Tuesdays & Thursdays
12:00-13:30 ET
DOW 1010

ME599-004: Data-Driven Methods for Control Systems

Winter 2025

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

MECHANICAL ENGINEERING
UNIVERSITY OF MICHIGAN

UI @ UMich

MAKE THE WORLD WORK BETTER

Uduak Inyang-Udoh

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PURDUE UNIVERSITY

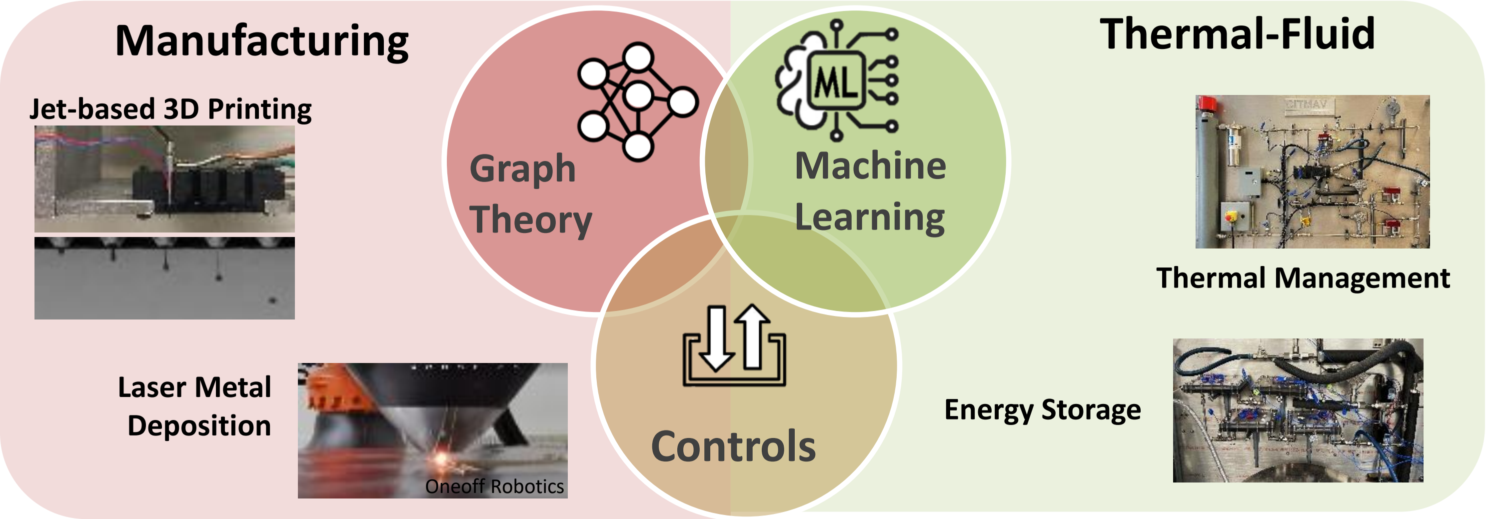
Ph.D. in ME '21

Rensselaer

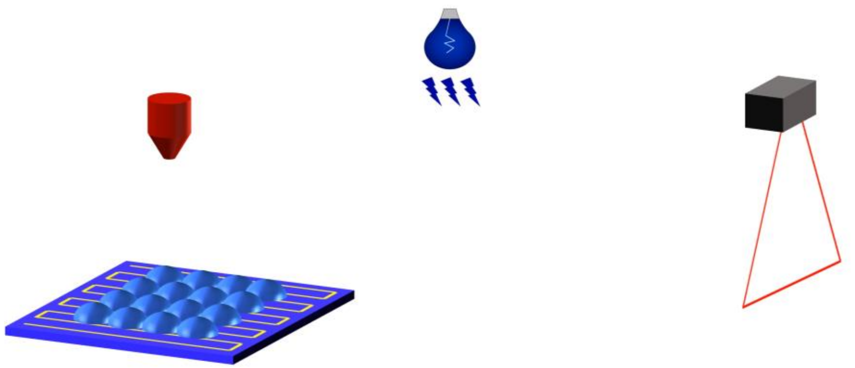
Autonomous & Intelligent Systems Lab

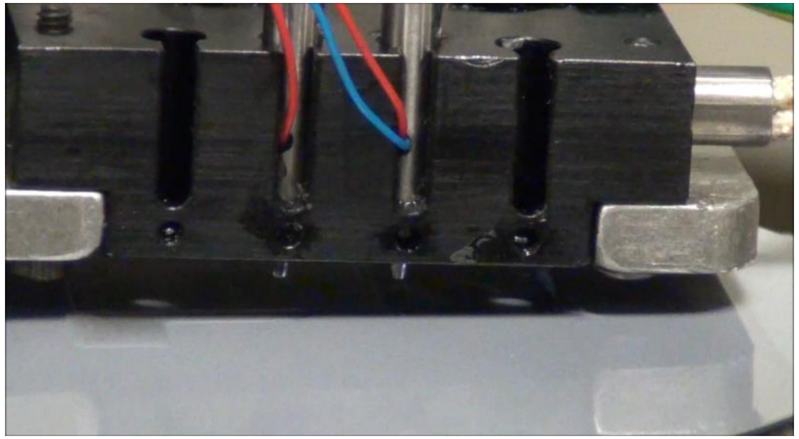
Research

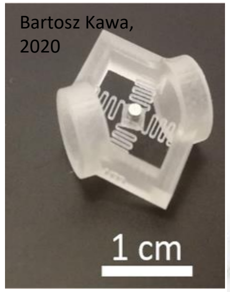
- graph theory + physics-guided machine learning for controls;
- *applications:* advanced manufacturing, thermal-fluid systems.

