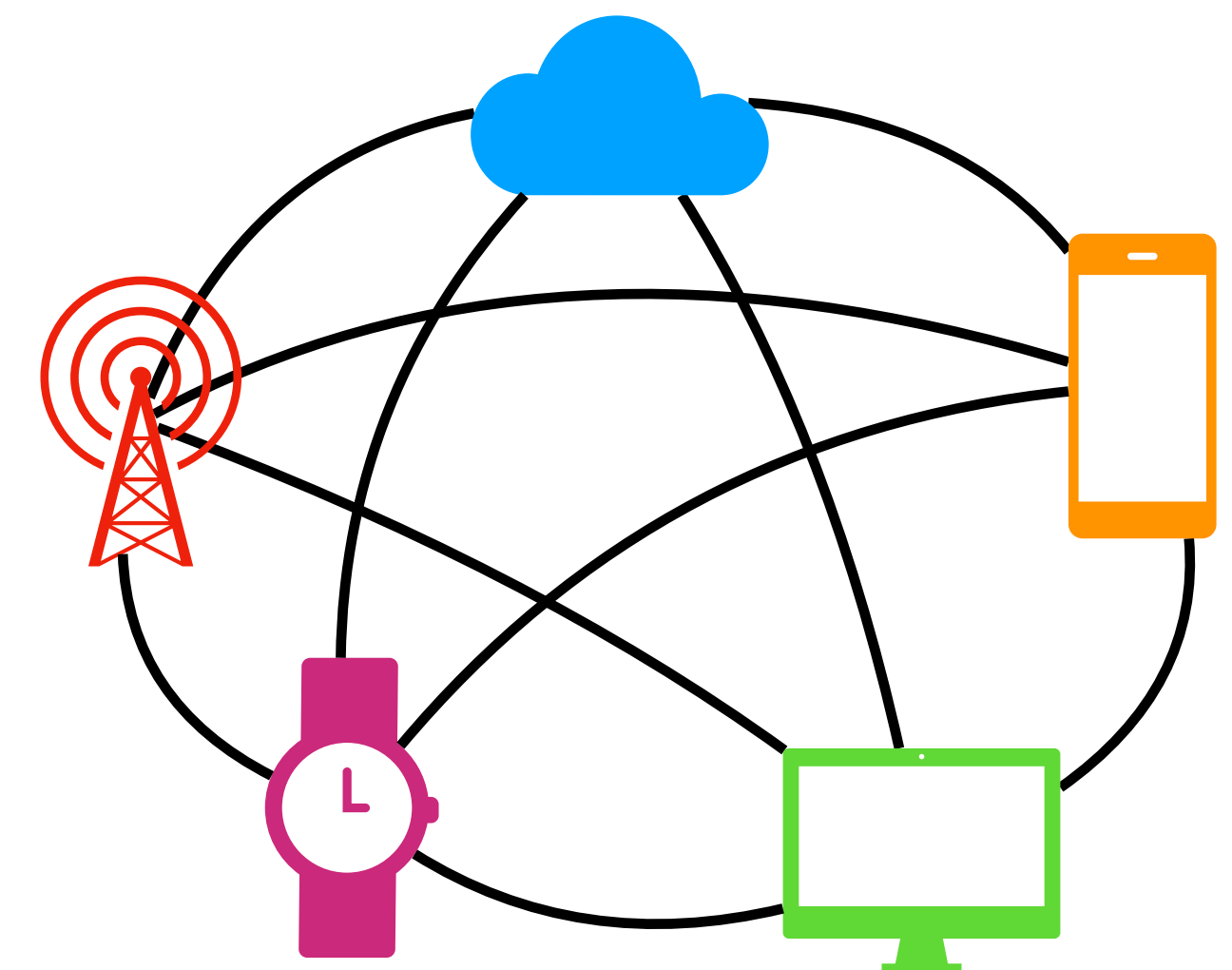
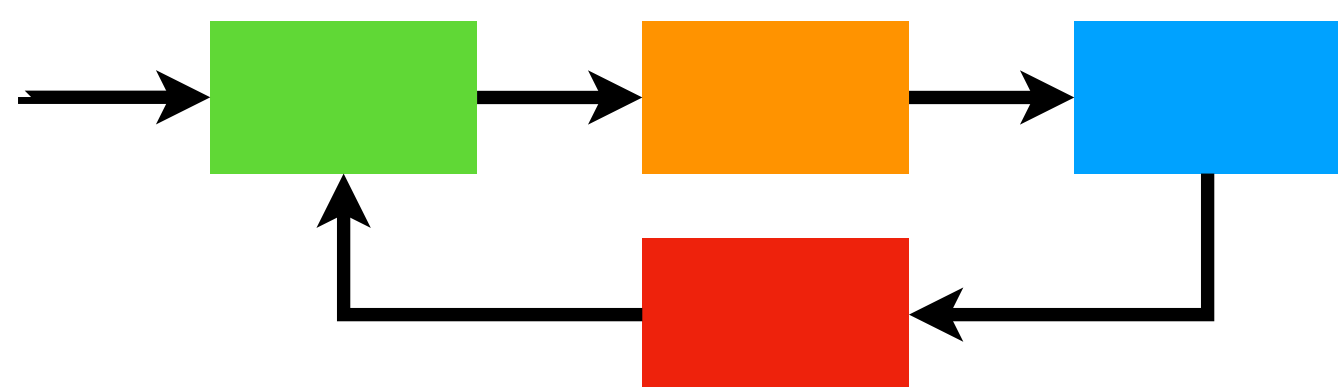


Autonomous Software Systems Design

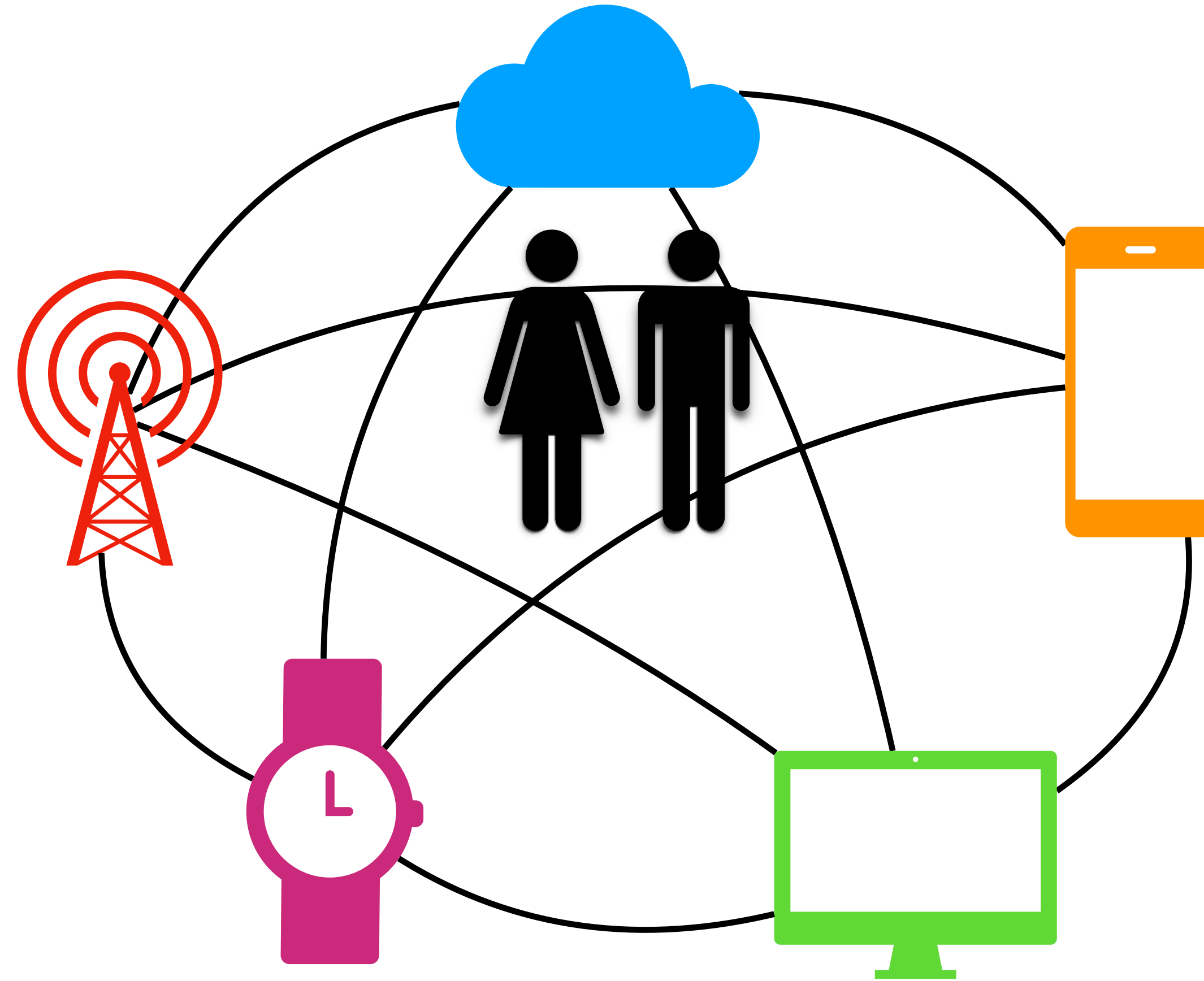
feat. Control Theory

Alessandro V. Papadopoulos
alessandro.papadopoulos@mdu.se
<http://www.idt.mdh.se/~aps01/>

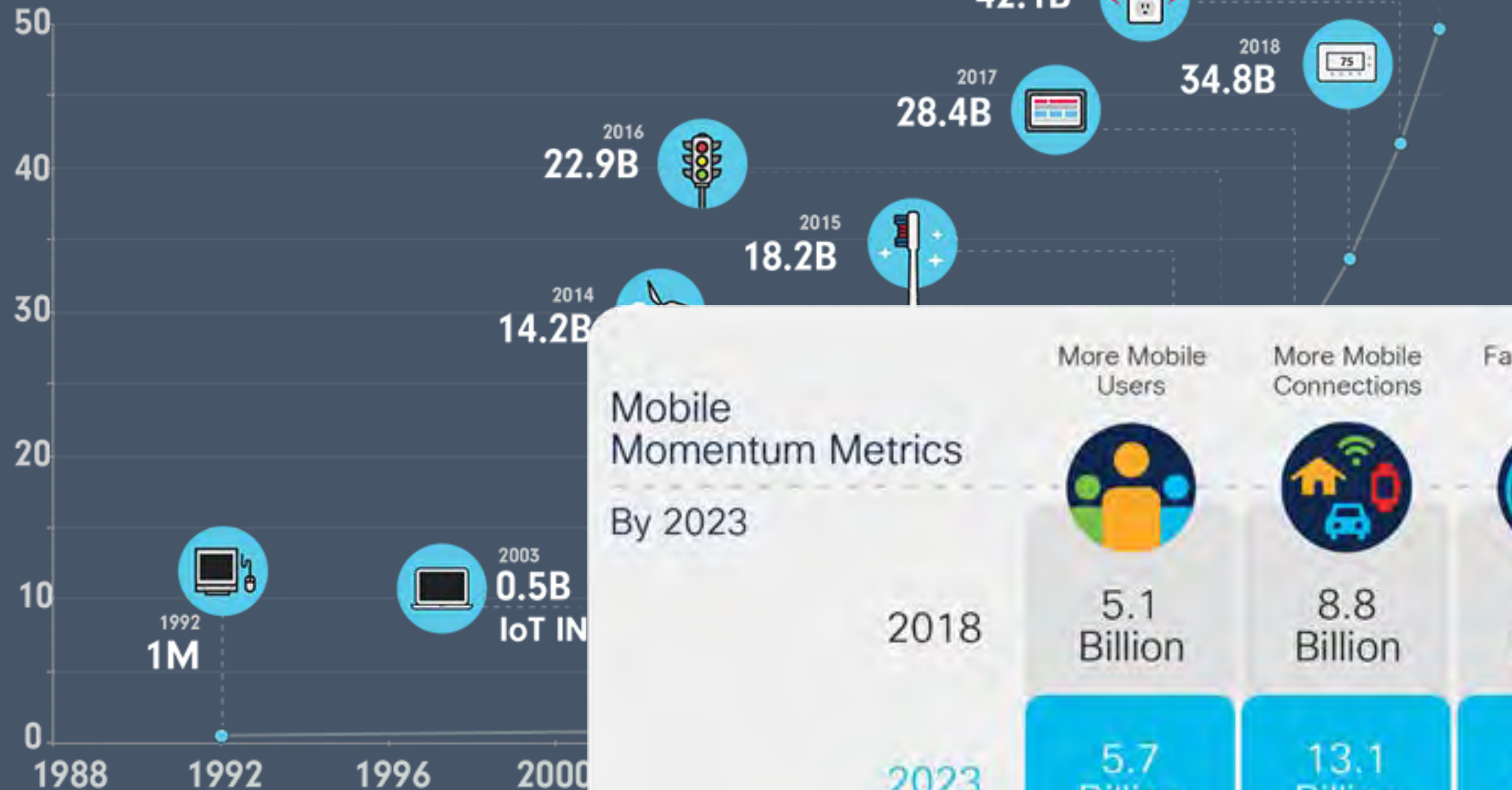
Sep 1st, 2022
CASTOR Software days @ KTH



Interconnected World Made of Computing Systems



BILLIONS OF DEVICES

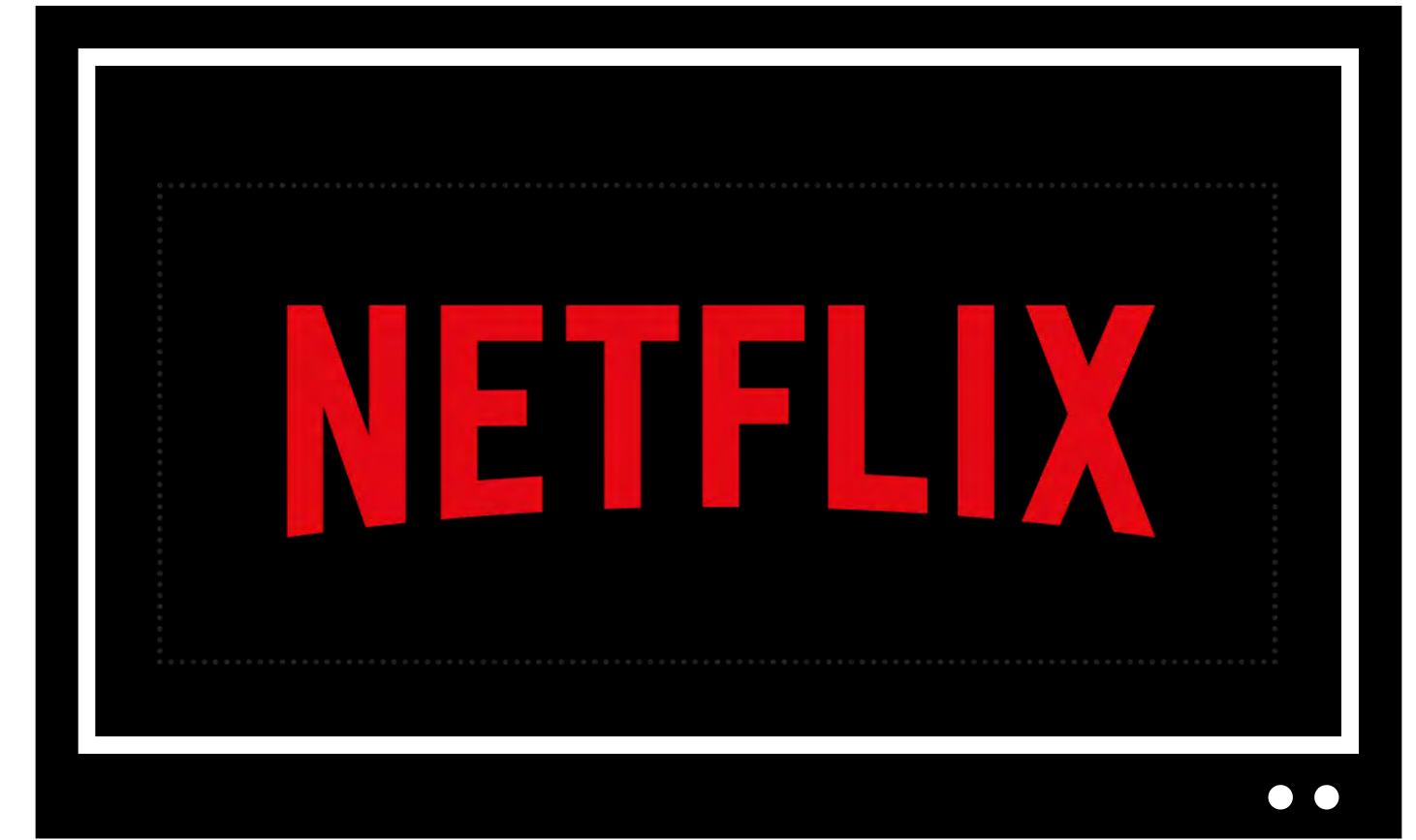
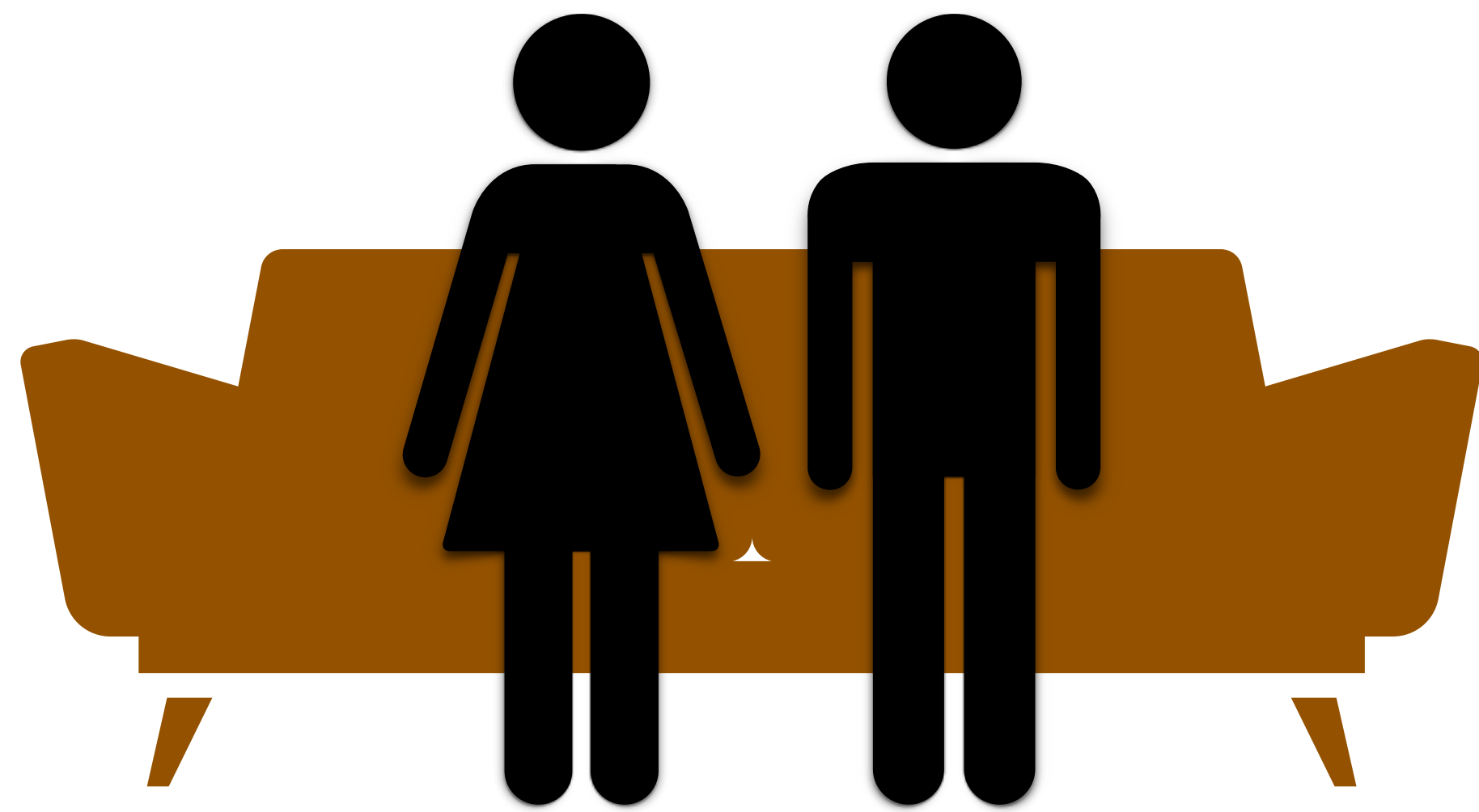


Mobile Momentum Metrics

By 2023

	More Mobile Users	More Mobile Connections	Faster Mobile Speeds
2018	5.1 Billion	8.8 Billion	13.2 Mbps
2023	5.7 Billion	13.1 Billion	43.9 Mbps

Source: Ericsson





Whoops, something went wrong...

