Tuesdays & Thursdays
12:00-13:30 ET
GGBL 2147

Hello

ME599-004: Data-Driven Methods for Control Systems

Winter 2024

Instructor: Uduak (*Who-dwak*) Inyang-Udoh

MECHANICAL ENGINEERING
UNIVERSITY OF MICHIGAN

UI @ UMich

Uduak Inyang-Udoh

Assistant Professor

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PURDUE UNIVERSITY

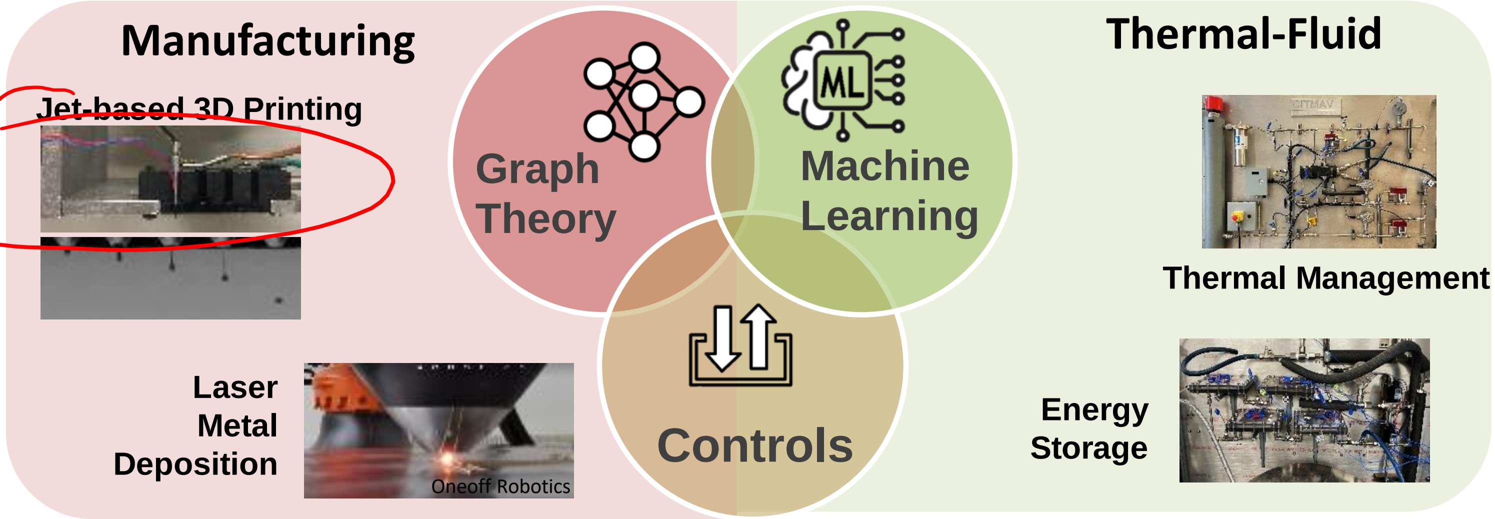
Ph.D. in ME ‘21

Rensselaer

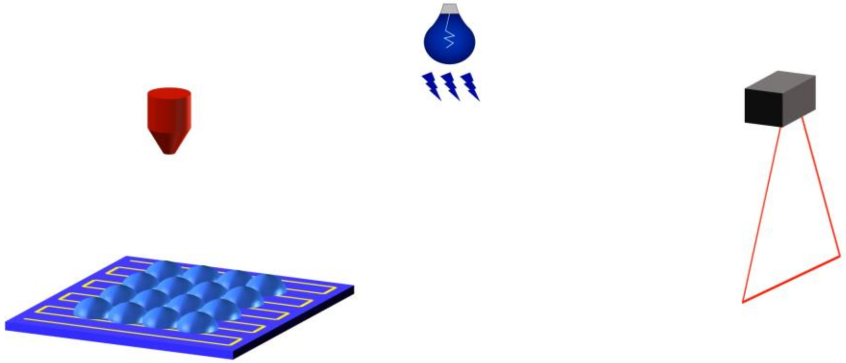
[Autonomous & Intelligent Systems Lab](#)

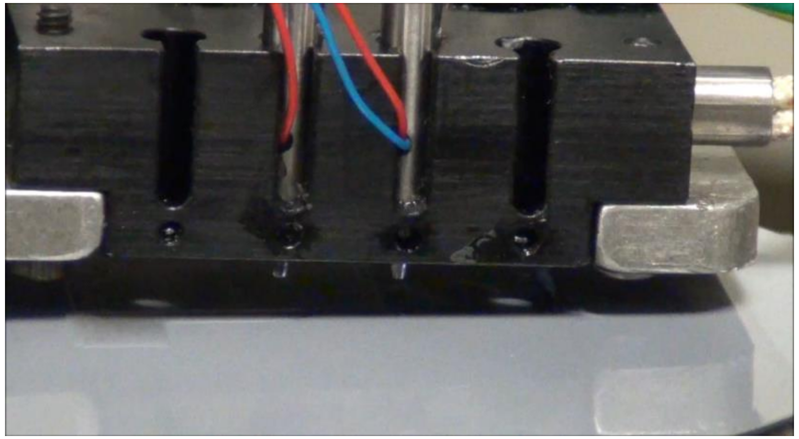
Research

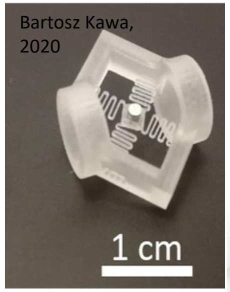
- graph theory + physics-guided machine learning for controls;
- *applications:* advanced manufacturing, thermal-fluid systems.

