Computers with Control Theory

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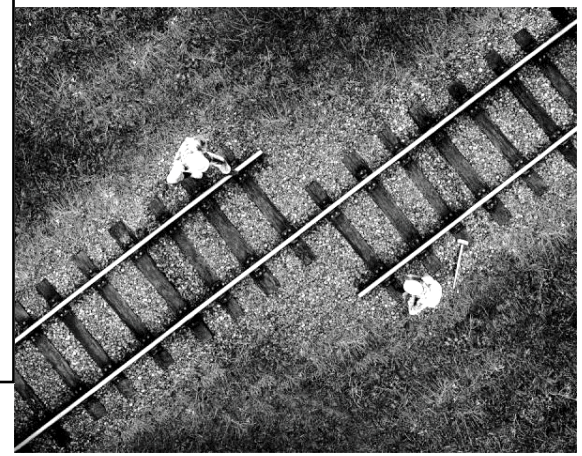
Don't Use Formal Control When You…

…hate high-level design

…believe you know **everything**

…love repentance over poor designs

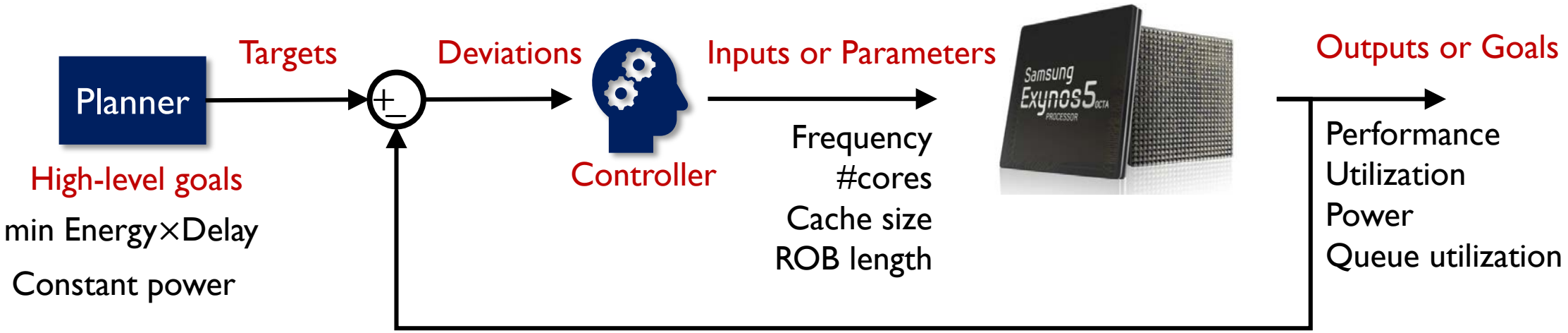


…don't care about the full system

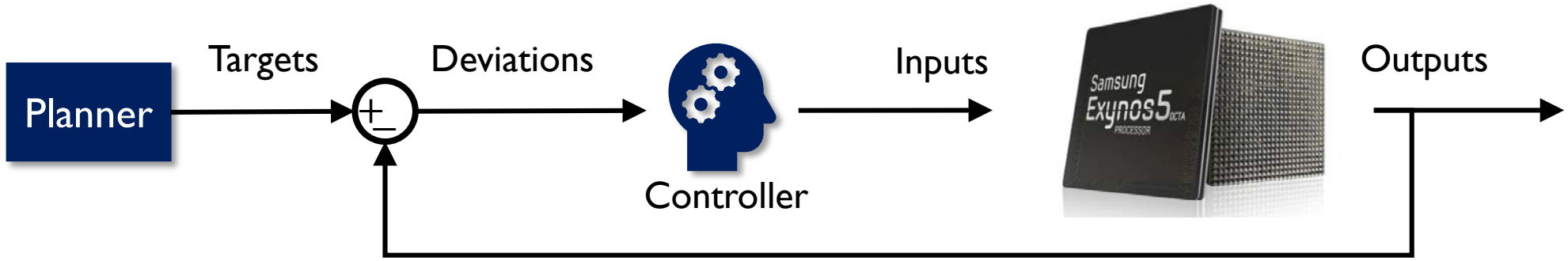
Goals of the Tutorial

- Know some ways in which formal control can be applied to computers
- Know about the types of formal controllers and their application
- Get a feel for the design of a formal controller
  - Hands-on in a longer version next time!
- Know the strengths and limitations of control theory

