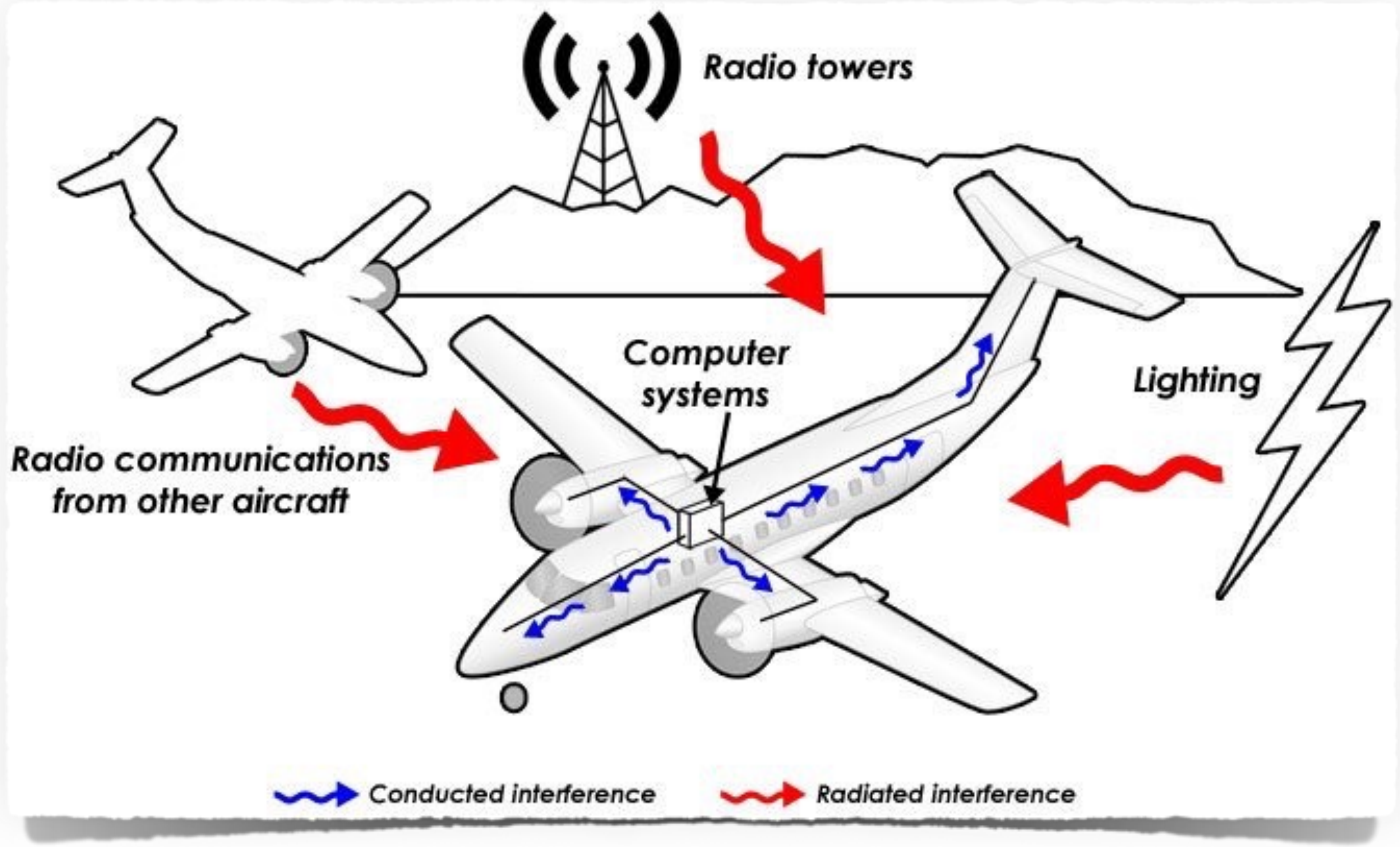
Real-Time Replica Consistency over Ethernet with Reliability Bounds

Arpan Gujarati, Sergey Bozhko,
and Björn B. Brandenburg

MAX PLANCK INSTITUTE
FOR SOFTWARE SYSTEMS

Environmentally-induced **transient faults**

- Harsh environments
  - ➡ Robots operating under **hard radiation**
  - ➡ Industrial systems near **high-power machinery**
  - ➡ **Electric motors, spark plugs** inside automobiles



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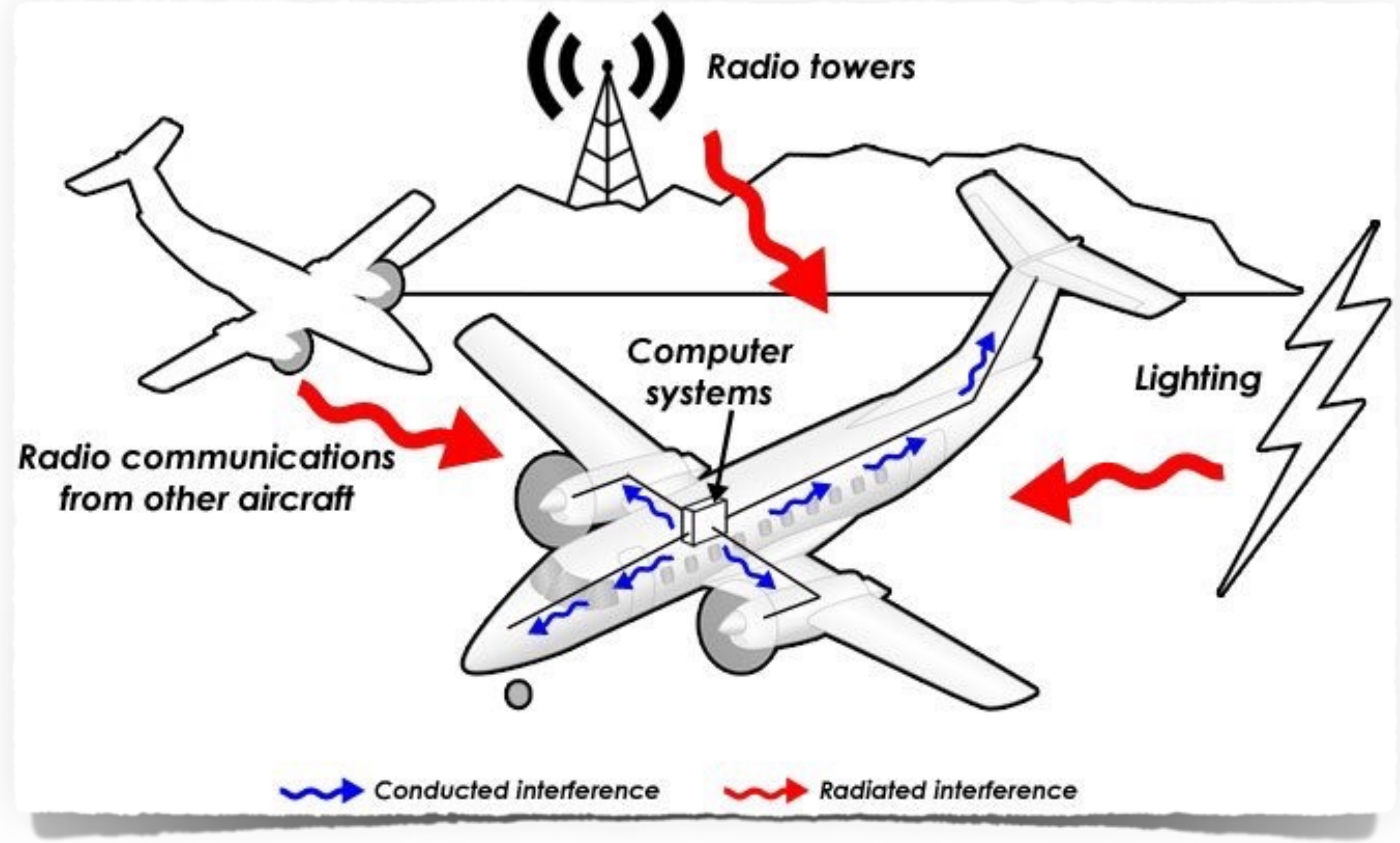

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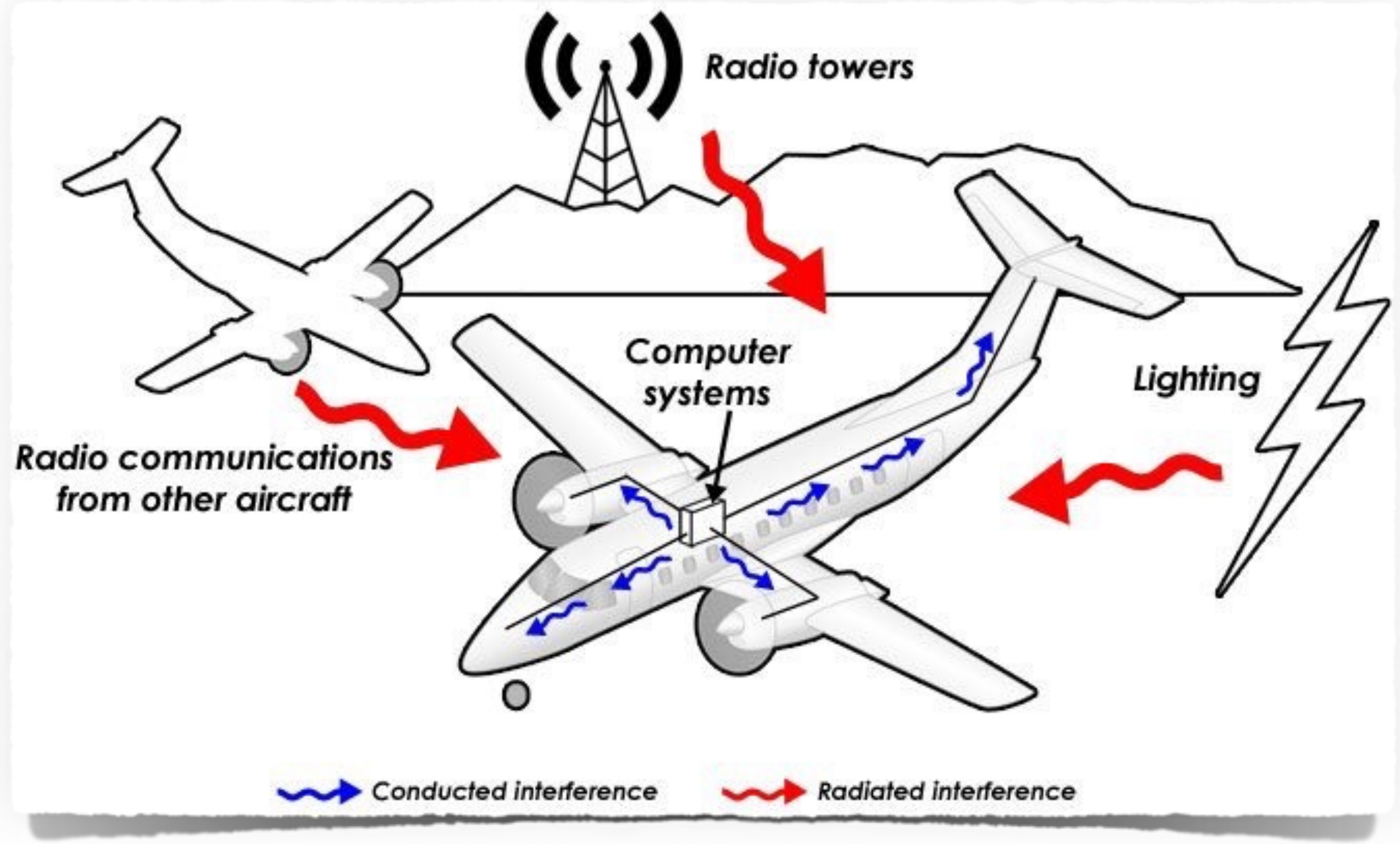

Example*

- ➡ One bit-flip in a 1 MB SRAM every 10^{12} hours of operation
- ➡ 0.5 billion cars with an average daily operation time of 5%
- ➡ **About 5000 cars are affected by a bit-flip every day**

* Mancuso. "Next-generation safety-critical systems on multi-core platforms." PhD thesis, UIUC (2017)

Errors and failures due to transient faults

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- Transmission errors
  - ➡ Faults on the network
- Omission errors
  - ➡ Fault-induced kernel panics, hangs
- Incorrect computation errors
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- Inconsistent broadcast errors
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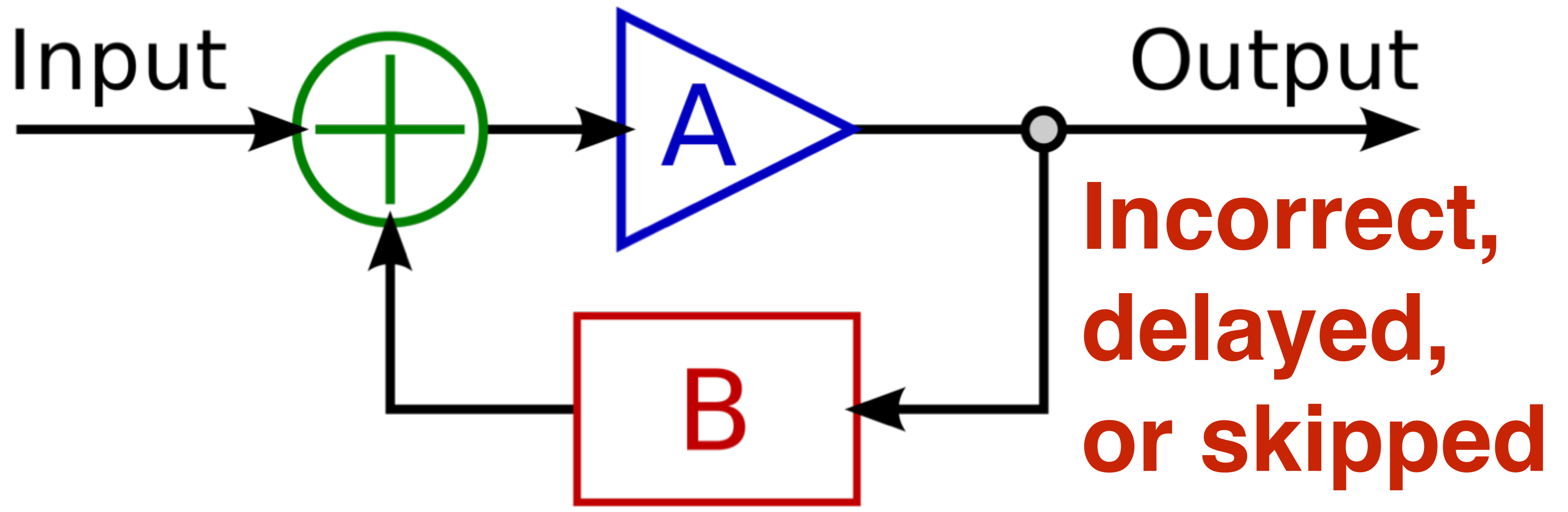
Failures in