Netflix Streaming Error

We're having trouble playing this title right now. Please try again later or select a different title.



Pokémon GO

Our servers are experiencing issues. Please come back later

Twitter is over capacity.

Please wait a moment and try again. For more informa



Your network is good, but Xbox Live isn't

Sorry, there's a problem on our side. We're working on it. Online features will come back in a while.

Check again

Continue

Select Back



502. That's an error.

The server encountered a temporary error and could not complete your request.

Please try again in 30 seconds. That's all we know.



Connection to the server has been terminated.
(CE-34861-2)



Suggested Actions

OK

facebook

Sorry, something went wrong.

We're working on getting this fixed as soon as we can.

[Go Back](#)

Facebook © 2014 · [Help](#)



This wiki has a problem

Sorry! This site is experiencing technical difficulties. Try waiting a few minutes and reloading.

(Cannot contact the database server: Unknown error (10.0.0.23))

You can try searching via Google in the meantime. Note that their indexes of our content may be out of date.

Search

Wikipedia - WWW

Canadian immigration website goes down as U.S. election results roll in

By Dana Guthrie Updated 7:20 am, Wednesday, November 9, 2016

✉ f t p g+

📄 3

Server Error

500 - Internal server error.

There is a problem with the resource you are looking for, and it cannot be displayed.



Autonomous

60
km/h

500m

**404
CAR
NOT
FOUND**

How Do We Tame Such Complexity?



Autonomous Software Systems Design

feat. Control Theory

What is control?



**Karl Johan
Åström**



**Richard M.
Murray**

“The term *control* has many meanings and often varies between communities. In this book, we define control to be the use of algorithms and feedback in engineered systems.”

–K.J. Åström & R. M. Murray, “Feedback Systems: An Introduction for Scientists and Engineers”, 2017

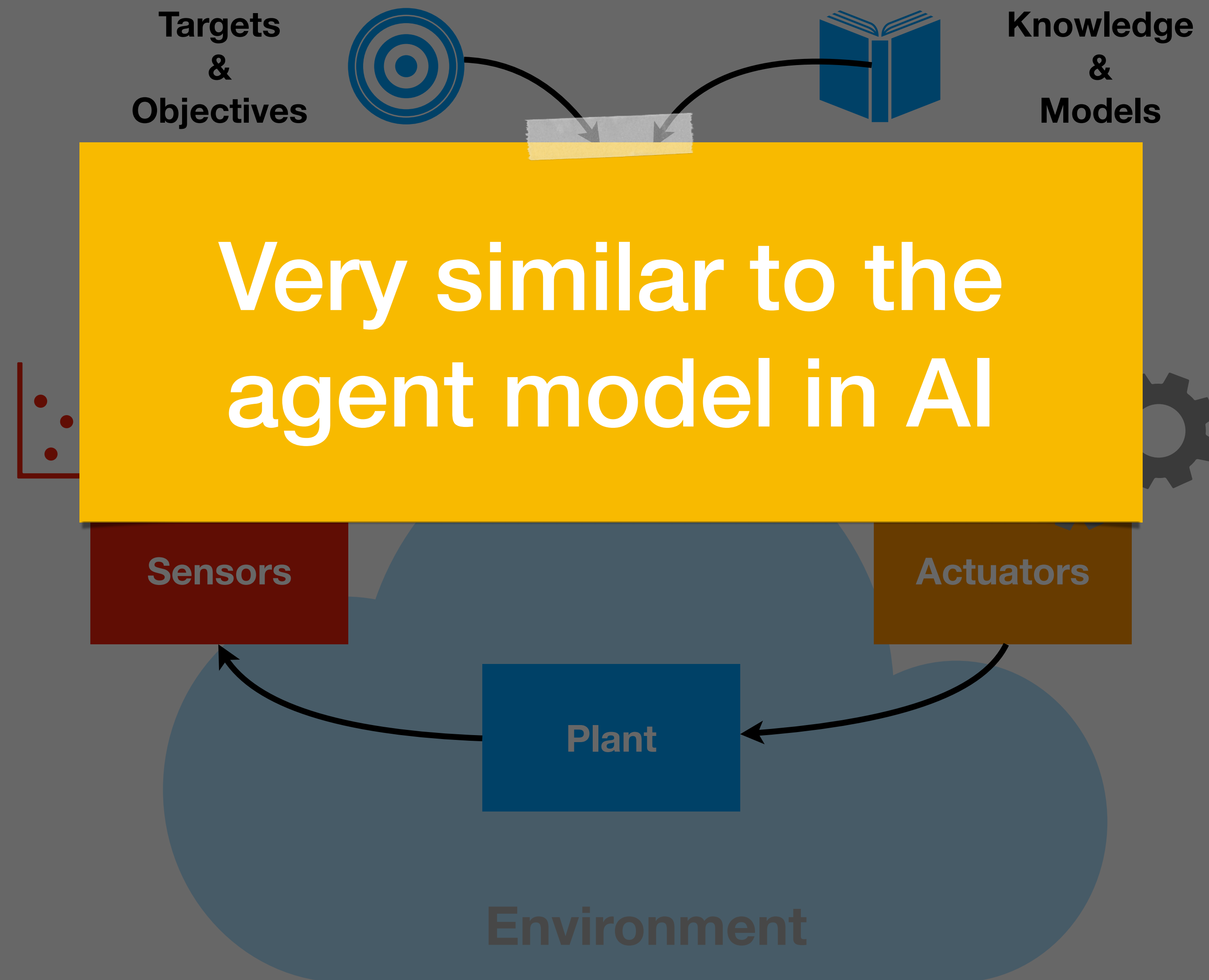
The Hidden Technology

- 😊 Widely used
- 😊 Very successful
- 😞 Seldom talked about
- 😞 Except when disaster strikes
- 😞 Why?

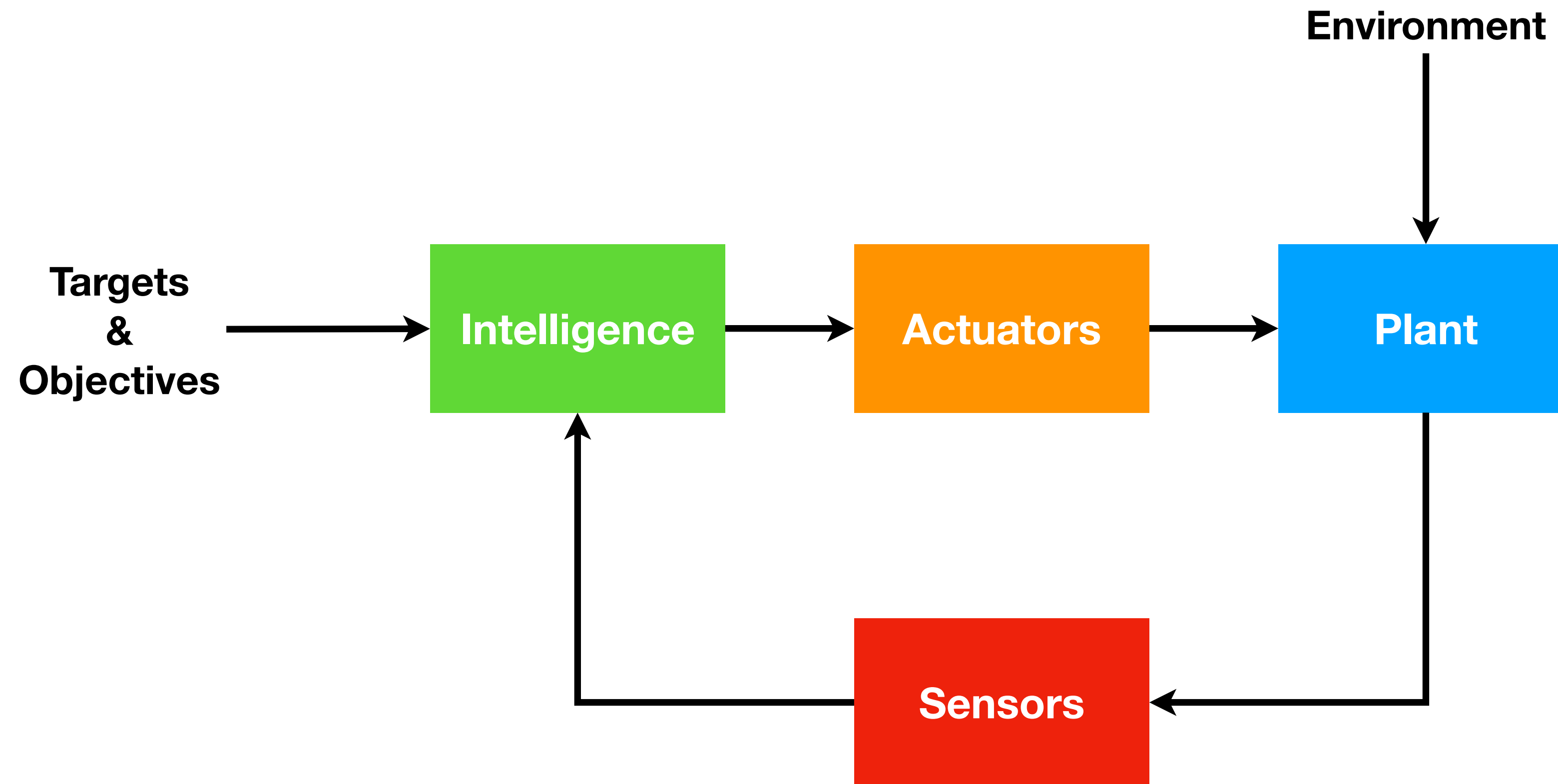
Easier to talk about devices than ideas
Not enough attention to popularization



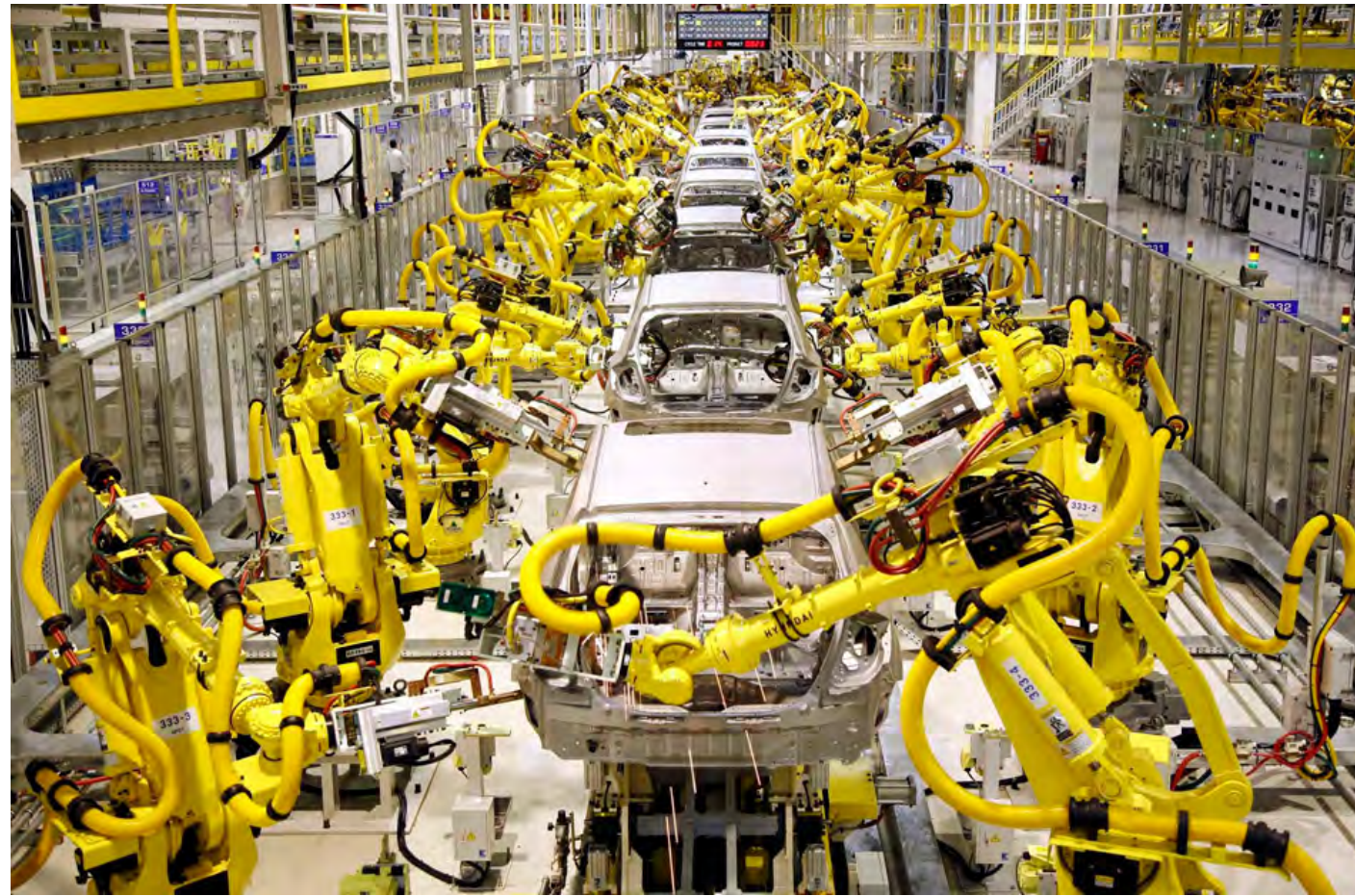
Control System: Conceptual Model



Control System: Block Diagram



Classical **Application Areas**



Robotics



Automotive



Industrial and Production

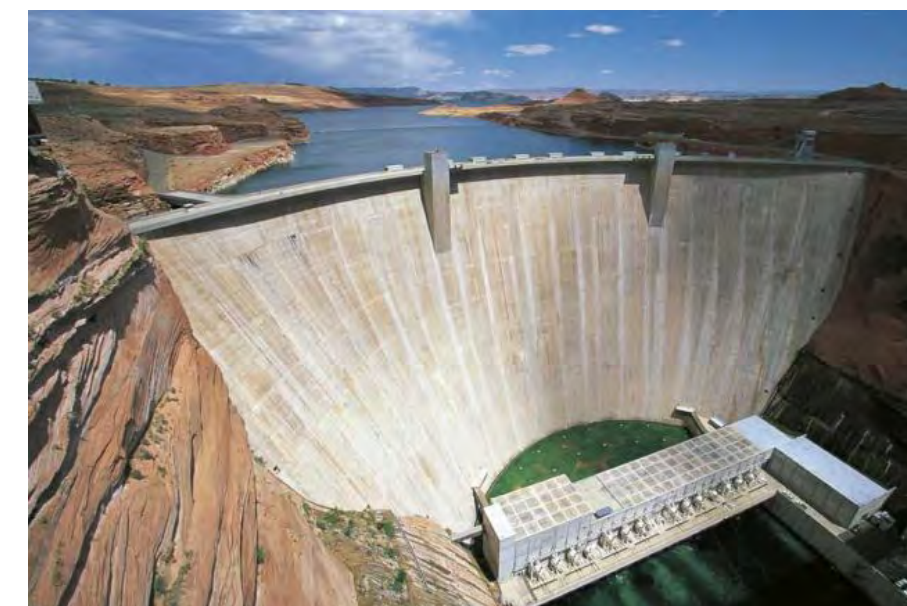
AND MANY MORE...



Avionics and Aerospace



Power plants



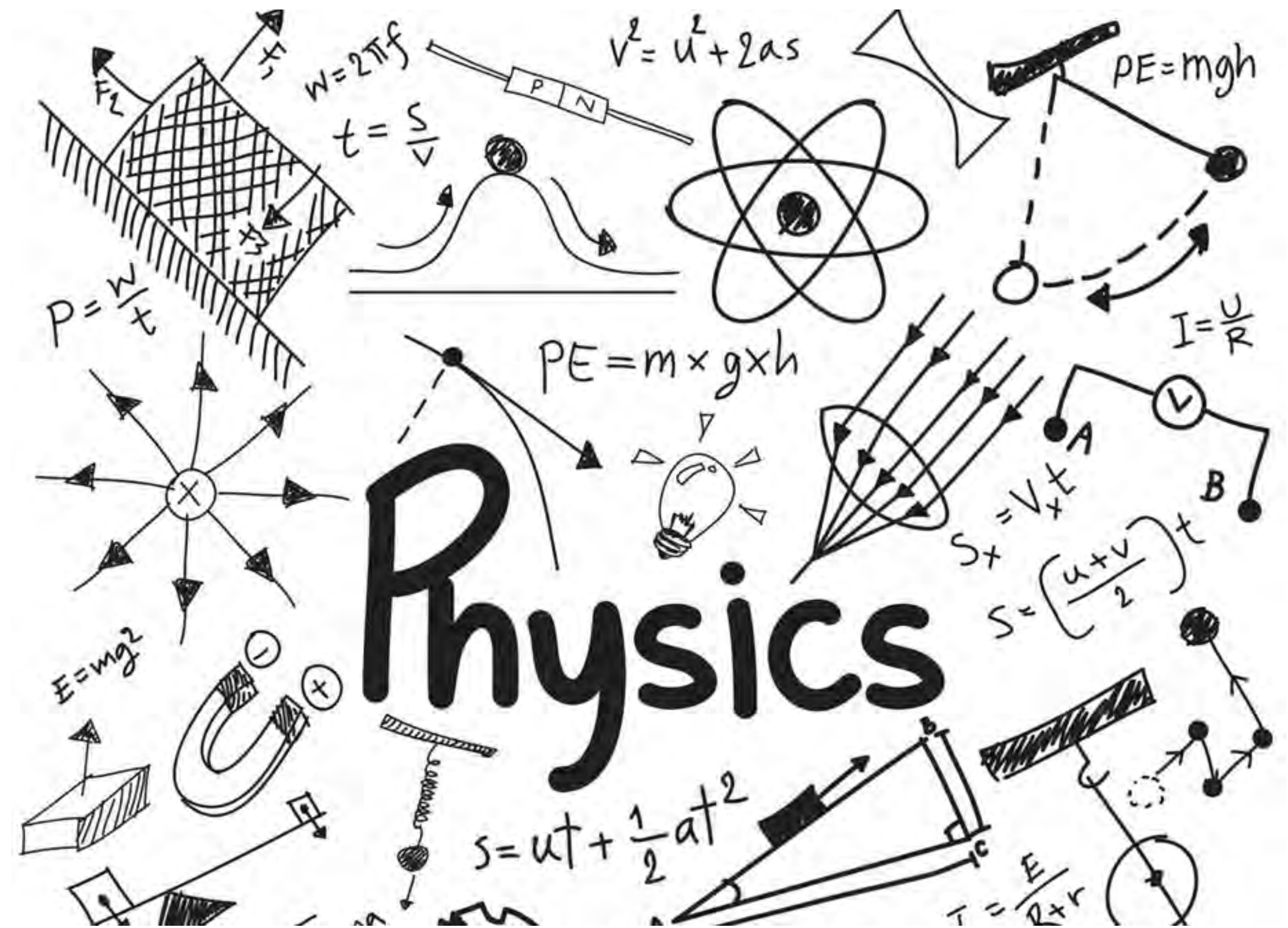
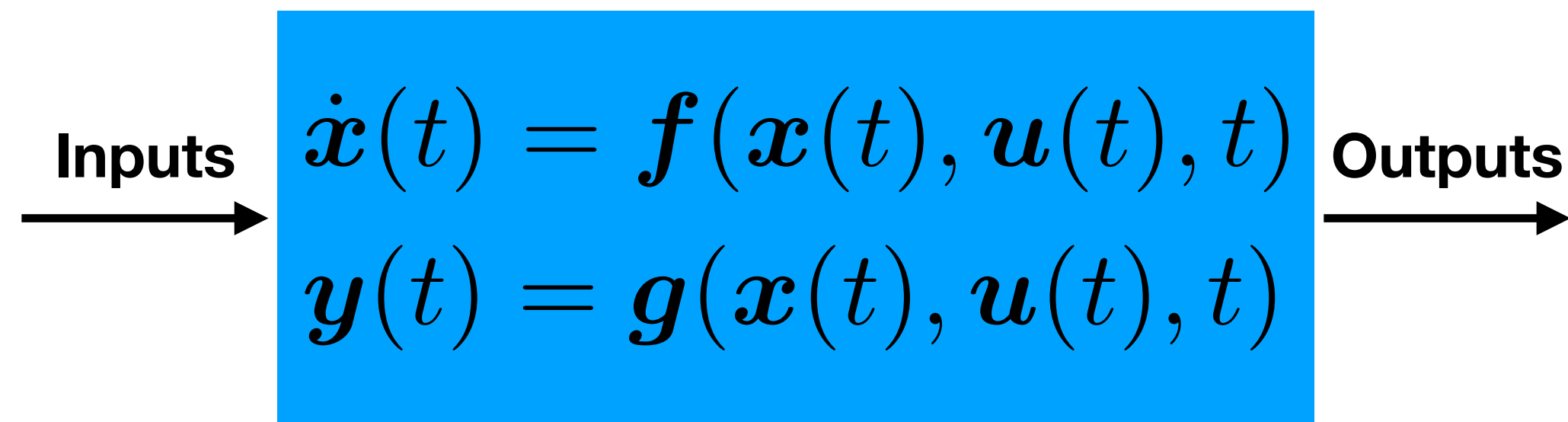
Water management



Medical and Biomedical

What is the common ground of these applications?