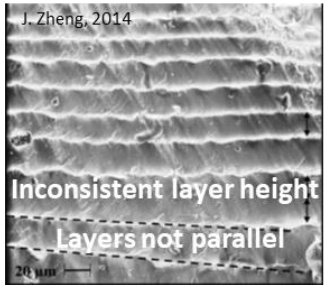


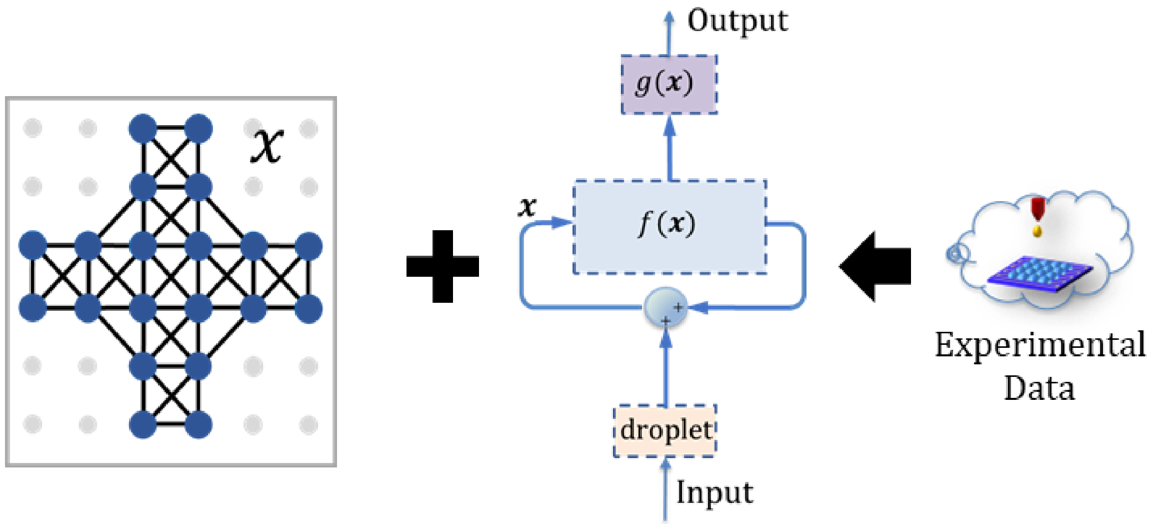
Input Pattern Control in Inkjet 3D Printing



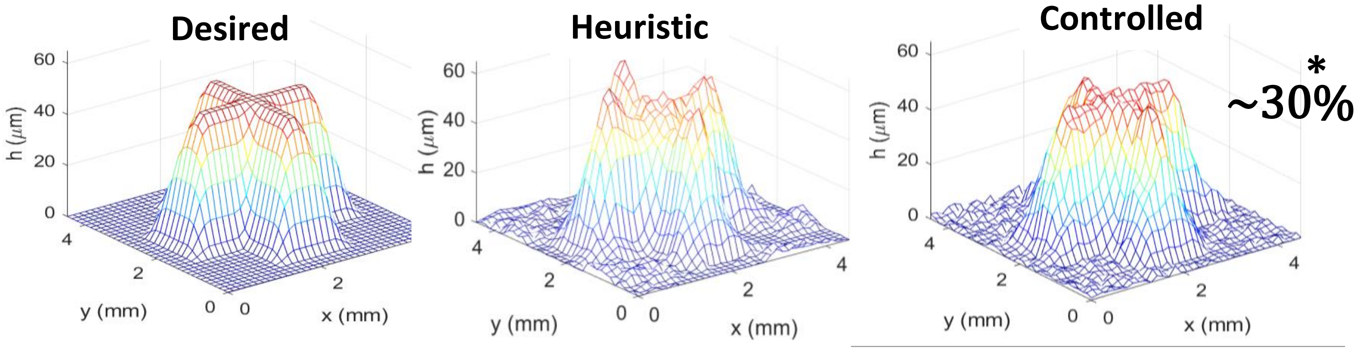




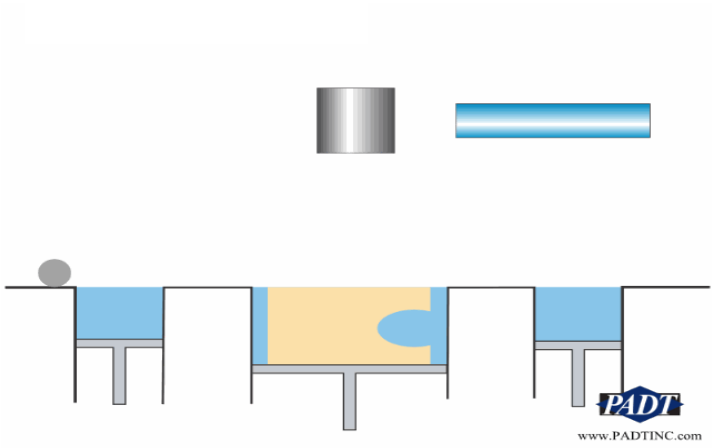


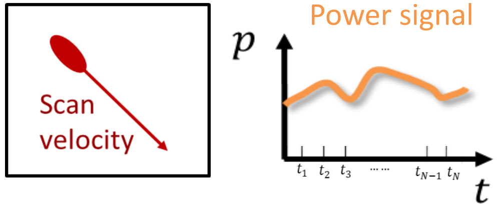


- Learn dynamics
- Lends itself to **in-process learning & control**

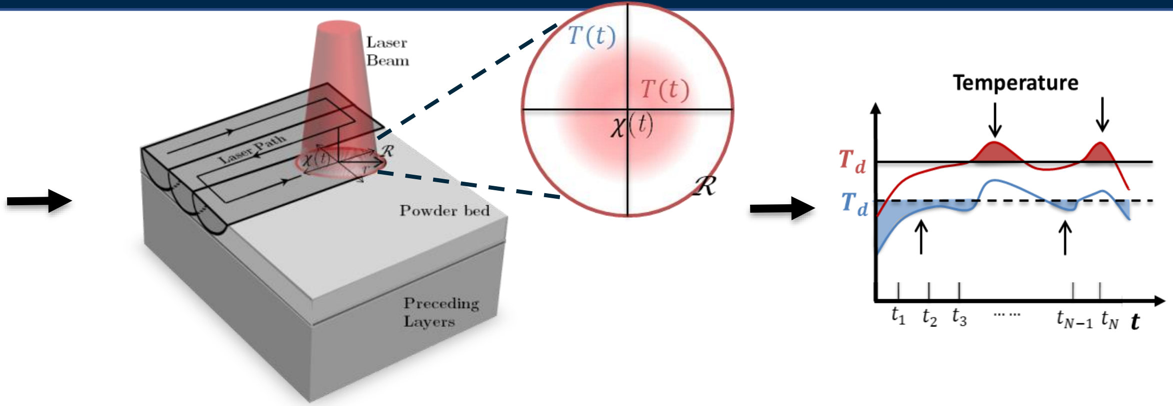


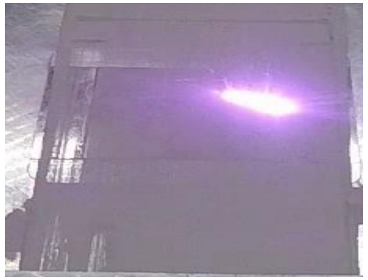
Input Shaping in Laser-Based Additive Manufacturing





Dynamically modulate input?





