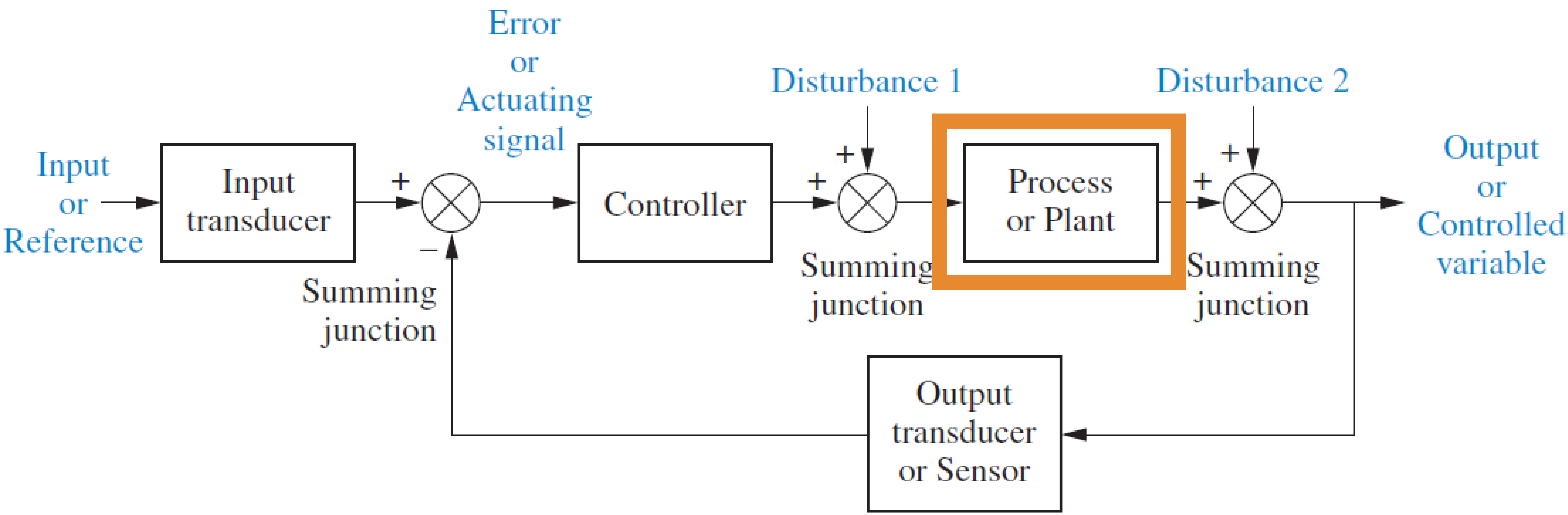
Course Syllabus

- Basic concepts in control theory
- Basic system classification
- Basic system properties
  - Static Characteristics
  - Dynamic Characteristics
- **System Identification**
- Basic types of controllers
- Control quality evaluation
- Control systems stability
- Controller design methods
- Digital control
- Sensors

System Identification



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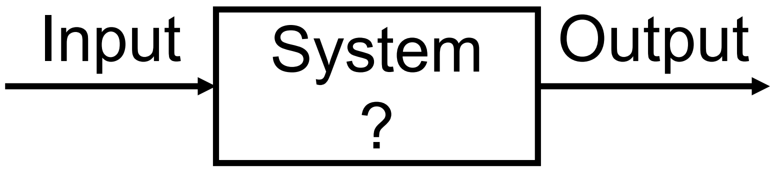
System Identification

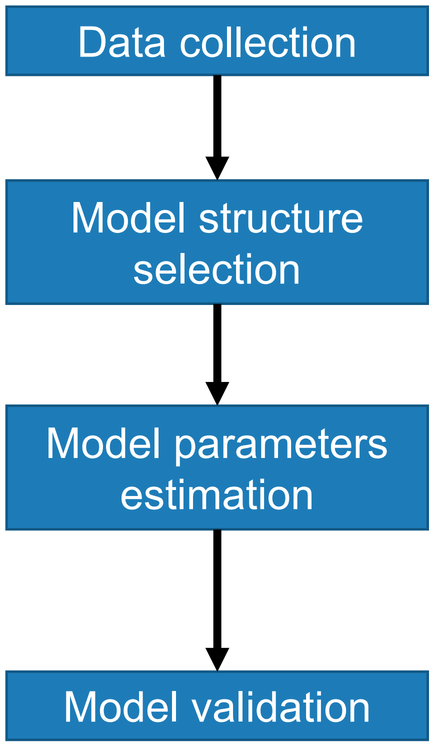
- Finding a mathematical model of a real system that describes its behavior as accurately as possible.