A Typical Control Loop



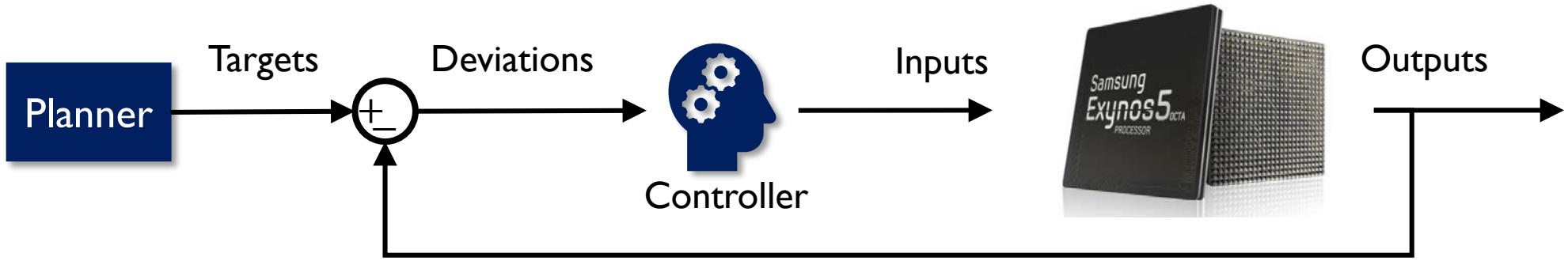
Using Formal Controllers



Meeting fixed output targets

Video processing

Using Formal Controllers

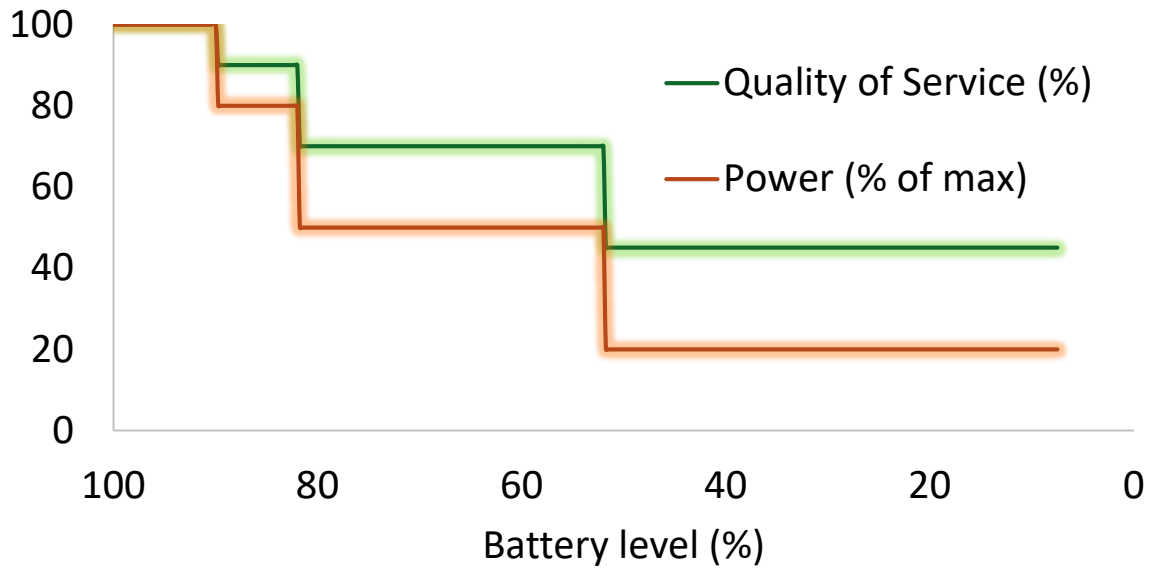


Meeting fixed output targets

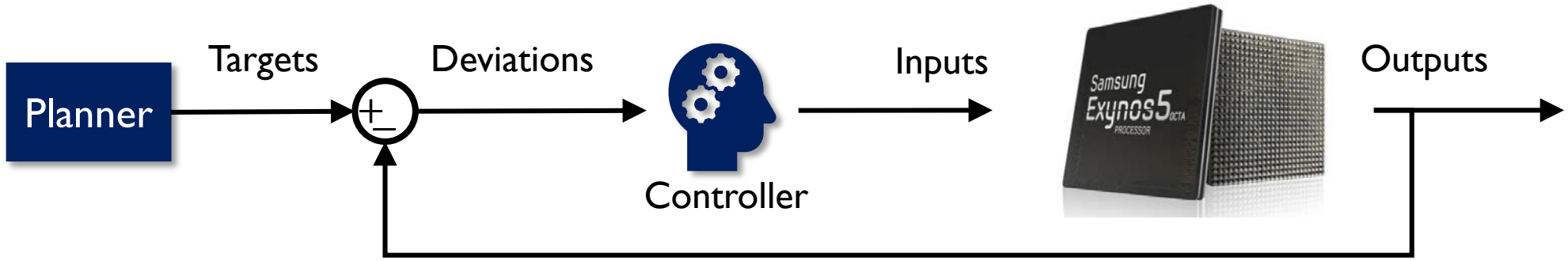
Video processing

Meeting changing output targets

Battery optimization



Using Formal Controllers



Meeting fixed output targets