- Physics provides **mathematical models** for describing the behaviour of physical systems



What Is the **PHYSICS** of **COMPUTING SYSTEMS?**



Research Context

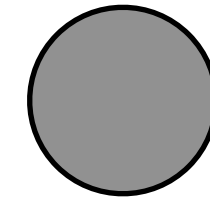
Pros

- Control-based approaches are very powerful
 - ▶ Autonomous-by-design
 - ▶ Easy to implement
 - Lightweight
 - Energy-efficient
 - ▶ Mathematically grounded-approaches
 - ▶ Guarantees

Cons

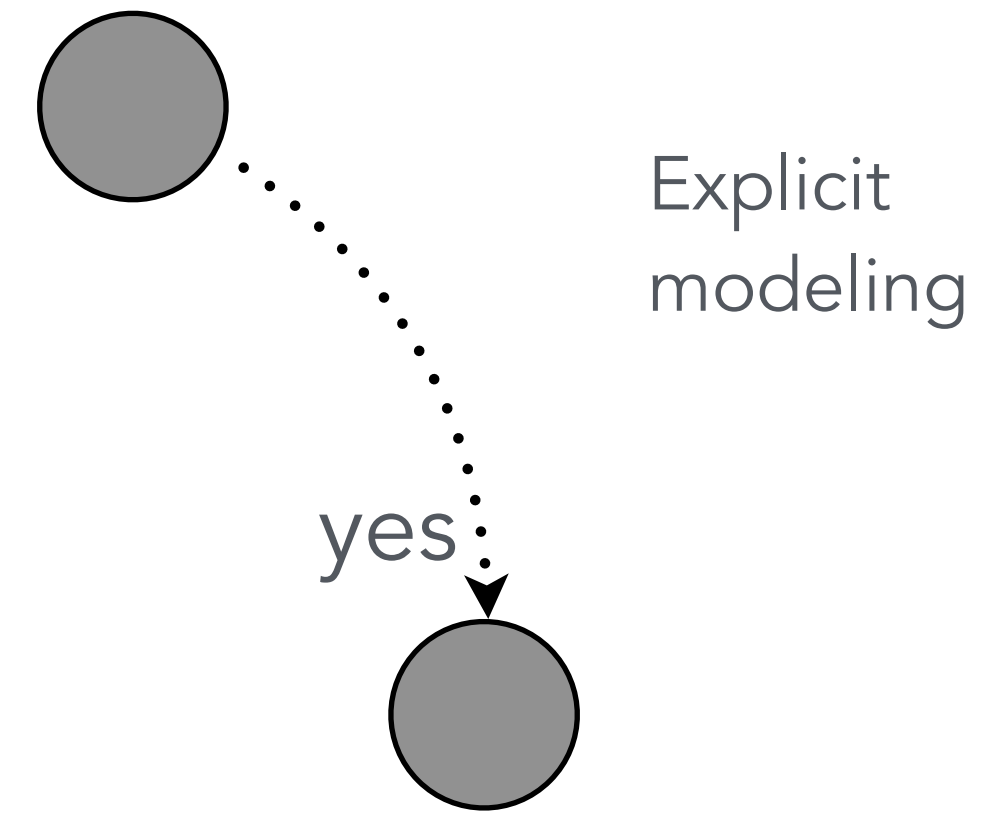
- They require **control experts** to design
 - ▶ Can we automate this?
- They often **require a model**

Control Theory Can Be Employed in Many Different Ways

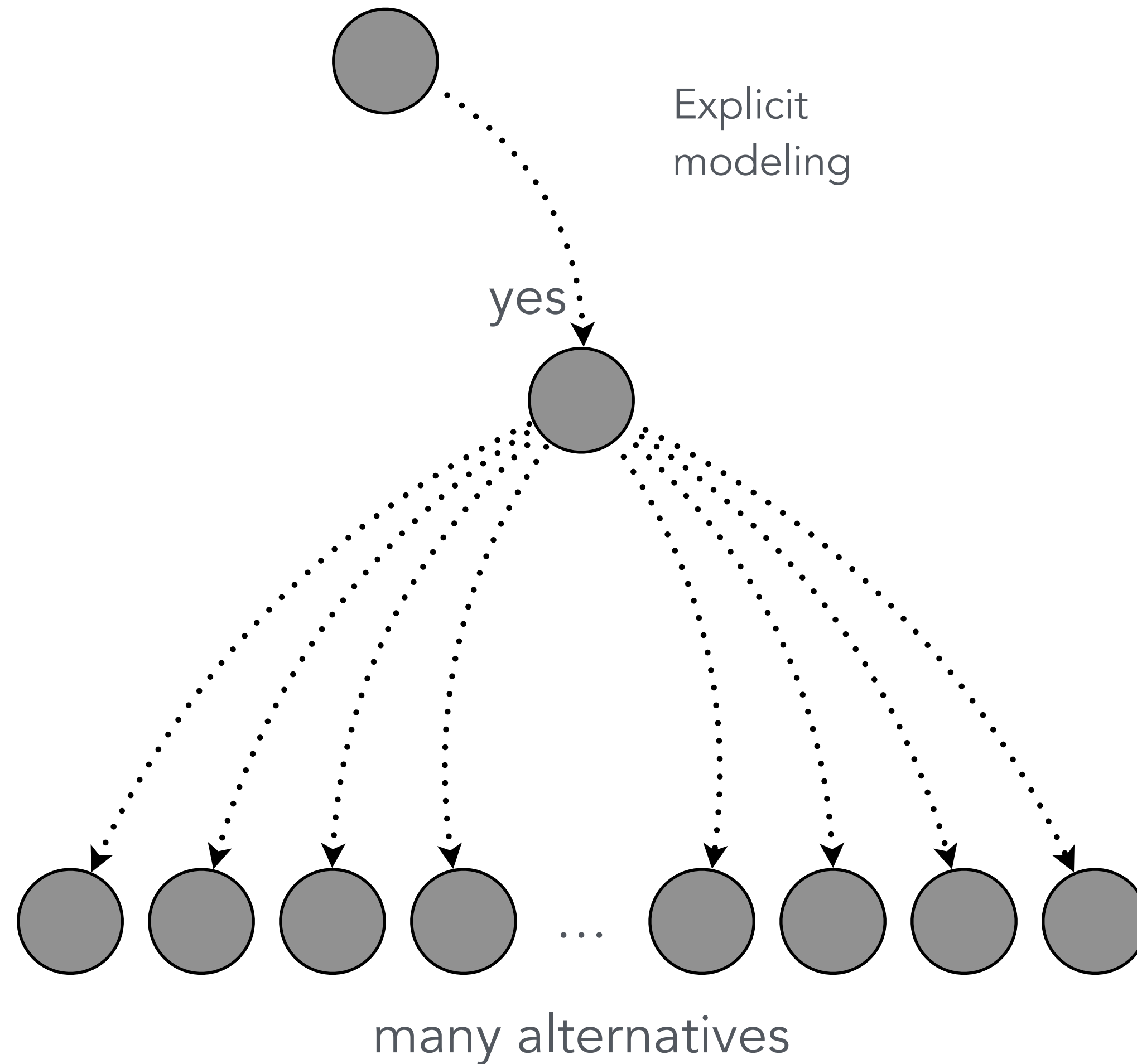


Explicit
modeling

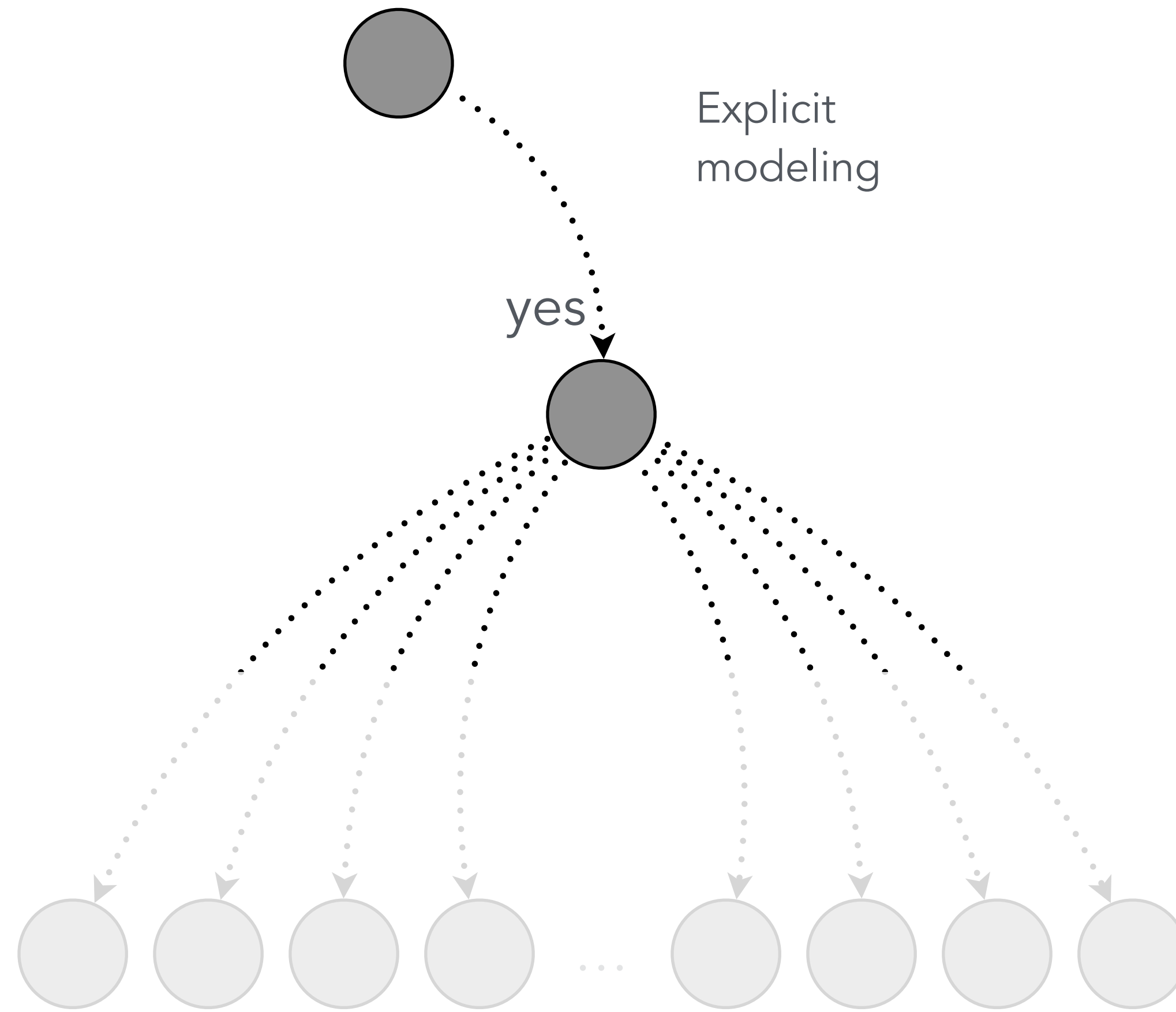
Control Theory Can Be Employed in Many Different Ways



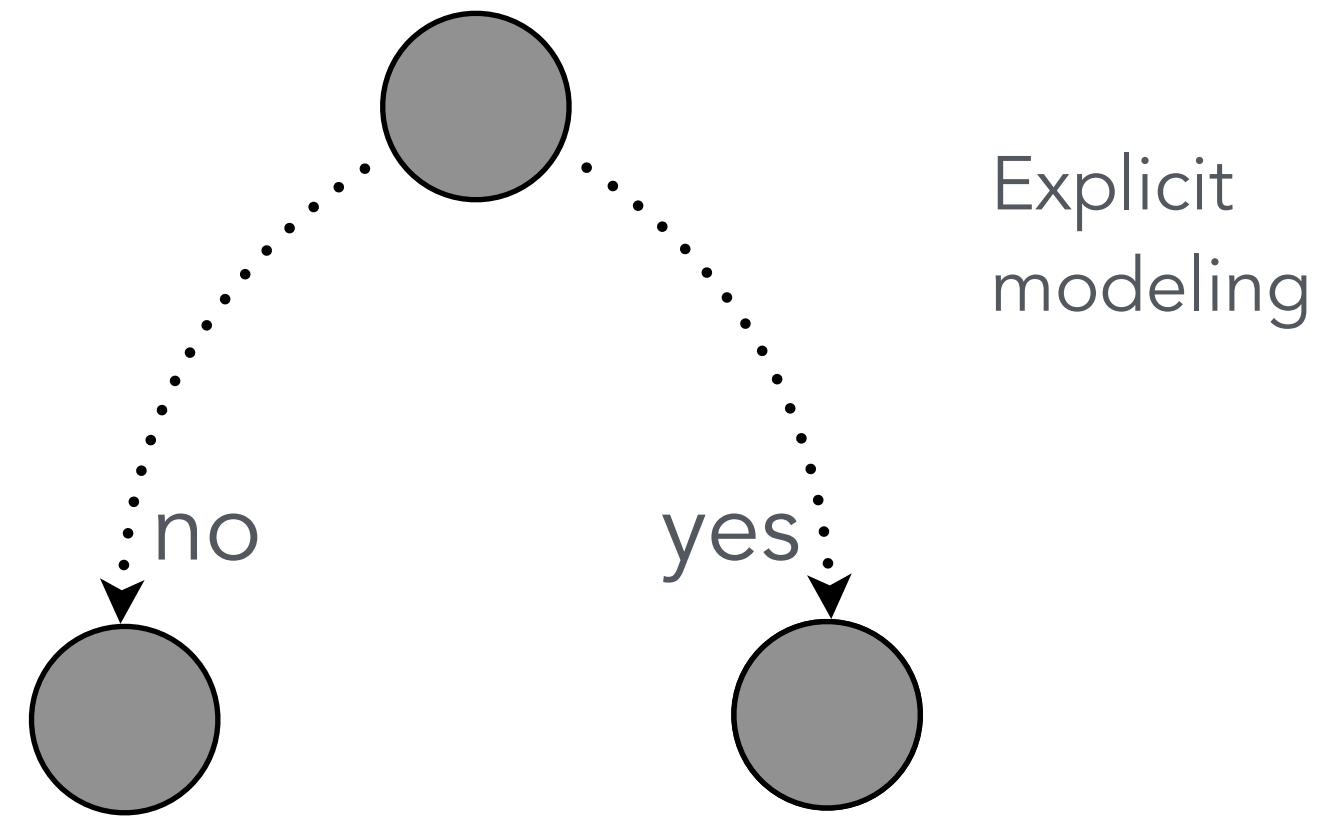
Control Theory Can Be Employed in Many Different Ways



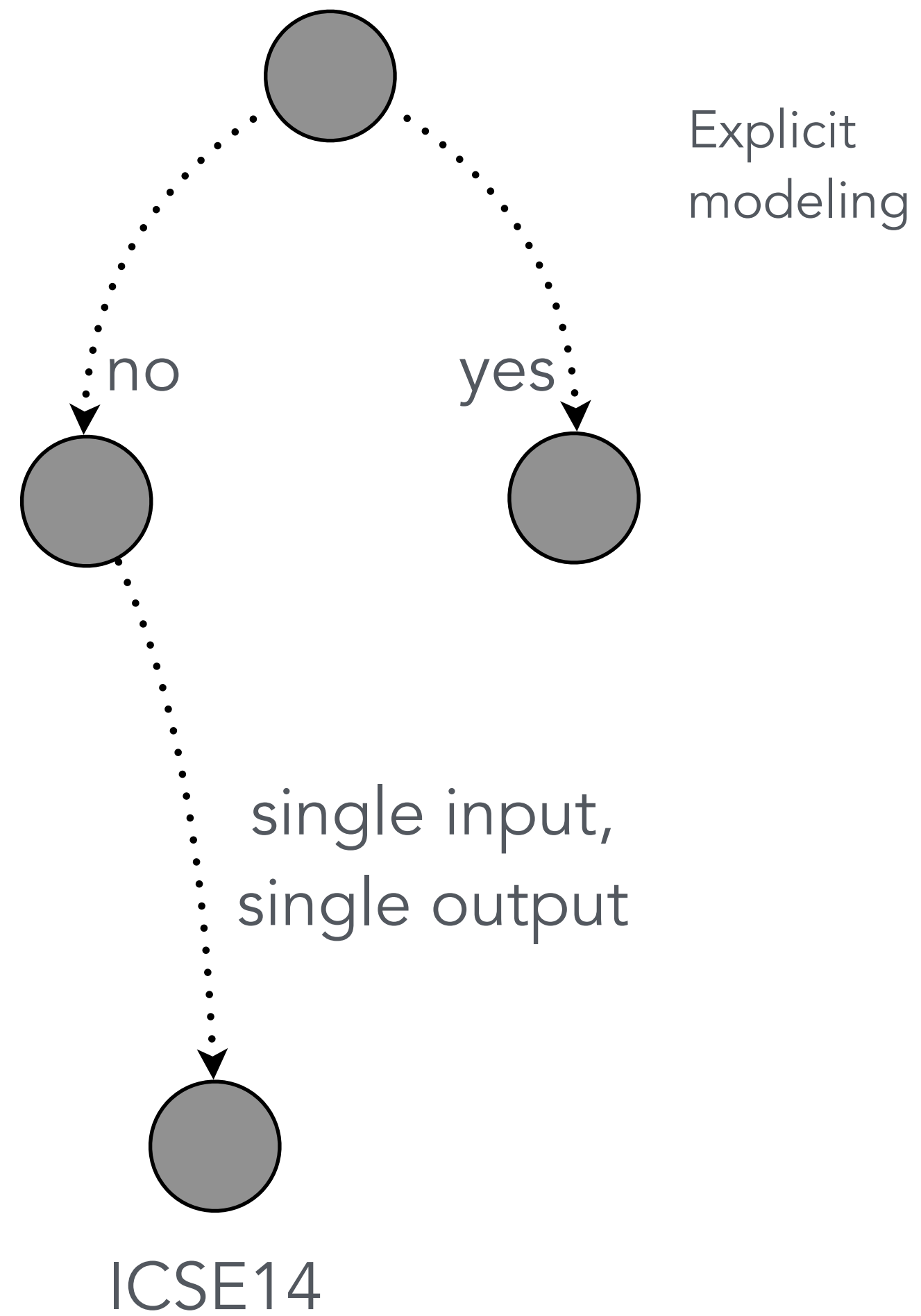
Control Theory Can Be Employed in Many Different Ways



