Cyber-Physical Systems

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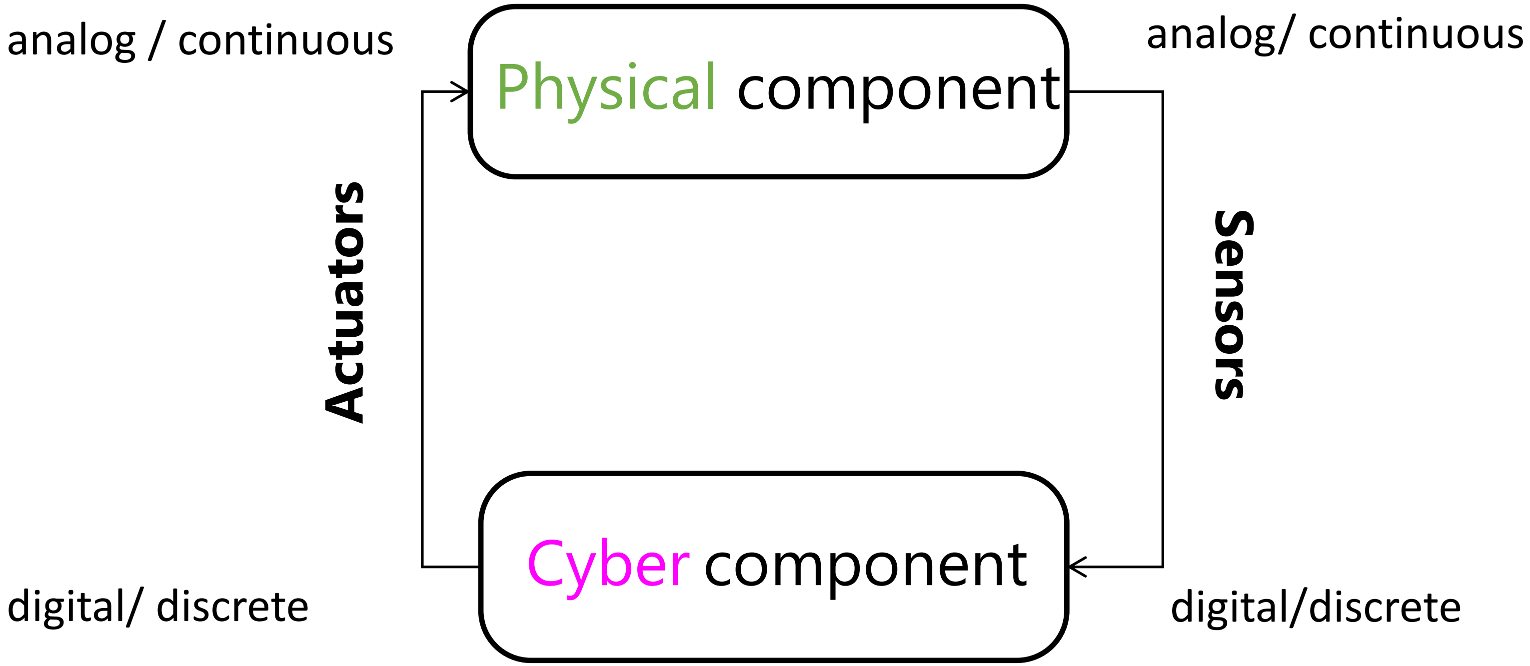
II Semestre 2020

Lecture 2: Modeling (Introduction)
Dynamical Systems

[Many Slides due to J. Deshmukh, Toyota]