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

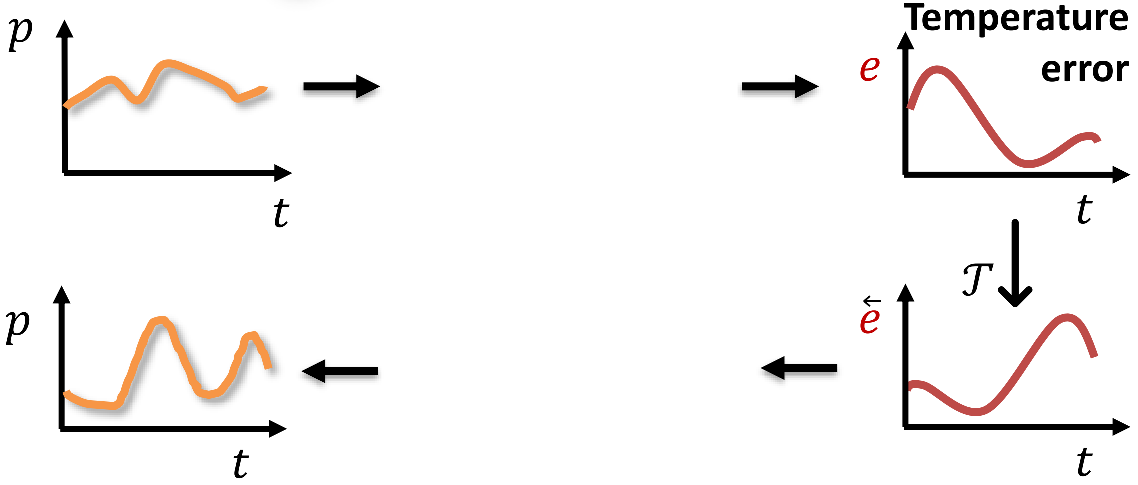
Gradient Descent:

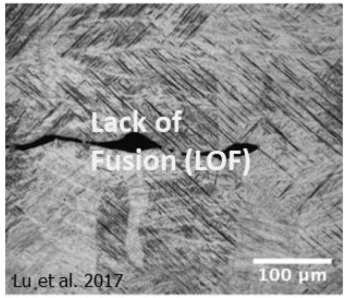
$$\boldsymbol{p}^{new} \leftarrow \boldsymbol{p}^{old} - \alpha \mathcal{G}^* \boldsymbol{e}^{old}$$

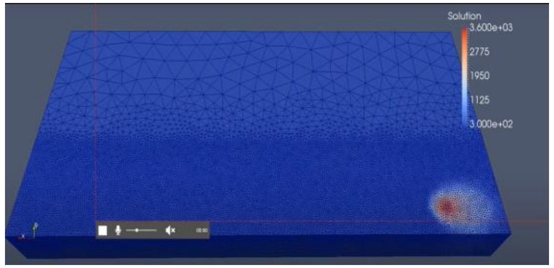
adjoint

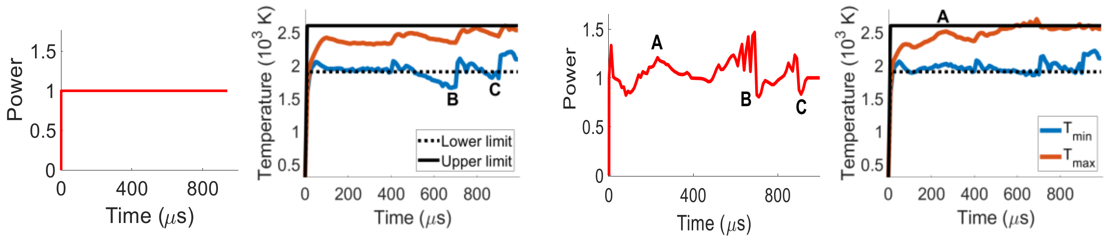
$$\boldsymbol{p} \xrightarrow{\mathcal{G}} \boldsymbol{E}$$