Control Theory Can Be Employed in Many Different Ways



Control Theory Can Be Employed in Many Different Ways



Control Theory Can Be Employed in Many Different Ways

FSE15

Filieri, Hoffmann, Maggio

Automated Multi-Objective Control for
Self-Adaptive Software Design

FSE16

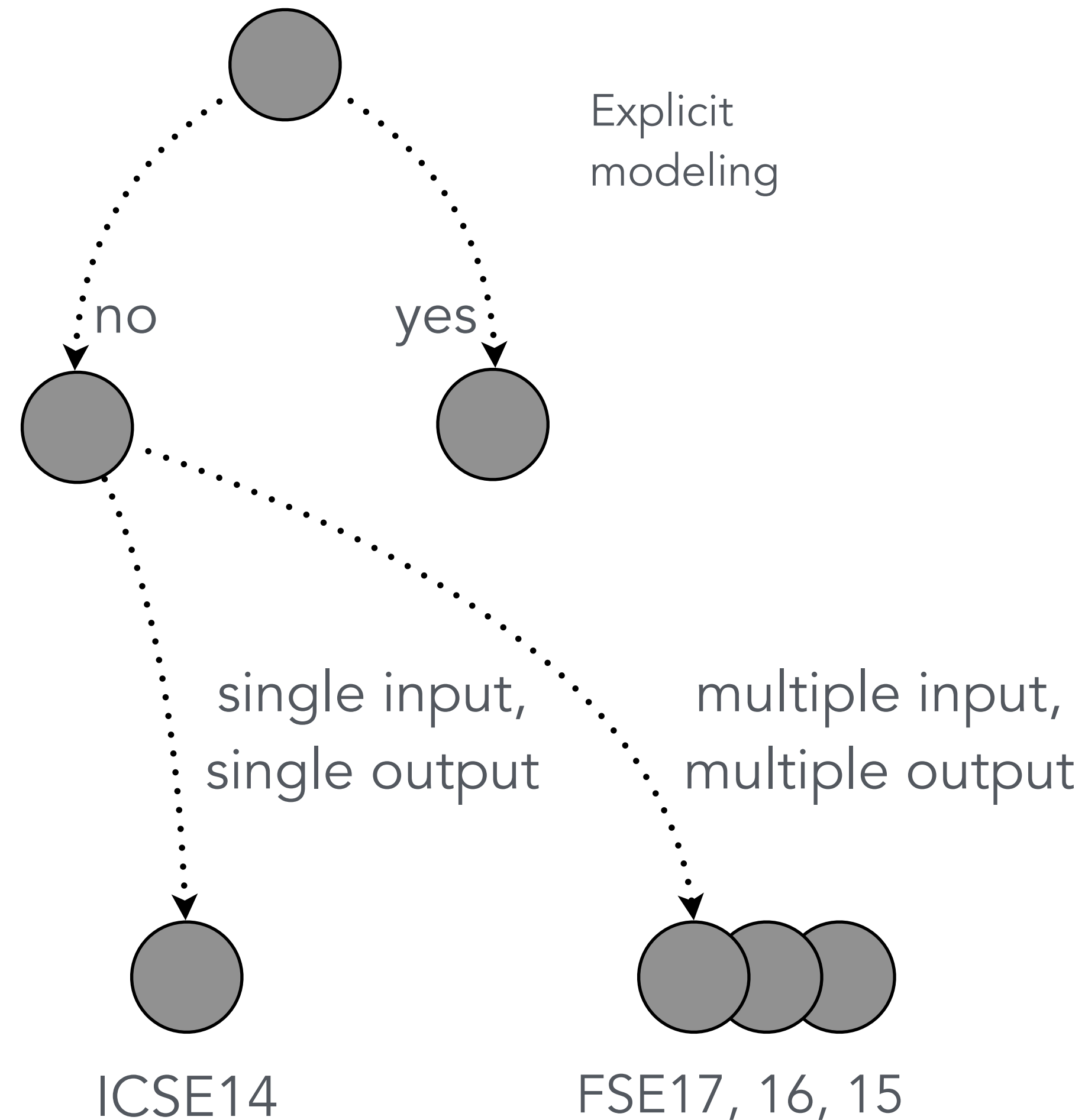
Shevtsov, Weyns

Keep It SIMPLEX: satisfying multiple
goals with guarantees in control-based
self-adaptive systems

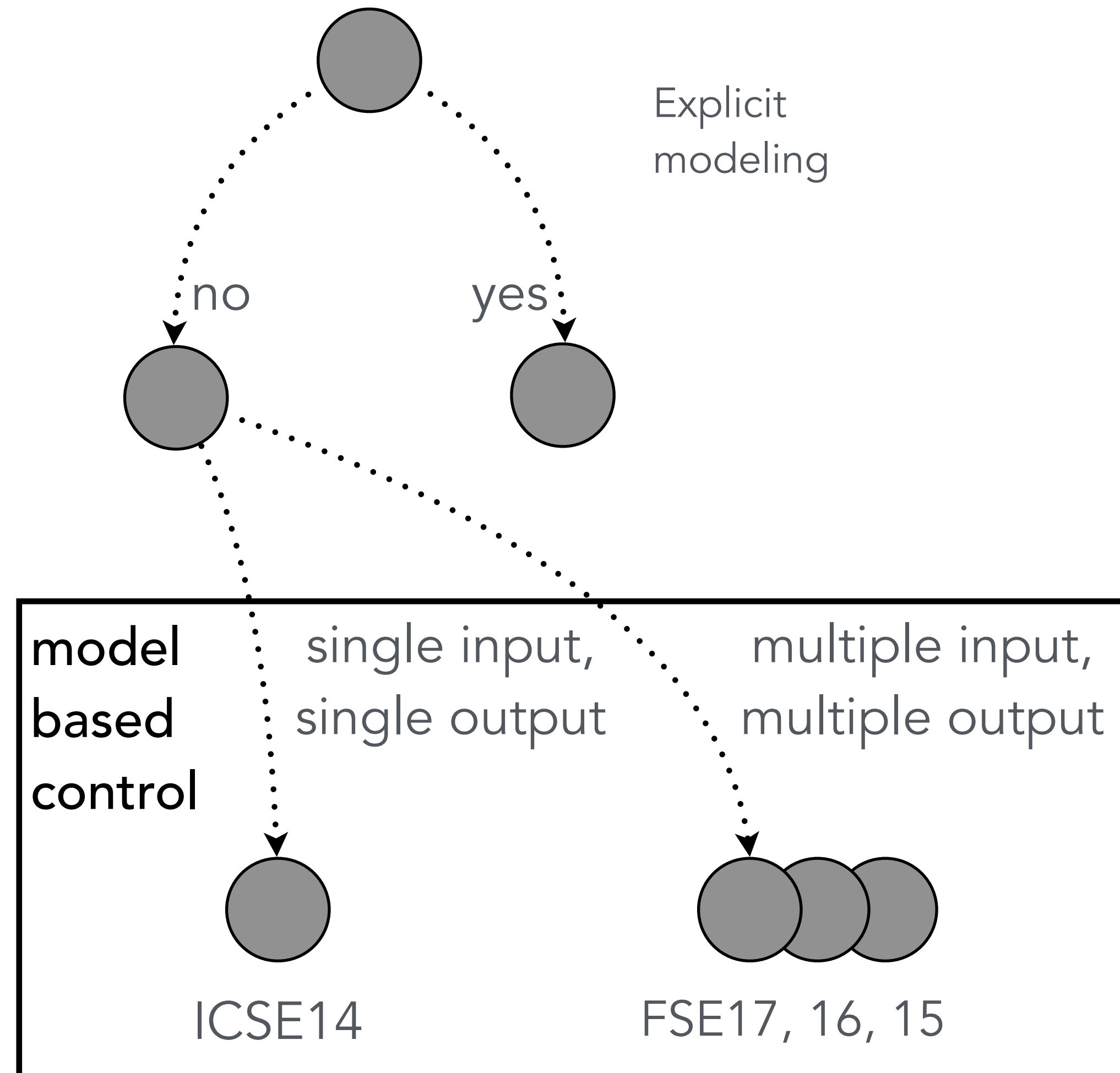
FSE17

*Maggio, Papadopoulos, Filieri,
Hoffmann*

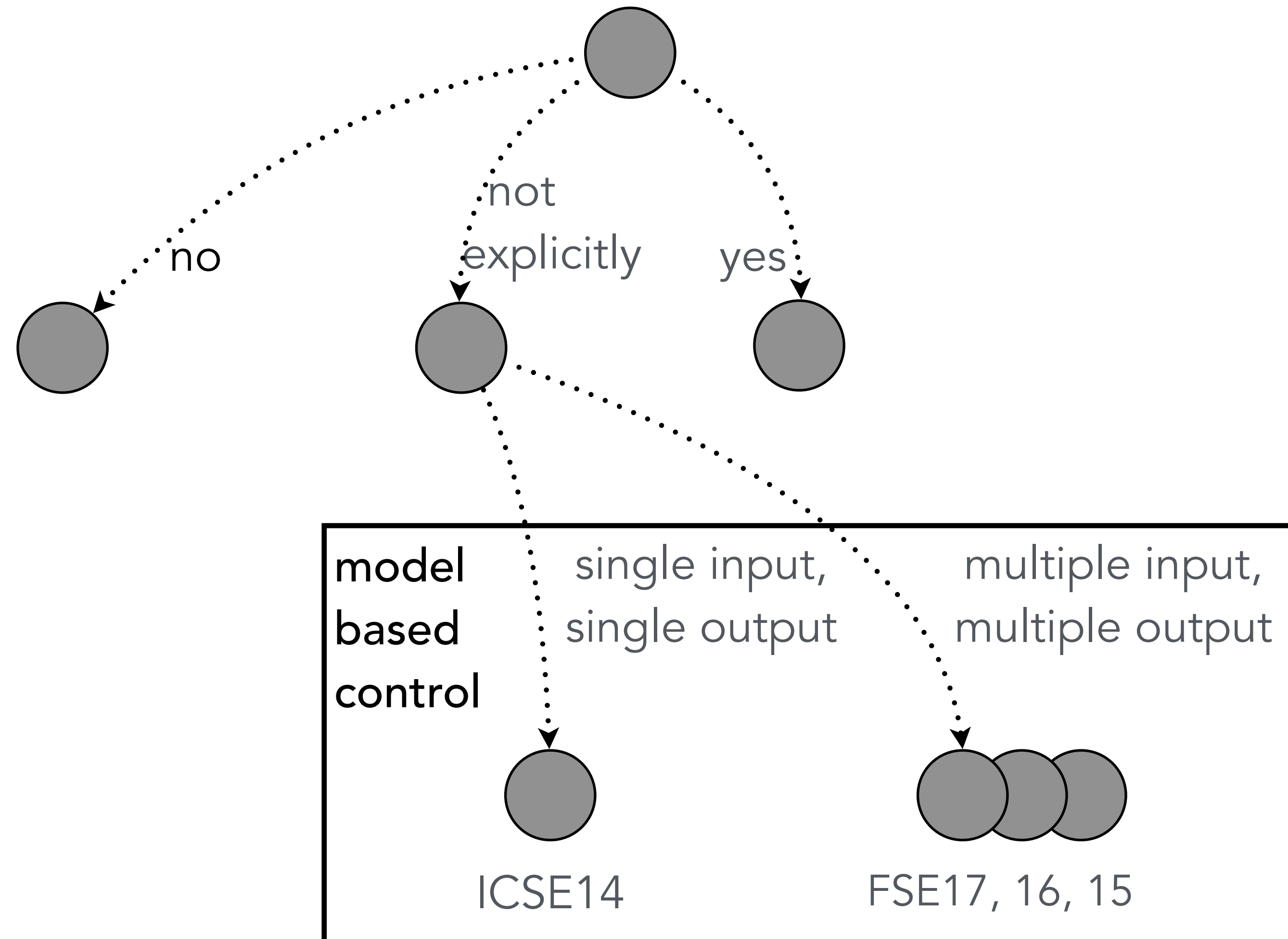
Automated Control of Multiple Software
Goals using Multiple Actuators



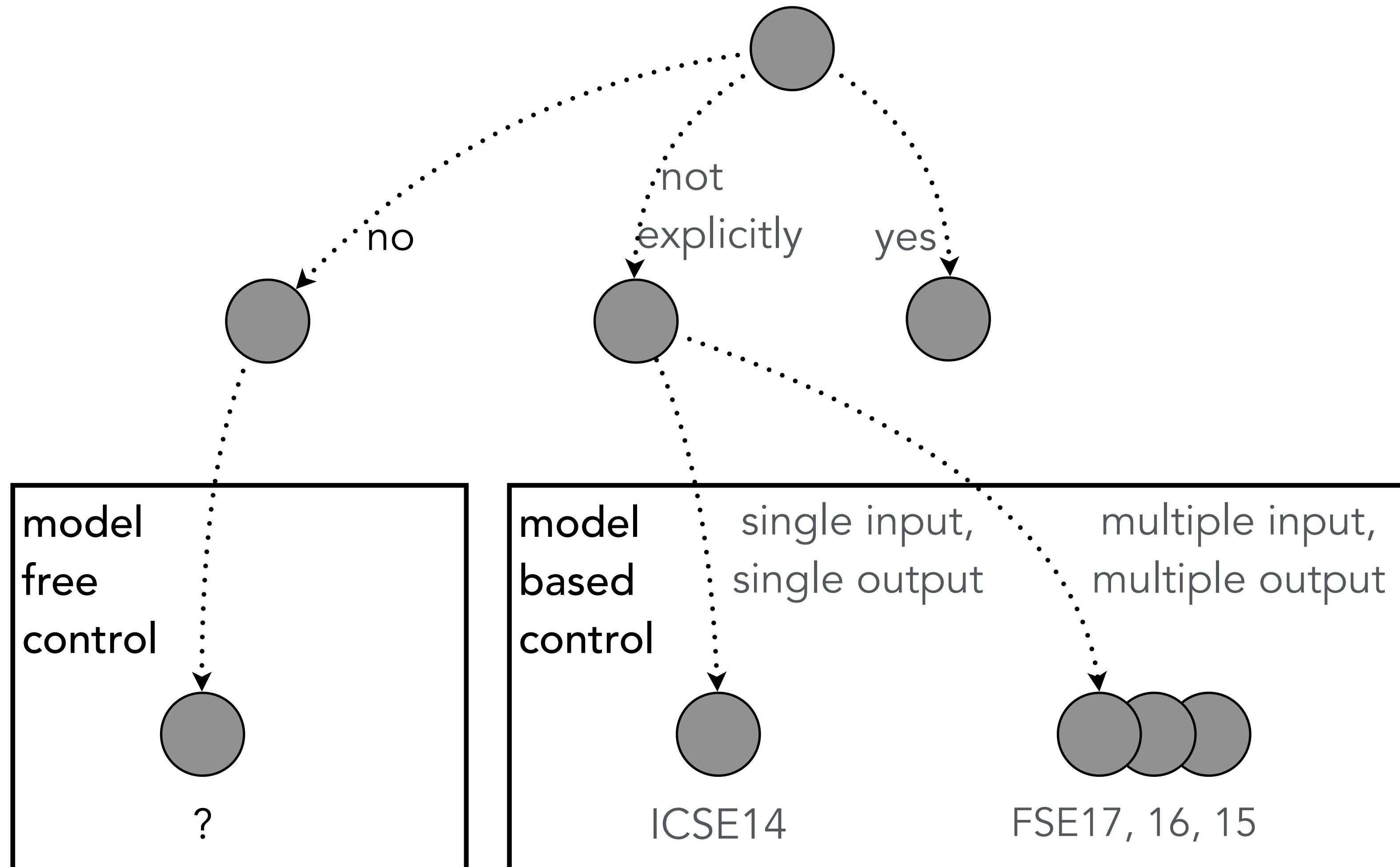
Control Theory Can Be Employed in Many Different Ways



Control Theory Can Be Employed in Many Different Ways



Control Theory Can Be Employed in Many Different Ways



Task Scheduling

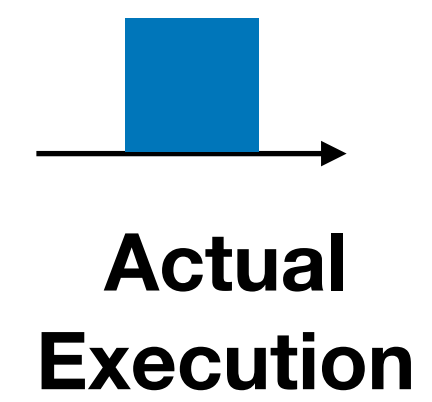
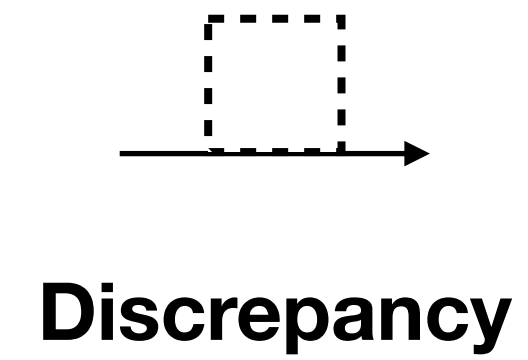
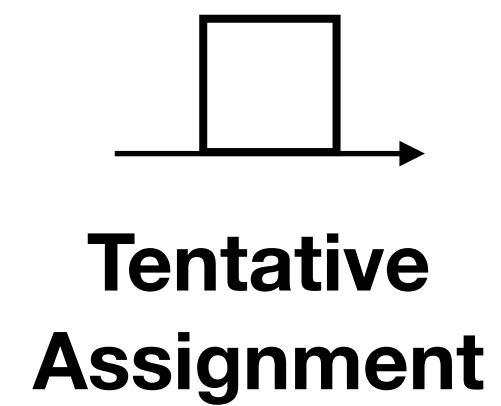
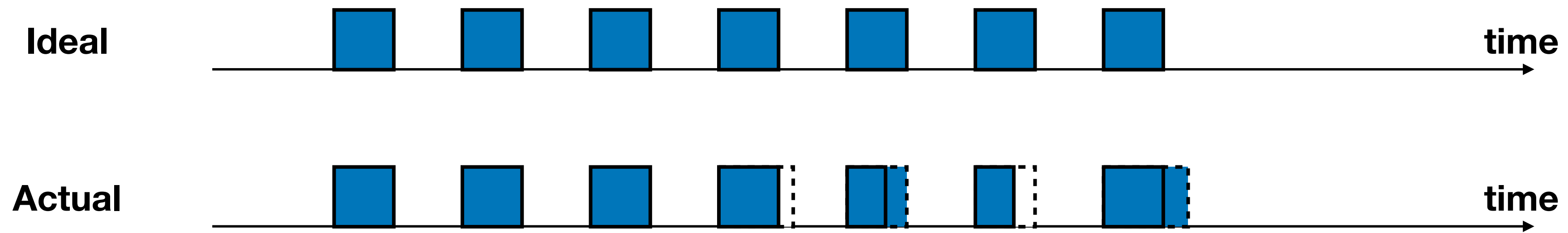
When a Model Does Exist

