In-ConcReTeS

Interactive Consistency meets Distributed Real-Time Systems, Again!

Arpan Gujarati and Ningfeng Yang (UBC)
Björn Brandenburg (MPI-SWS)

This paper in a nutshell …

In-ConcReTeS

Distributed key-value store

Time-sensitive, fault-tolerant replica coordination

Random environmentally induced faults

Motivation

Embedded Systems are Susceptible to Transient Faults

Harsh environments

- **Electric motors, spark plugs** inside automobiles
- Industrial systems and robots operating under **hard radiation** and **near high power** machinery

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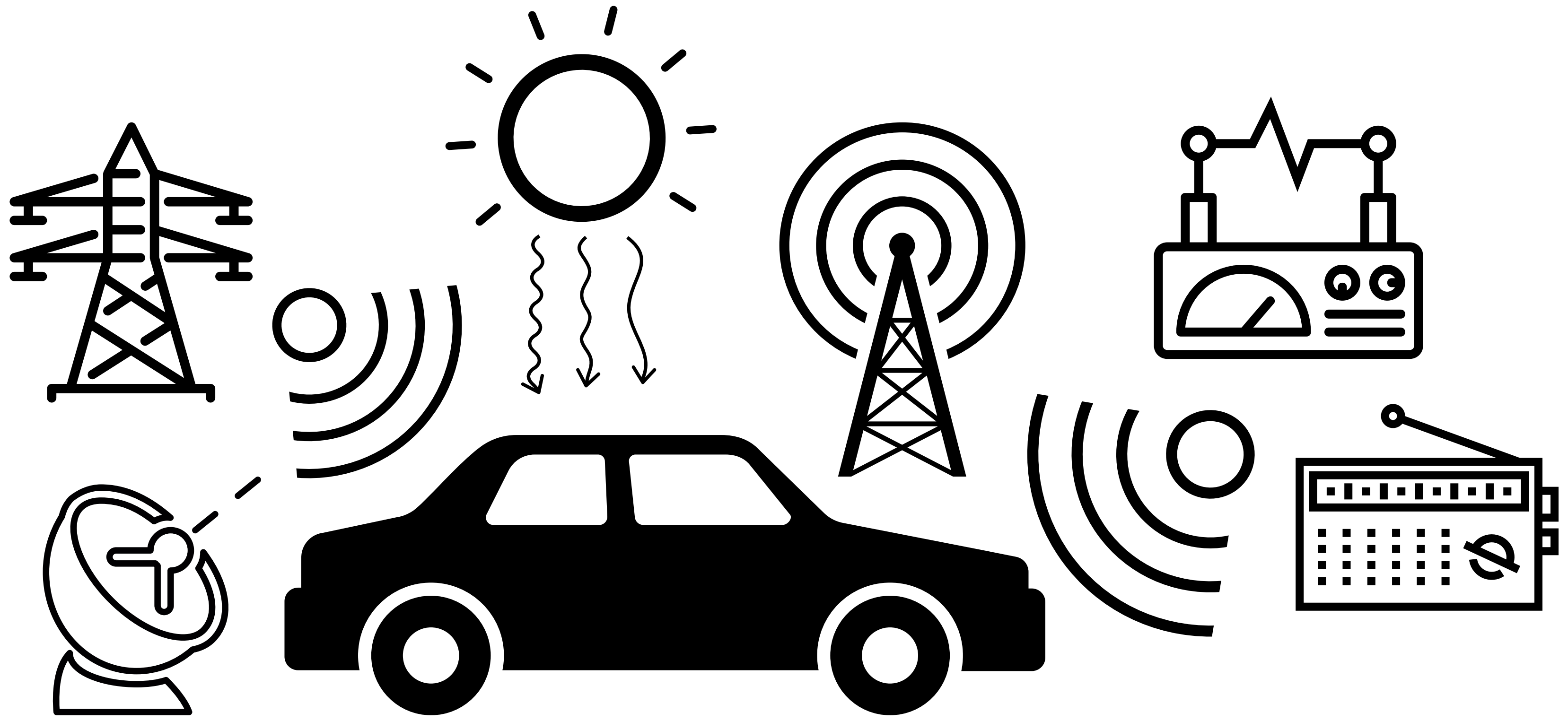
Transient faults or bit flips in registers, buffers, and networks

- For example, with 1 bit flip in a 1 MB SRAM every 10^{12} hours of operation
- and 0.5 billion cars with an average daily operation time of 5%
- **about 5000 cars may be affected by a bit flip every day!***



* Mancuso. "Next-Generation Safety-Critical Systems on Multi-Core Platforms." PhD Thesis, UIUC (2017)

Transient Faults can lead to Errors and Failures

Transmission errors
- Faults in the network

Omission errors
- Fault-induced kernel panics, hangs

Incorrect computation errors
- Faults in memory buffers

Byzantine / inconsistent broadcast errors*
- Faults in distributed systems

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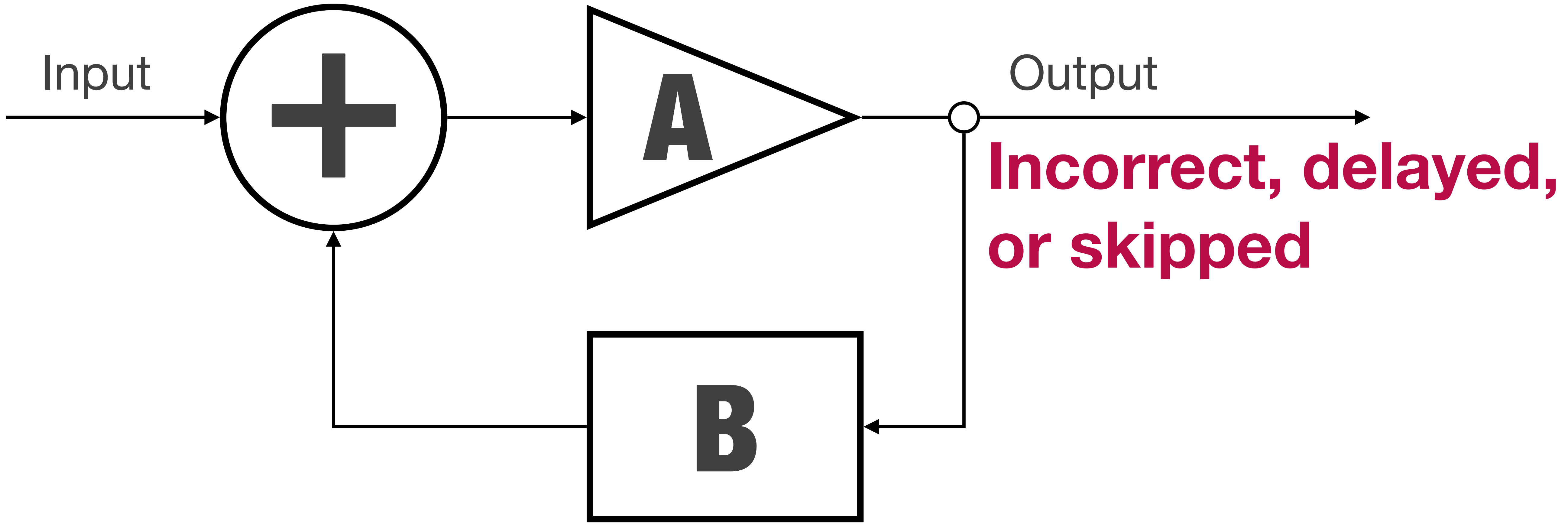
Example: Safety-critical control systems can fail in both time and value domains



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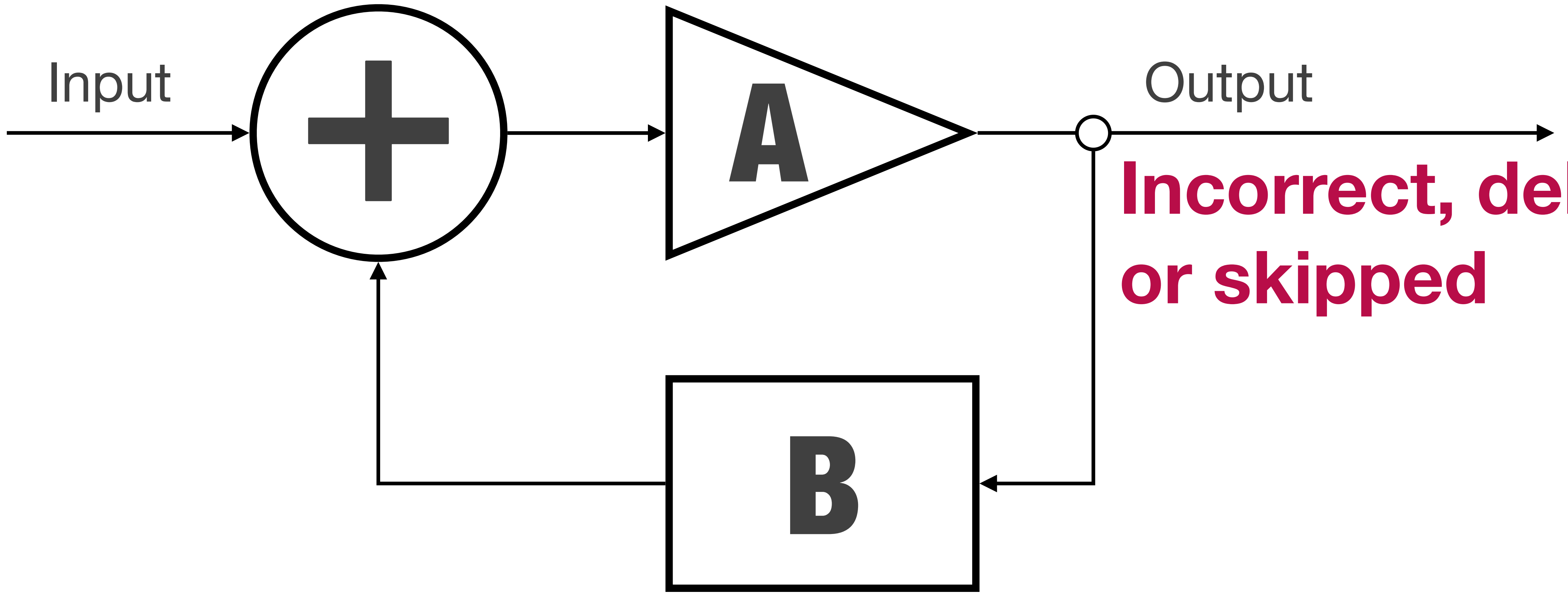

Incorrect, delayed, or skipped

Many influential avionics domain architectures in the 80s and 90s designed for safety-critical real-time systems addressed this problem in depth!

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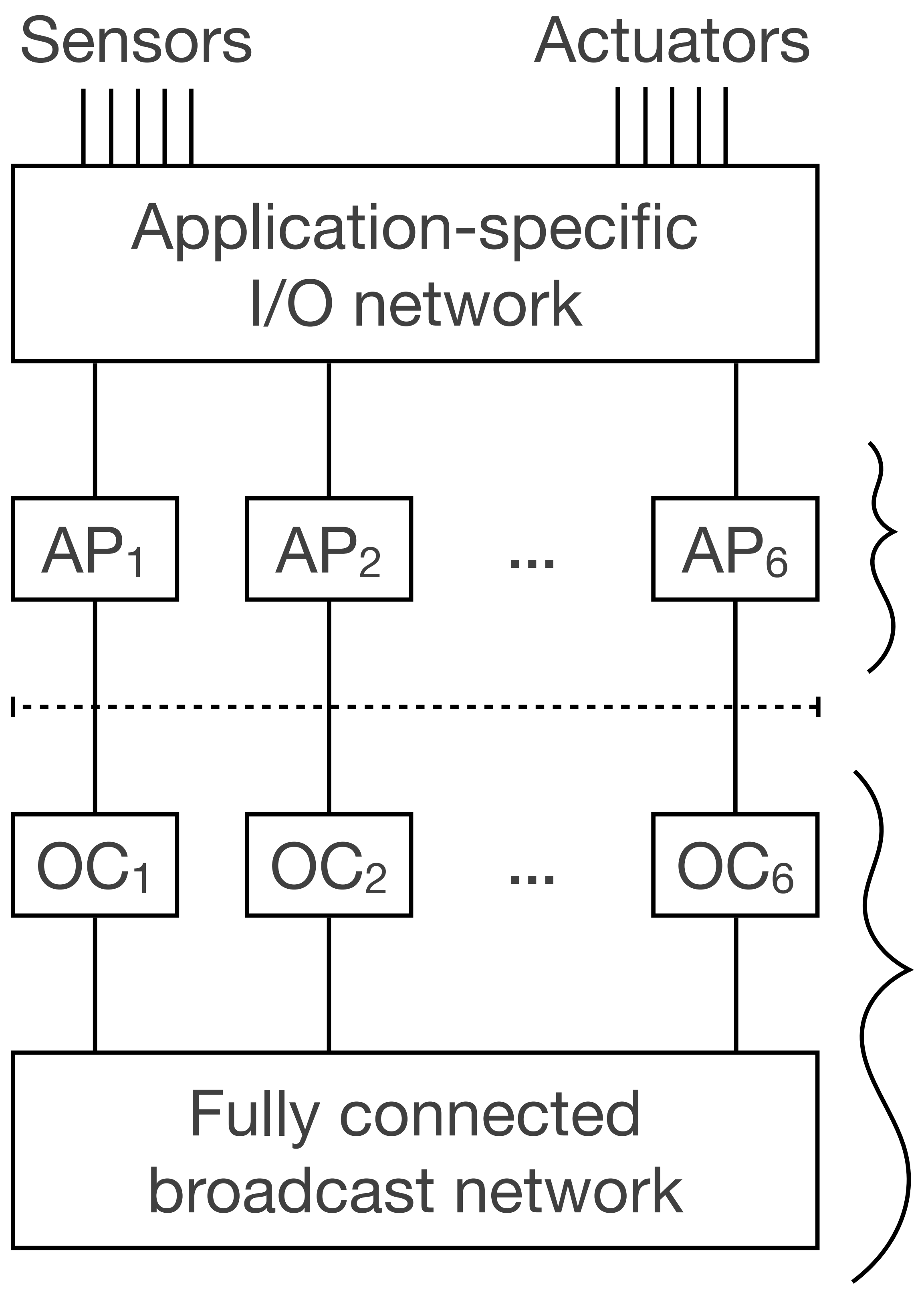
Multiprocessor Architecture for Fault Tolerance (MAFT)*



General-purpose application processors (APs)

Custom operation controllers (OCs) for voting, scheduling, synchronization, etc.

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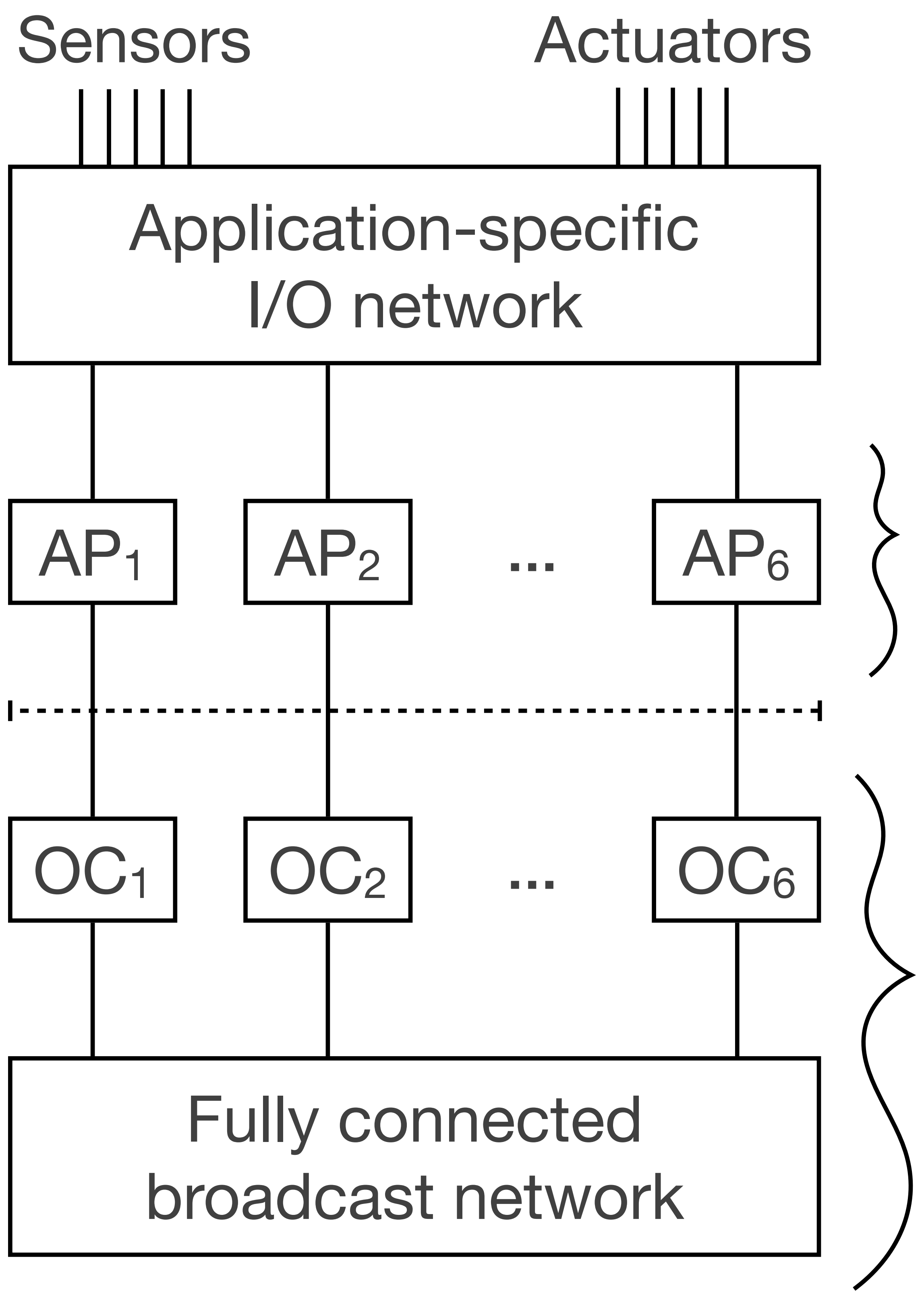

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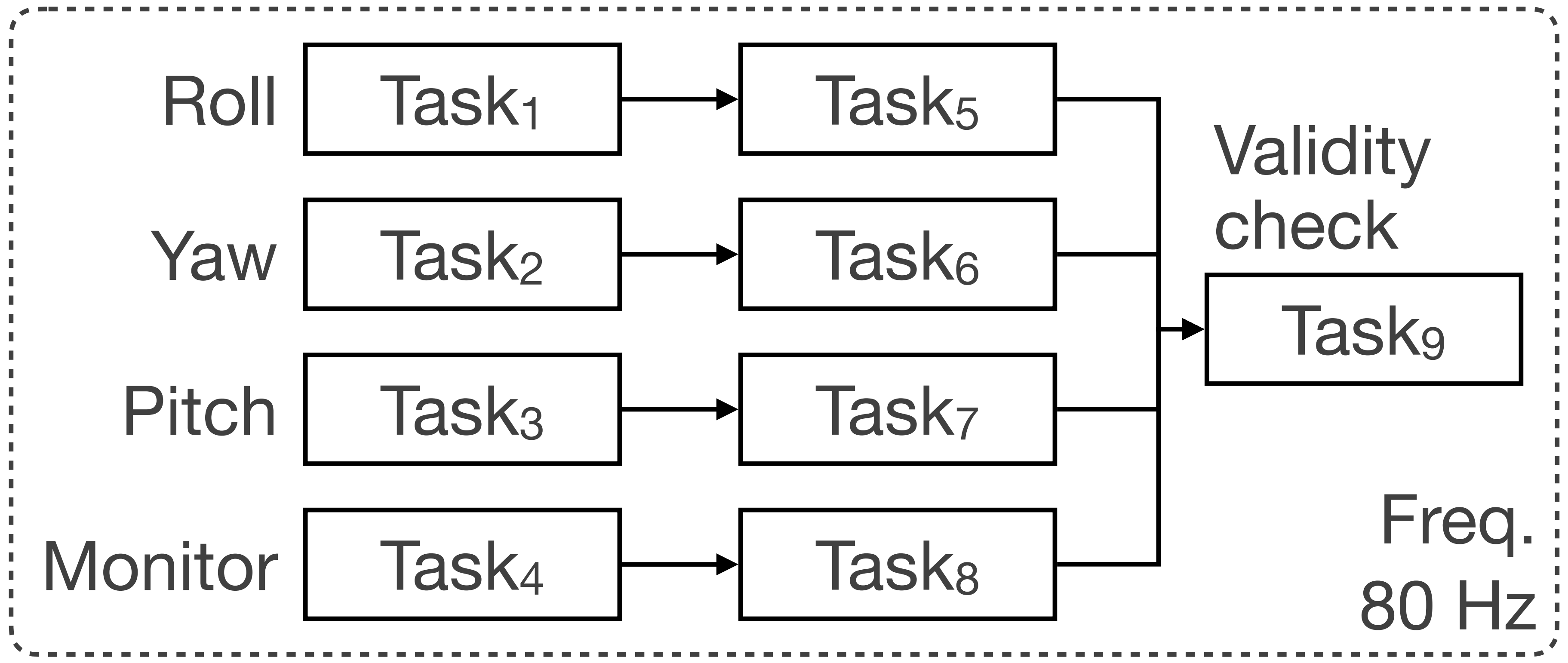
Simple periodic real-time workload



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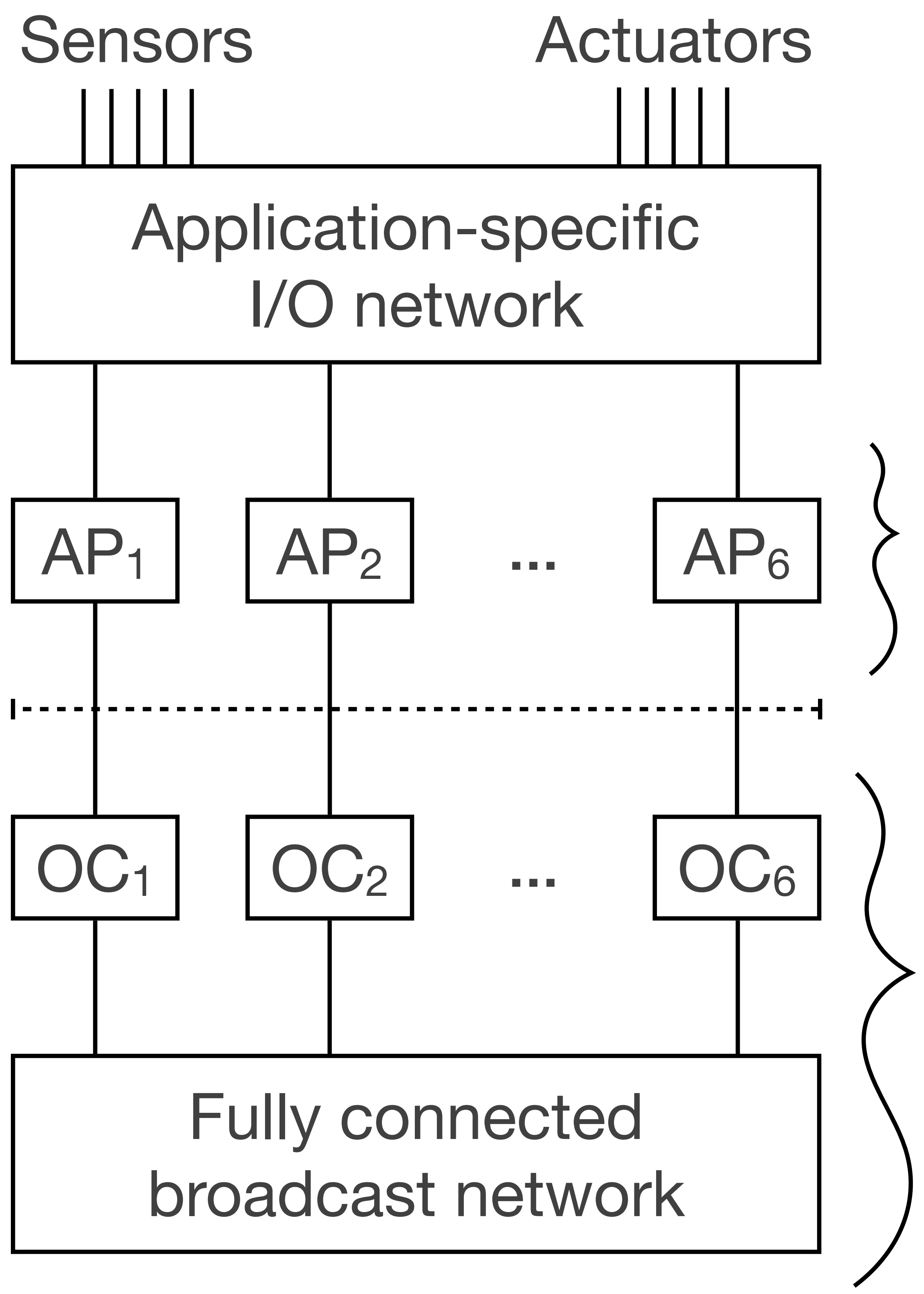