- ➡ **value domain (incorrect output)**
- ➡ **time domain (delayed output)**

E.g., safety-critical control system



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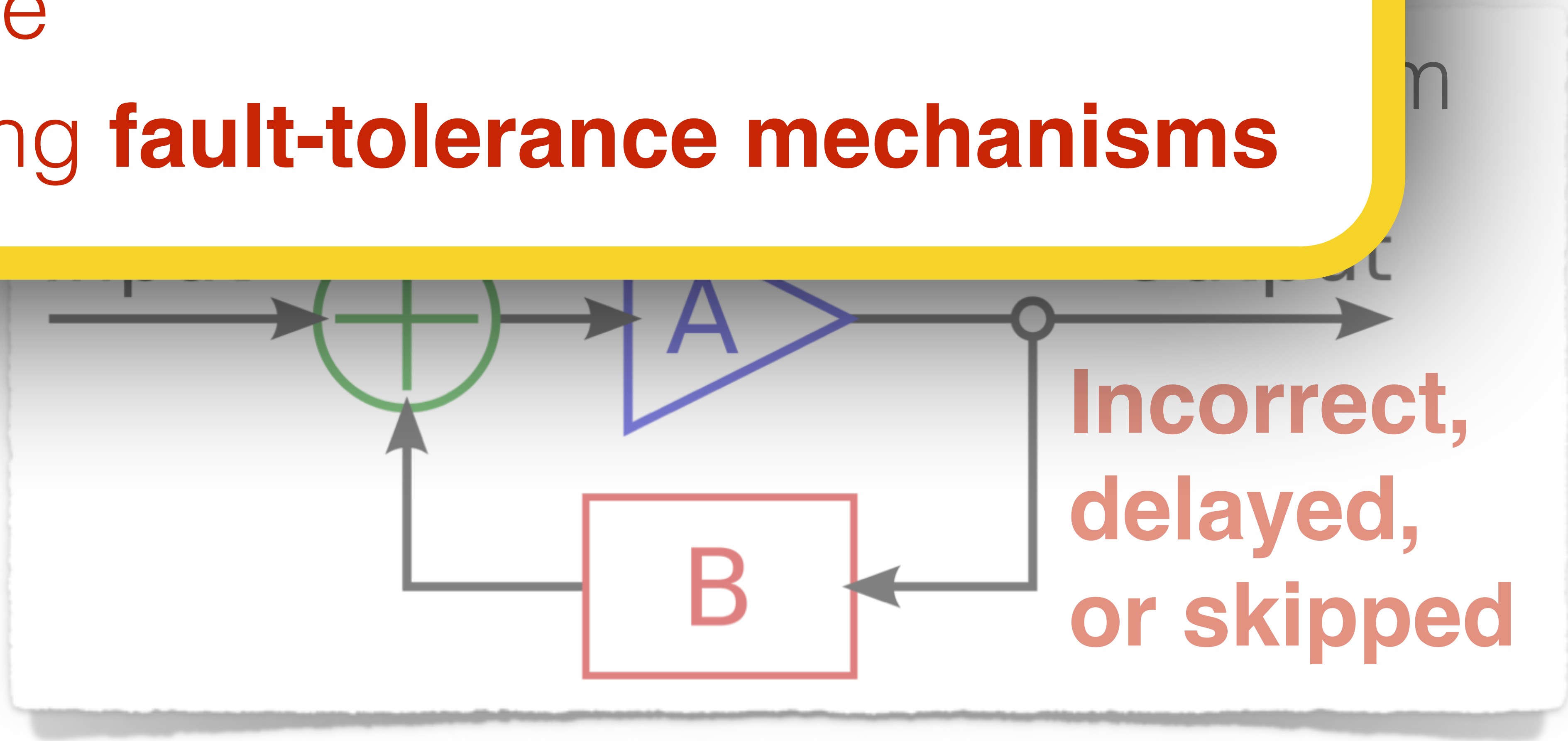
Failures in

- ➡ **value domain (incorrect output)**
- ➡ **put)**

Fault-induced errors are **random events**

- ➡ **Cannot be predicted** in advance
- ➡ Must be tolerated at runtime using **fault-tolerance mechanisms**



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Checksums and retransmissions

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Dual Modular Redundancy (DMR)

- Incorrect computation errors
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ECC Memory +
Triple Modular Redundancy (TMR)

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Byzantine Fault Tolerance (BFT)

Which of these mechanisms (or a combination thereof) should be **used** in practice?

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Industry:  **RULE**

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Size, Weight, and Power ... plus Cost

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This work!

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Focus

Design and reliability analysis of a **BFT protocol**
for **Ethernet-based** distributed real-time systems

System design

Network control system

Physical plant reliable

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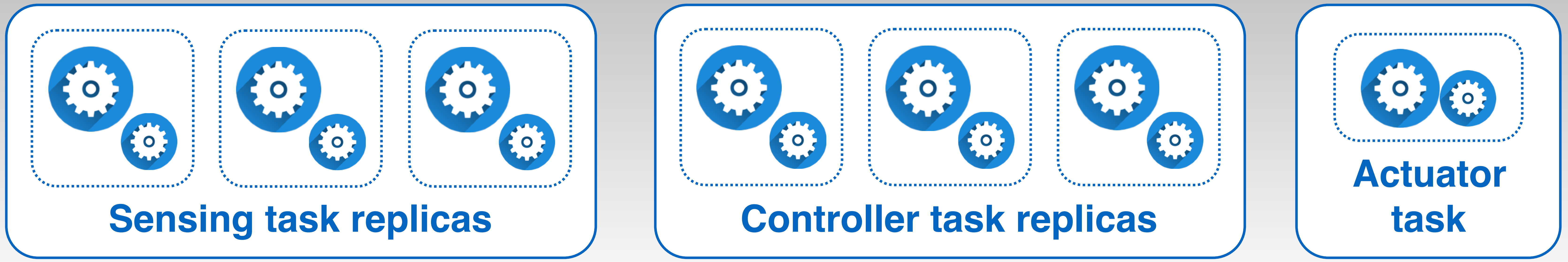
Active Replication

DMR / TMR / Hybrid



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Physical sensor — **Controlled plant** — **Physical actuator**

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Sensing task replicas

Controller task replicas

Actuator task

Ethernet Time-Sensitive Networking (TSN)

Statically reserved routes

Priority classes

Decreasing priority

Priority 1
Priority 2
Priority 3
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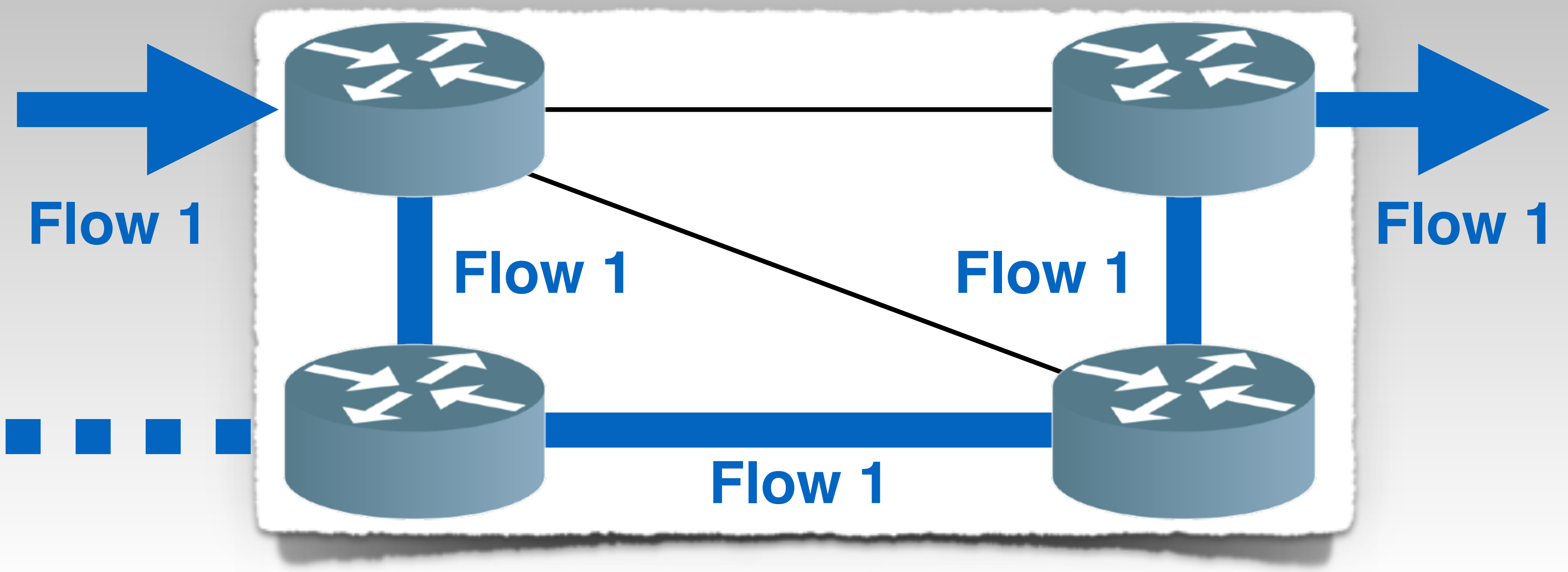
Priority 8

FIFO queues for each priority



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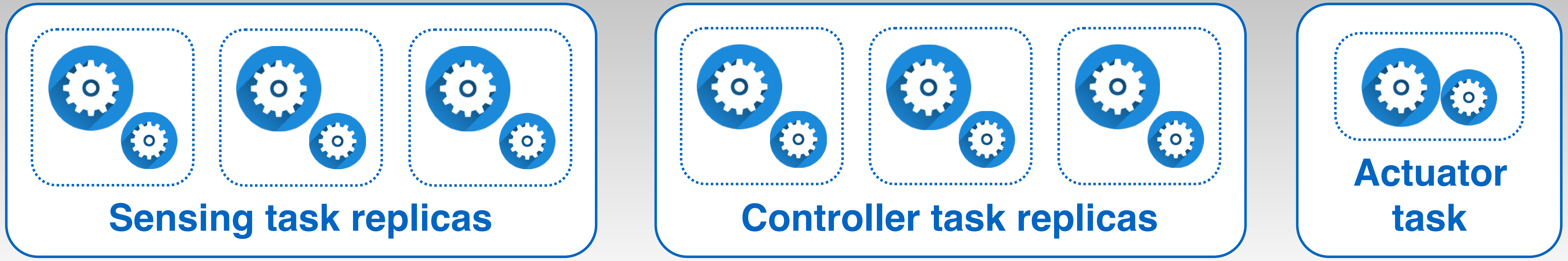

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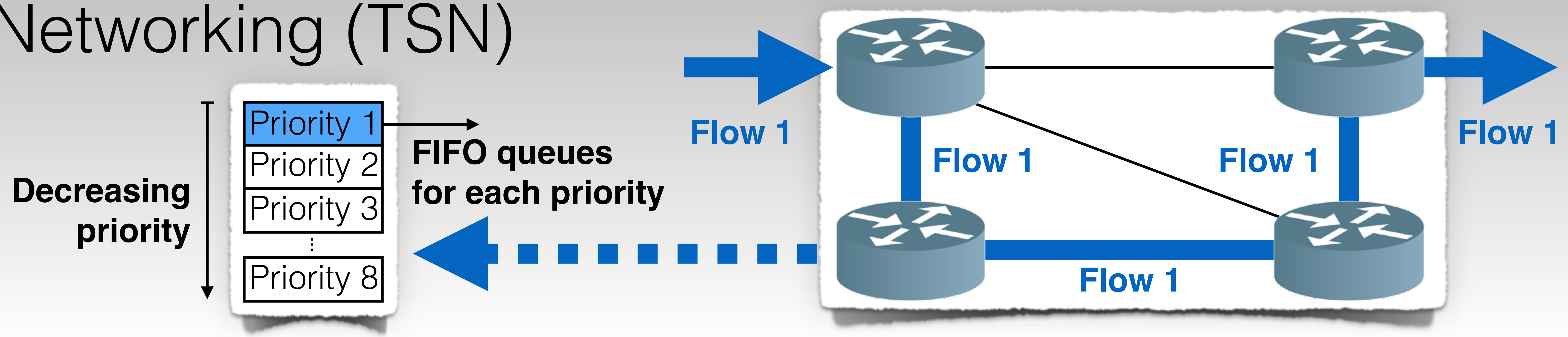