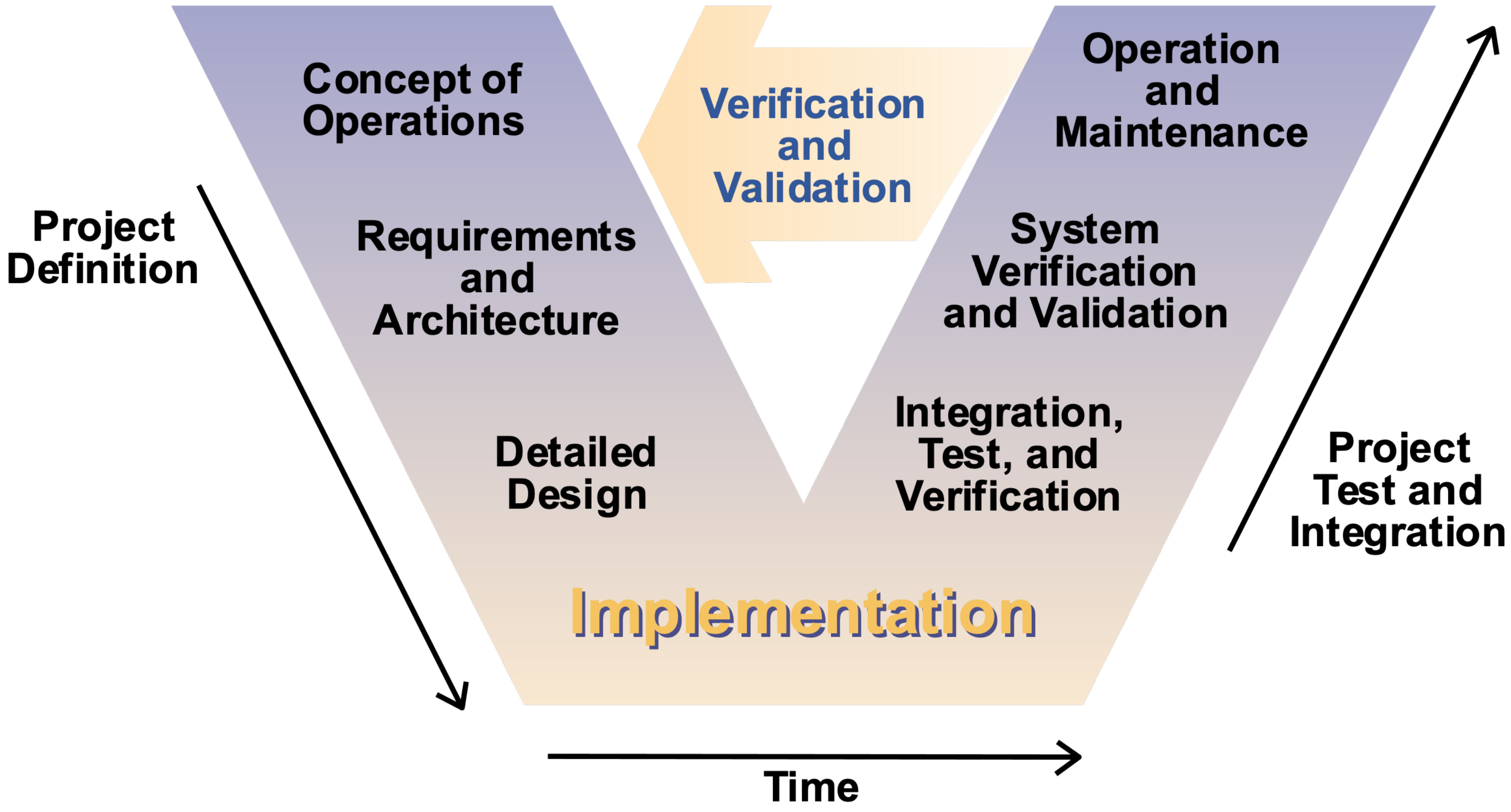
Cyber-Physical System (CPS)

Combination of physical (environment / plant / process / system) with a cyber (computation / software / code) components **potentially networked** and **tightly interconnected**



even-thermostats-have-a-heart

Model-based Design Approach

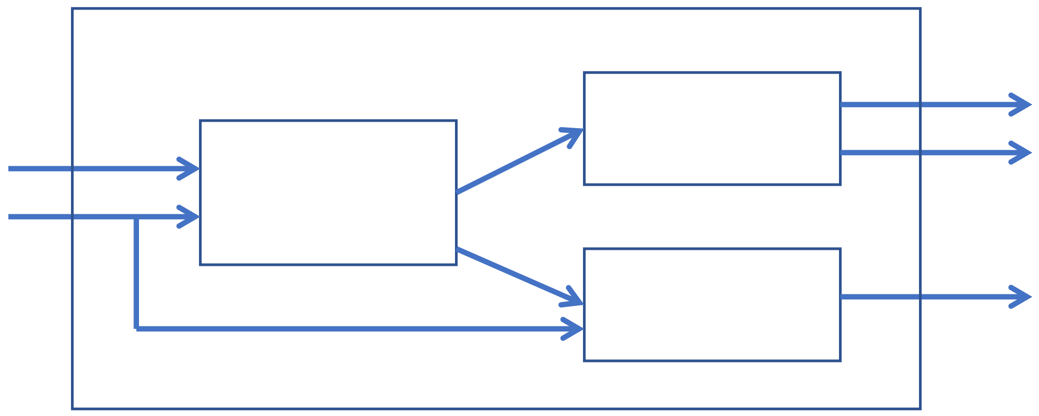


Validation : "Are you building the right thing?"

Verification : "Are you building it right?”