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





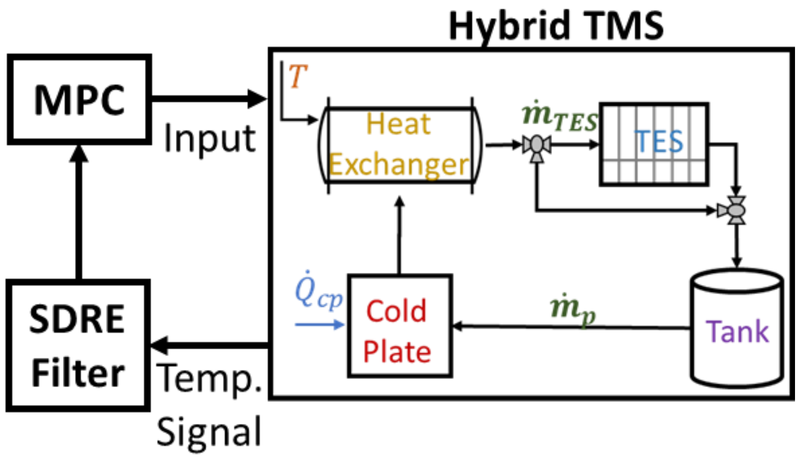




U. Inyang-Udoh et al., 2022

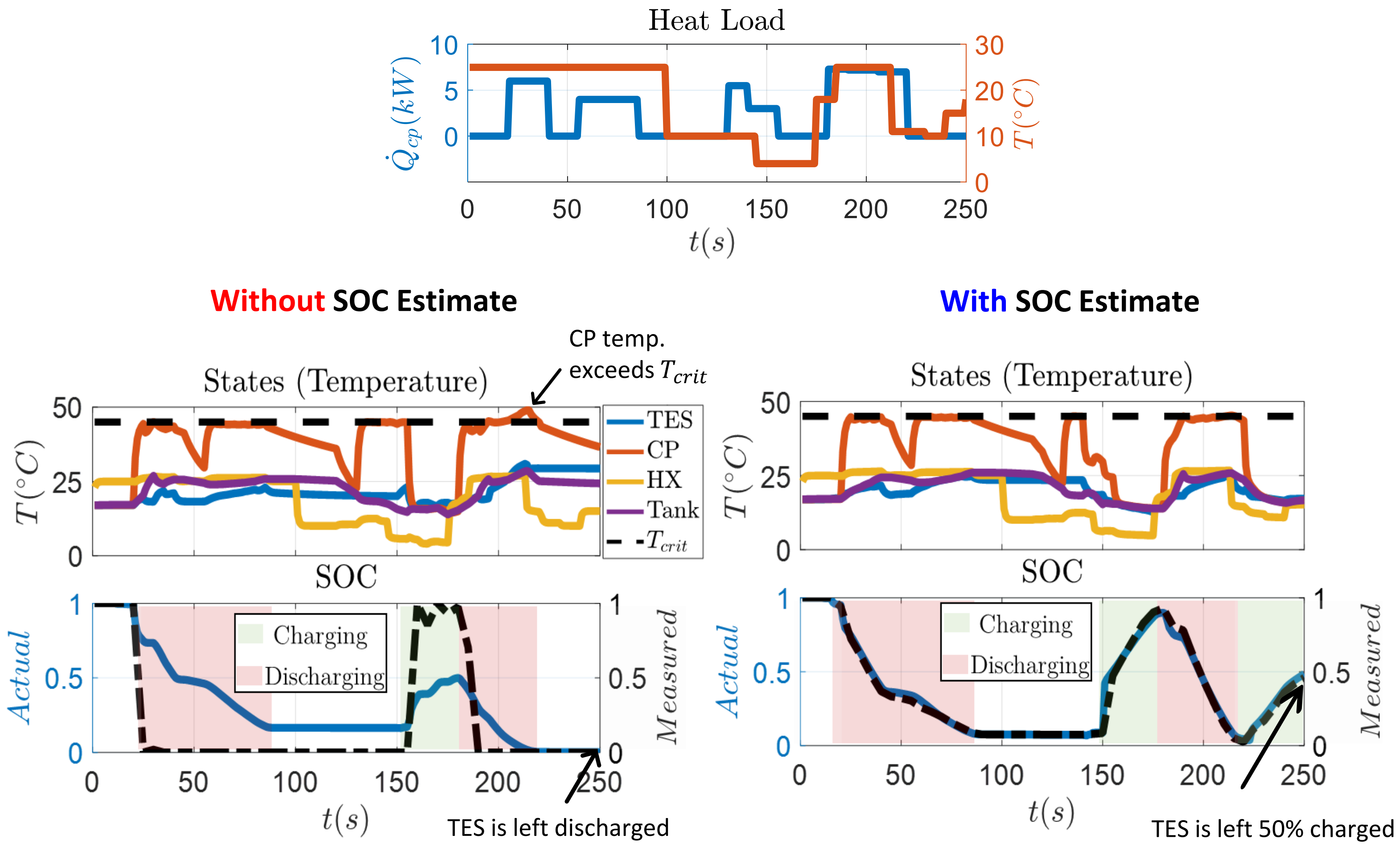
Control in Hybrid Thermal Management

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}



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) – 4% (Bonus points)

Homework

- Eight (8) problem sets
- At least, one (1) week to complete each
- Mostly entail programming
- Refer to document on Canvas for more information about homework submission & academic integrity

Homework

Homework	Points	Due	Posted (On/before)
1	14	January 28	January 9
2	12	February 11	January 14
3	10	February 20	January 23
4	10	March 4	February 6
5	10	March 13	February 20
6	10	March 25	March 6
7	8	April 3	March 13
8	6	April 15	March 27

(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 3 or 4, 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

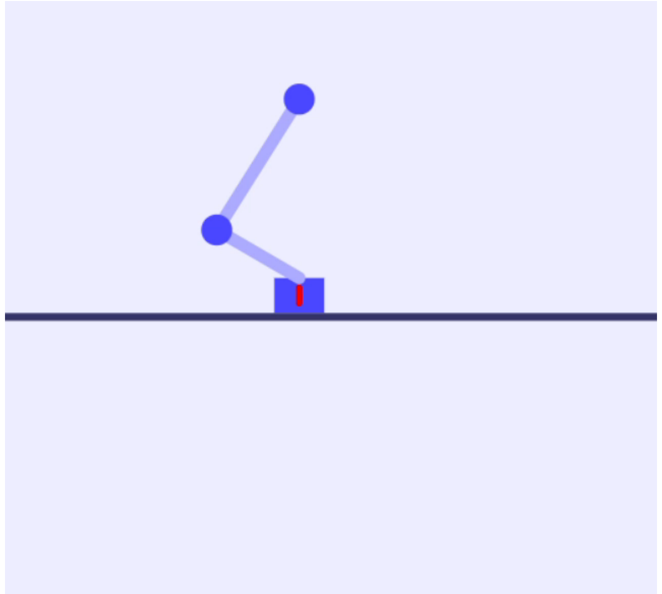
Bonus Quizzes (Optional)

- Few in-class quizzes (optional), time permitting

References

1. Brunton and Kutz, *Data-Driven Science and Engineering: Machine Learning, Dynamical Systems, and Control*, 2nd ed., Cambridge University Press, 2022
2. Keesman, *System Identification: An Introduction*, Springer, 2011
3. Duda, Hart, and Stork, *Pattern classification*, Wiley, 2001
4. Moore, *Iterative Learning Control: An Expository Overview* In: Datta, B.N. (eds) Applied and Computational Control, Signals, and Circuits. Springer, 1999
5. Powell, *Approximate Dynamic Programming : Solving the Curses of Dimensionality*, Wiley, 2011
6. Goodfellow, Bengio, Courville, *Deep Learning*, MIT Press, 2016
7. Ljung, *System Identification: Theory for the User*, 2nd ed.,Prentice Hall, 1999

Why this Course?