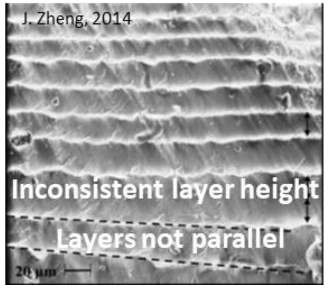


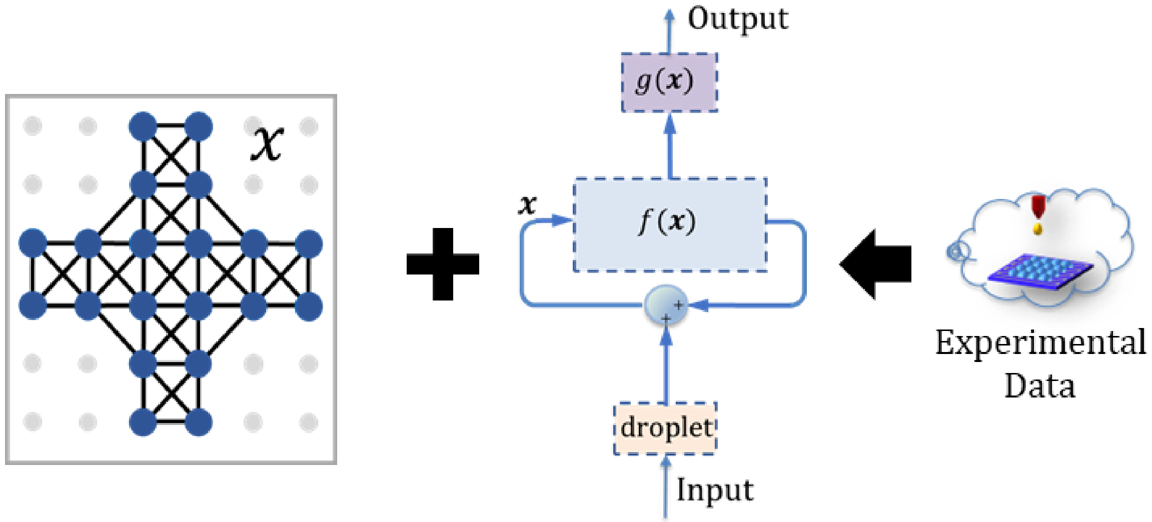
Input Pattern Control in Inkjet 3D Printing



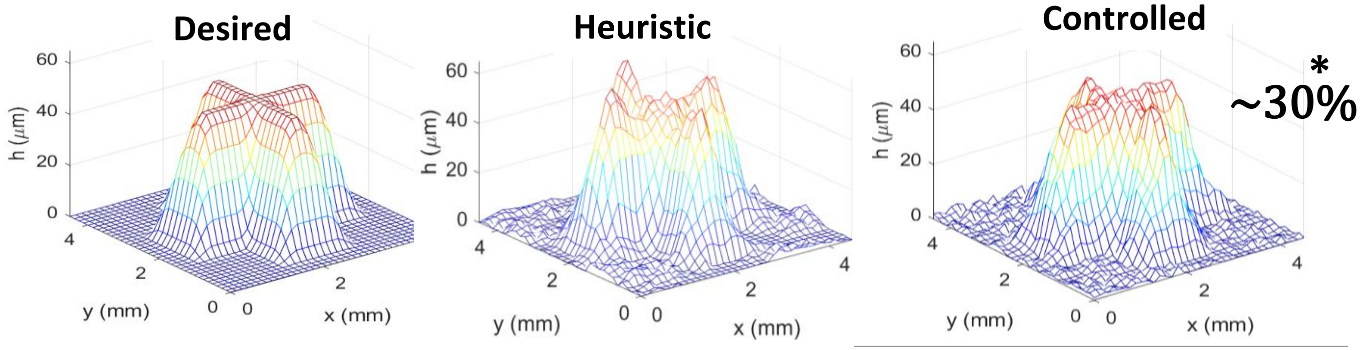




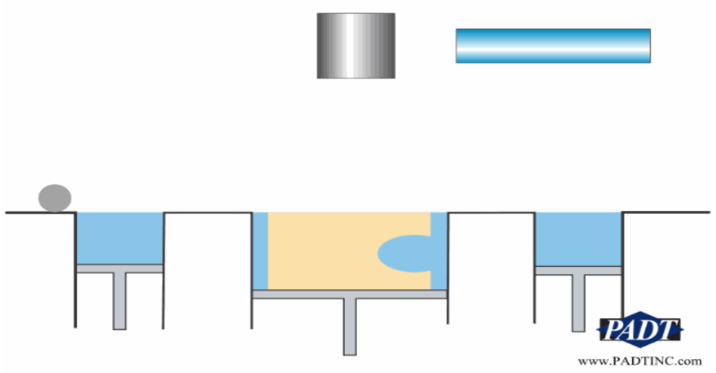


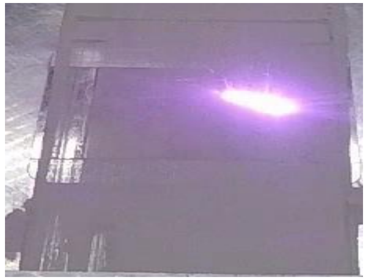


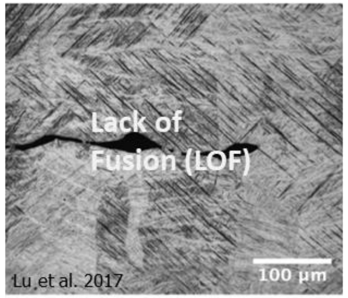
- Learn dynamics
- Lends itself to **in-process learning & control**



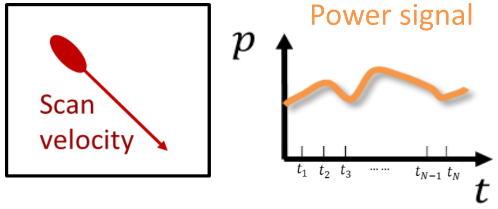
Input Shaping in Laser-Based Additive Manufacturing



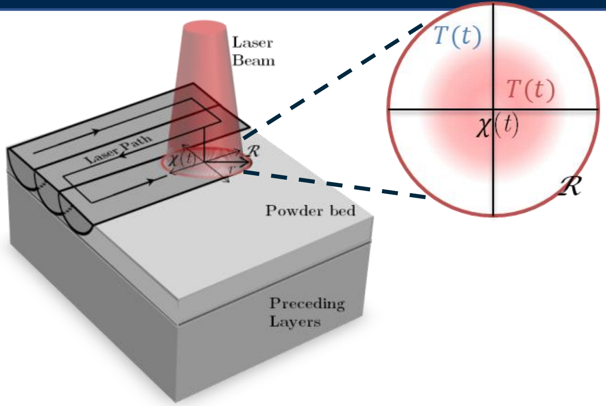


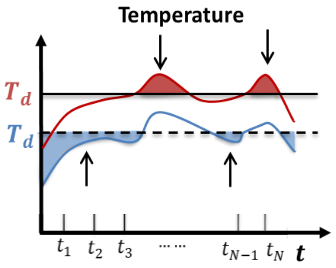


U. **Inyang-Udoh** et al., 2022



Dynamically modulate input?