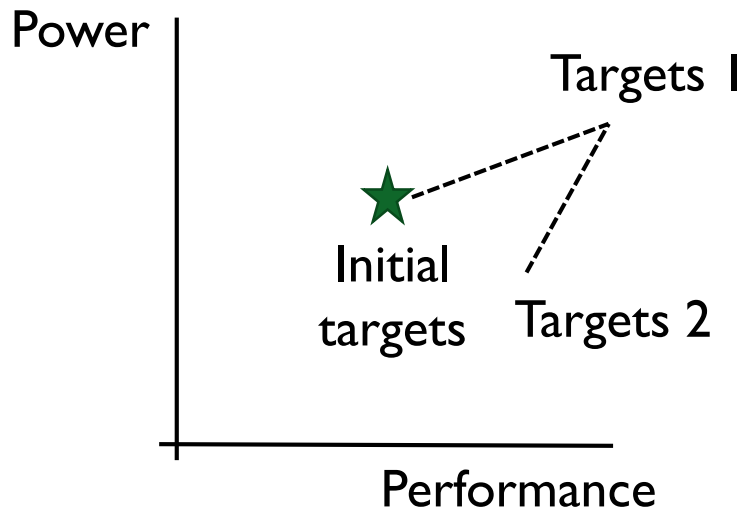
Video processing

Meeting changing output targets

Battery optimization

Optimization

min Energy×Delay



First Step for Controller Design

Dynamic system model

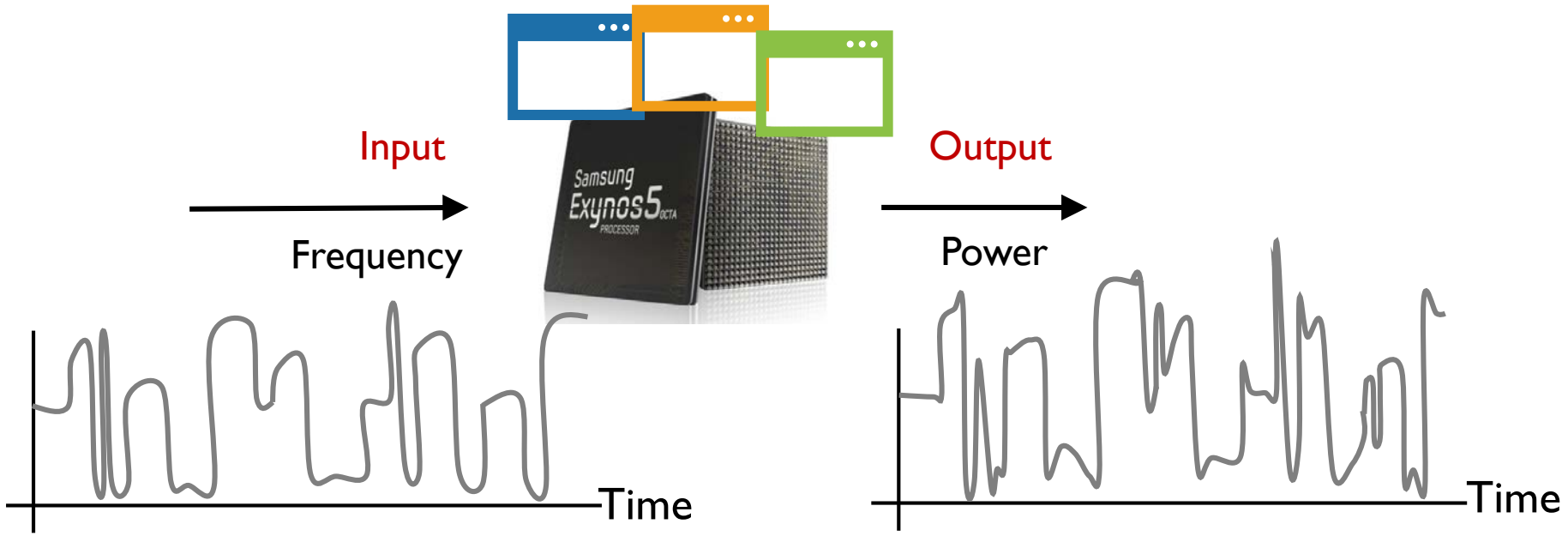
$$\text{outputs}(T) = m_1 \times \text{outputs}(T-1) + m_2 \times \text{outputs}(T-2) + \cdots +$$
$$n_0 \times \text{inputs}(T) + n_1 \times \text{inputs}(T-1) + \cdots$$