Double inverted pendulum on a guide rail

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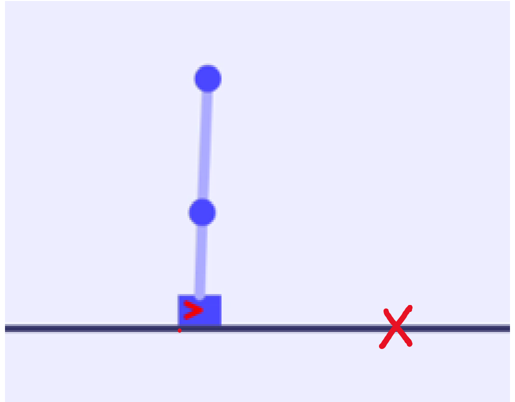

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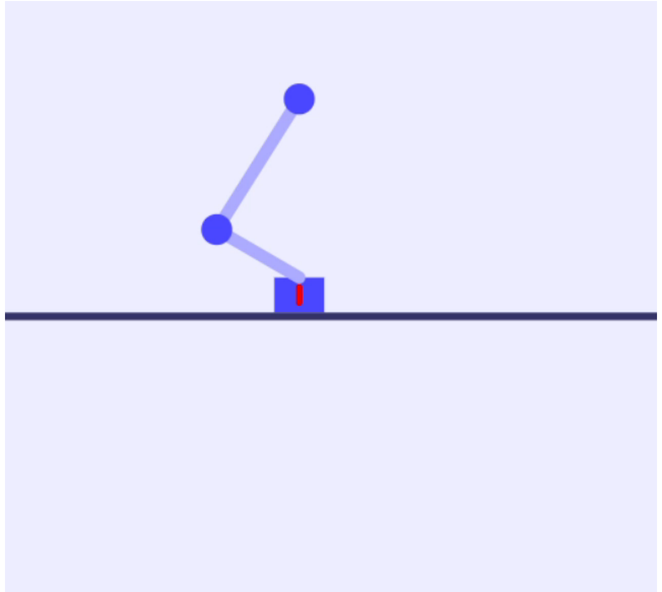

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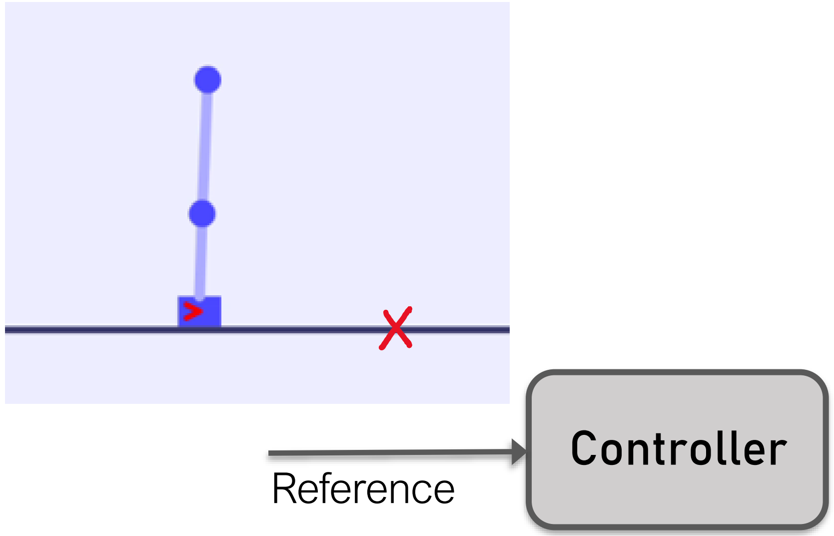

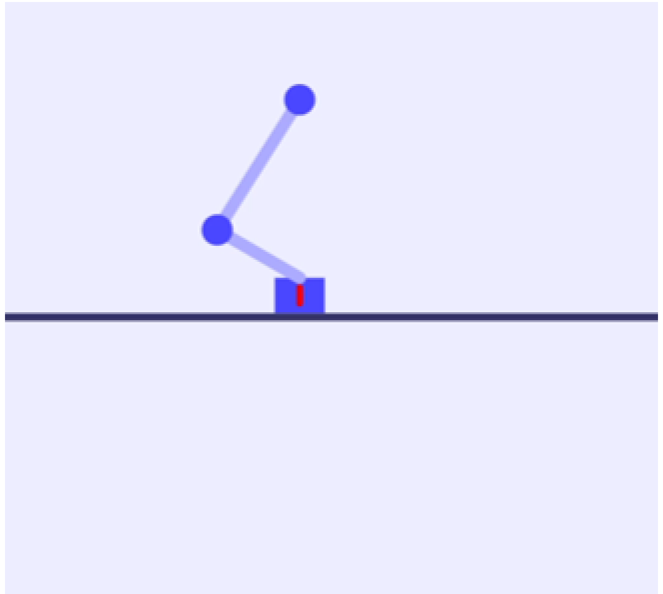

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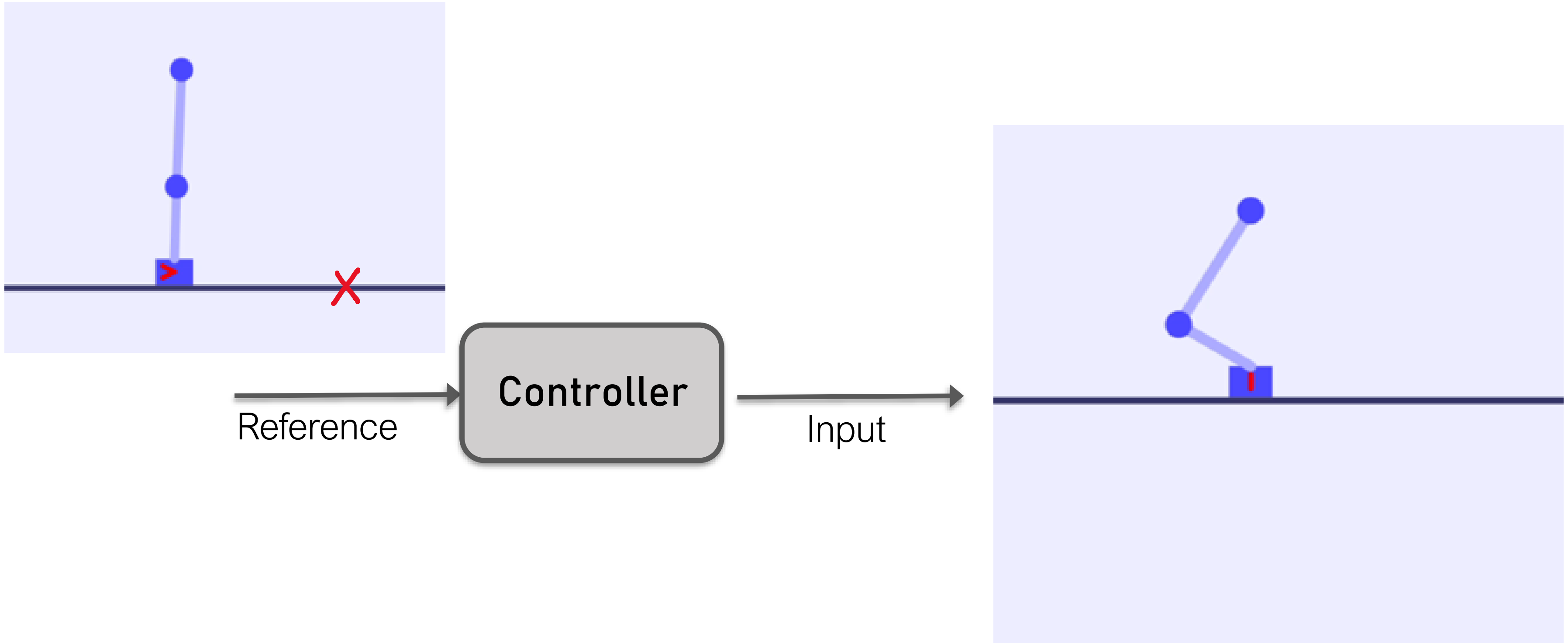

