for real-time use

Physical Counterpart

- Sparse, noisy clinical data
- Patient heterogeneity
- Multi-modal data integration

Bidirectional Flow

- Real-time data assimilation
- Treatment optimization under uncertainty
- Continuous model personalization

Systemic & Translational

- Clinician-in-the-loop design
- Regulatory pathways (FDA, CE)
- Interoperability standards (FHIR, OMOP)
- Federated learning for privacy

Healthcare DTs: Key Research Techniques and Issues

Virtual Representation

- Physics-informed ML
- Multi-scale physiological modeling
- Surrogate models for real-time use

Physical Counterpart

- Sparse, noisy clinical data
- Patient heterogeneity
- Multi-modal data integration

Bidirectional Flow

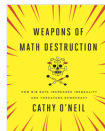
- Real-time data assimilation
- Treatment optimization under uncertainty
- Continuous model personalization

Systemic & Translational

- Clinician-in-the-loop design
- Regulatory pathways (FDA, CE)
- Interoperability standards (FHIR, OMOP)
- Federated learning for privacy



THERE ARE ETHICAL
CHOICES IN EVERY SINGLE
ALGORITHM WE BUILD



Issues such as privacy, equity, consent, autonomy, algorithmic transparency, data ownership, inclusive design

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.

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.

Our Related Research on Healthcare Digital Twins

- Mekki, Y. M., Luijten, G., Hagert, E., Belkhair, S., Varghese, C., **Qadir, J.**, ... & Stotland, M. A. (2025). *Digital twins for the era of personalized surgery*. **npj Digital Medicine**, 8(1), 283.

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.

Our Related Research on Healthcare Digital Twins

- Mekki, Y. M., Luijten, G., Hagert, E., Belkhair, S., Varghese, C., **Qadir, J.**, ... & Stotland, M. A. (2025). *Digital twins for the era of personalized surgery*. **npj Digital Medicine**, 8(1), 283.
- Alam, M., Bilal, M., Ashraf, S. Q., Omar, N. E. H., **Qadir, J.**, et al. (2025). *Digital Twins for Precision Oncology: Modelling Foundations, Clinical Applications, and Open Challenges*. **Authorea**. DOI: 10.22541/au.175753019.93675772/v1

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.

Our Related Research on Healthcare Digital Twins

- Mekki, Y. M., Luijten, G., Hagert, E., Belkhair, S., Varghese, C., **Qadir, J.**, ... & Stotland, M. A. (2025). *Digital twins for the era of personalized surgery*. **npj Digital Medicine**, 8(1), 283.
- Alam, M., Bilal, M., Ashraf, S. Q., Omar, N. E. H., **Qadir, J.**, et al. (2025). *Digital Twins for Precision Oncology: Modelling Foundations, Clinical Applications, and Open Challenges*. **Authorea**. DOI: 10.22541/au.175753019.93675772/v1
- **Qadir, J.**, Qoronfleh, M. W., & Senturk, R. (2025). *Toward Multiplex Health: Integrating Complexity, Normativity, and Open Science*. **Frontiers in Psychology**, 16, 1603474.

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.

Our Related Research on Healthcare Digital Twins

- Mekki, Y. M., Luijten, G., Hagert, E., Belkhair, S., Varghese, C., **Qadir, J.**, ... & Stotland, M. A. (2025). *Digital twins for the era of personalized surgery*. **npj Digital Medicine**, 8(1), 283.
- Alam, M., Bilal, M., Ashraf, S. Q., Omar, N. E. H., **Qadir, J.**, et al. (2025). *Digital Twins for Precision Oncology: Modelling Foundations, Clinical Applications, and Open Challenges*. **Authorea**. DOI: 10.22541/au.175753019.93675772/v1
- **Qadir, J.**, Qoronfleh, M. W., & Senturk, R. (2025). *Toward Multiplex Health: Integrating Complexity, Normativity, and Open Science*. **Frontiers in Psychology**, 16, 1603474.

Our research focus: advancing **Multiplex Healthcare Digital Twins** that use *both—and modeling*—combining mechanistic, empirical, AI, and statistical approaches—to create holistic, ethical solutions for **personalized medicine and population health**.

Thank You!

Junaid Qadir

Professor of Computer Engineering
Qatar University

✉ jqadir@qu.edu.qa

Questions?