Fermilab

September 2, 2026

Digital Twin Concepts from Twinac

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4th EIC-BeamAI Collaboration Meeting, Cornell, September 1-3, 2026

U.S. DEPARTMENT of ENERGY

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Mirrored spaces

Virtual Space

Functional Object$_v$ A

Functional Object$_v$ B

Functional Object$_v$ C

Physical Functional Object:
"A real thing with attributes that can be measured."

- More interesting if it has behavior
- Even more interesting if it's behavior can be modified

Physical Space

Functional Object$_p$ A

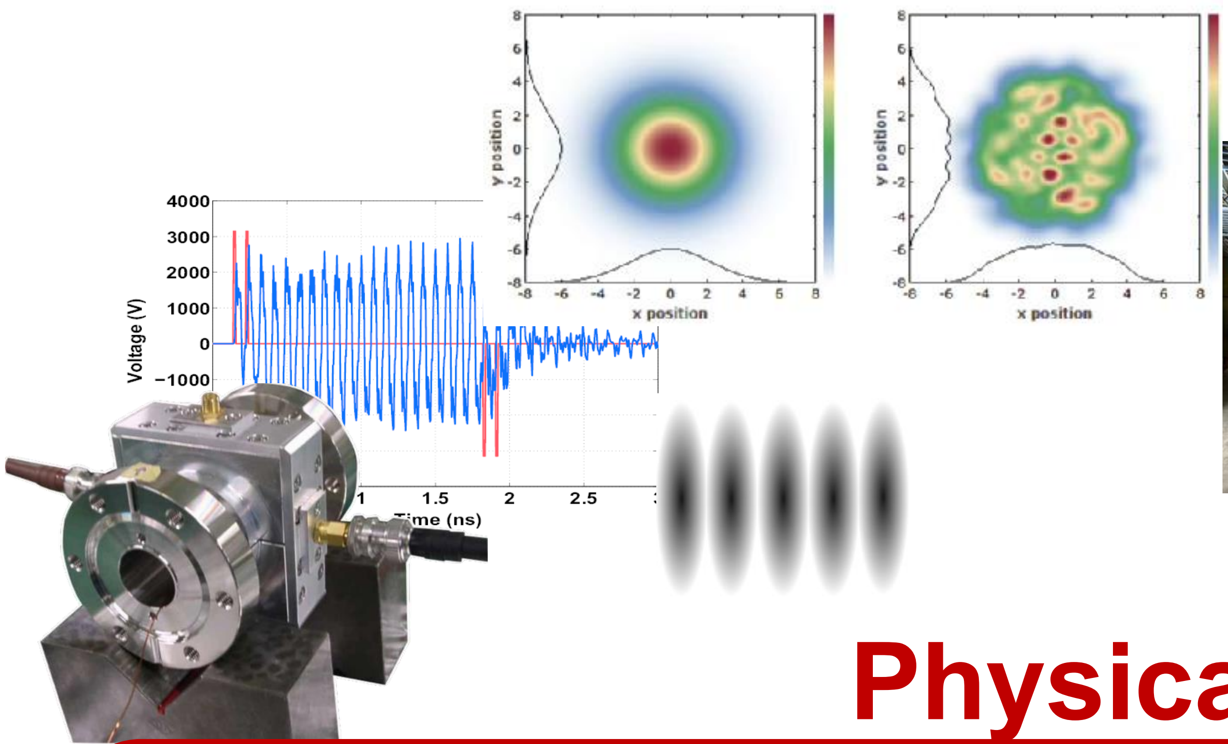
Functional Object$_p$ B

Functional Object$_p$ C

Functional Object$_p$ D

Functional Object$_p$ E

Mirrored spaces



Physical Space

Functional Object$_p$ A

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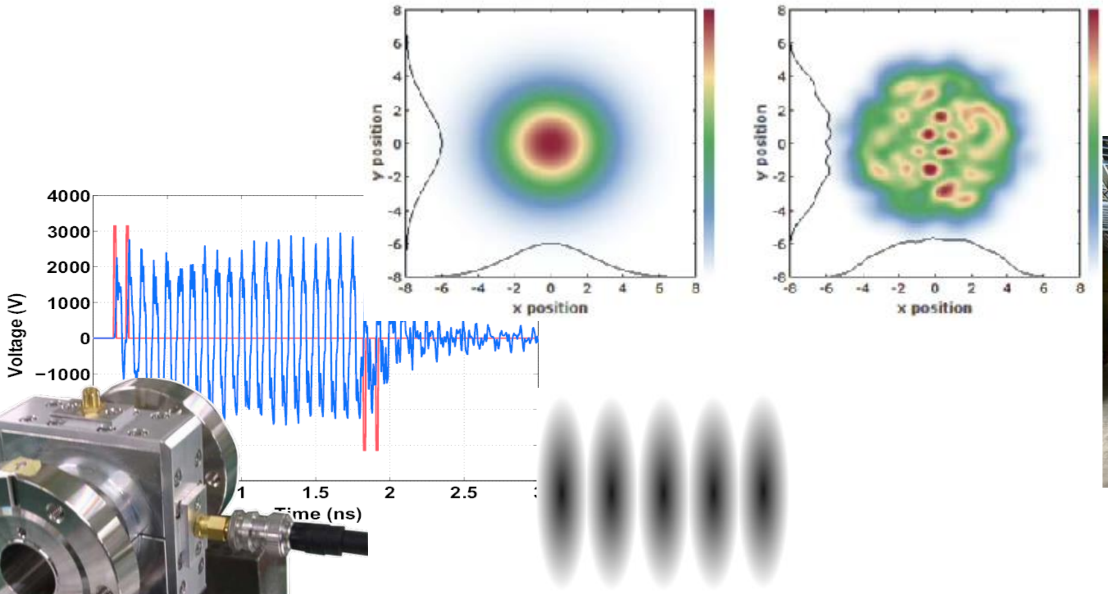
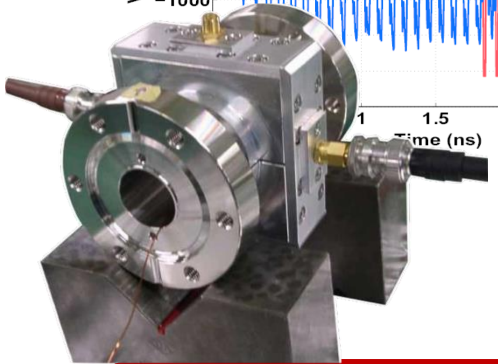
Mirrored spaces





Physical Space

Beam Instruments	Optical Elements	Environment	Infrastructure	Beam

Mirrored spaces

Virtual Space

Functional Object$_v$ A

Functional Object$_v$ B

Functional Object$_v$ C

Functional Object$_v$ D

Functional Object$_v$ E

Physical Spac

Functional Object$_p$ A

Functional Object$_p$ B

Funct
Objec

Working Definition

Virtual Functional Object:
"A model with attributes that can be measured."

- More interesting if it has behavior
- Even more interesting if it's behavior can be modified

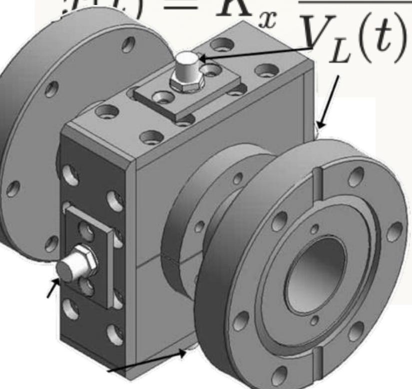
Mirrored spaces

Virtual Space

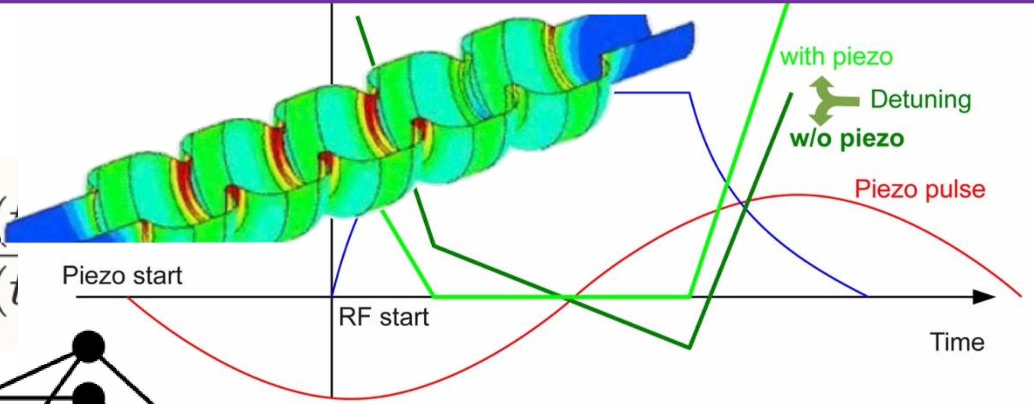
Functional Object$_v$ A	Functional Object$_v$ B	Functional Object$_v$ C	Functional Object$_v$ D	Functional Object$_v$ E

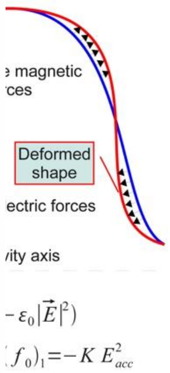
$$\frac{d\bar{\mathbf{v}}}{dt} = q\left(\bar{\mathbf{E}} + \bar{\boldsymbol{\beta}} \times \bar{\mathbf{B}}\right)$$

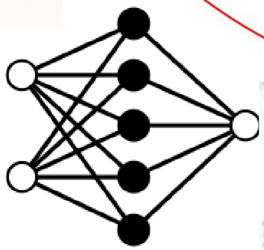
$$x(t) = K_x \frac{V_L(t) - V_R(t)}{V_L(t) + V_R(t)}, \qquad y(t) = K_y \frac{V_T(t) - V_B(t)}{V_T(t) + V_B(t)}$$