Papadopoulos et al., “Hard real-time guarantees in feedback-based resource reservations”, *Real-Time Systems*

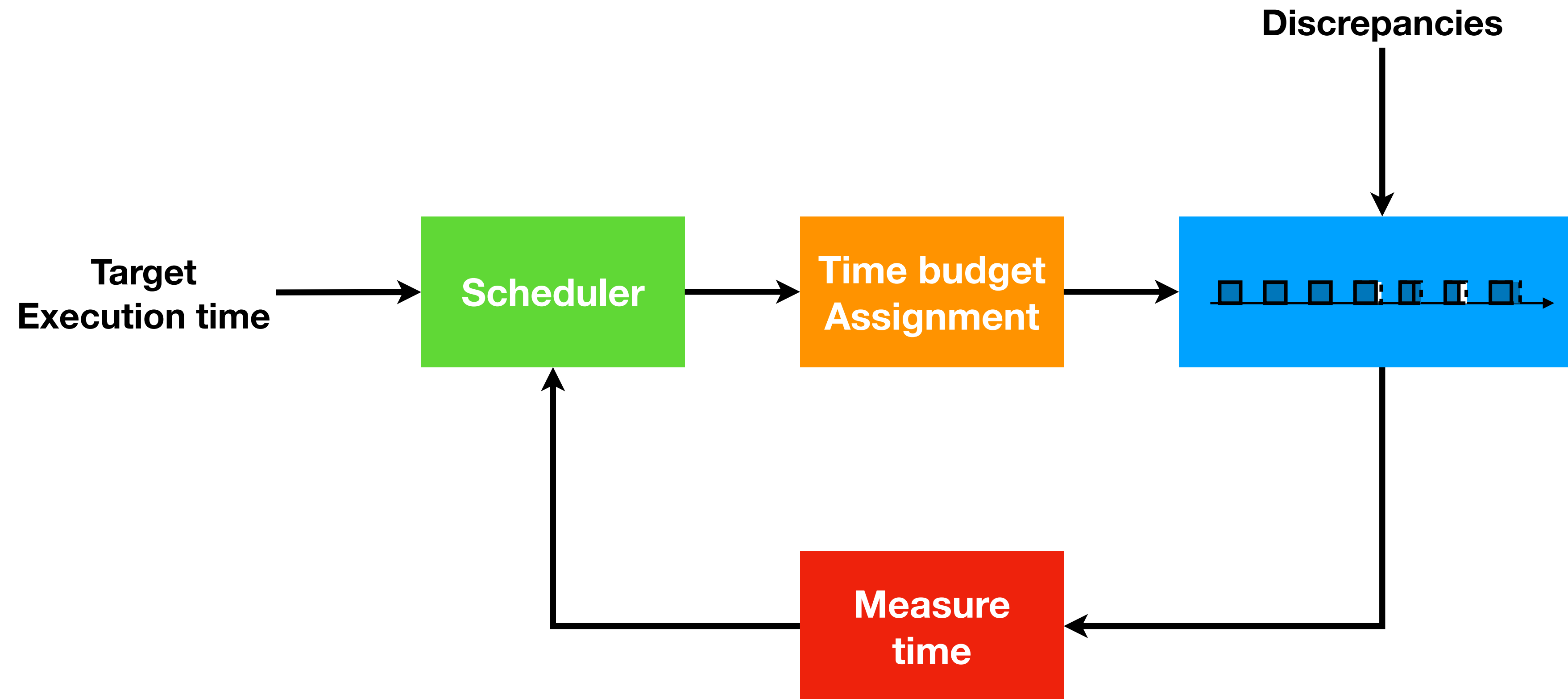
Papadopoulos et al., “AdaptMC: A Control-Theoretic Approach for Achieving Resilience in Mixed-Criticality Systems”, *ECRTS 2018*

Papadopoulos et al., “Feedback-Based Resource Management for Multi-Threaded Applications”, *Real-Time Systems*

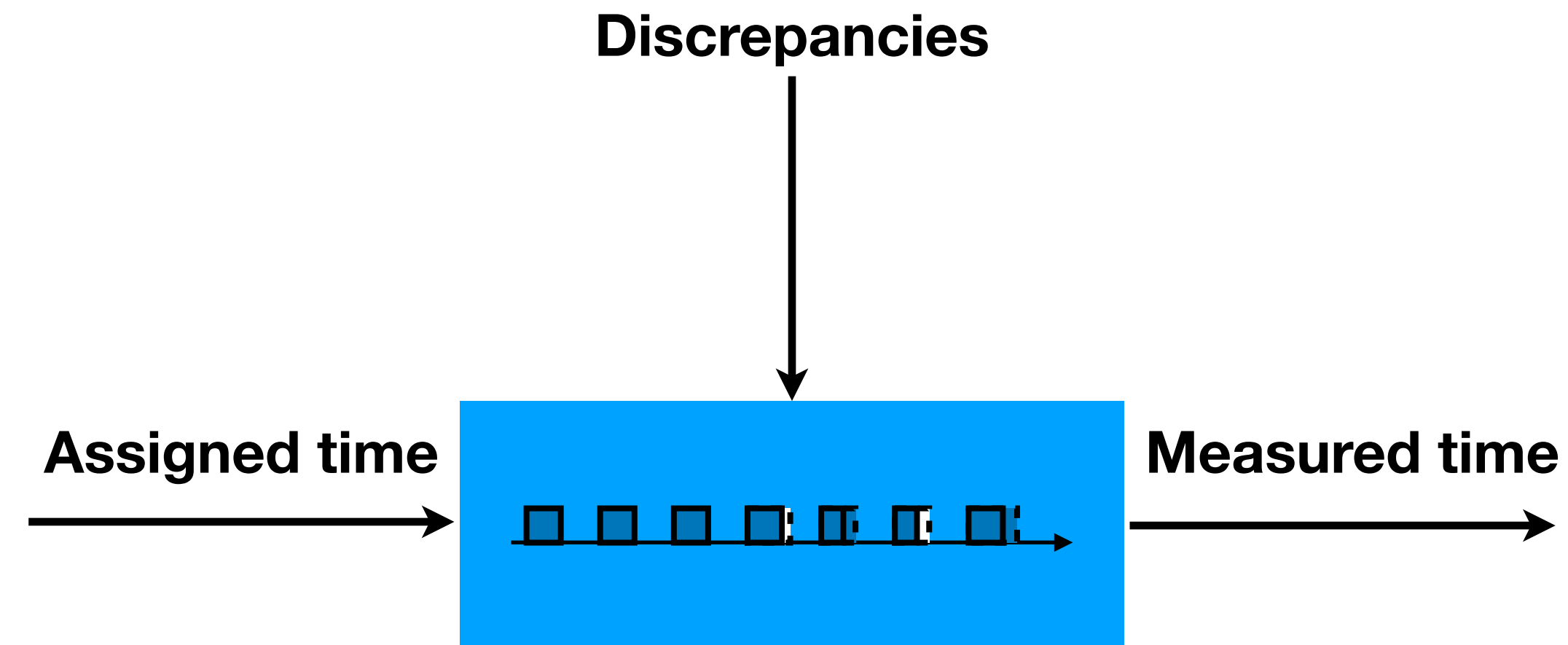
Scheduling Problem



Control-Based Scheduling



Model of the Task



Measured time = Assigned time + Discrepancy

$$x(k) = u(k - 1) + d(k)$$

Controlling the Task Budget of Time

Extremely simple
model

- The allocated time budget of a task is controlled based on an “Integral controller”

$$u(k) = u(k - 1) + K(\text{measuredBudget}(k) - \text{measuredBudget}(k))$$

- K is the only parameter that needs to be tuned, and it can be chosen in the range $(0, 1]$ (stability reasons that we do not discuss)

Hard Real-Time
guarantees can be
provided

Easy to implement
the scheduling
strategy



CLOUD COMPUTING

Cloud Computing Applications

When the Model Is Hard To Find

Klein et al., “Improving Cloud Service Resilience using Brownout- Aware Load-Balancing”, SRDS 2014

Papadopoulos et al., “PEAS:A Performance Evaluation Framework for Auto-Scaling Strategies in Cloud Applications”, TOMPECS 2016

Lakew et al., “KPI-agnostic Control for Fine-Grained Vertical Elasticity”, CCGrid 2017



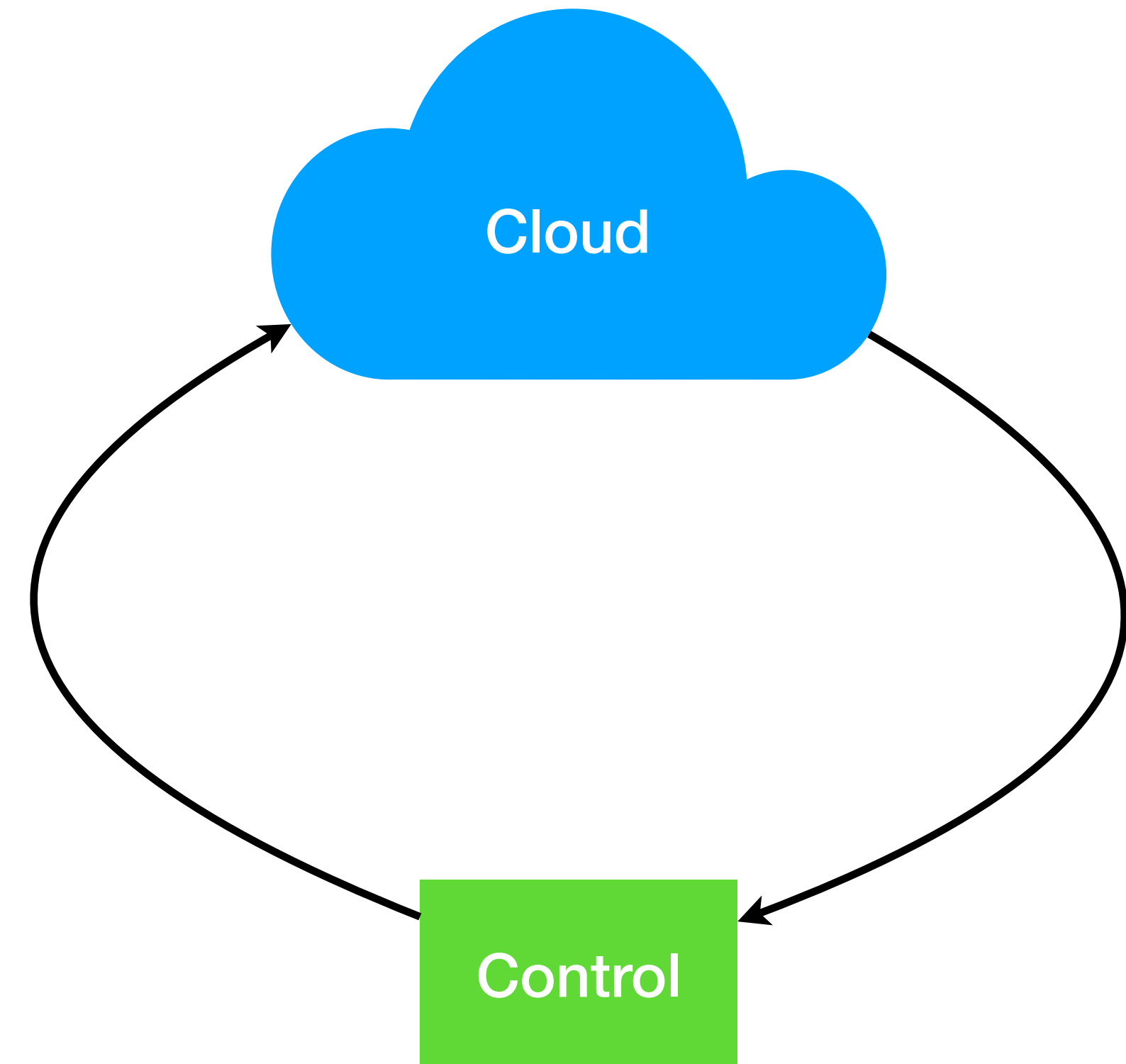
Cloud computing promises an infinite capacity but...



**There is no cloud
it's just someone else's computer**

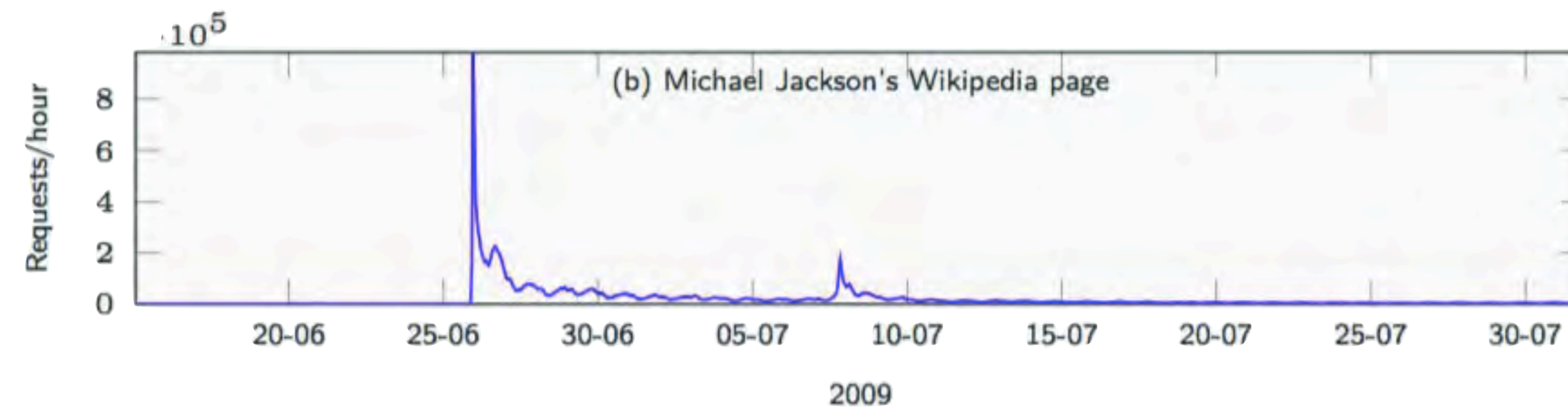
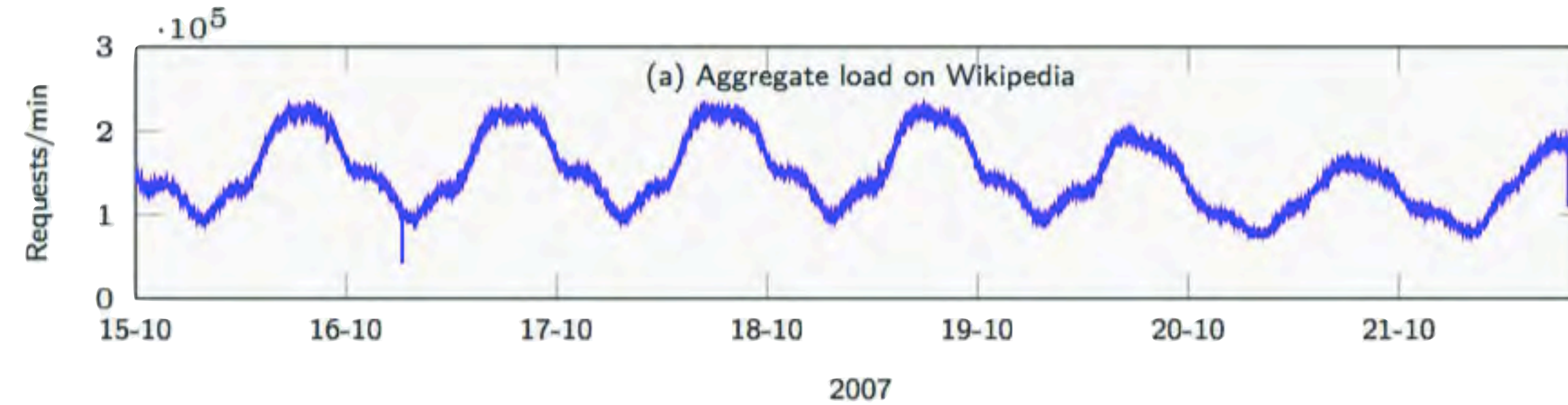
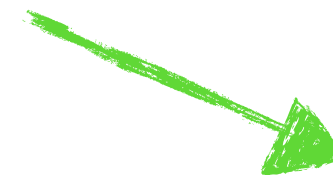
Cloud control

- Several different problems
 - ▶ Load balancing
 - ▶ Autoscaling
 - ▶ Fault tolerance
 - ▶ Performance
 - ▶ Real-time guarantees
 - ▶ Resiliency



Workload Characterisation

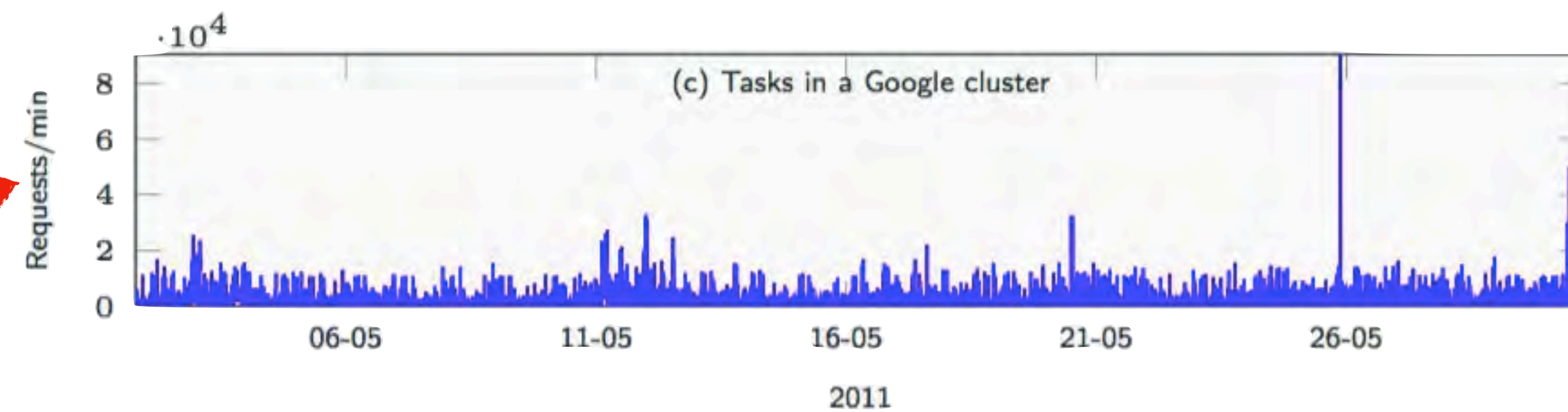
Easy and predictable



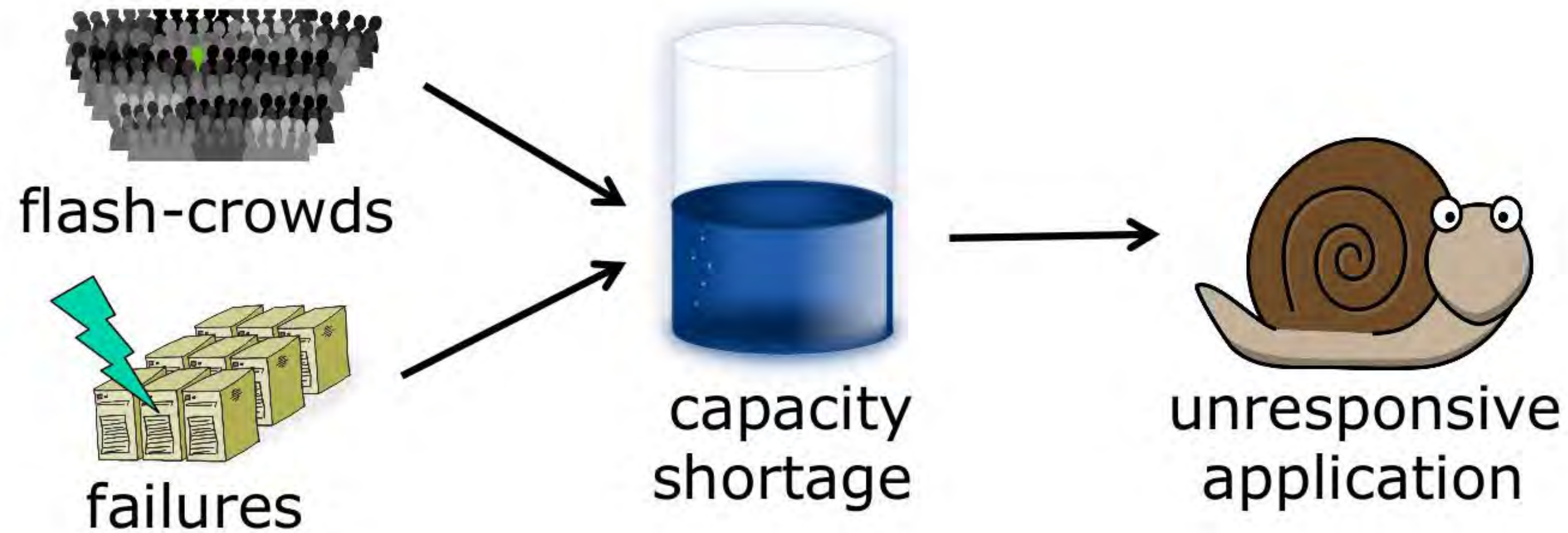
Flash crowd



Completely unpredictable



Problem



- 82% of end-users give up on a lost payment transaction
- 25% of end-users leave if load time > 4s
- 1% reduced sale per 100ms load time
- 20% reduced income if 0.5s longer load time