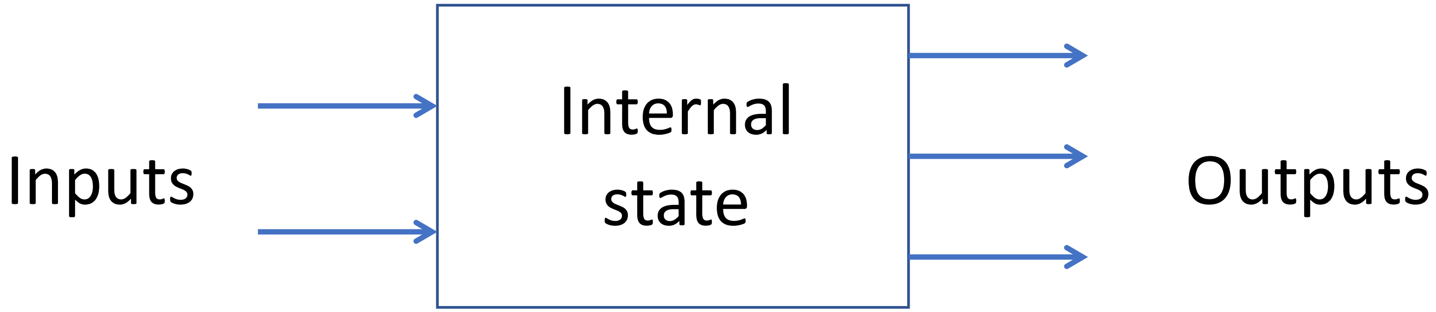
Model-based Design Approach

MBD languages are often visual and block-diagram based, e.g. Simulink



Reactive Component

Most convenient model of computation for an (Autonomous) CPS is a ***reactive and concurrent model of computation.***



An autonomous CPS can be viewed as a ***network of components*** *that communicate either* ***synchronously*** *or* ***asynchronously.***

Models: abstractions of CPS

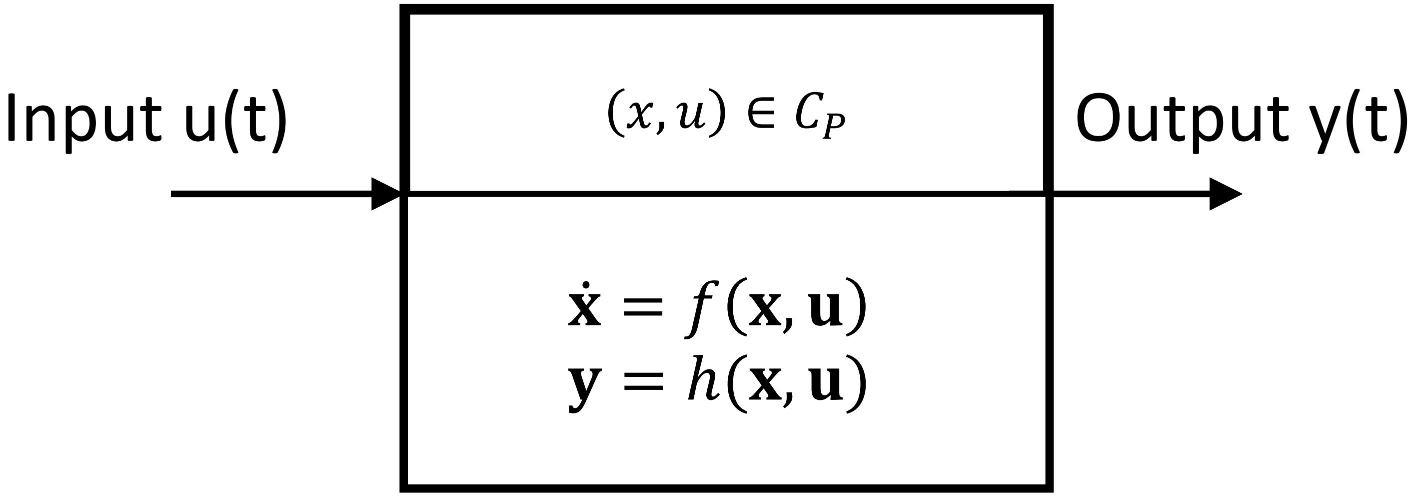
Examples of type of modeling for CPS components:

- Modeling physical phenomena (dynamical systems) – differential equation
- Feedback control systems – time-domain modeling
- Modeling modal behavior – FSMs, hybrid automata, …
- Modeling sensors and actuators – models that help with calibration, noise elimination,
- Modeling hardware and software – capture concurrency, timing, …
- Modeling networks – latencies, error rates, packet loss,