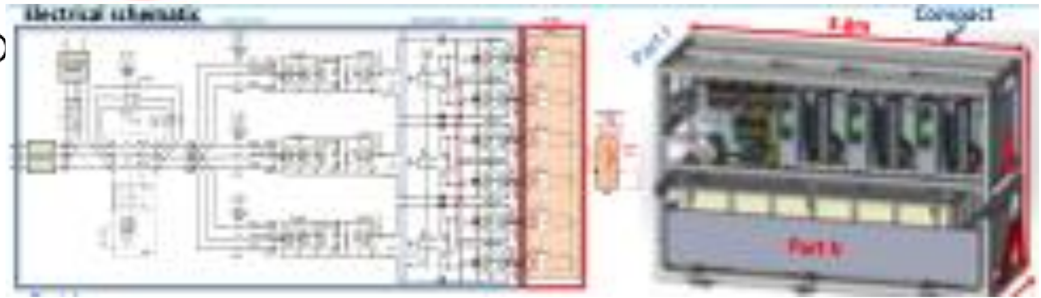


$$Q_i = \int_{t_1}^{t_2} I_i(t)\,\mathrm{d}t$$









Mirrored spaces

Virtual Space

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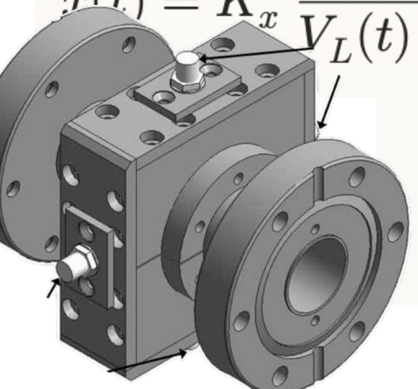
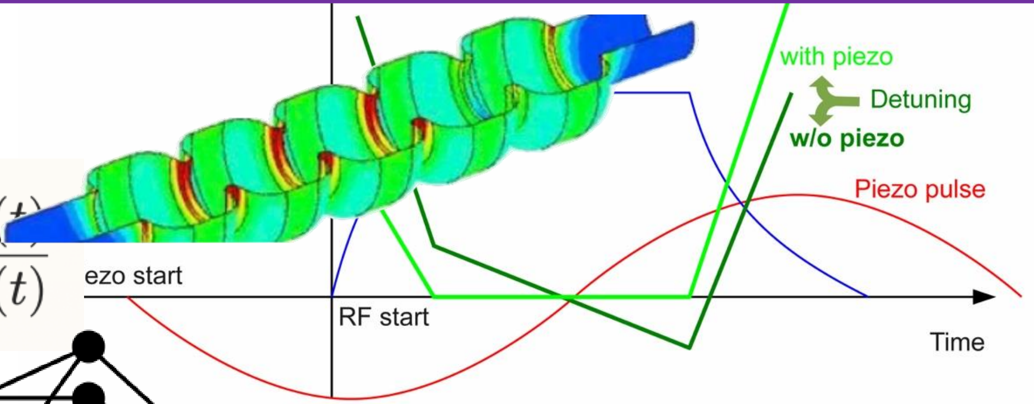
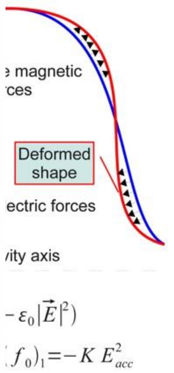
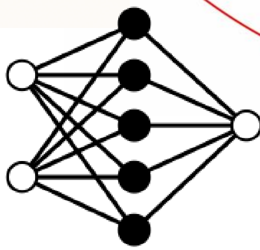
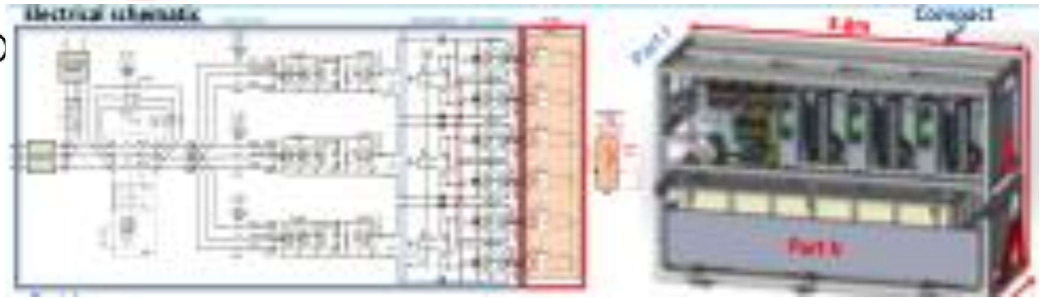










Mirrored spaces

Virtual Space

- Beam Instruments
- Optical Elements
- Environment
- Infrastructure
- Beam

Physical Space

- Beam Instruments
- Optical Elements
- Environment
- Infrastructure
- Beam

Mirrored spaces

Virtual Space

- Beam Instruments
- Optical Elements
- Environment
- Infrastructure
- Beam

This would be an amazingly high-fidelity composite model!

Not practical.

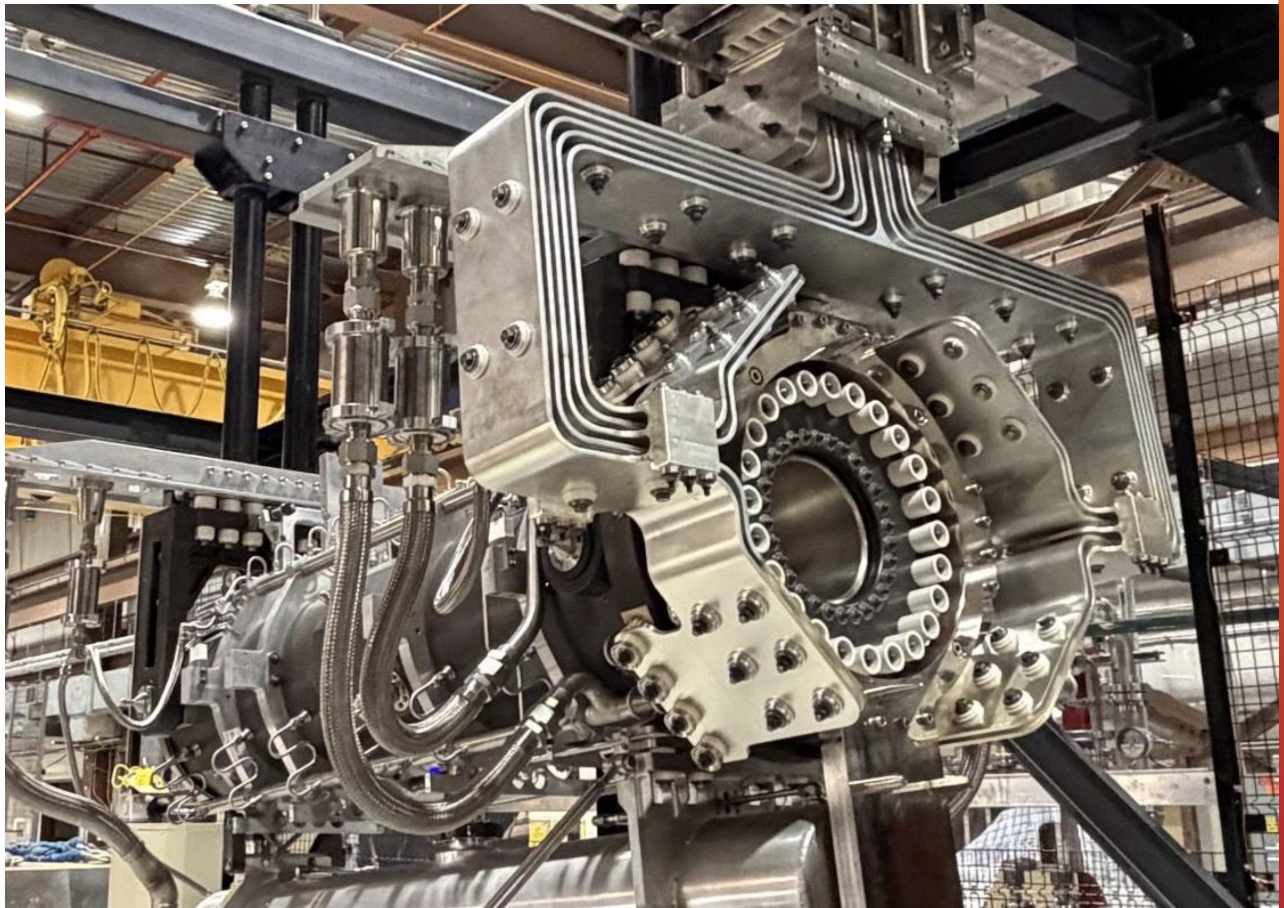
Choose wisely!

Physical Space

- Beam Instruments
- Optical Elements
- Environment
- Infrastructure
- Beam

Selecting what to mirror

- Beam! (duh!) – object for which we want to predict correct attributes
- Things that can affect accelerator operations
  - Sensitive things (RF cavity shape)
  - Expensive things (magnetic horns for neutrino beams)
  - Critical things (instrumentation degradation)



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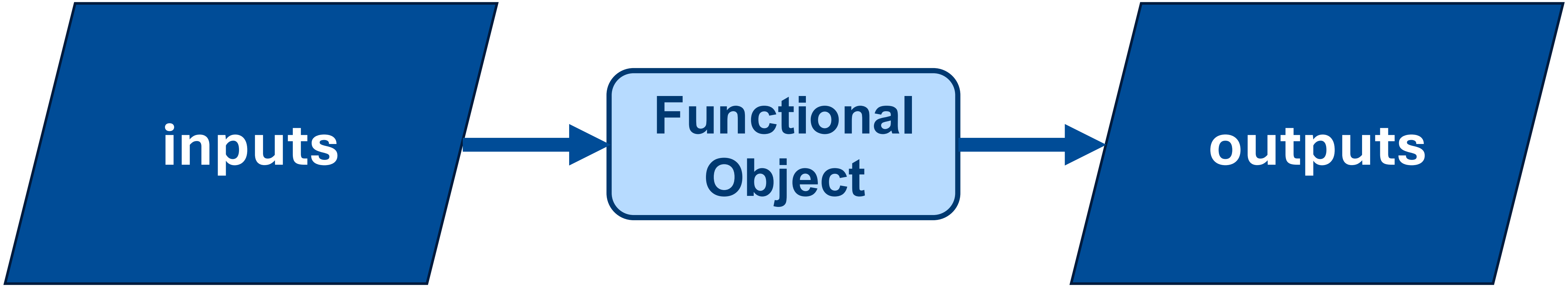
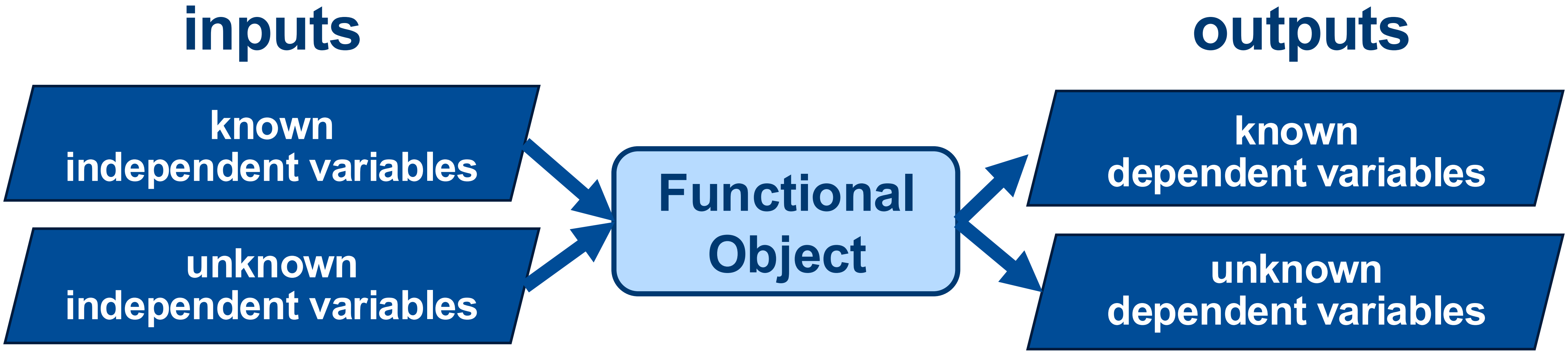
Functional Objects