- System identification has two broad approaches:
  - **Analytical** (first-principles modeling)
    - Based on the laws of physics, chemistry, or mechanics of the system.
    - Derive equations directly from fundamental principles (e.g., Newton’s laws, Kirchhoff’s laws, thermodynamics).
  - **Experimental** (data-driven modeling)
    - Based on measured input–output data without fully relying on physics.
    - Model structure and parameters are estimated from data rather than derived from laws.

System Identification

- System identification involves the following steps:
  - obtaining good **experimental data**
    - apply input signals like impulse, step, sinusoidal, pseudo-random signal (PRBS) or white noise
    - measure input and output data under the chosen excitation
  - selecting a suitable **model structure**
    - mathematical relationship between input and output variables that contains unknown parameters
    - examples: transfer function (with adjustable poles and zeros), state-space equations, nonlinear parameterized functions
  - estimating the **model parameters**
    - first, select the cost function – mathematical expression that measures the “error” between the measured system output and the model’s predicted output, e.g. mean squared error $\frac{1}{N}\sum_1^N (y - y_M)^2$
    - then, minimize this cost function through an optimization process by adjusting the model parameters
  - evaluating the **model accuracy**
    - determine if the identified model is good enough for its intended purpose
    - test the model on new input–output data not used in training

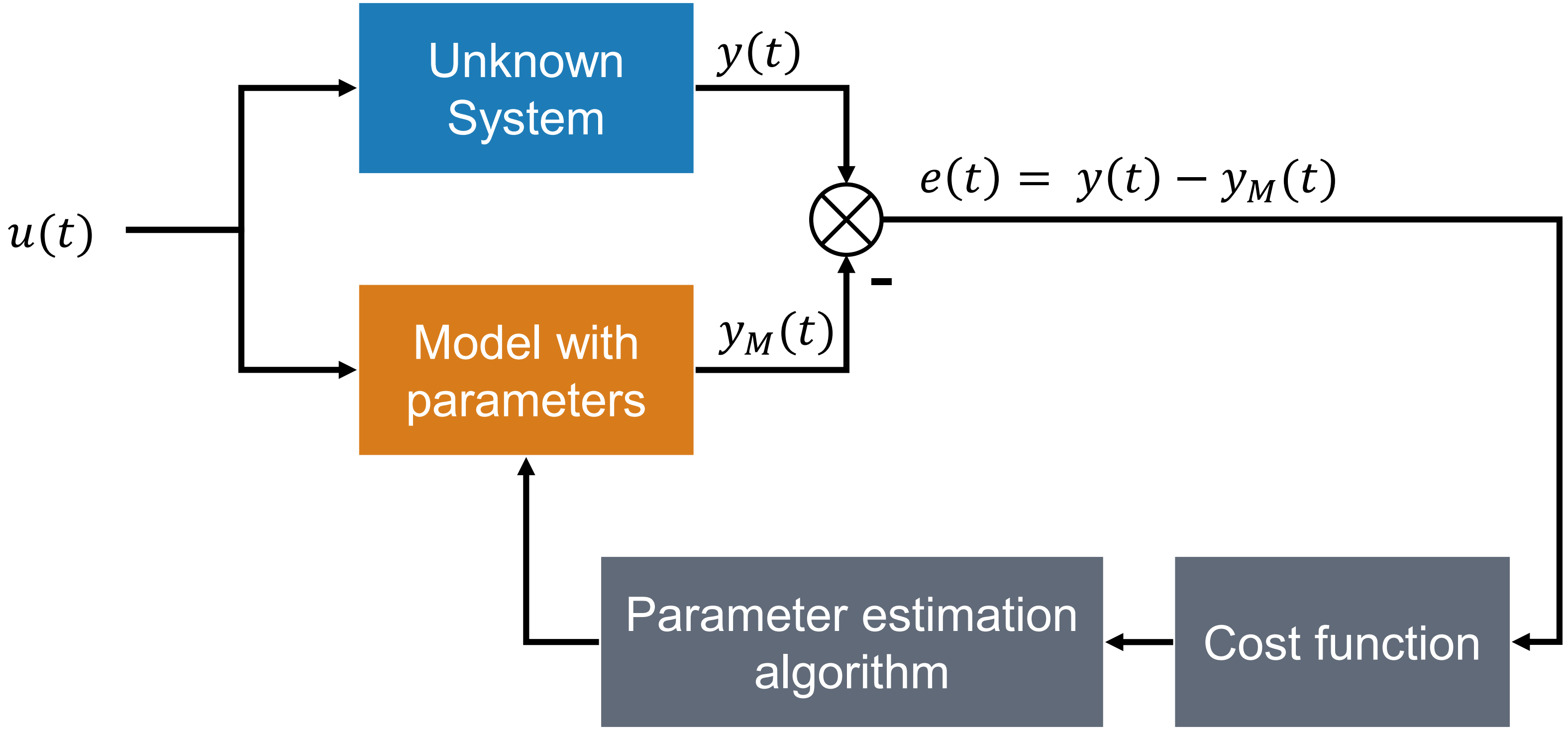


System Identification

- System identification can be categorized depending on *when* and *how* the model is estimated
  - **Offline Identification** (Batch)
    - Collect input-output data first, then process it afterward (in one batch) to estimate model parameters.
    - More accurate results since full dataset is used.
    - Used in system that don’t change with time and can be run and repeated.
  - **Online Identification** (Adaptive)
    - Update model parameters continuously as new measurements arrive.
    - Parameters are refined in real time.
    - Useful for time-varying systems (whose parameters change over time).
    - Can adapt to disturbances, wear, or changes in system behavior.

System Identification

- Model parameter estimation process



System Identification