Regular
operation



Regular
operation



Brownout



Brownout in Cloud Systems

The screenshot shows the Amazon.co.uk product page for the Kindle Wireless Reading Device. The page is divided into several sections: a main product image with a video player, a detailed description, pricing, and availability information. A yellow box highlights the main product image and video player, while a green box highlights the 'Live Outside the UK?' section.

amazon.co.uk Hello. Sign in to get personalised recommendations. New Customer? Start here.
Your Amazon.co.uk Today's Deals Gift Cards Gifts & Wish Lists

Shop All Departments Search Kindle Store

Kindle Store Buy A Kindle Kindle eBooks Newspapers Blogs Magazines Accessories Dis

Kindle Wireless Reading Device, Wi-Fi, Graphite, 6" Display with Pearl Technology
by Amazon
★★★★★ (4,472 customer reviews)
Kindle is our #1 bestseller and has the most 5-star reviews of any product in its category.

Price: **£111.00** & this item **Delivered FREE in the UK** with Super Saver conditions

In stock.
Dispatched from and sold by Amazon.co.uk. Gift-wrap available.

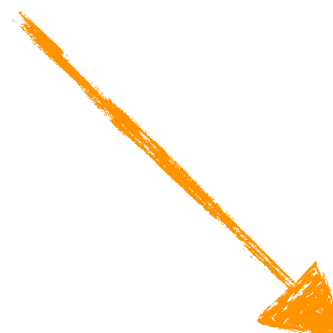
Want guaranteed delivery by Thursday, February 17? Order it in the next 6 hours. Express delivery at checkout. See Details

Live Outside the UK?
Kindle is available on Amazon.com for shipment outside the UK
> Visit the Kindle international page on Amazon.com

Also Available
> Kindle 3G (Free 3G + Wi-Fi, 6") is available for **£152**.

Need help choosing? Learn the difference between Wi-Fi and 3G

Optional Content



The screenshot shows the 'Buy This Product and Related Accessories' section of the Amazon.co.uk product page. It features a grid of product recommendations, including monitors, cables, and other accessories. A yellow box highlights the 'Product Ads from External Websites' section, which contains several product listings with prices and seller information. A green arrow points from the 'Mandatory Content' box to this section.

Buy This Product and Related Accessories

HP W2338H 23-Inch Widescreen Monitor
£113.00 ~~£133.56~~

Most Popular
Service Plans
Surge Protectors
Screen Cleaners
Video Cables

3 Year TV, Monitor, Top Customer Support, 5 Year Service Guarantee...
£299.00

3 Year Service Plan for Desktop £299.00
£299.00

In Stock from 360 Customer Service Centres, etc...

Monitor, Digital News Center, HD P, 960 x 600 SuperPower and USB Sharing...
£128.00 ~~£44.95~~

Monitor Cable, HP AV100 Super-Proprietary...
£13.00 ~~£13.00~~

Page 1 of 4

Product Ads from External Websites (1/2/2/2/2)

HP W2338H 23-Inch Full HD Widescreen LCD Monitor ★★★★★ (22) £219.99 + Free Shipping Seller: 123	HP L2405w 24-Inch Widescreen LCD Monitor £299.00 + Free Shipping Seller: XYZ	Toshiba W2055 20" Wide LCD PC Monitor £249.00 No Shipping Fee Seller: ABC	HP 2605n 26-Inch Widescreen LCD Monitor ★★★★★ (23) £454.99 + Free Shipping Seller: 456	Green 28PMV 20" Pure View Monitor £175.00 No Shipping Fee Seller: DEF
--	---	--	---	--

See a problem with these advertisements? Let us know.

25 Inch Monitor Sale (7)
Buy new 25" (25") Monitors - Save up to 82% on 25 Inch Monitor bargains!

See a problem with these advertisements? Let us know.

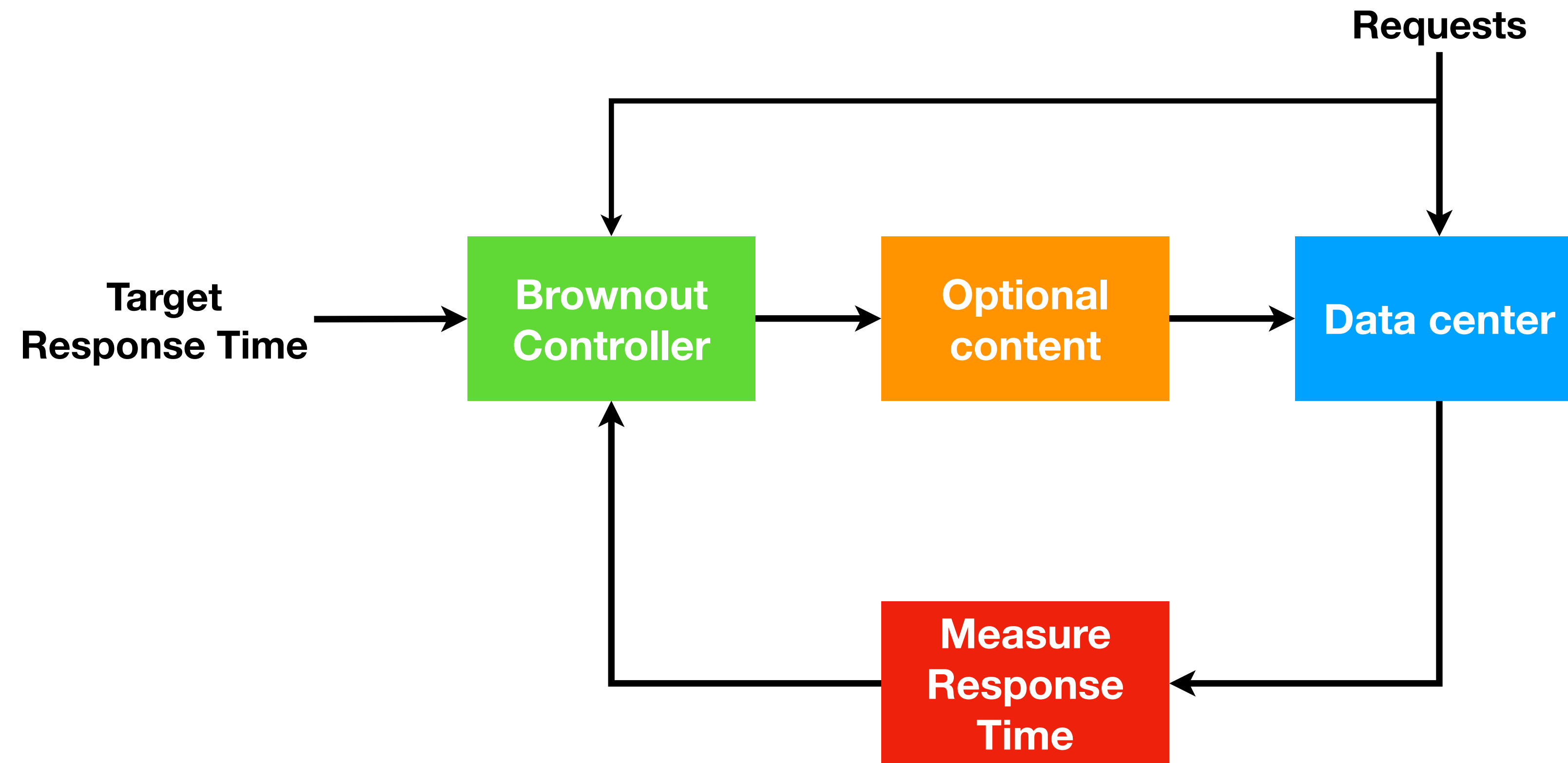
Product Ads from External Websites (1/2/2/2/2)

HP W2338H 23-Inch Full HD Widescreen LCD Monitor ★★★★★ (22) £219.99 + Free Shipping Seller: 123	HP L2405w 24-Inch Widescreen LCD Monitor £299.00 + Free Shipping Seller: XYZ	Toshiba W2055 20" Wide LCD PC Monitor £249.00 No Shipping Fee Seller: ABC	HP 2605n 26-Inch Widescreen LCD Monitor ★★★★★ (23) £454.99 + Free Shipping Seller: 456	Green 28PMV 20" Pure View Monitor £175.00 No Shipping Fee Seller: DEF
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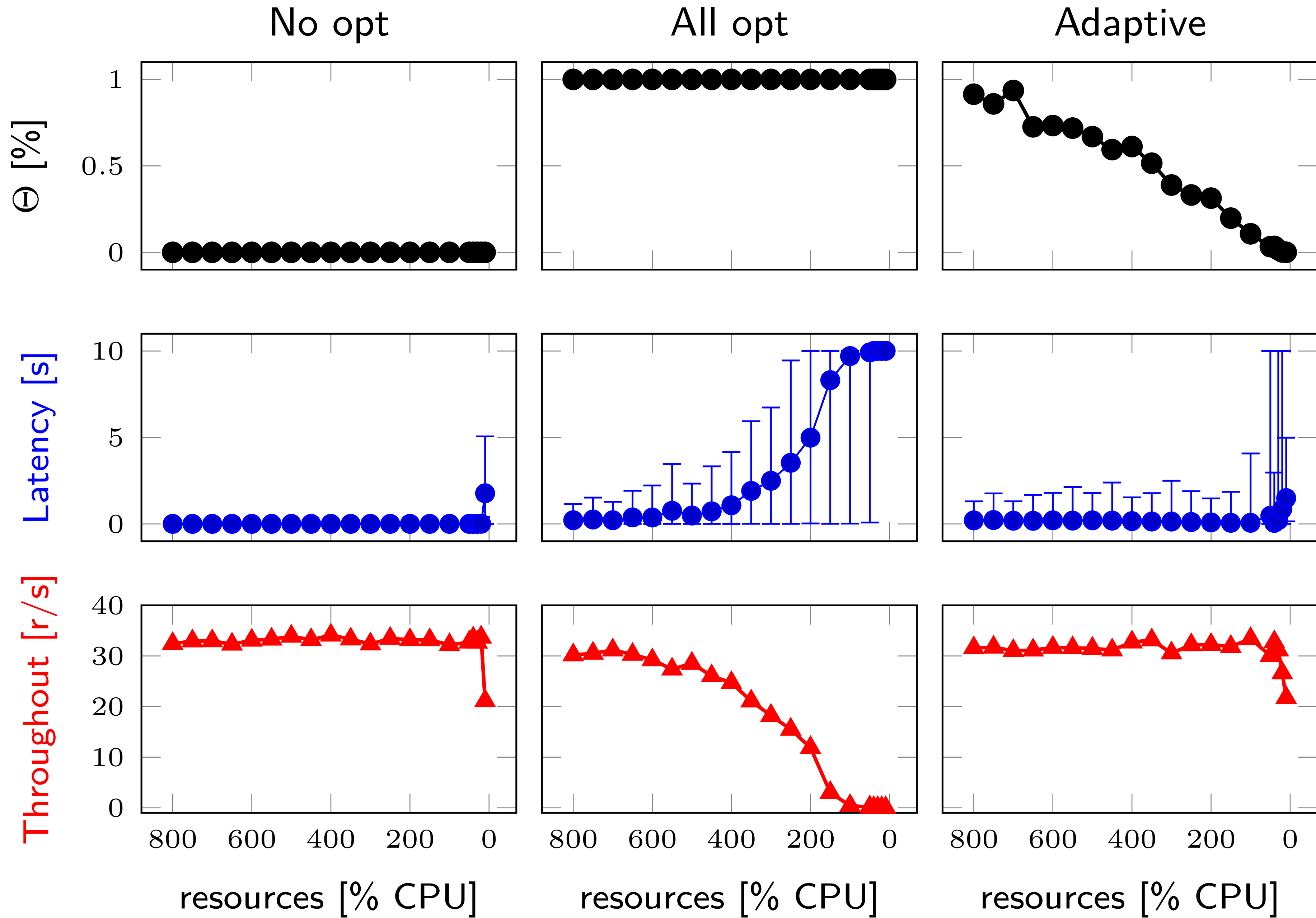
Mandatory Content



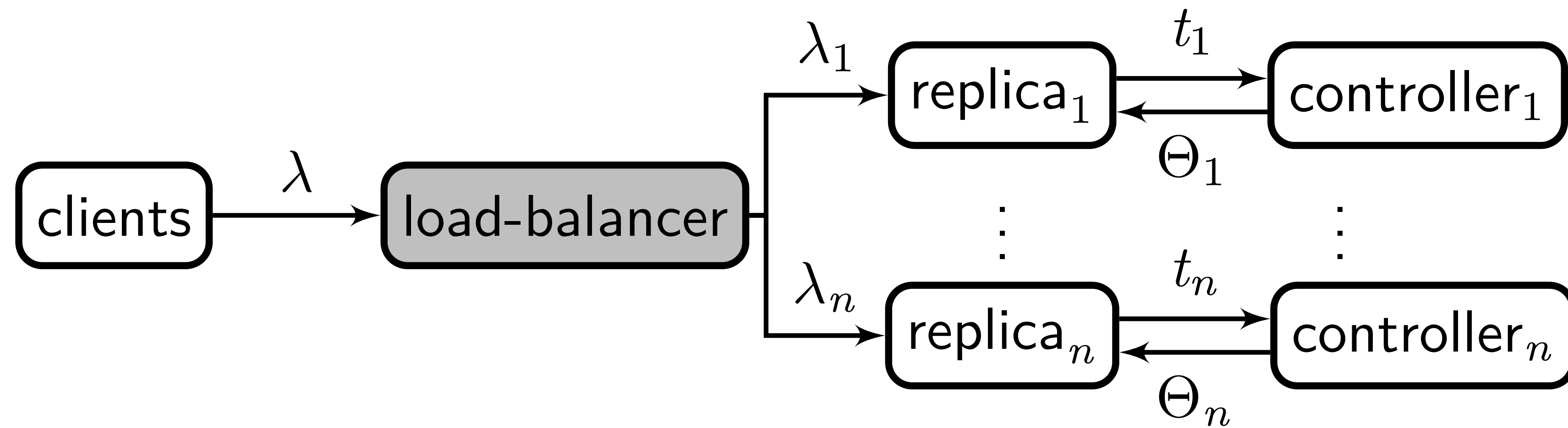
Brownout in Cloud Systems



- Higher Resiliency
- Better User Experience
- Increased Revenue



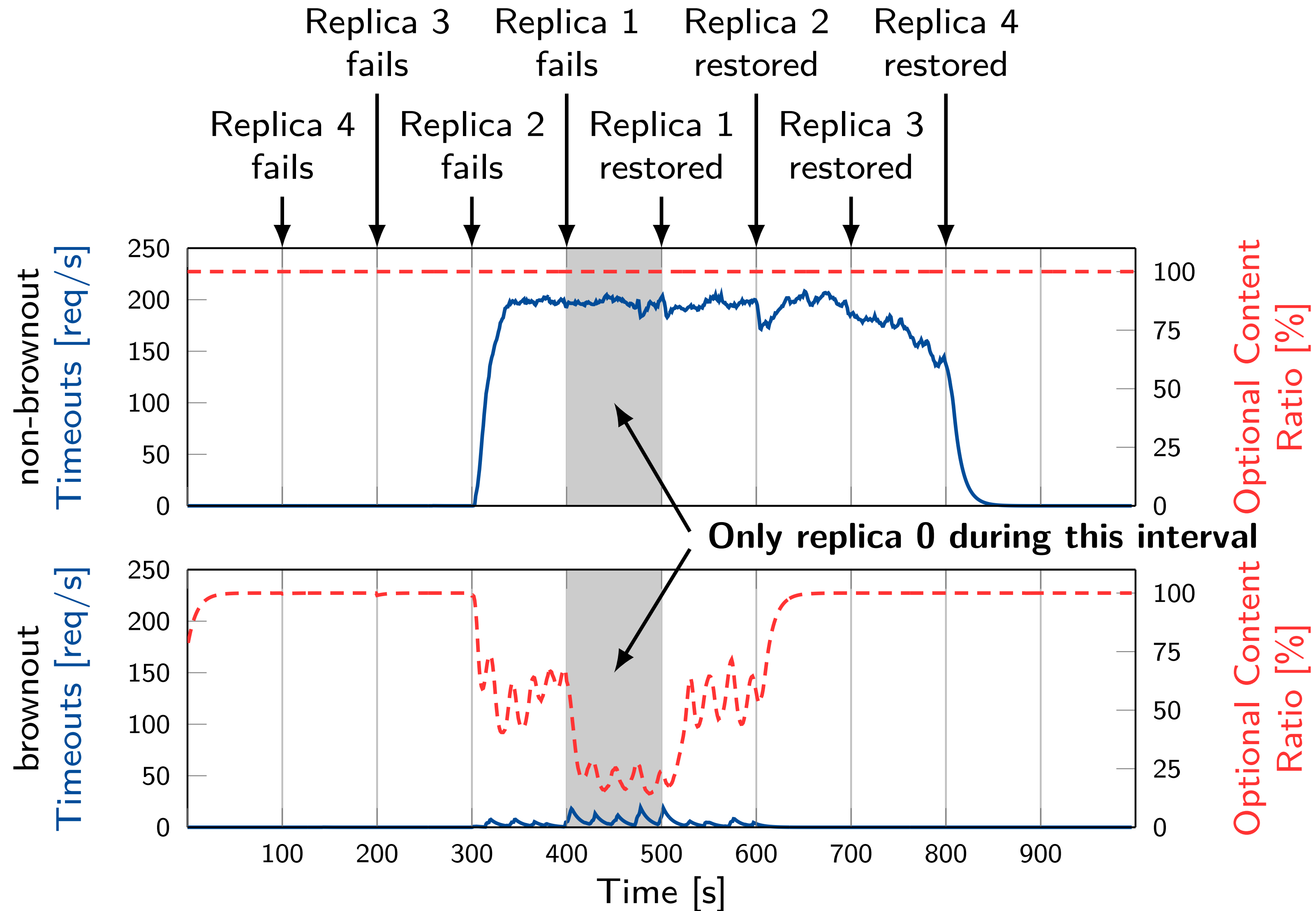
Multiple Replicas Load Balancing



- Useful for
 - ▶ Scale beyond a physical machine
 - ▶ Resilience
 - Hide auto-scaling mishaps
 - Hide infrastructure failures

GOAL: Maximize Optional Content

Multiple Failures Scenario with SQF



Can One Do Better?