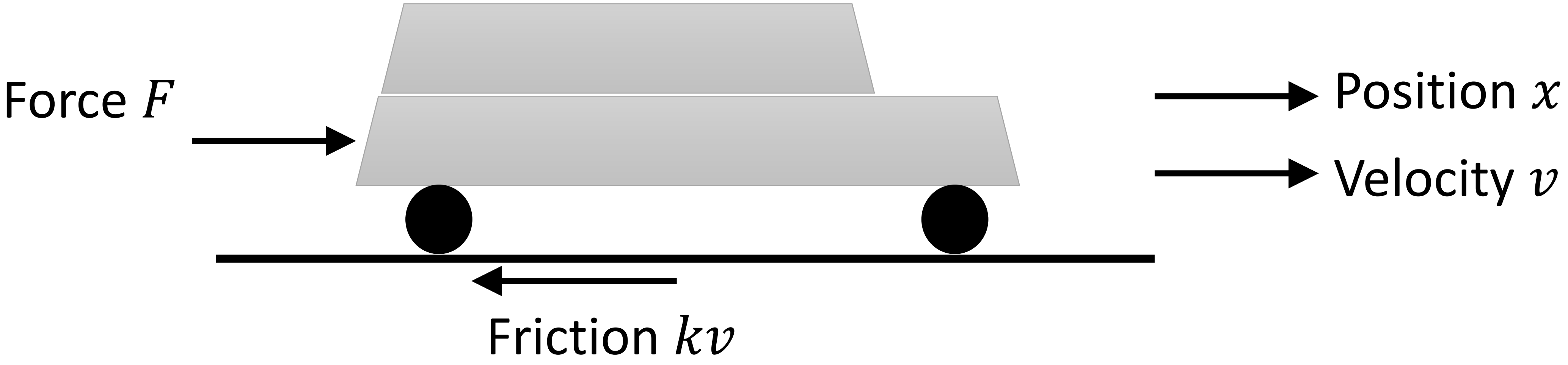
Dynamical Systems

- Most natural model for describing most physical systems
- Systems that continuously evolve over time
- It is represents by equations that involve the rates of change of quantities that describe the state of the phenomena
- Quantities describe the state of the phenomena, modeled as state variables
  - Pressure, Temperature, Velocity, Acceleration, Current, Voltage, etc.
- Could include algebraic relations between state variables

Dynamical Systems



Order Differential Equation



Newton's law of motion: $F = m\frac{d^2x}{dt^2} + kv$; $v = \frac{dx}{dt}$

State-Space representation

$$\dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{u})$$
$$\mathbf{y} = h(\mathbf{x}, \mathbf{u})$$

Example:

Convert

$$\dot{x} = v(t)$$
$$\dot{v} = \frac{F(t) - kv(t)}{m}$$

- It is numerically efficient to solve
- It can handle complex systems
- It allows for a more geometric understanding of dynamic systems
- It forms the basis for much of modern control theory

Order Differential Equation

All derivatives are with respect to single independent variable, often representing time.

Order of ODE is determined by highest-order derivative of state variable function appearing in ODE

ODE with higher-order derivatives can be transformed into equivalent first-order system.

$$x^{(k)} = f(x, \ldots, x^{(k-1)})$$

$$z_1 = x,\ z_2 = \dot{x}, \ldots, z_k = x^{(k-1)}$$

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \\ . \\ . \\ . \\ \dot{z}_k \end{bmatrix} = \begin{bmatrix} z_2 \\ z_3 \\ z_4 \\ . \\ . \\ . \\ f(x, \ldots, x^{(k-1)}) \end{bmatrix}$$

Executions of Car

- Let $\mathbb{T}$ represent a set representing time instants, i.e. $\mathbb{T} \subseteq \mathbb{R}^{\geq 0}$

- Input Signal: Function F from $\mathbb{T} \to \mathbb{R}$
  - Input signal is assumed to be continuous or piecewise-continuous

- Given an initial state (x_0, v_0) and an input signal $F(t)$, the execution of the system is defined by ***state-trajectories*** $x(t)$ and $v(t)$ (from $\mathbb{T}$ to $\mathbb{R}$) that satisfy the ***initial-value problem***:
  - $x(0) = x_0; v(0) = v_0$
  - $\dot{x} = v(t); \dot{v} = \frac{F(t) - kv(t)}{m}$

Sample Execution of Car

Suppose $\forall t: F(t) = 0, x_0 = 5\text{ m}, v_0 = 20\text{ m/s}, m = 1000\text{kg}, k = 50Ns/m$

- Then, we need to solve:
  - $x(0) = 5; v(0) = 20$
  - $\dot{x} = v; \dot{v} = -\frac{kv}{m}$

- Solution to above differential equation (solve for v first, then x):
- $v(t) = v_0 e^{-\frac{kt}{m}}; x(t) = \frac{mv_0}{k}\left(1 - e^{-\frac{kt}{m}}\right)$
- Note, as $t \to \infty$, $v(t) \to 0$, and $x(t) \to \frac{mv_0}{k}$

Differential Equation

The state of the system is characterized by state variables, which describe the system. The rate of change is (usually) expressed with respect to time

Simple Example: Temperature equations

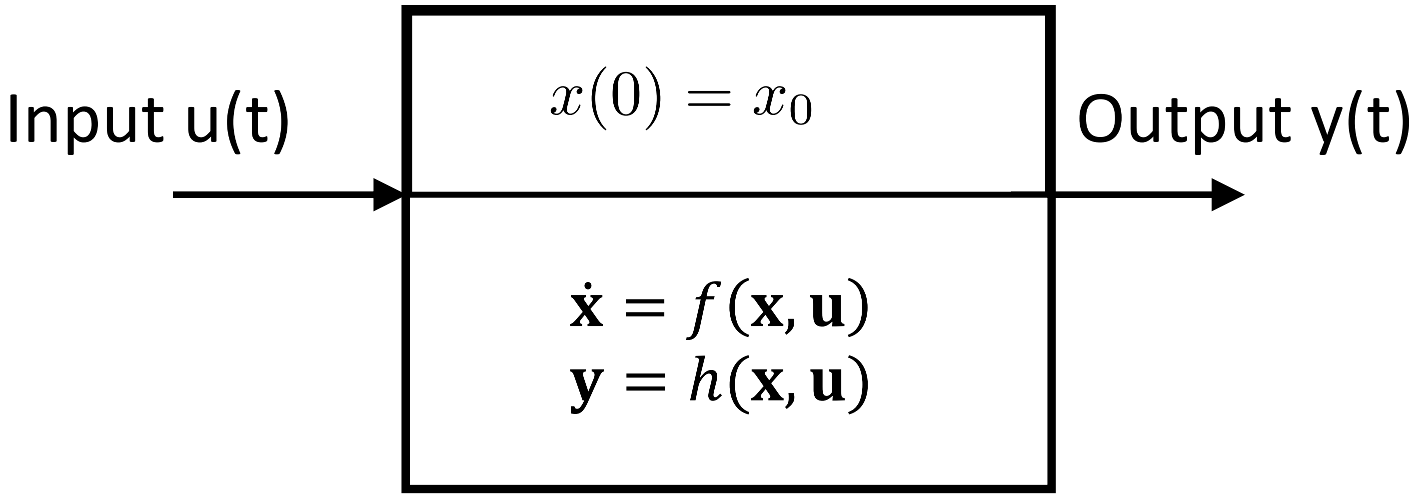
$$\frac{dT}{dt} = -aT + T_{ext} + K_H u$$