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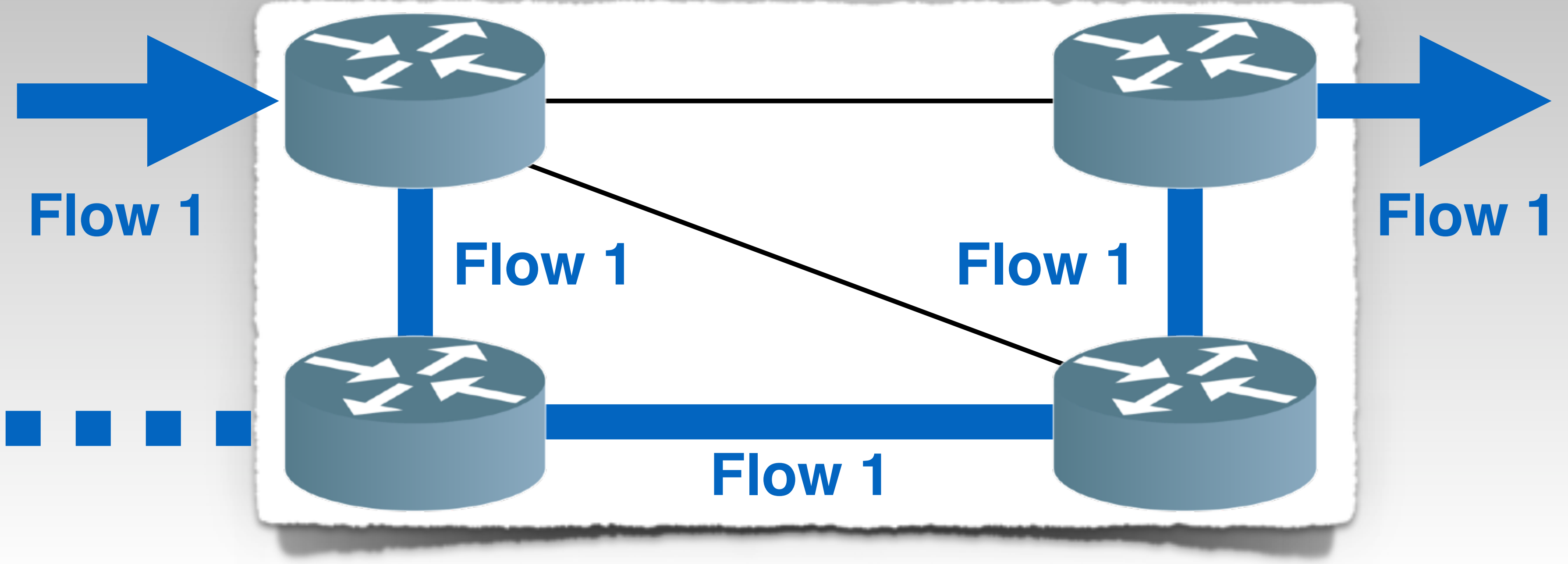

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Challenge: Prior work does not consider hard real-time predictability

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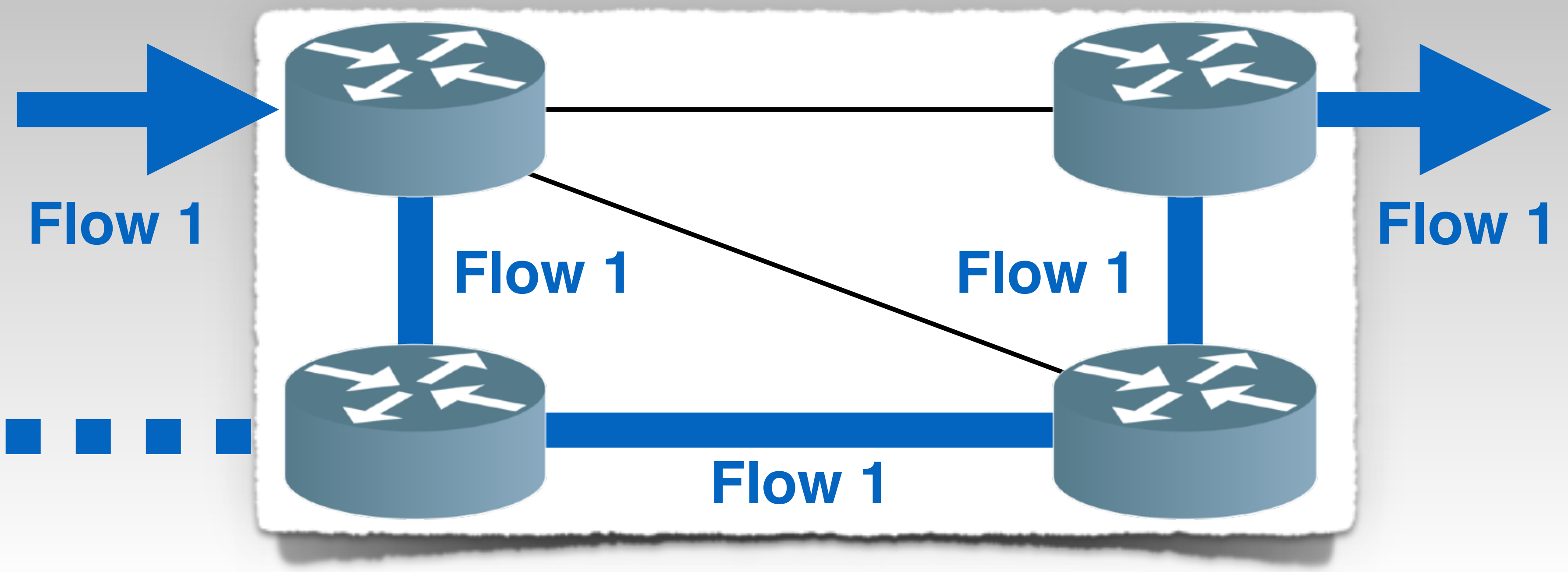

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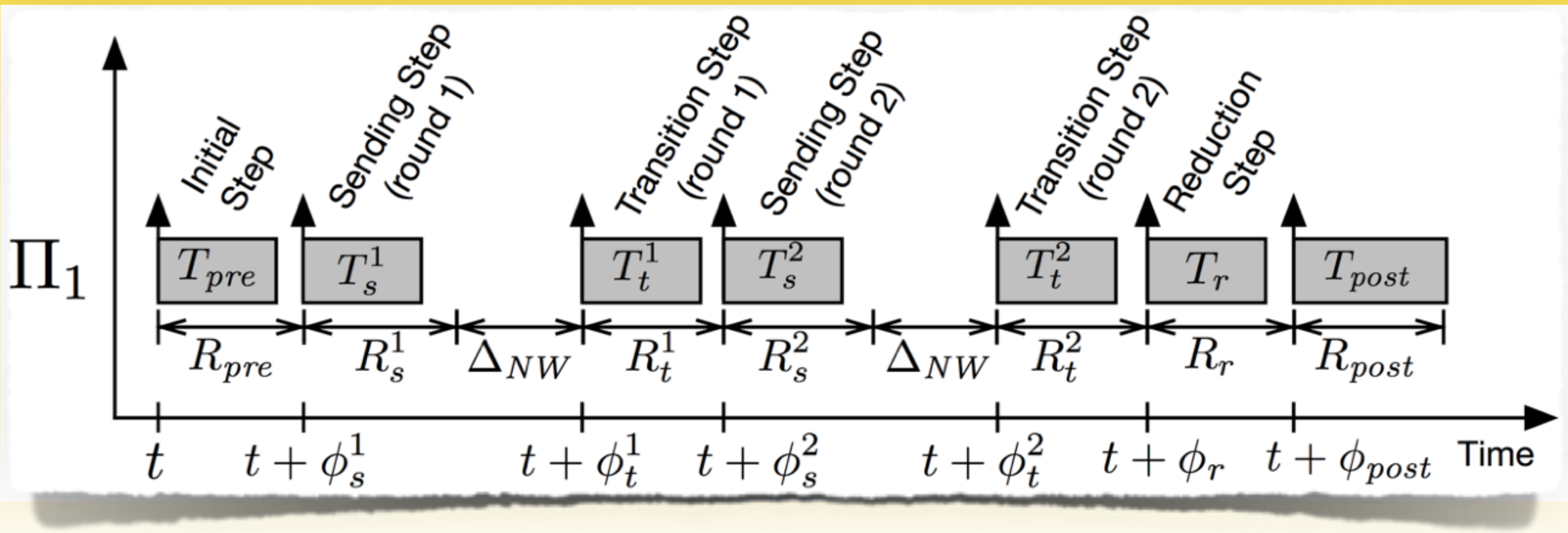
Statically-checked hard real-time protocol

Synchronous BFT protocol [Pease et al., 1980]

Periodic tasks and messages



Clock synchronization

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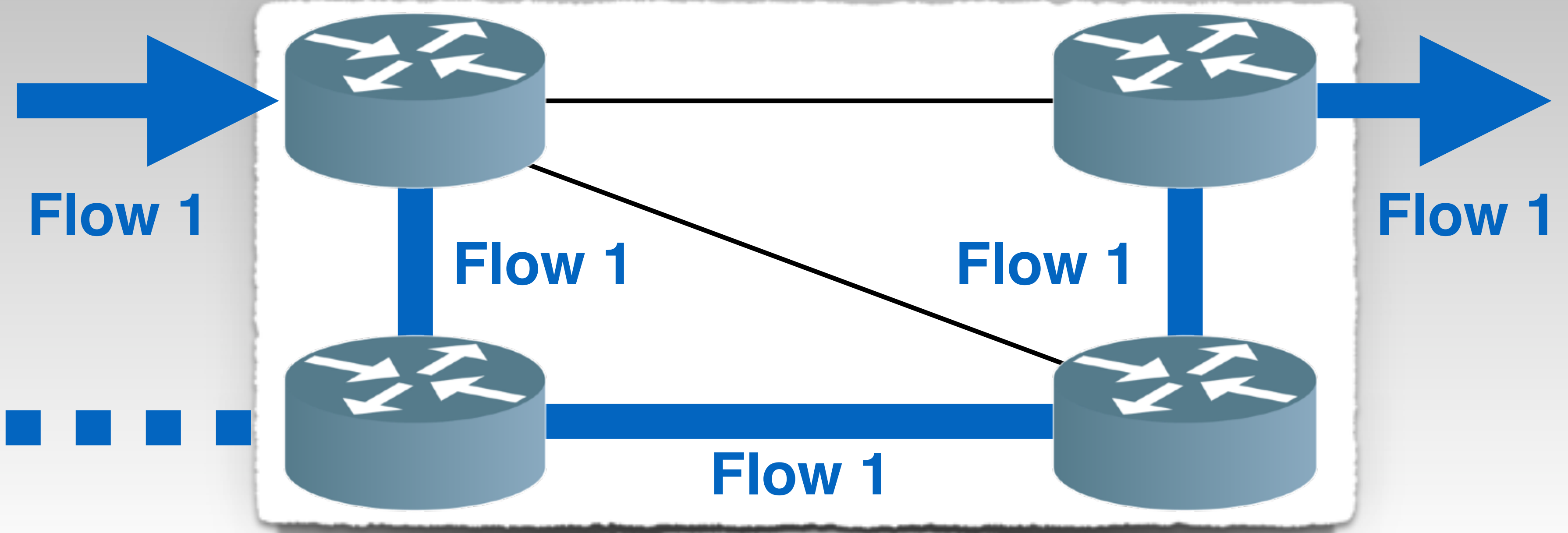

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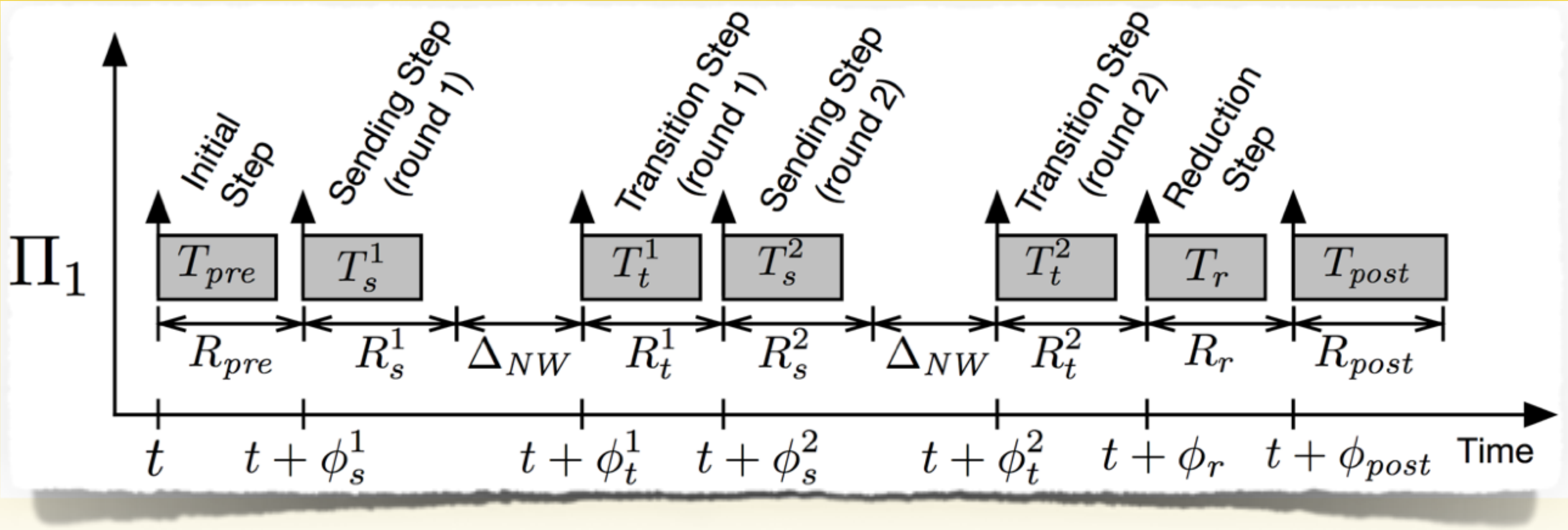