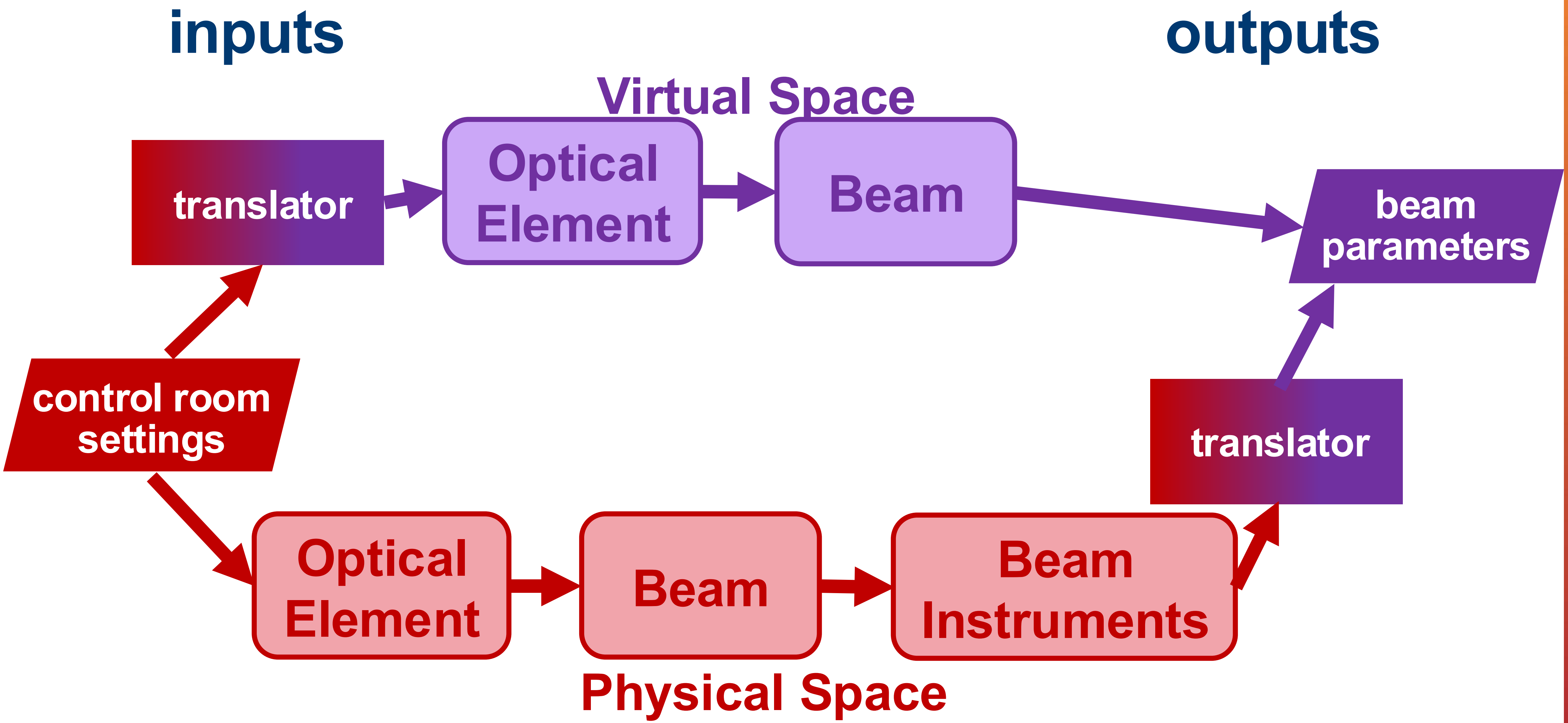
F(inputs) = outputs



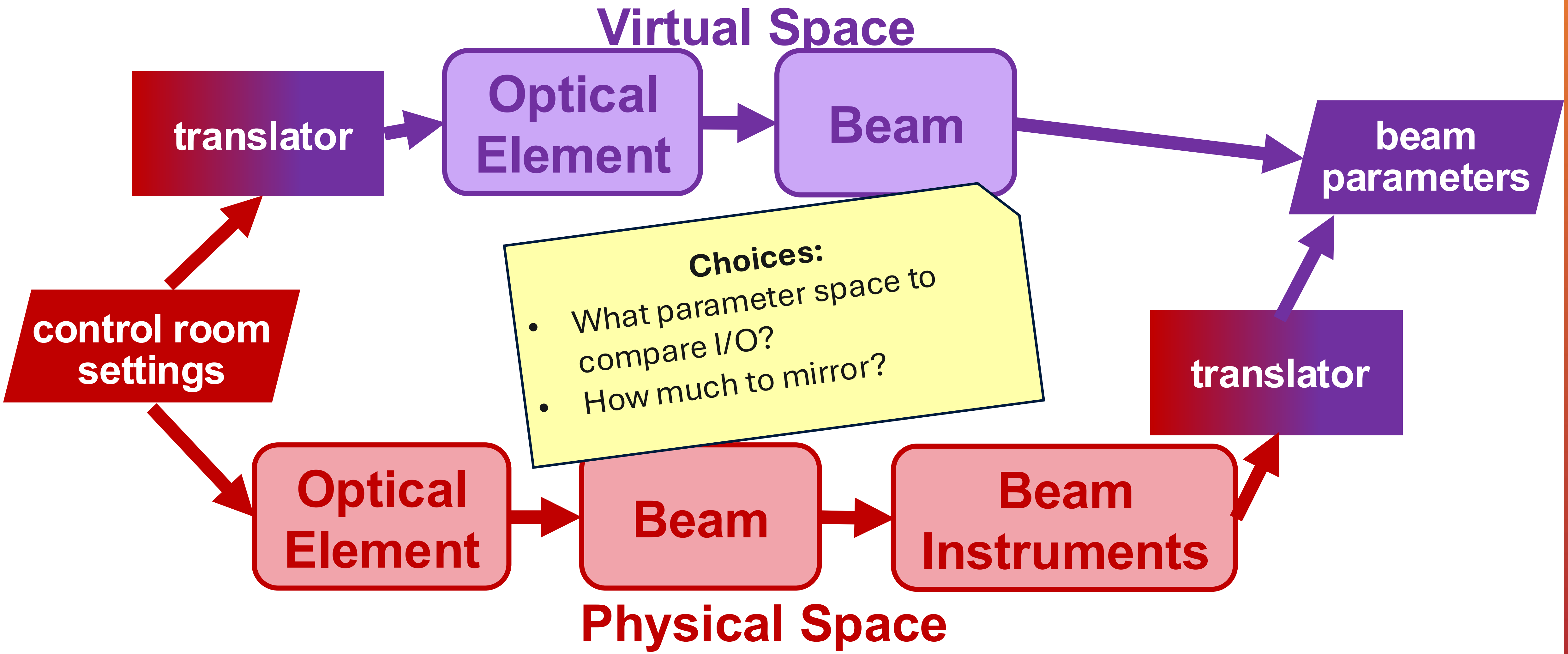
We may not know everything



Digital shadow of optical element and beam



Digital Model “Virtual Accelerator” of optical element and beam



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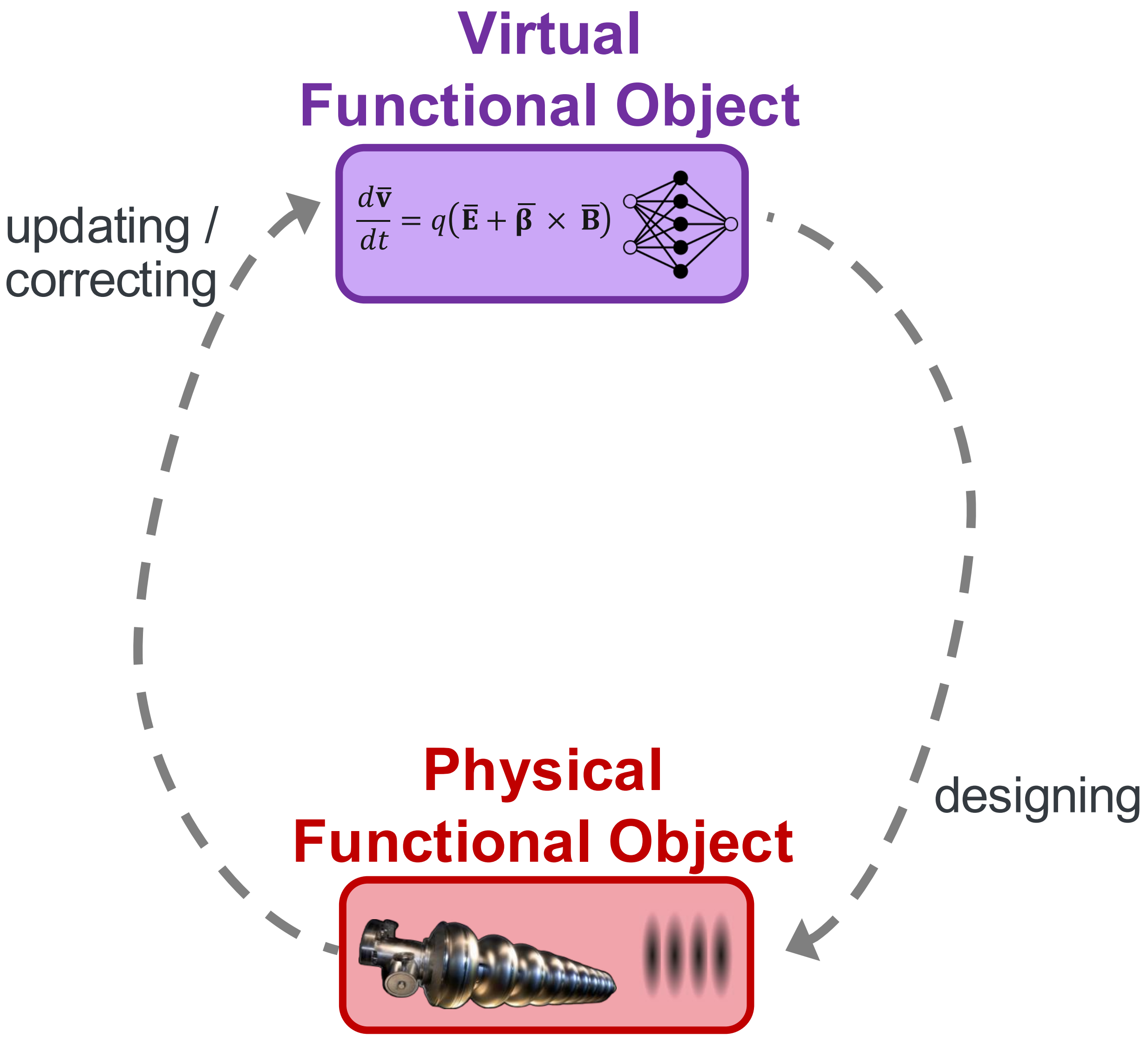
Virtual Accelerator (Digital Model)