When designing heuristics, the model was called intuition, and was implicit

System Identification

Get models from experimental data

System Identification



Time

DVFS	Power
1.2	5
1.8	7.1
1.1	4.3

Time

DVFS	Power
1.1	5
1.3	5.6
1.7	7

Time

DVFS	Power
2.1	8.5
0.5	1.2
2.8	9

Choices of Controllers

Controllers differ based on:

- their policy (how they generate inputs from deviations)
- the hyper-parameters they offer
- the properties they guarantee

Properties of Interest

Stability: Controller is not crazy

For small deviations, controller does not generate increasingly large input values

Convergence: Controlled system meets targets

Deviation will eventually get close to zero

Robustness: Controller is not crazy and controlled system meets targets in reality

Stability and convergence hold when design assumptions differ from reality

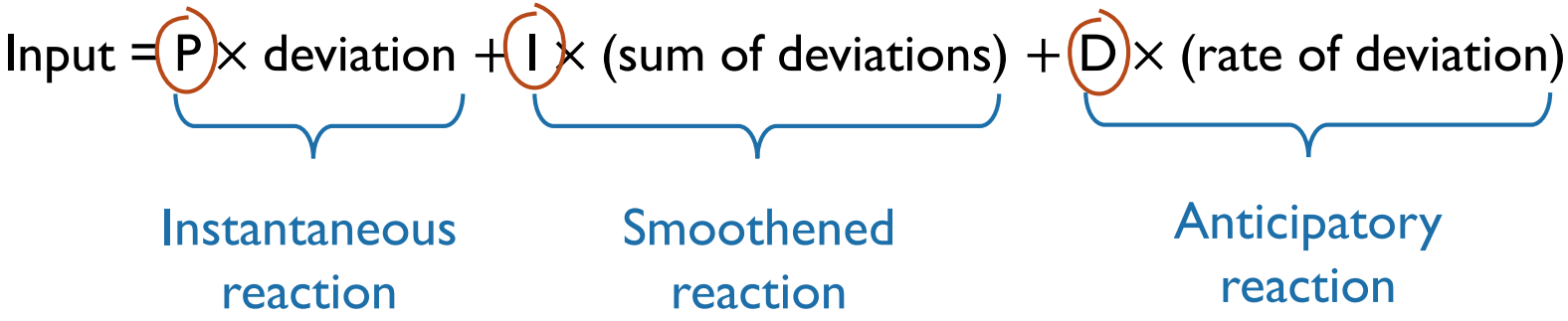
e.g., 20% model error, or unpredictable changes

Optimality: Controller is the best

Controller changes inputs in the best way to minimize deviations

PID Controller

PID: Proportional-Integral-Derivative



Tools (Matlab, Octave, Mathematica) automatically tune P, I and D

Report stability, convergence

No optimality

Limited robustness

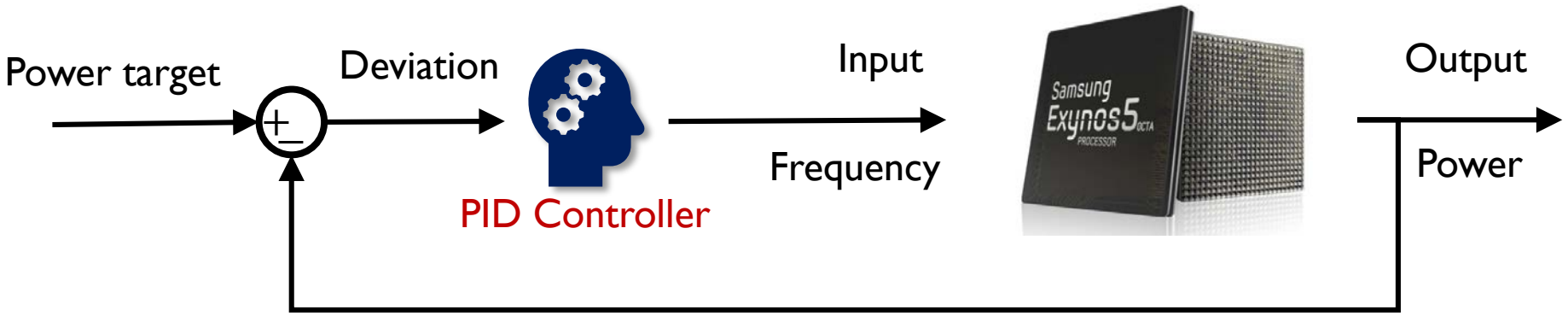
Guarantees may not hold when inputs can take only a few discrete values

e.g., #cores : 1, 2, 3, 4

[PACT'17]