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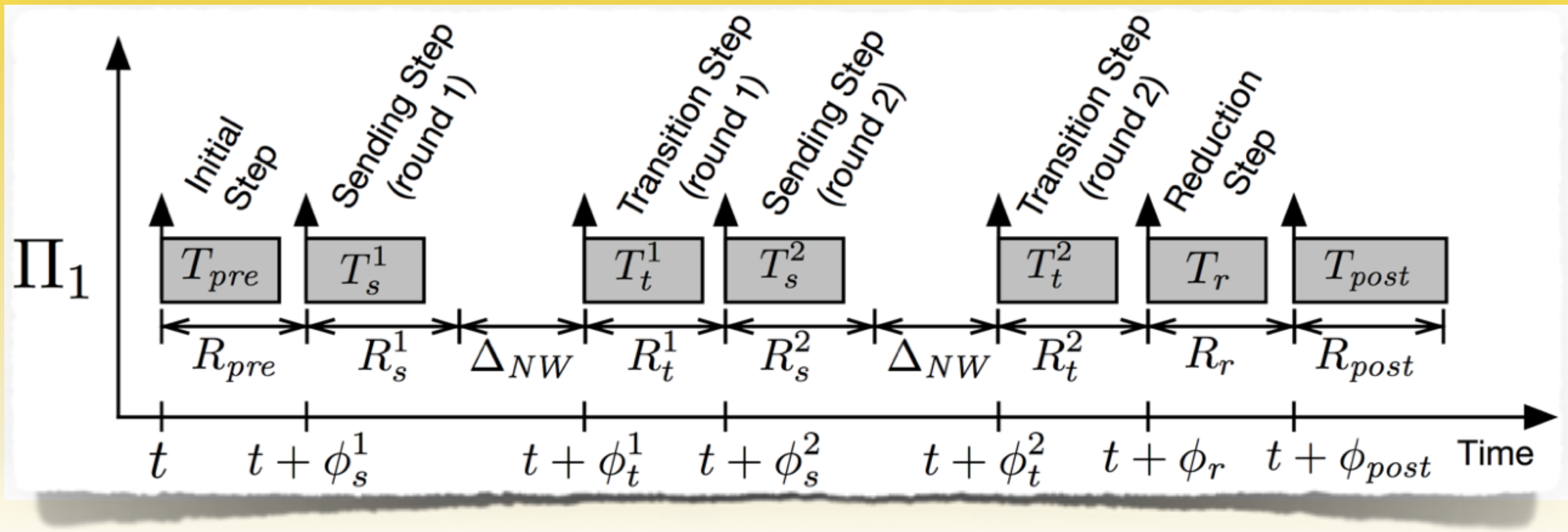

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This talk: Reliability Analysis

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What is the probability of an **atomic broadcast failure?**

Transient fault-induced errors

Ethernet frame corruptions / omissions

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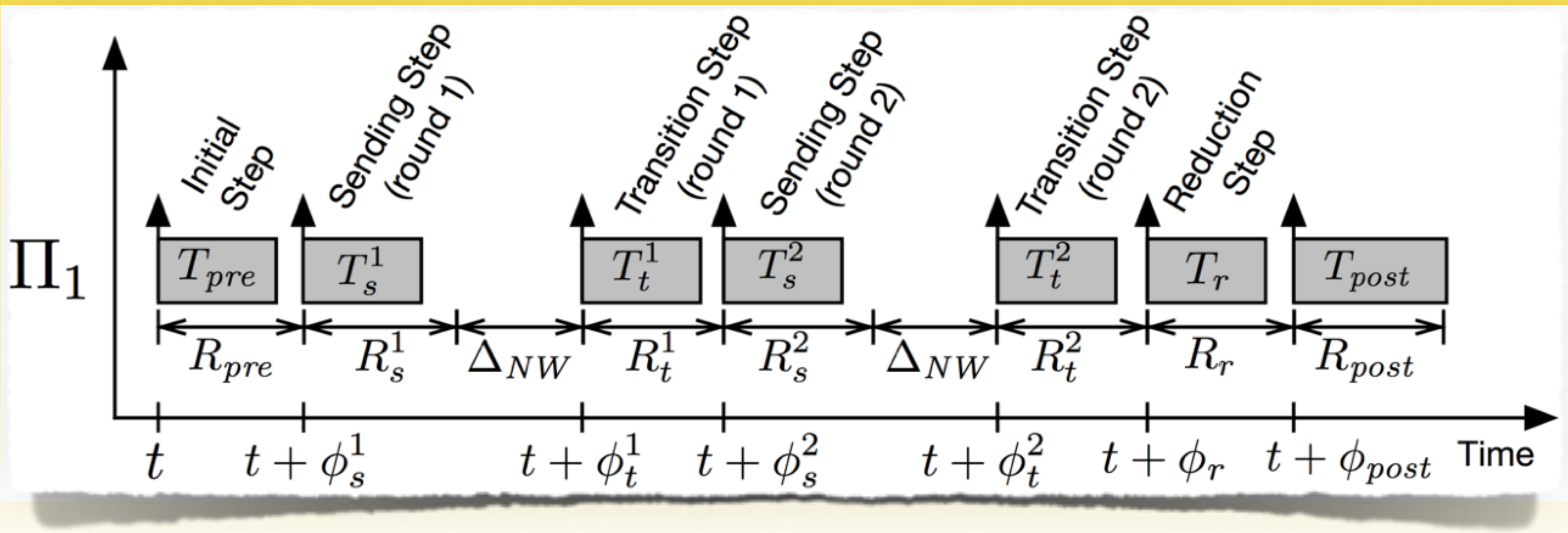

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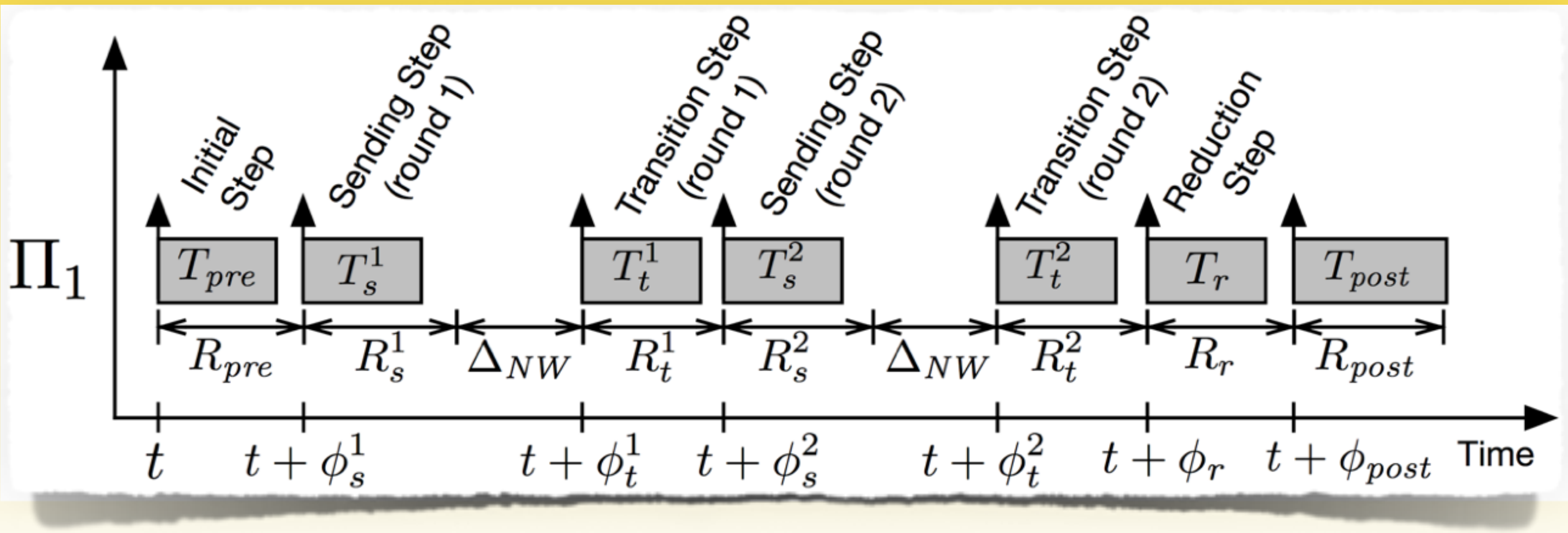

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Stochastically modeled basic errors

Basic errors due to transient faults are random, independent events

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Poisson distribution using **peak rates** from maximum interference periods

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Poisson distribution using **peak rates** from maximum interference periods

For processors and switches	**Poisson(n, δ, λ_{crash})** = Pr(n crashes in an interval of length δ | crash rate λ_{crash})
For processors, switches, and network links	**Poisson(n, δ, $\lambda_{corruption}$)** = Pr(n corruptions in an interval of length δ | corruption rate $\lambda_{corruption}$)

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Ethernet frame corruptions / omissions

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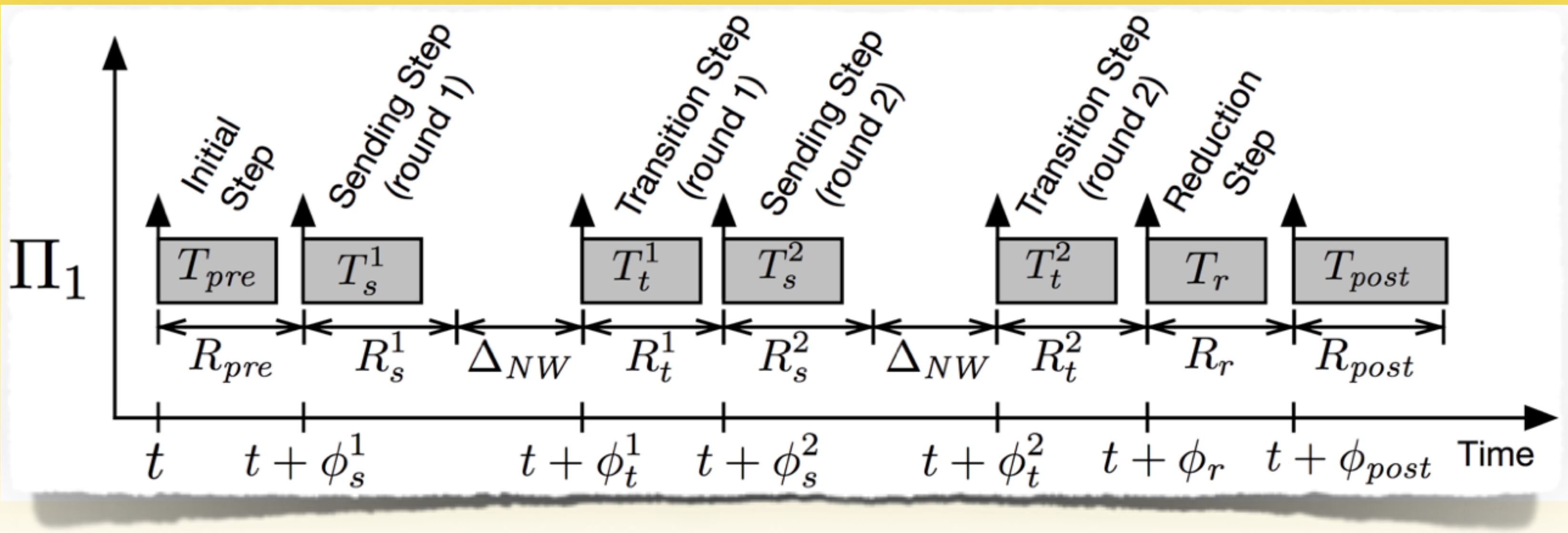