Optimize: $\underset{\boldsymbol{p}}{arg\min}\ \boldsymbol{E}$

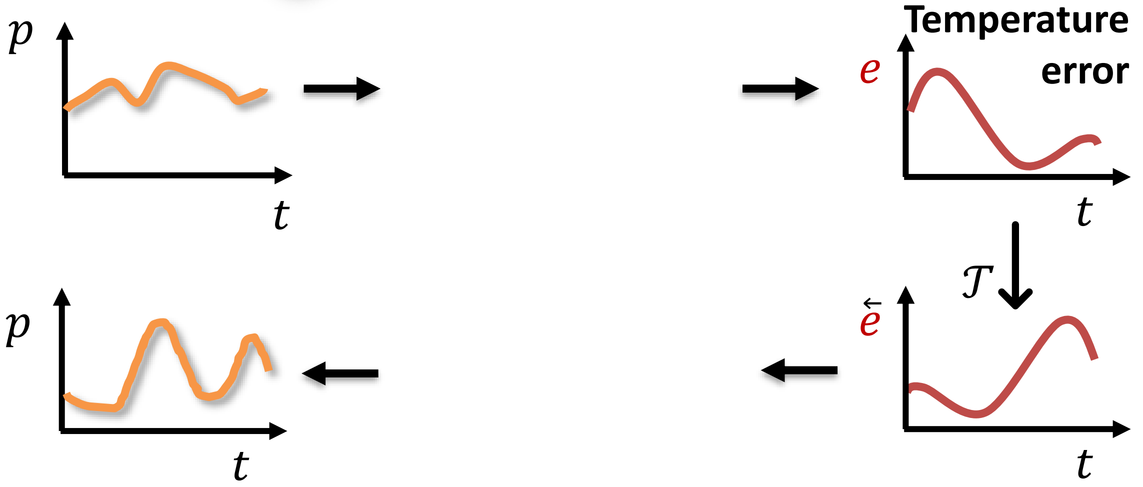
Gradient Descent:

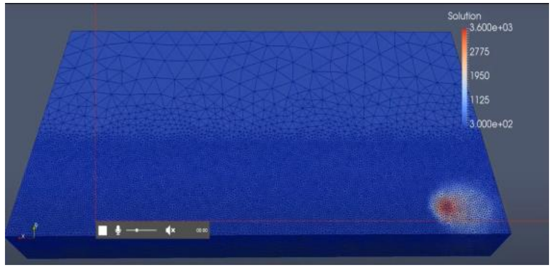
$$\boldsymbol{p}^{new} \leftarrow \boldsymbol{p}^{old} - \alpha G^{*} \boldsymbol{e}^{old}$$

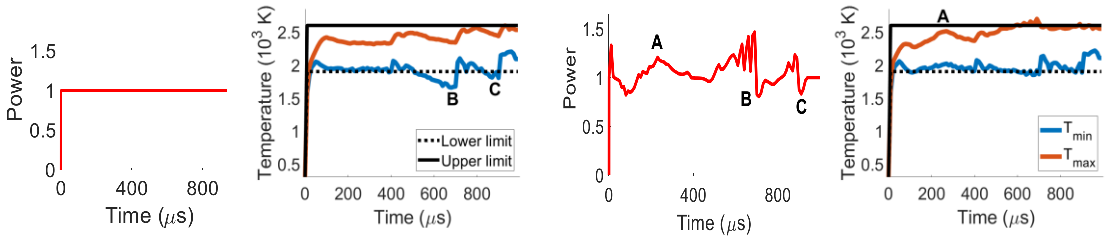
adjoint

$$\boldsymbol{p} \xrightarrow{\mathcal{G}} \boldsymbol{E}$$

- **Unknown, complex**
- **High dimensional**

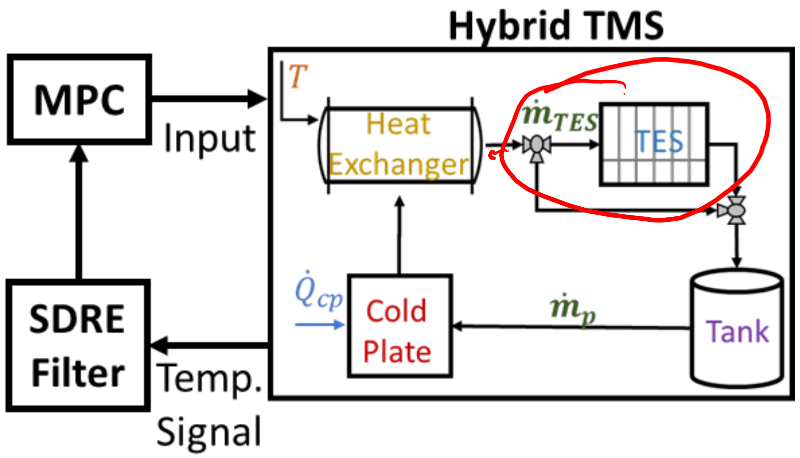






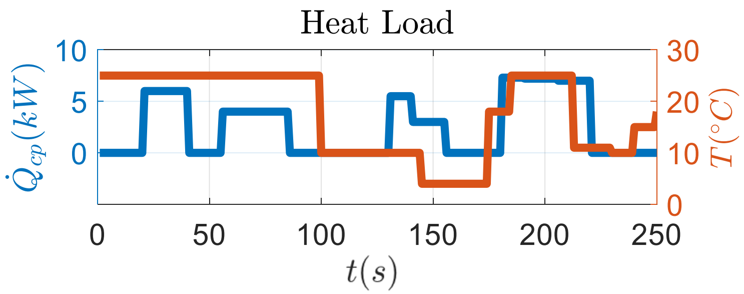
Control in Hybrid Thermal Management

A TMS with a **Thermal energy storage** (TES) device → "hybrid TMS"