Continuous-Time Component Definition

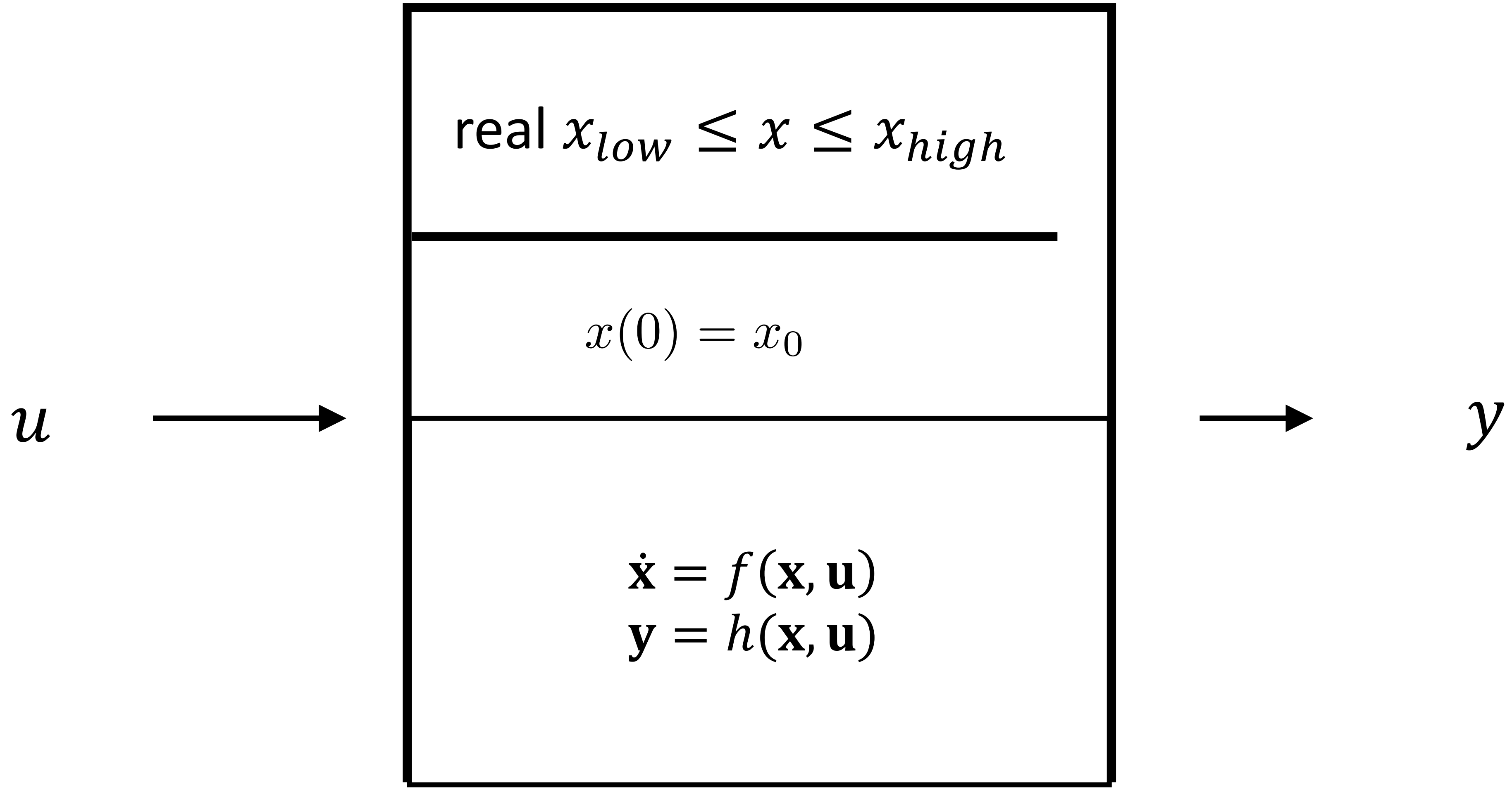
- Set I of real-valued input variables
- Set O or real-valued output variables
- Set X of real-valued (continuous) state variables
- Initialization $Init$ specifying a set $X_0$of initial values for states
- Dynamics: for each state variable, x, a real valued expression f over I and X
- Output Function: for each output variable, y, a real valued expression h over I and X.