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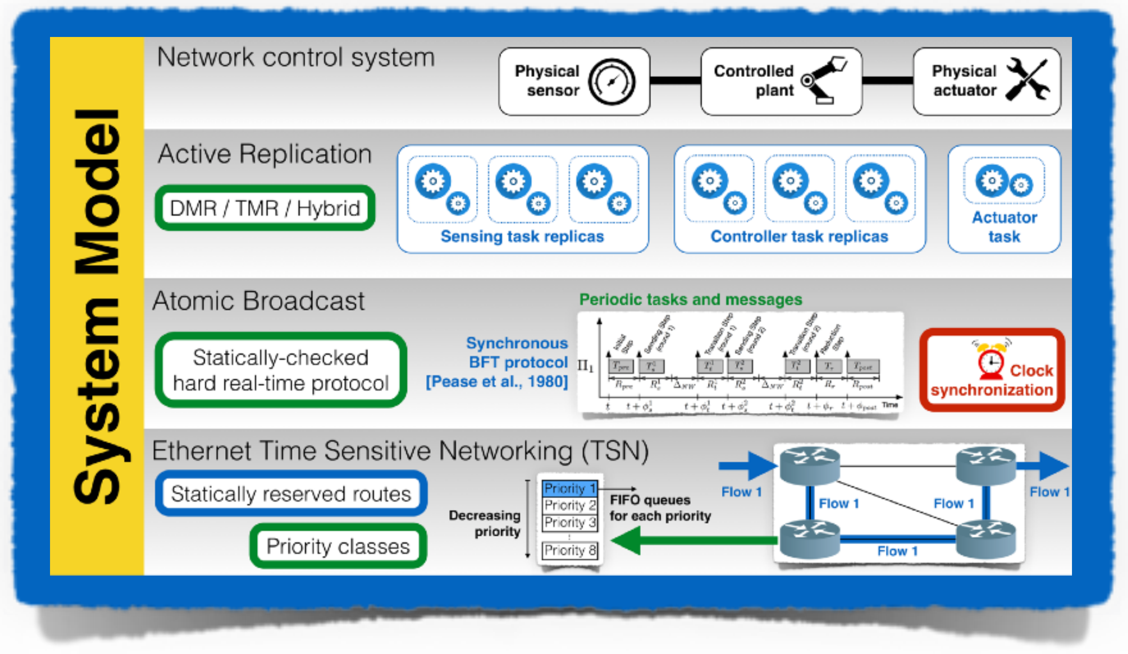
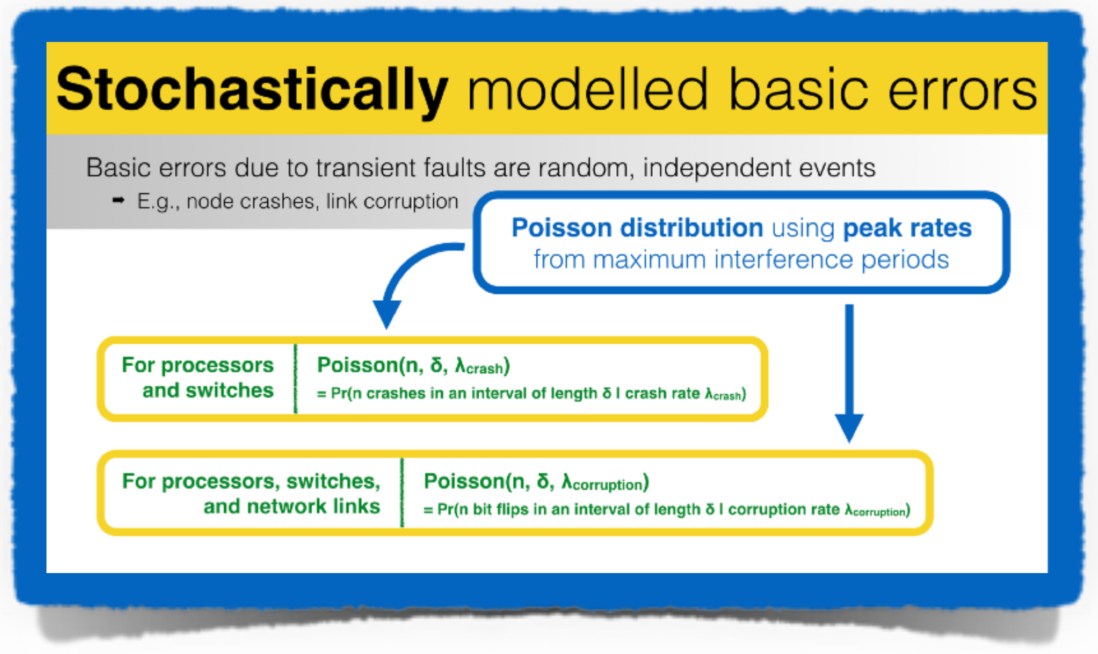
Straw-man solutions

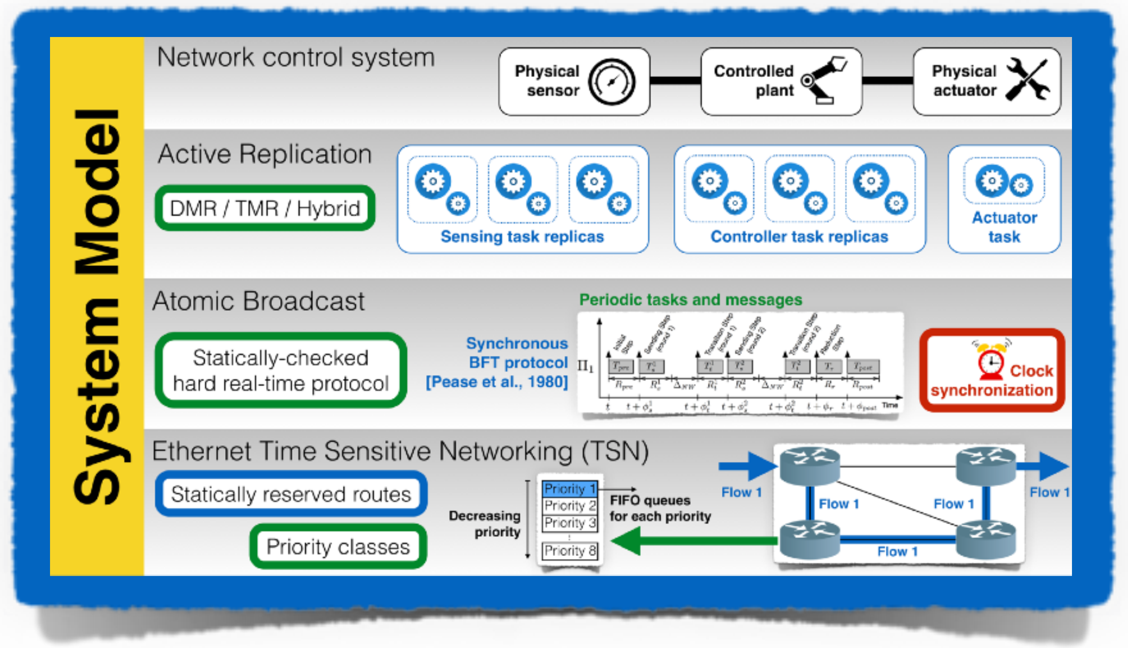


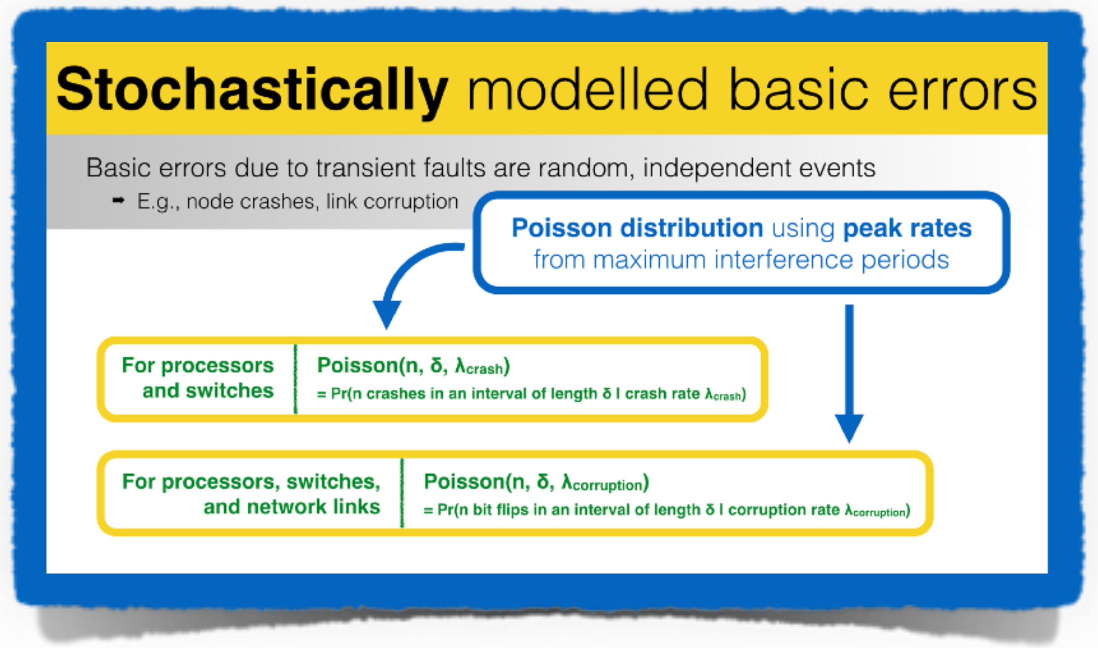


Model checking or simulation

Pr (atomic broadcast failure)

Straw-man solutions





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- ➡ Formal methods often do not scale beyond small distributed models

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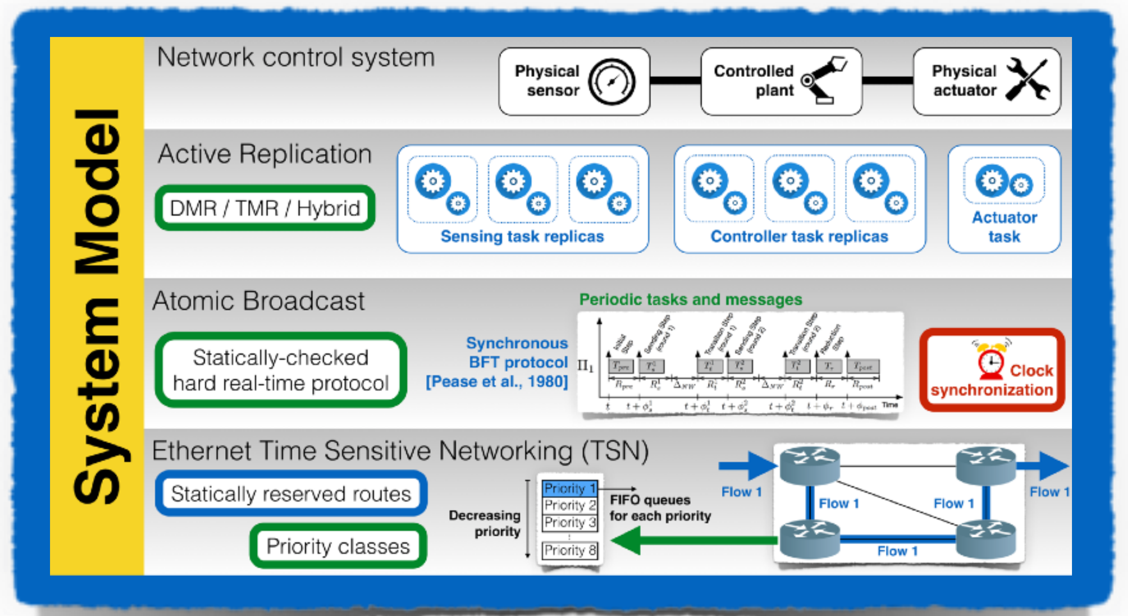

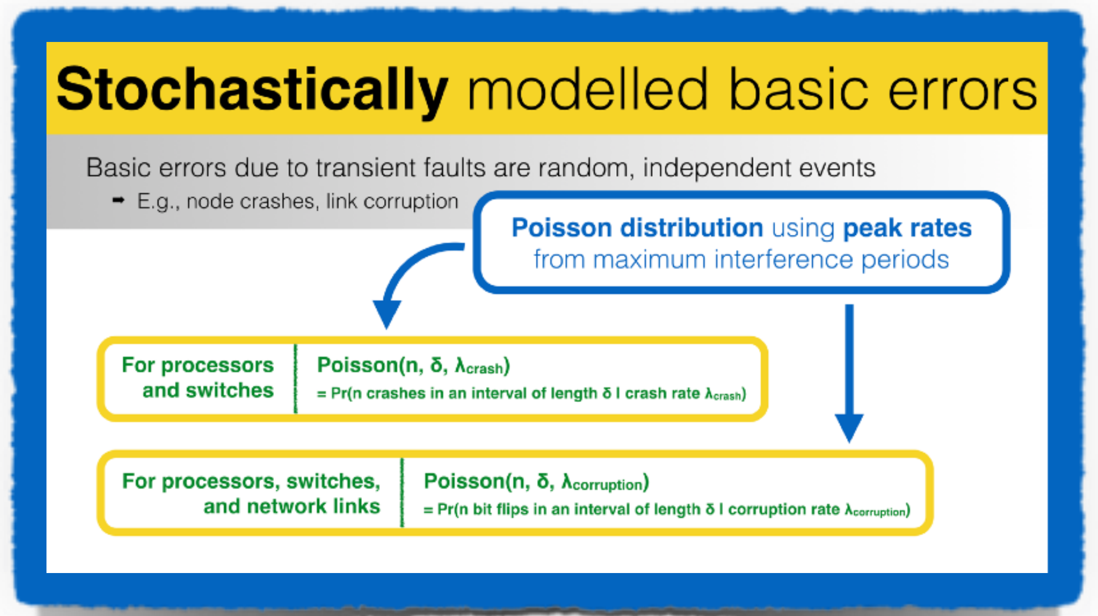

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Reliability anomalies

- ➡ In practice, the failure probability may **significantly exceed** the estimated Pr (atomic broadcast failure)

Key idea 1: Scalability through **abstraction** and **pruning**

Goal: P_{UB} > Pr (atomic broadcast failure)

Key idea 1: Scalability through **abstraction** and **pruning**

Msg. M_1

- ➡ **Corrupted** at source, network, or destination
- ➡ **Omitted** at source or network

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Application-specific message errors

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Group identical messages into a single error event

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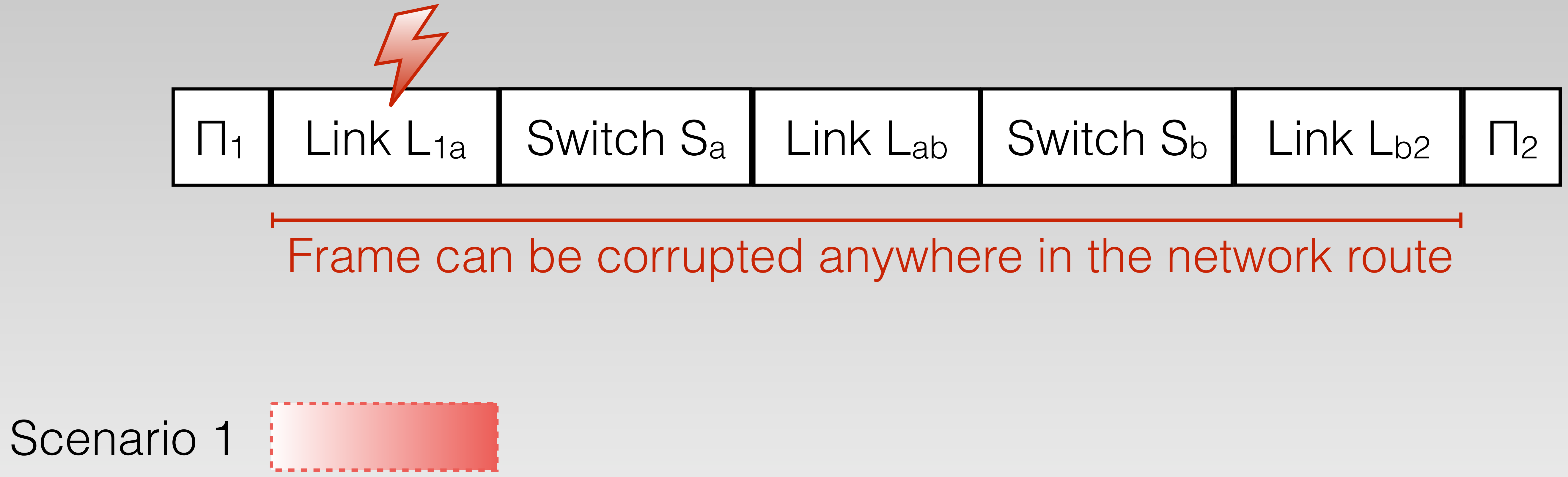