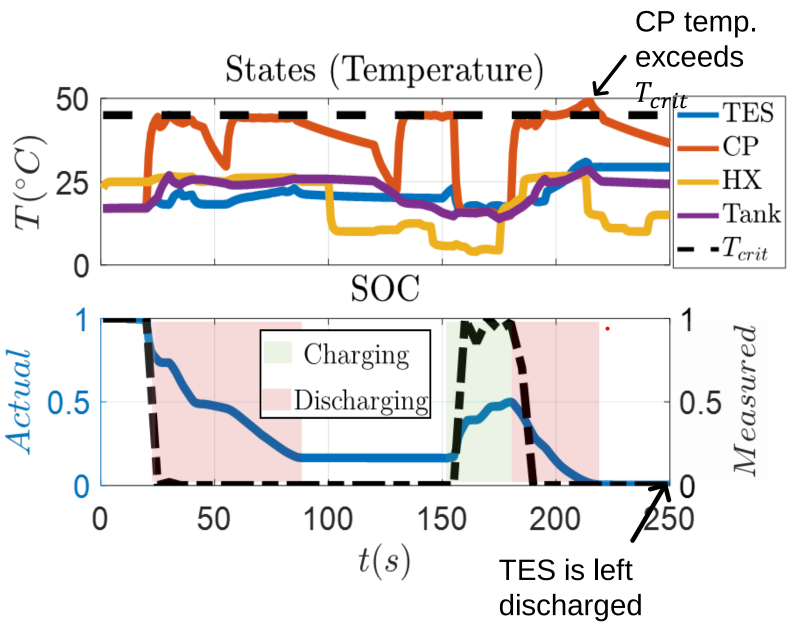


State of charge (SOC): remaining energy storage capacity of TES

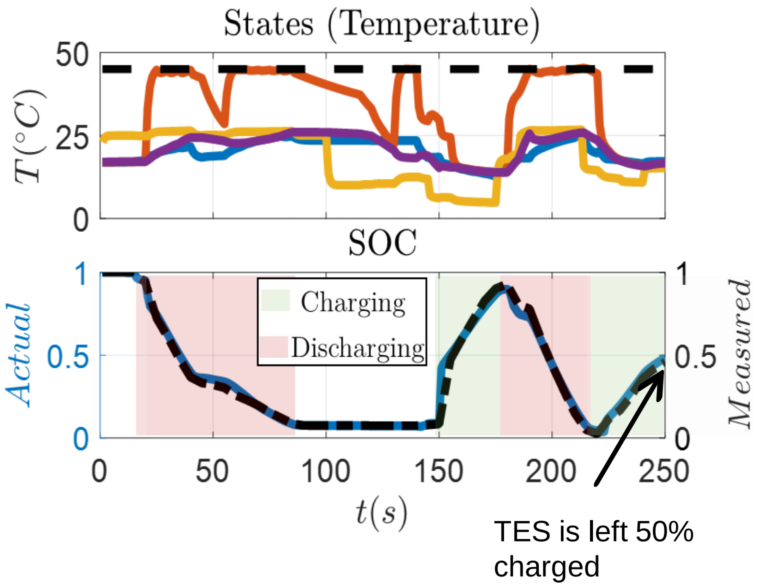
- Designed to keep cold plate (CP) temp. below T_{crit} while coordinating charging of TES.
- In presence of heat loads Q_{cp} and chiller temperature T_{ch}



Without SOC Estimate



With SOC Estimate



Would be nice to …

- Be familiar with writing codes

have a background

- classical controls (basic knowledge of controls),
- linear algebra (mostly the matrix algebra part)

…even better, to have knowledge of

- state-space modeling

Assessment

- Homework Problems – 80%
- (Group) Project/Study – 20%
- Quizzes/additional homework problems (optional) – 5% (Bonus points)

Homework

- Eight (8) problem sets
- At least, one (1) week to complete each
- Mostly entail programming
- Submission report should include:
  - *Method(s)*
  - *Assumption(s)*
  - *Results (results will be graded based on rubric on Canvas)*
- Refer to document on Canvas for more information about homework submission & academic integrity

(Group) Project/Study

- Exercise the knowledge gained from this course and explore topics that may be beneficial to your graduate research
- Expected to work in teams of 2 or 3, or justify working alone
- Propose topic (I will also have a list of few suggestions) and submit abstract (*tentatively* by March 18)
- Deliverables: Project reports, short presentation
- Grading: Peer review based on rubric provided by instructor

Bonus Quizzes/Additional Homework Problems (Optional)

- Few in-class quizzes (optional), time permitting; or
- Optional homework problems

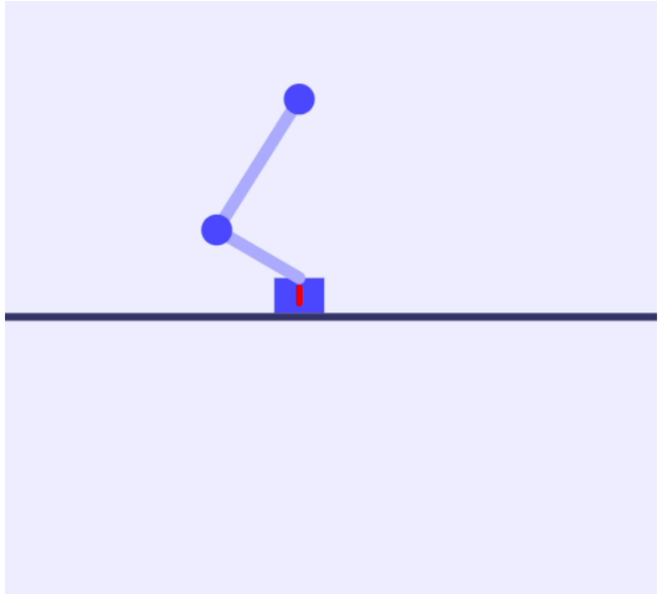
References

1. Brunton and Kutz, *Data-Driven Science and Engineering: Machine Learning, Dynamical Systems, and Control*, 2nd ed., Cambridge University Press, 2023

2. Ljung, *System Identification: Theory for the User*, 2nd ed.,Prentice Hall, 1999

3. Keesman, *System Identification: An Introduction*, Springer, 2011

Why this Course?



Double inverted pendulum on a guide rail

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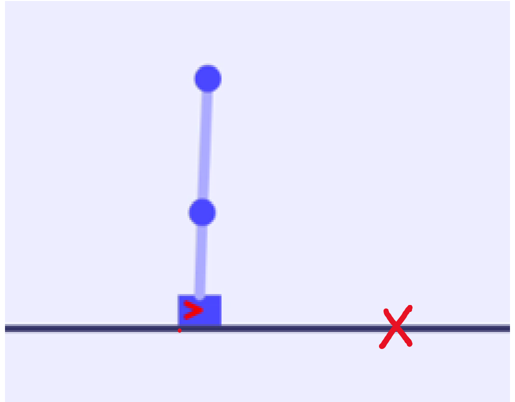

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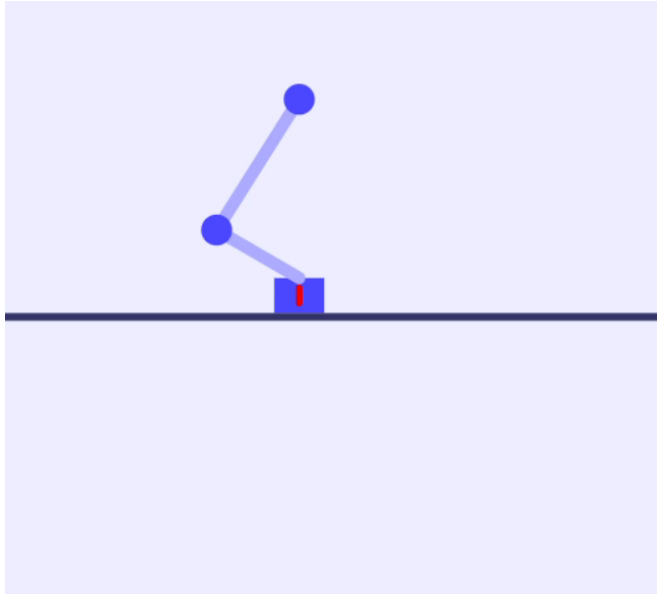

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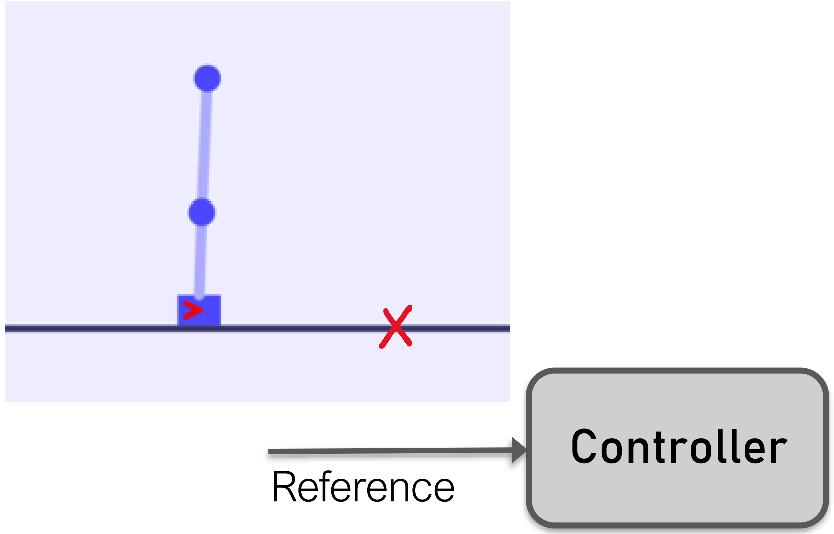