Static simulation

- No automatic information flow
- Manual matching only



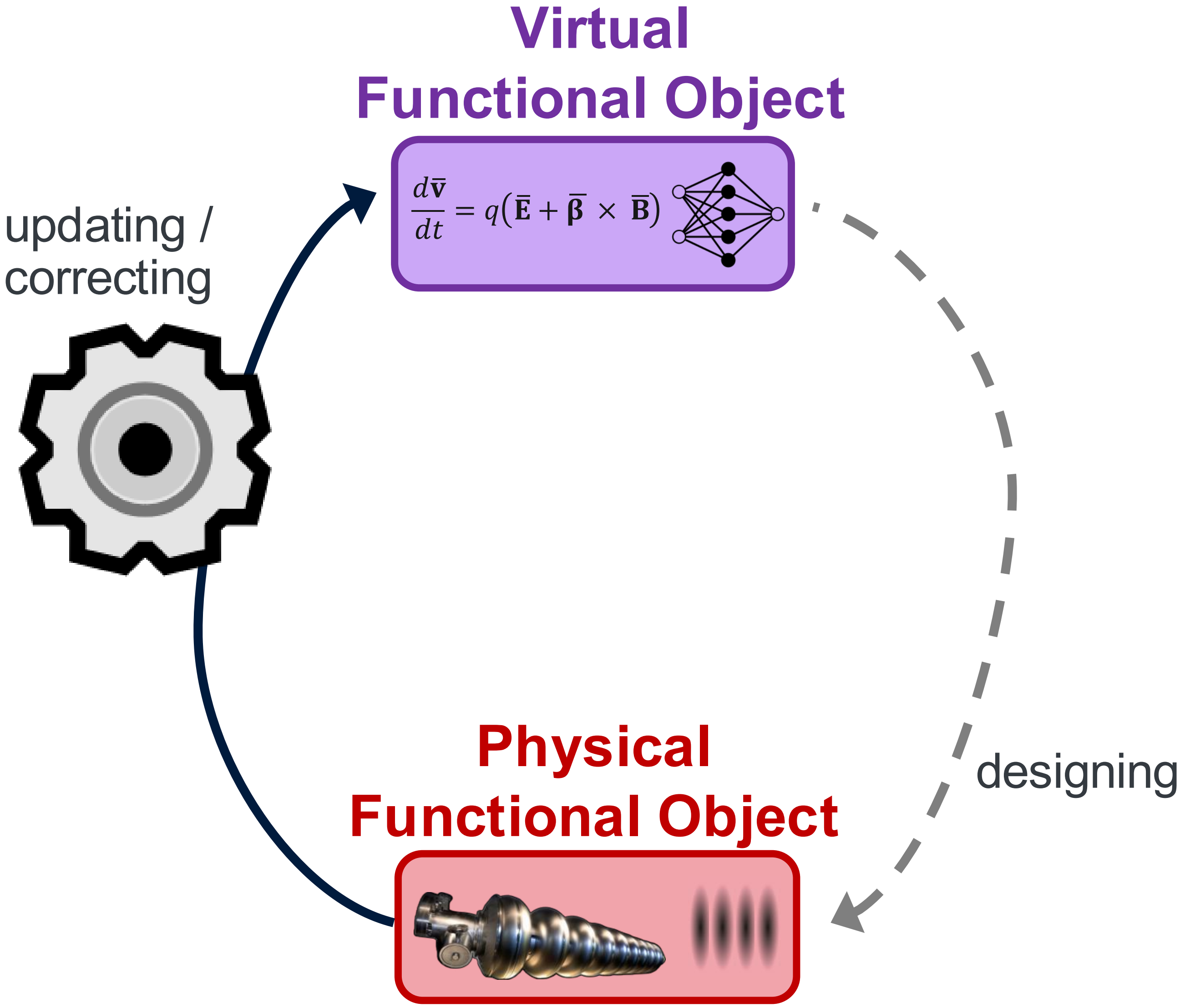
- Utility:
  - Virtual space copies for coarse behavior predictions
  - Prototyping application I/O

Digital Shadow

Up-to-date simulation

- One-way automated information flow
- physical → virtual

- Utility:
  - Virtual space copies for accurate behavior predictions
  - Prototyping controls



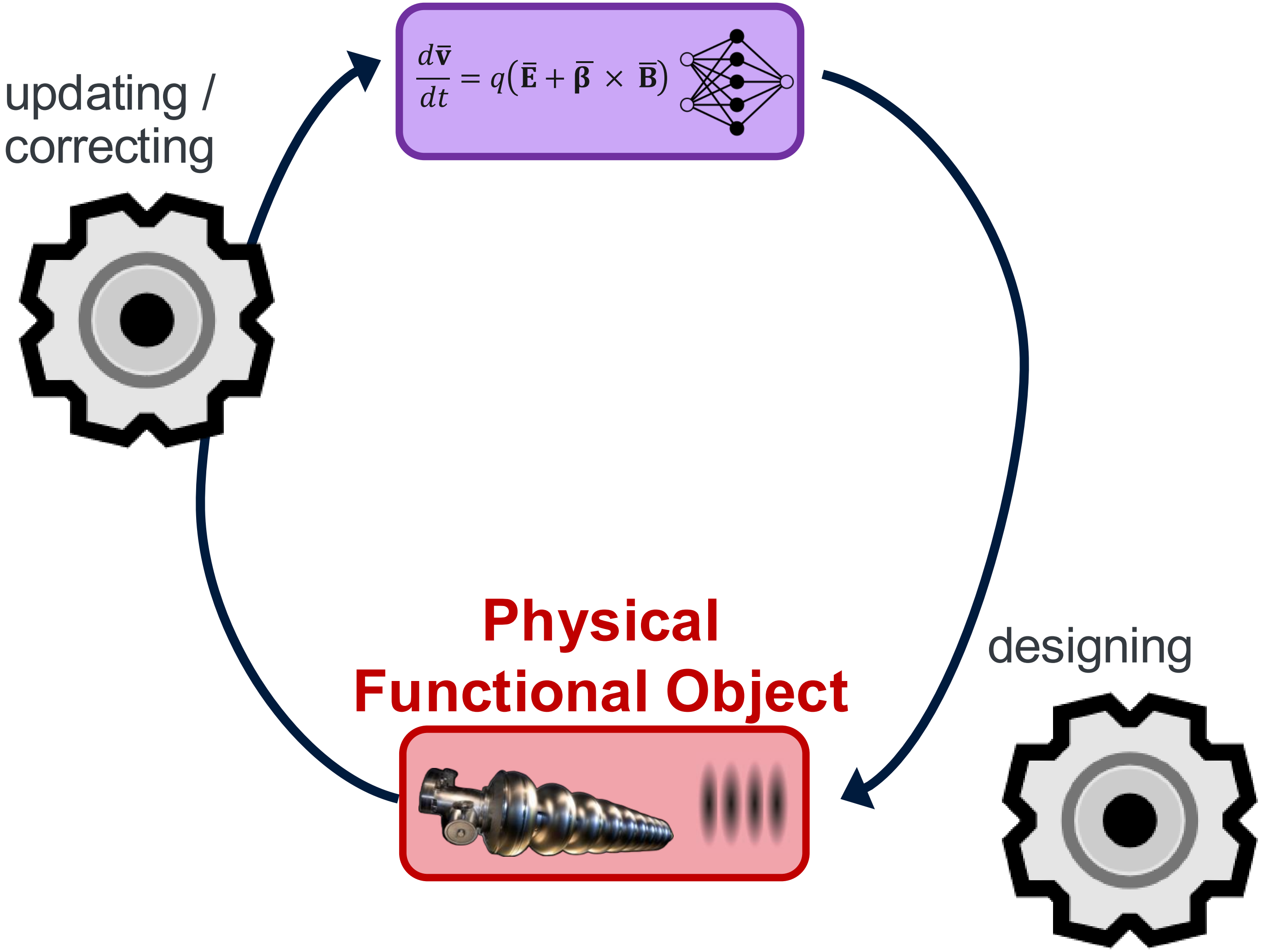
Digital Twin

Coupled system

1. **Bidirectional interaction**
2. **Mimics structure, context, behavior of physical system**
3. **Predictive capability**
4. **Informs decisions**

- Fully bi-directional flow
- physical ⟵⟶ virtual
- Utility:
  - Live control feedback (self-tuning, autocorrecting)
  - “super” PID loop

Virtual Functional Object



Digital Twin

Coupled system

- Fully bi-directional flow
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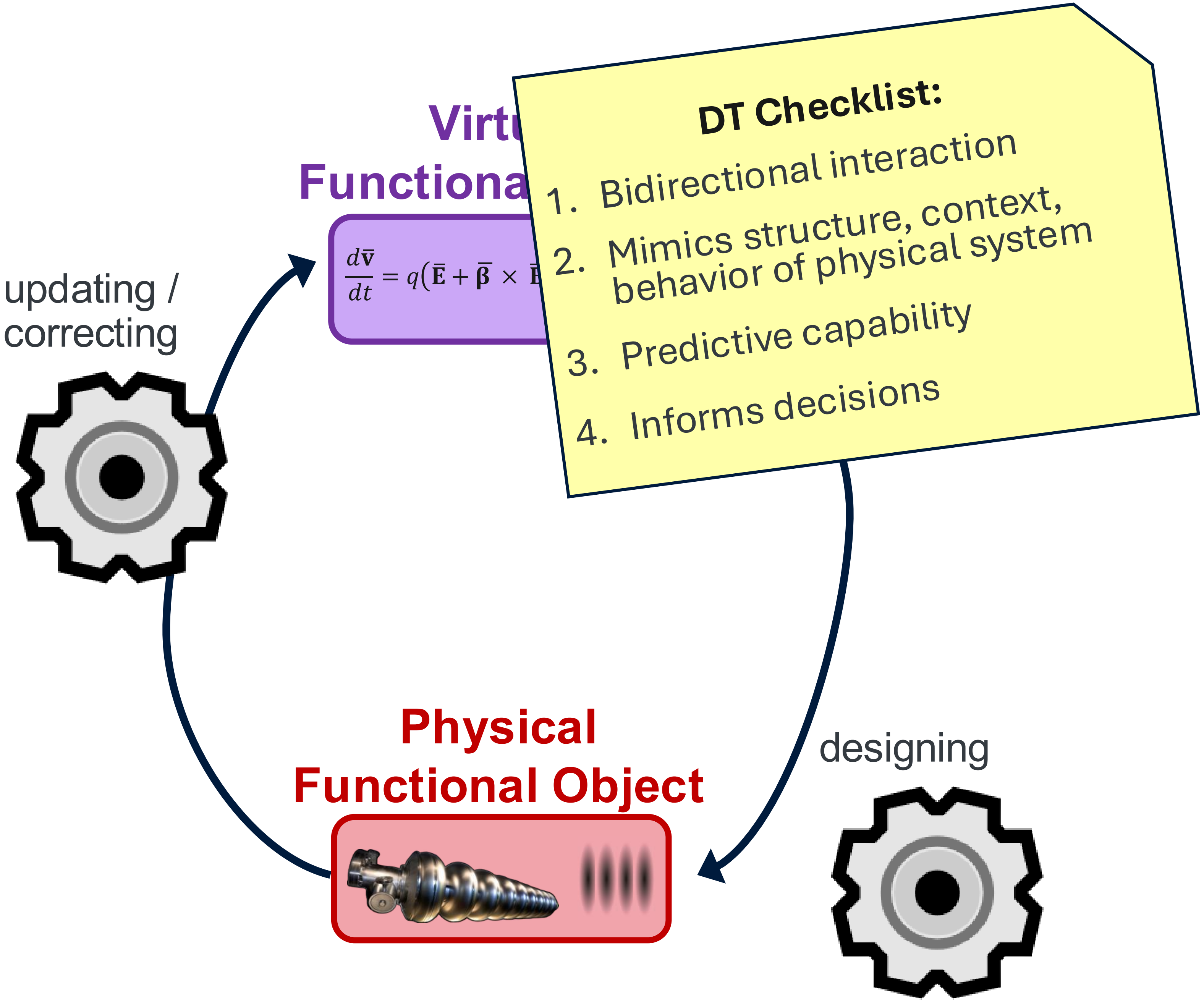
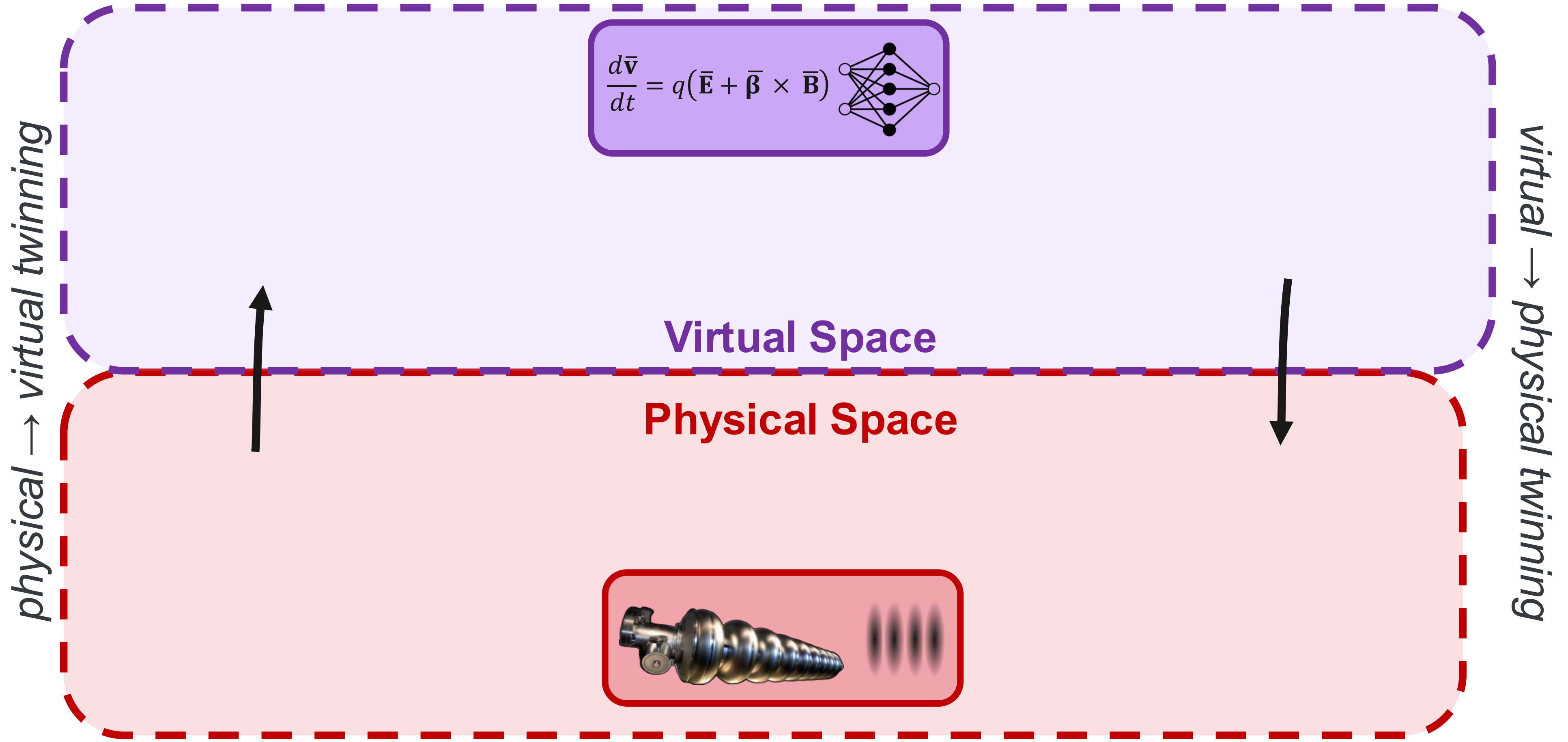


Twinning

Updating model

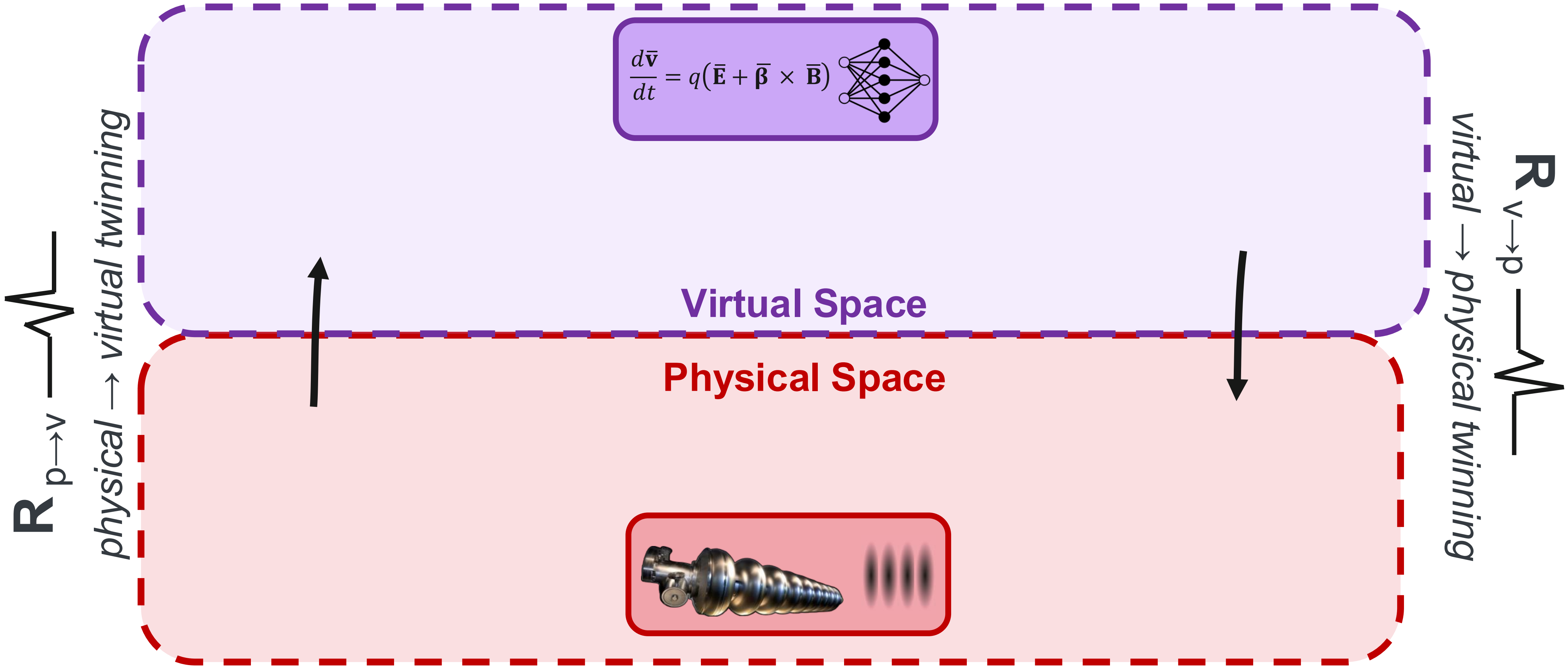


Adapted from: Characterising the Digital Twin: A systematic literature review, D. Jones et al. CIRP J. Manuf. Sci. Technol. 29 (2020) 36–52

Twinning

Updating model

Twinning Rates: **R**



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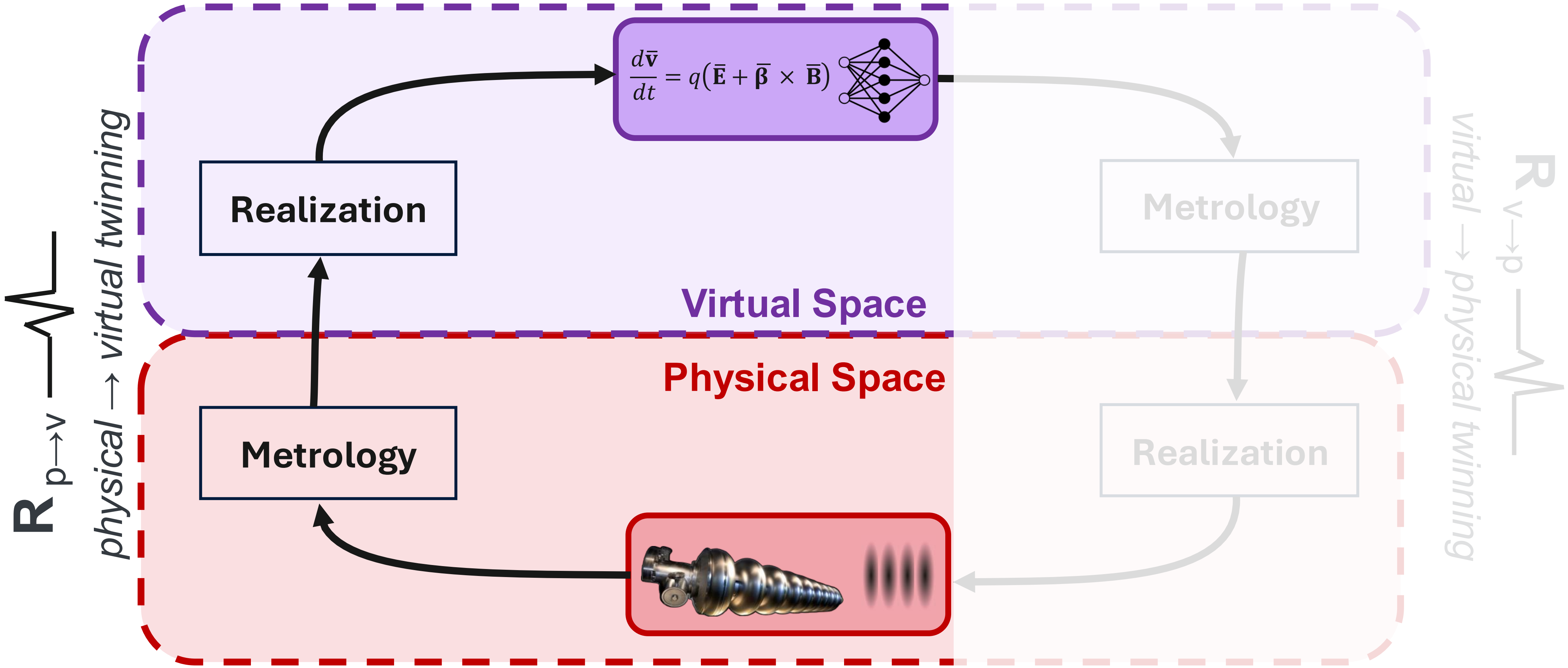
Twinning

Updating model

Metrology: observable outputs

Realization: translated inputs

Twinning Rates: R



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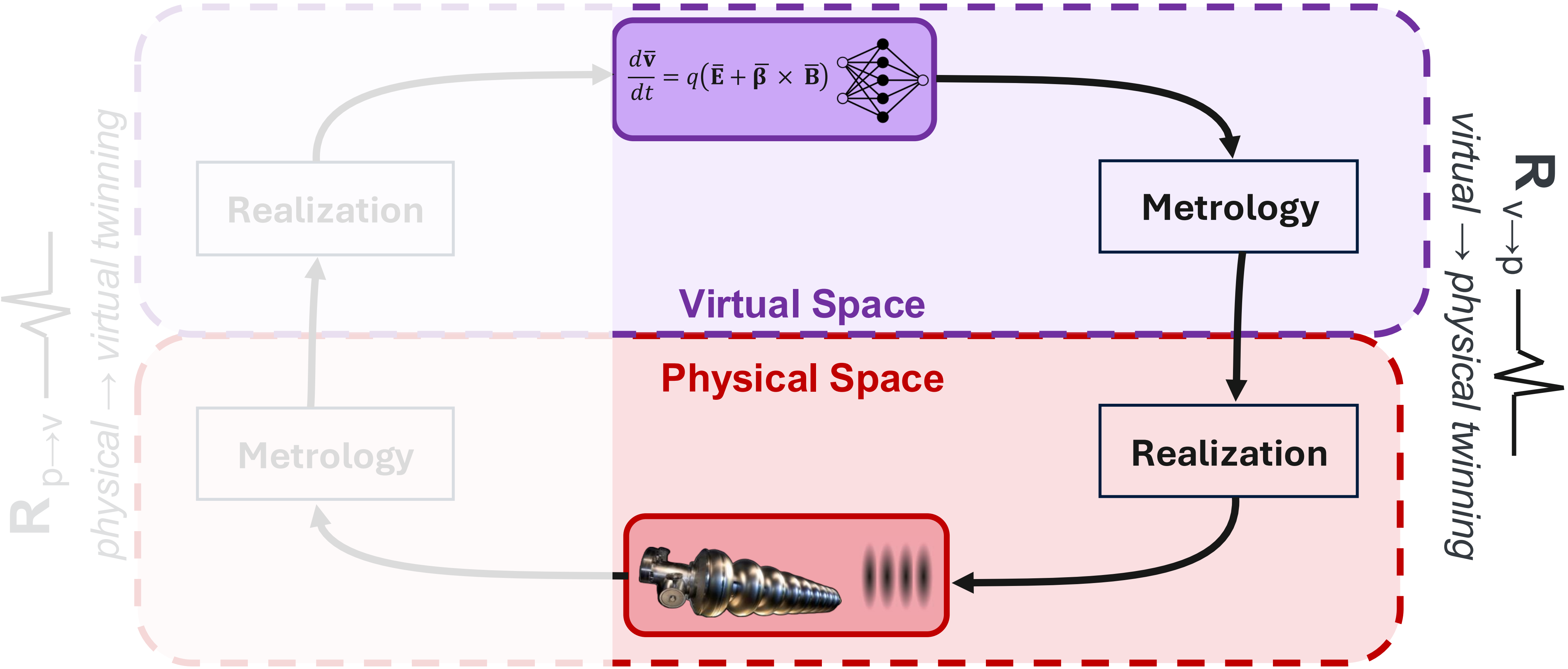
Twinning

Controlling the accelerator

Metrology: observable outputs

Realization: translated inputs

Twinning Rates: **R**



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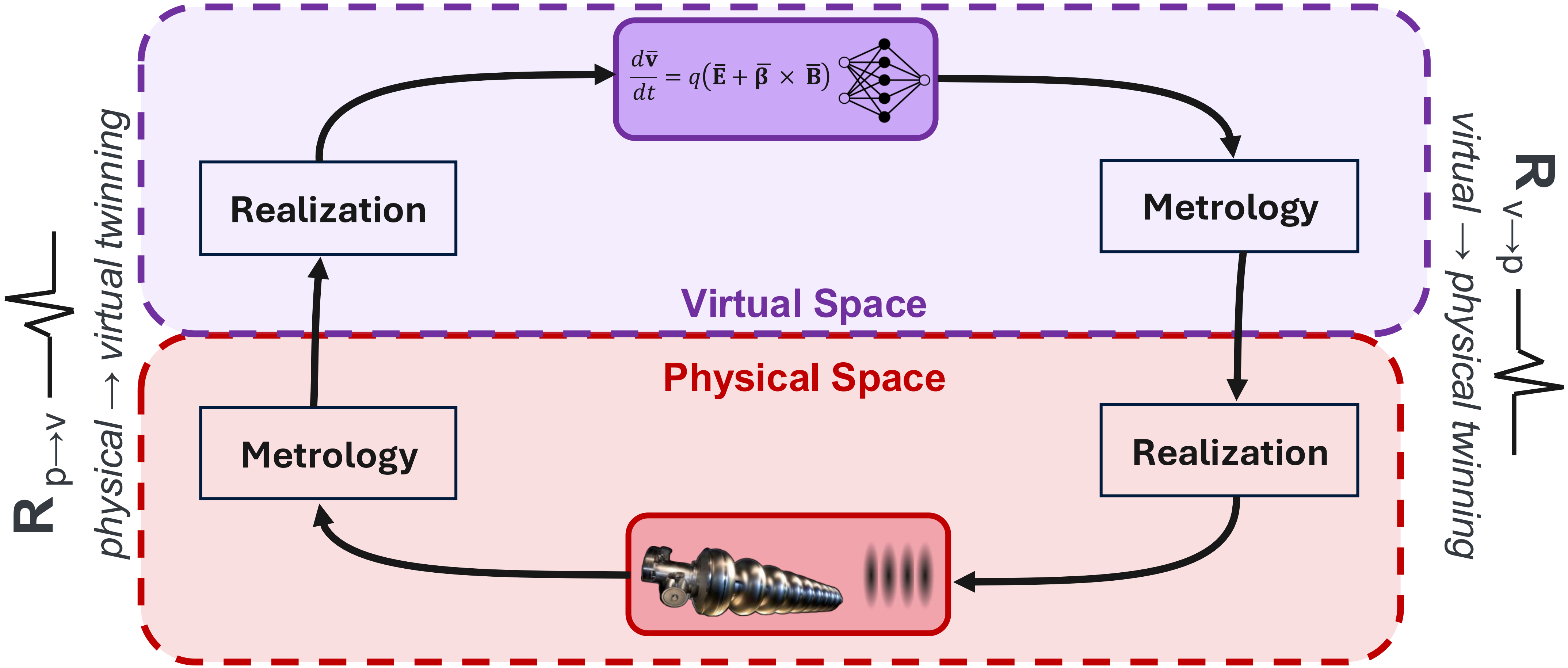
Twinning

Spaghetti

<u>Metrology</u>: observable outputs

<u>Realization</u>: translated inputs

<u>Twinning Rates</u>: **R**



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Twinning

Spaghetti

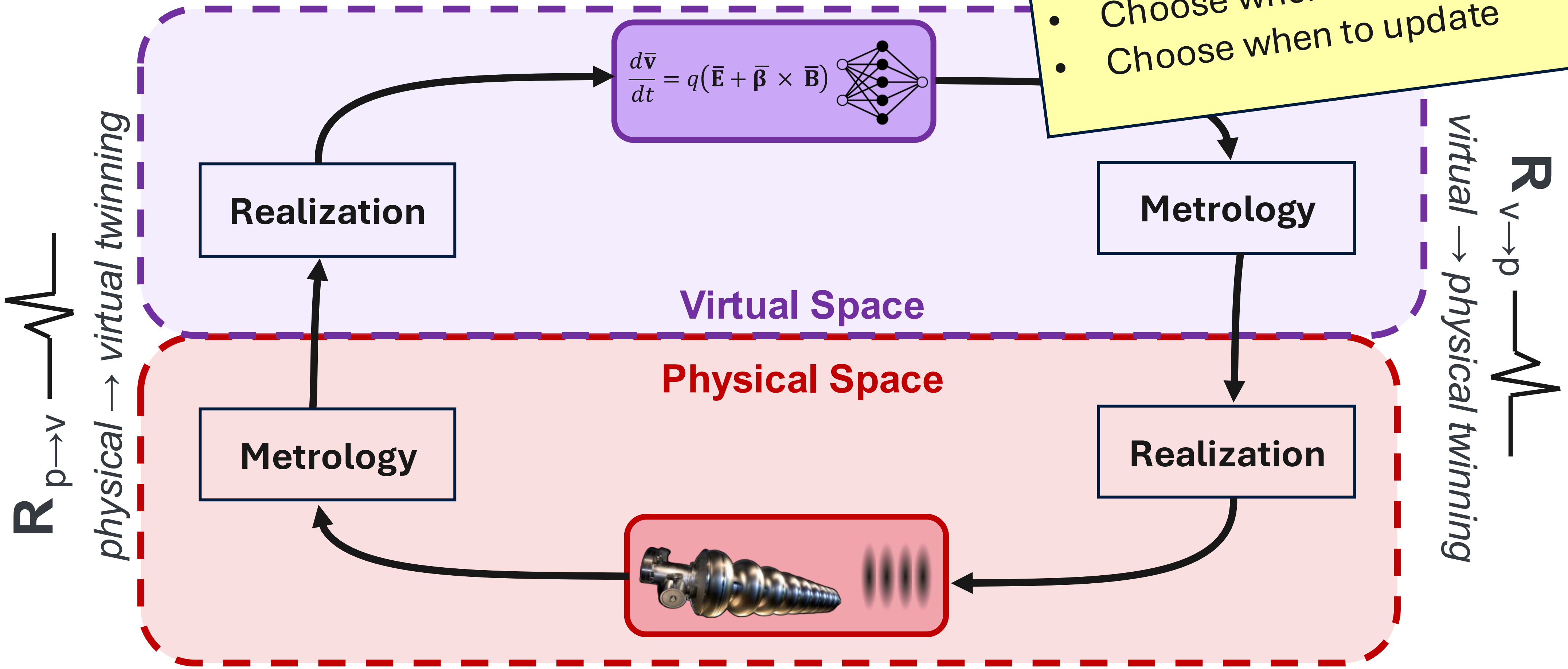
Metrology: observable outputs

Realization: translated inputs

Twinning Rates: **R**

Caution with Closed Loop:

- Choose when to monitor
- Choose when to update



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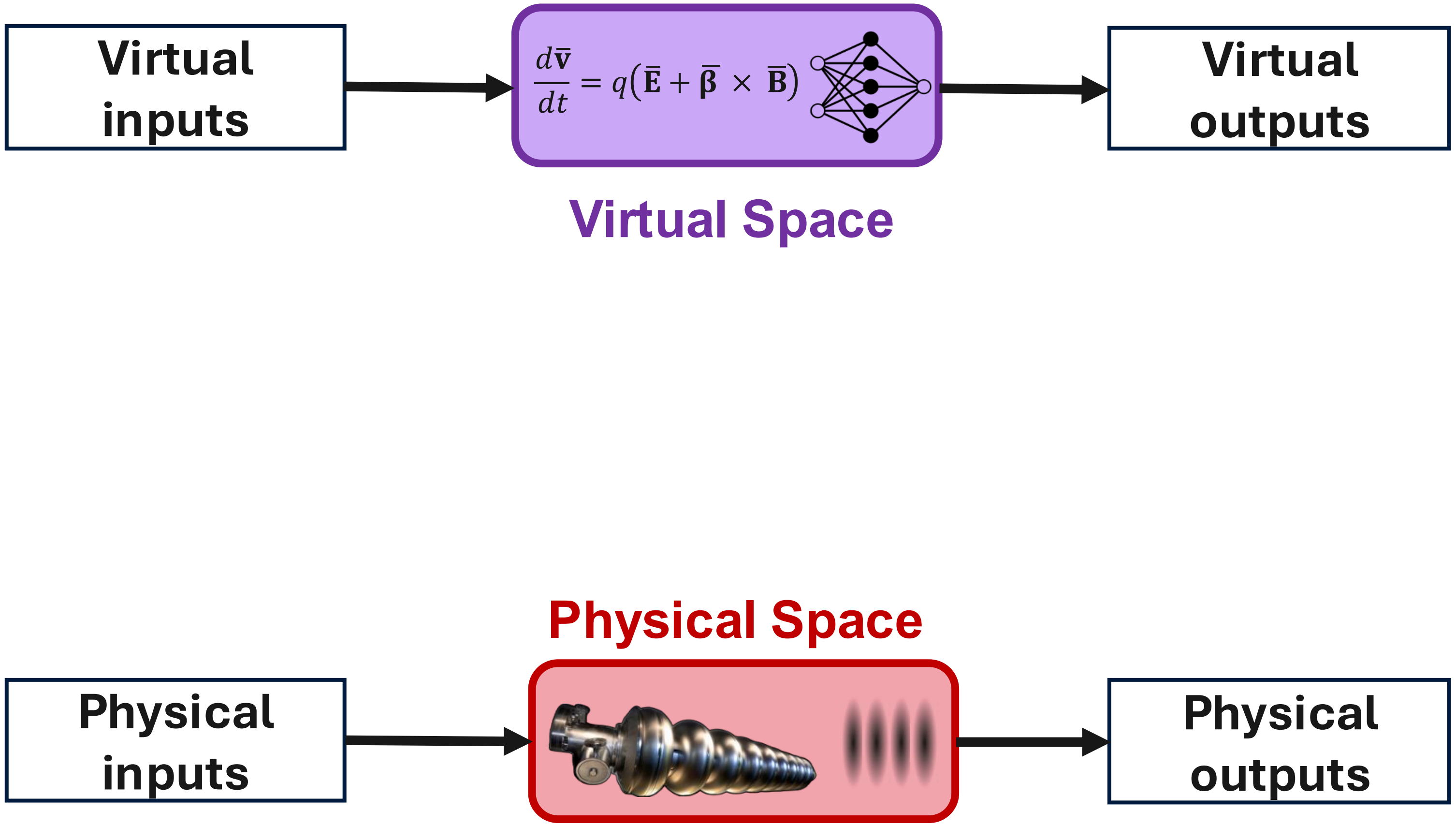
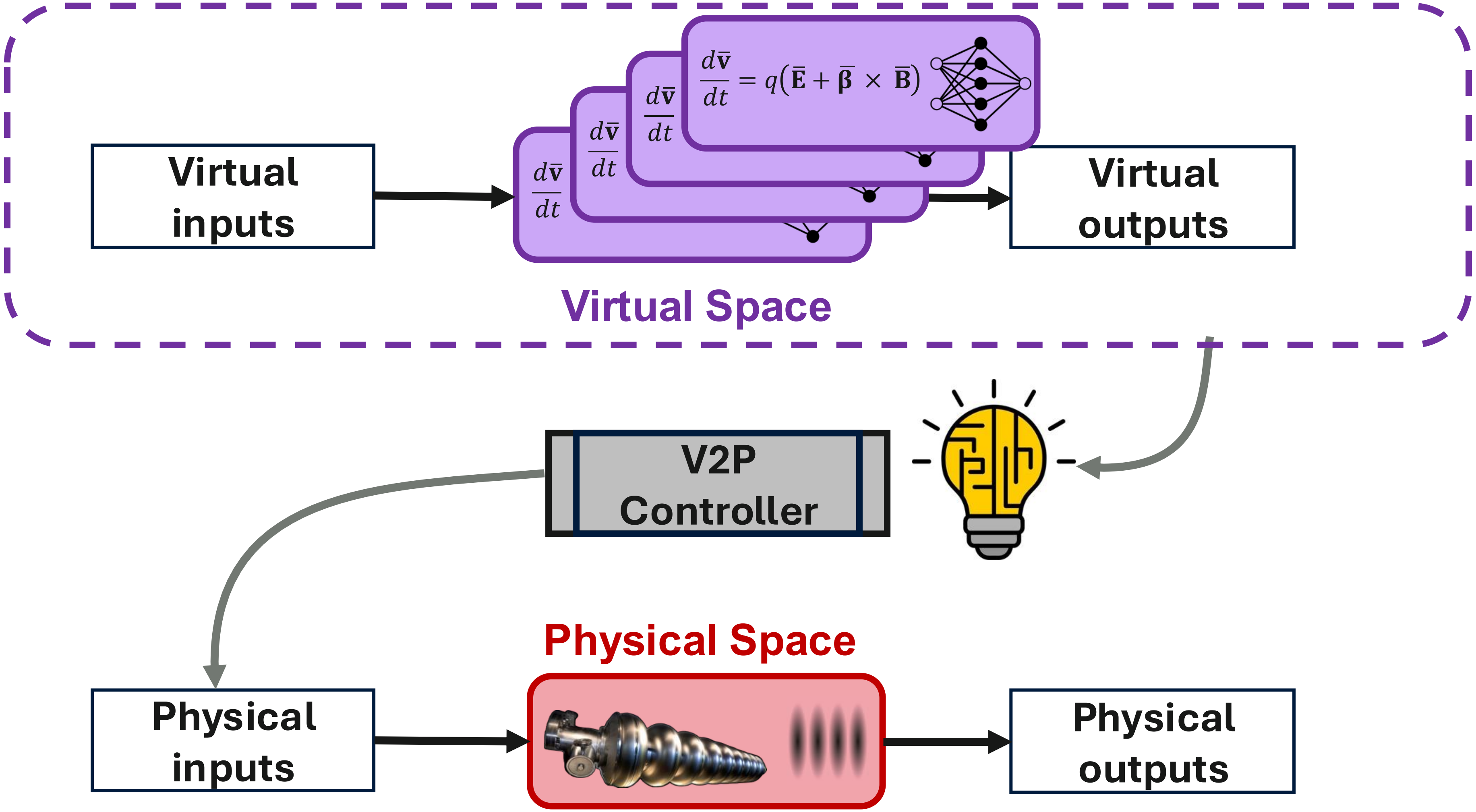
Twinac Modes

Selecting how to use the coupled system for our benefit



Twinac Modes: Virtual2Physical Controller

Decision logic to examine independent variables in VA; select settings for PA



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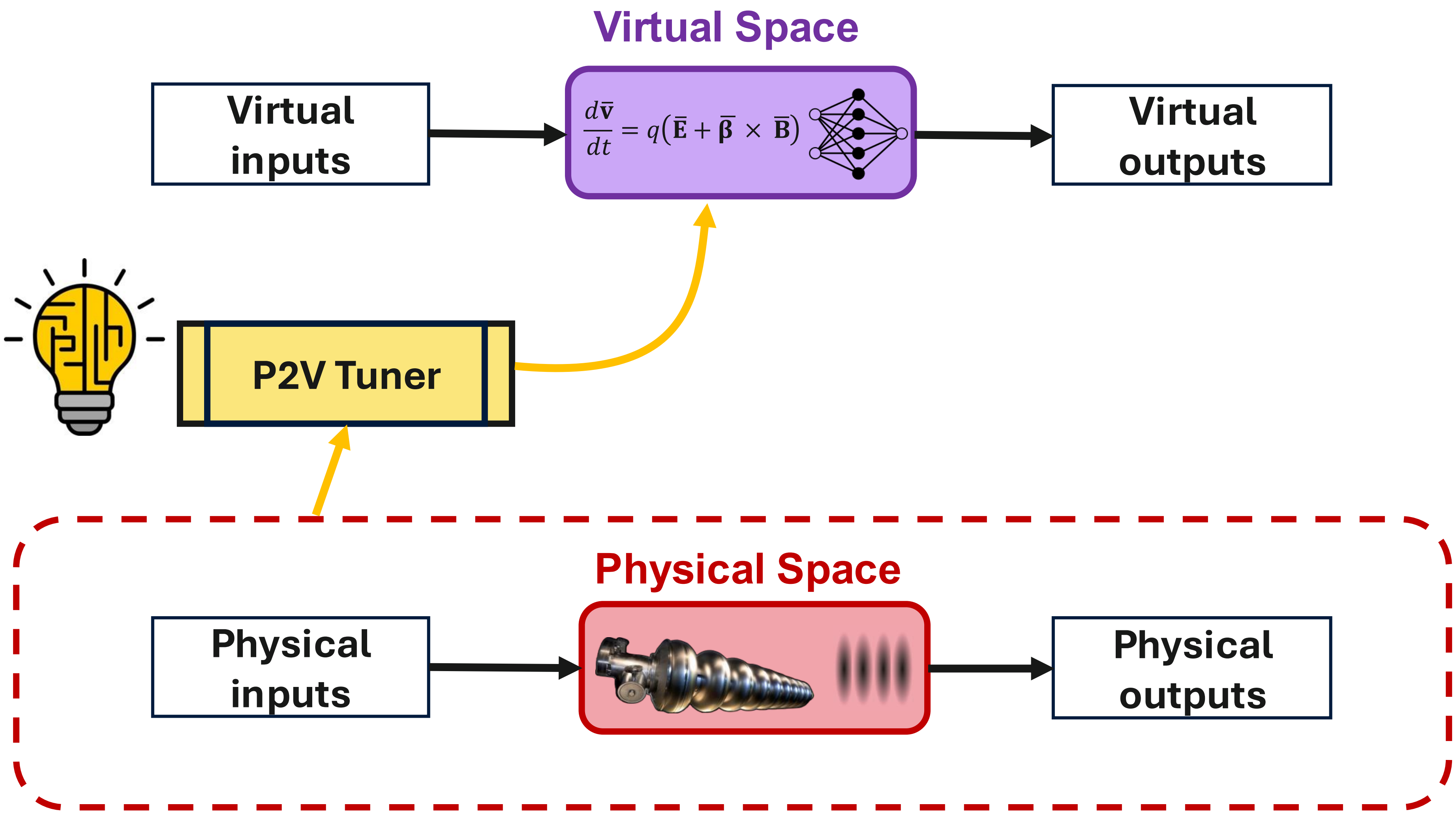
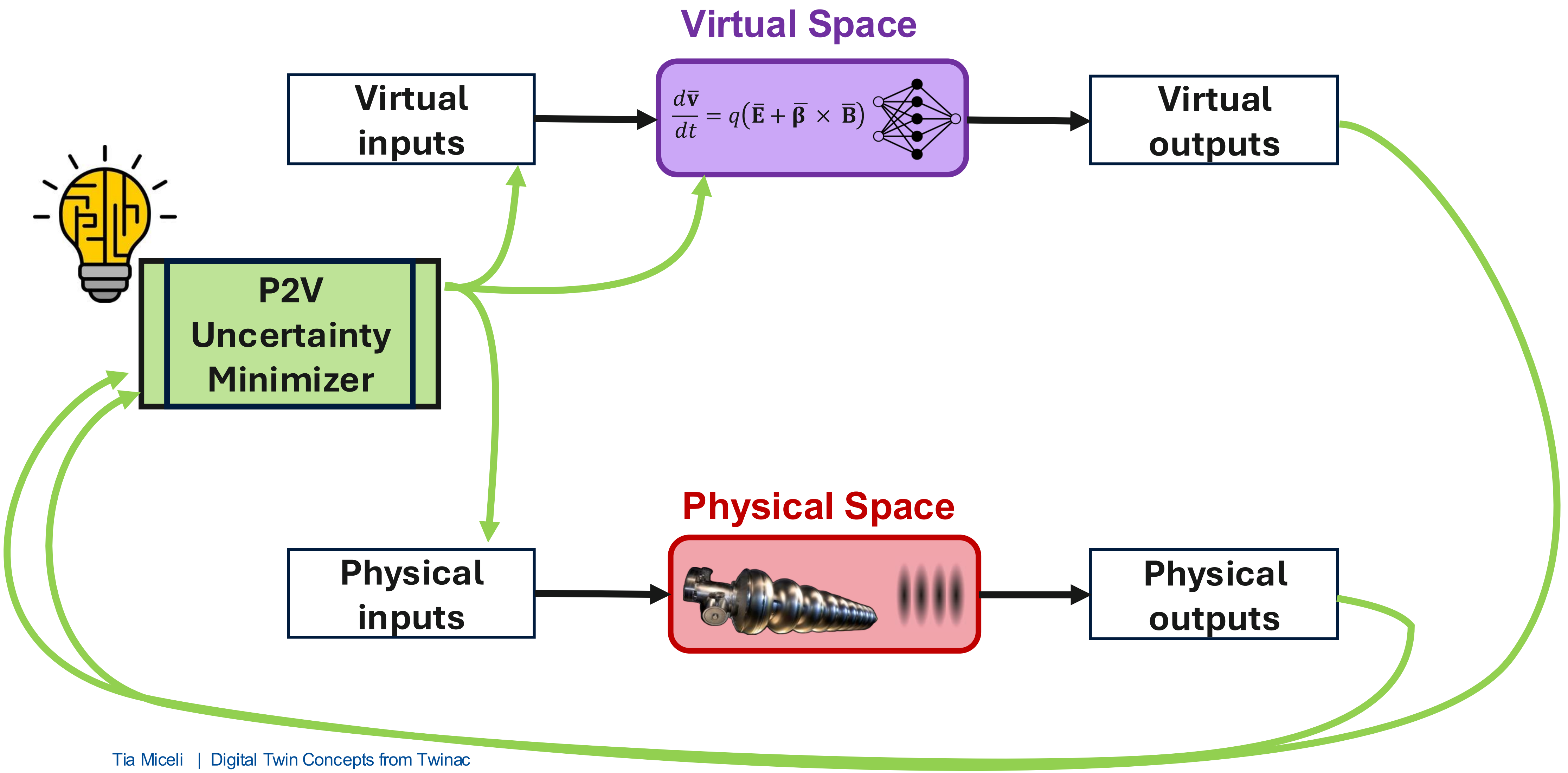
Twinac Modes: Physical2Virtual Tuner