PID Controller: Uses

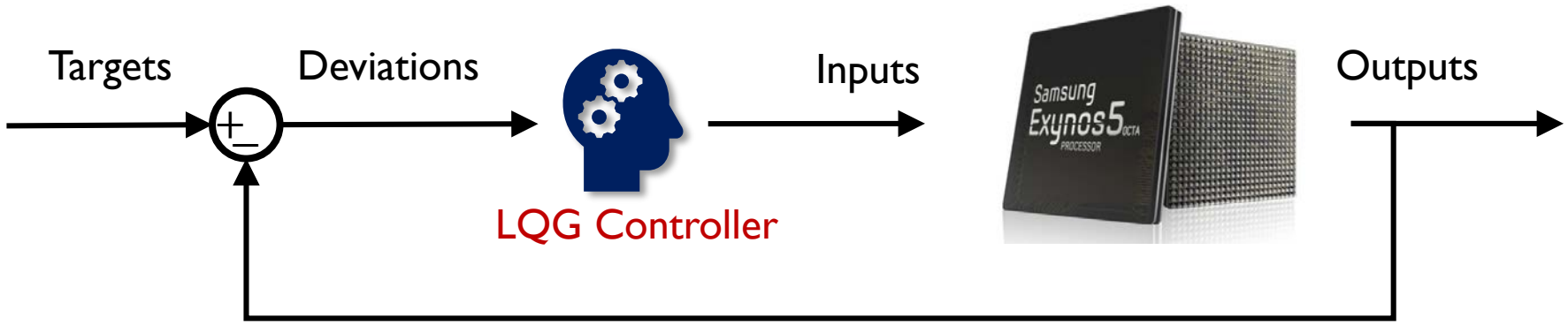
Applicable for Single Input Single Output (SISO) systems (e.g., RAPL)



LQG Controller

LQG: Linear Quadratic Gaussian

Multiple Input Multiple Output



Matrices [**A, B, C, D**] and *state*

$$\text{inputs} = \mathbf{C} \times \text{state} + \mathbf{D} \times \text{deviations}$$
$$\text{state}_{\text{new}} = \mathbf{A} \times \text{state} + \mathbf{B} \times \text{deviations}$$

} Every T time-units

[ISCA'16]

LQG Controller: Hyper-parameters

Relative output priorities

e.g., power: 10 and performance: 1

Relative input cost

e.g., Frequency: 1 and #cores: 10

Relative ratio of output priorities and input costs determines inertia

Percentage of random error possible with the model

e.g., sensor noise, interrupts

[ISCA'16]