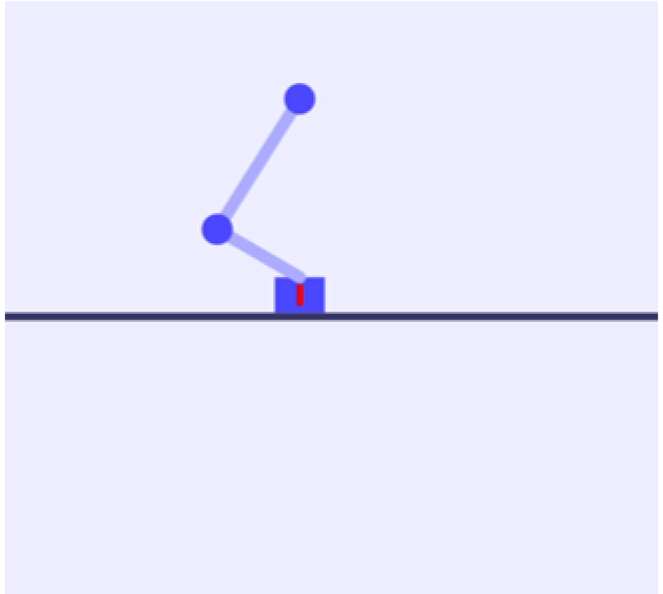

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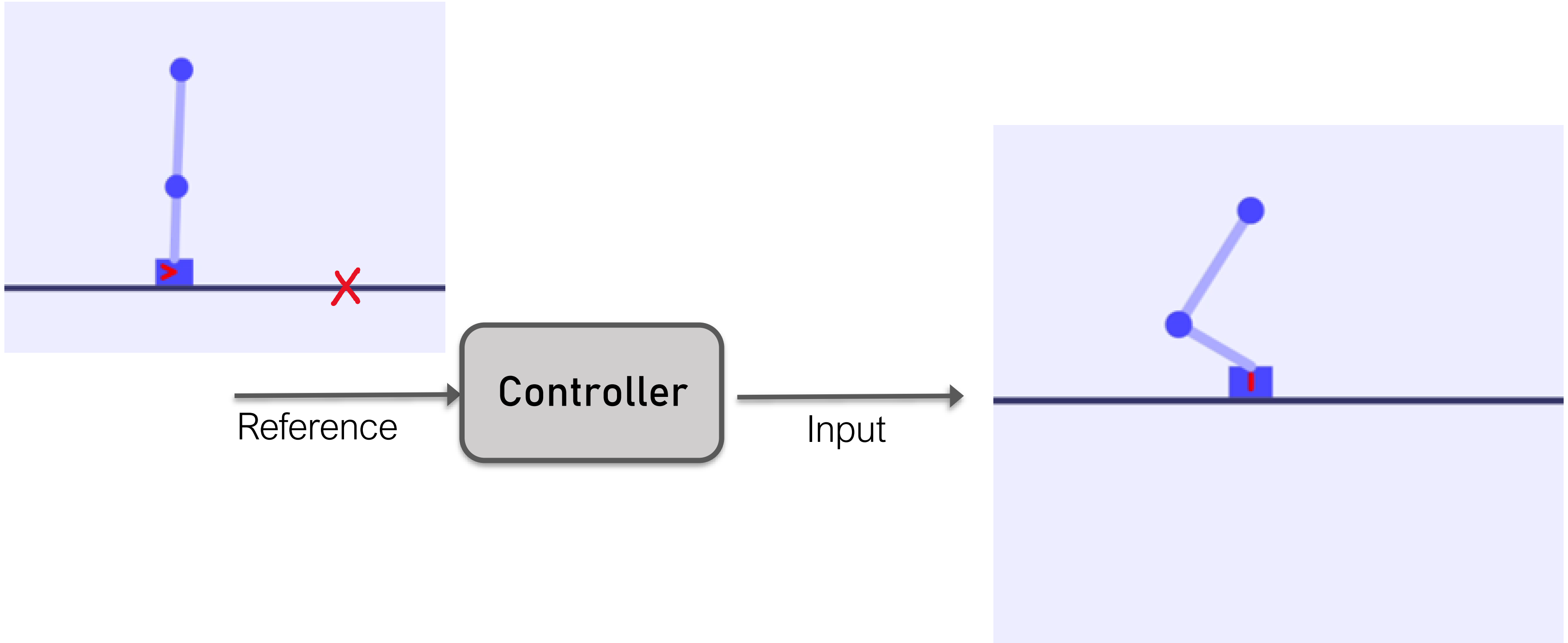

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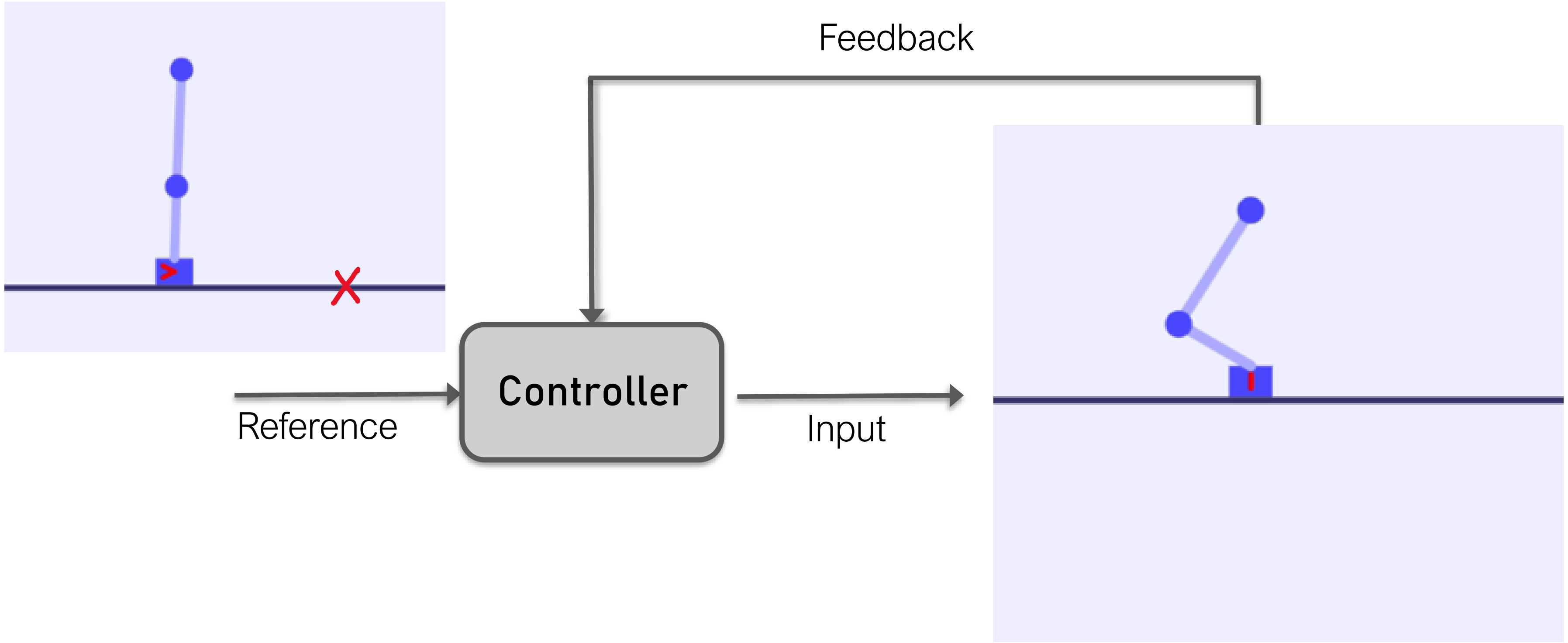