Execution Definition

- Convention: $\mathbf{x} = (x_1, x_2, \ldots x_n), \mathbf{y} = (y_1, y_2, \ldots, y_m)$
- Given an input signal $u: \mathbb{T} \to \mathbb{R}$, an execution consists of a *differentiable* state signal $\mathbf{x}(\mathrm{t})$, and an output signal $\mathbf{y}(t)$, such that:
  1. $\mathbf{x}(0) \in X_0$
  2. For each output variable y and time t, $y(t) = h\big(u(t), x(t)\big)$
  3. For each state variable x, $\frac{d}{dt}x(t) = f(u(t), x(t))$



Order Differential Equation



Existence and Uniqueness of Solutions

- Given an input signal $u(t)$, when are we guaranteed that the system has at least one execution? Is there nondeterminism in continuous-time components?

- Input signal should be piecewise-continuous, and additional conditions need to be imposed on the RHS of dynamics (f) and output functions (h)

- Related to solutions for the initial value problem in the classical theory of ODEs

$$\dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{u})$$
$$\mathbf{y} = h(\mathbf{x}, \mathbf{u})$$

Existence

- There exists at least one solution $\mathbf{x}(t)$ if the function f is continuous

- Definition of continuity uses notion of distance between points
  - Euclidean distance: $d(\mathbf{x}, \mathbf{y}) = \|\mathbf{x} - \mathbf{y}\|_2 = \sqrt{(x_1 - y_1)^2 + \cdots + (x_n - y_n)^2}$

- f is continuous if for all $\mathbf{x} \in \mathbb{R}^n$, for all $\epsilon > 0$, there exists a $\delta > 0$, such that for all $\mathbf{y} \in \mathbb{R}^n$, if $\|\mathbf{x} - \mathbf{y}\|_2 < \delta$, then $\|f(\mathbf{x}) - f(\mathbf{y})\|_2 < \epsilon$.

- Example when solution does not *globally* exist:
  - $\frac{dx}{dt} = 1/t$

Uniqueness

- Solution to initial value problem is unique if f is Lipschitz continuous
- Lipschitz-continuity is a stronger version of continuity: upper bounds how fast a function can change
- Function f is **Lipschitz-continuous** if there exists a constant L (called the Lipschitz constant) such that:

$$\forall \mathbf{x}, \mathbf{y} \in \mathbb{R}^n: \|f(\mathbf{x}) - f(\mathbf{y})\| \leq L\|\mathbf{x} - \mathbf{y}\|$$

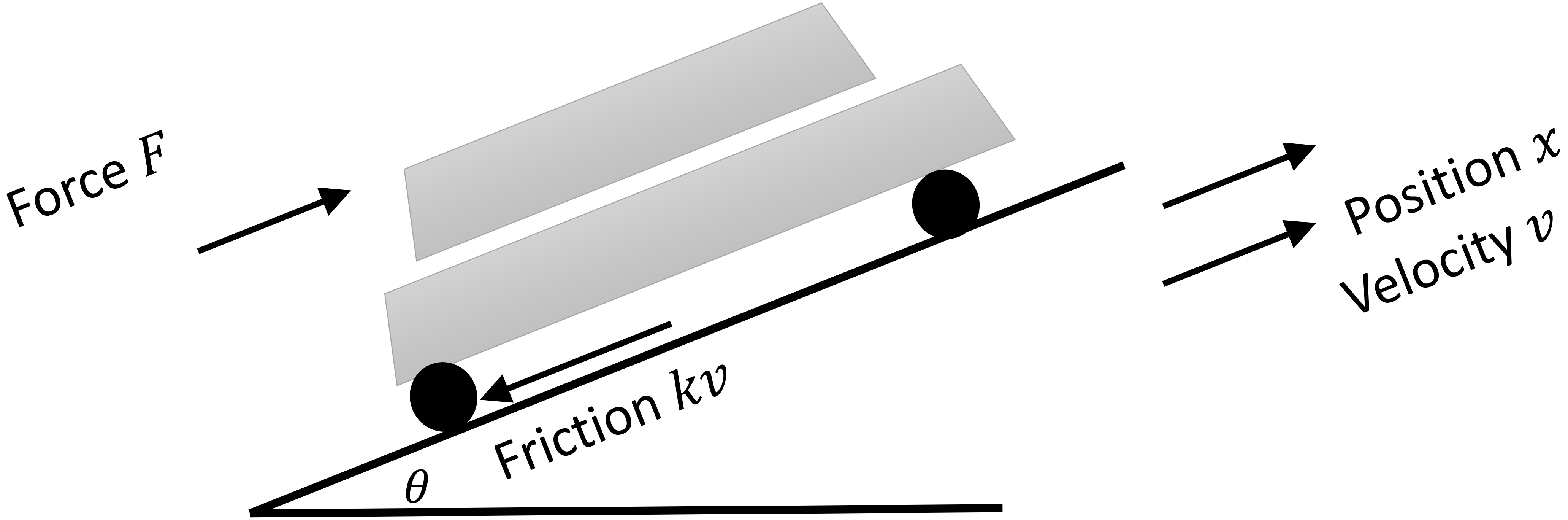
- Examples:
  - Linear functions (e.g. $x_1 - 3x_2$) are Lipschitz continuous
  - Functions: x^2, $\sqrt{x}$ are not Lipschitz continuous over $\mathbb{R}^n$