- Models can be classified according to several key characteristics, depending on how they represent the system's behavior and how they are derived:
  - **Physical vs. Mathematical Models**
    - Physical – based on physical laws, parameters have physical meaning
    - Mathematical – derived from input-output data without explicit physical interpretation
  - **Static vs. Dynamic Models**
    - Static – output depends only on current input
    - Dynamic – output depends on present and past inputs (and possibly past outputs)
  - **Stationary vs. Non-Stationary Models**
    - Stationary – model parameters do not change with time
    - Non-Stationary (Time-Varying) – model parameters change over time

System Identification

- Classification of models:
  - **Deterministic vs. Stochastic Models**
    - Deterministic – no randomness, same input always gives same output
    - Stochastic – includes random processes or noise
  - **Linear vs. Nonlinear Models**
    - Linear – superposition principle holds
    - Nonlinear – output not proportional to input
  - **Continuous-Time vs. Discrete-Time Models**
    - Continuous-Time – variables defined for all $t \in \mathbb{R}$
    - Discrete-Time – variables defined only at sampling instants $t = kT_s$

System Identification

- **Methods of experimental identification**
  - Experimental (data-driven) identification determines a system's model from measured input–output data, rather than from physical laws.

Category	Handles noise?	Updates in Real Time?	Example Methods
Deterministic Methods	× No	× No	Step / Impulse response, Frequency response
Stochastic Methods	✓ Yes	× No	ARX, ARMAX, BJ
Adaptive Methods	✓ Yes	✓ Yes	Recursive Least Squares, Kalman Filter, Least Mean Square

System Identification

- **Methods of experimental identification**
  - **Deterministic Methods**
    - These assume no randomness – the relationship between input and output is deterministic (noise-free or negligible).
    - Step response, Impulse response, Frequency response, Bode analysis
  - **Stochastic Methods**
    - These explicitly model random disturbances and noise in the data.
    - ARX (AutoRegressive with eXogenous input)
    - ARMAX (AutoRegressive Moving Average with eXogenous input)
    - Output Error (OE), Box-Jenkins (BJ)
  - **Adaptive Methods**
    - These update parameters continuously or recursively as new data arrives.
    - Used when the system is time-varying or operating conditions change.
    - Recursive Least Squares, Kalman Filter, Least Mean Square…