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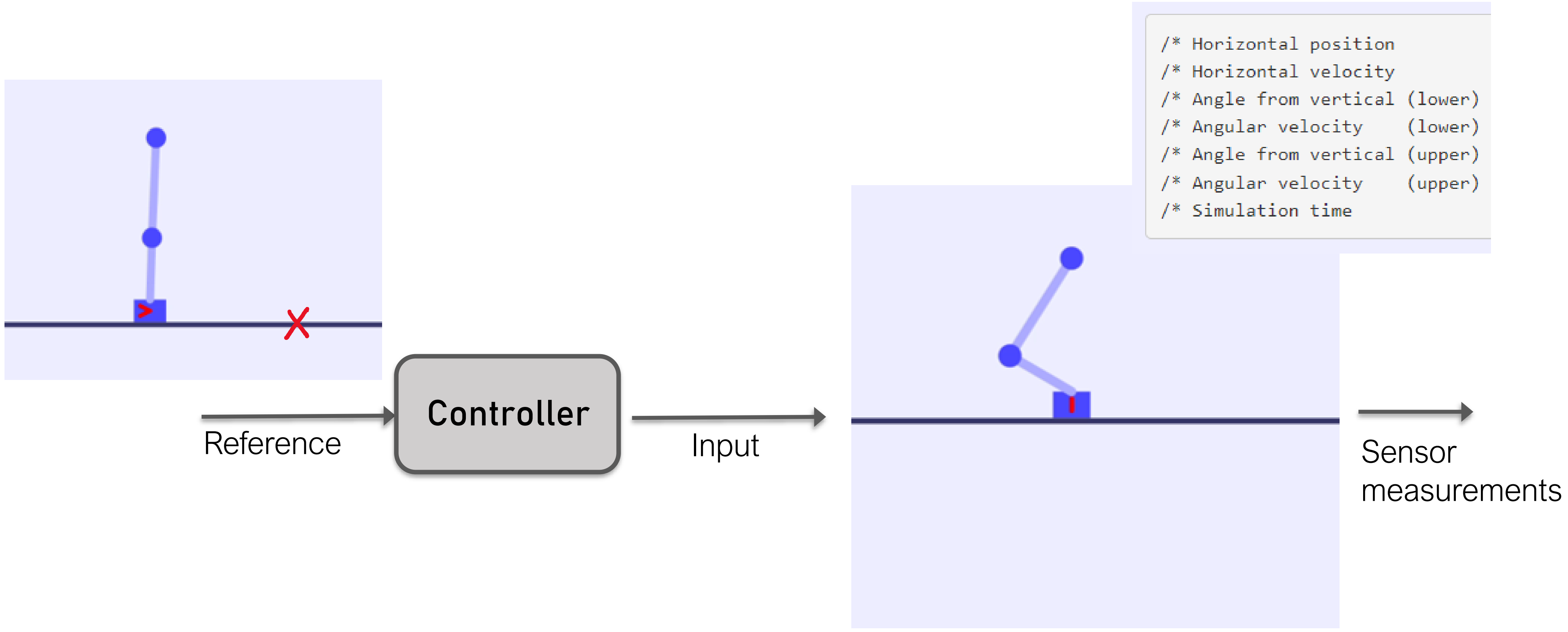

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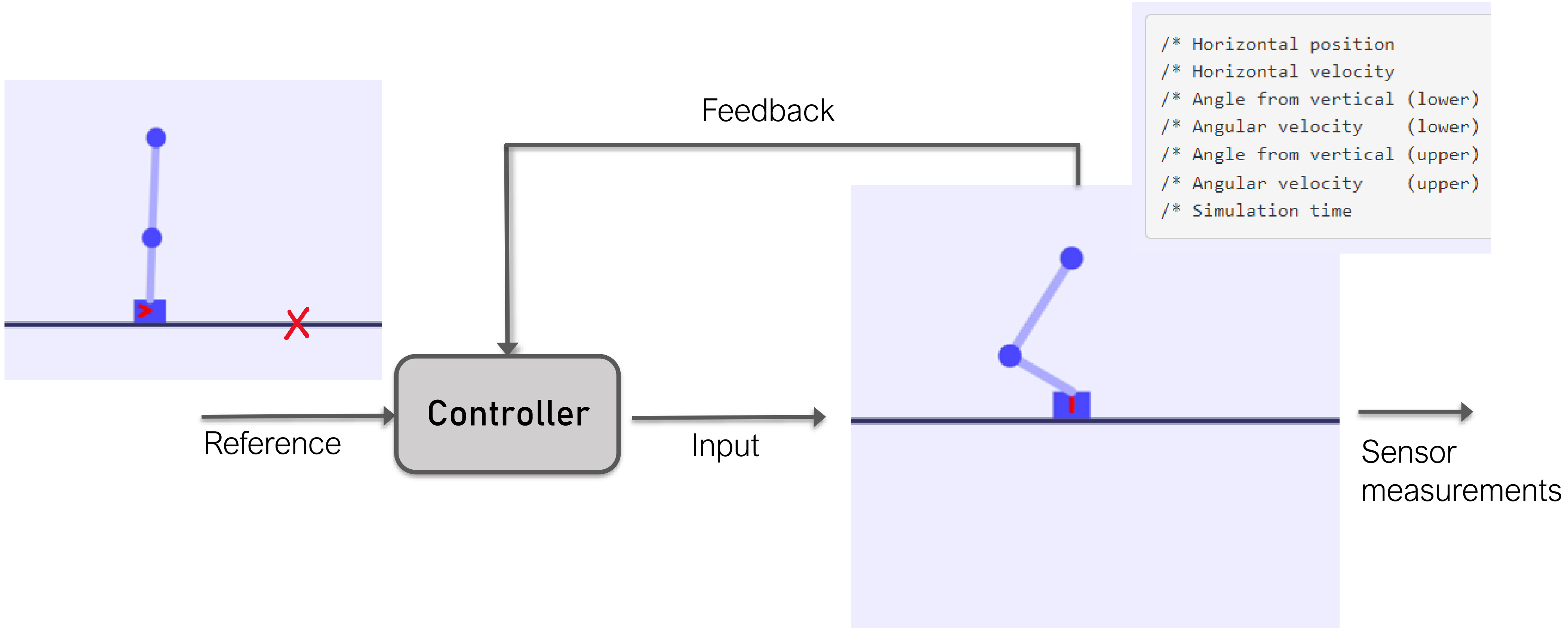