LQG Controller: Properties and Uses

Properties: stability, convergence, optimality

Limited robustness

Non-random modeling errors are common in reality

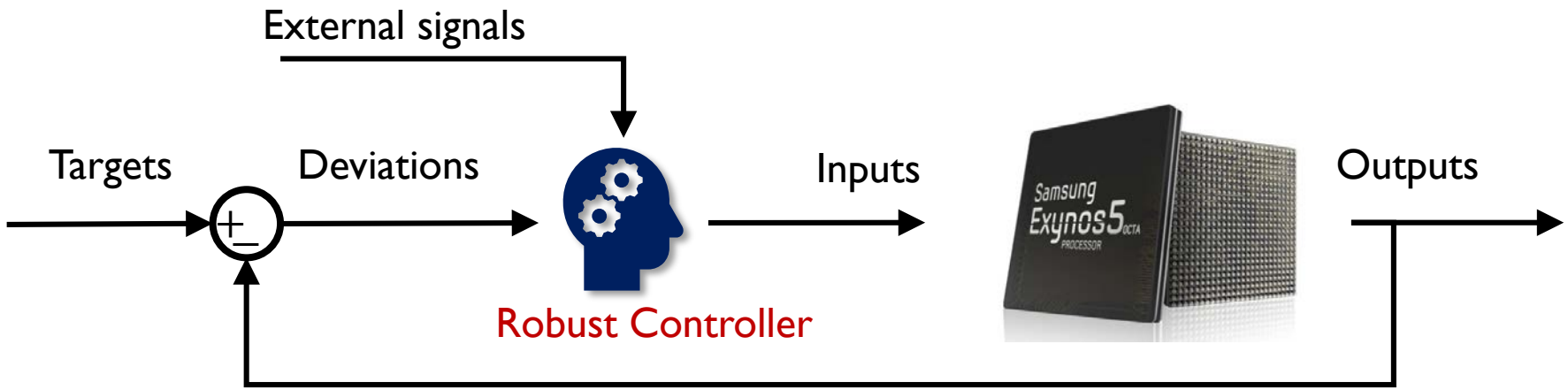
e.g., multi-controller systems

Guarantees may not hold when inputs can take only a few discrete values

e.g., #cores : 1, 2, 3, 4

Useful when models are accurate, and inputs have many values

Robust Controller



[**A, B, C, D**] and *state*

$$\text{inputs} = \mathbf{C} \times \text{state} + \mathbf{D} \times [\text{deviations, external signals}]$$

$$\text{state}_{\text{new}} = \mathbf{A} \times \text{state} + \mathbf{B} \times [\text{deviations, external signals}]$$

So far: Controller is designed to work for the nominal specification: model, hyperparameters

Now: Controller works for a range of specifications: model, Δ, hyperparameters

Robust Controller: Hyper-parameters

Uncertainty guardband for modeling error

Worst case, and can be large, e.g., 60%

Doesn't matter the reason why the models are wrong

Uncertainty guardband for many other phenomenon

Interference: In multi-controller systems, another controller may override inputs

Input discretization

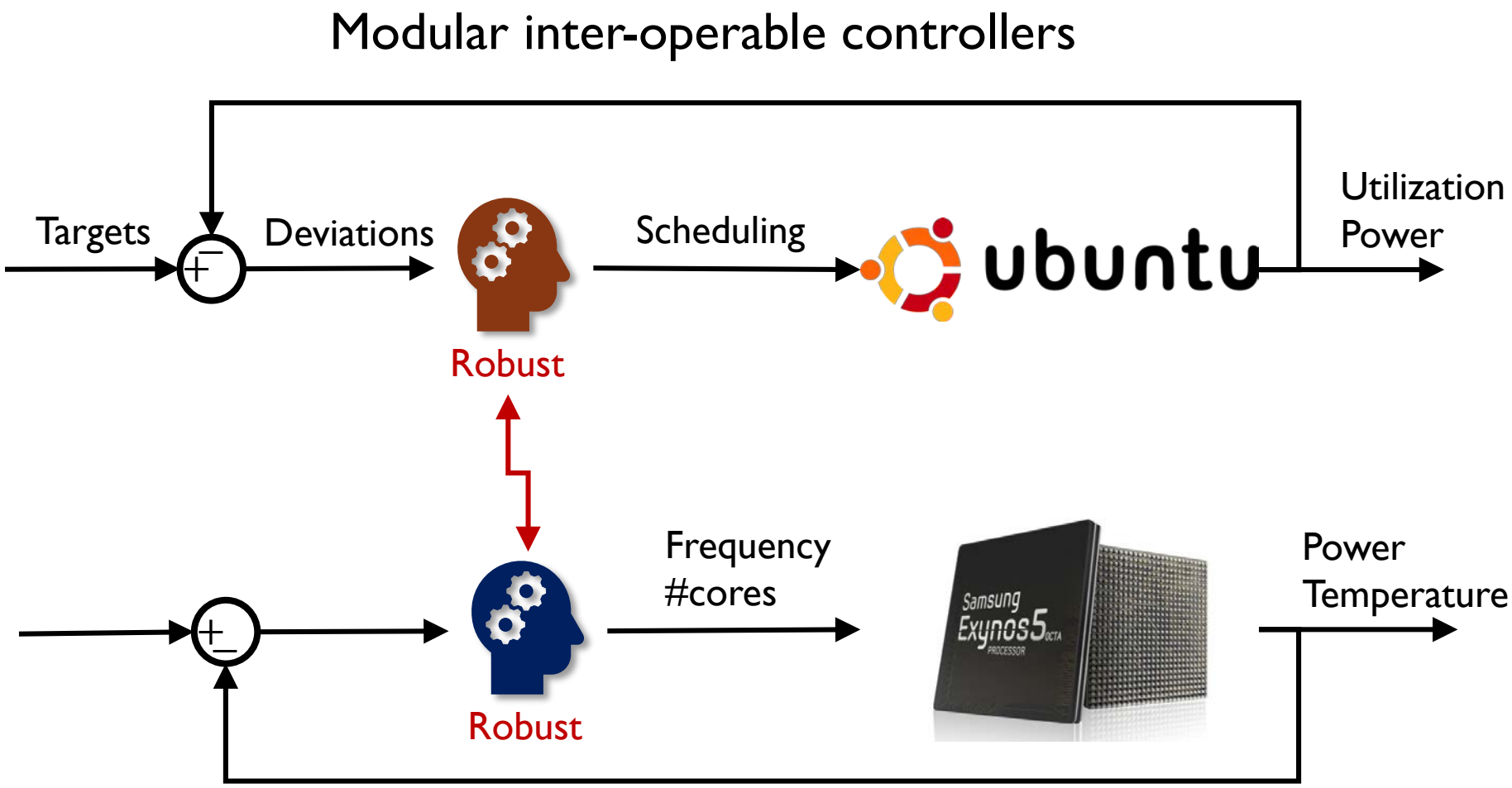
Deviation bounds

e.g., power deviations must be below 10%

Input weights

Robust Controller: Properties and Uses

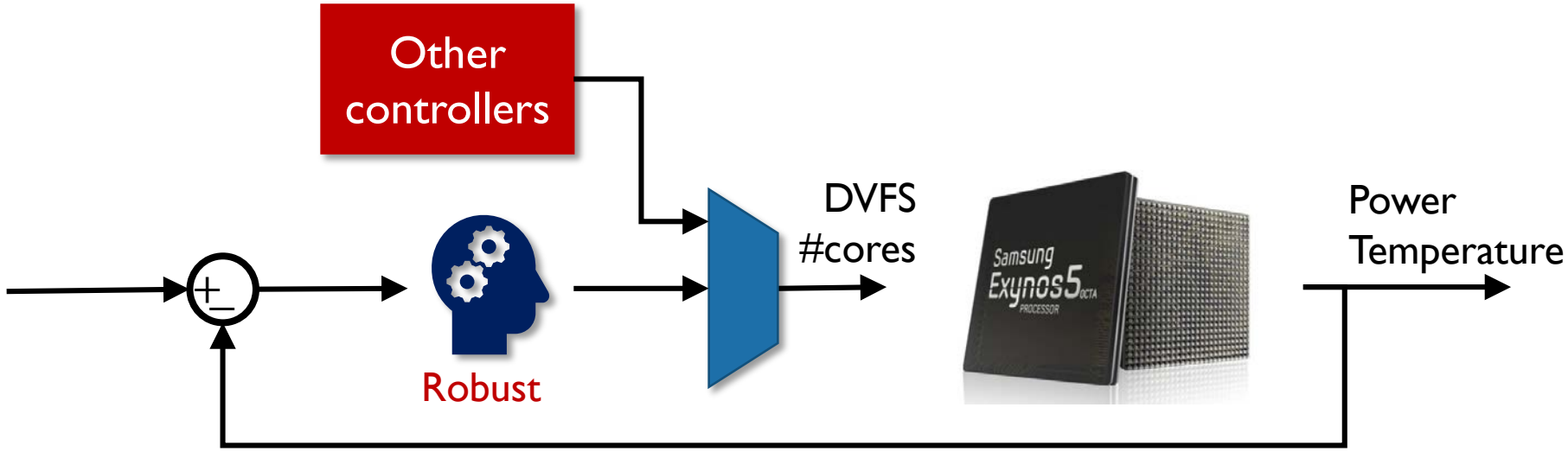
Wide applicability and composability because of robustness



Robust Controller: Properties and Uses

Wide applicability and composability because of robustness

Interfering controllers

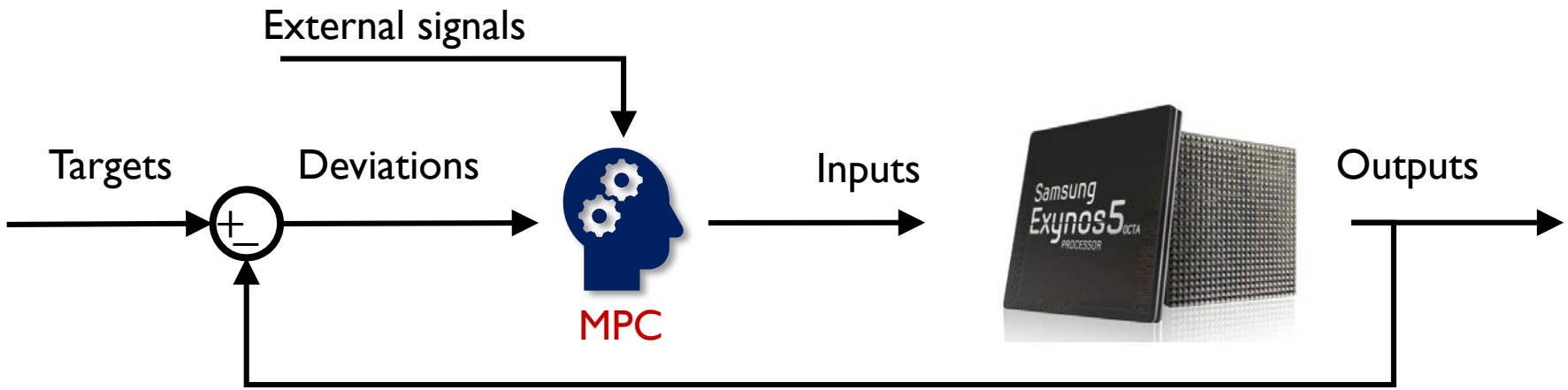


Limitations:

If errors are beyond the guardband, no guarantees

When guardband is too large, controller becomes slow

Model Predictive Controller (MPC)



At time T, generate: inputs(T)
inputs$(T+1)$
$\vdots$
inputs$(T+X)$

deviations will be minimized by this step

use model and current deviations for forecasting

apply inputs(T)

MPC: Hyper-parameters

Output priorities

Input overheads

Constraints

E.g., range of inputs

Length of control plan

[FSE'17]

MPC: Properties and Uses

Provides stability, convergence, optimality

Good robustness

However, model accuracy plays a critical part because of prediction

Limitation: computationally intensive

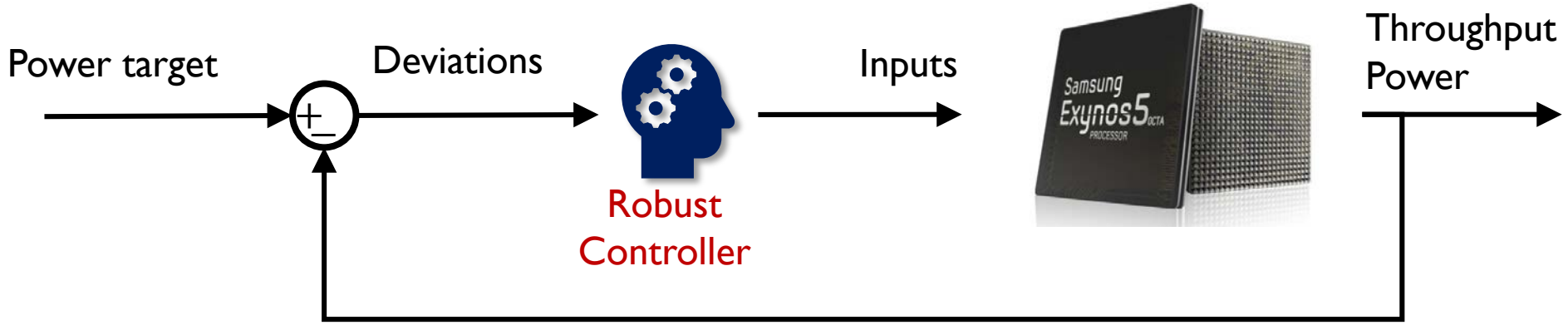
Useful in many scenarios

The continuous re-planning approach makes it suitable for changing conditions

Summary of Controller Choices

	PID	LQG	Robust	MPC
Stability and Convergence	✓	✓	✓	✓
Optimality	✗	✓	✓	✓
Robustness	✗	✗	✓	ⓘ
Forecasting	✗	✗	✗	✓
Overhead	**Very low**	**Low**	**Low – Medium**	**Medium – High**
Uses	SISO e.g., RAPL	MIMO, accurate model, random noise	MIMO, poor models, multi-control systems	MIMO, multi-control systems and forecasting if accurate models

Demo



- Inputs:
  - Dynamic Voltage-Frequency Scaling
  - Idleness

Robust Control: Design

- Dynamic model of the system → Already done
- Specify hyper-parameters → Use intuition, tools
  - Guardband for modeling error
  - Finite and discrete inputs
  - Deviation bounds
  - Input overheads

What's the difference from heuristic design?

- Able to think at a high-level
- Only a few obvious settings
- Easily know impact of choices

- Analyze controller

Control Theory: When and When Not?

Dynamic systems

Quantitative inputs e.g., #cores: 1, 2, 3, …

Fast and low-overhead decisions

Cannot handle categorical inputs

Scheduling policy A vs policy B

Which cores? (different from, how many cores?)

Less effective when runtime system behavior is very different

Guardbands and robustness help to a good extent – what if we need extreme-efficiency?

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