- Can restrict $\mathbb{T}$ and X to some bounded and closed set such that f is piecewise-continuous and Lipschitz to get unique solutions over such compact domains

We simulate

- Allow modeling arbitrarily complex functions: even functions with unbounded discontinuities
- May not be even possible to check for Lipschitz conditions for what’s implemented in a Matlab function/Simulink model
- Rely on numerical integration schemes/solvers to obtain solutions
  - ode45, ode23, ode15, etc.
- We assume that any continuous component model we will use can be numerically simulated by Matlab/Simulink

Model with disturbance



Newton's law of motion: $F = m\frac{d^2x}{dt^2} + kv + mg\sin(\theta)$

Time Invariant System

The system is time invariant because the output does not depend on the particular time the input is applied.

f does not depend on time

$$\frac{dx}{dt} = \dot{x} = f(x, u)$$

The underlying physical laws themselves do not typically depend on time.

Linear Systems

- Equation of simple car dynamics can be written compactly as:

$$\begin{bmatrix}\dot{x}\\ \dot{v}\end{bmatrix} = \begin{bmatrix}0 & 1\\ 0 & -k/m\end{bmatrix}\begin{bmatrix}x\\ v\end{bmatrix} + \begin{bmatrix}0\\ 1\end{bmatrix}[F]$$

- Letting $A = \begin{bmatrix}0 & 1\\ 0 & -k/m\end{bmatrix}$, $B = \begin{bmatrix}0\\ 1\end{bmatrix}$, we can re-write above equation in the form:

- $\dot{\mathbf{x}} = A\mathbf{x} + \mathrm{B}\mathbf{u}$, where $\mathbf{x} = [x \quad v]$, and $\mathbf{u} = [F]$

Linear Components

- Linear components model linear systems
  - f is of the form $a_1x_1 + a_2x_2 + \cdots + a_nx_n$ or compactly, $f = A\mathbf{x}$
  - h is of the form $b_1u_1 + b_2u_2 + \cdots + b_mu_m$ or compactly, $h = B\mathbf{u}$

- Linear systems have many nice properties:
  - Many analysis methods in the frequency domain (using Fourier/Laplace transform methods)

  - Superposition principle (net response to two or more stimuli is the sum of responses to each stimulus)

Solutions to Linear Systems

- ***Autonomous*** linear system has no inputs: $\dot{\mathbf{x}} = A\mathbf{x}$

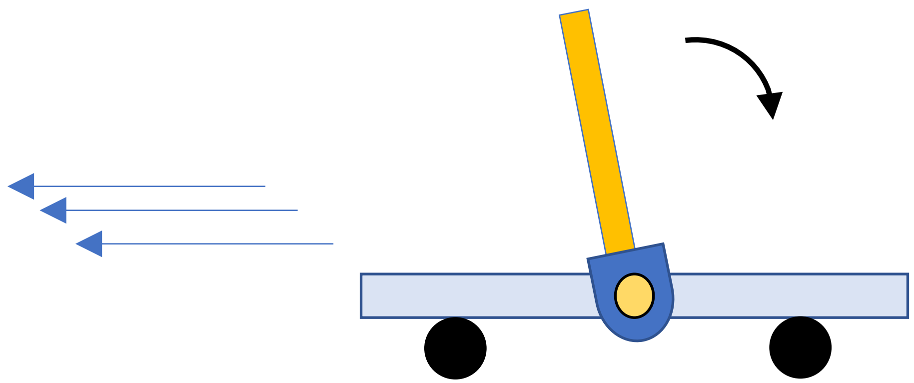
- Solution of autonomous linear system can be fully characterized:
  - $\mathbf{x}(t) = e^{At}\mathbf{x}_0$
  - Computing e^A is easy if A is a diagonal matrix (non-zero elements are only on the diagonal)

- For a linear system with ***exogenous*** inputs?
  - $x(t) = e^{At}x_0 + \int_0^t e^{A(t-\tau)}Bu(\tau)d\tau$

- In practice, numerical integration methods outperform matrix exponential

Stability of Systems

- Property capturing the ability of a system to return to a quiescent state after perturbation
  - Stable systems recover after disturbances, unstable systems may not
  - Almost always a desirable property for a system design
- Fundamental problem in control: design controllers to *stabilize* a system