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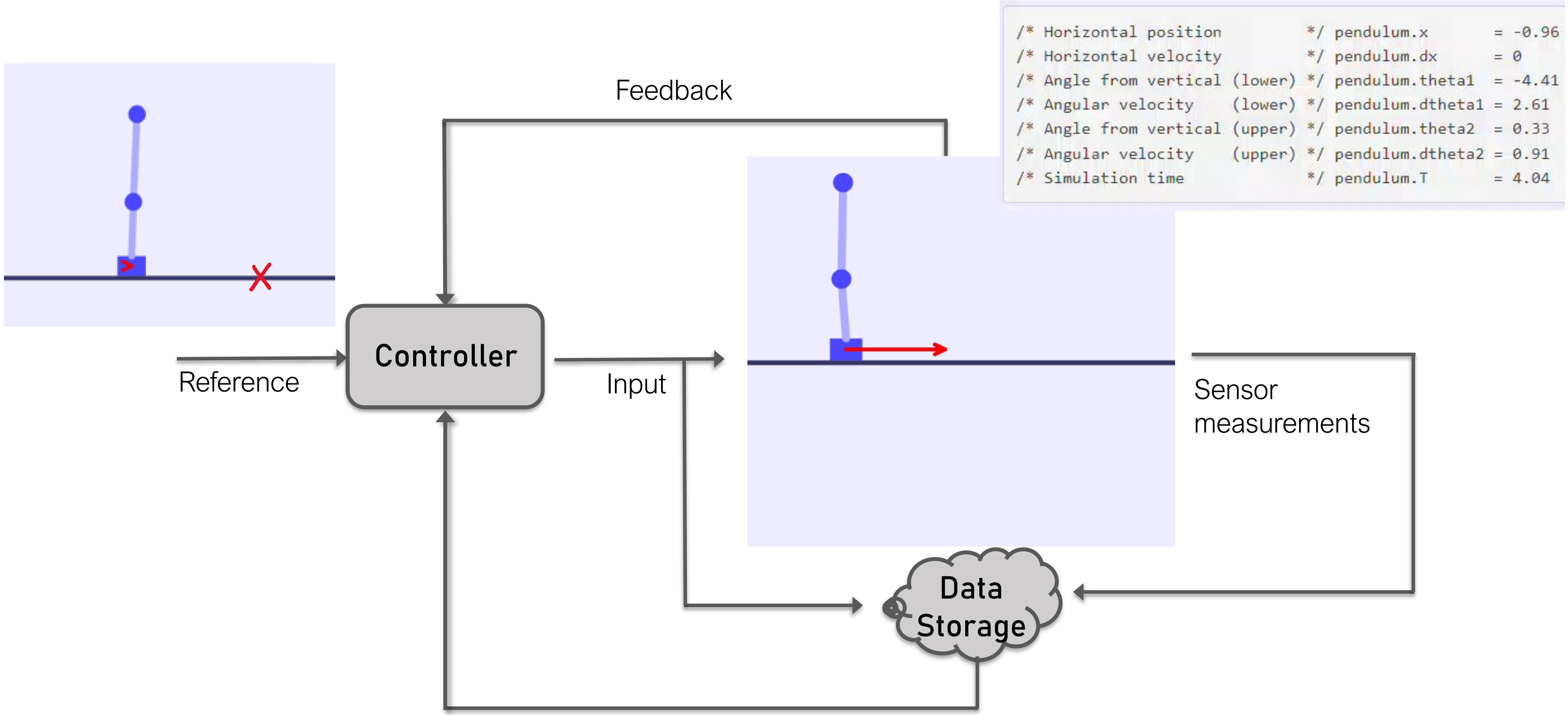

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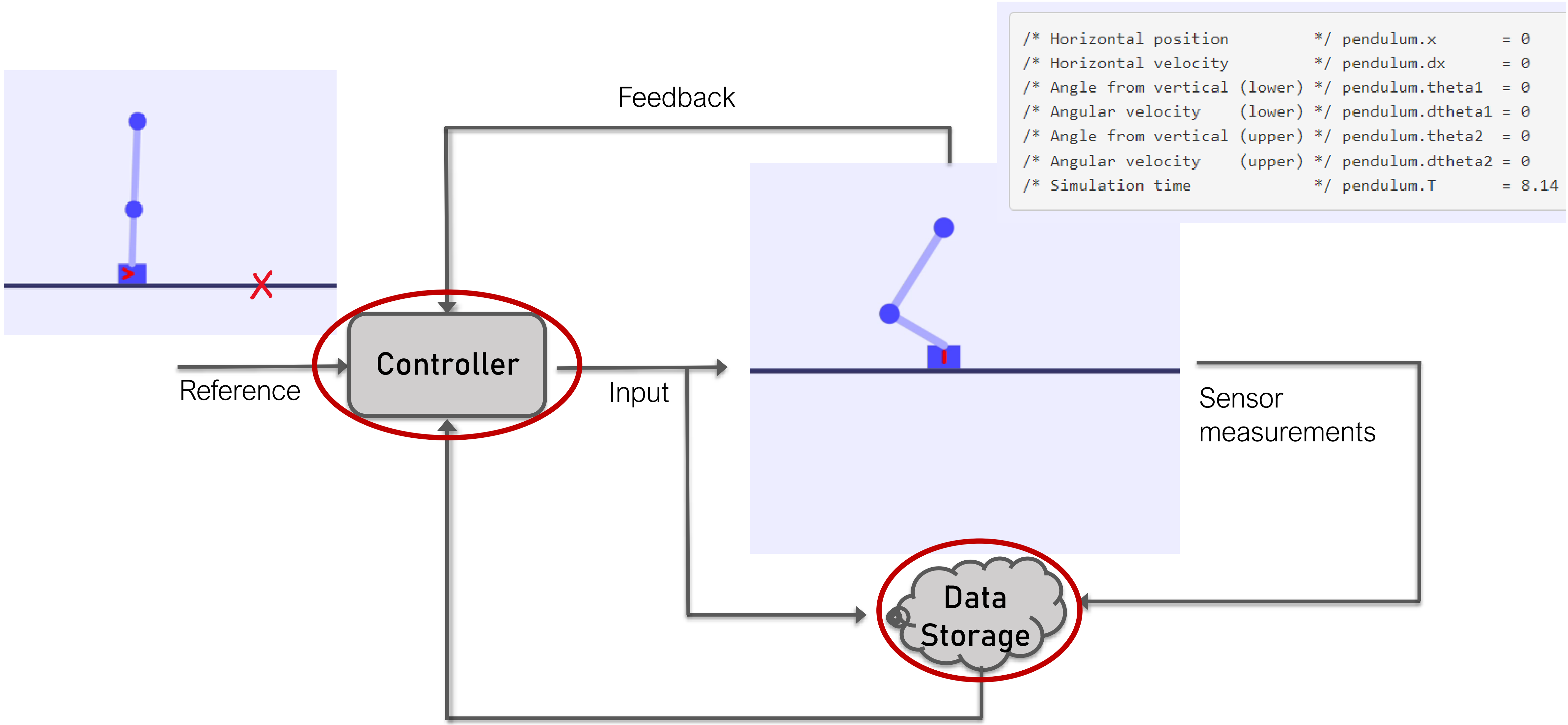


Contents

introduce approaches for controlling systems using data

1. Data Analysis & Machine Learning Preliminaries

- Fourier Transforms & Applications, Dimensionality Reduction
- Regression Analysis: Least Squares, Nonlinear regression
- Review of unconstrained optimization
- Classification: Discriminants, Support Vector Machine, Clustering, Neural Networks

2. Dynamical Systems & Control (P)review

- ODE's, Transfer functions, State Space representations
- Classical and linear controls theories; nonlinear control

Contents

MAKE THE WORLD WORK BETTER

3. Learning Control

- Iterative Learning Control
- Reinforcement Learning (RL)

4. Learning Models for Controls

- Classical System Identification (ID) and Controls
- Koopman Operator, Dynamic Mode Decomposition (DMD), Sparse Identification of Nonlinear Dynamics (SINDy)

5. Deep Learning for Controls & Recent Topics

- Deep neural networks
  - Multilayer NN,
  - Recurrent NNs,
  - Convolutional NN,
  - Autoencoders,
  - Generative Adversarial Networks
- Physics-Informed Deep Learning

Prof Daniel Bruder

Quick Linear Algebra Review

Vector (Linear) Spaces

A Vector Space (V, F) is a set of vectors V and a field of scalars F, along with two operations: vector addition $(+)$ and scalar multiplication $(\cdot)$; such that

$\mathbb{R}, \mathbb{C}$

Addition $(+)$:

(i) associative $(x + y) + \cancel{x}\,z = x + (y + z) \quad \forall x, y \in V$.

(ii) commutative $x + y = y + x$.

(iii) $\exists$ additive identity $0 \in V$ such that $x + 0 = 0 + x = x$.

(iv) $\exists$ additive inverse, i.e., $\forall x \in V, \exists(-x)$ such that $x + (-x) = 0$

Vector (Linear) Spaces

MAKE THE WORLD WORK BETTER

Scalar Multiplication $(\cdot)$

(v) $(\alpha\beta) \cdot x = \alpha \cdot (\beta \cdot x) \ \ \forall x \in V, \ \ \forall \alpha, \beta \in F.$

(vi) $1 \cdot x = x$, where 1 is the multiplicative identity for the field F.

(vii) $0 \cdot x = \mathbf{0}$, where 0 is the additive identity for the field F.

(viii) distributive (1) $\forall x \in V, \forall \alpha, \beta \in F (\alpha + \beta) \cdot x = \alpha \cdot x + \beta \cdot x.$

(ix) distributive (2) $\forall x, y \in V, \forall \alpha \in F \alpha \cdot (x + y) = \alpha \cdot x + \alpha \cdot y.$

Examples $(\mathbb{R}, \mathbb{R})$, $(\mathbb{R}^n, \mathbb{R})$, $(\mathbb{R}^n, \mathbb{C})$

$\checkmark$ F $\checkmark$ F

Subspaces

Let (V, F) be a linear space (vector space) and $W \subset V$. Then, (W, F) is called a *subspace* of (V, F) if (W, F) itself is a vector space (with the same inherited operations).

Ex. $W = \mathbb{R}^+$ and $F = \mathbb{R}$ Is (W, F) a subspace of (V, F) where $V = \mathbb{R}^2$?

$w_1 = 3 \qquad \alpha = 2$

$w_2 = 1 \qquad \beta = -8$

$\alpha v_1 + \beta v_2 = 6 - 8 = -2 \notin \mathbb{R}^+$

Linear Independence

Suppose (V, F) is a vector space. The set of vectors $\{v_1, v_2, \ldots, v_p\}$ is said to be *linearly independent* iff $\alpha_1 v_1 + \alpha_2 v_2 + \cdots + \alpha_p v_p = 0 \Leftrightarrow \alpha_1 = \alpha_2 = \cdots = \alpha_p = 0$.

The set of vectors is said to linearly dependent iff $\exists$ scalars $\alpha_1, \alpha_2, \cdots \alpha_p$ not all zero, such that, $\alpha_1 v_1 + \alpha_2 v_2 + \cdots + \alpha_p v_p = 0$.

Basis

Suppose (V, F) is a linear space. Then a set of vectors $B = \{b_1, b_2, \cdots b_n\}$ is called a *basis* if
(i) $\{b_1, b_2, \cdots b_n\}$ spans V; and
(ii) $\{b_1, b_2, \cdots b_n\}$ is a linearly independent set.

Coordinate Representation of Vectors

$x \in \mathbb{R}^n$

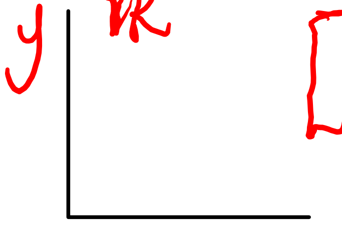
$x \in V, \quad x = \sum_{i=1}^{n} \xi_i b_i$

ξ_i is a scalar

$\mathbb{R}^3$

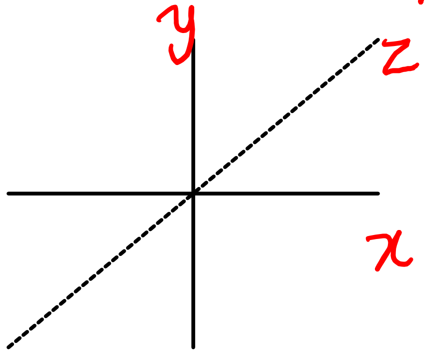
$$\begin{bmatrix} x \\ y \end{bmatrix} = \alpha \begin{bmatrix} 1 \\ 0 \end{bmatrix} + \beta \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$\mathbb{R}^2$



$\begin{bmatrix} 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \end{bmatrix}$

$\begin{bmatrix} 1 \\ 1 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \end{bmatrix}$



MAKE
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