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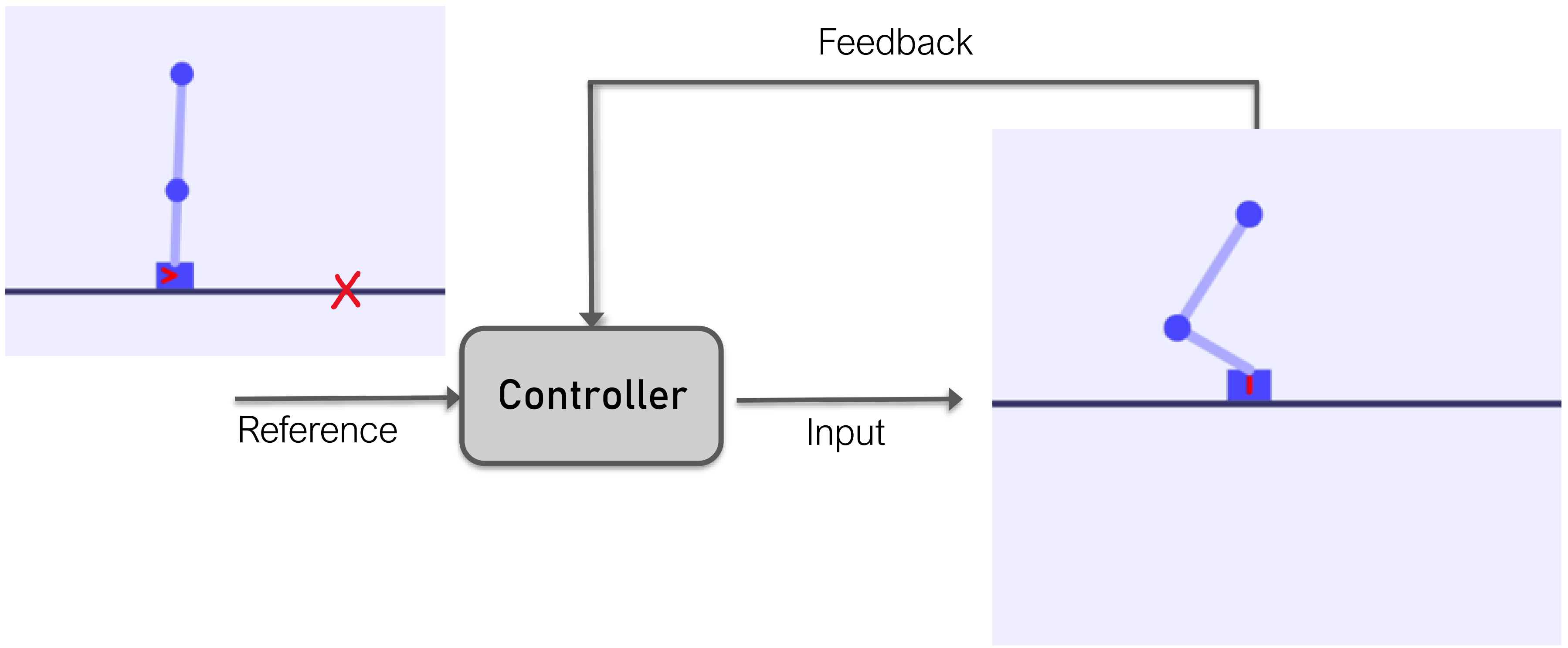

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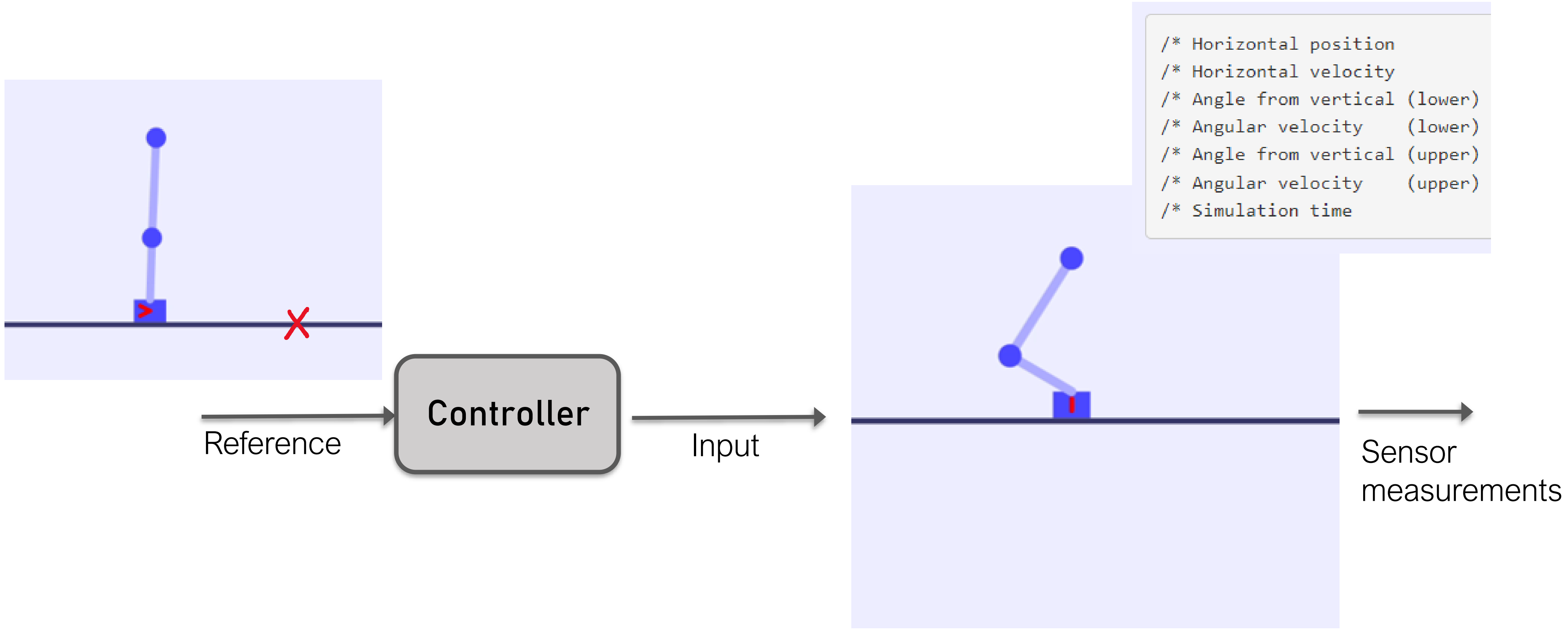