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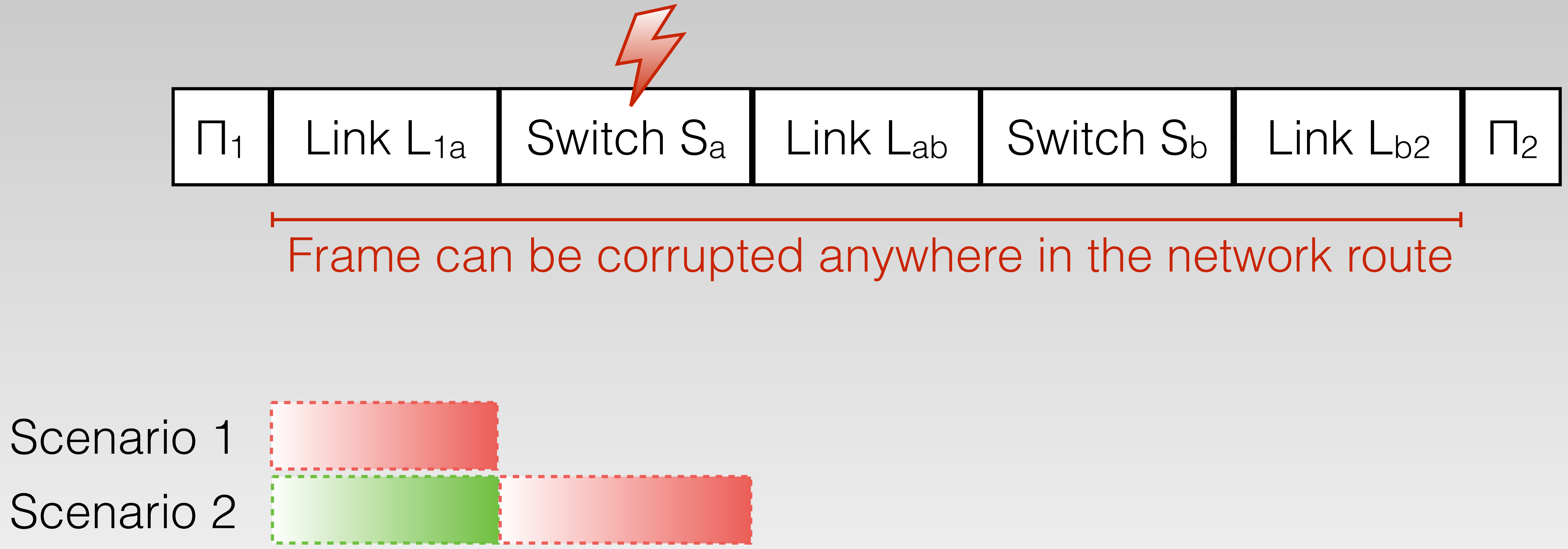

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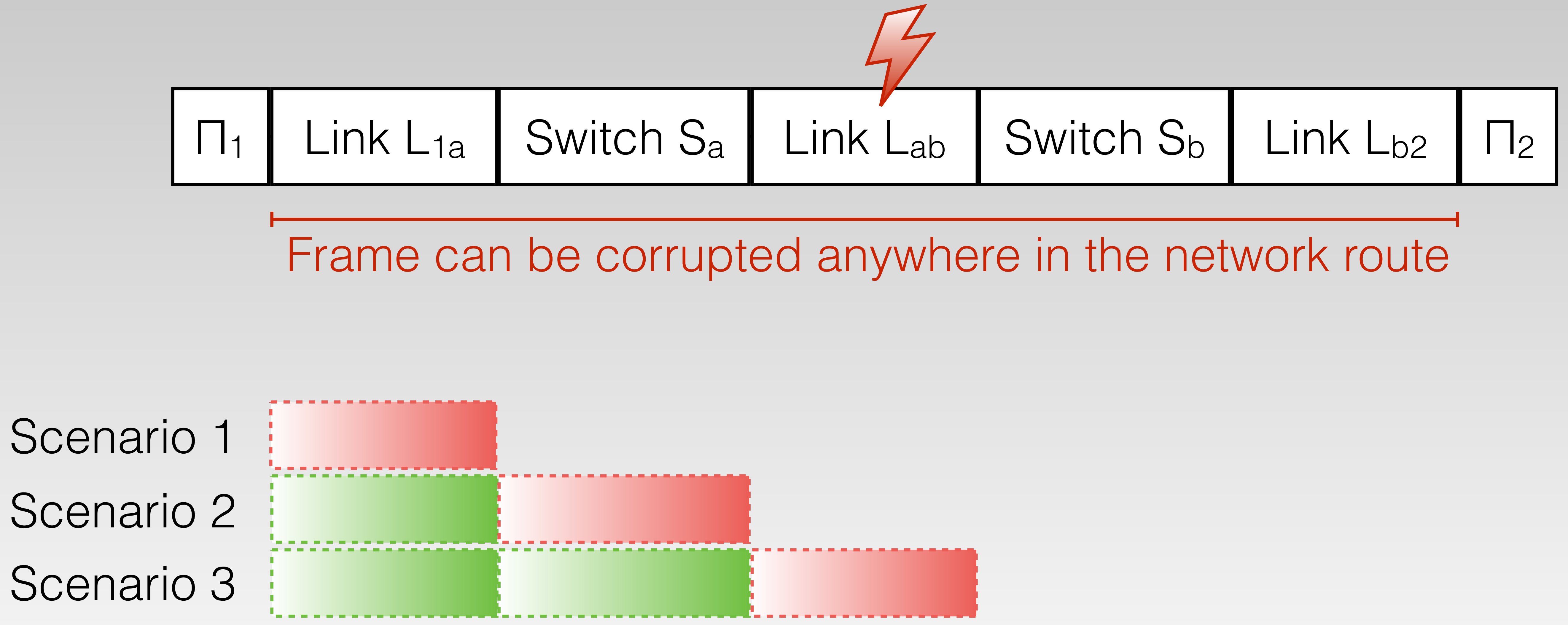

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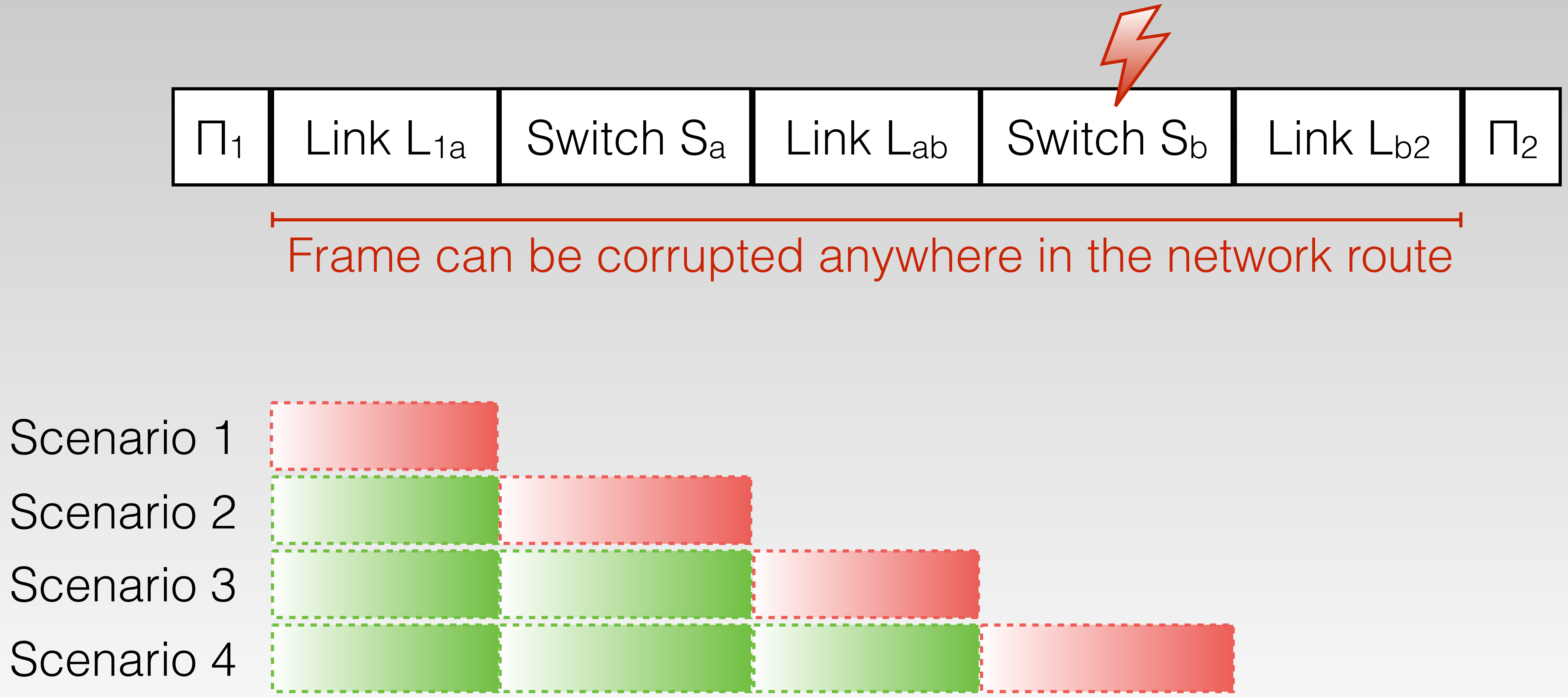

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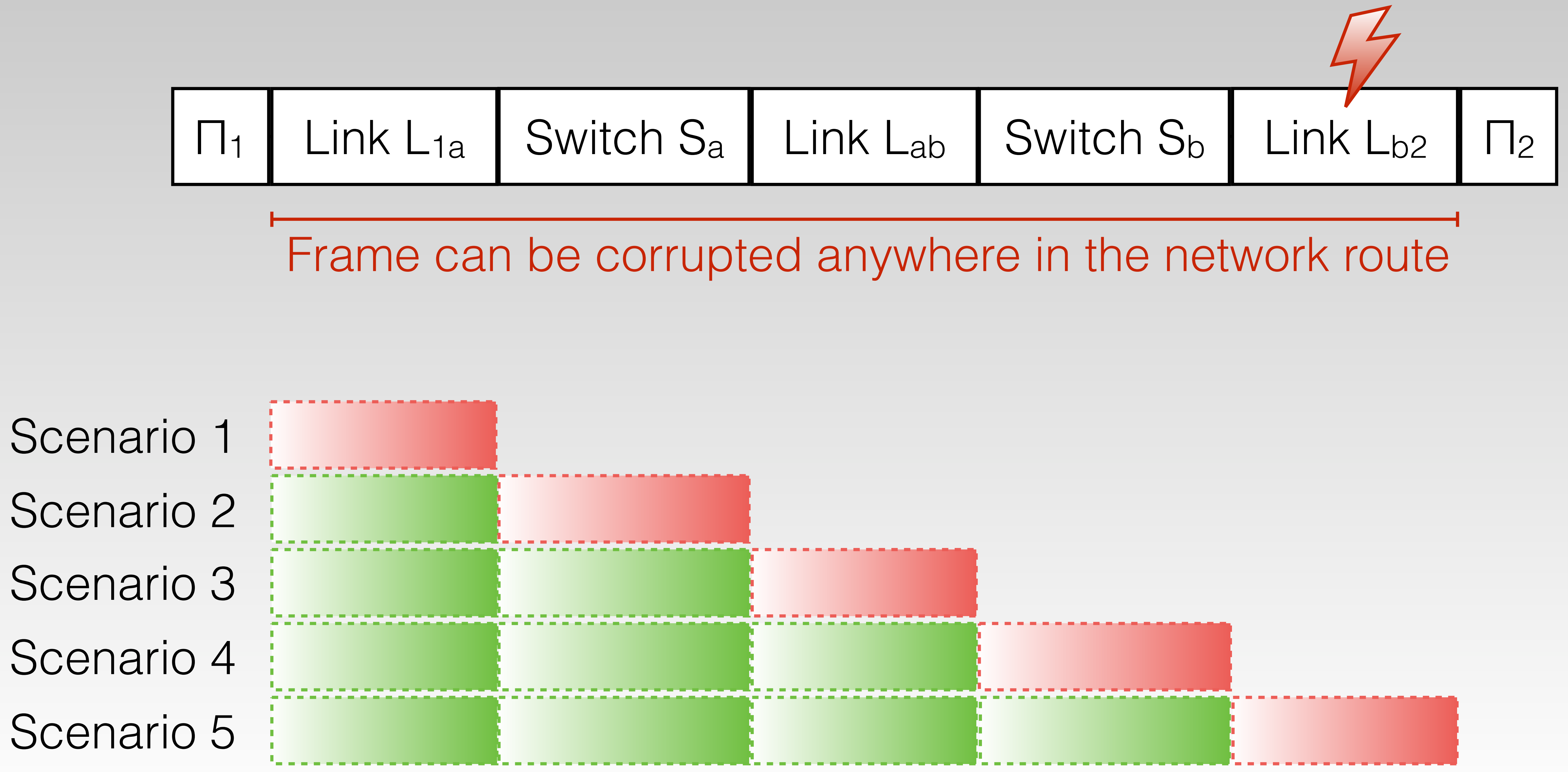

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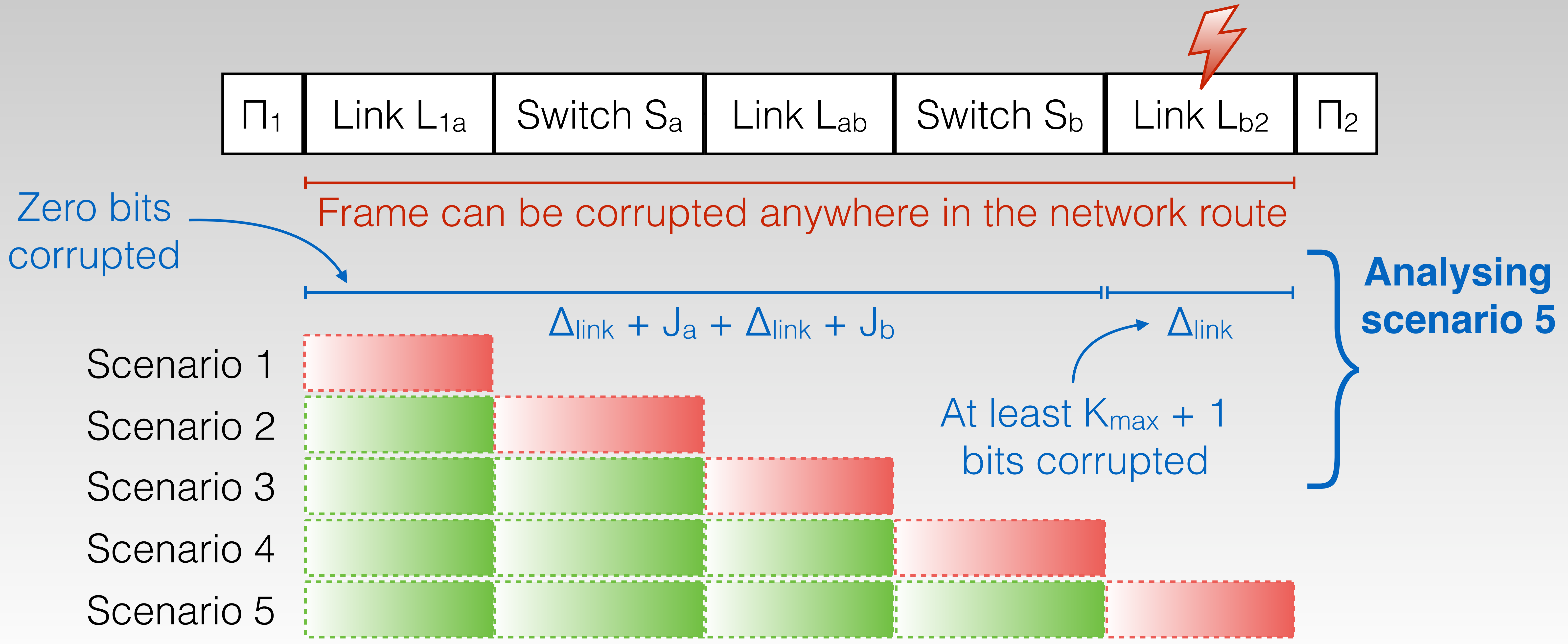

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Δ_{link} = Link transfer time

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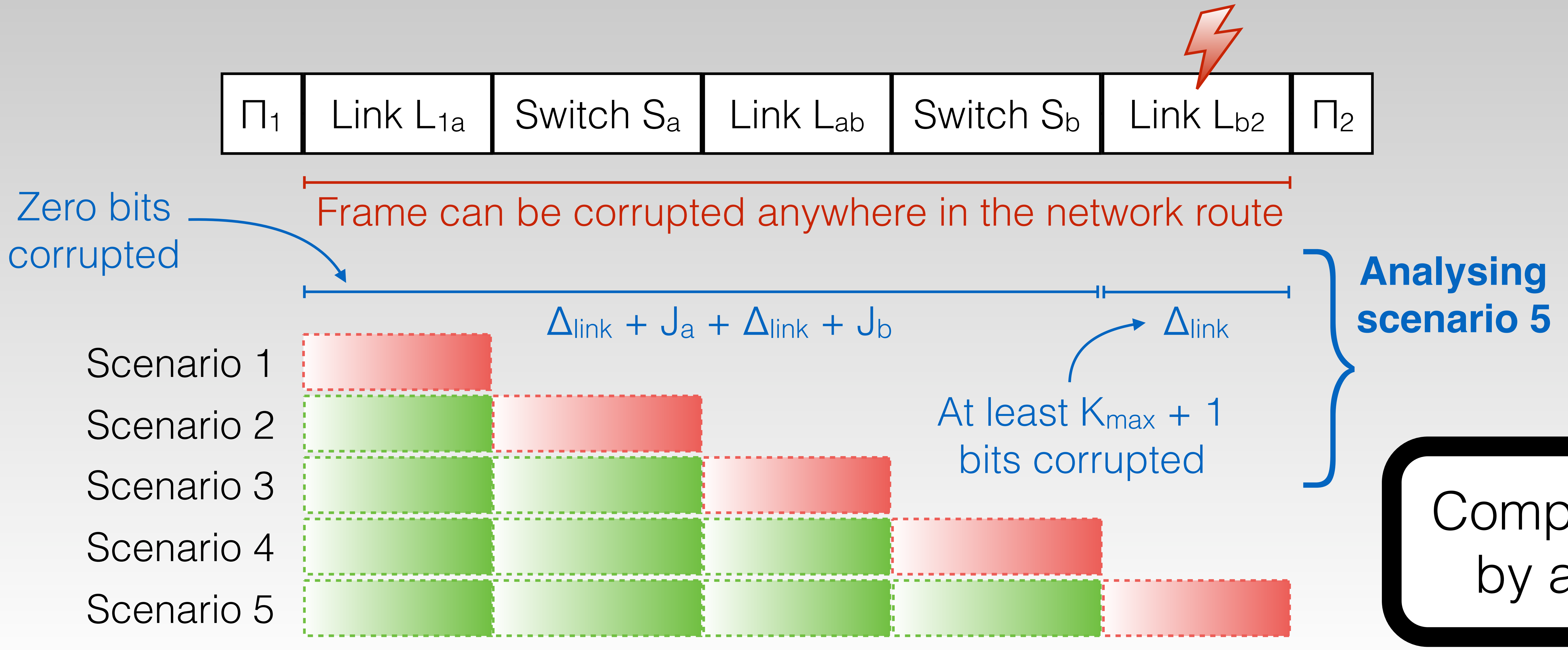

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Compute upper bound $\mathbf{P_3 \geq Pr(E_3)}$ by accounting for all scenarios

Key idea 1: Scalability through **abstraction** and **pruning**

Msg. M_1
- **Corrupted** at source, network, or destination
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Abstraction

Group identical messages into a single error event

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Goal: P_{UB} > Pr (atomic broadcast failure)

Application-specific message errors

For each E_i, derive **upper bound $P_i \geq Pr(E_i)$**

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Combinatorial analysis

Basic Errors + Poisson Model + Timing Analysis

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- Cannot omit a message twice
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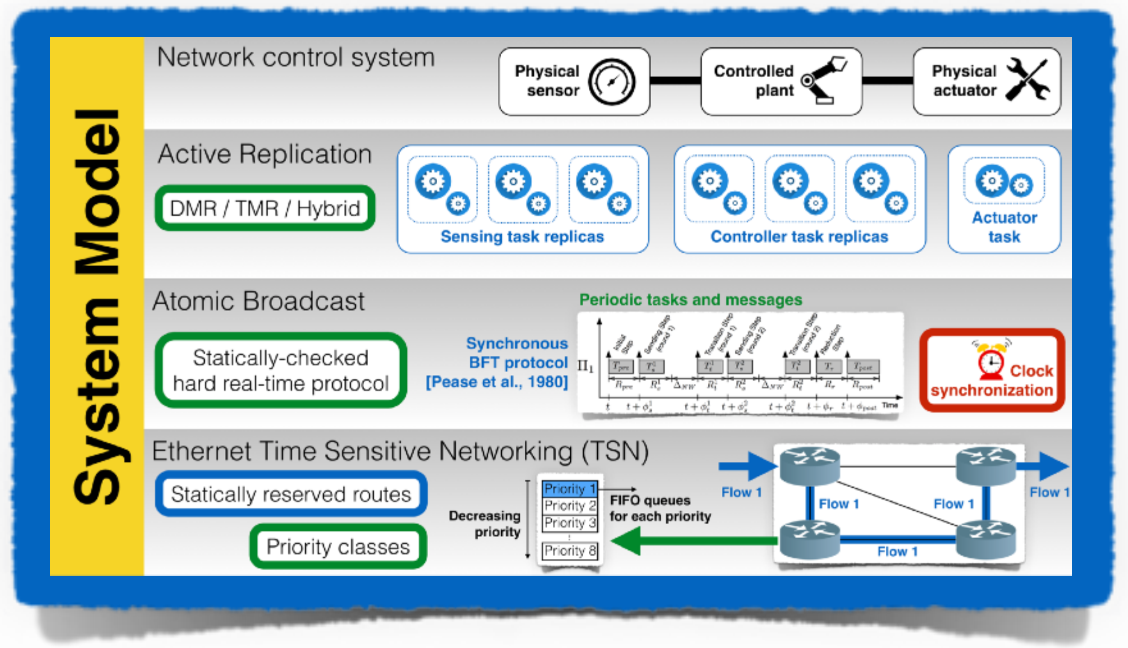
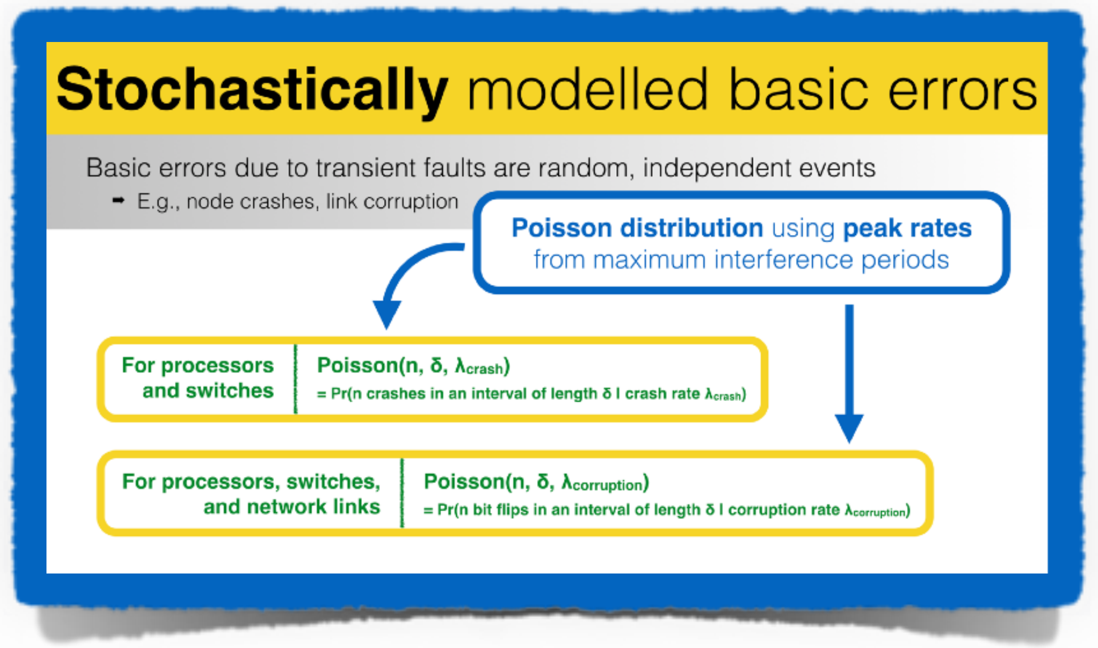




Model checking or simulation

Pr (atomic broadcast failure)