Control-Based Approach

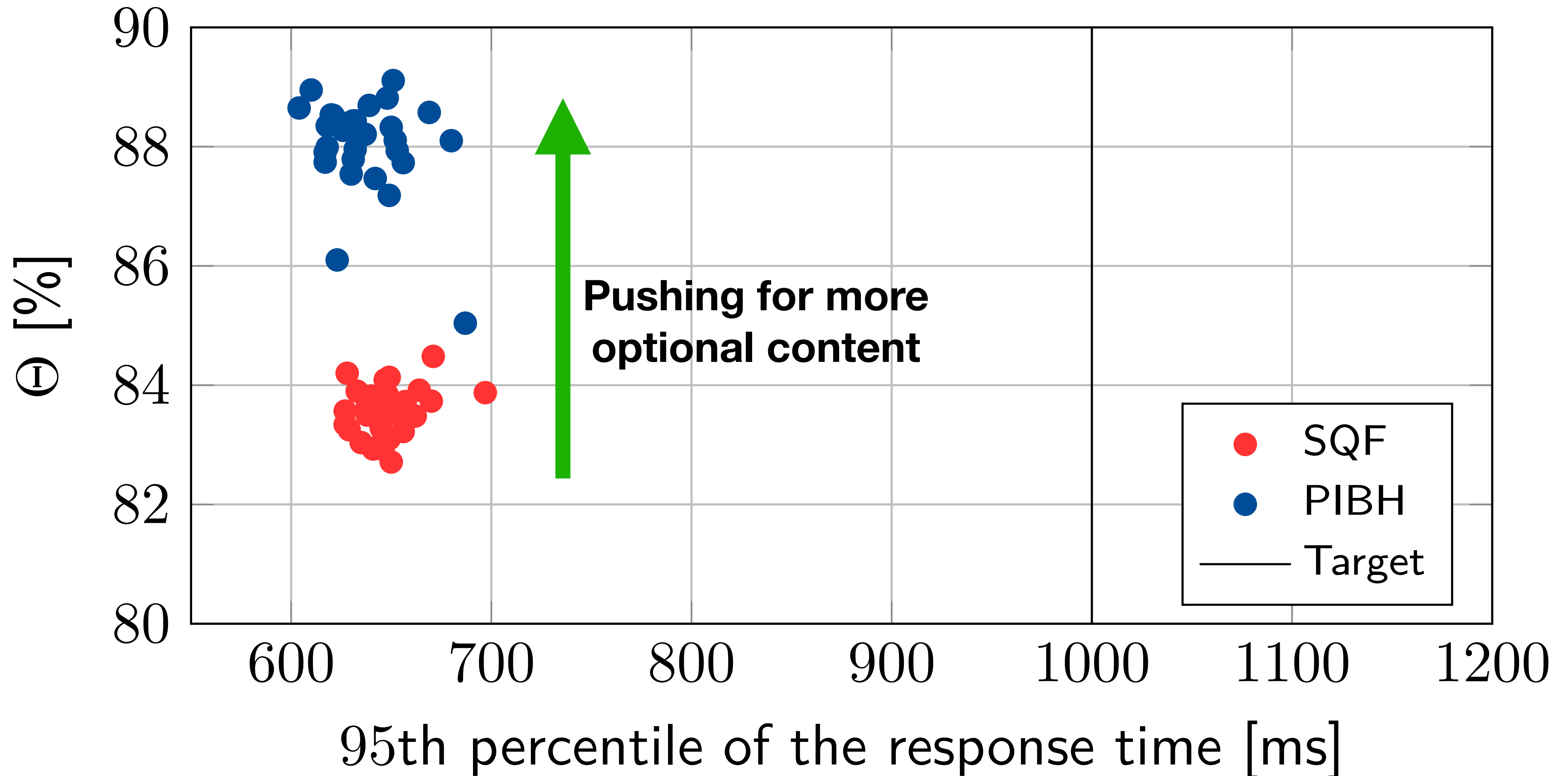
- **Idea:** Modify the SQF policy to maximize the optional content served Θ , and minimize the queue-length q
 - ▶ **We measure:** queue-lengths q_i , and dimmers Θ_i
 - ▶ **We control:** queue-offsets u_i
 - SQF picks the replica with smallest value of $q_i - u_i$
 - Queue-offsets computed with a “PI-Based Heuristic” (PIBH) policy:

$$u_i(k+1) = (1 - \gamma) \left[u_i(k) + \gamma_P \Delta \Theta_i(k) + \gamma_I \Theta_i(k) \right] + \gamma q_i(k)$$

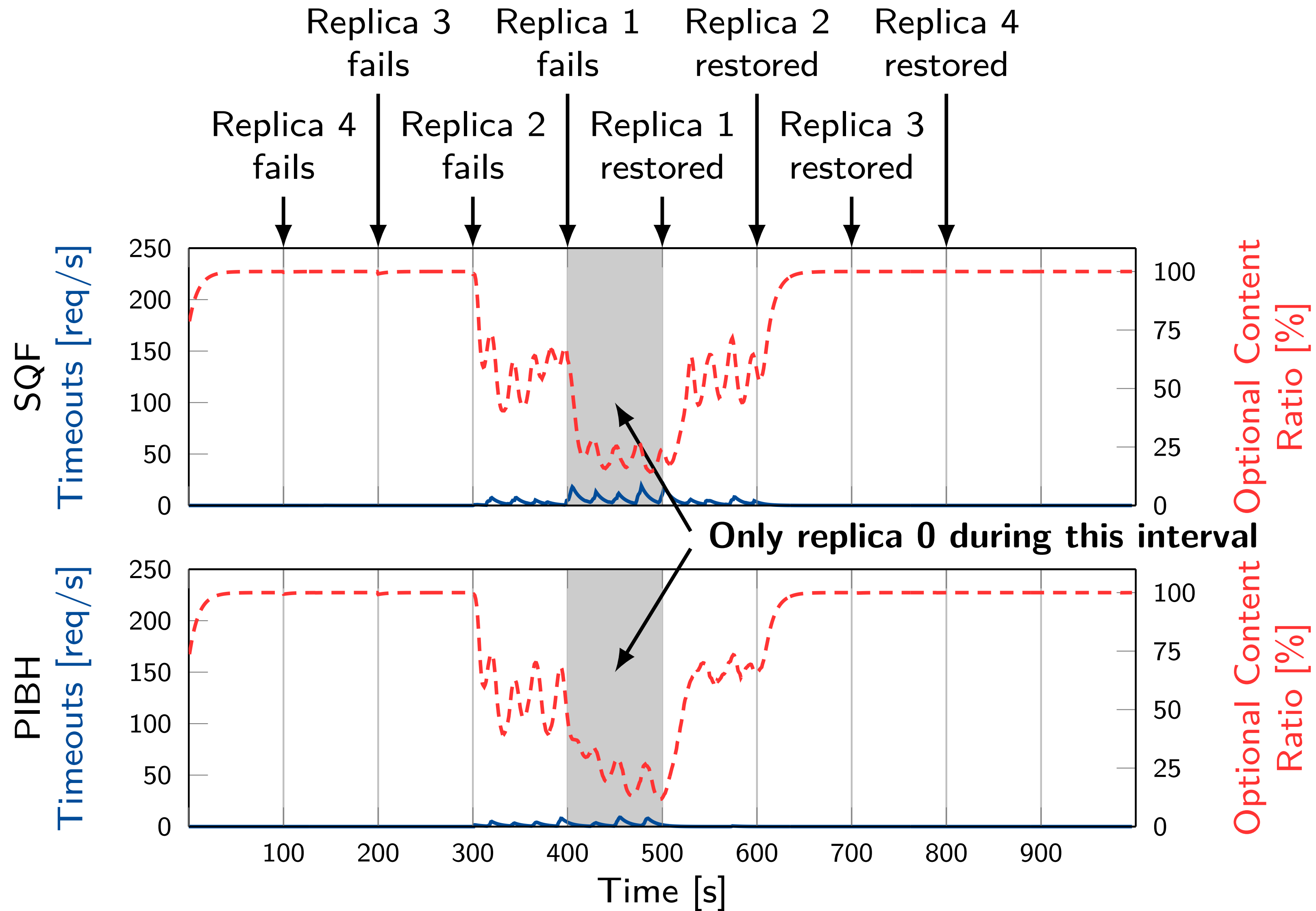
Maximize the optional content

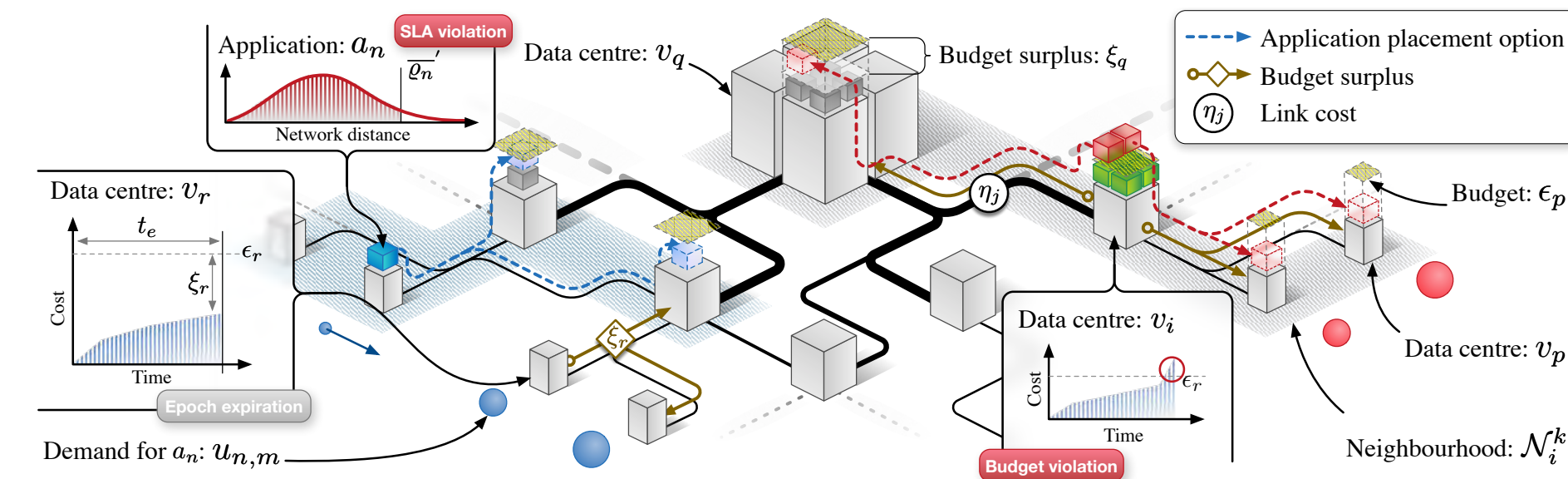
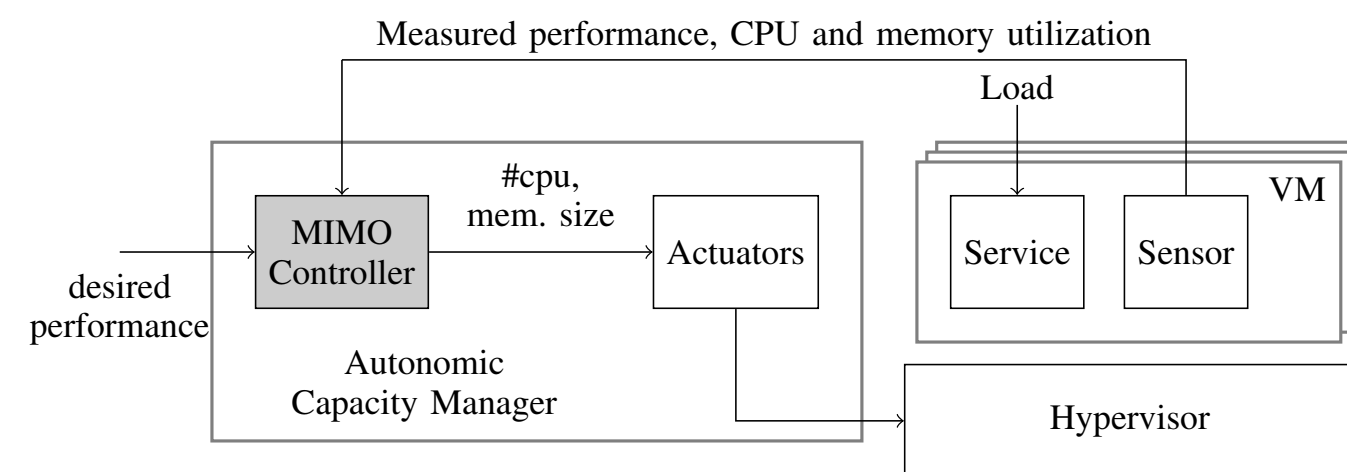
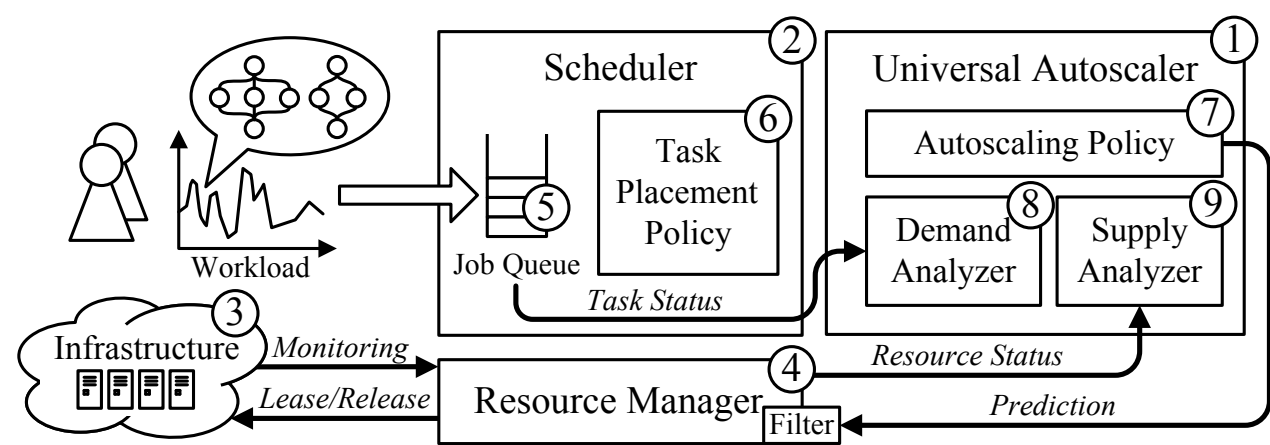
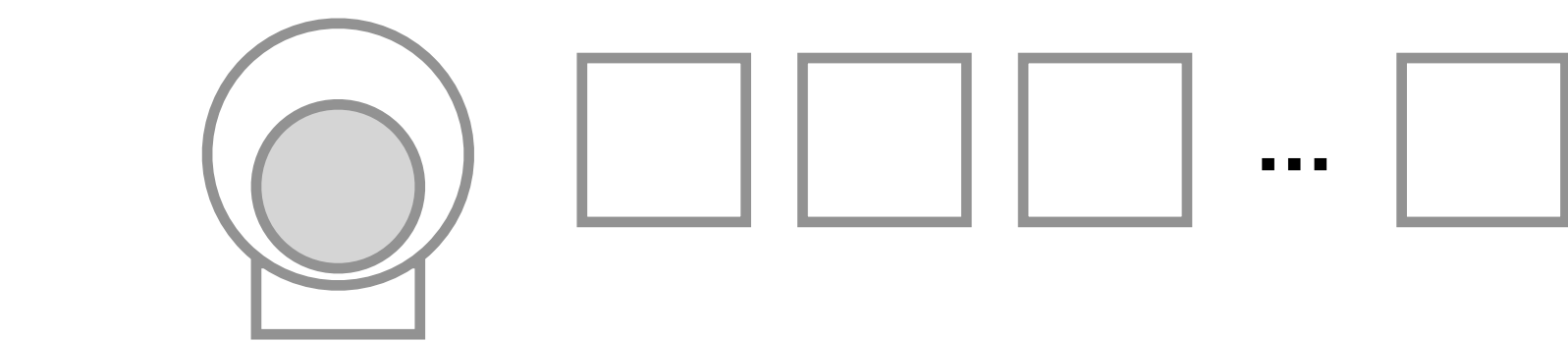
Minimize the queue length