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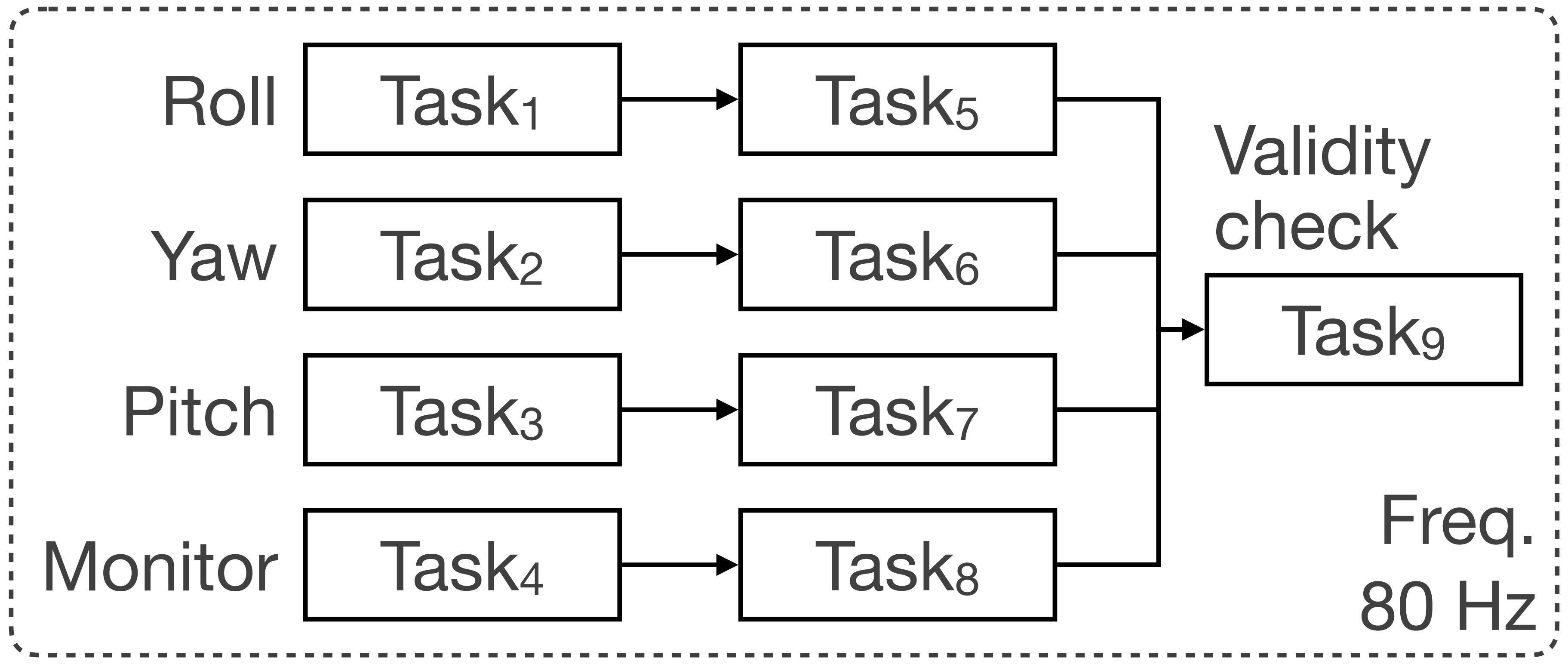

Reliability goals

- $P_{fail} < 10^{-10}$ / hour

Tolerate

- crashes,
- corruptions,
- omissions, …
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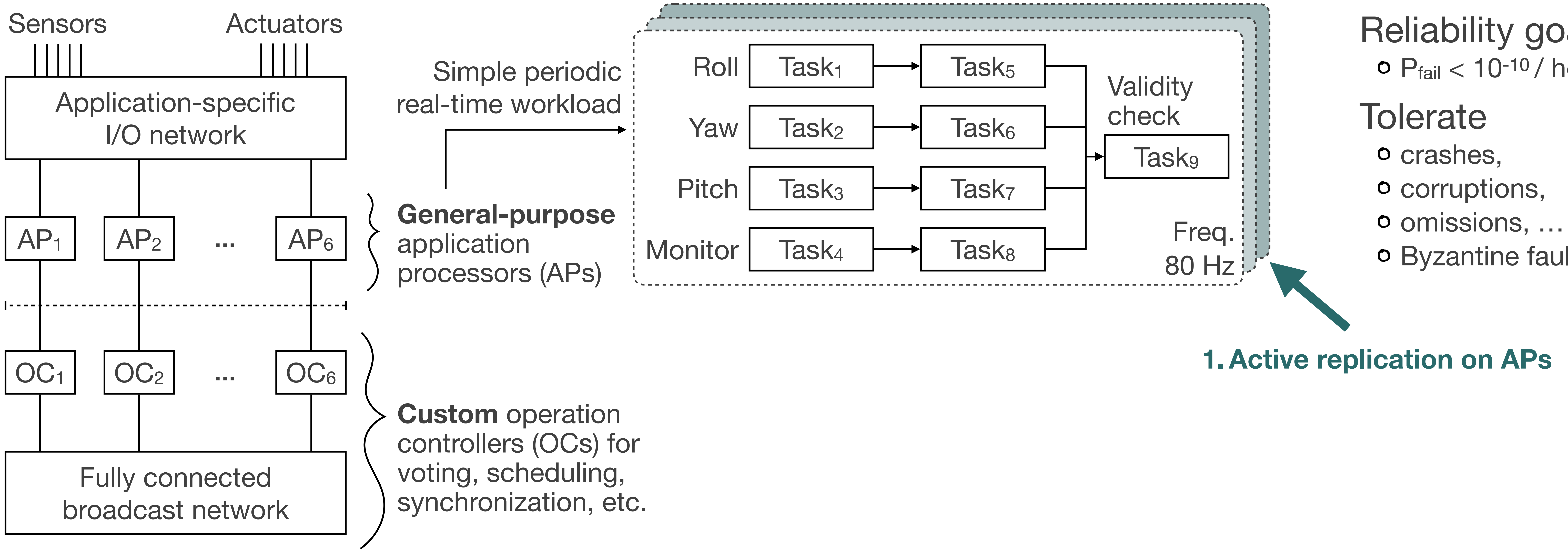

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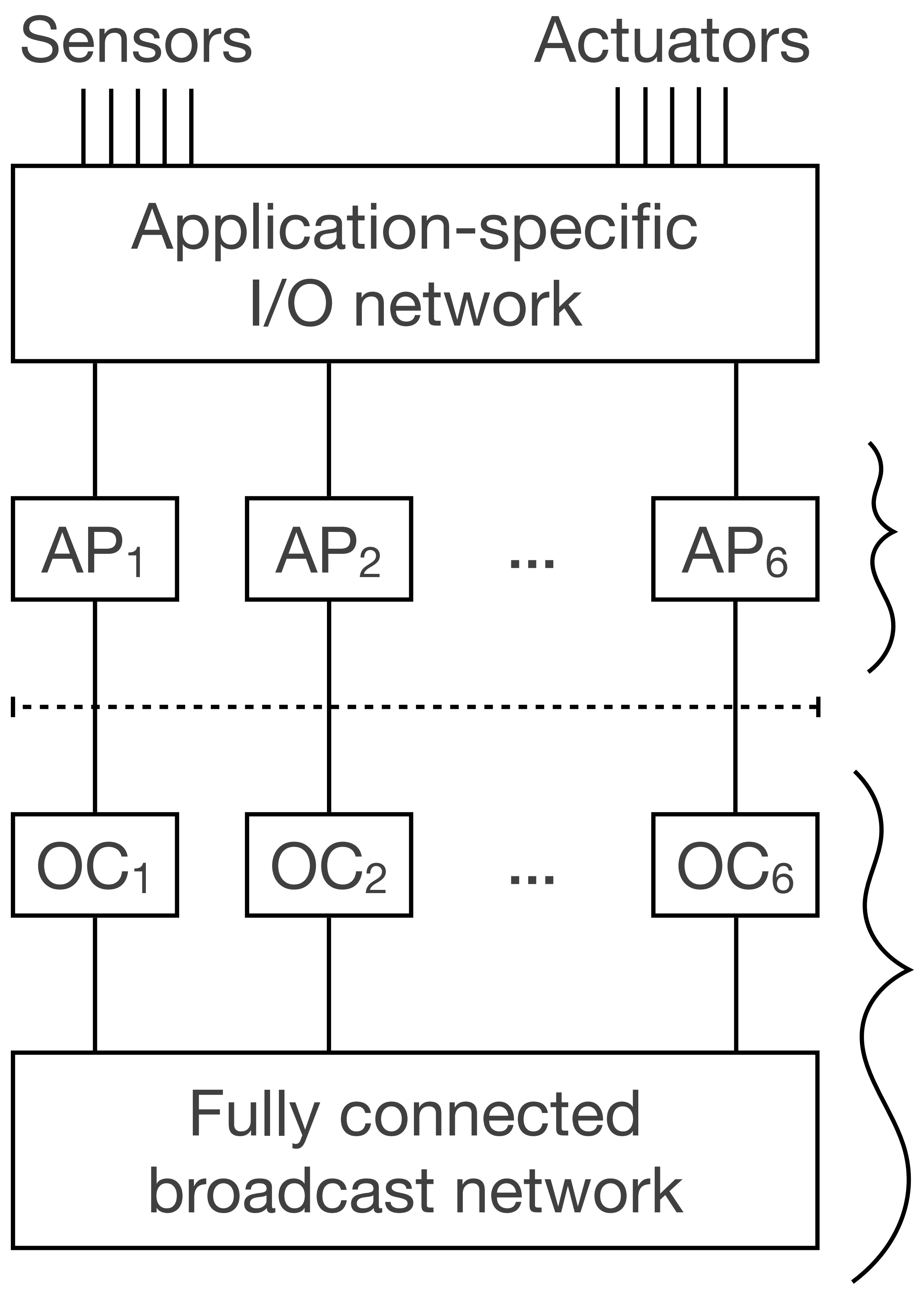

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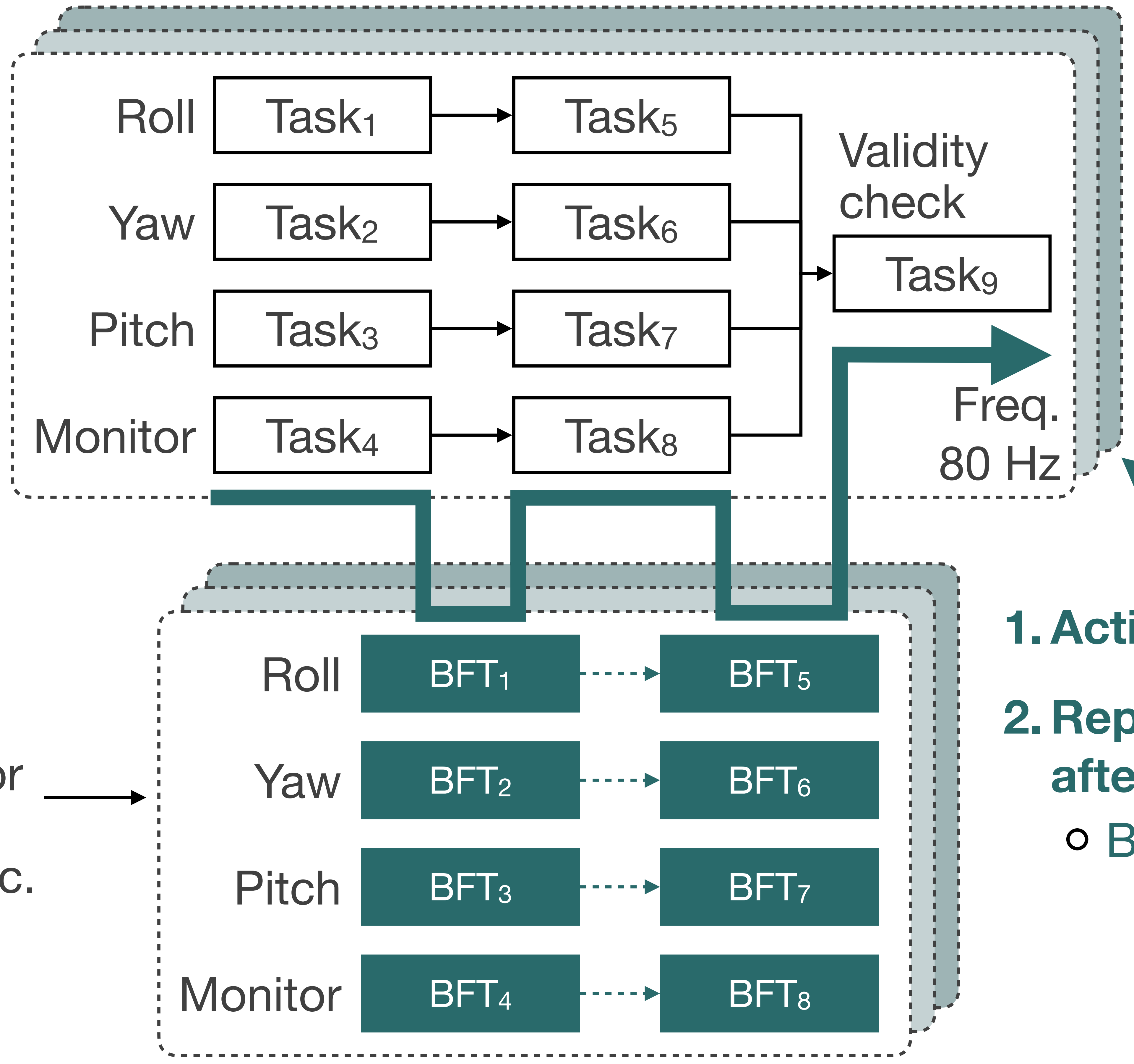

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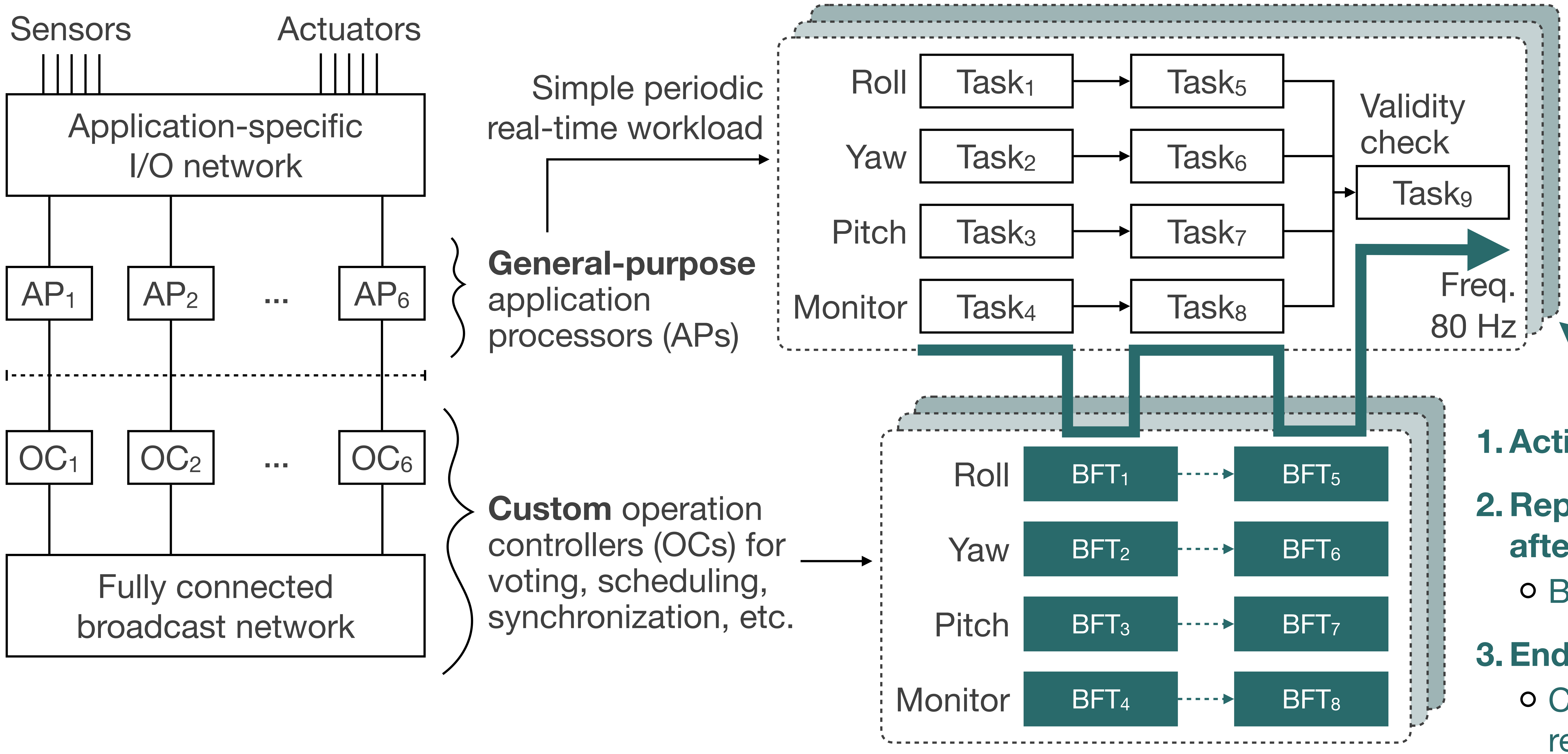

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2. **Replica coordination on OCs after every task**
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3. **End-to-end timing analysis**
   - Considering application tasks & replica coordination services

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Not all CPS are engineered as reliably as airplanes[1]

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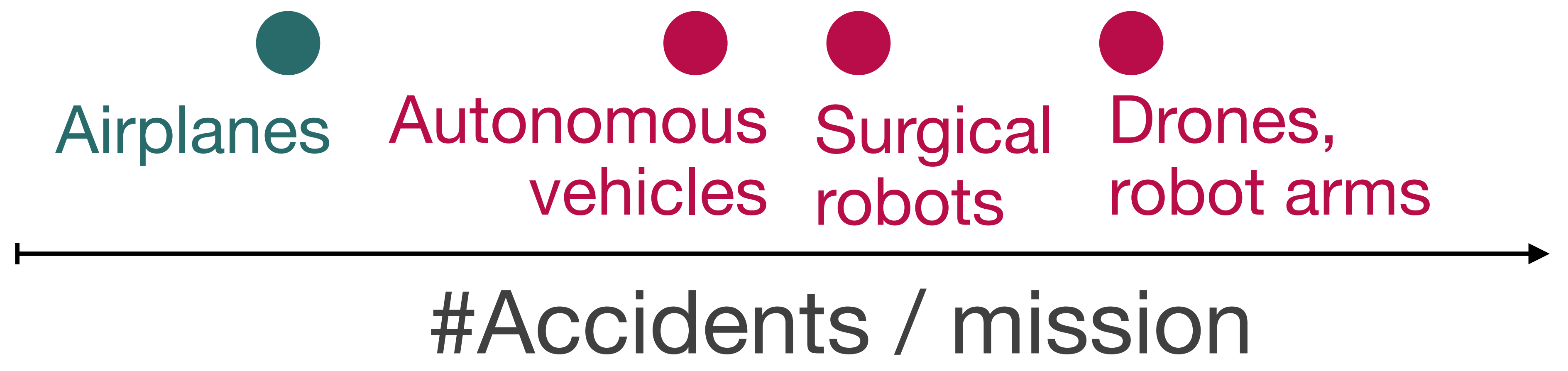
Contemporary CPS, e.g., autonomous vehicles, drones, robot arms, surgical robots, etc.

- Inexpensive but unreliable commercial off-the-shelf (COTS) hardware
- Inadequate resources (developer hours, computing power, component costs)
- Time to market pressures!



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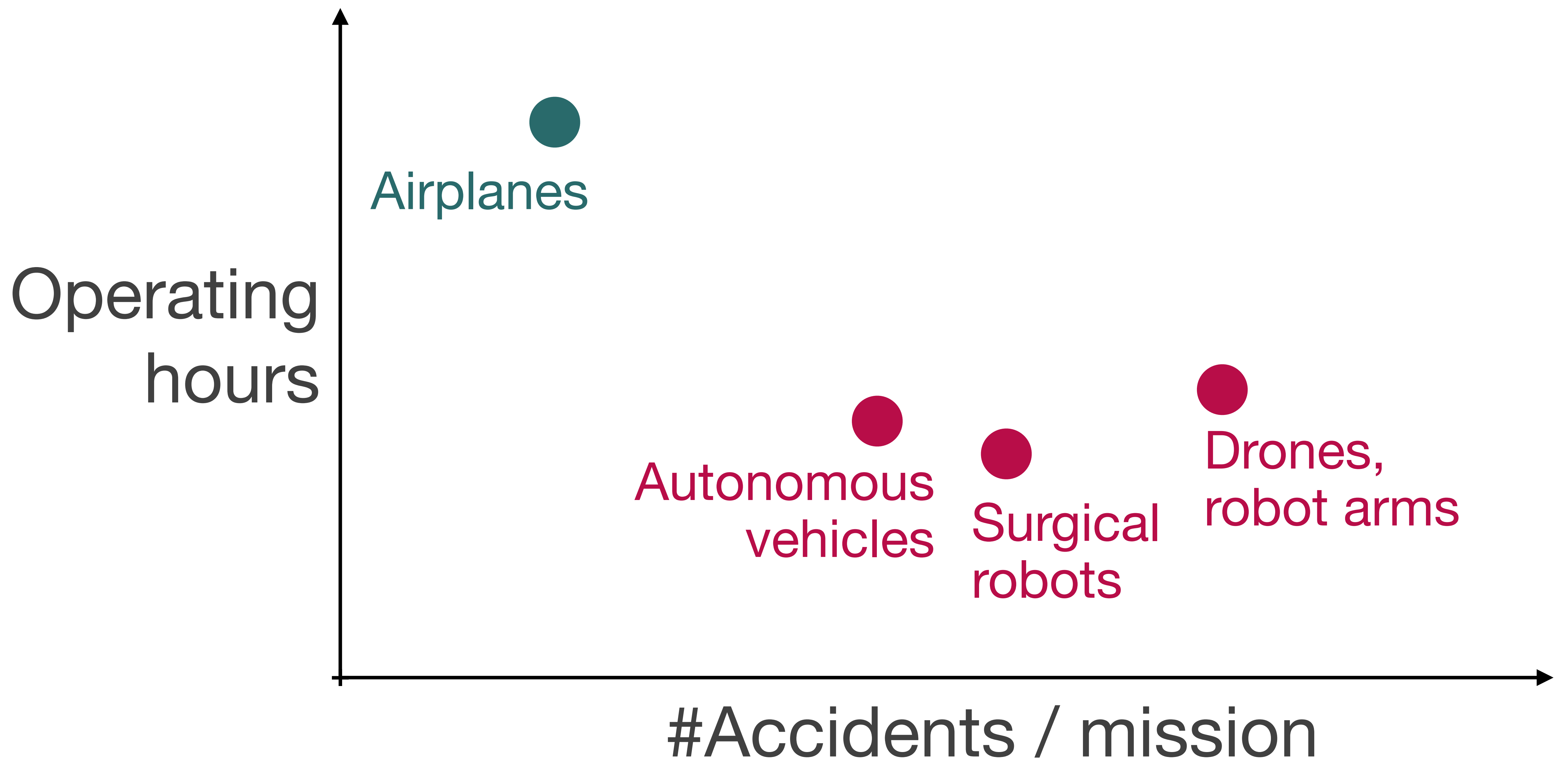

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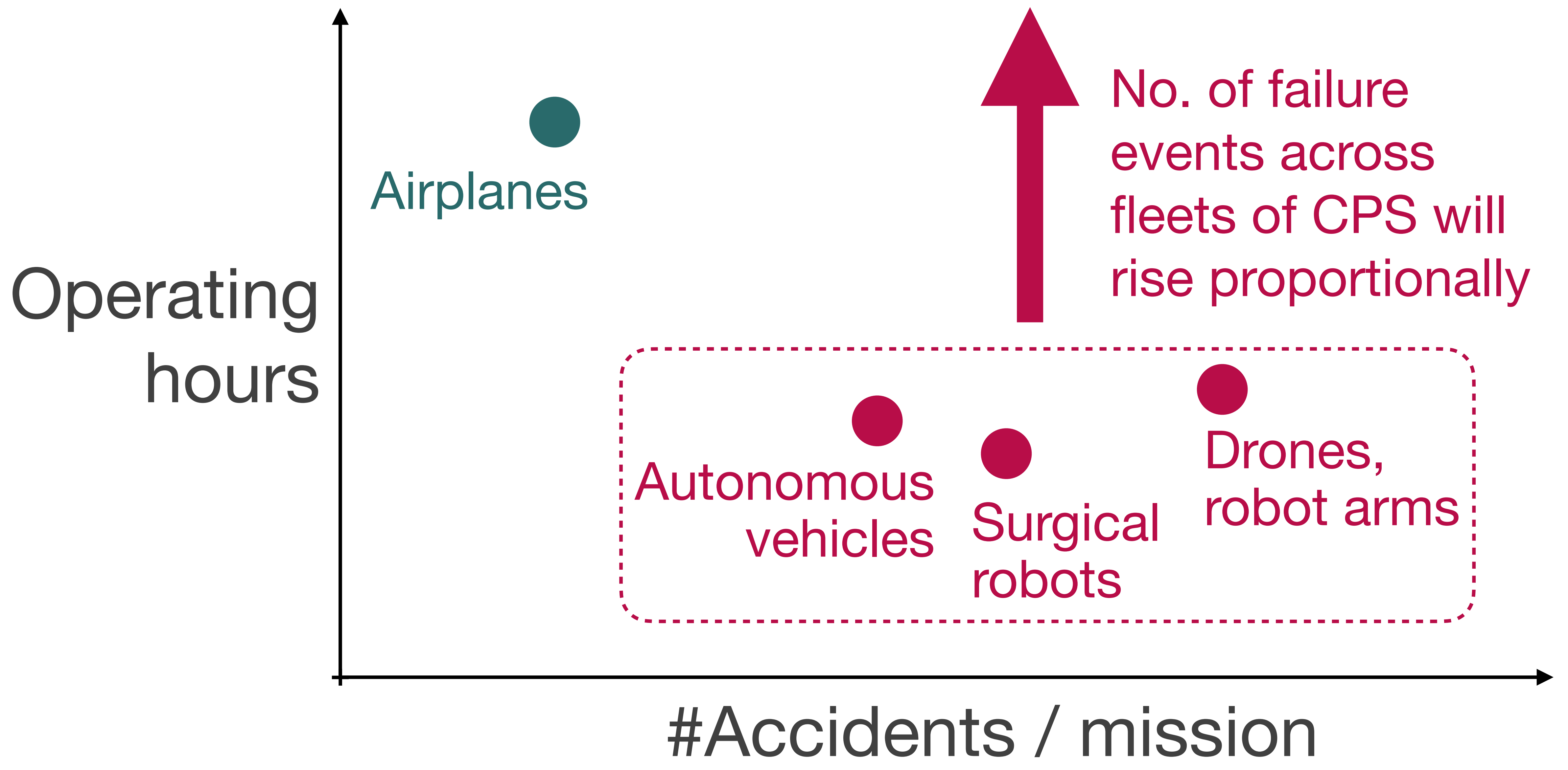
As these CPS permeate our everyday lives

- … their cumulative operating times are increasing[2]



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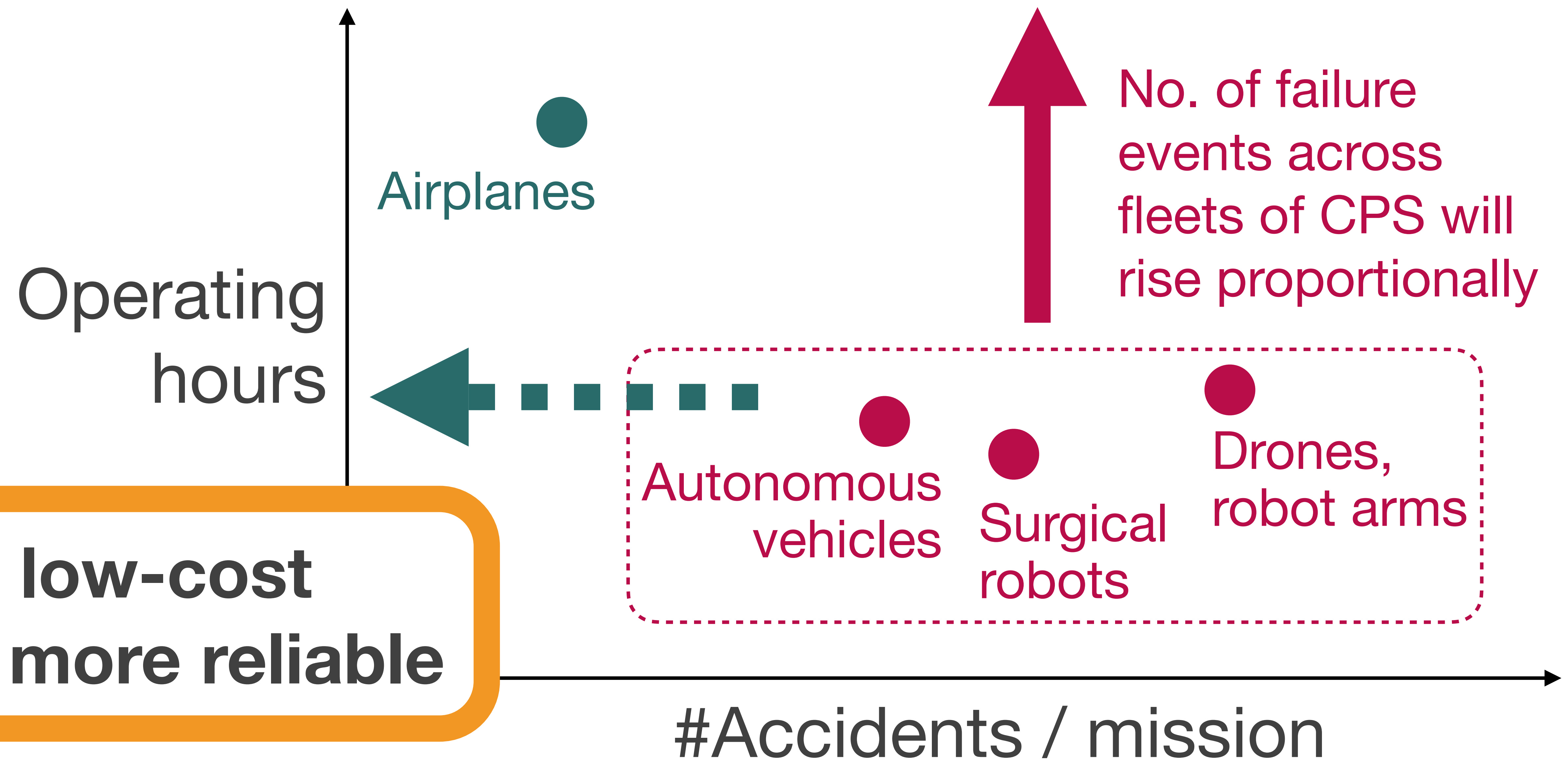

Goal: Make low-cost consumer CPS more reliable

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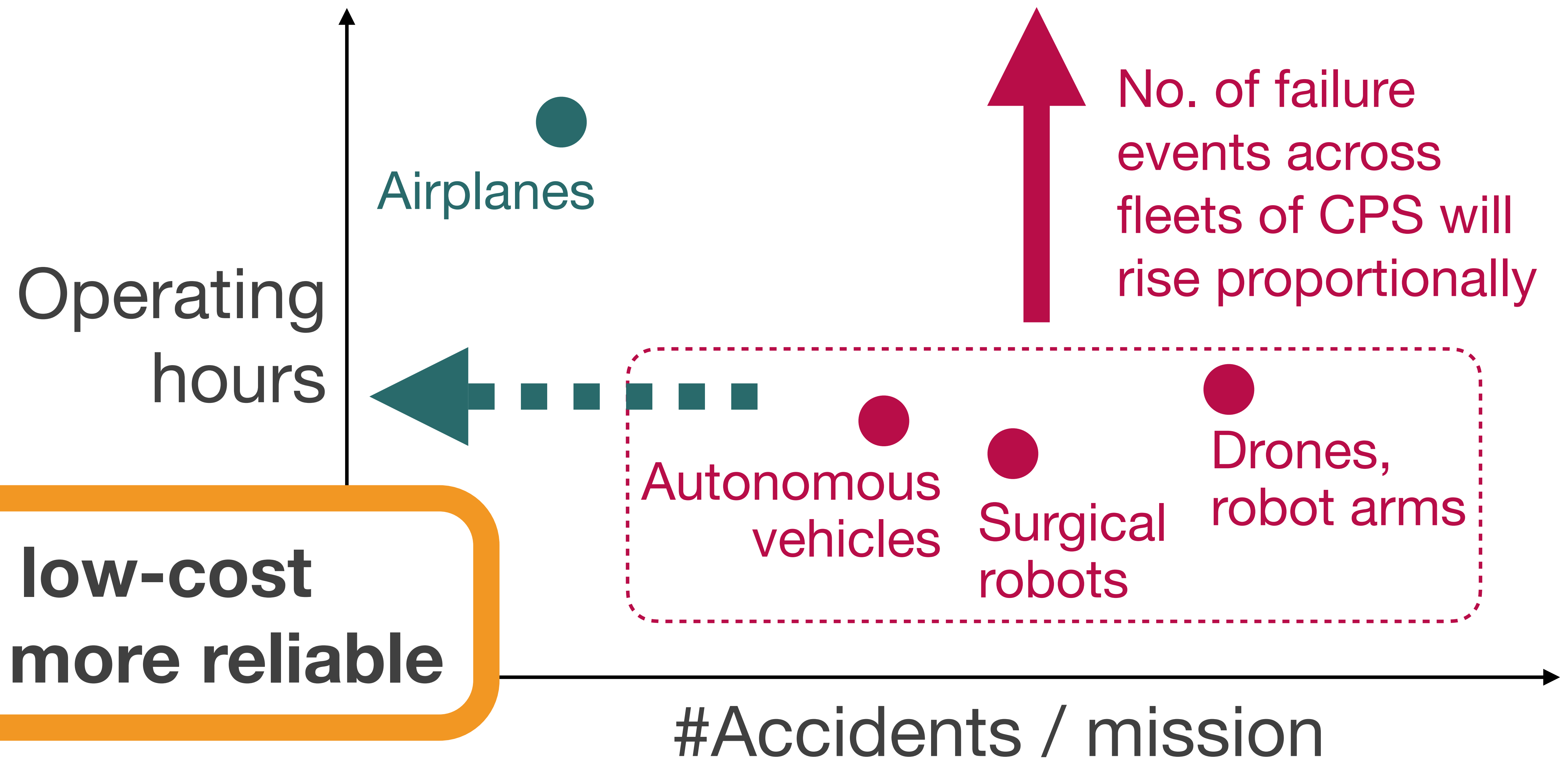

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Like MAFT, can we realize
<u>replica coordination with Byzantine fault tolerance</u> (BFT)
for real-time workloads in low-cost consumer CPS?

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robots

#Accidents / mission

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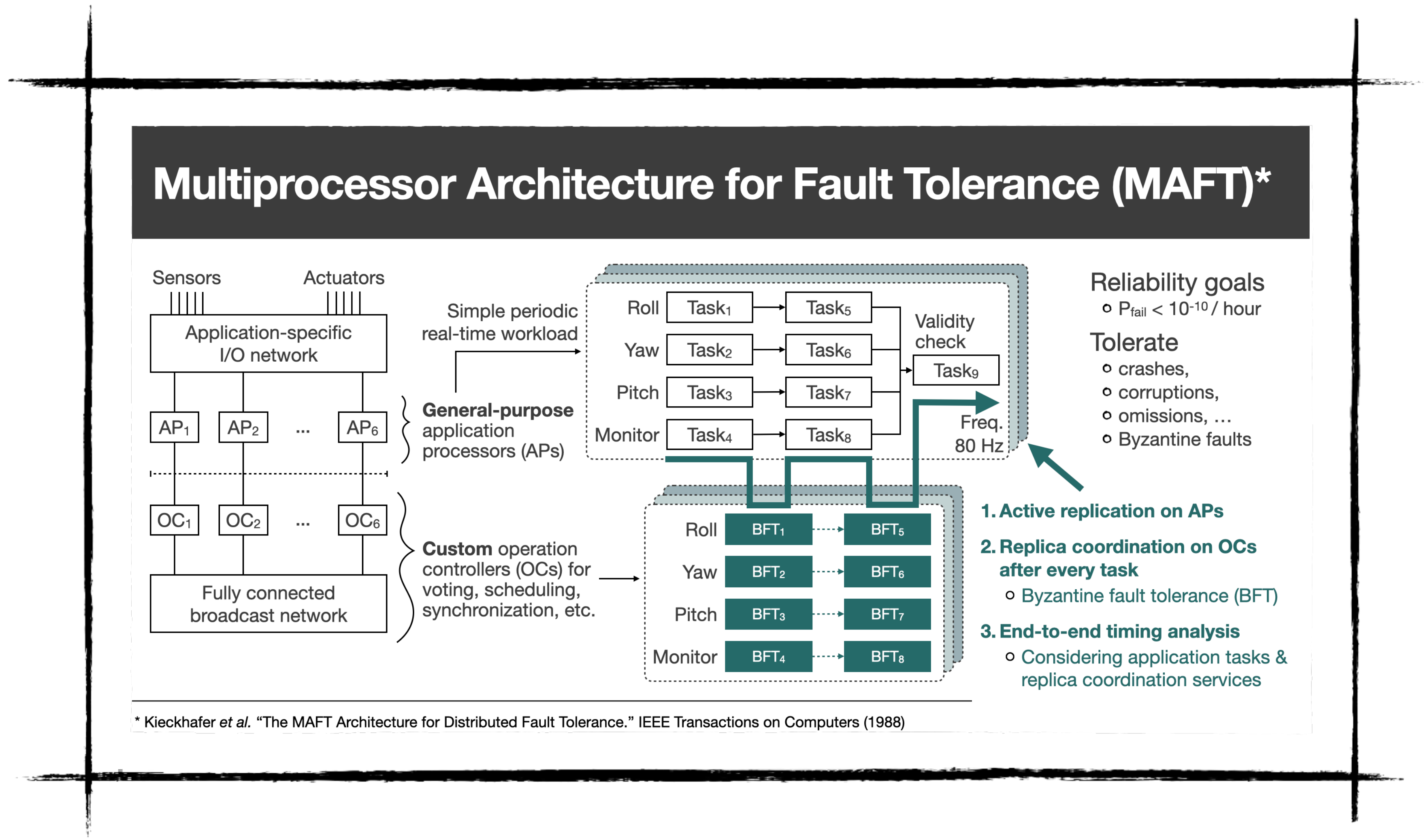
BFT Replica Coordination for CPS



Few domains use custom hardware

Let alone for Byzantine fault tolerance

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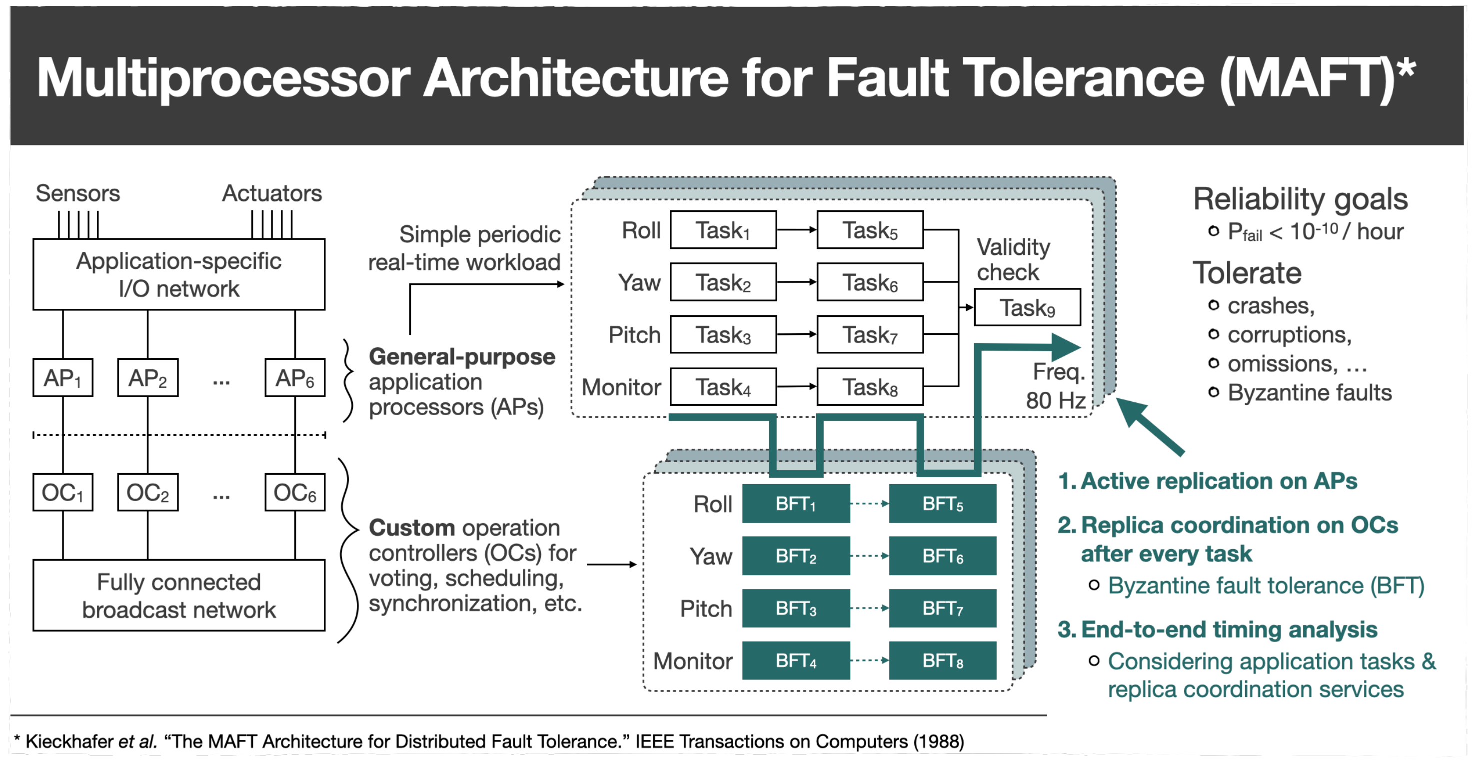

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Easy to build a drone using off-the-shelf hardware and open-source software

But no BFT solutions that can be retrofitted onto these real-time platforms

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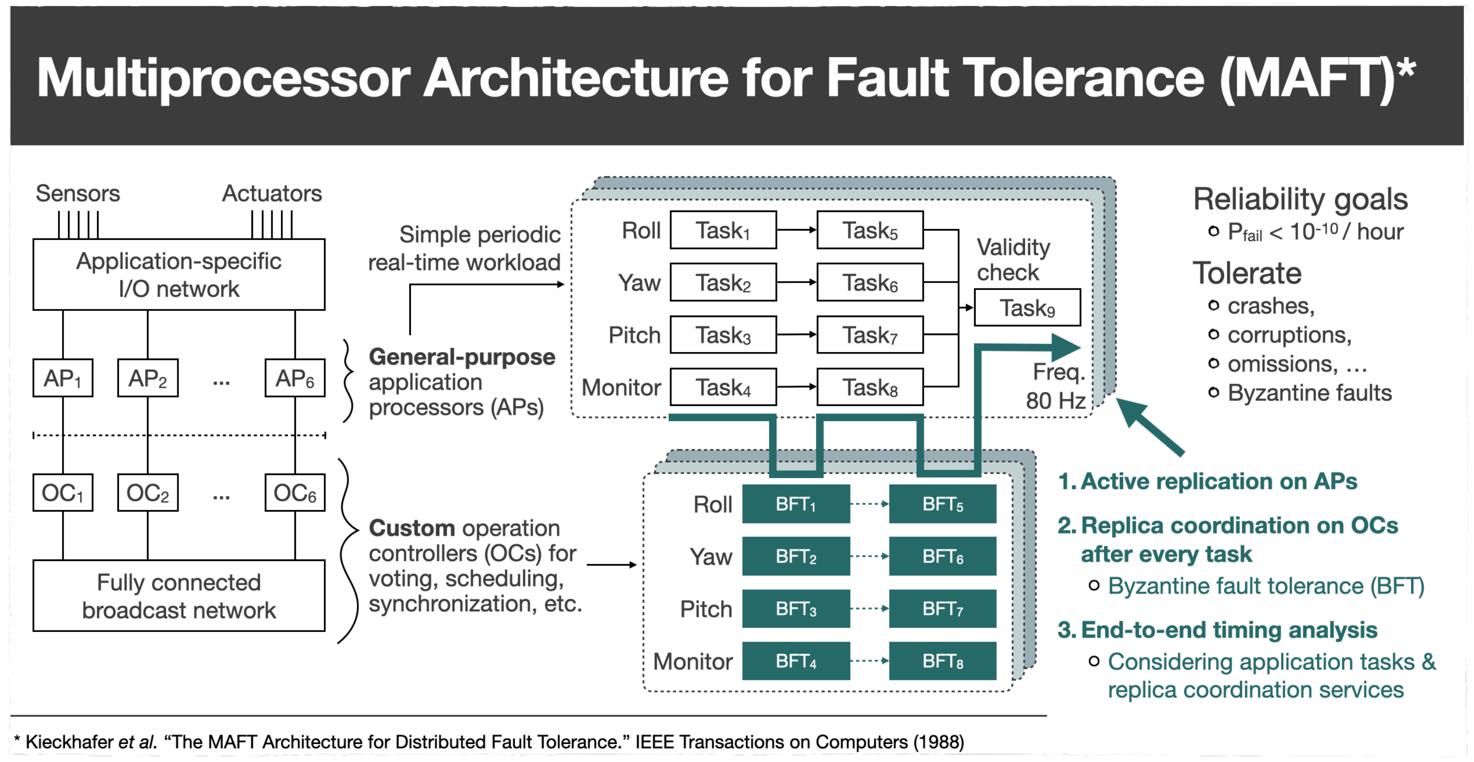

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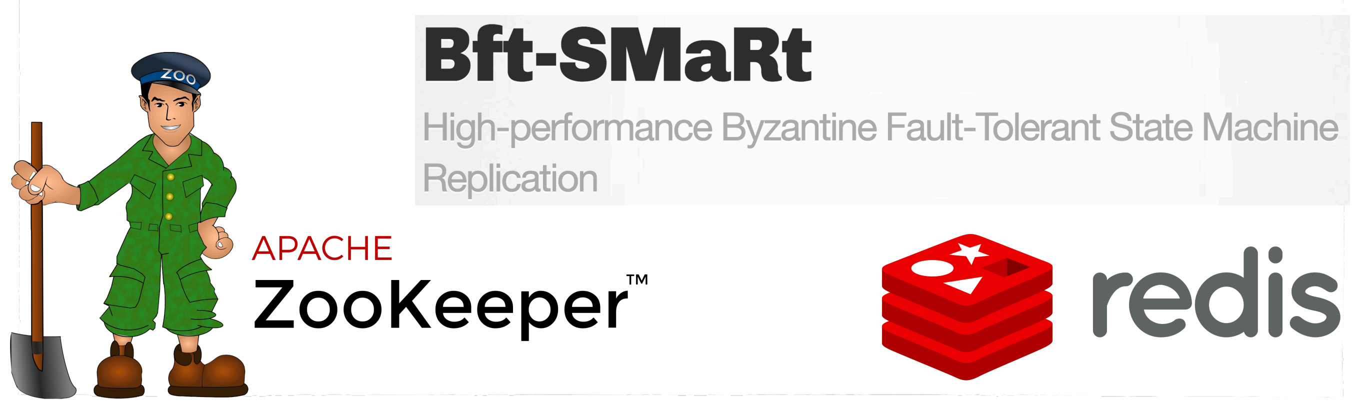

Best-effort, throughput-oriented BFT libraries are not suitable

Performance suffers on resource-constrained embedded device or in terms of predictability

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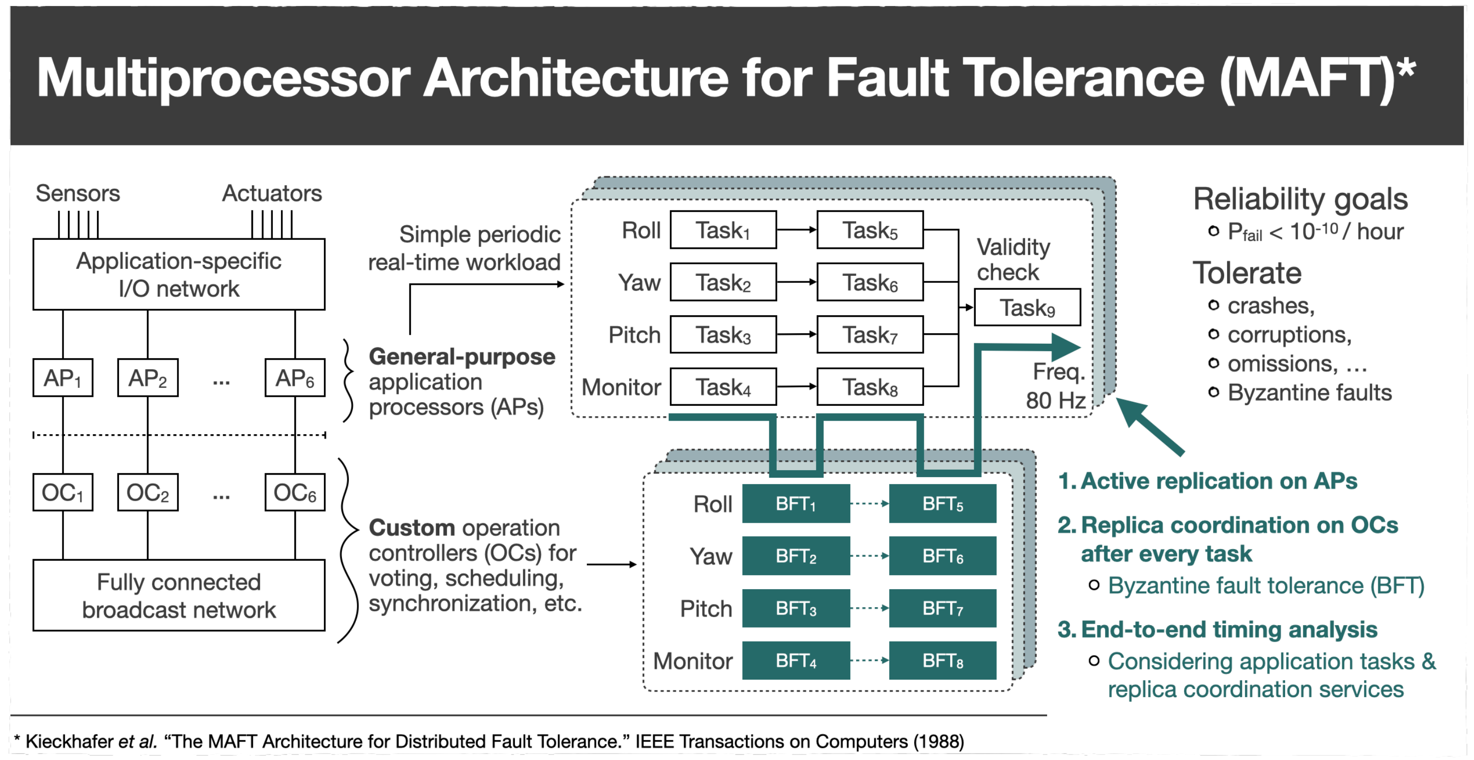


Few domains use custom hardware

Let alone for Byzantine fault tolerance

1. Focused on **BFT** with **real-time predictability**

Easy to build a drone using off-the-shelf hardware and open-source software

But no BFT solutions that can be retrofitted onto these real-time platforms

2. Deployable on **COTS platforms** like Raspberry Pis and Ethernet

Bft-SMaRt
High-performance Byzantine Fault-Tolerant State Machine Replication
APACHE ZooKeeper™
redis

In-ConcReTeS

Best-effort, throughput-oriented BFT libraries are not suitable

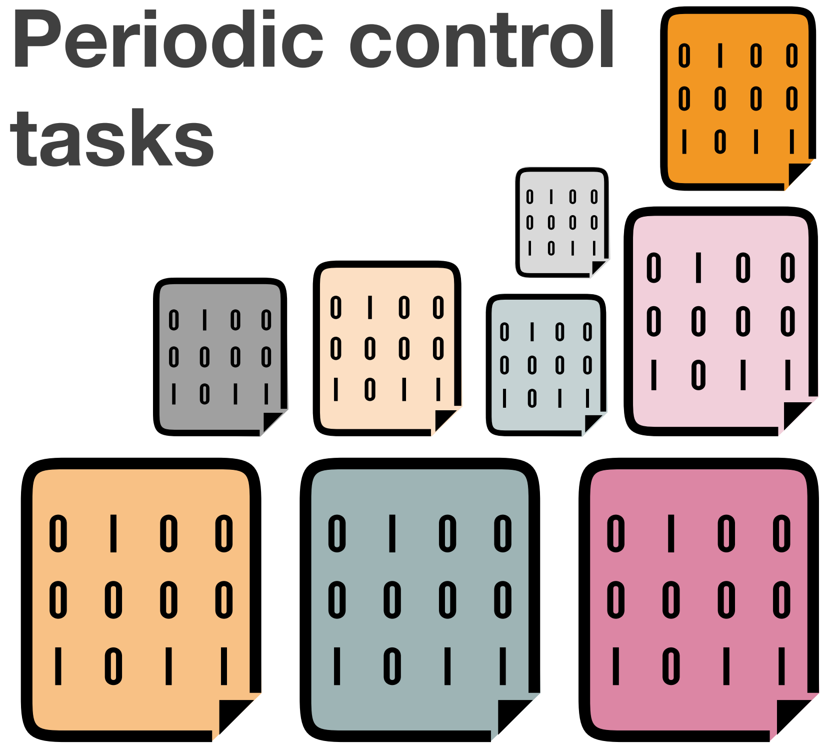
Performance suffers on resource-constrained embedded device or in terms of predictability

3. **Easy to integrate** with existing control applications

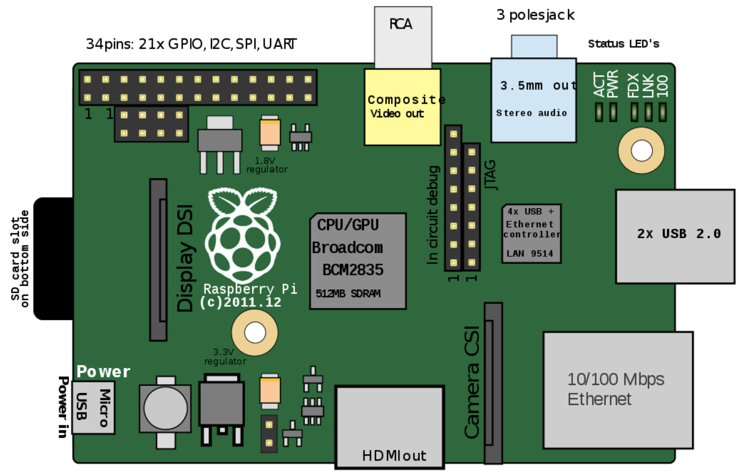
Design and Implementation

Overview

Periodic control tasks



Embedded platform (node 1)



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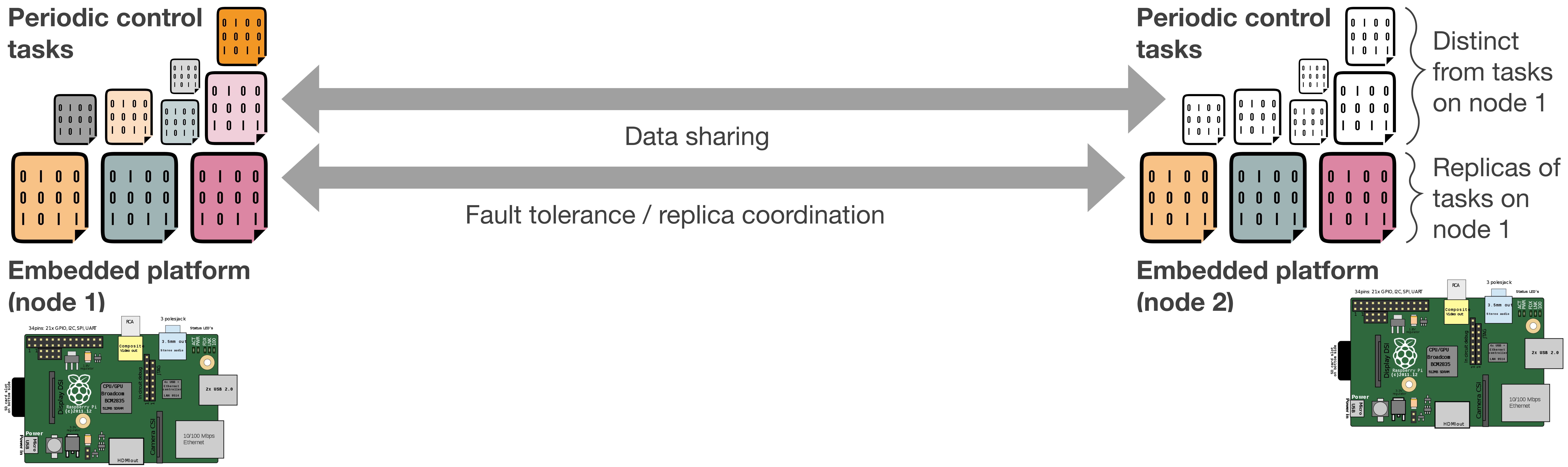
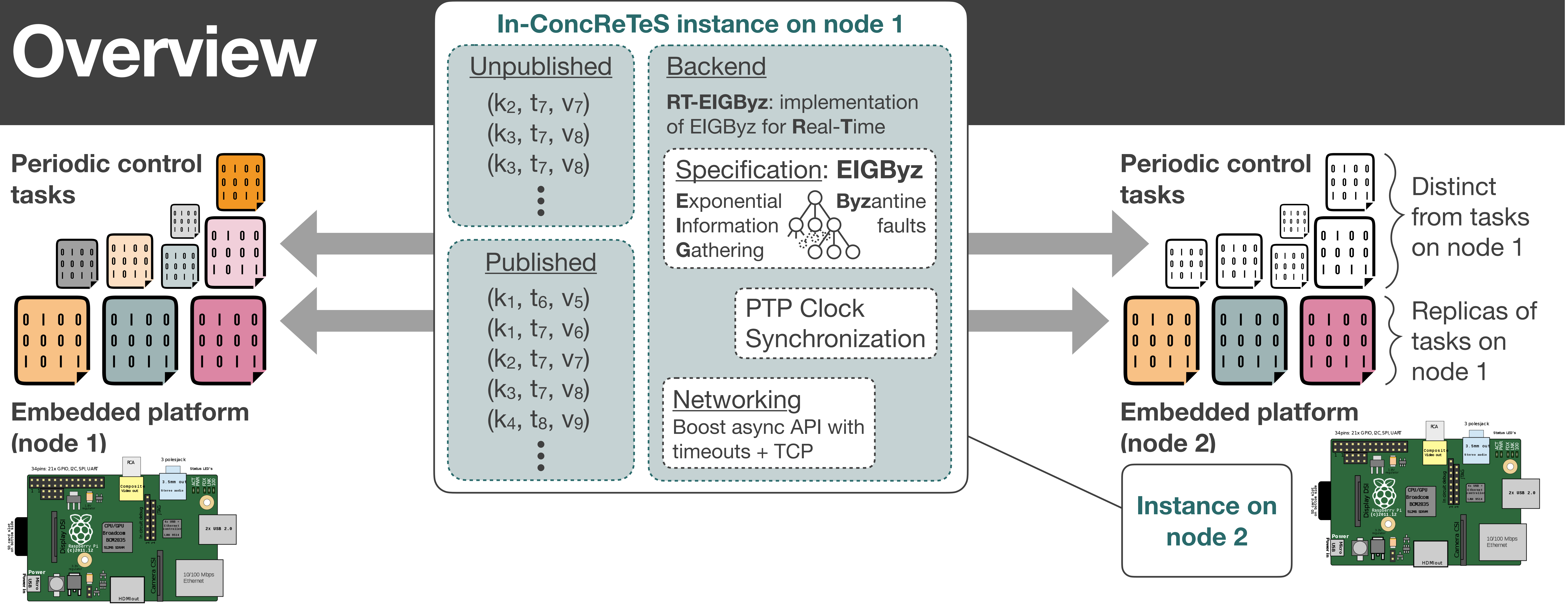

Periodic control tasks
Embedded platform (node 1)
Data sharing
Fault tolerance / replica coordination
Periodic control tasks
Distinct from tasks on node 1
Replicas of tasks on node 1
Embedded platform (node 2)

Overview



In-ConcReTeS instance on node 1
Unpublished
(k_2, t_7, v_7)
(k_3, t_7, v_8)
(k_3, t_7, v_8)
⋮
Published
(k_1, t_6, v_5)
(k_1, t_7, v_6)
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(k_4, t_8, v_9)
⋮
Backend
RT-EIGByz: implementation of EIGByz for **R**eal-**T**ime
Specification: **EIGByz**
Exponential **I**nformation **G**athering
Byzantine faults
PTP Clock Synchronization
Networking
Boost async API with timeouts + TCP
Periodic control tasks
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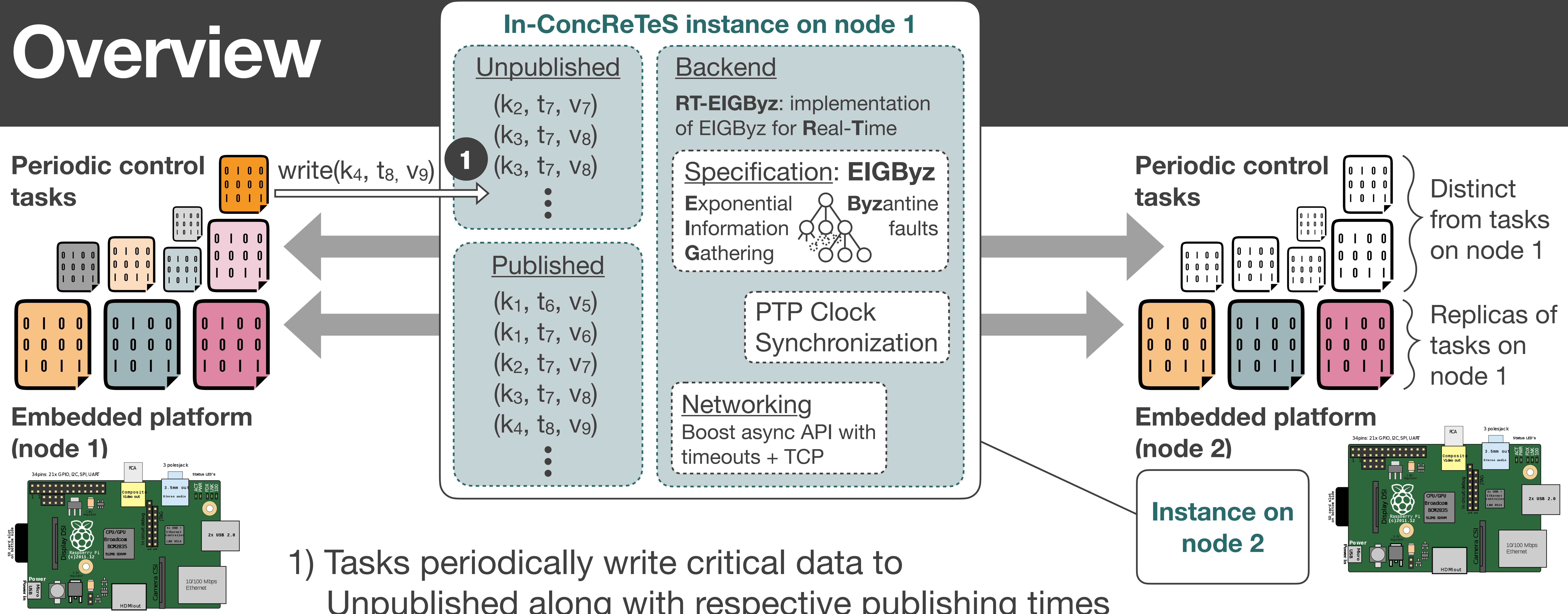
Instance on node 2

Overview



1) Tasks periodically write critical data to
Unpublished along with respective publishing times

Overview

In-ConcReTeS instance on node 1

Periodic control tasks

write(k_4, t_8, v_9)

Unpublished

(k_2, t_7, v_7)
(k_3, t_7, v_8)
(k_3, t_7, v_8)
⋮

Published

(k_1, t_6, v_5)
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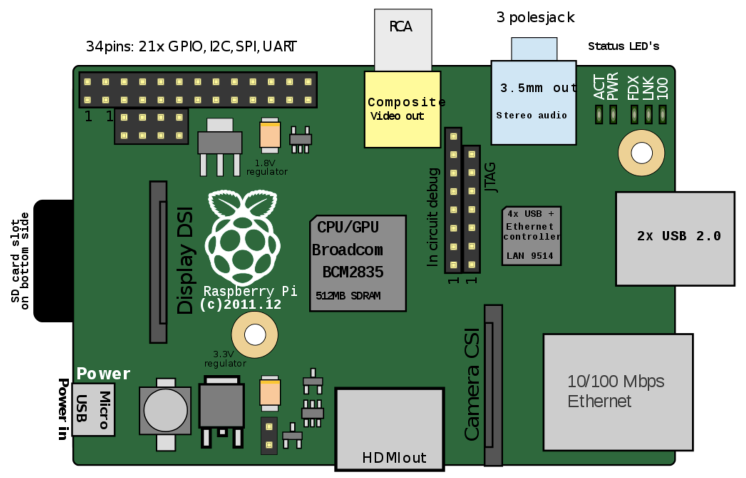

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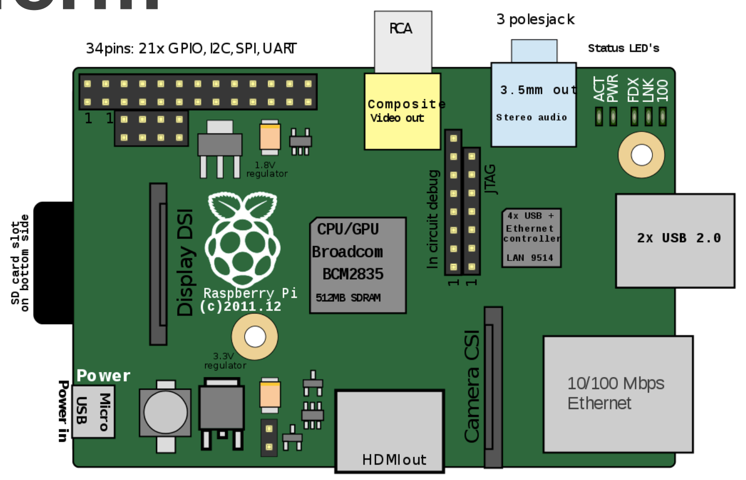
Embedded platform (node 2)

Instance on node 2



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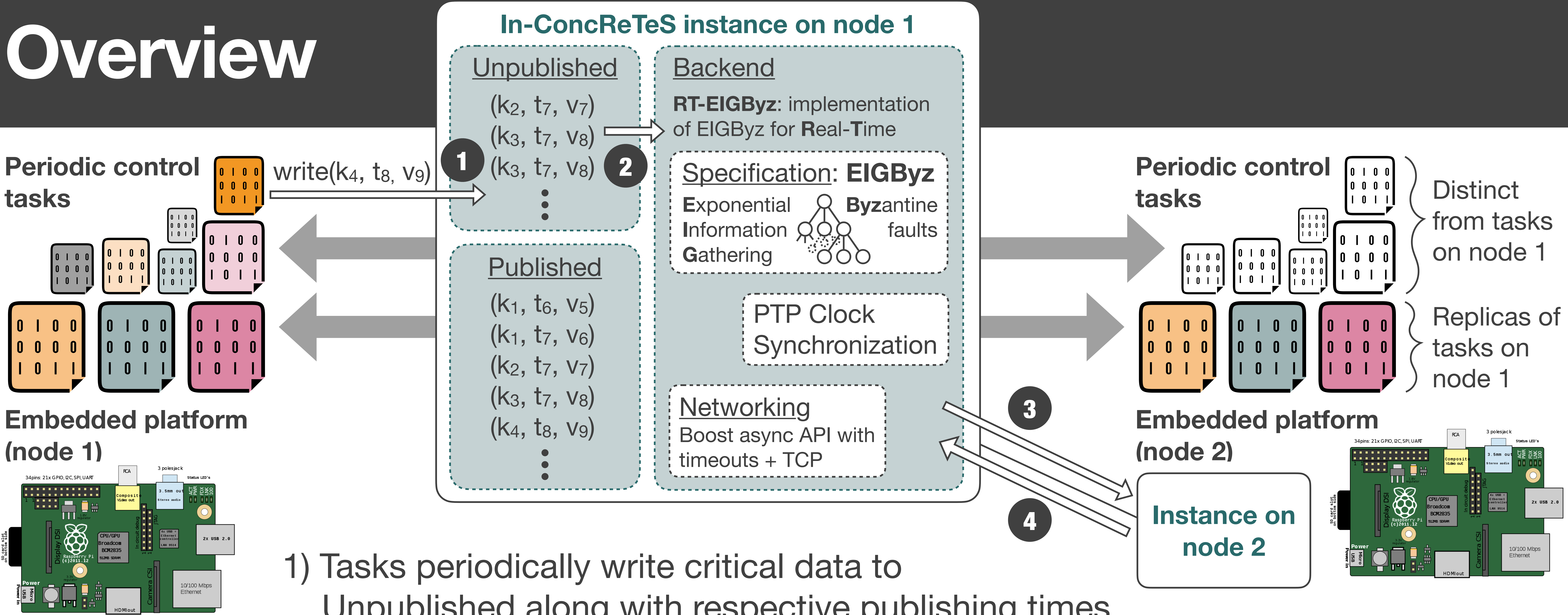

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3, 4) Backend coordinates with remote nodes so that all replicas agree on the same set of values

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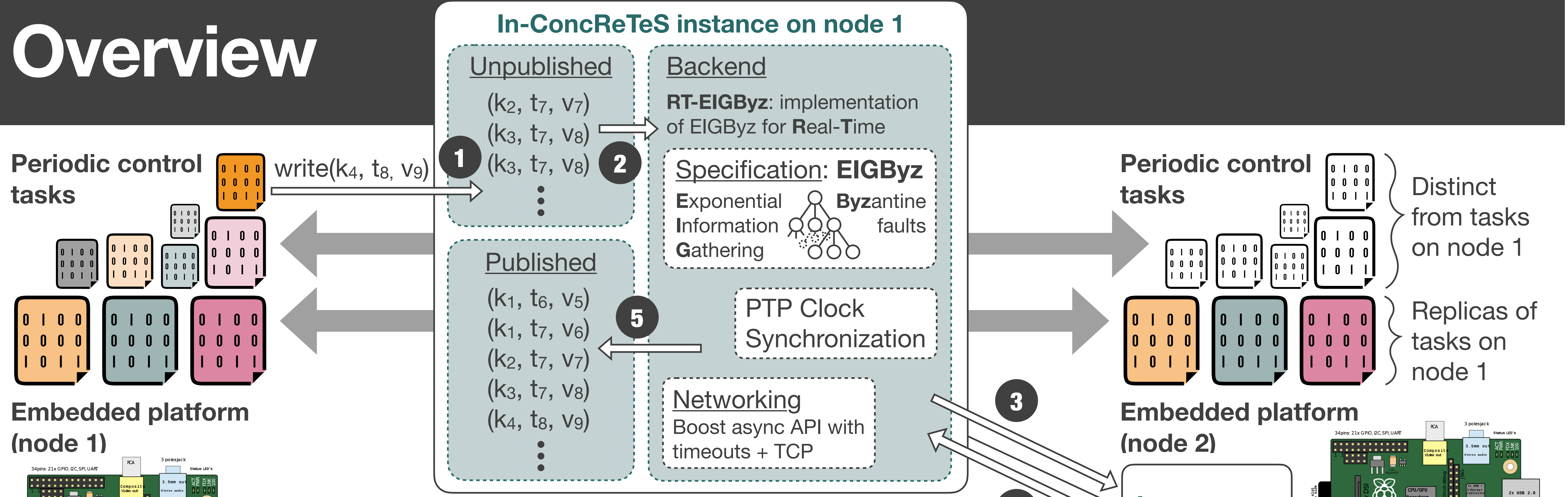

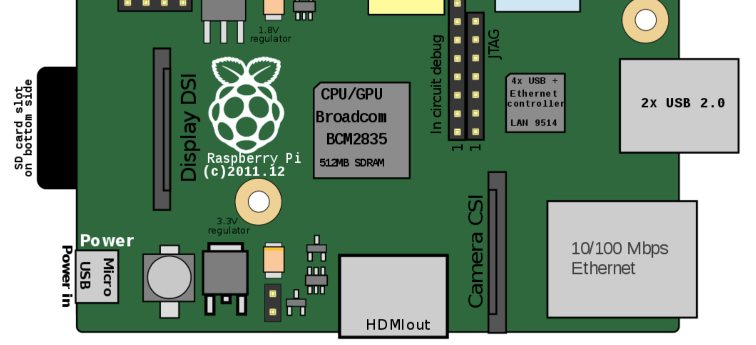

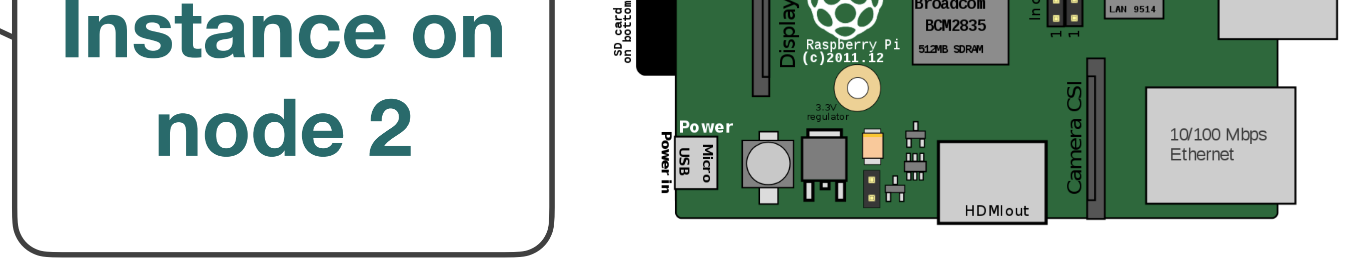

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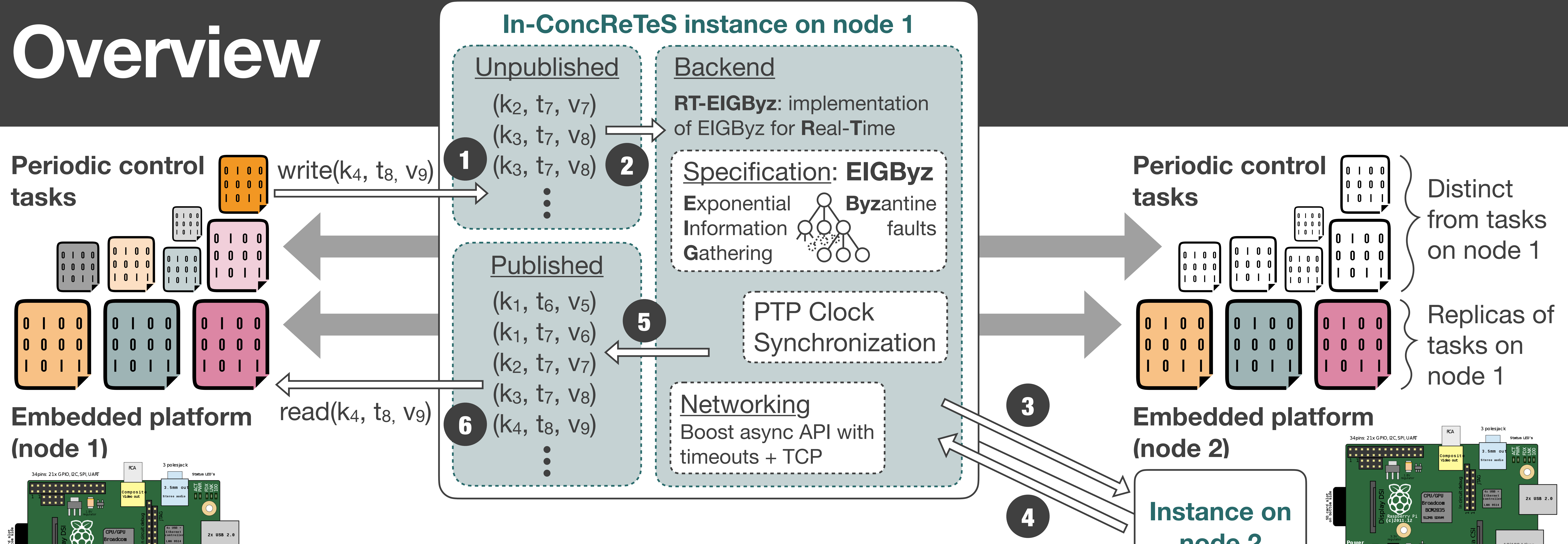

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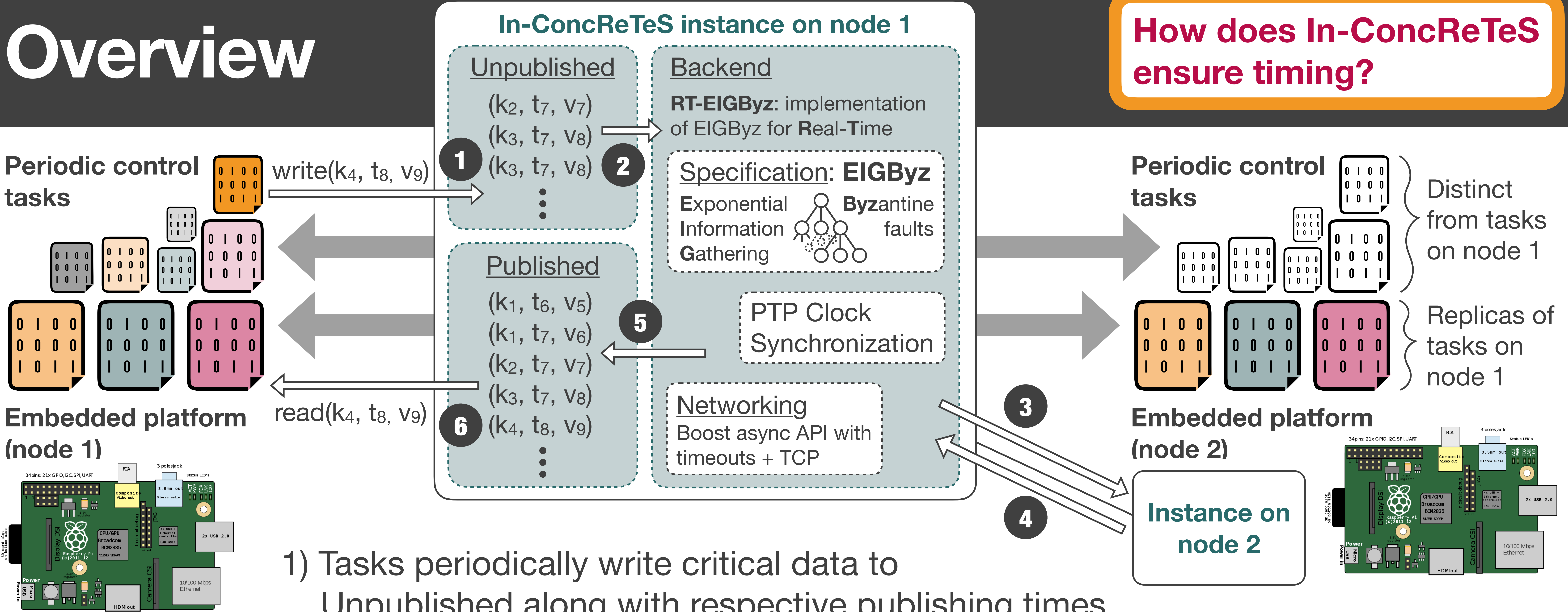

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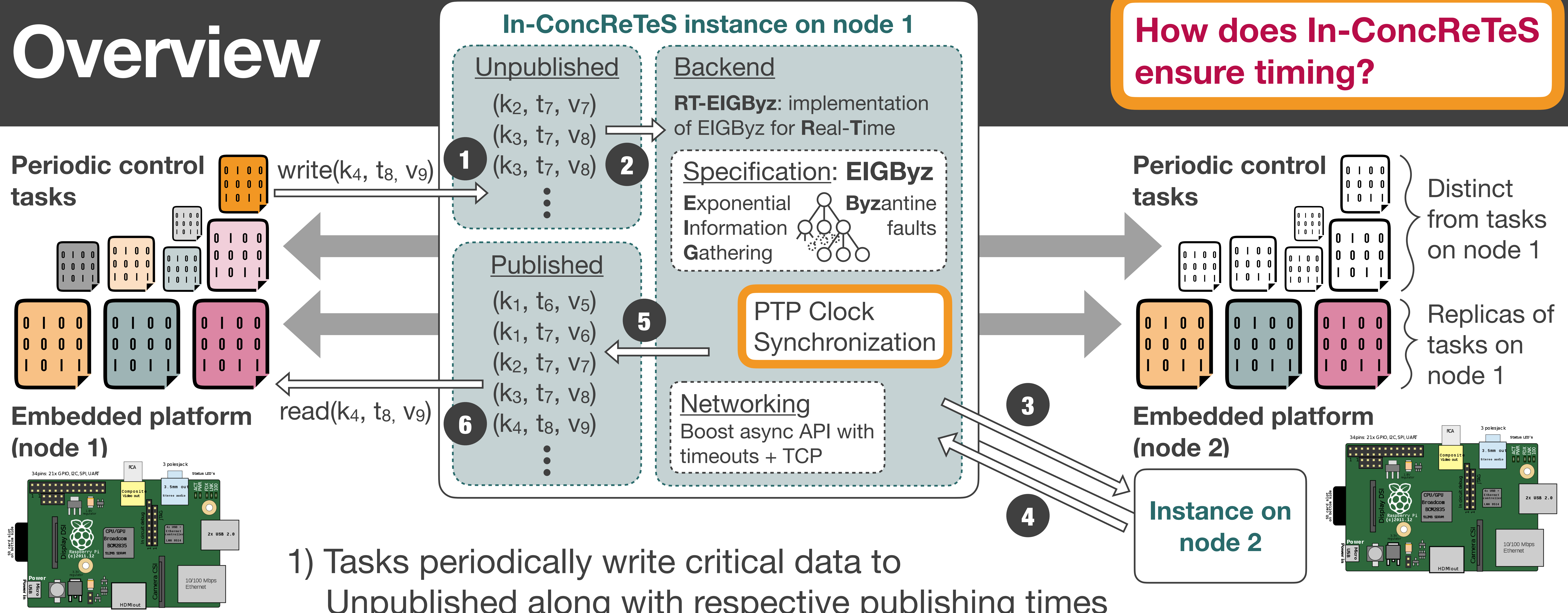
Overview

How does In-ConcReTeS ensure timing?



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Key Idea 1: Time-aware Key-value API inspired by LET*

* Kirsch and Sokolova. "The Logical Execution Time Paradigm." Advances in Real-Time Systems (2012)

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Algorithm 1 Controller interfaced with In-ConcReTeS

```
procedure KVSBackedInvertedPendulum
    time ← LastActivationAt()                              ▷ Compute freshness constraint
    globalTarget ← KVS.read("target", time)                ▷ Get globally consistent
    globalIntegral ← KVS.read("integral", time)            ▷ ... values of key
    globalError ← KVS.read("error", time)                  ▷ ... parameters
    current ← GetSensorData()
    error ← globalTarget − current
    integral ← globalIntegral + error
    derivative ← error − globalError
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Algorithm 1 Controller interfaced with In-ConcReTeS

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API enables **static analysis** as it informs about the time budget available for replica coordination

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Key Idea 2: Interactive Consistency[1] → EIGByz[2] → RT-EIGByz

[1] Kieckhafer *et al.* “The MAFT Architecture for Distributed Fault Tolerance.” IEEE Transactions on Computers (1988)

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Byzantine agreement problem

- **Consensus over a vector of data**
- Enables **application-specific voting**, such as using median or weighted mean

Node 1 Node 2 Node 3 All nodes agree on this

$$\begin{bmatrix} v_{1,1} \\ v_{1,2} \\ v_{1,3} \end{bmatrix}, \begin{bmatrix} v_{2,1} \\ v_{2,2} \\ v_{2,3} \end{bmatrix}, \begin{bmatrix} v_{3,1} \\ v_{3,2} \\ v_{3,3} \end{bmatrix} \xrightarrow{\text{Interactive Consistency}} \begin{bmatrix} \mathbf{v_1} \\ \mathbf{v_2} \\ \mathbf{v_3} \end{bmatrix} \xrightarrow{\text{Application-specific voting function}} \mathbf{v_{final}}$$

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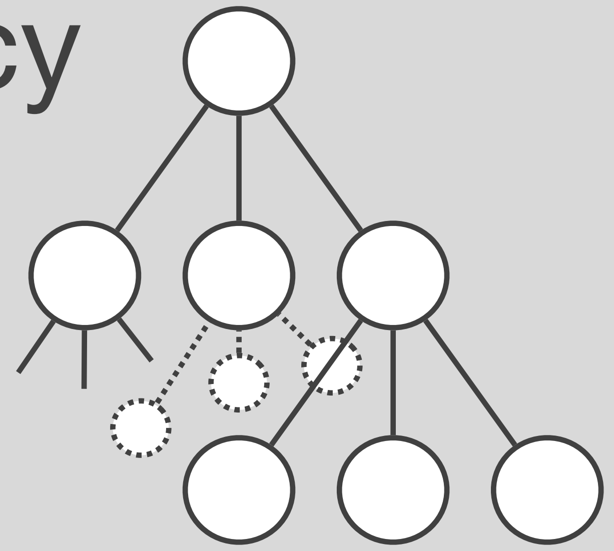
Synchronous leader-free protocol for interactive consistency

- EIG trees
- Clock synchronization
- Deterministic rounds



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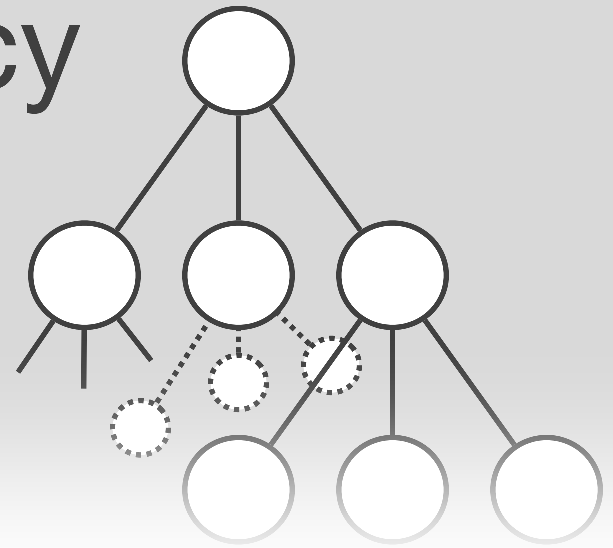

Predictable real-time friendly implementation of EIGByz

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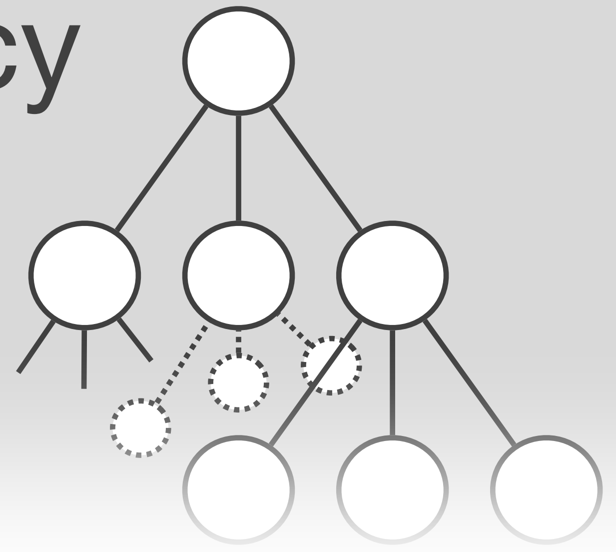

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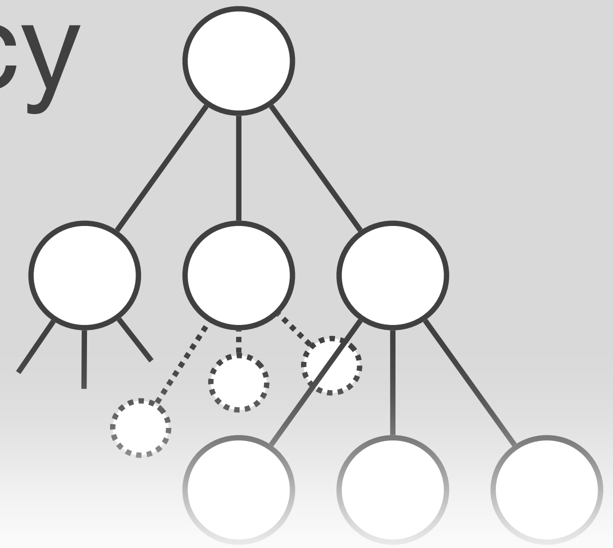

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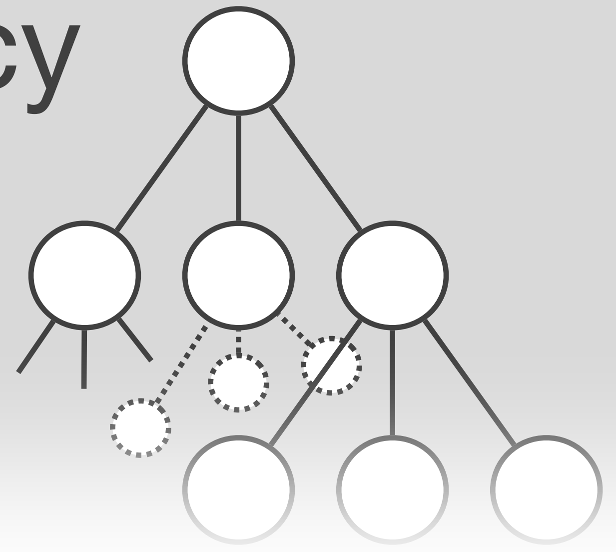

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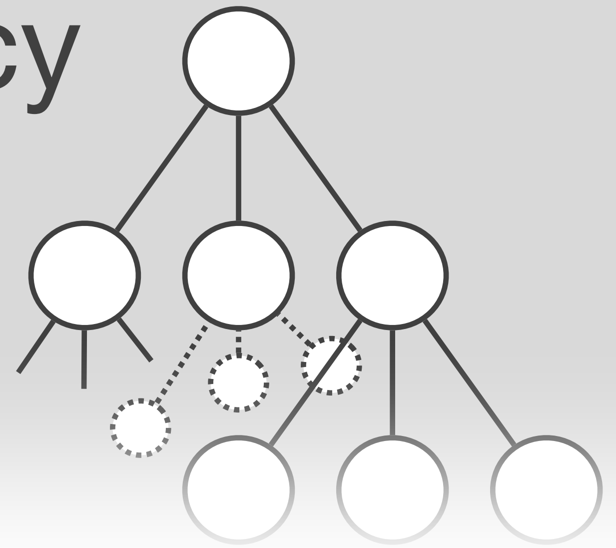

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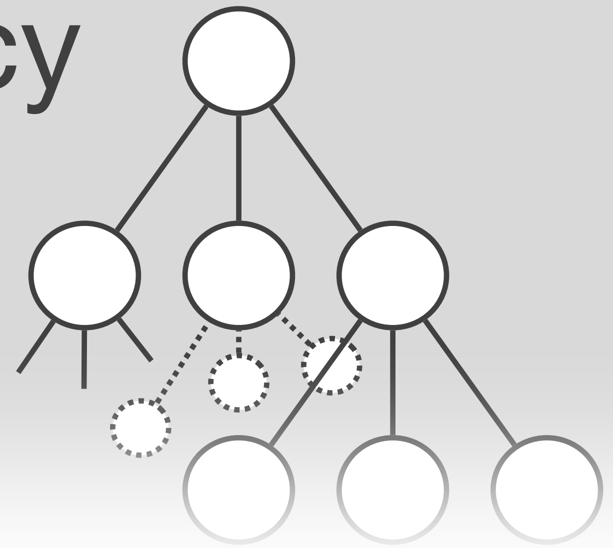

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- Batching → multiples keys

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Implementation

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RT-EIGByz realized as a **single-threaded real-time periodic task**

- Implemented in C++ using Linux's `clock_gettime` and `clock_nanosleep` APIs

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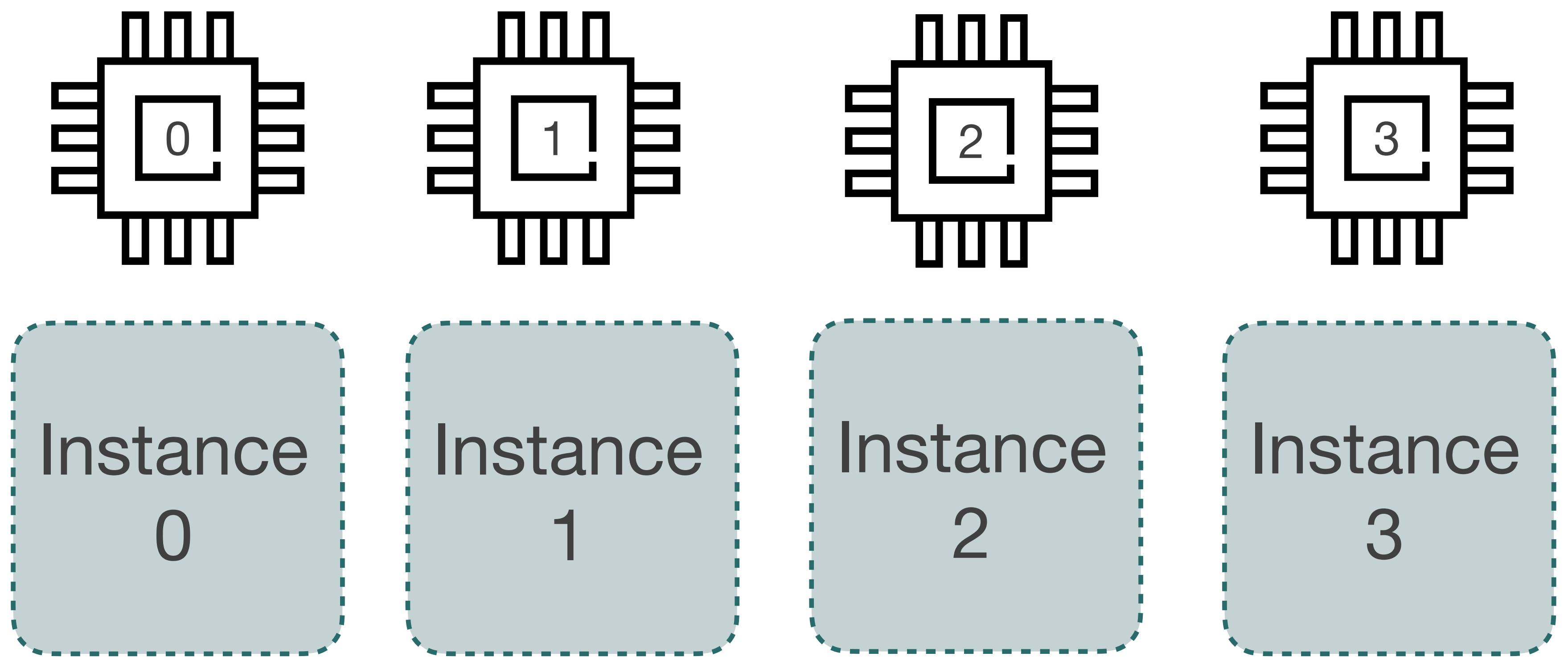

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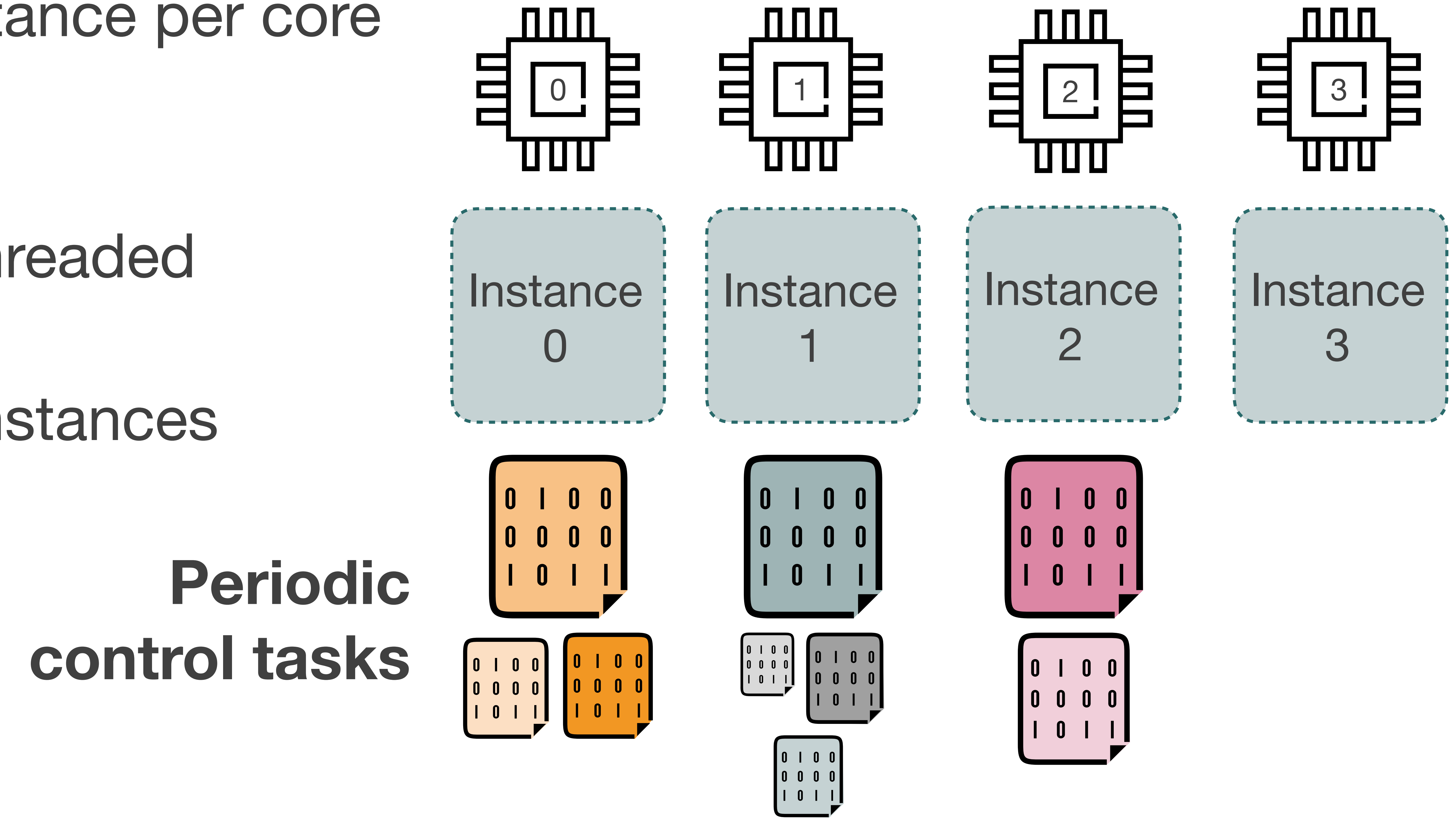
Control applications

- Also modelled as single-threaded real-time periodic tasks
- Interface with core-local instances



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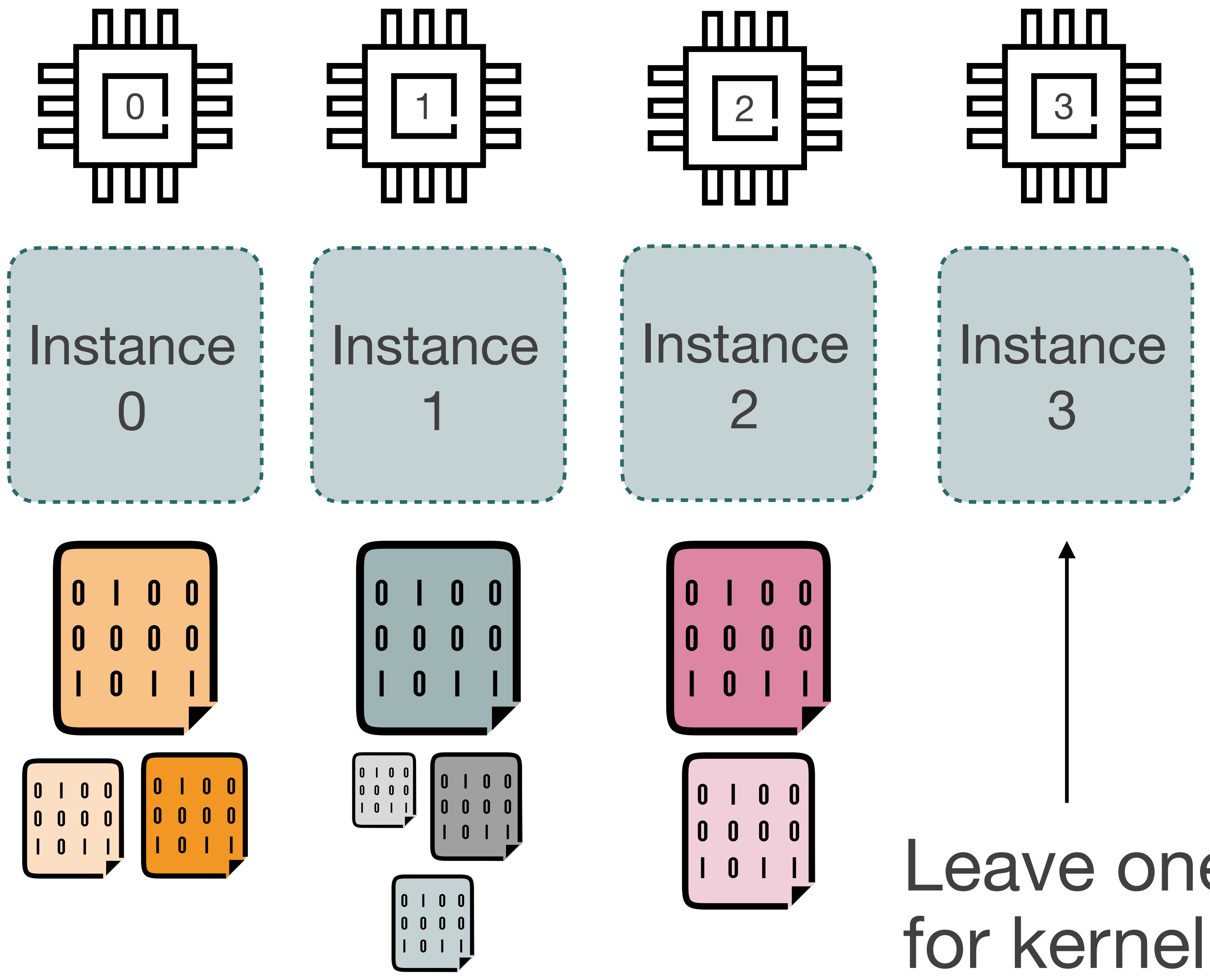


Periodic control tasks

Leave one core **idle** for kernel and networking utilities

Evaluation

Questions

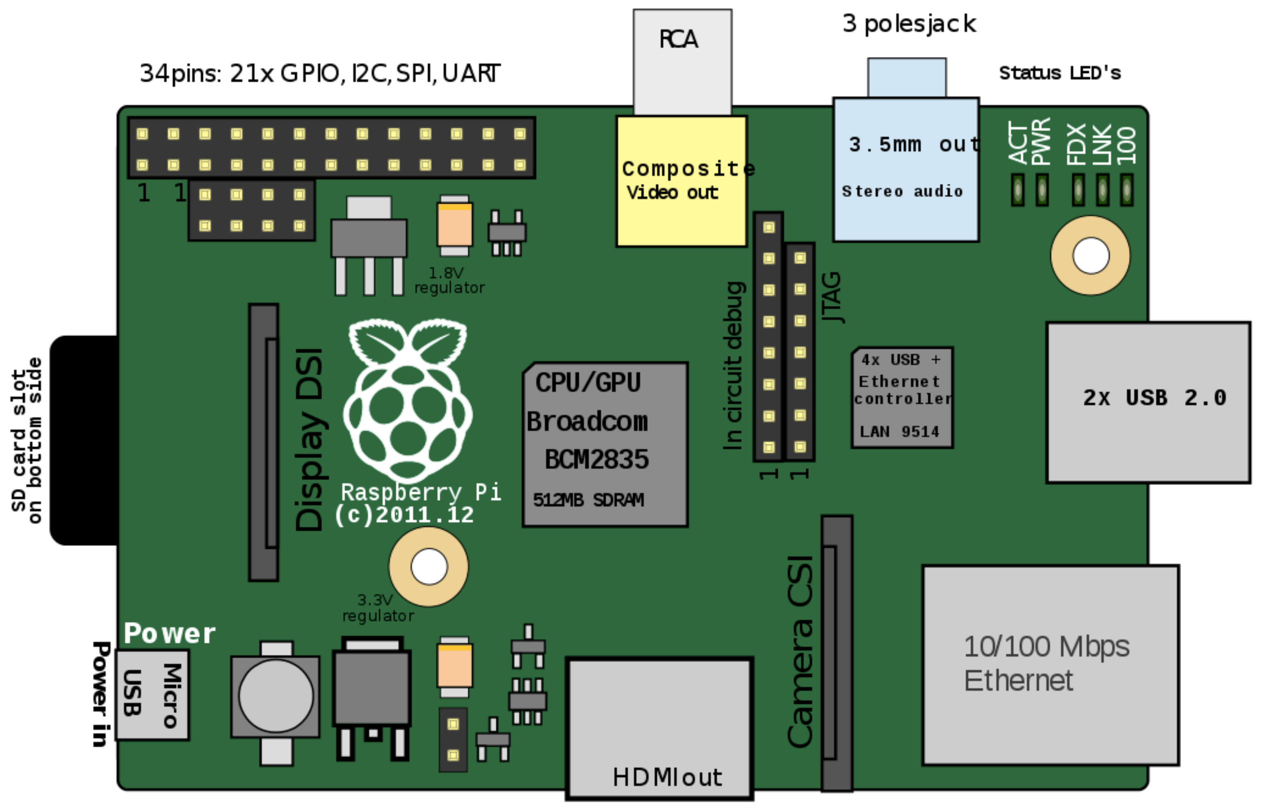
How does In-ConcReTeS compare against well-known KVS?

Can In-ConcReTeS deal with complex distributed real-time workloads?

Setup

Four Raspberry Pi 4 Model B units

- Cortex A72 **quad-core** processor
- 4GB memory
- Raspbian GNU/Linux 10
- **Ethernet**



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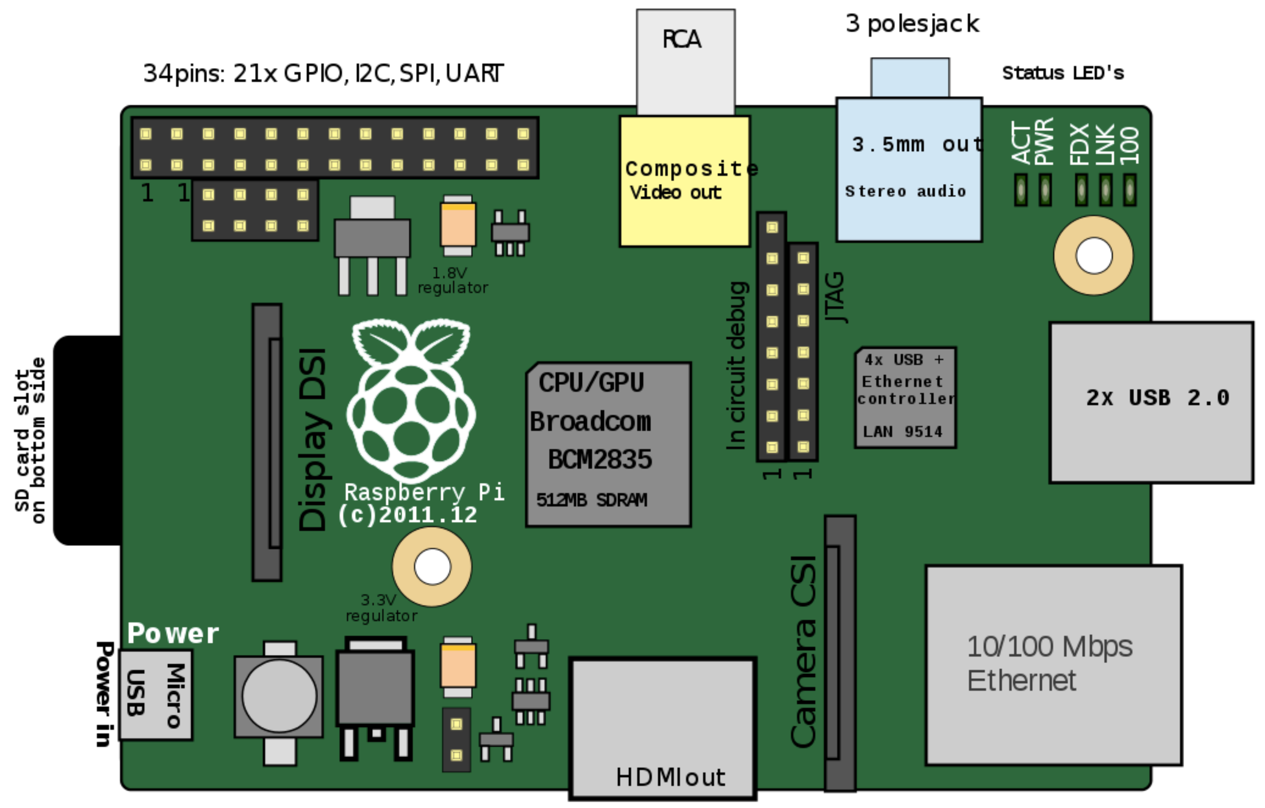
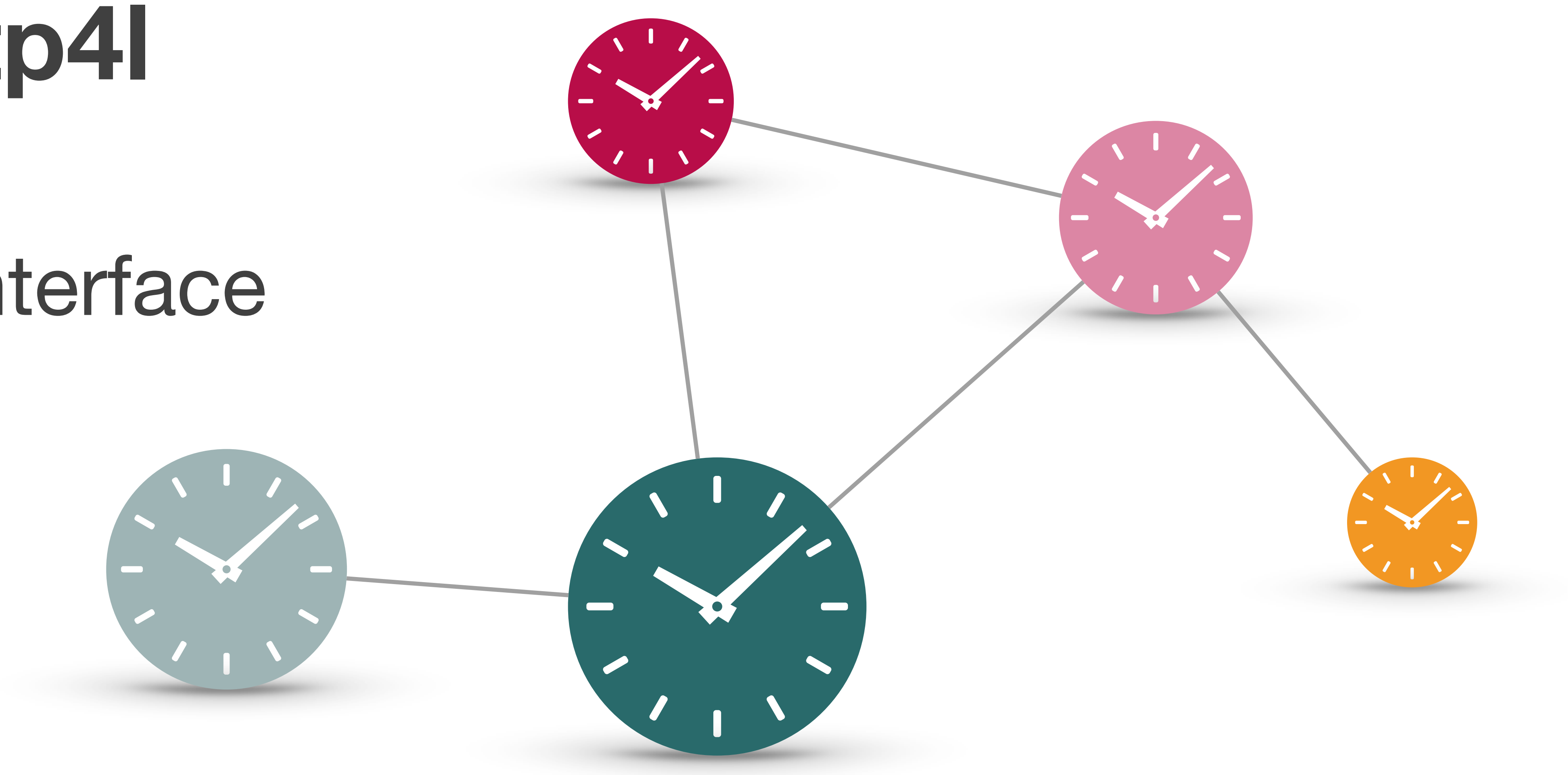


Clock synchronization using **ptp4l**

- Highest real-time priority
- Uses a separate virtual network interface
- **Software time-stamping**



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redis

In-memory data store