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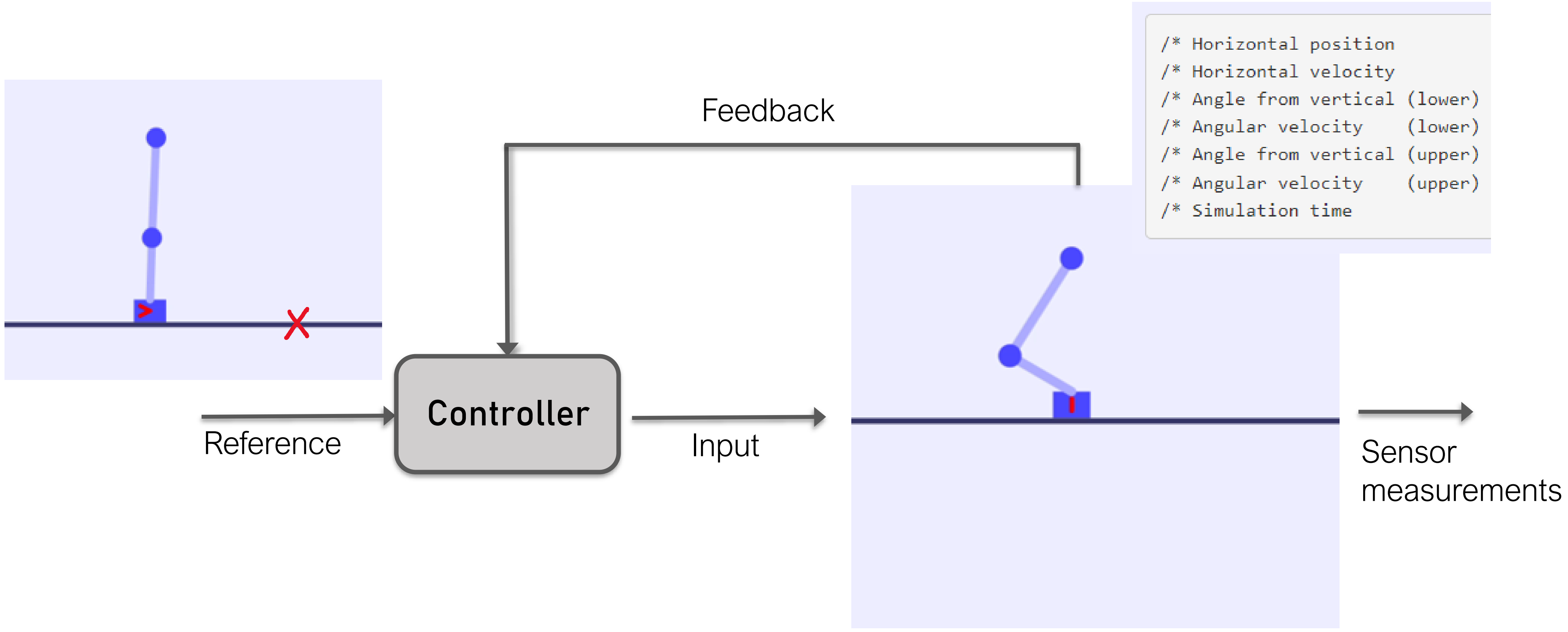

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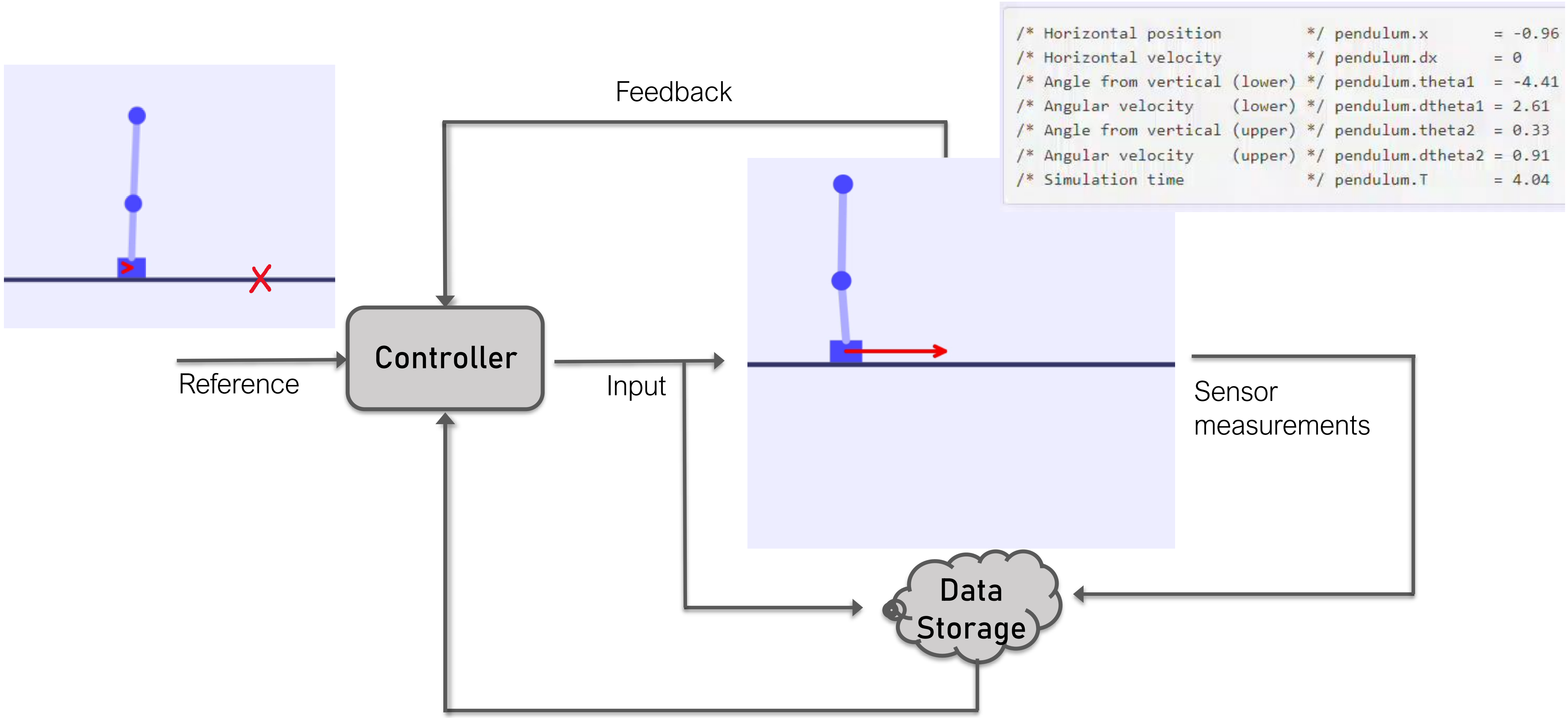

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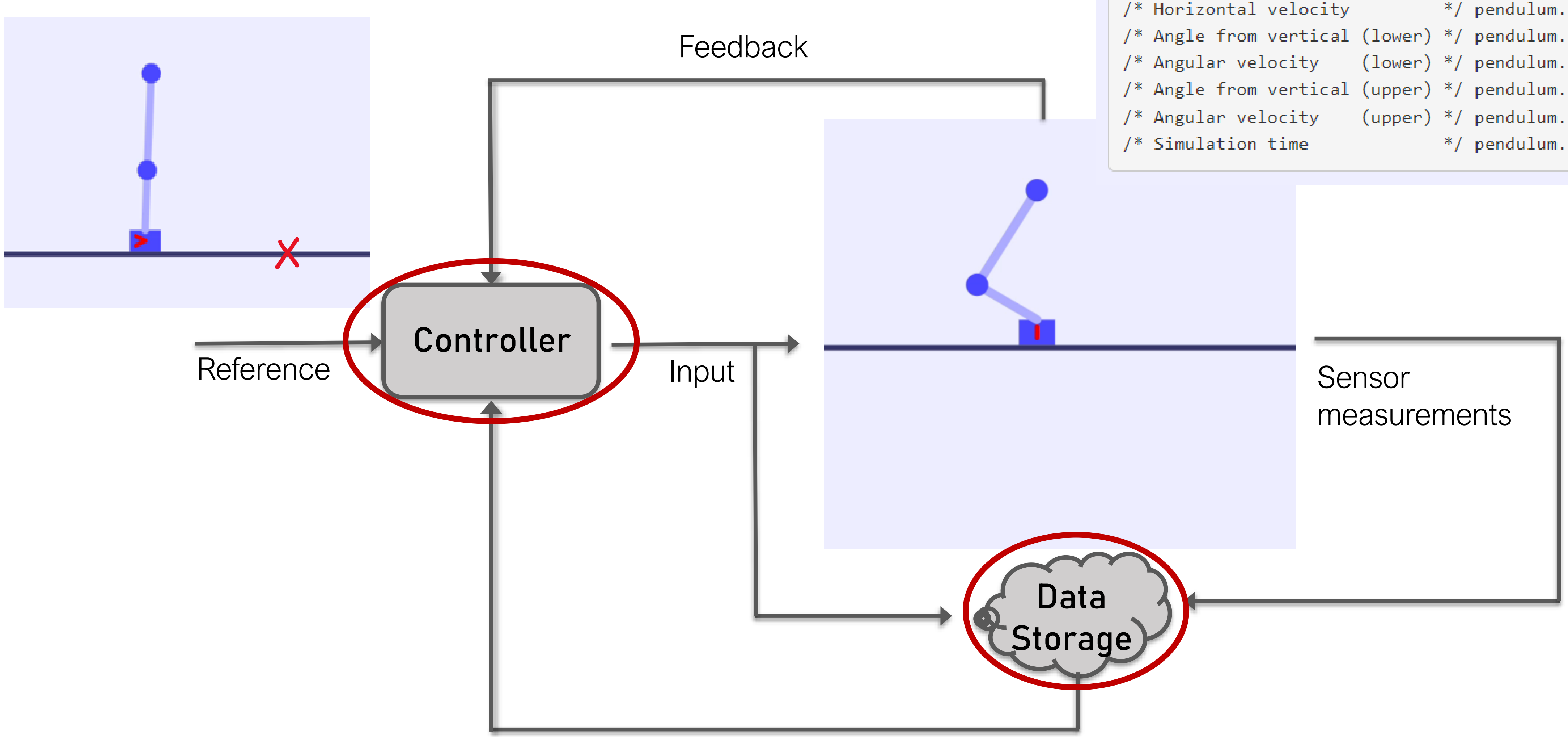


```
/* Horizontal position          */ pendulum.x       = 0
/* Horizontal velocity          */ pendulum.dx      = 0
/* Angle from vertical (lower) */ pendulum.theta1  = 0
/* Angular velocity    (lower) */ pendulum.dtheta1 = 0
/* Angle from vertical (upper) */ pendulum.theta2  = 0
/* Angular velocity    (upper) */ pendulum.dtheta2 = 0
/* Simulation time              */ pendulum.T       = 8.14
```

Contents

introduce approaches for controlling systems using data

1. Data Analysis & Machine Learning Preliminaries

- Fourier Transforms & Applications, Dimensionality Reduction

- 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

Quick Linear Algebra Review

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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

Addition $(+)$:

(i) associative $(x+y)+x = x+(y+z) \;\; \forall x, y \in V.$

(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

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

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).

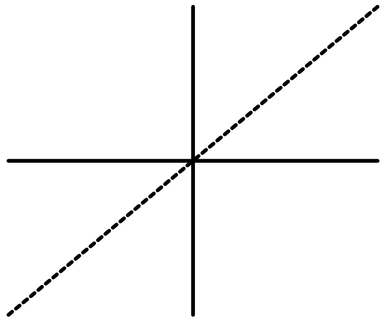
Linear Independence

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.



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