Optional Content vs Response Time

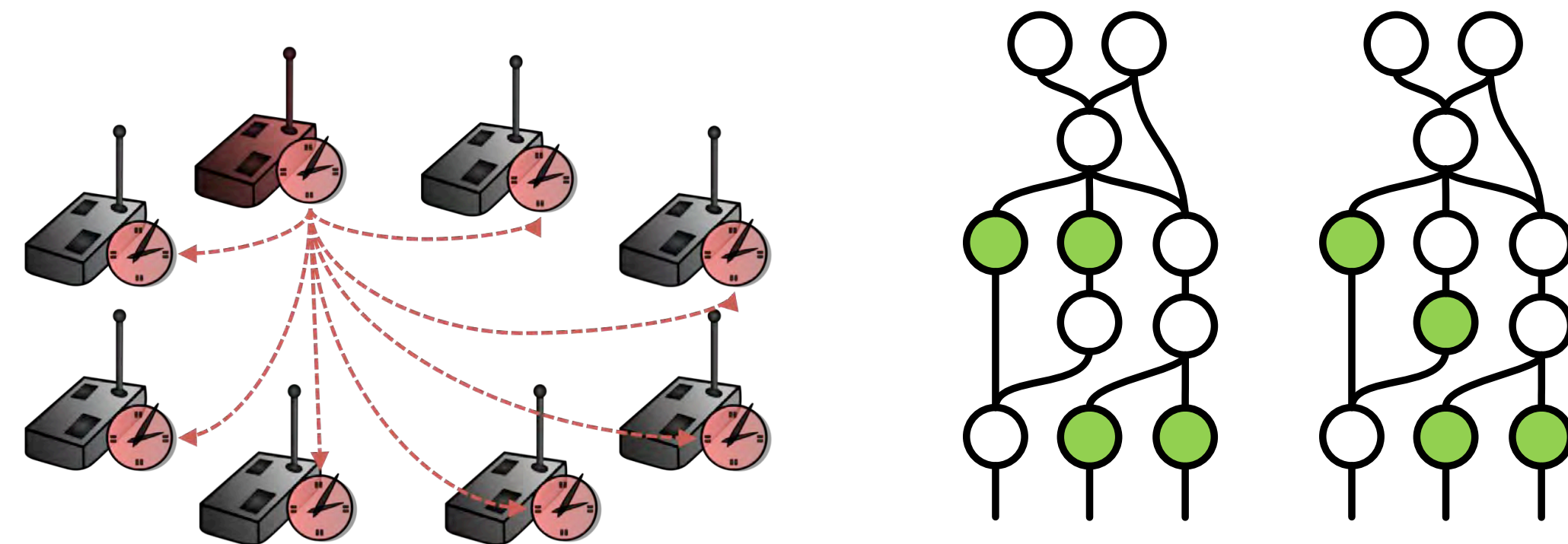
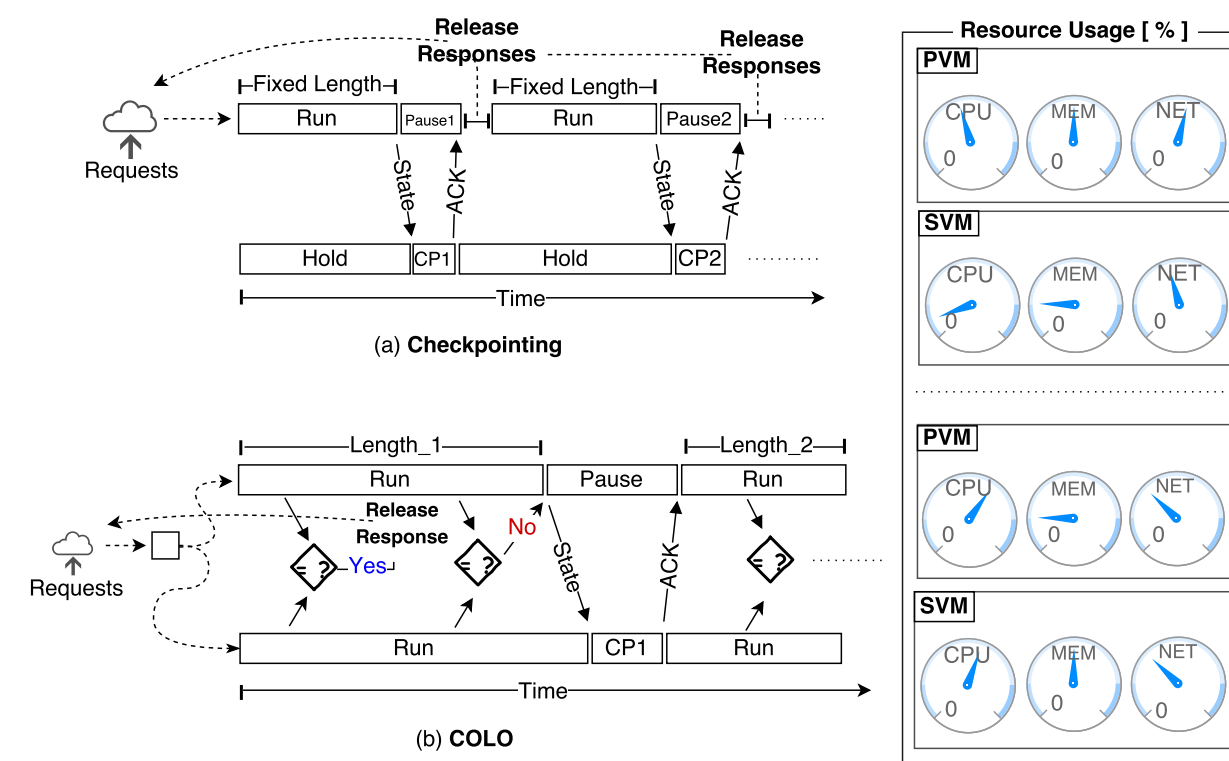
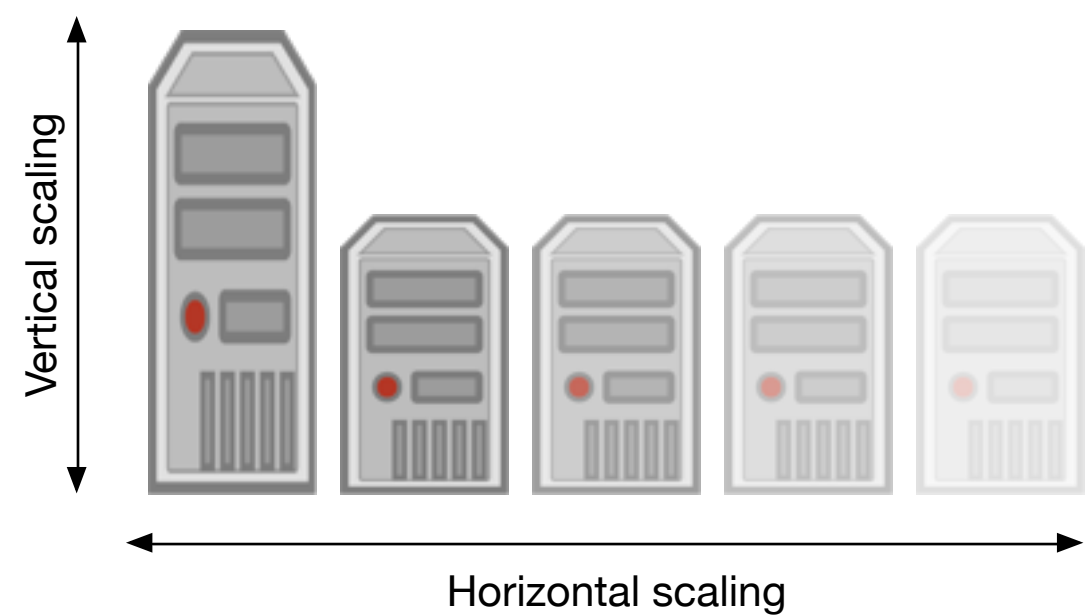


Resiliency

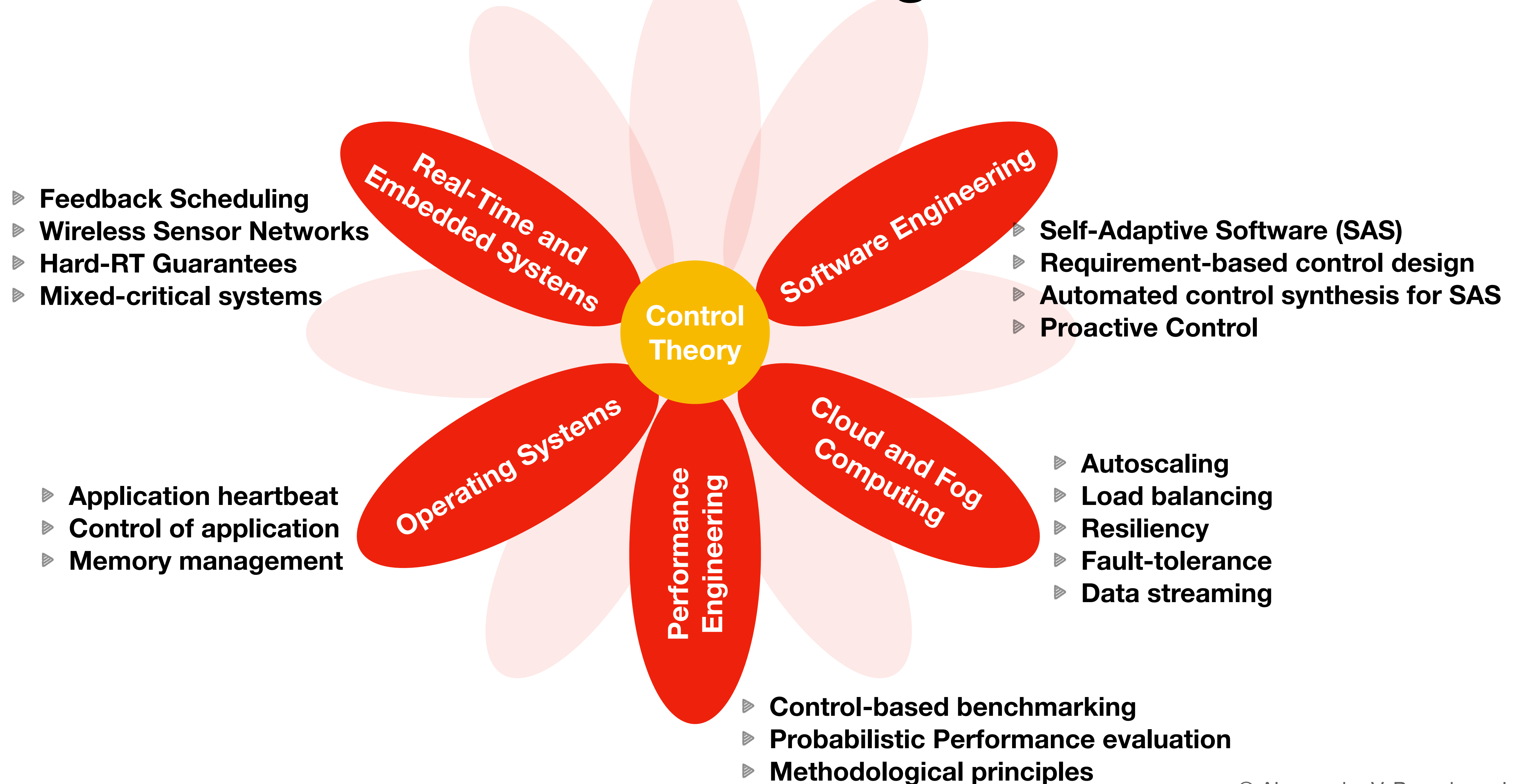




Control Has Proven Useful in the Design of Autonomous Software Components



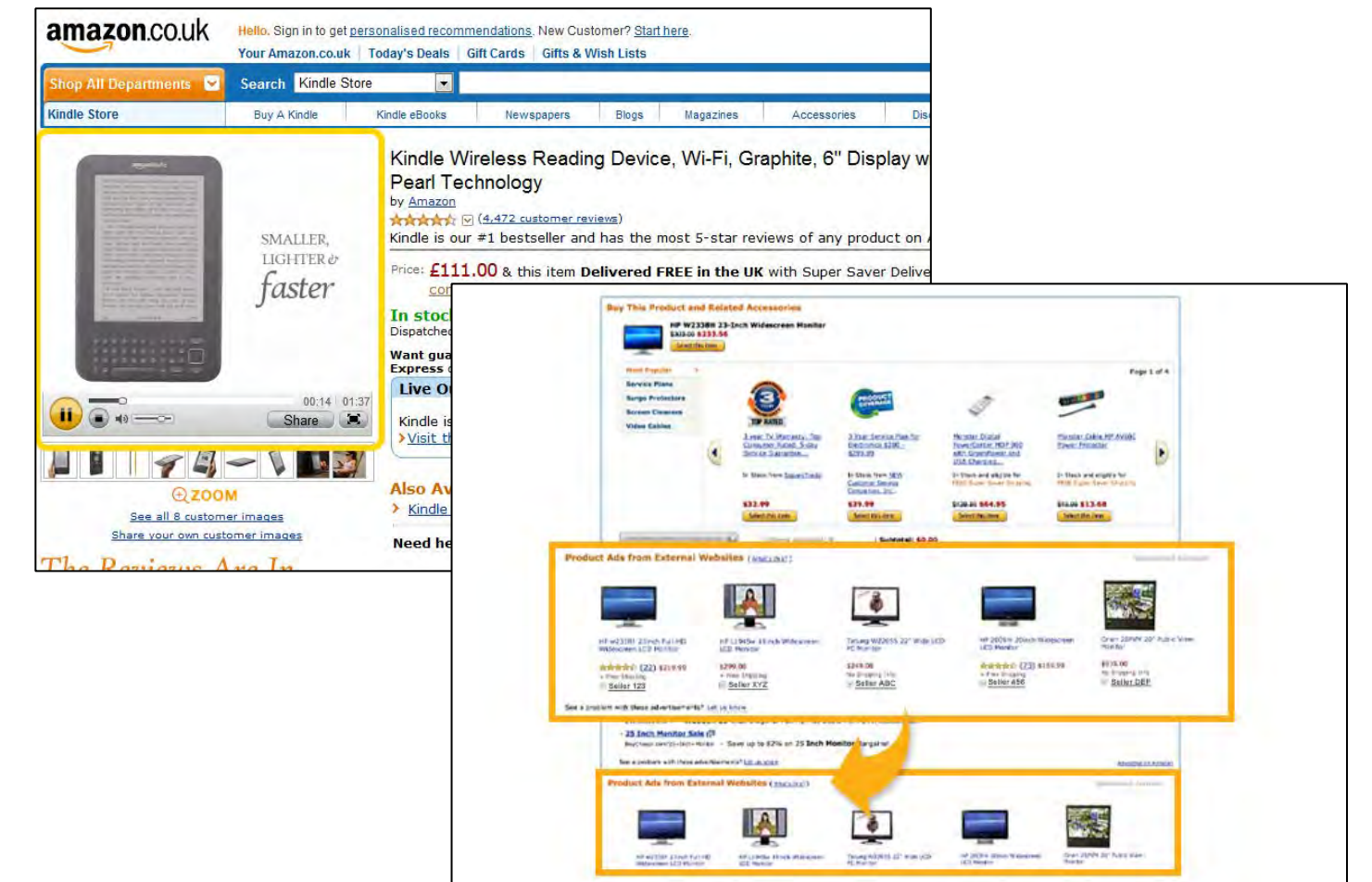
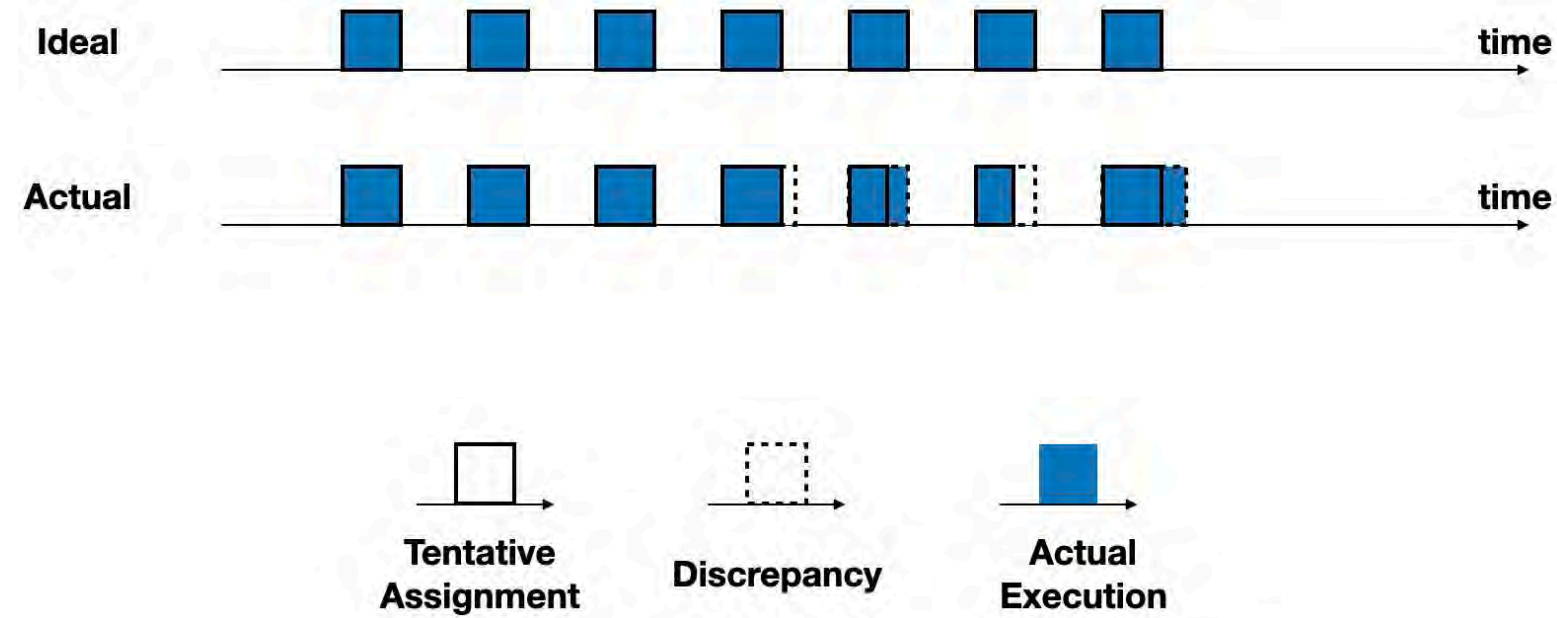
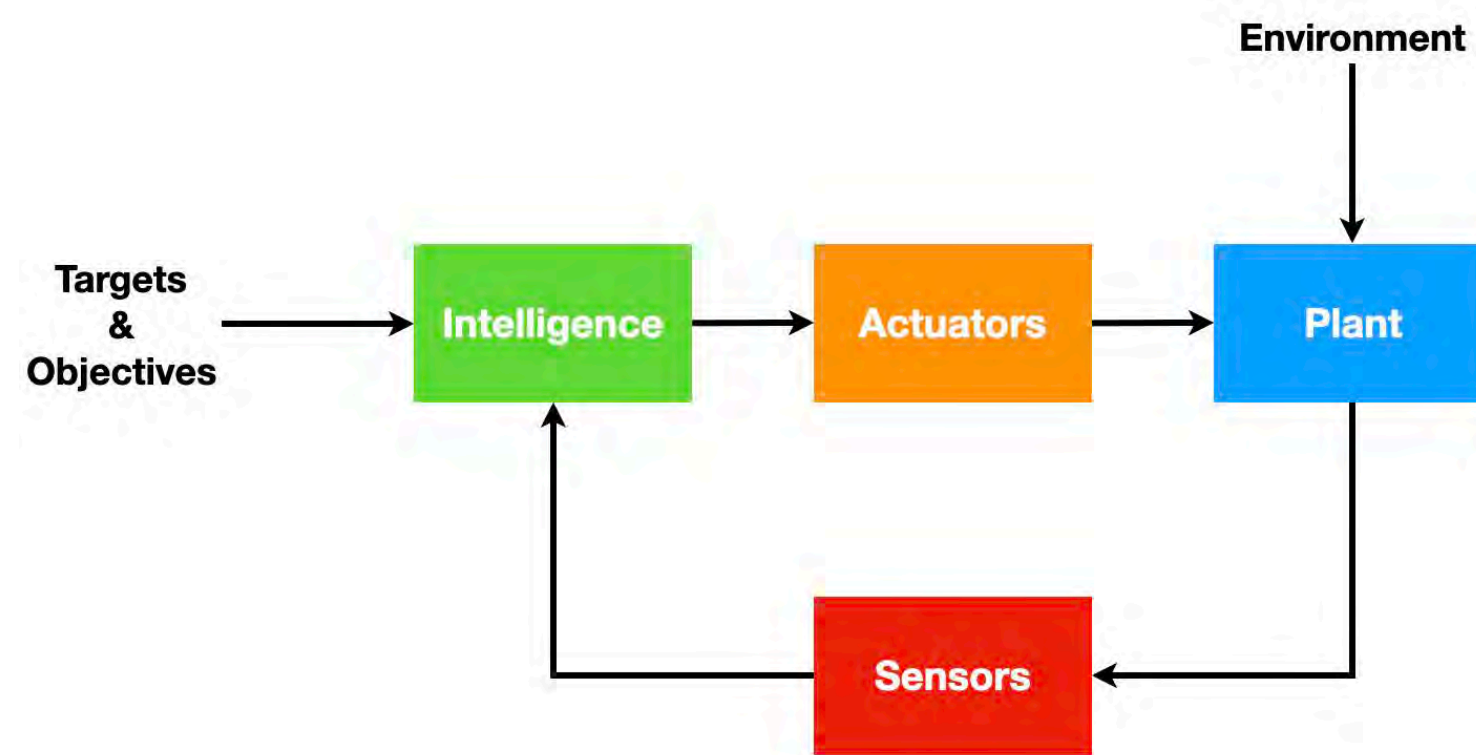
Autonomous Software Design With Control



Current Challenges

- **Automate** the decision-making algorithm design
- Include and model **Humans-In-The-Loop**
- Cross-fertilisation with other fields
 - ▶ Artificial Intelligence
 - ▶ Machine learning
 - ▶ Formal Methods
 - ▶ Real-Time Systems
- **General formulation of Physics Theory of Computing Systems**

Comments, Feedback, and Questions Are Welcome



This work has been supported by:

