Building Fault-Tolerant Distributed Real-Time Systems

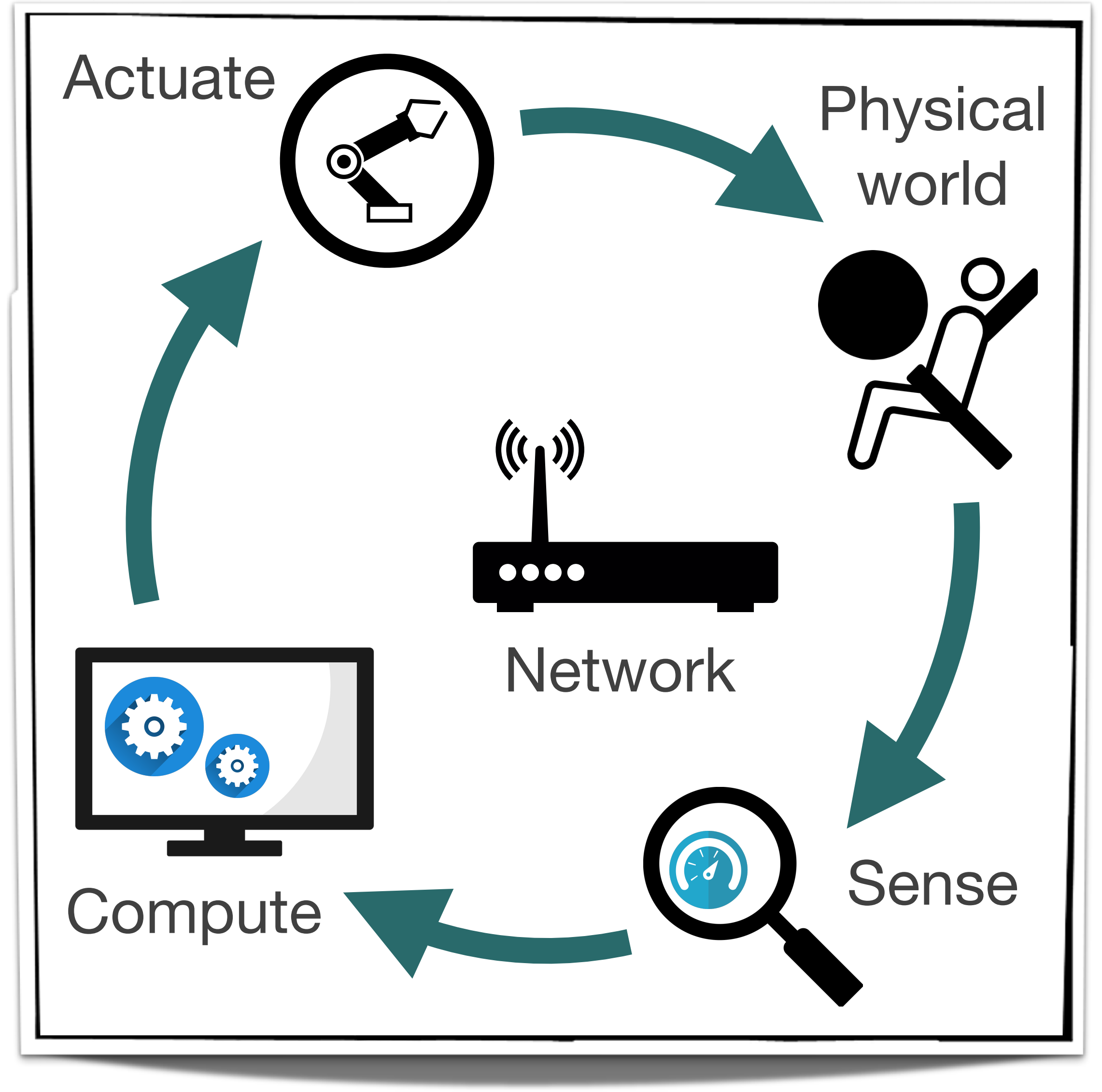
Arpan Gujarati | University of British Columbia, Vancouver (Canada)

Cyber-Physical Systems (CPS)

Tight and seamless integration

- Computation
- Networking
- Actuation and control
- Sensing of the physical world

Feedback control loops



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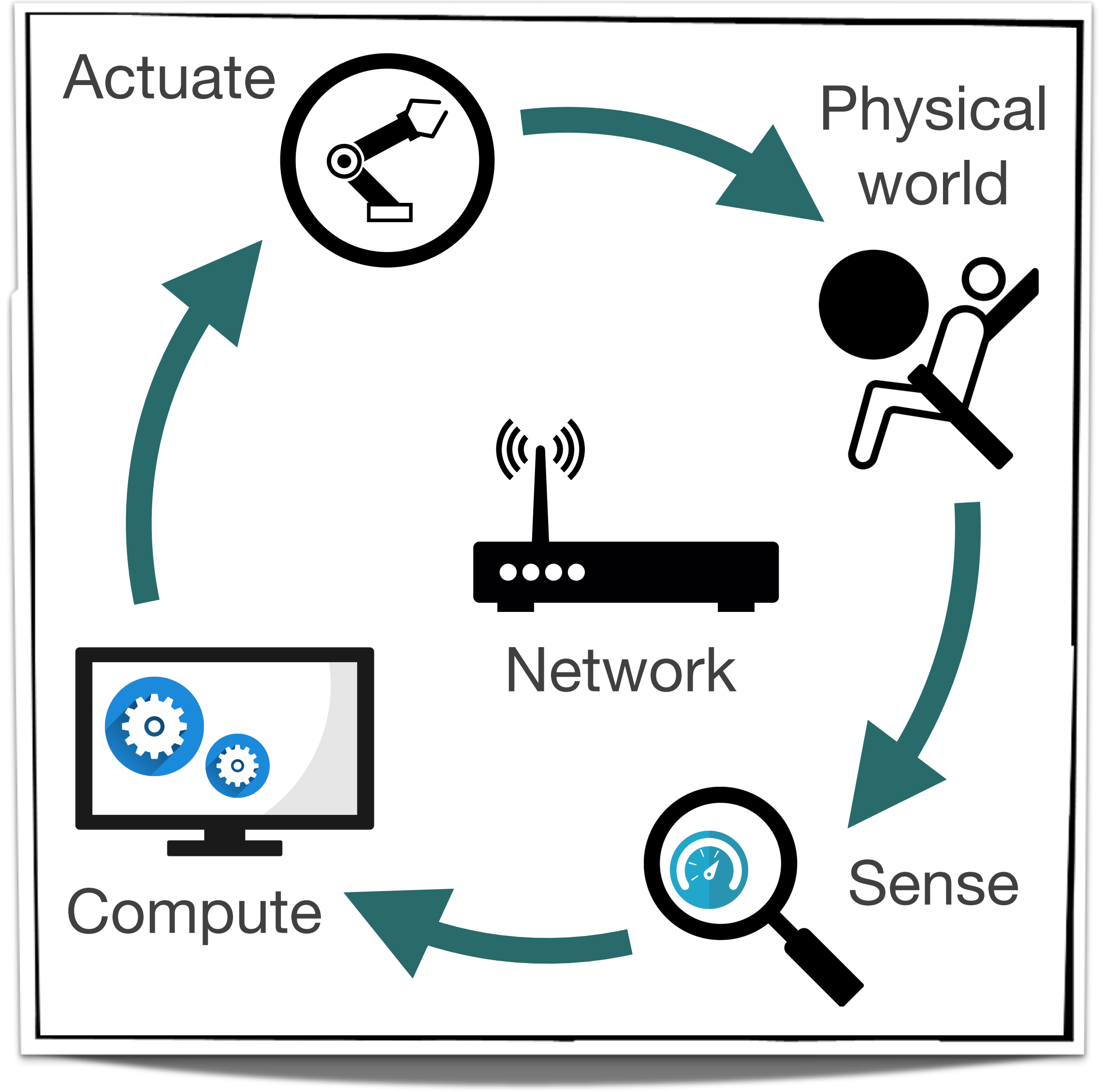
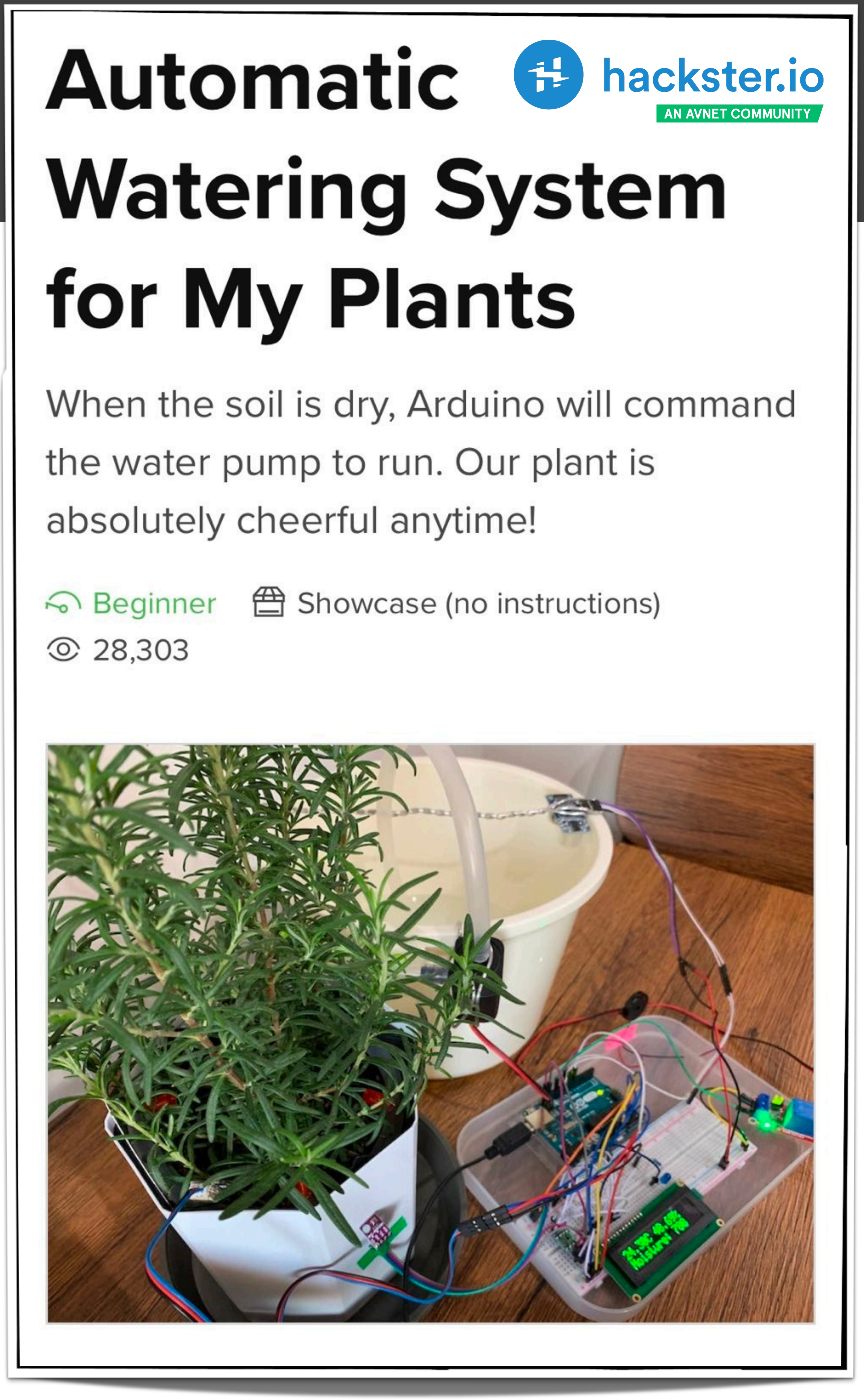
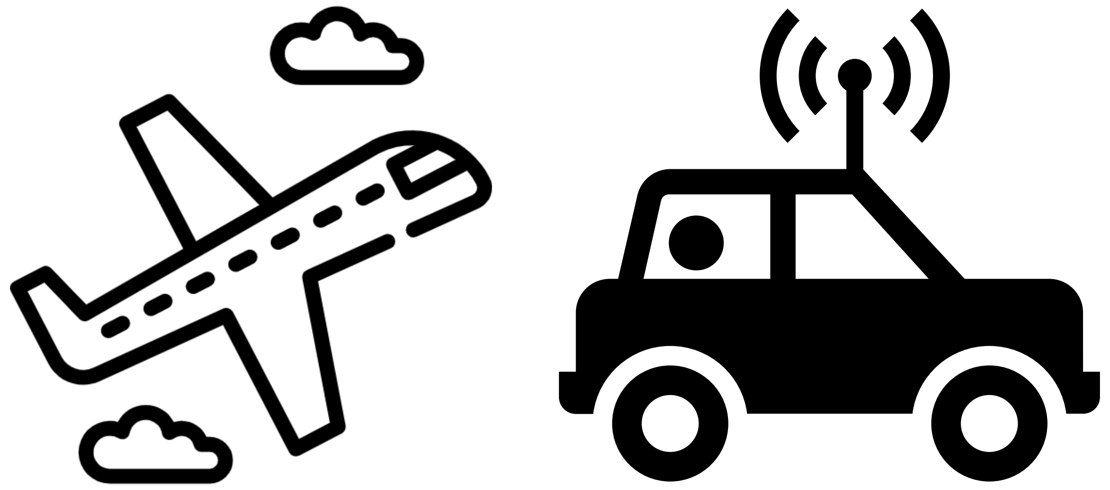




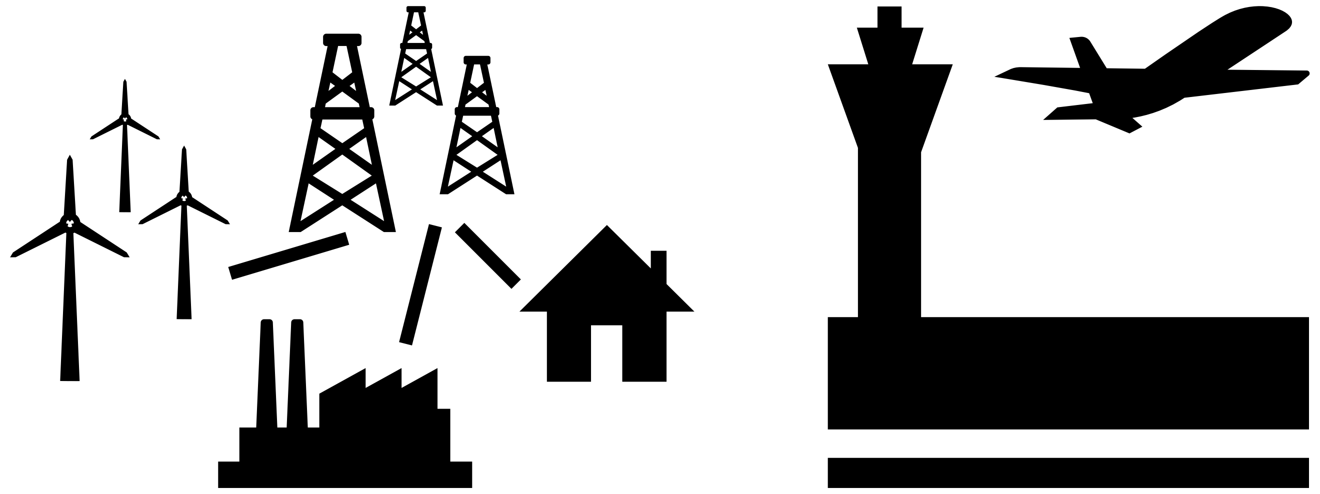
CPS are Ubiquitous, Diverse, and Safety-Critical

Large-scale systems



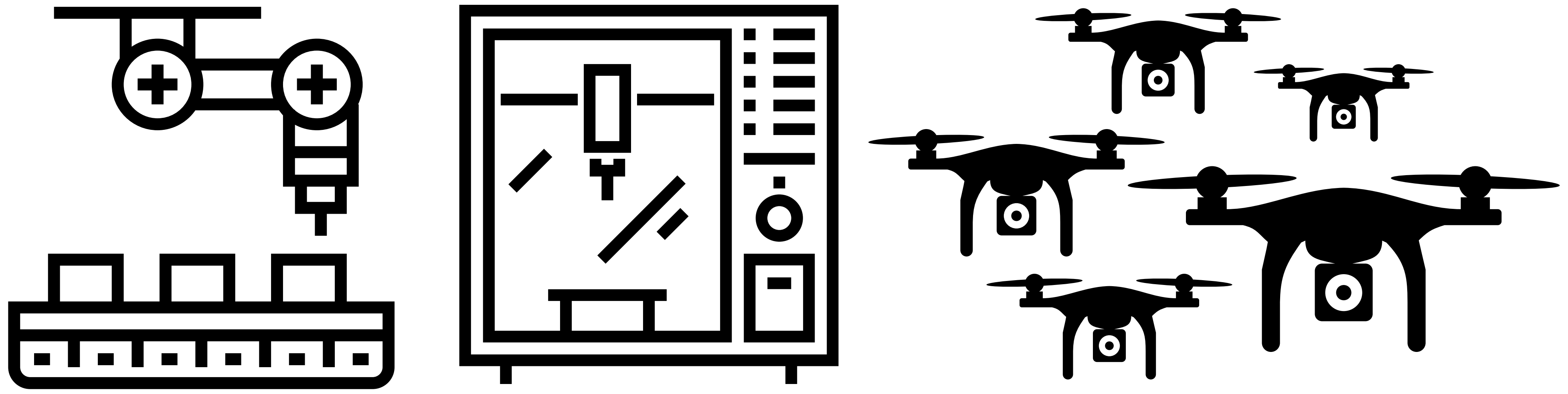
Airplanes Automobiles

Integration of diverse systems



Smart power grids Air traffic control

Small-scale systems



Robotic arms 3D printer Drone fleets

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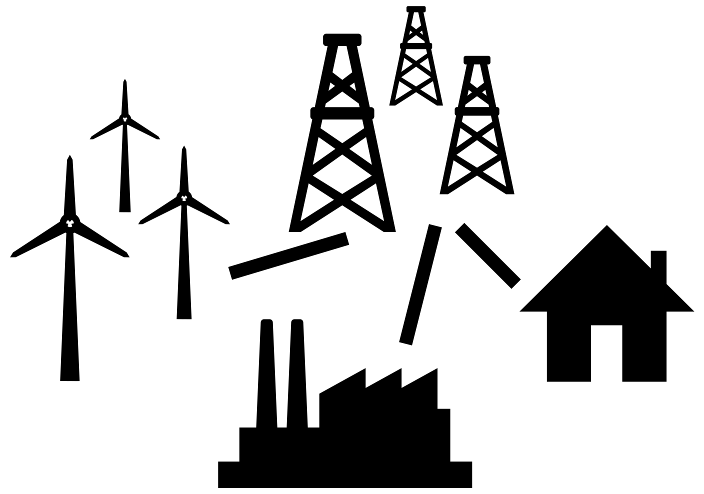
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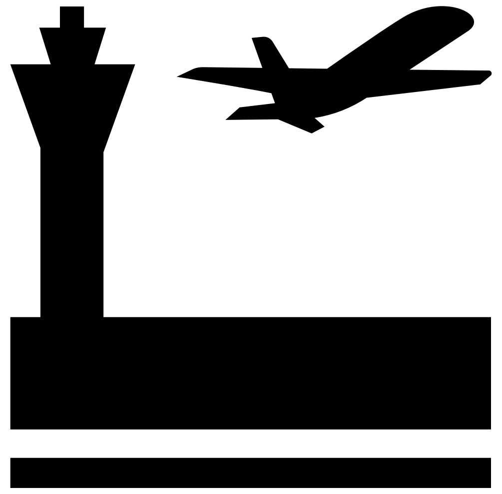
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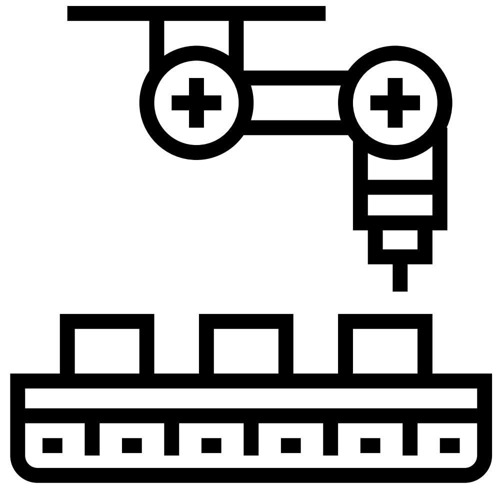
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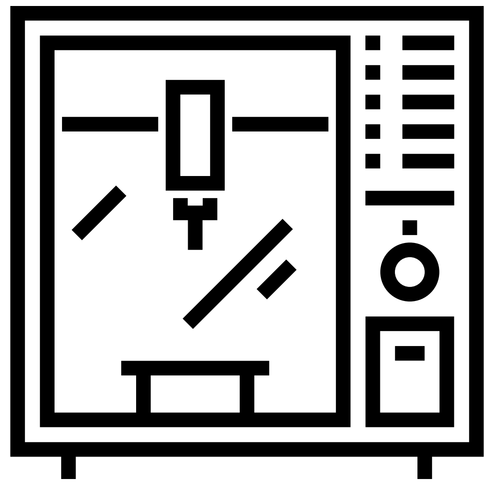

3D printer


Drone fleets

Failures can be catastrophic!

- Severe **damage to property**
- **Death or serious injury** to humans

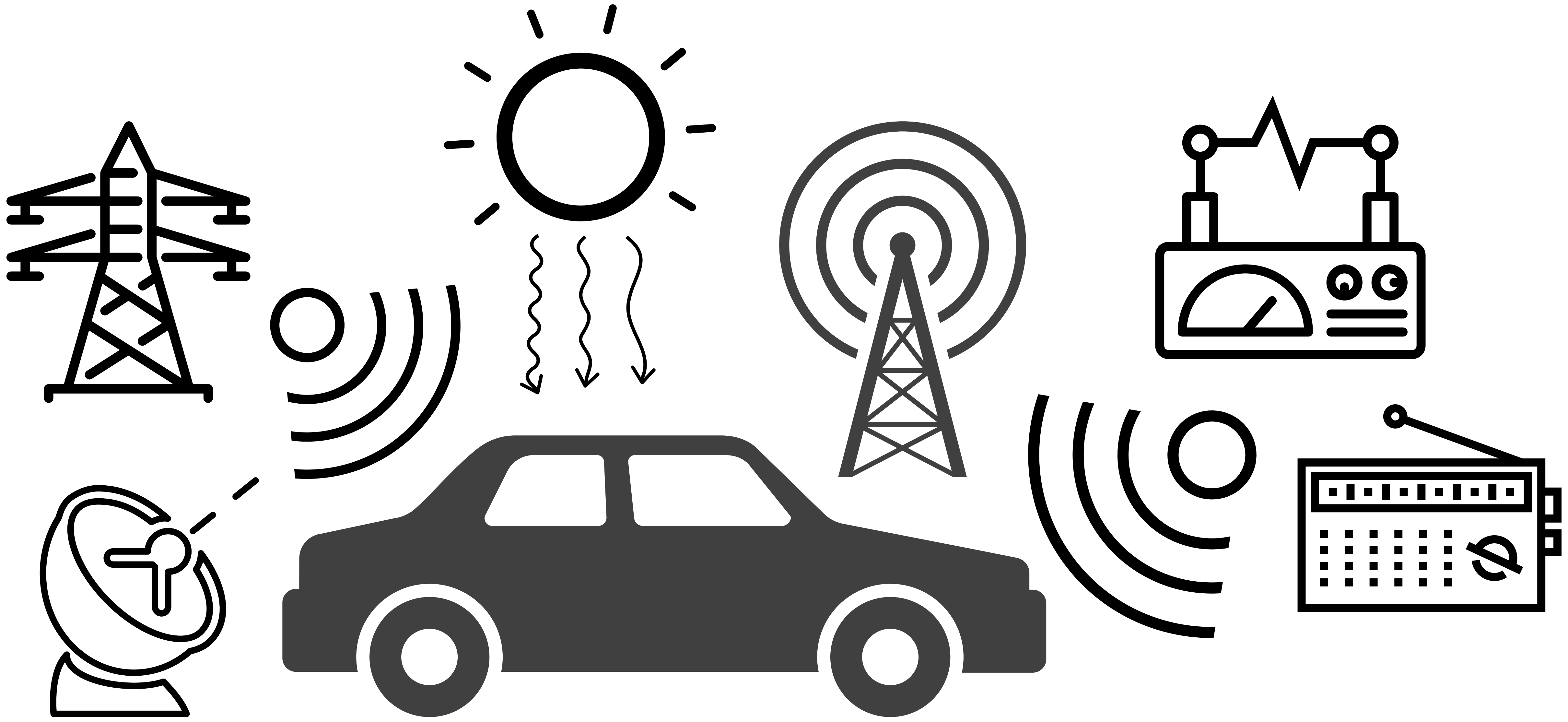
CPS are Susceptible to Transient Faults

Harsh environments

- Motors, spark plugs
- High power machinery, hard radiation
- Electromagnetic interference

Transient faults or soft errors

- Bit flips in registers, buffers, networks



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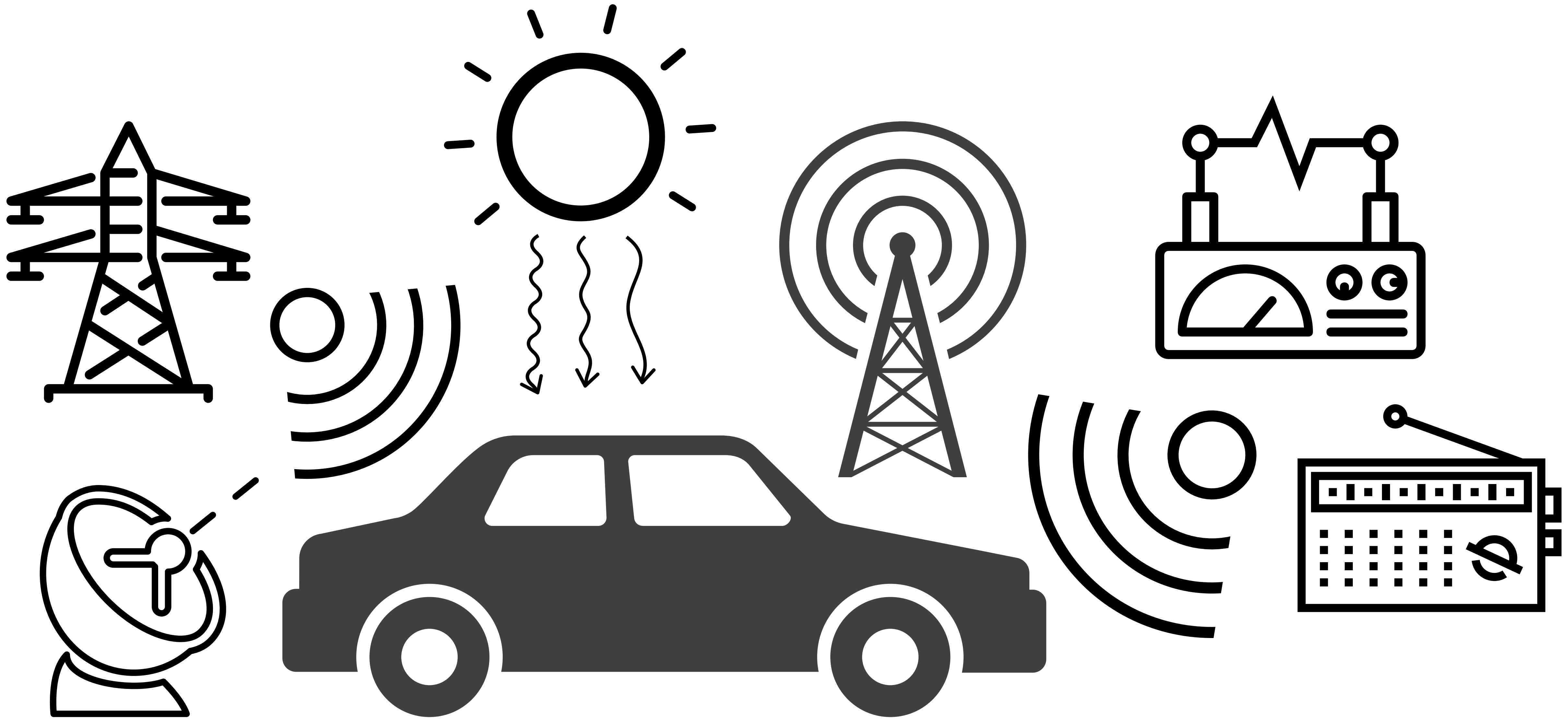

*"About **5000 vehicles per day** will be affected by a soft error, with potentially catastrophic consequences." **

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

Transient Faults can Lead to Complex Errors

Transmission: Faults in the network

Omission: Fault-induced kernel panics, hangs

Incorrect computation: Faults in memory buffers

Byzantine: Inconsistent broadcasts in distributed systems

- Environmentally-induced non-malicious Byzantine errors

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Honeywell

Driscoll *et al.* Byzantine Fault Tolerance, from Theory to Reality. SAFECOMP (2003)

7 Conclusions

Byzantine Problems are real. The probability of their occurrence is much higher than most practitioners believe. The myth that Byzantine faults are only isolated transients is contradicted by real experience. Their propensity for escaping normal fault containment zones can make each Byzantine fault a threat to whole system dependability.

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For high reliability targets

- E.g., $P_{fail} < 10^{-10}$/hr
- Every type of error must be handled

Honeywell

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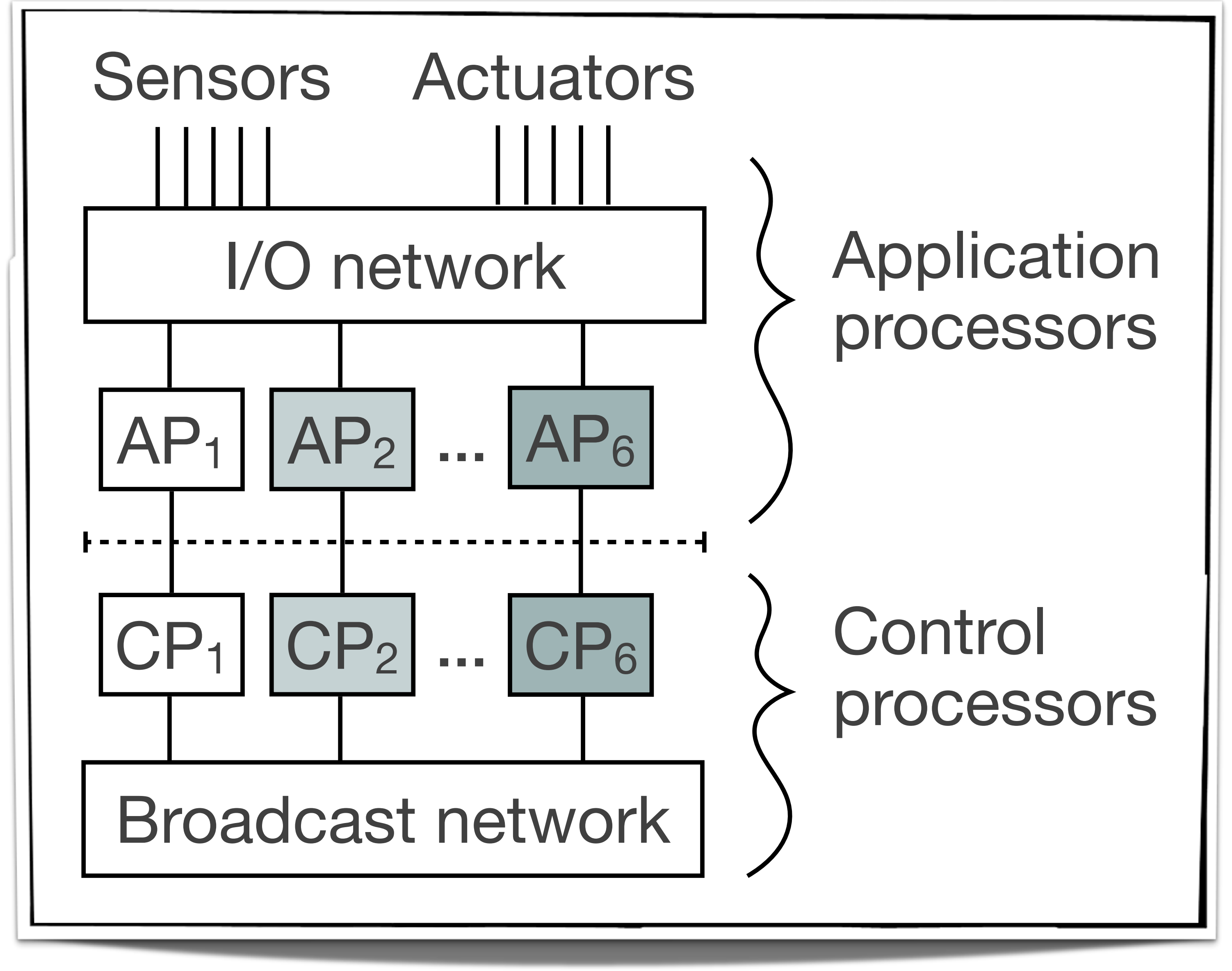
Example: Dependable CPS for Airplanes

Expensive custom-made fault-tolerant architectures

- Classical example: “The MAFT Architecture for Distributed Fault Tolerance” by Kieckhafer *et al.* (1988)



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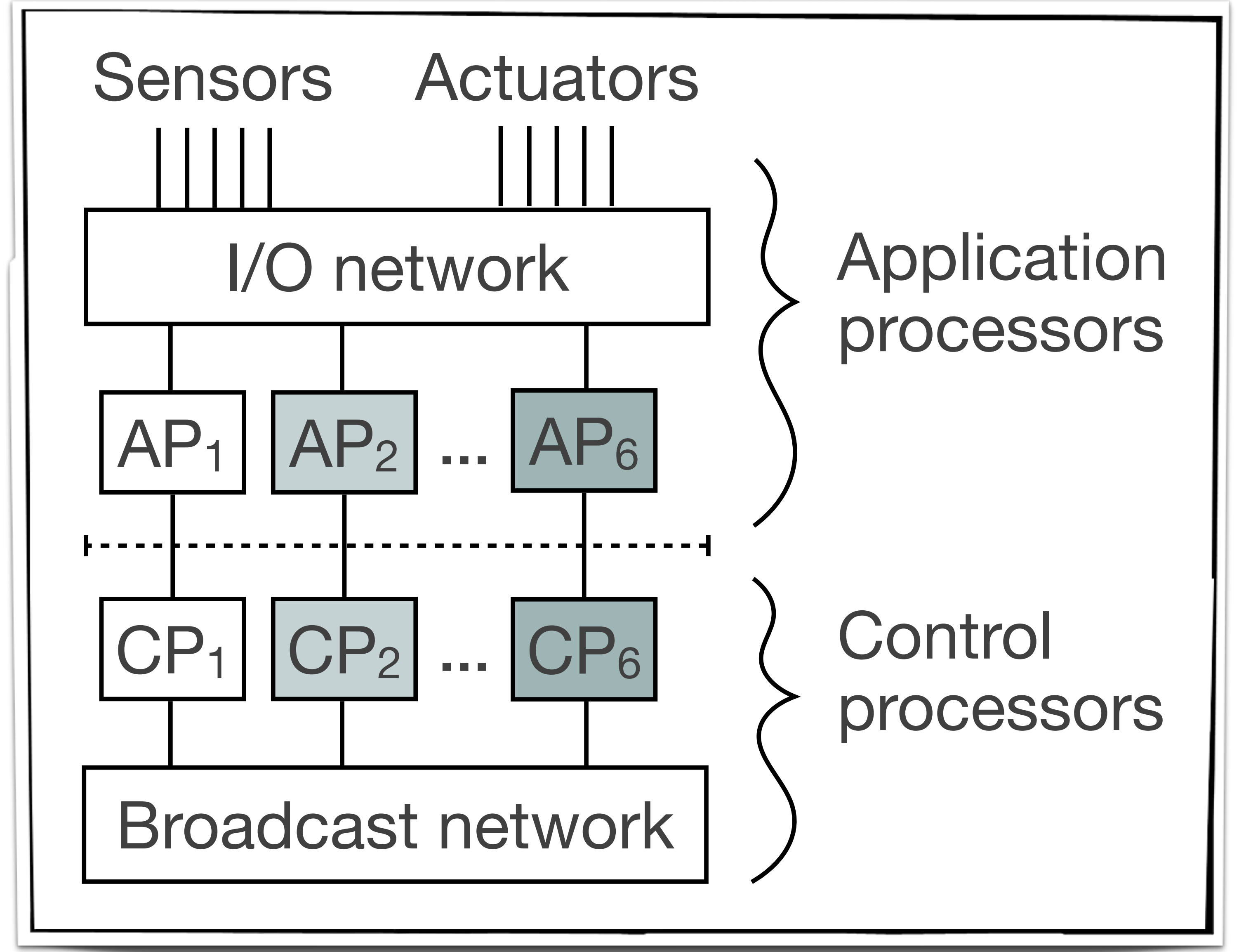
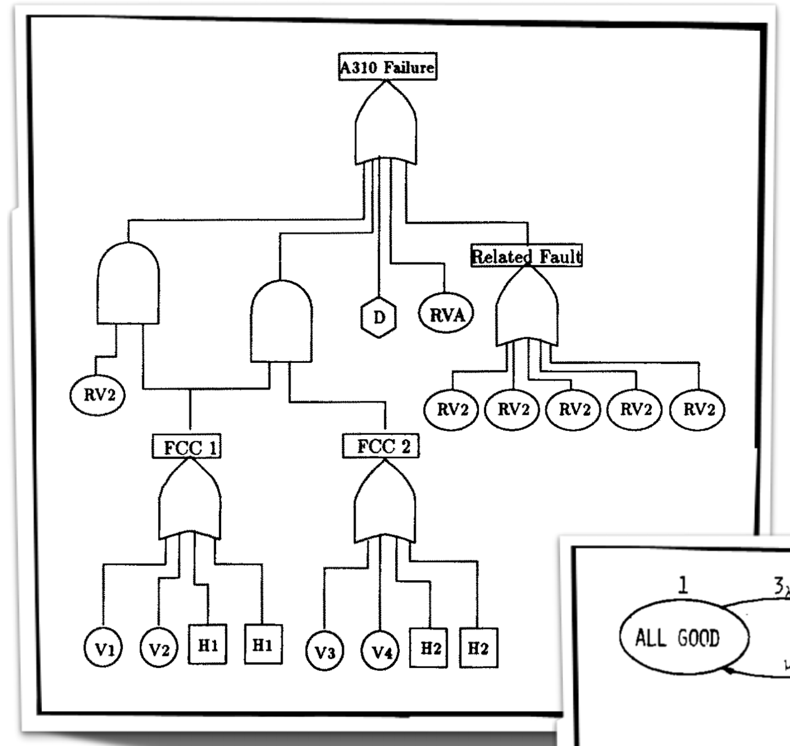
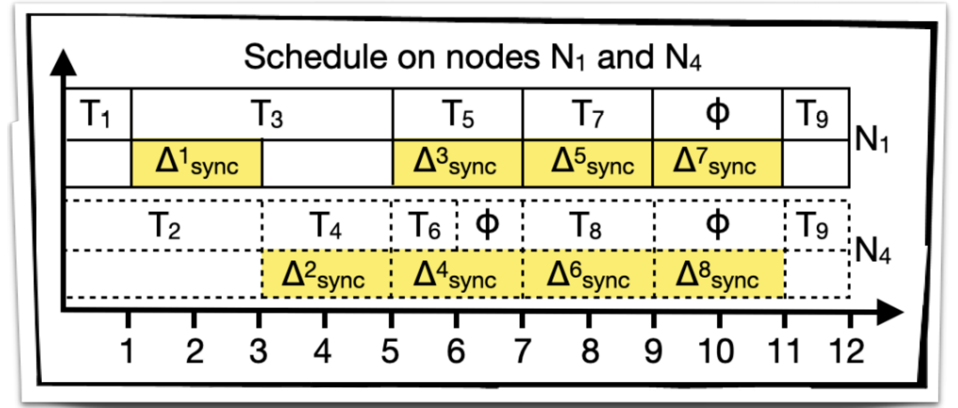


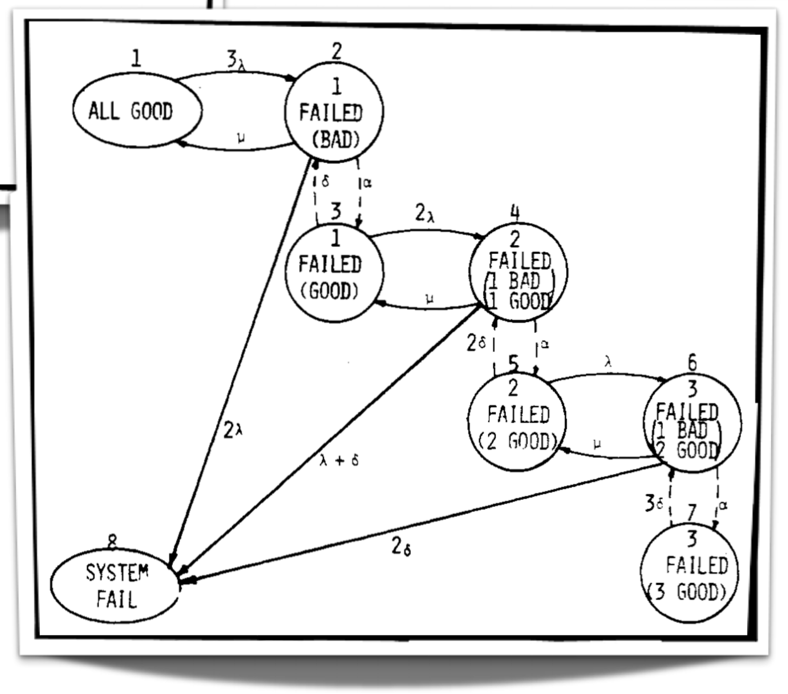
Rigorous testing and mathematical analyses



Fault trees

Timing analyses



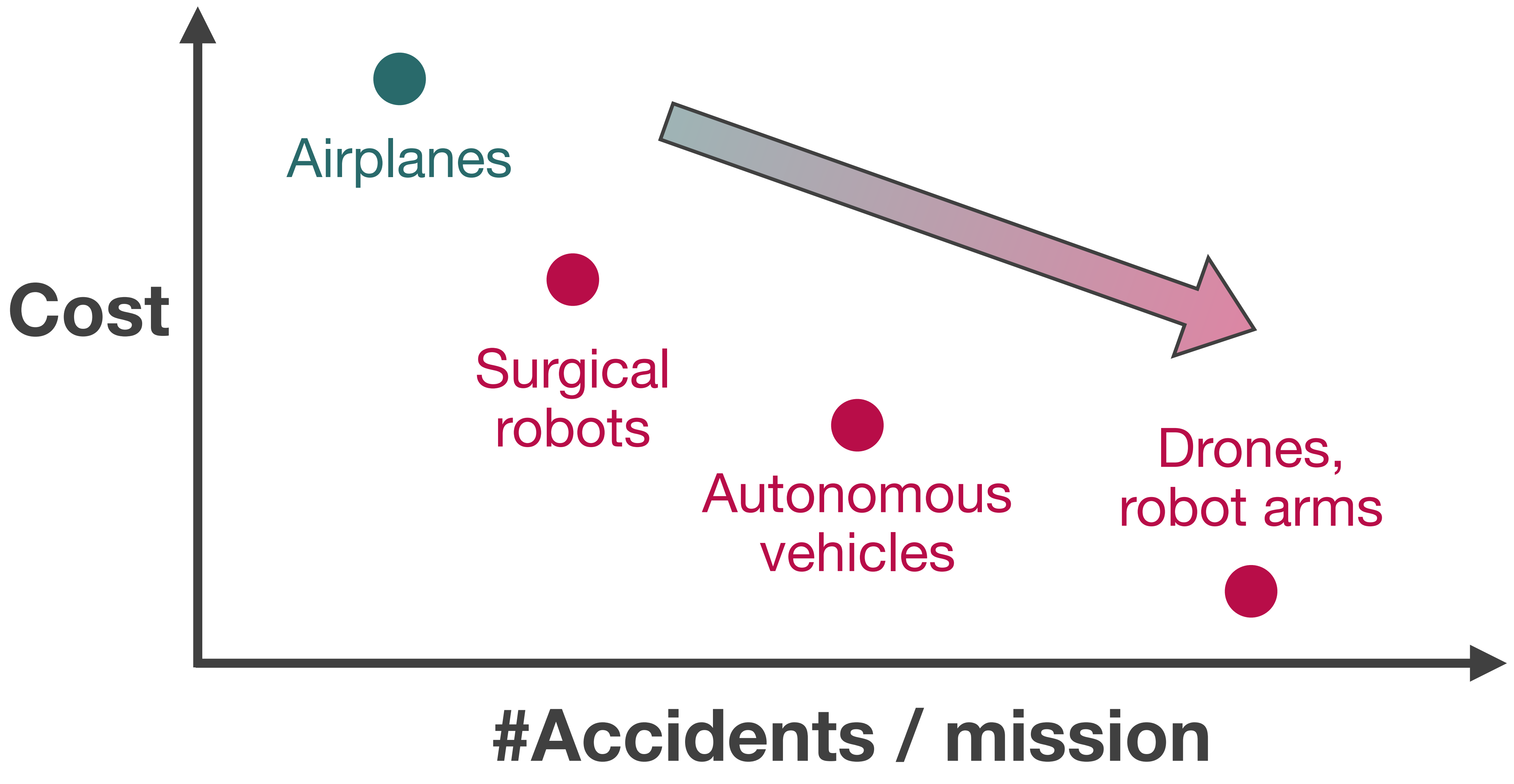


Markov processes

"Ultra-reliability"

- Quantifiably negligible failure rates
- $P_{fail} < 10^{-10}$ / hour

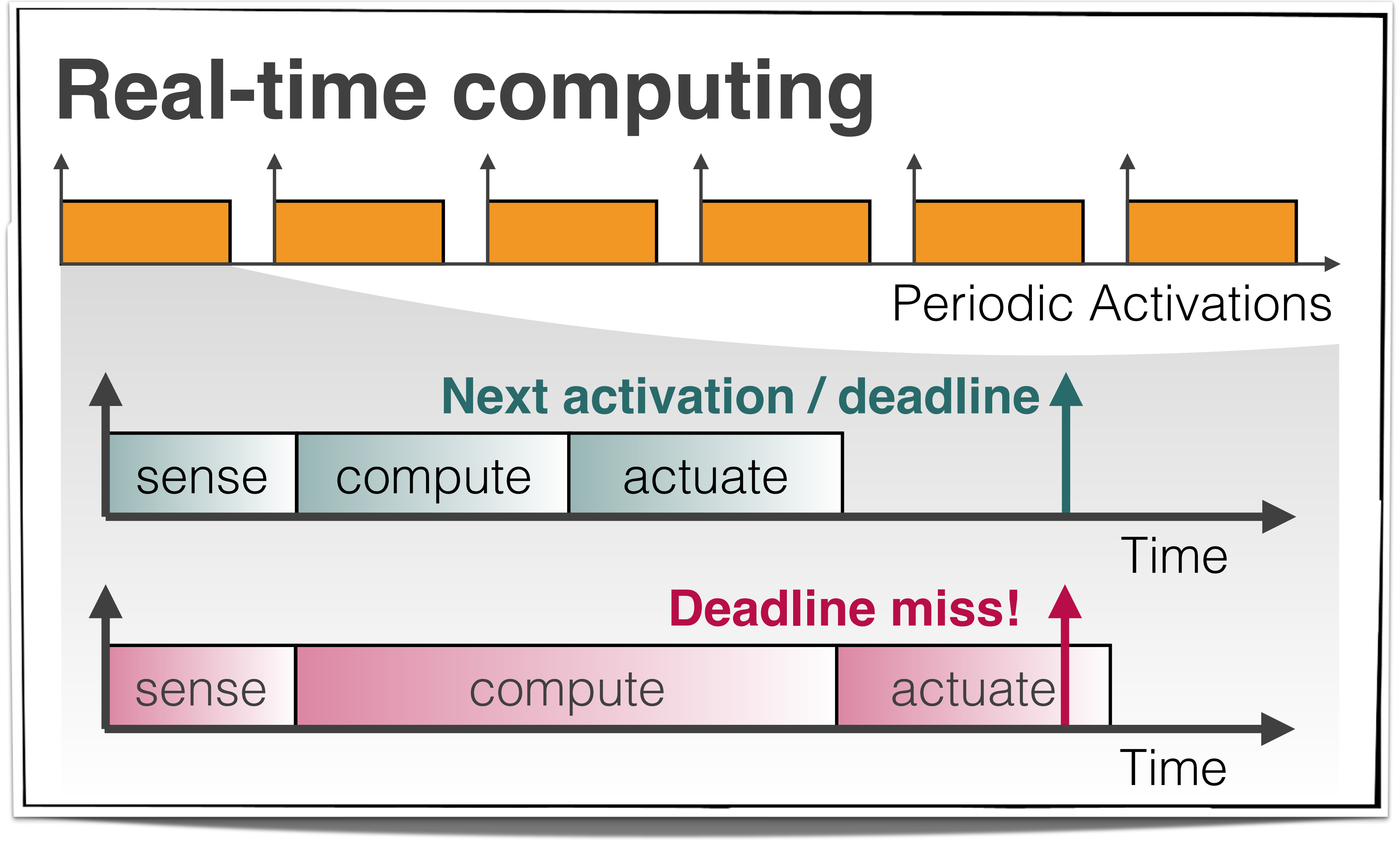
Not all CPS are Engineered like Airplanes

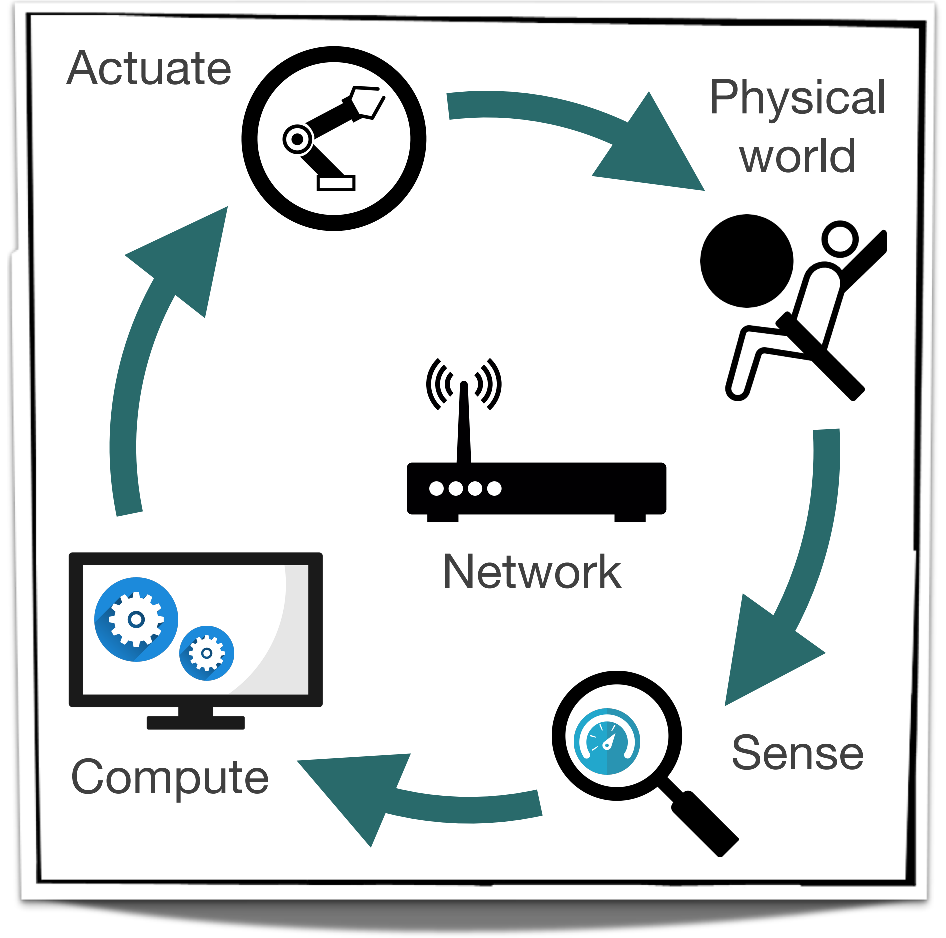


- × Inexpensive but **unreliable** off-the-shelf hardware
- × Open-source **unpredictable** software
- × **Inadequate resources**
- × Safety concerns regarding **ML** and **security**

Goal: Make such low-cost consumer CPS more reliable

Focus: Real-Time Computing and Fault-Tolerance





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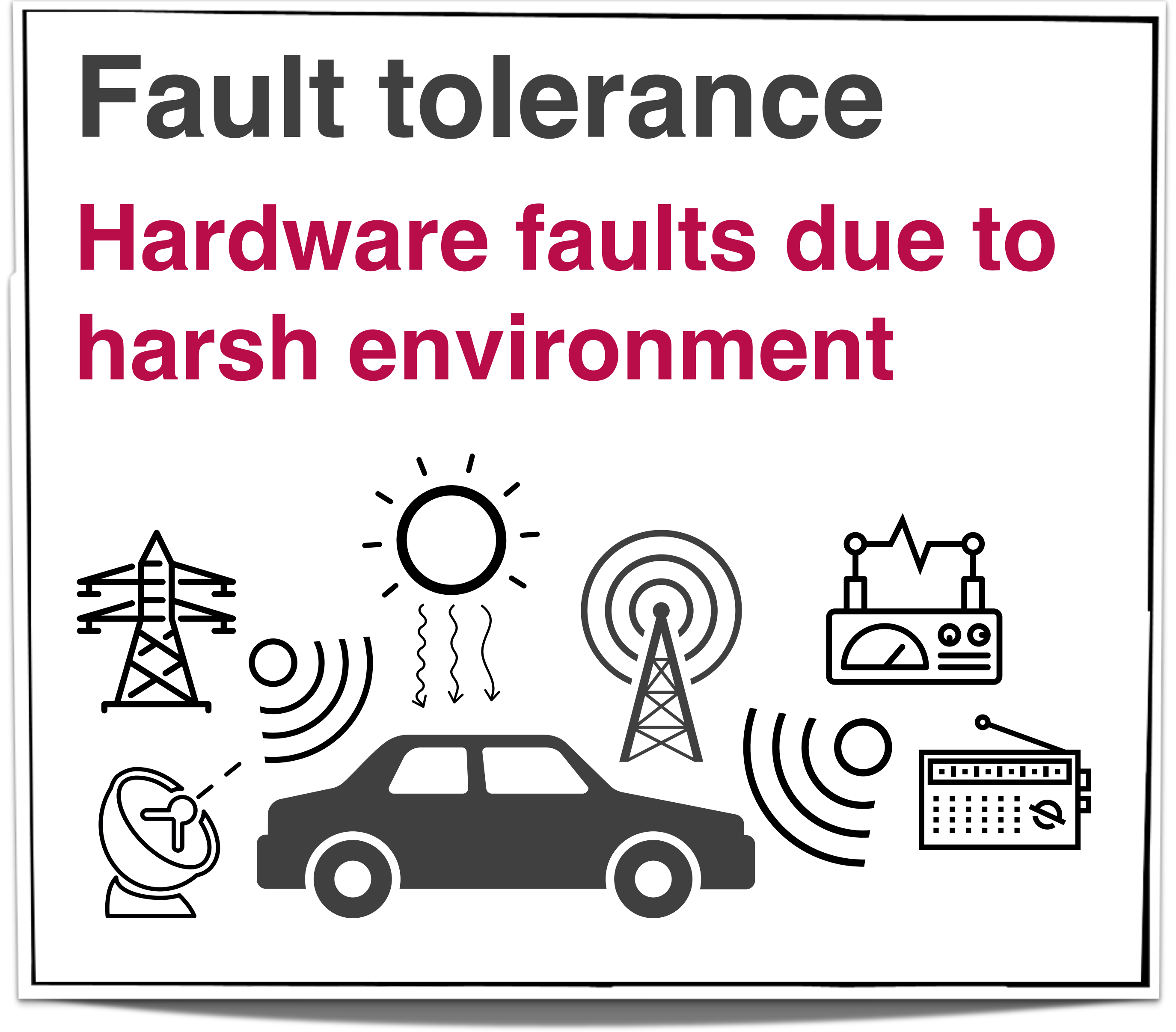

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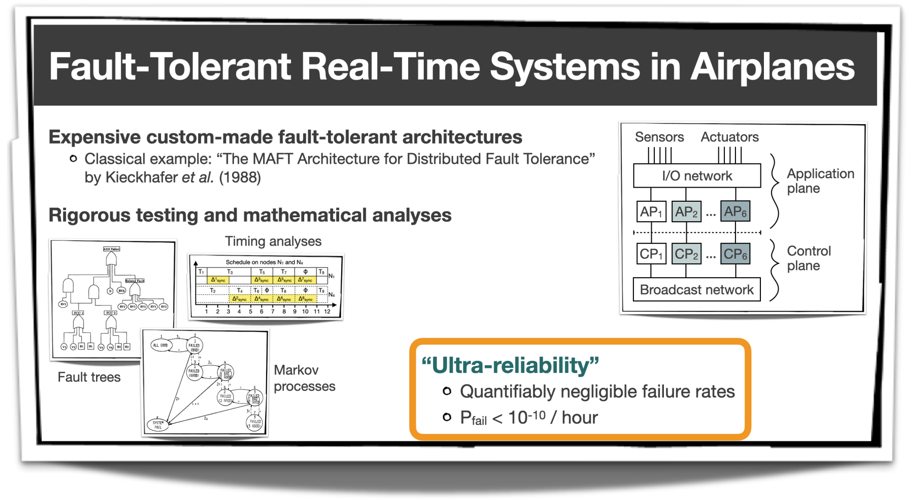

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Custom hardware	✔	✔	✘

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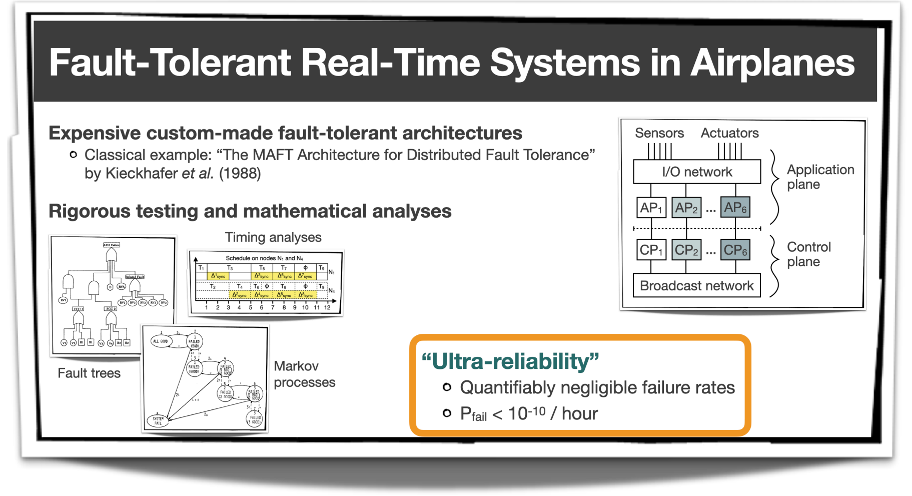

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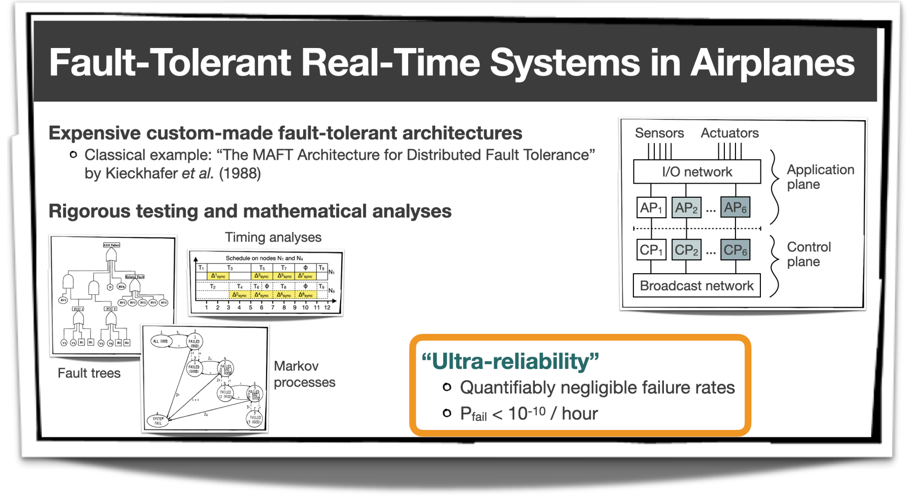

Bft-SMaRt
High-performance Byzantine Fault-Tolerant State Machine Replication

APACHE ZooKeeper™ etcd redis

ARDUPILOT ROS

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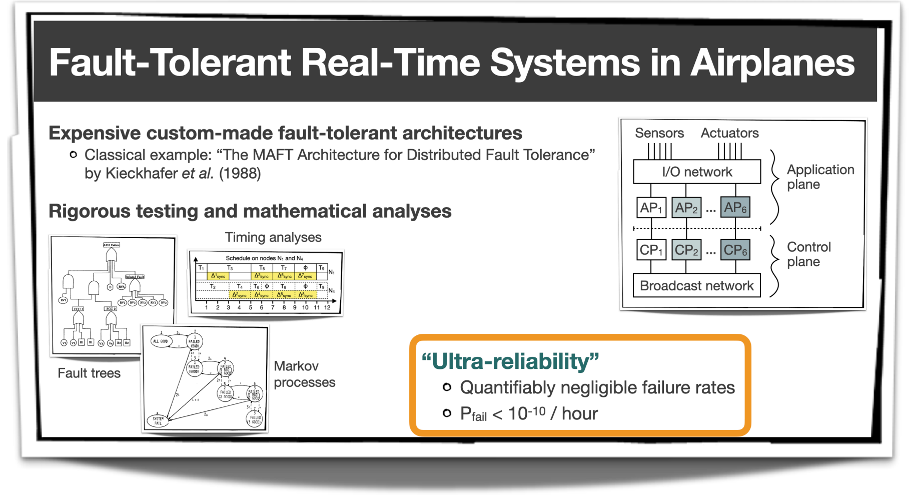

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Achal KVS	✔	✔	✔

Distributed timestamped KVS

KVS Semantics

Key-Value Store (KVS)

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API

- `read(key k) -> value v | key error`
- `write(key k, value v) -> success | write error`

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What are the benefits of a KVS API?

- Simplifies programming
- Data sharing
- …

Timestamped KVS

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Revised API

- `read(key k, time t) -> value v | key error | time error`
- `write(key k, time t, value v) -> success | write error | time error`

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- `read(key k, time t) -> value v | key error | time error`
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How to interpret the `time` parameter?

- **Freshness constraint** during `read`
  - Return any value `v` that was written at or later than time `t`
- **Publishing time** during `write`
  - Ensure that value `v` cannot be read before time `t`
  - Ensure that value `v` can be read at or later than time `t`
- For simplicity, consider the **unique key** $\mathbf{k_{unique}} = \mathbf{(k,\ t)}$**!**

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What are the benefits of a timestamped KVS?

- Data versioning in financial markets
- Sensor data in cyber-physical systems
- …

Distributed Timestamped KVS

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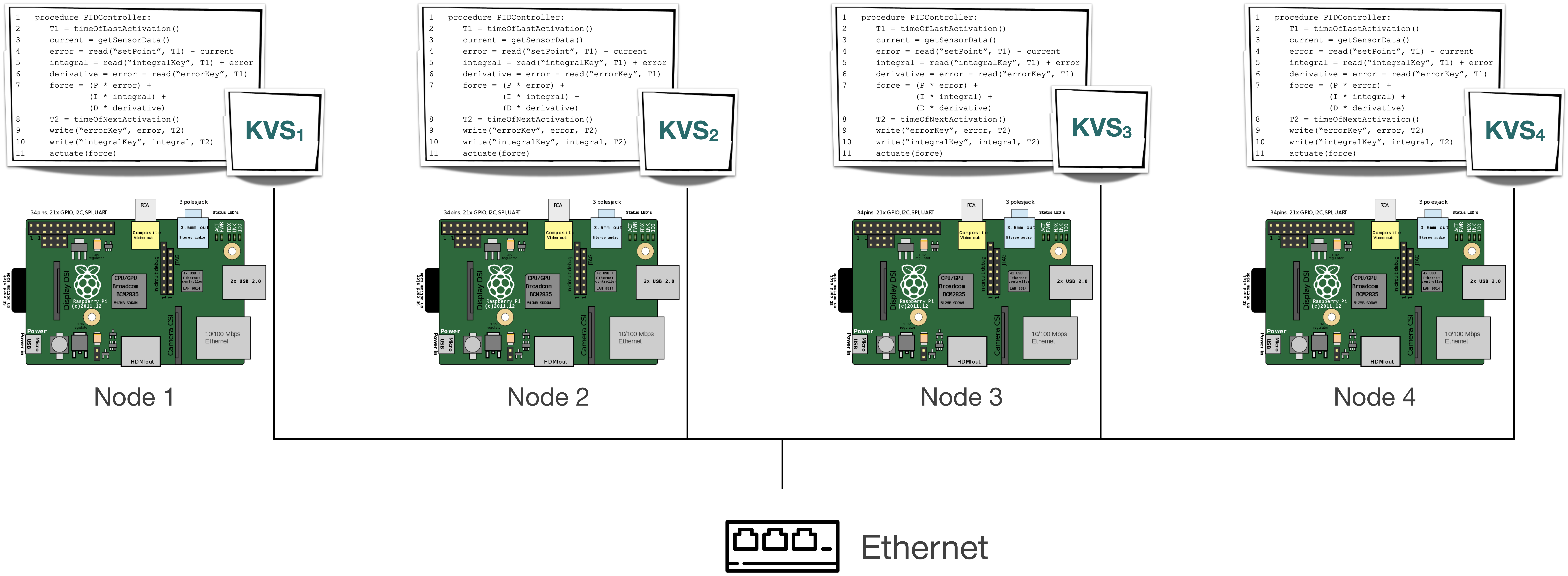

Distributed Timestamped KVS

What are the benefits of a distributed KVS?

- Applications may inherently be distributed
- Fault tolerance
  - Crash
  - Incorrect computation
  - Network issues
- …

Achal KVS

Inverted Pendulum: A Prototypical Control Application

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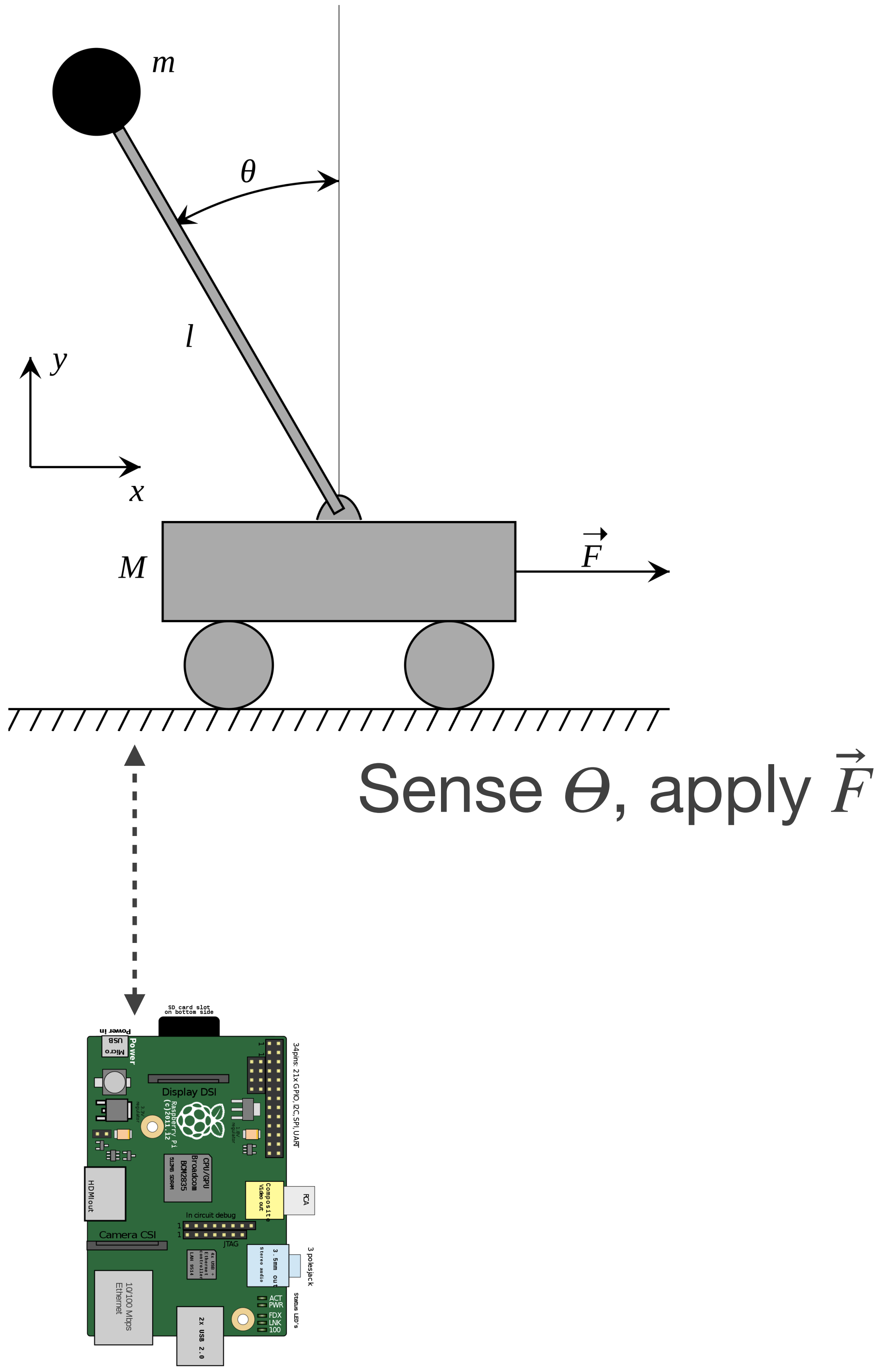
```
procedure PIDController:              // balance an inverted pendulum

    current = getSensorData()         // get angle encoder value
    error = setPoint - current        // compute absolute error
    integral = integral + error       // compute cumulative error
    derivative = error - oldError     // compute change in error
    force = (P * error) +             // compute force using PID
            (I * integral) +
            (D * derivative)

    oldError = error

    actuate(force)                   // apply force on the cart
```



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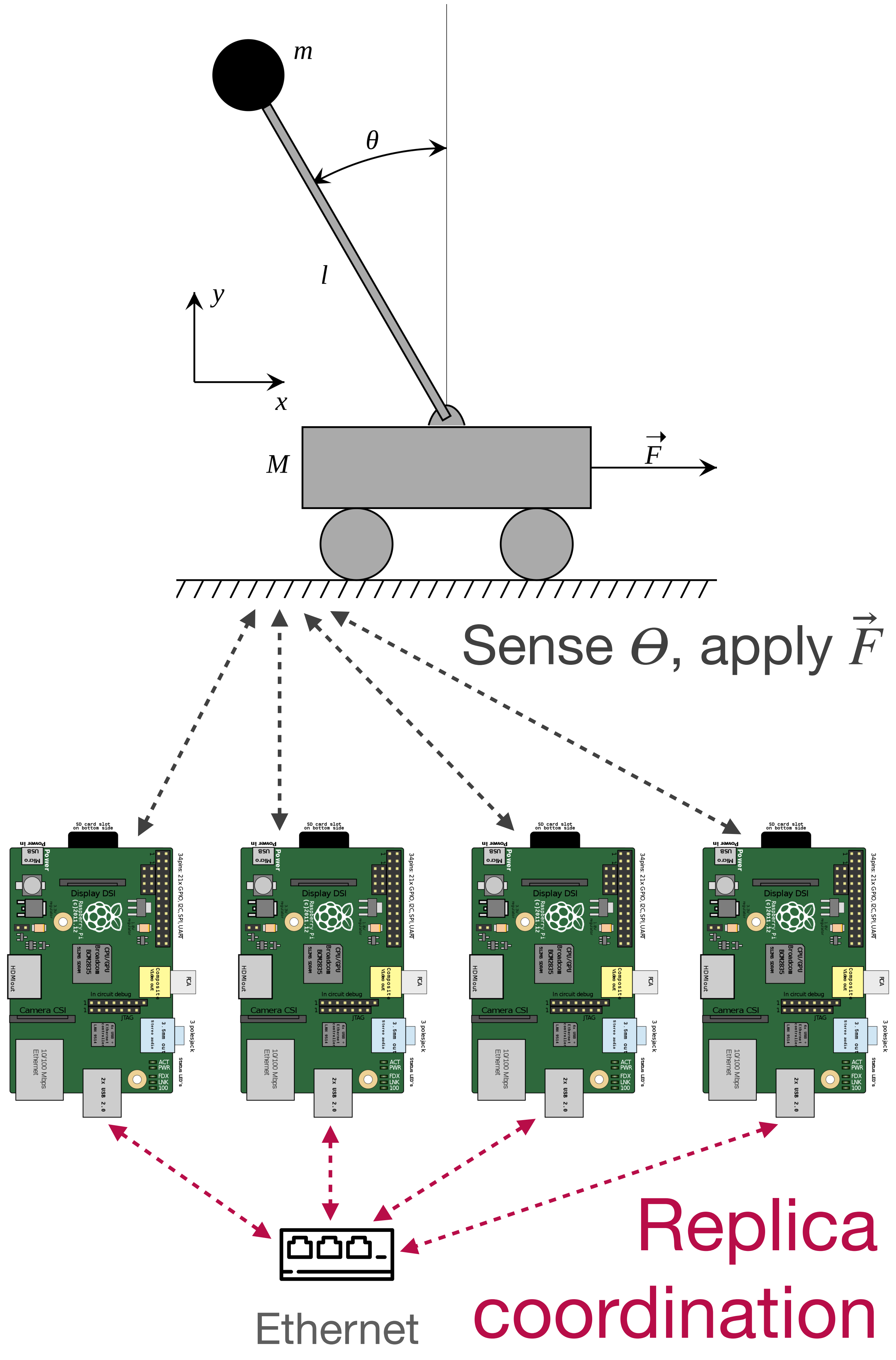

Nontrivial for control application developers!

Time-Aware Key-Value API

```
procedure PIDController:
   T1 = timeOfLastActivation()
   current = getSensorData()
   error = read(“setPoint”, T1) - current
   integral = read(“integralKey”, T1) + error
   derivative = error - read(“errorKey”, T1)
   force = (P * error) +
           (I * integral) +
           (D * derivative)
   T2 = timeOfNextActivation()
   write(“errorKey”, error, T2)
   write(“integralKey”, integral, T2)
   actuate(force)
```

T1 is a **data freshness** constraint

T2 denotes **publishing time**

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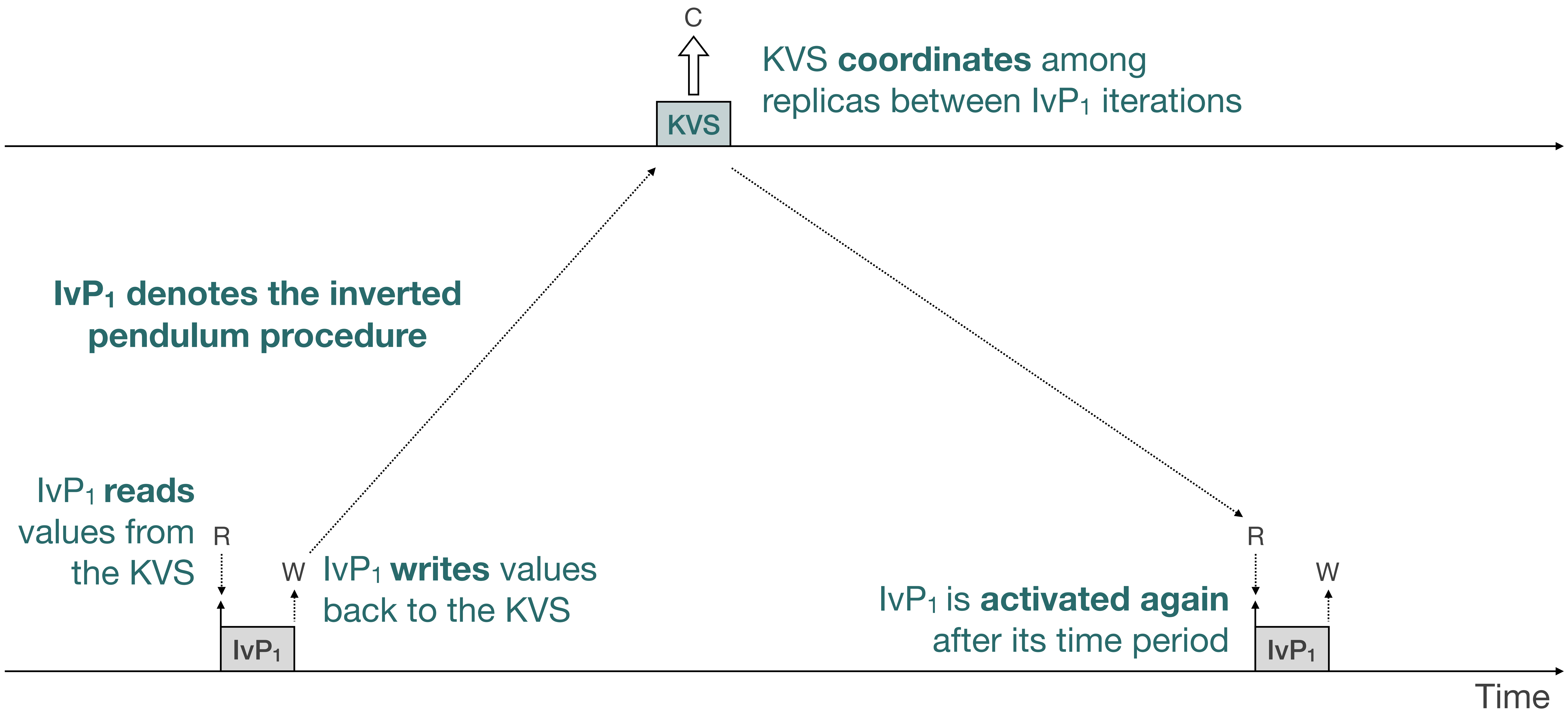
T1 is a **data freshness** constraint

Key-value API **simplifies replica coordination**

T2 denotes **publishing time**

Time parameters help with **temporal determinism**

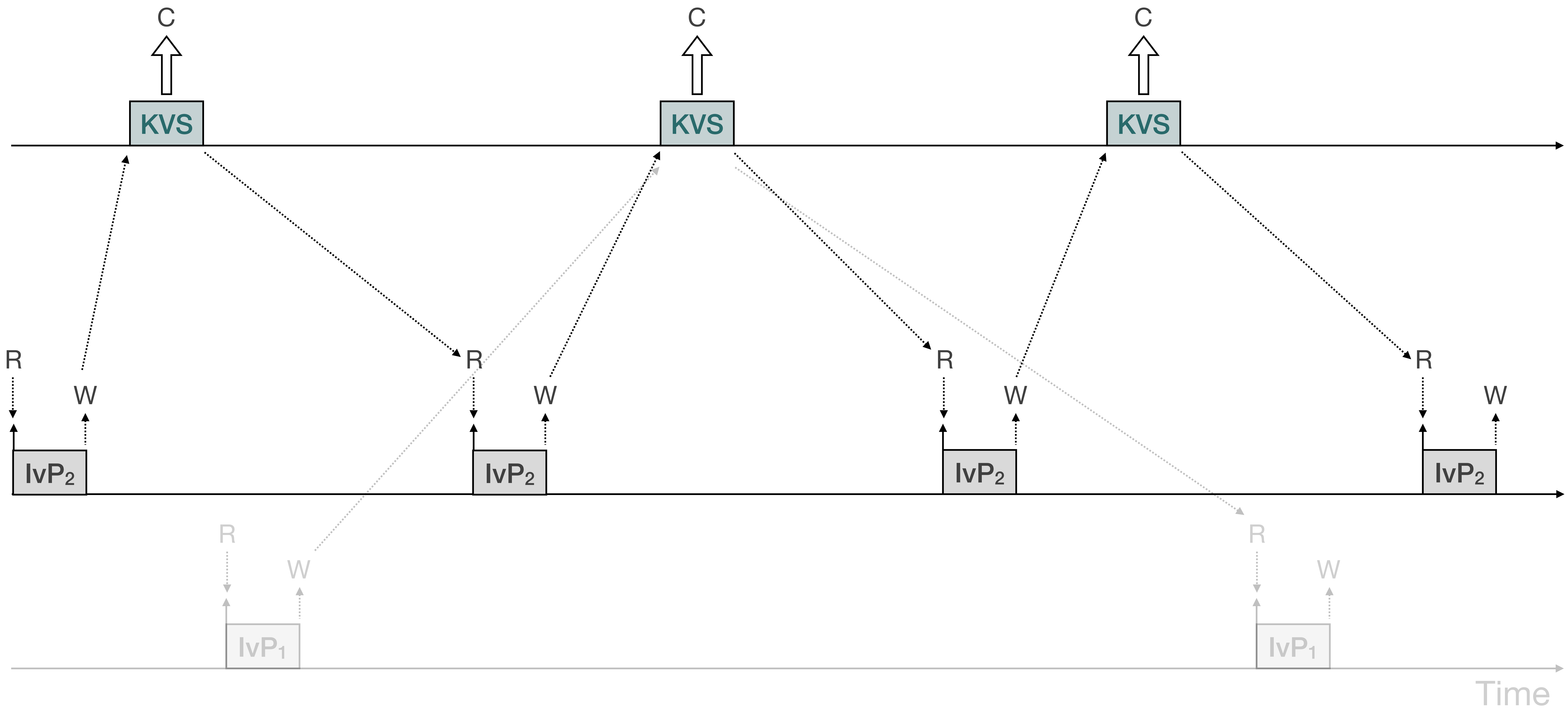


Schedule on node 1

Assume a single core in use

R = read, W = write, C = coordination

IvP = Inverted pendulum control application, KVS = Achal's backend



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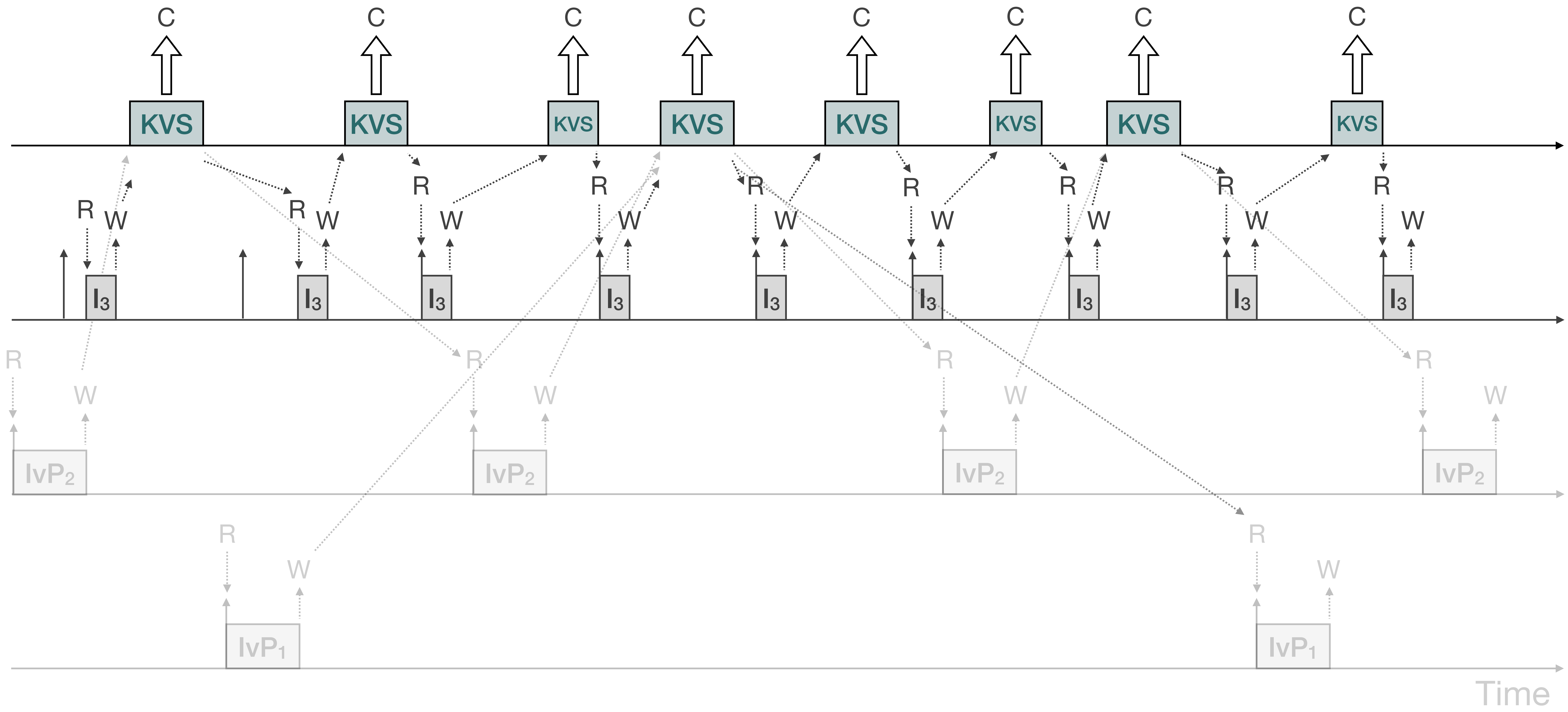

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Building Blocks

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Clock synchronization

- Make sense of absolute publishing times across distributed nodes

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EIGByz*# for Byzantine fault tolerance

- **Synchronous** → Exploits clock synchronization for better performance
- **Leaderless** → Higher reliability!
- **Interactive consistency** → Useful for noisy sensor values
- Simple algorithm → Can be easily parameterized in #nodes, #rounds
- **E**xponential **I**nformation **G**athering trees → Easily flattened for fast reads and writes

---

* Pease, Shostak, and Lamport. "Reaching agreement in the presence of faults." J. ACM (1980)

Borran and Schiper. "A Leader-Free Byzantine Consensus Algorithm." ICDCN (2010)

Design Principle: Make the KVS Strictly Periodic

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Achal is tuned as a function of both the workload and the platform!

Evaluation

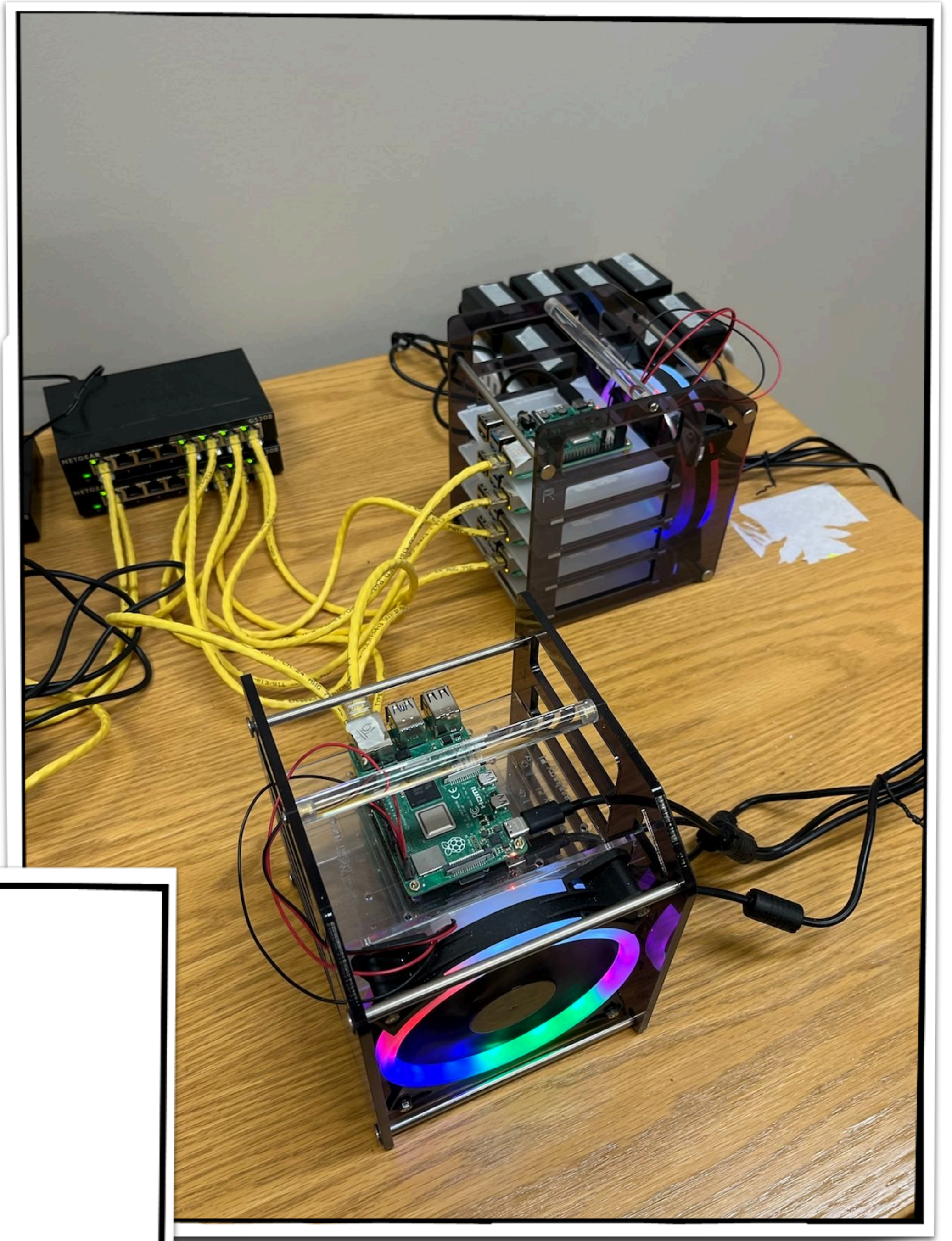
How does Achal compare against well-known datastores?