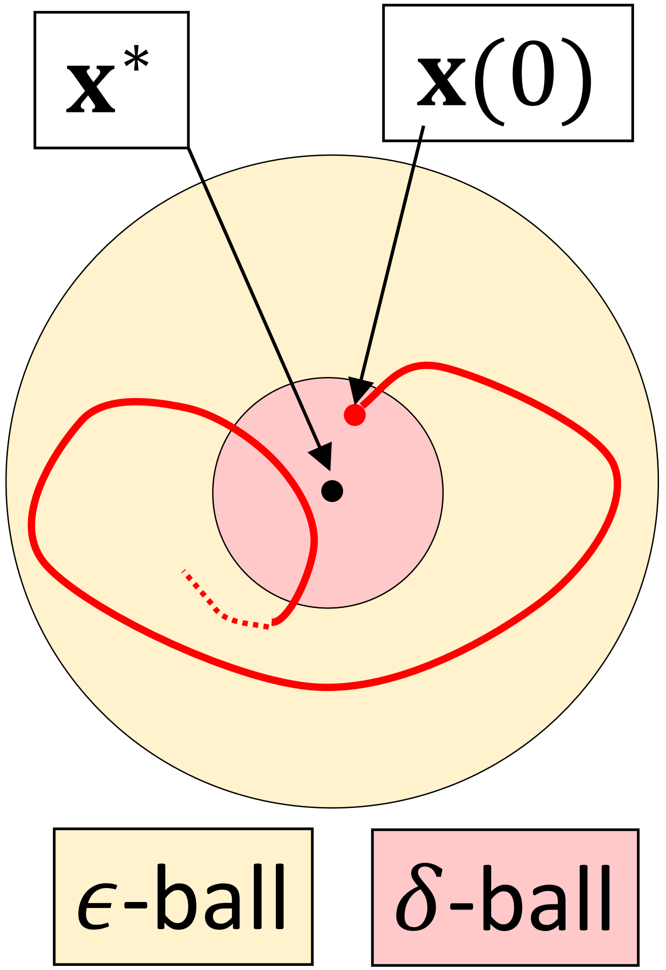


- Problem: Inverted Pendulum on a moving cart is inherently unstable, aim: keep it upright
- Solution Strategy: Move cart in direction in the same direction as the pendulum’s falling direction
- Design problem: Design a controller to stabilize the system by computing velocity and direction for cart travel

Lyapunov stability

Solutions starting δ close from equilibrium point must remain close (within ϵ) forever

- System $\dot{\mathbf{x}} = f(\mathbf{x})$ with f Lipschitz continuous
- Equilibrium point when $f(\mathbf{x})$ is zero (say $\mathbf{x}^*$)
- Equilibrium point $\mathbf{x}^*$ is Lyapunov-stable if:
  - For every $\epsilon > 0$,
    - There exists a $\delta > 0$, such that
      - if $\|\mathbf{x}(0) - \mathbf{x}^*\| < \delta$, then,
      - for every $t \geq 0$, we have $\|\mathbf{x}(t) - \mathbf{x}^*\| < \epsilon$



Asymptotic Stability

Solutions not only remain close, but also converge to the equilibrium

- System $\dot{\mathbf{x}} = f(\mathbf{x})$
- Equilibrium point $\mathbf{x}^*$ is asymptotically-stable if:
  - $\mathbf{x}^*$ is Lyapunov-stable +
  - There exists $\delta > 0$ s.t. if $||\mathbf{x}(0) - \mathbf{x}^*|| < \delta$, then $\lim_{t \to \infty} ||\mathbf{x}(t) - \mathbf{x}^*|| = 0$

Exponential Stability

Solutions not only converge to the equilibrium, but in fact converge at least as fast as a known exponential rate

- All stable linear systems are exponentially stable
- This need not be true for nonlinear systems!

- System $\dot{\mathbf{x}} = f(\mathbf{x})$
- Equilibrium point $\mathbf{x}^*$ is exponentially-stable if:
  - $\mathbf{x}^*$ is asymptotically stable +
  - There exist $\alpha > 0, \beta > 0$ s.t. if $\|\mathbf{x}(0) - \mathbf{x}^*\| < \delta$, then for all $t \geq 0$:

$$\|\mathbf{x}(t) - \mathbf{x}^*\| \leq \alpha \|\mathbf{x}(0) - \mathbf{x}^*\| e^{-\beta t}$$

Bounded-Input-Bounded-Output (BIBO) stability

If the output signal is bounded for all input signals that are bounded.

Example:

- $x(0) = x_0; v(0) = v_0$
- $\dot{x} = v(t); \dot{v} = \frac{F(t) - kv(t)}{m}$

Feedback Linearization

- Equations of motion for inverted pendulum:
$$m\ell^2\ddot{\theta} + d\dot{\theta} + m\ell g\cos\theta = u$$
- Control Input: Torque u
- Rewriting, with $x_1 = \theta, x_2 = \dot{\theta}$:
- $\dot{x_1} = x_2$
- $\dot{x_2} = \left(-\frac{d}{m\ell^2}x_2 \; - \frac{g}{\ell}\cos x_1\right) + \left(\frac{1}{ml^2}u\right)$