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Single-threaded C server

- Not designed to benefit from multiple cores
- Like Achal, **one instance per each core, on each Pi**

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Query all
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Strongly consistent, distributed

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- Raft Consensus for fault tolerance
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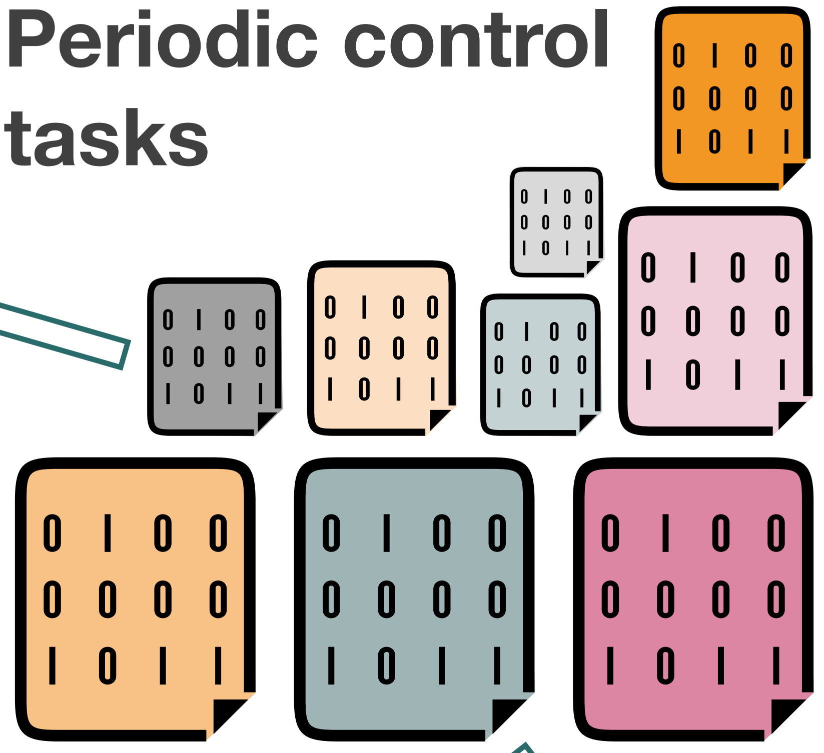
Core-local proxies

Periodic control tasks



Mimic In-ConcReTeS's real-time periodic task model, time-aware API

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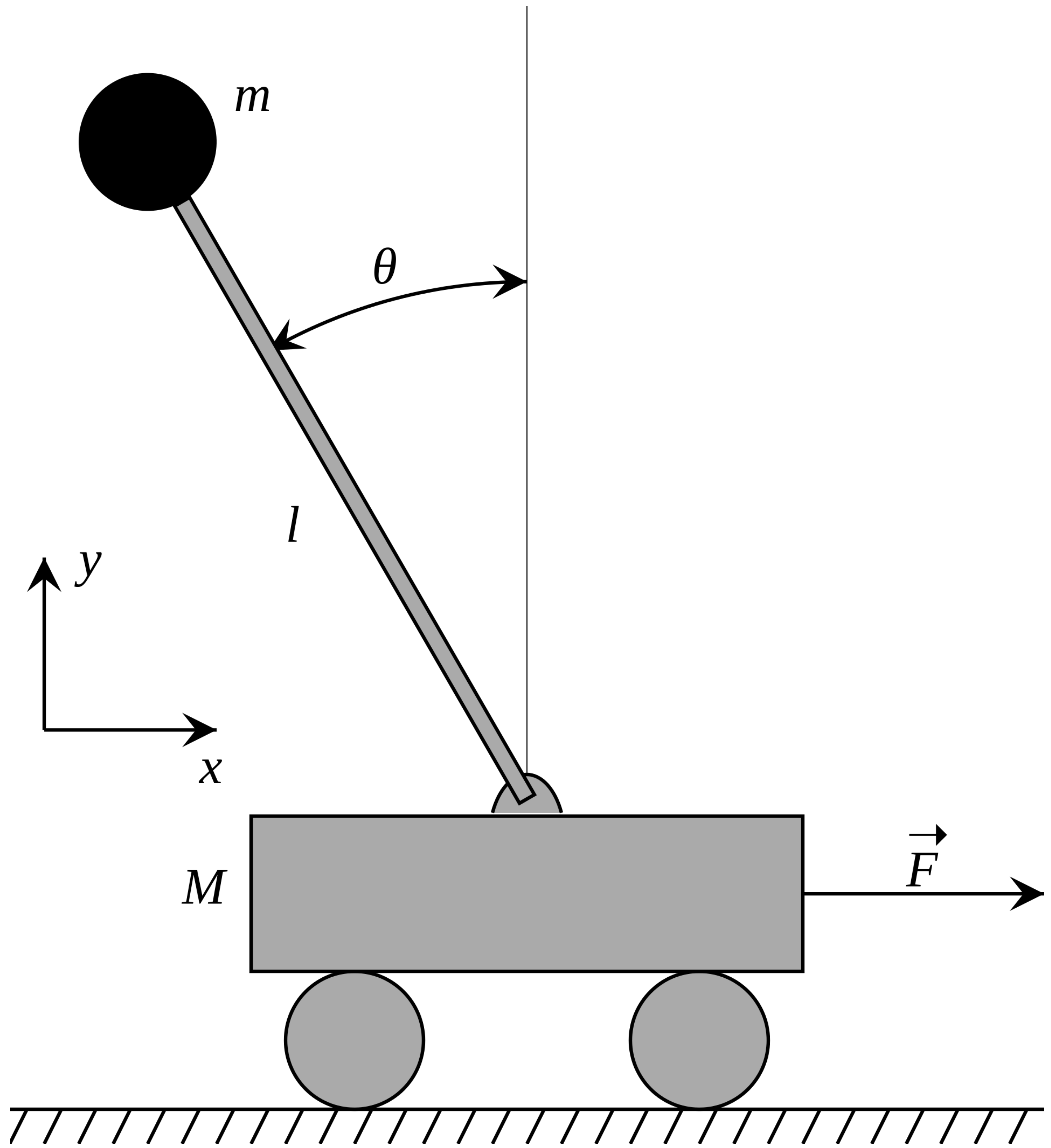
Workload: Inverted Pendulum Simulation*



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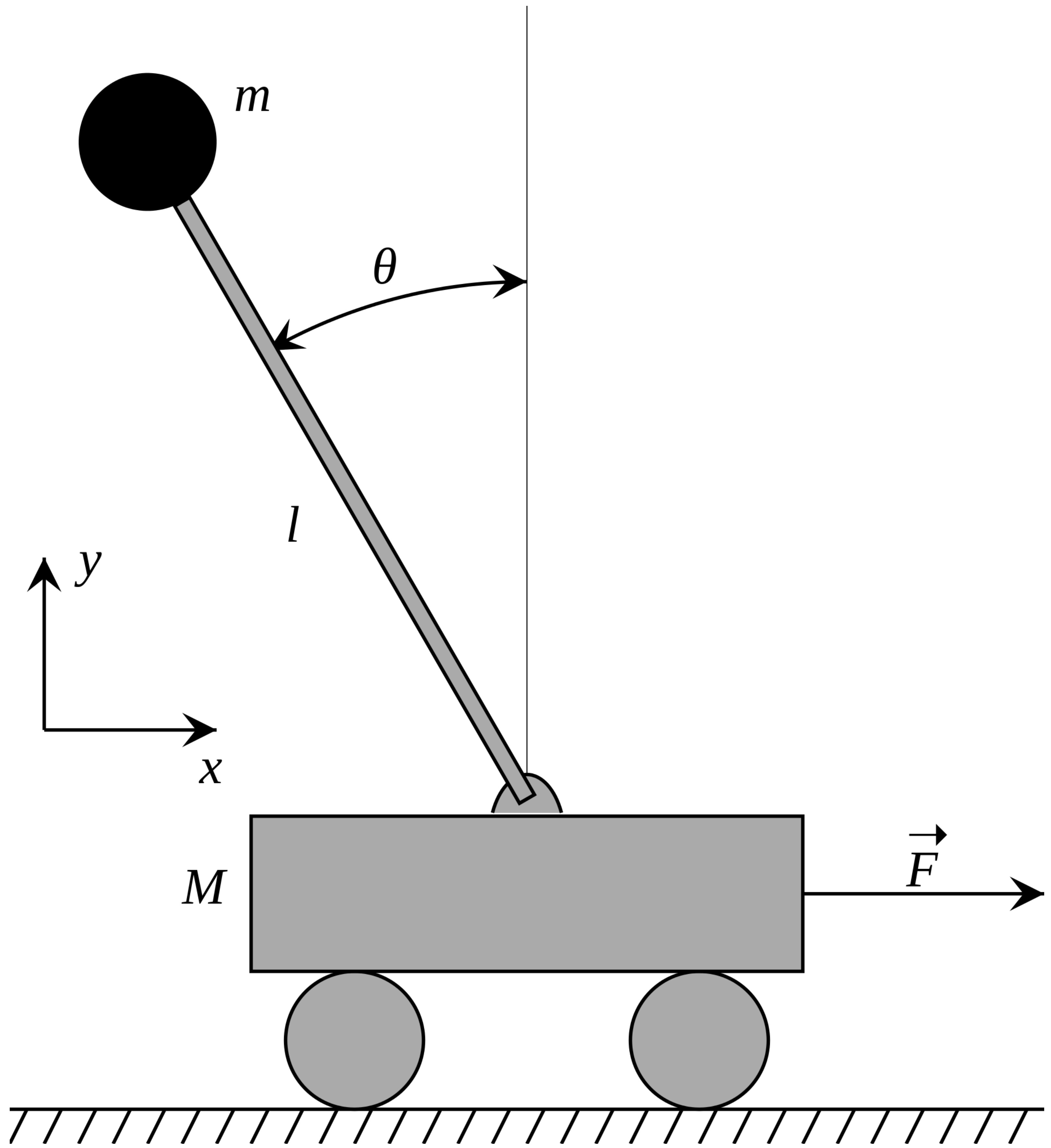
Workload: Inverted Pendulum Simulation*

Prototypical control application

IvPSim

- Periodic real-time task
- Reads and writes 19 floats to the datastore
- Time period can be adjusted



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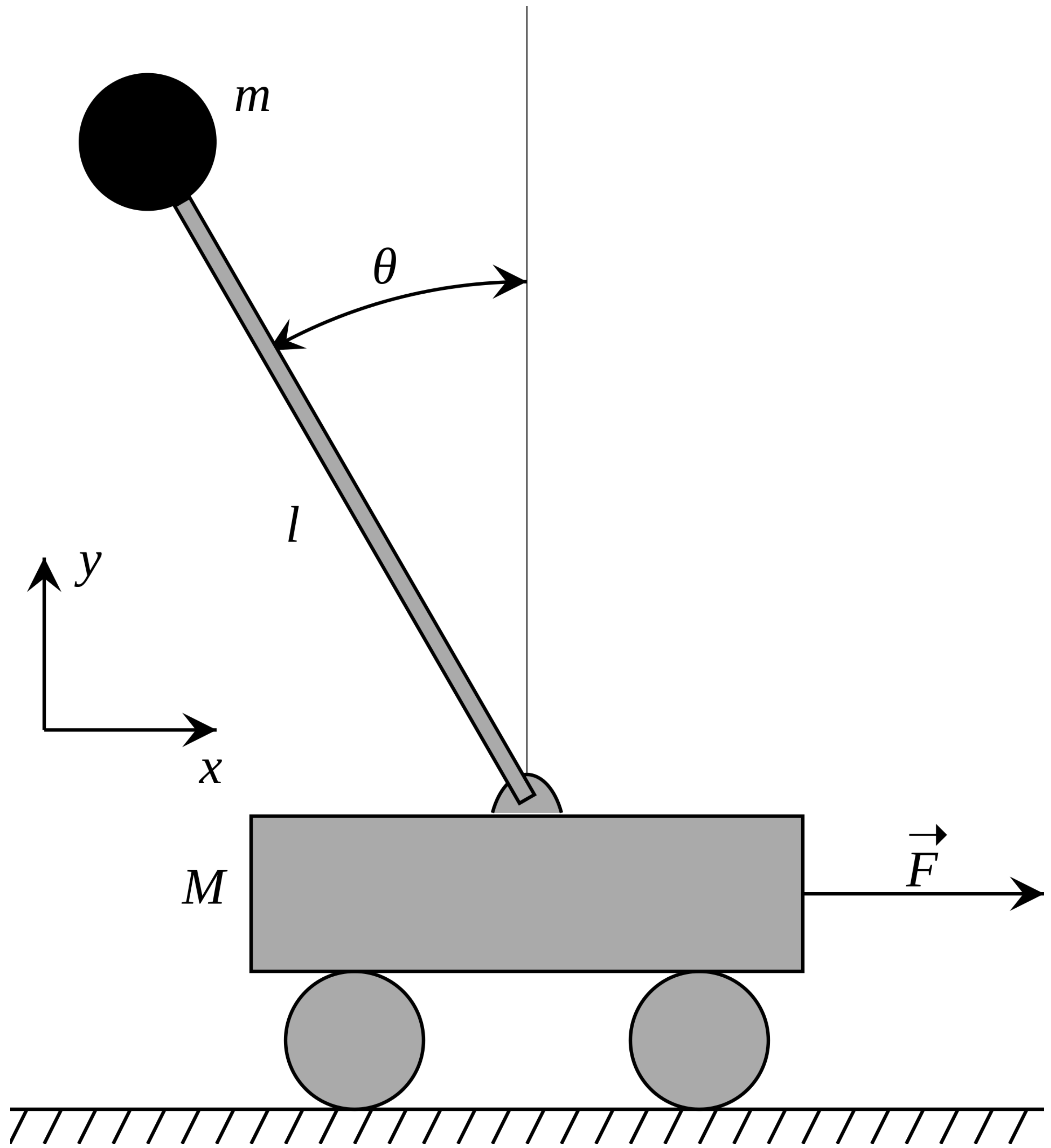
Objective

- Run replicas of IvPSim on separate nodes synchronously



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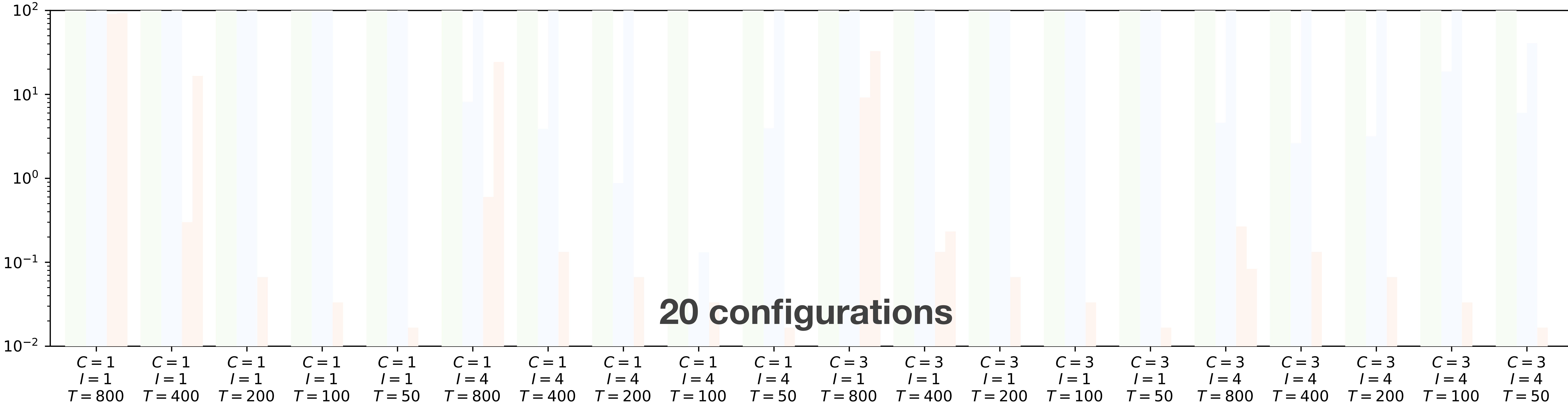
Results



10^2
10^1
10^0
10^{-1}
10^{-2}
20 configurations
$C=1$, $I=1$, $T=800$
$C=1$, $I=1$, $T=400$
$C=1$, $I=1$, $T=200$
$C=1$, $I=1$, $T=100$
$C=1$, $I=1$, $T=50$
$C=1$, $I=4$, $T=800$
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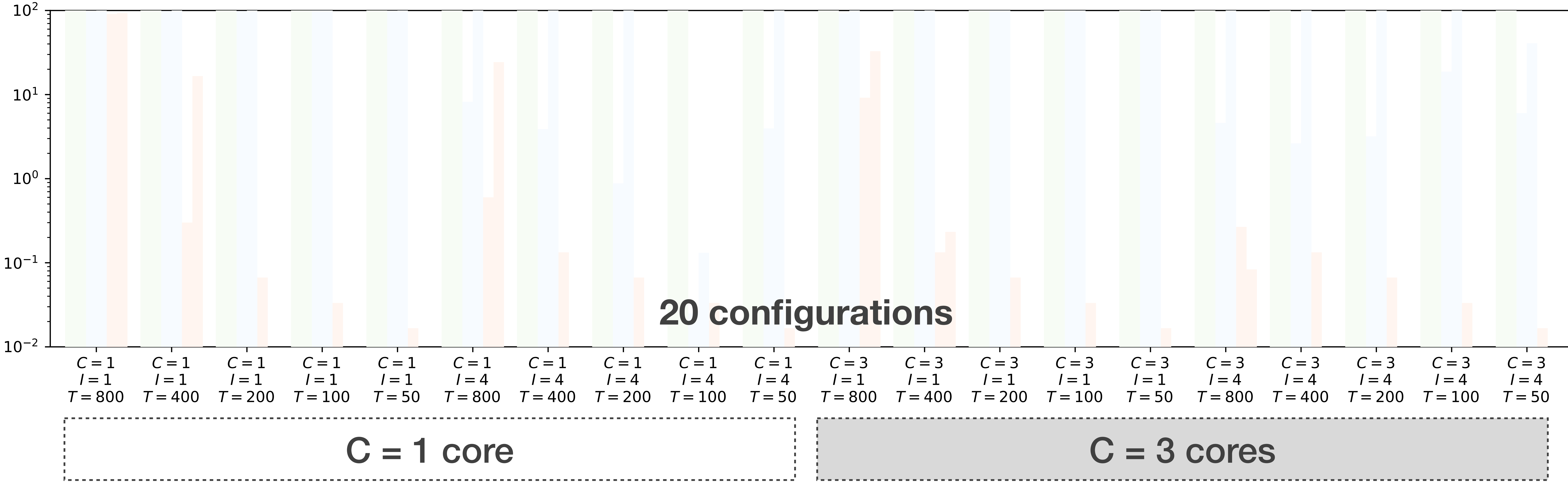

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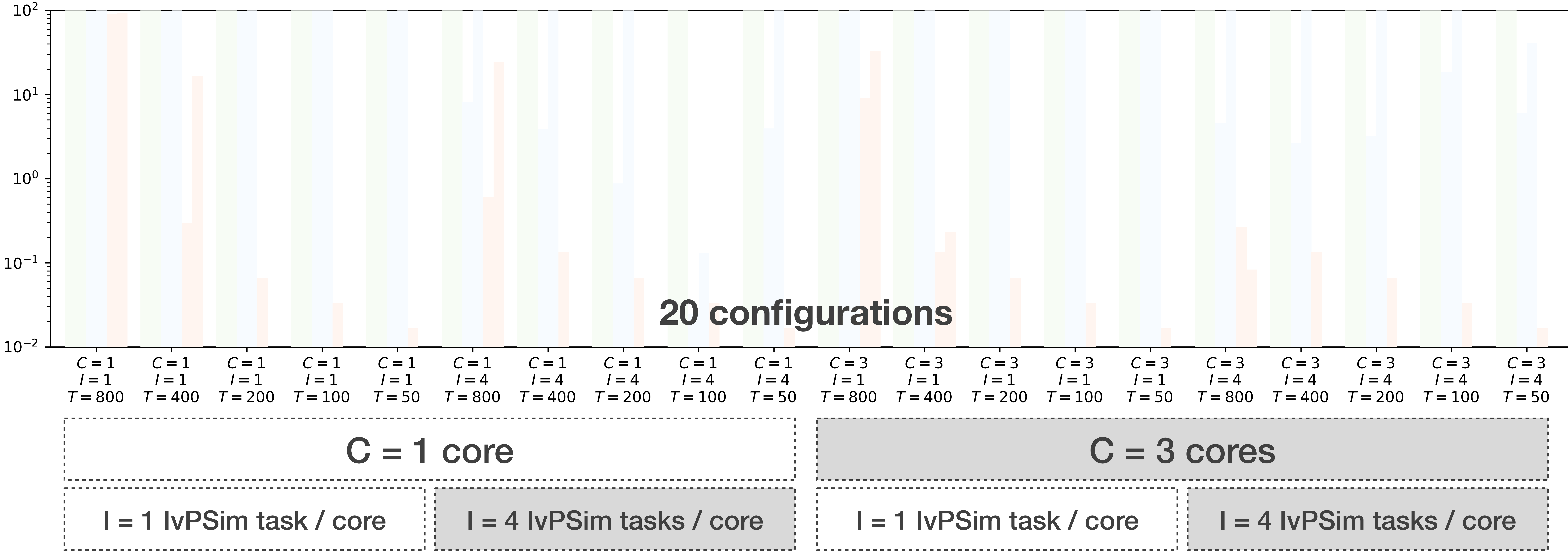
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$C=1$ $I=1$ $T=800$
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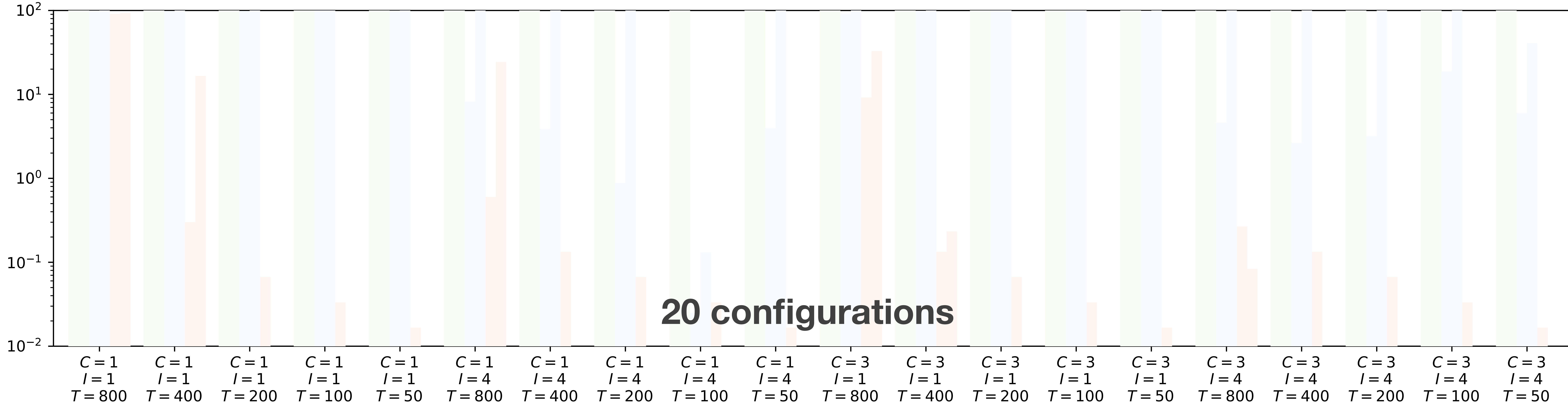
$C=1$ $I=1$ $T=200$
$C=1$ $I=1$ $T=100$
$C=1$ $I=1$ $T=50$
$C=1$ $I=4$ $T=800$
$C=1$ $I=4$ $T=400$
$C=1$ $I=4$ $T=200$
$C=1$ $I=4$ $T=100$
$C=1$ $I=4$ $T=50$
$C=3$ $I=1$ $T=800$
$C=3$ $I=1$ $T=400$
$C=3$ $I=1$ $T=200$
$C=3$ $I=1$ $T=100$
$C=3$ $I=1$ $T=50$
$C=3$ $I=4$ $T=800$
$C=3$ $I=4$ $T=400$
$C=3$ $I=4$ $T=200$
$C=3$ $I=4$ $T=100$
$C=3$ $I=4$ $T=50$
C = 1 core
C = 3 cores
I = 1 IvPSim task / core
I = 4 IvPSim tasks / core
I = 1 IvPSim task / core
I = 4 IvPSim tasks / core

Results



C = 1 core | C = 3 cores

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Decreasing Period → | Decreasing Period → | Decreasing Period → | Decreasing Period →

Results

Evaluation metrics

- For read operations, percentage of IvPSim iterations during which all reads succeeded
- Respectively, for writes …

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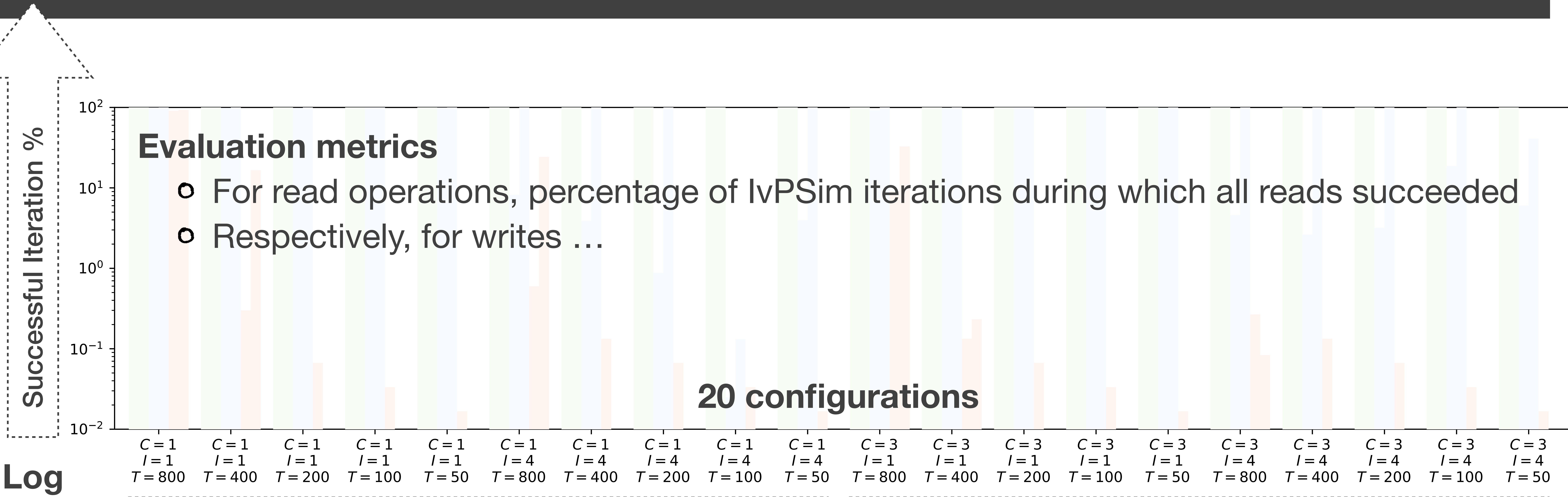

Log scale

Higher is better!

C = 1 core		C = 3 cores	
I = 1 IvPSim task / core	I = 4 IvPSim tasks / core	I = 1 IvPSim task / core	I = 4 IvPSim tasks / core
Decreasing Period →	Decreasing Period →	Decreasing Period →	Decreasing Period →

Results

- **In-ConcReTeS success rate is 100%**

Results

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Results

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- etcd almost always underperforms

Redis and etcd are not build for timeliness on the timescales encountered in CPS

Questions

How does In-ConcReTeS compare against well-known KVS?

Can In-ConcReTeS deal with complex distributed real-time workloads?

Workload: Real-Automotive Benchmark from Bosch*

* Kramer *et al.* “Real World Automotive Benchmarks for Free.” WATERS (2015)

Workload: Real-Automotive Benchmark from Bosch*

TABLE I. DISTRIBUTION OF LABEL SIZES

Size (byte)	Share
1	35 %
2	49 %
4	
5 - 8	
9 - 16	
17 - 32	
33 - 64	
> 64	

TABLE II. INTER-TASK COMM

Period	1 ms	2 ms	5 ms	10 ms	20 ms	50 ms				
1 ms				I	I					
2 ms				I	I					
5 ms		I	IV	IV	II	II				
10 ms	II	II	II	VI	IV	II	IV	II	III	IV
20 ms	I	I	I	IV	VI	II	IV	I	II	IV
50 ms			II	II	II	III	I			
100 ms		I	I	V	IV	II	VI	II	III	IV
200 ms				I	I		I	I	I	
1000 ms				III	II		III	I	IV	I
Angle-sync	I	I	I	IV	IV	I	III	I	I	V

TABLE III. RUNNABLE DISTRIBUTION AMONG PERIODS

Period	Share
1 ms	3 %
2 ms	2 %
5 ms	
10 ms	
20 ms	
50 ms	
100 ms	

TABLE IV. RUNNABLE AVERAGE EXECUTION

Period	Average Execution Tim		
	Min.	Avg.	
1 ms	0,34	5,00	
2 ms	0,32	4,20	
5 ms	0,36	11,04	
10 ms	0,21	10,09	
20 ms	0,25	8,74	
50 ms	0,29	17,56	
100 ms	0,21	10,53	
200 ms	0,22	2,56	
1000 ms	0,37	0,43	
angle-synchronous	0,45	6,52	
Interrupts	0,18	5,42	12,59

TABLE V. FACTORS FOR DETERMINING RUNNABLE BEST- AND WORST-CASE EXECUTION TIMES

Period	Best		Worst	
	f_{min}	f_{max}	f_{min}	f_{max}
1 ms	0,19	0,92	1,30	29,11
2 ms	0,12	0,89	1,54	19,04
5 ms	0,17	0,94	1,13	18,44
10 ms	0,05	0,99	1,06	30,03
20 ms	0,11	0,98	1,06	15,61
50 ms	0,32	0,95	1,13	7,76
100 ms	0,09	0,99	1,02	8,88
200 ms	0,45	0,98	1,03	4,90
1000 ms	0,68	0,80	1,84	4,75
angle-synchronous	0,13	0,92	1,20	28,17
Interrupts	0,12	0,94	1,15	4,54

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Workload: Real-Automotive Benchmark from Bosch*

Generated multiple random workload instances

- Mix of tasks with time periods in {50, 100, 200, 1000} ms
- Number of keys between 100 and 1000
- Value sizes ranging from 1 to 16 bytes

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Metrics: Successful iteration % for read operations

- Writes to the local unpublished datastore are always successful

* Kramer *et al.* "Real World Automotive Benchmarks for Free." WATERS (2015)

Results

Keys	Read success %				KVS latency (ms)	
	Pi 1	Pi 2	Pi 3	Pi 4	ACET	WCET
270						
363						
476						
573						
689						
744						
849						
905						

Results

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	Pi 1	Pi 2	Pi 3	Pi 4	ACET	WCET
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476	100.00	100.00	100.00	100.00	14.87	32.88
573	100.00	100.00	100.00	99.85	17.50	35.36
689	100.00	100.00	100.00	100.00	17.89	35.62
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905						

Successful replica coordination for more complex workloads

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573	100.00	100.00	100.00	99.85	17.50	35.36
689	100.00	100.00	100.00	100.00	17.89	35.62
744	100.00	99.97	99.96	100.00	19.72	35.86
849	99.81	99.91	99.74	99.98	20.43	36.59
905	98.71	99.56	44.82	99.07	23.49	41.82

Successful replica coordination for more complex workloads

WCET closer to 50ms, which is also the T_{min}, results in little slack and increased deadline violations

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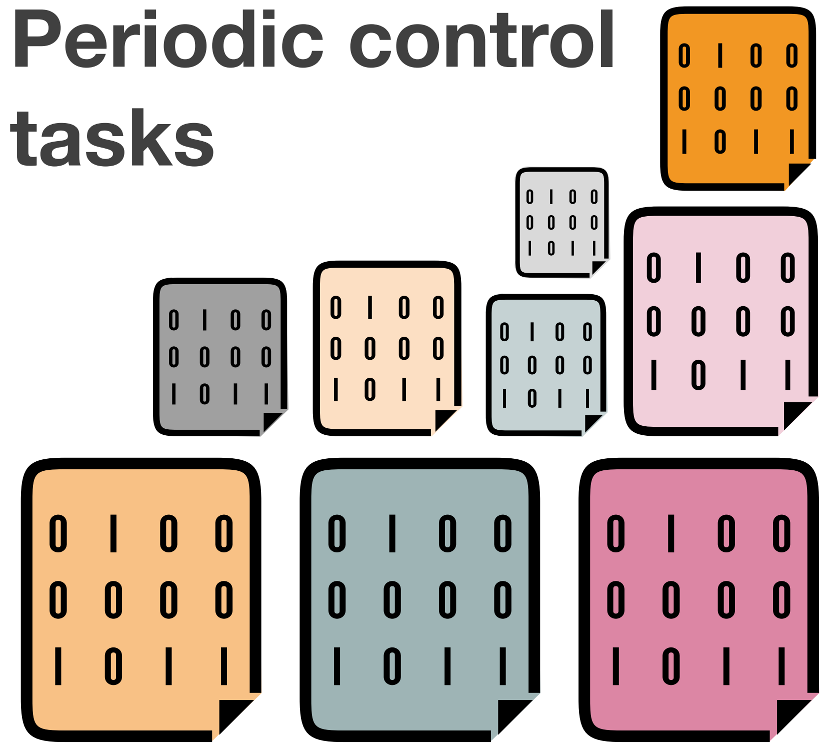
Successful replica coordination for more complex workloads

WCET closer to 50ms, which is also the T_{min}, results in little slack and increased deadline violations

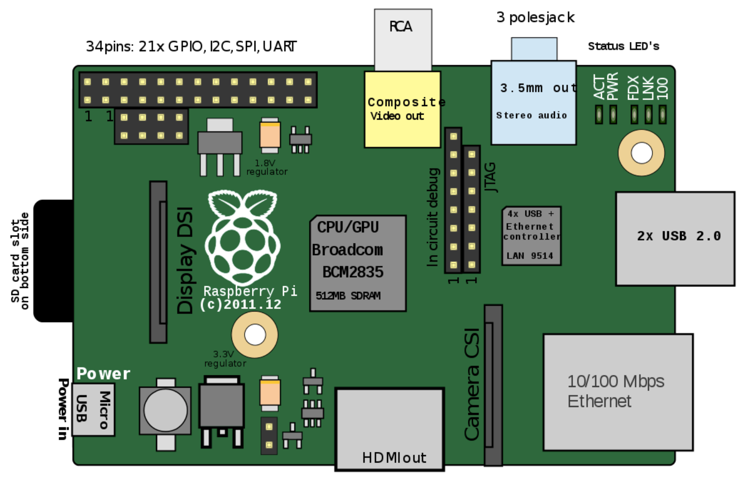
Increasing the #keys pushes In-ConcReTeS on the Raspberry Pi cluster to its limits!

Summary

Periodic control tasks



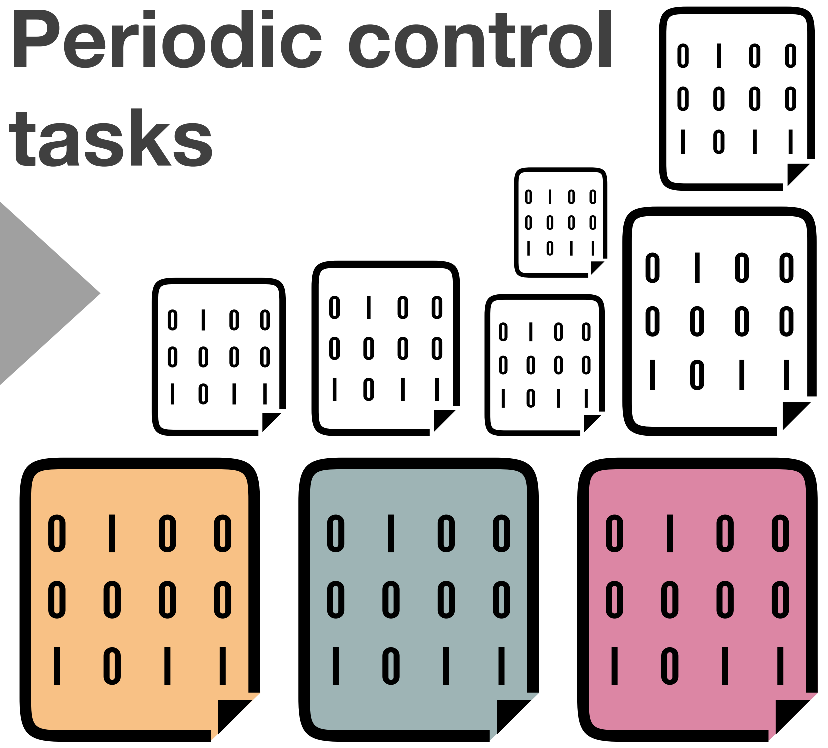
Embedded platform (node 1)



Data sharing

Fault tolerance / replica coordination

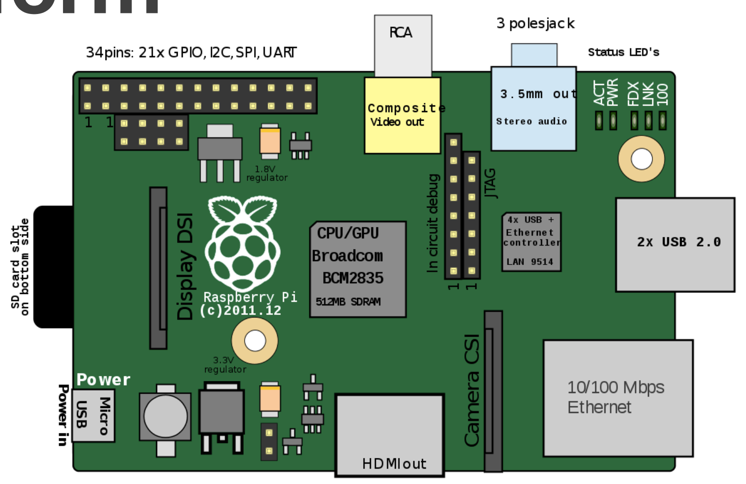
Periodic control tasks



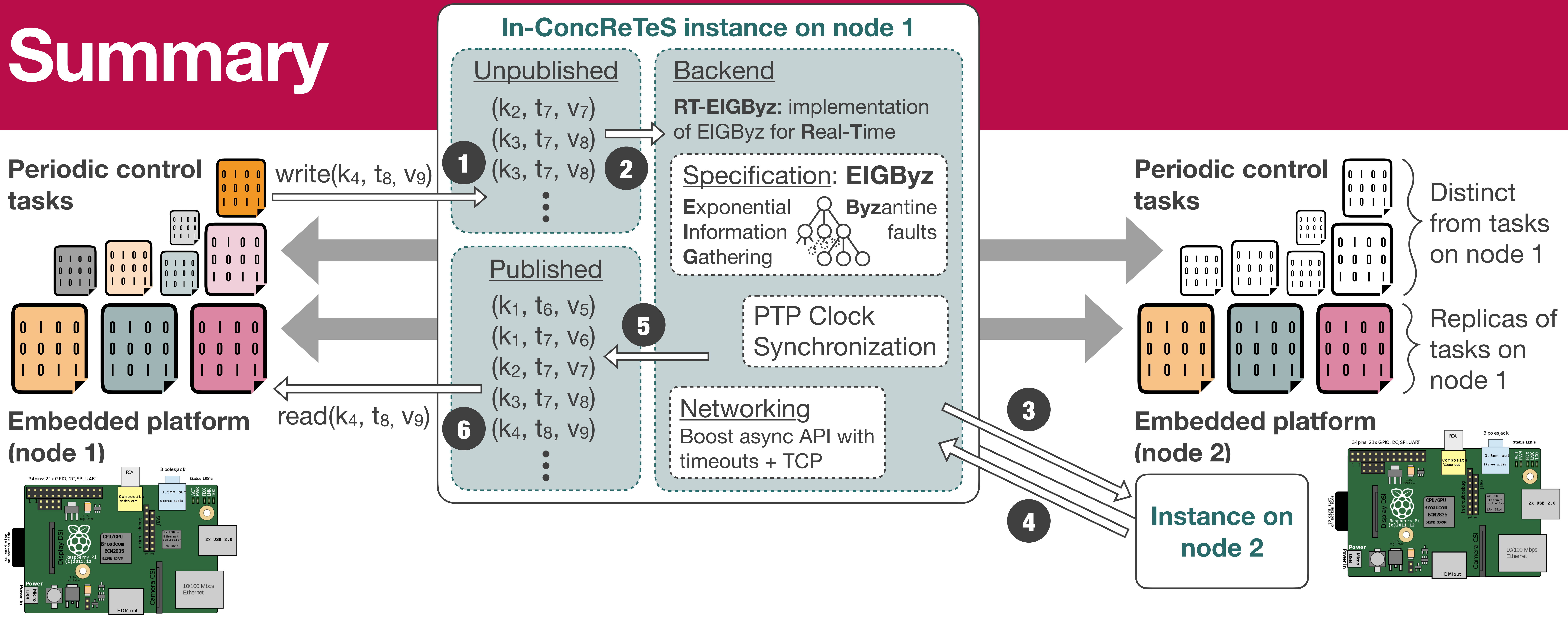
Distinct from tasks on node 1

Replicas of tasks on node 1

Embedded platform (node 2)

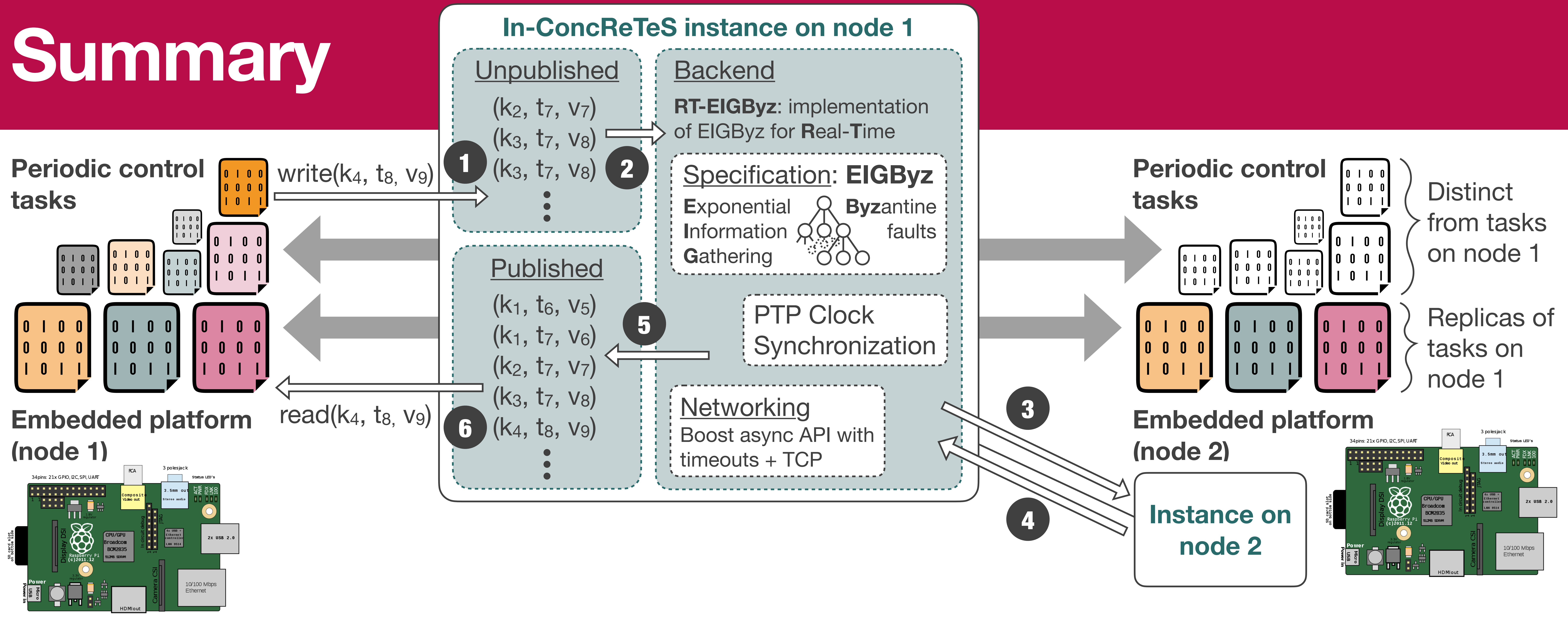


Summary



In-ConcReTeS instance on node 1
Unpublished
(k_2, t_7, v_7)
(k_3, t_7, v_8)
(k_3, t_7, v_8)
Backend
RT-EIGByz: implementation of EIGByz for Real-Time
Specification: EIGByz
Exponential Information Gathering
Byzantine faults
Published
(k_1, t_6, v_5)
(k_1, t_7, v_6)
(k_2, t_7, v_7)
(k_3, t_7, v_8)
(k_4, t_8, v_9)
PTP Clock Synchronization
Networking
Boost async API with timeouts + TCP
1
2
3
4
5
6
Periodic control tasks
write(k_4, t_8, v_9)
read(k_4, t_8, v_9)
Embedded platform (node 1)
Periodic control tasks
Distinct from tasks on node 1
Replicas of tasks on node 1
Embedded platform (node 2)
Instance on node 2

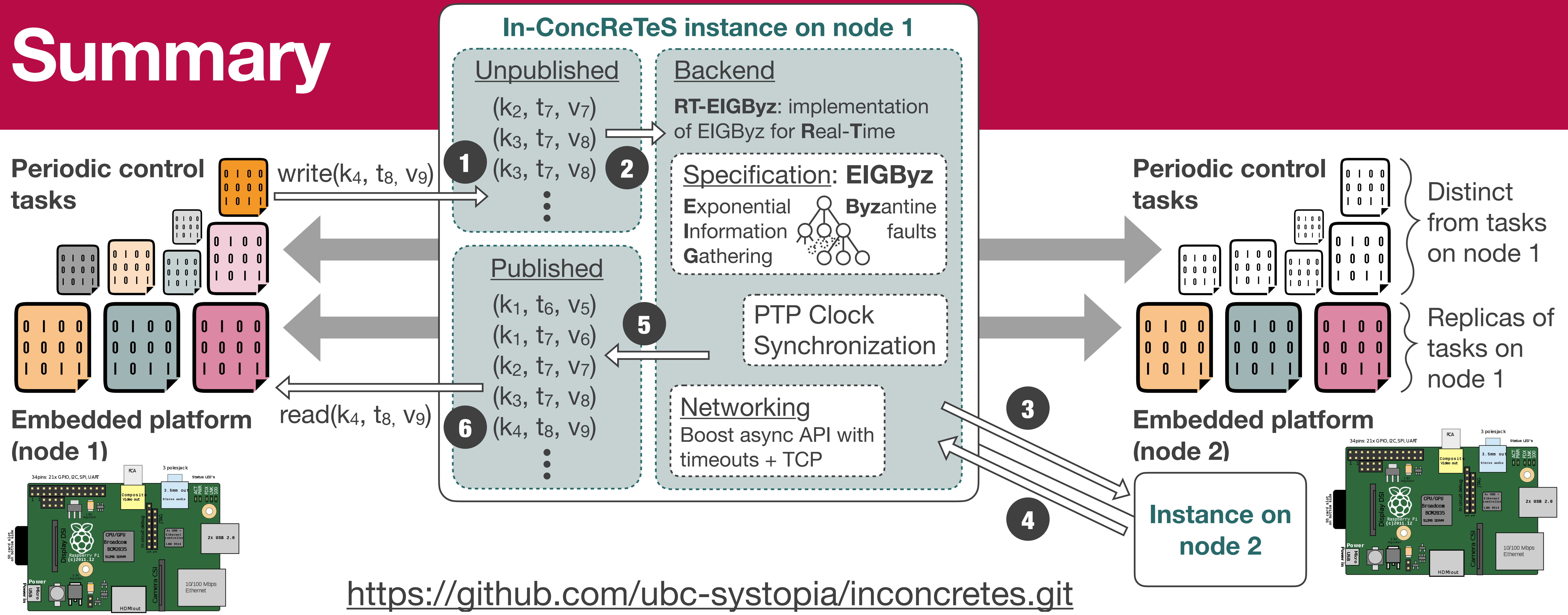
Summary



By making **design choices** around the needs of **periodic real-time applications**

- **In-ConcReTeS is able to outperform** generic datastores such as redis and etcd

Summary



https://github.com/ubc-systopia/inconcretes.git

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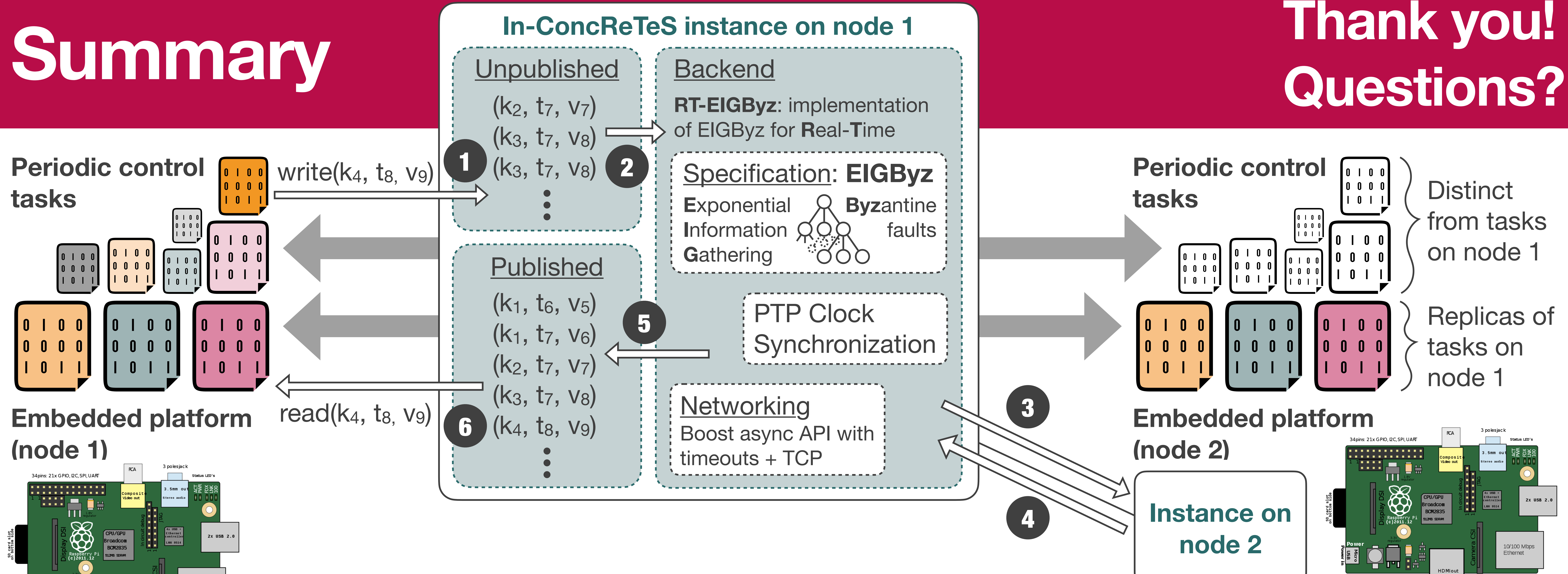
Summary

Thank you! Questions?



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