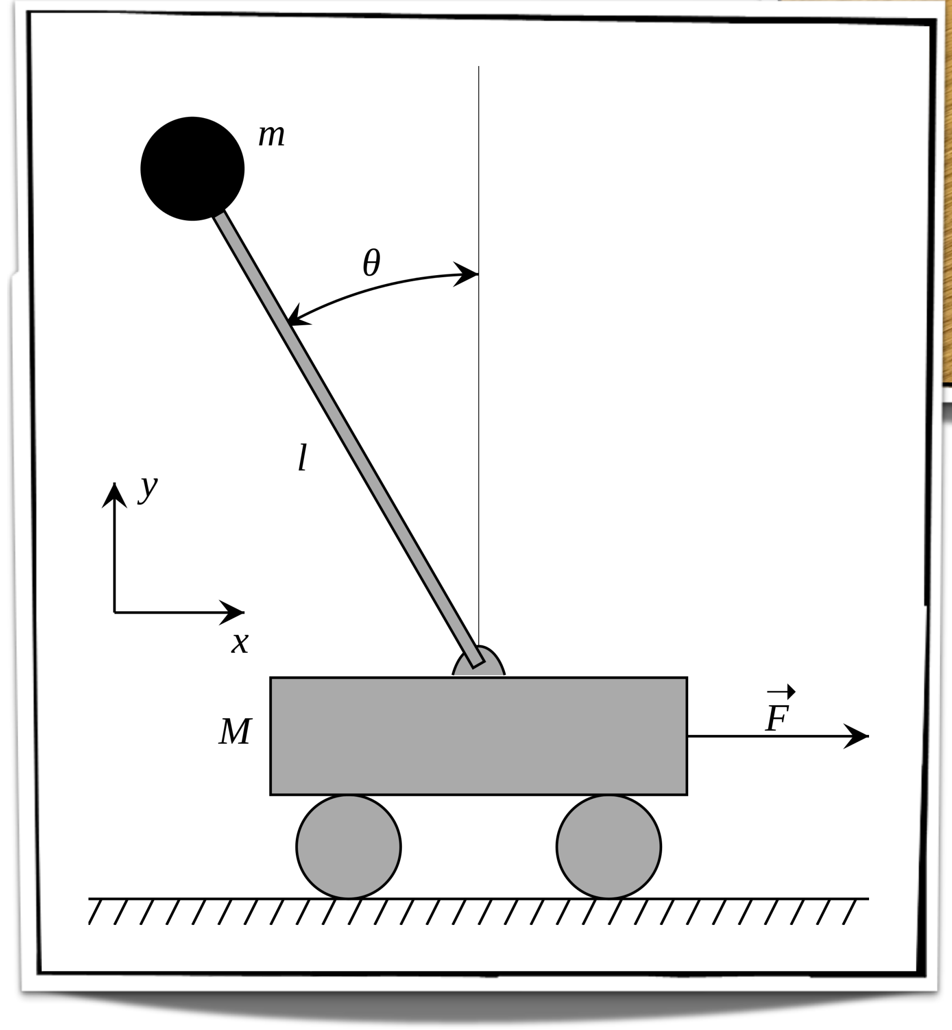
Platform: Four **Raspberry Pi** 4 Model B + Ethernet

Baselines: redis etcd

Workload

- **IvPSim:** Periodic task simulating inverted pendulum control
- Each task reads/writes 20 floats
- Coordinate data written by IvPSim replicas every iteration





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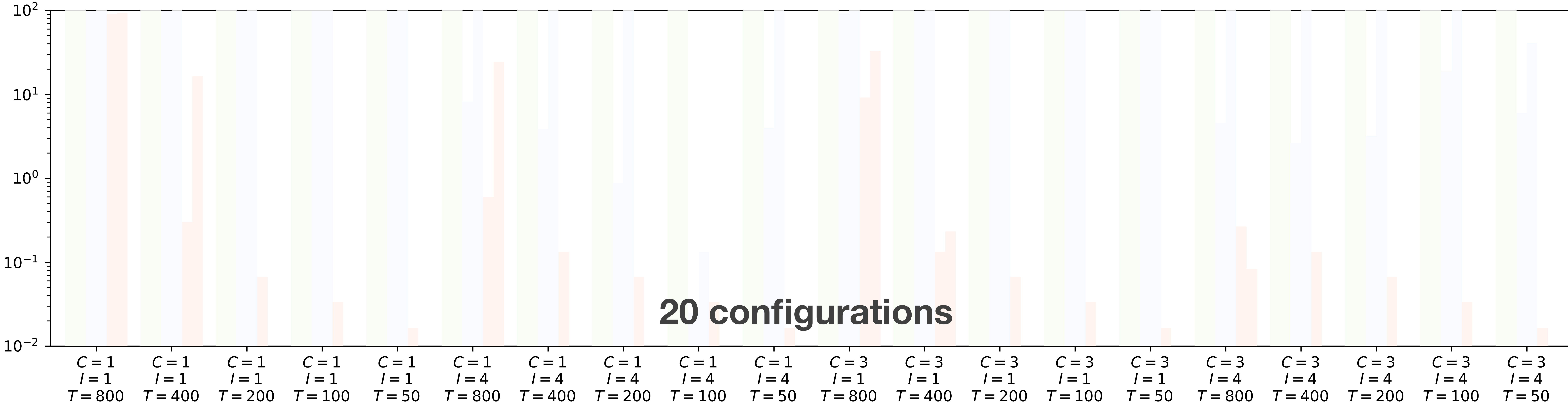

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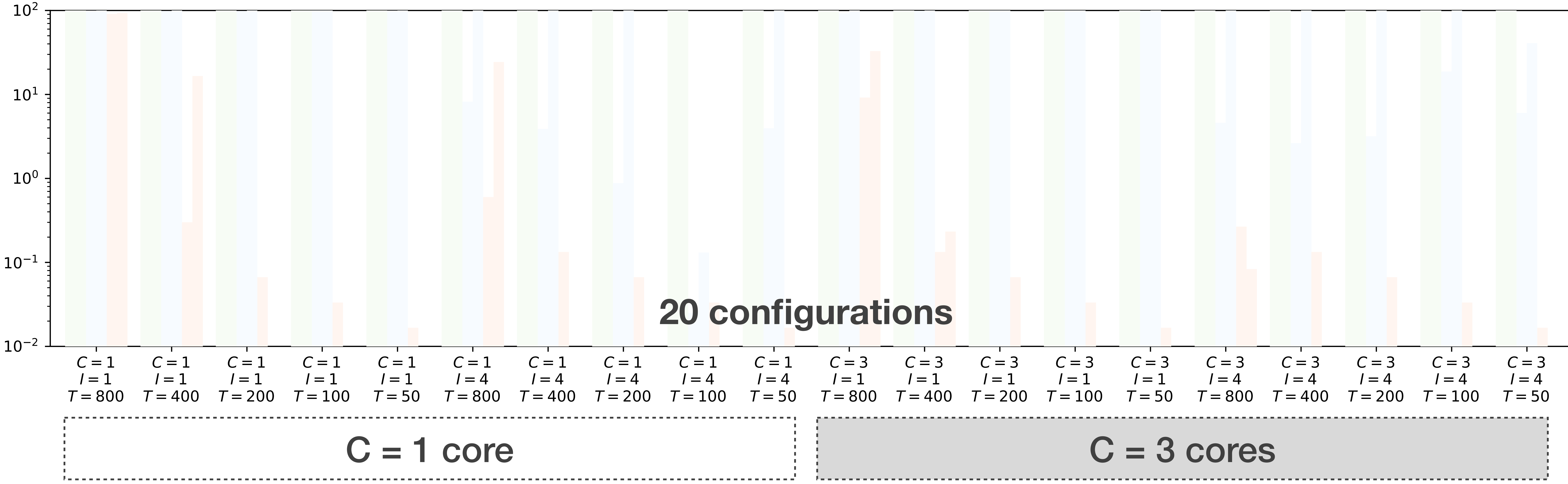

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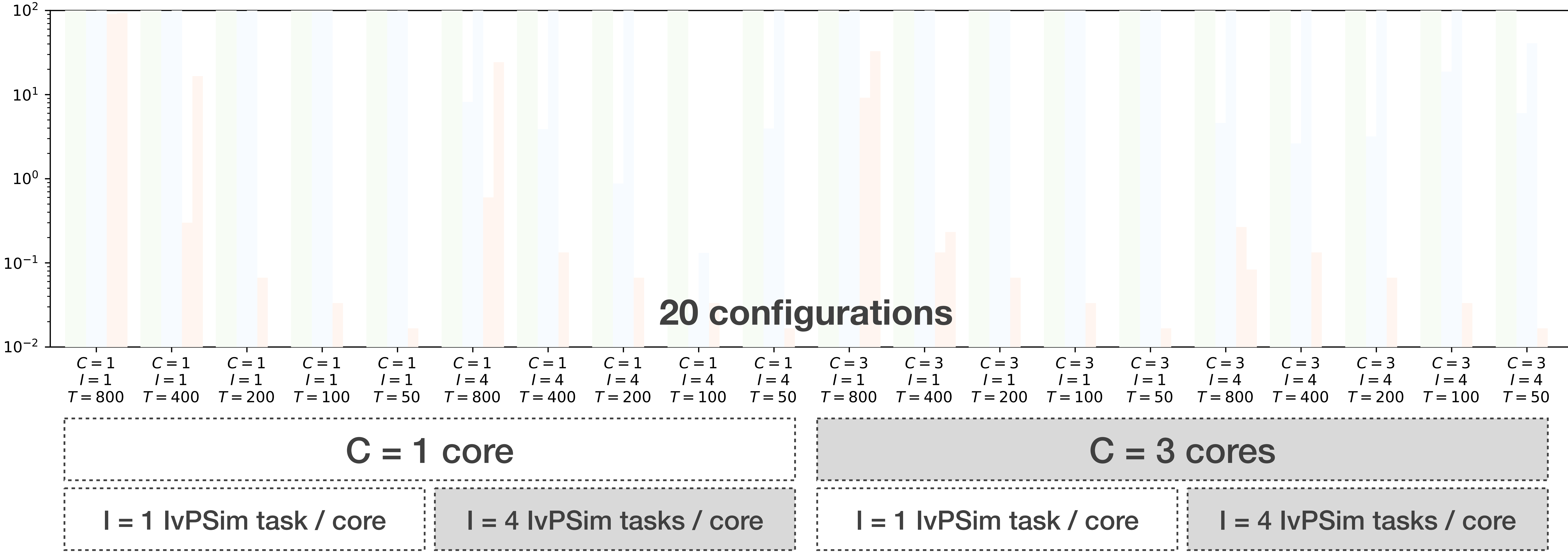

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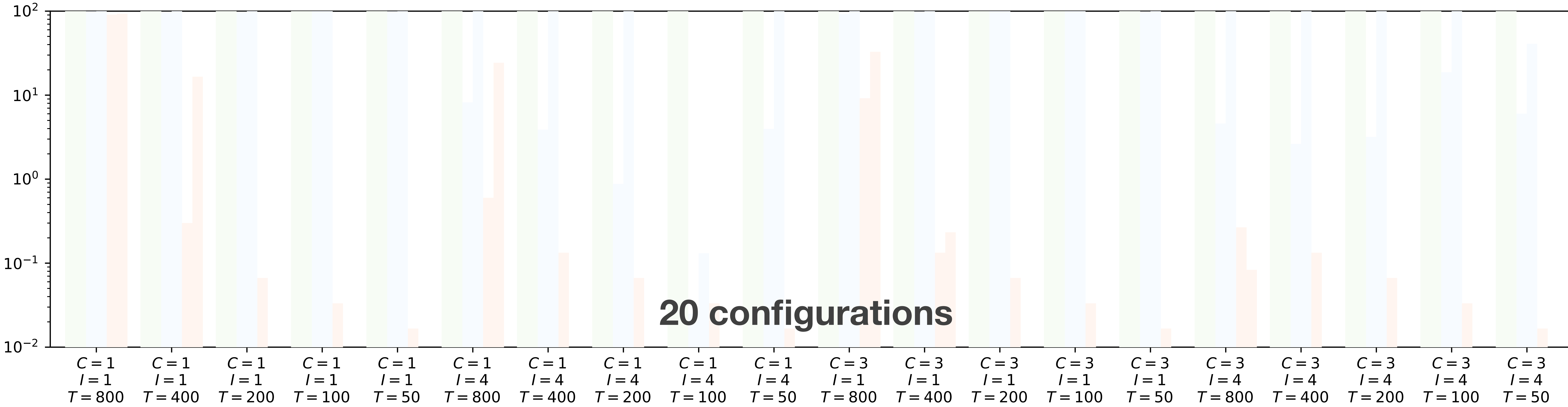

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C = 3 cores

I = 1 IvPSim task / core

I = 4 IvPSim tasks / core

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Decreasing Period →

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How does Achal compare against well-known KVS?

Metrics

- Read: % of iterations where all reads were successful
- Write: …

Higher is better!

Log scale

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
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Redis underperforms when the workload is increased

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Achal successfully managed an automotive workload 10x-100x lvPSim BOSCH

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Need for *a priori* timing and reliability analyses makes the system design problem even more challenging!

- How often does Achal fail? Is $P_{fail} < 10^{-10}$/hr?
- Can we add yet another control task without affecting the system timeliness?

Key Takeaways

Interplay between timing and fault tolerance is nontrivial

- Lots of interesting system design problems to be explored in the space of distributed real-time systems in the CPS domain …

Need for *a priori* timing and reliability analyses makes the system design problem even more challenging!

- How often does Achal fail? Is $P_{fail} < 10^{-10}$/hr?
- Can we add yet another control task without affecting the system timeliness?

More details about Achal in the paper …

- "Interactive Consistency meets Distributed Real-Time Systems, Again!" at RTSS 2022

CPS Research

Developing **foundations** needed to engineer complex CPS

… which require **“dependable, high-confidence, or provable behaviors”***

1. **Runtime mechanisms**
2. **Analysis techniques**

* https://beta.nsf.gov/funding/opportunities/cyber-physical-systems-cps

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