Decision logic to update VA's functional object F_v based on physical system



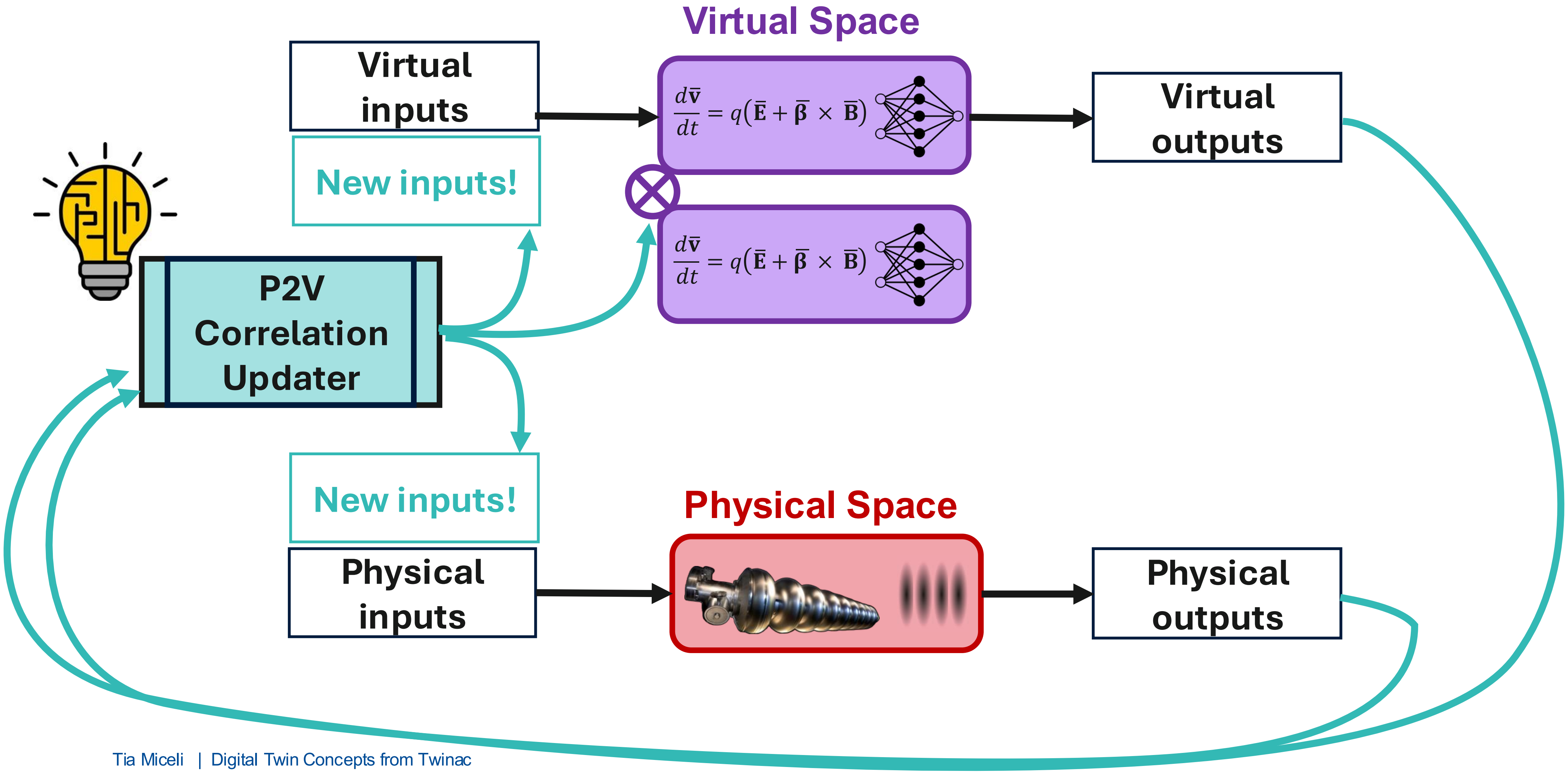
Twinac Modes: Physical2Virtual Uncertainty Minimizer

Decision logic to explore independent variables to update VA's functional object F_v



Twinac Modes: Physical2Virtual Correlation Updater

Decision logic to include new independent variables and update VA's functional object F_V

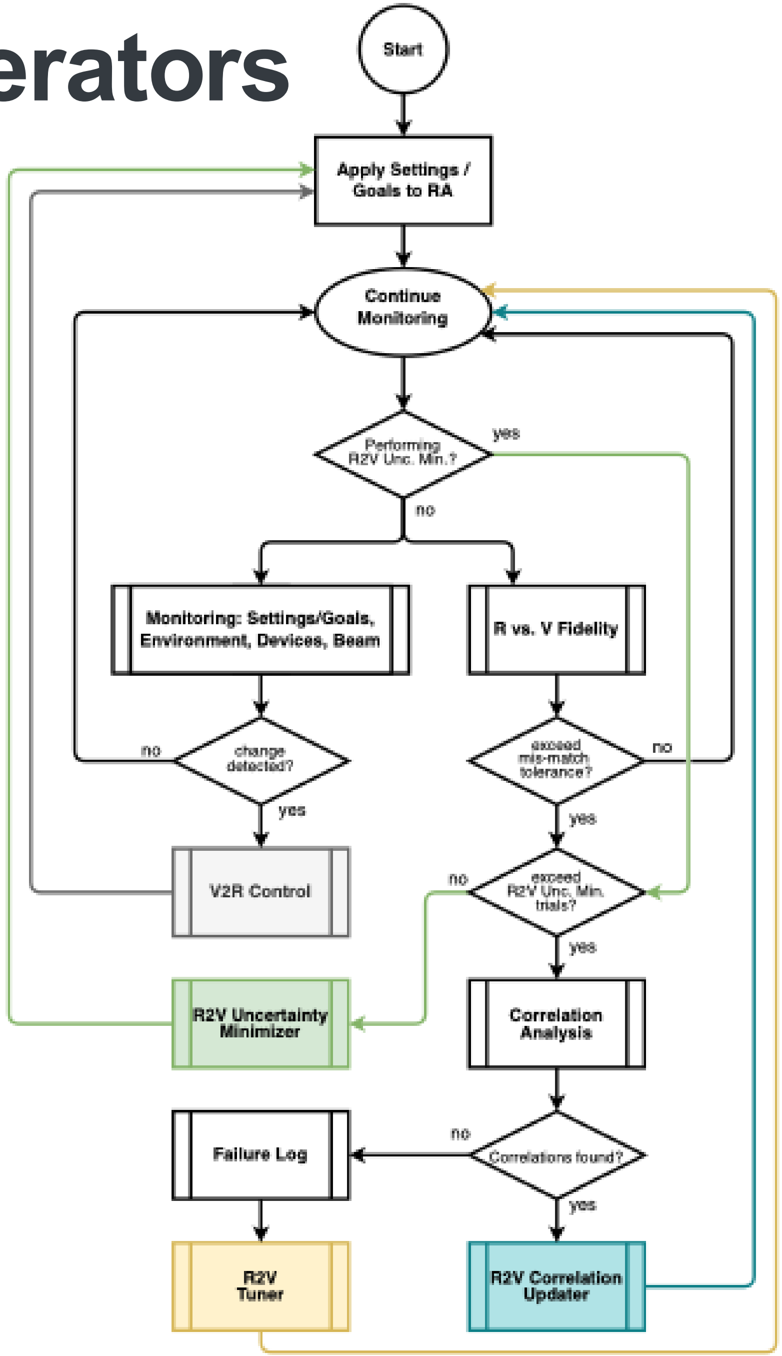


Safe logic for autonomous accelerators

Good to have a plan! Implement with care!

How to start?

- Focus on your facility's greatest pain points!
- Interview your operators to prioritize efforts!



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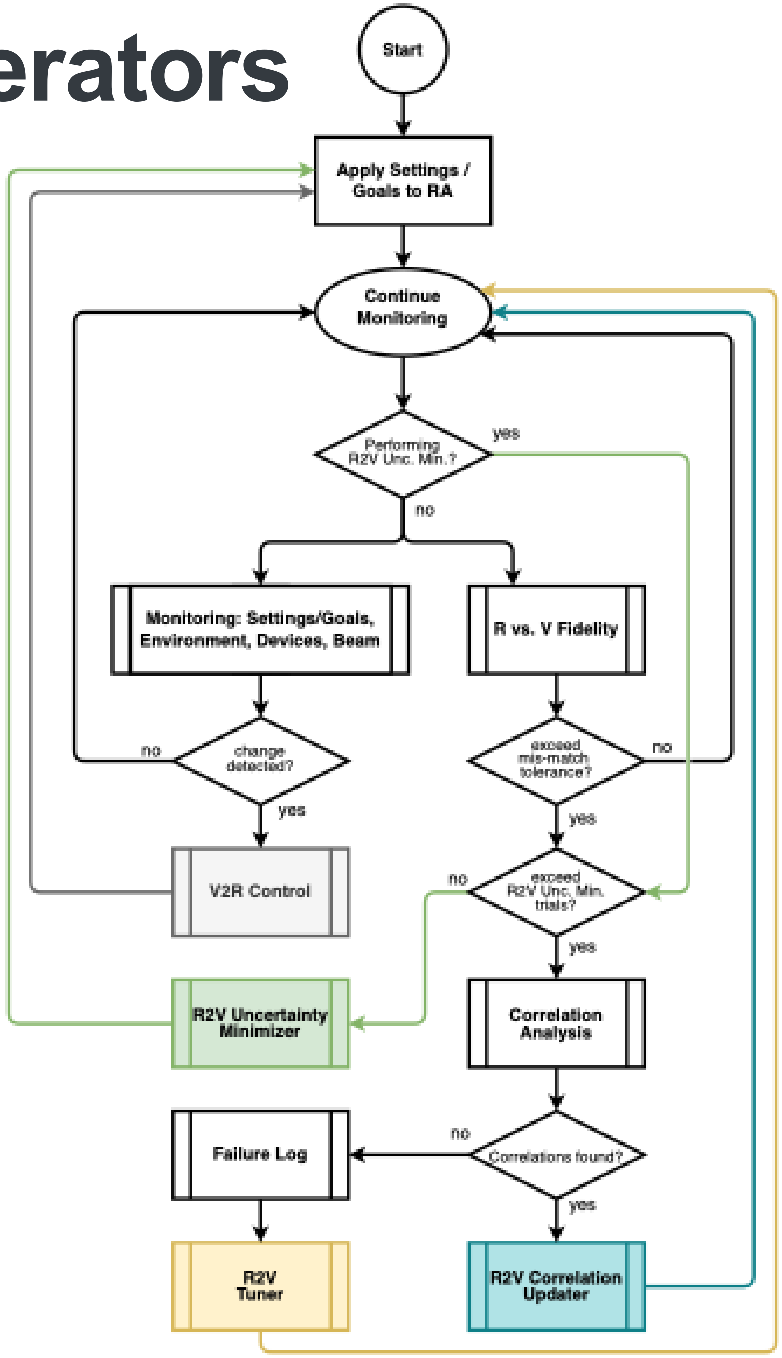

How to start?

- Focus on your facility's greatest pain points!
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Priorities at Fermilab:

- Commissioning PIP-II
    - Optical element placement
    - High-level applications
    - Operational PV setpoints

Collaborate with the Twinac team!

- Concepts:
  - Twinac: A Universal Framework for Virtual Accelerator Controls https://arxiv.org/pdf/2507.20493
- GitHub coming soon:
  - See next talk from Abhishek Pathak
- We are a small group at Fermilab, with first focus on PIP-II commissioning

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