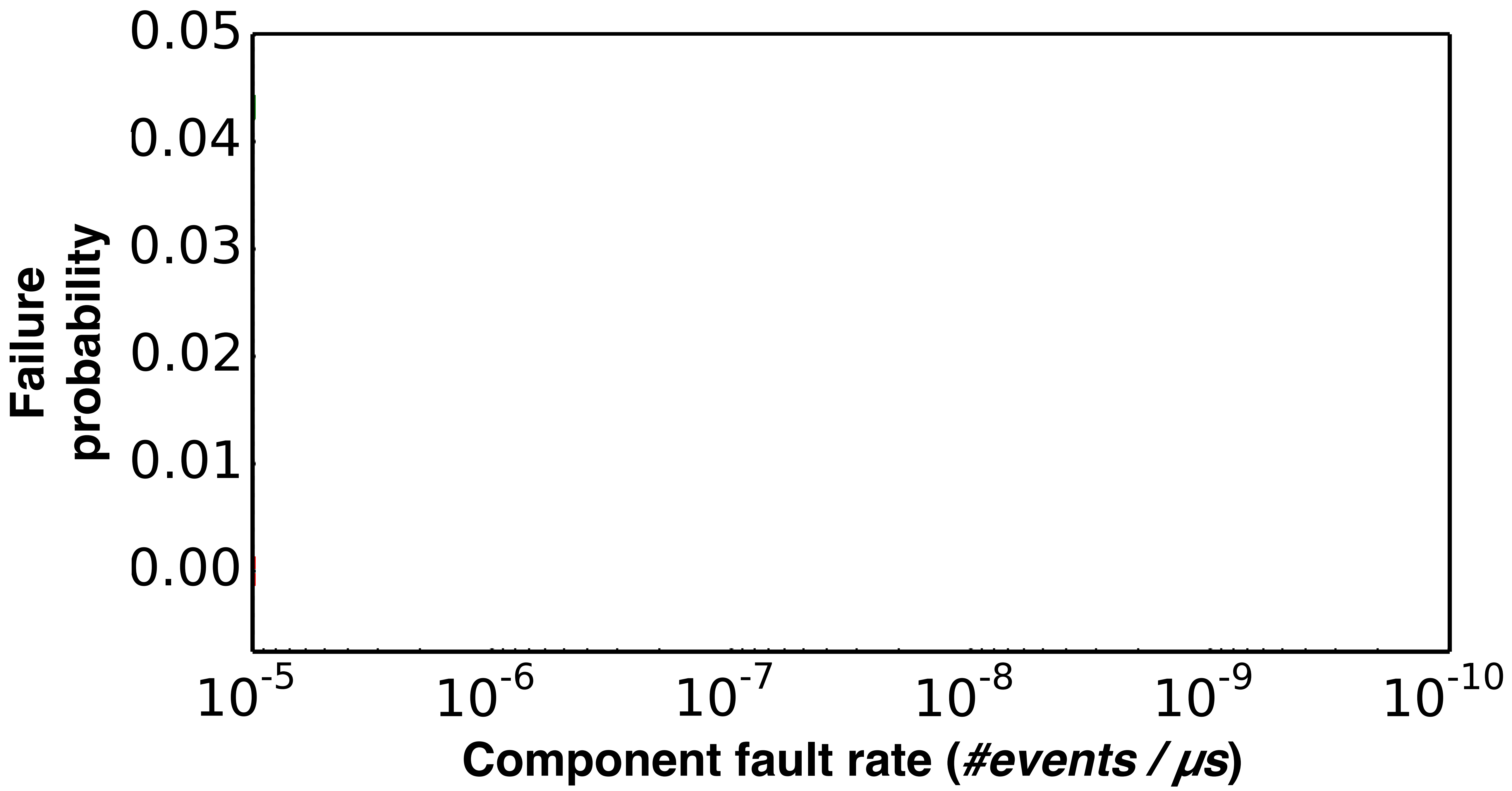
Scalability challenges

Key idea 1: Tackle scalability through *abstraction and pruning*

Reliability anomalies

➡ In practice, the failure probability may **significantly exceed** the estimated Pr (atomic broadcast failure)

The problem of **reliability anomalies**



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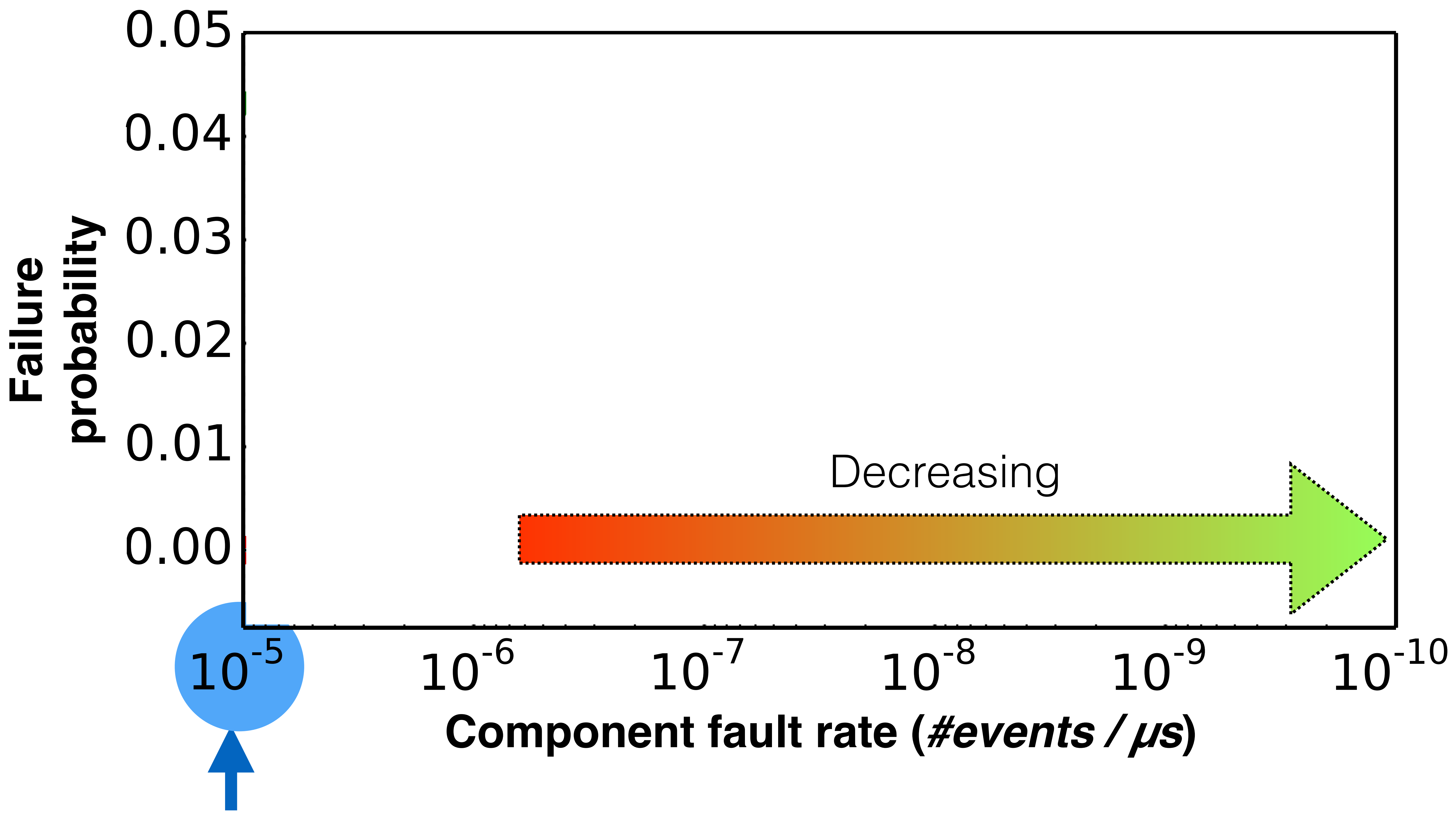

Peak fault rate

- From measurements / environmental modeling assuming worst-possible operating conditions
- Include safety margins as deemed appropriate by reliability engineers or domain experts.

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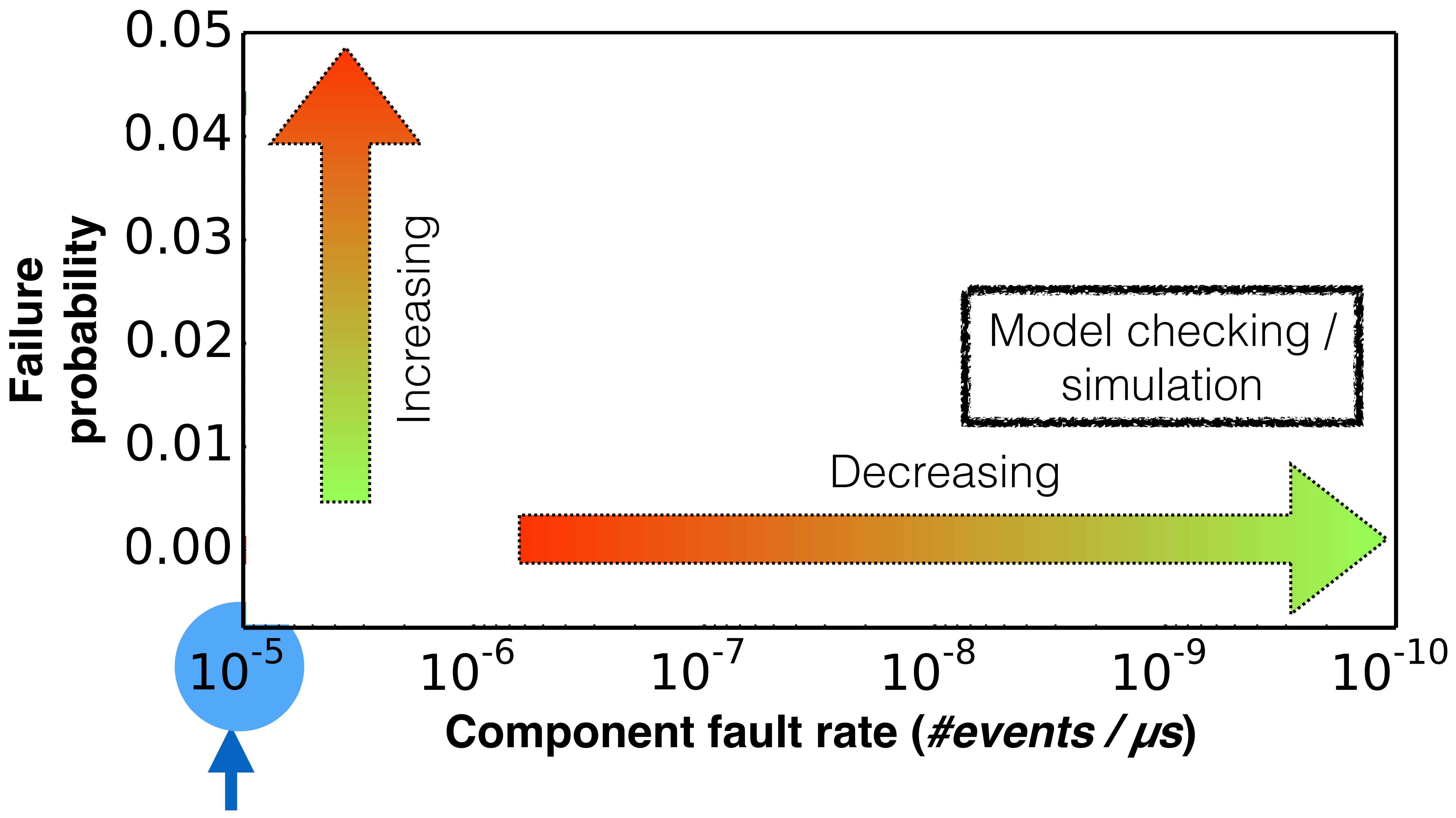

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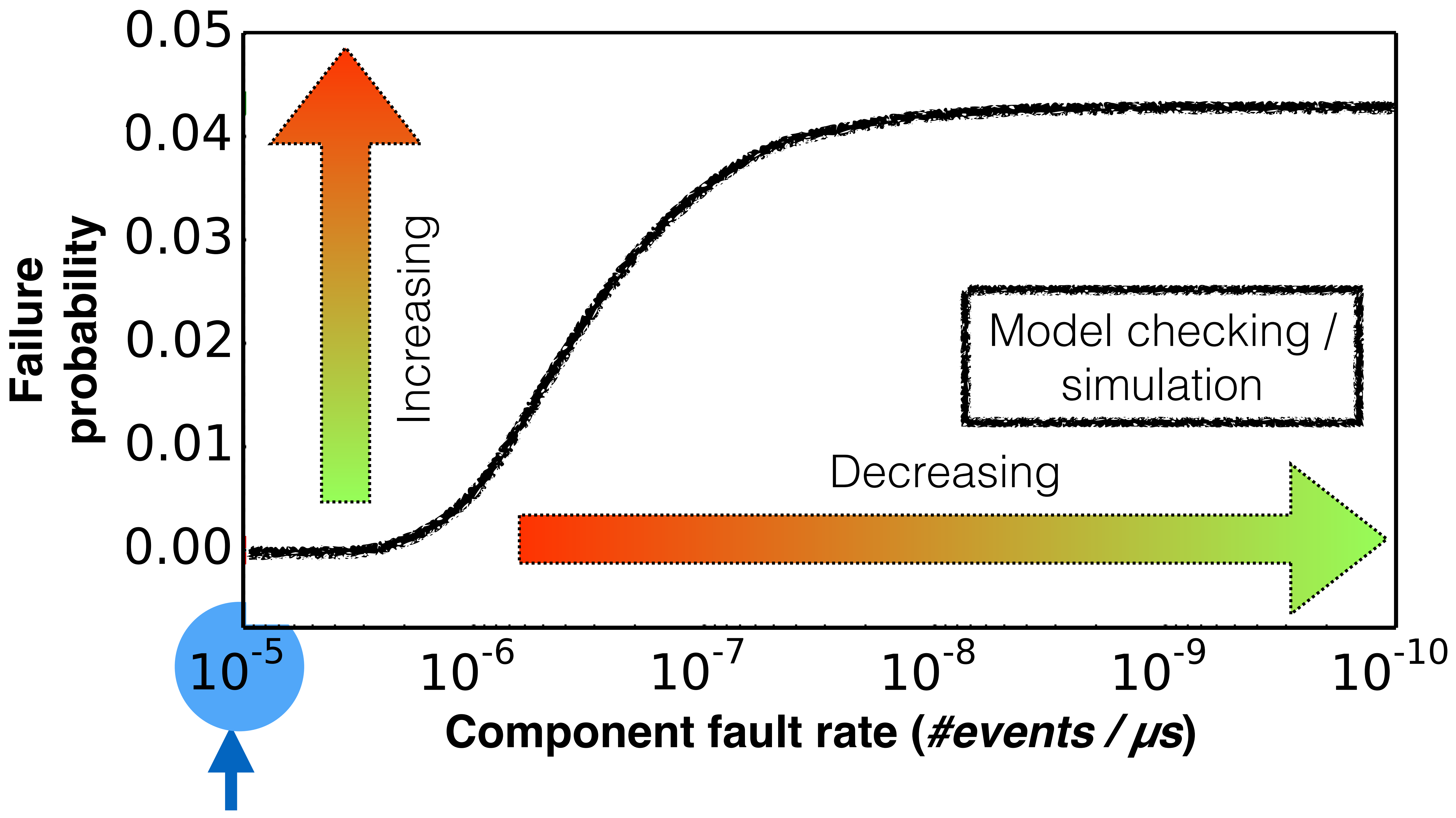

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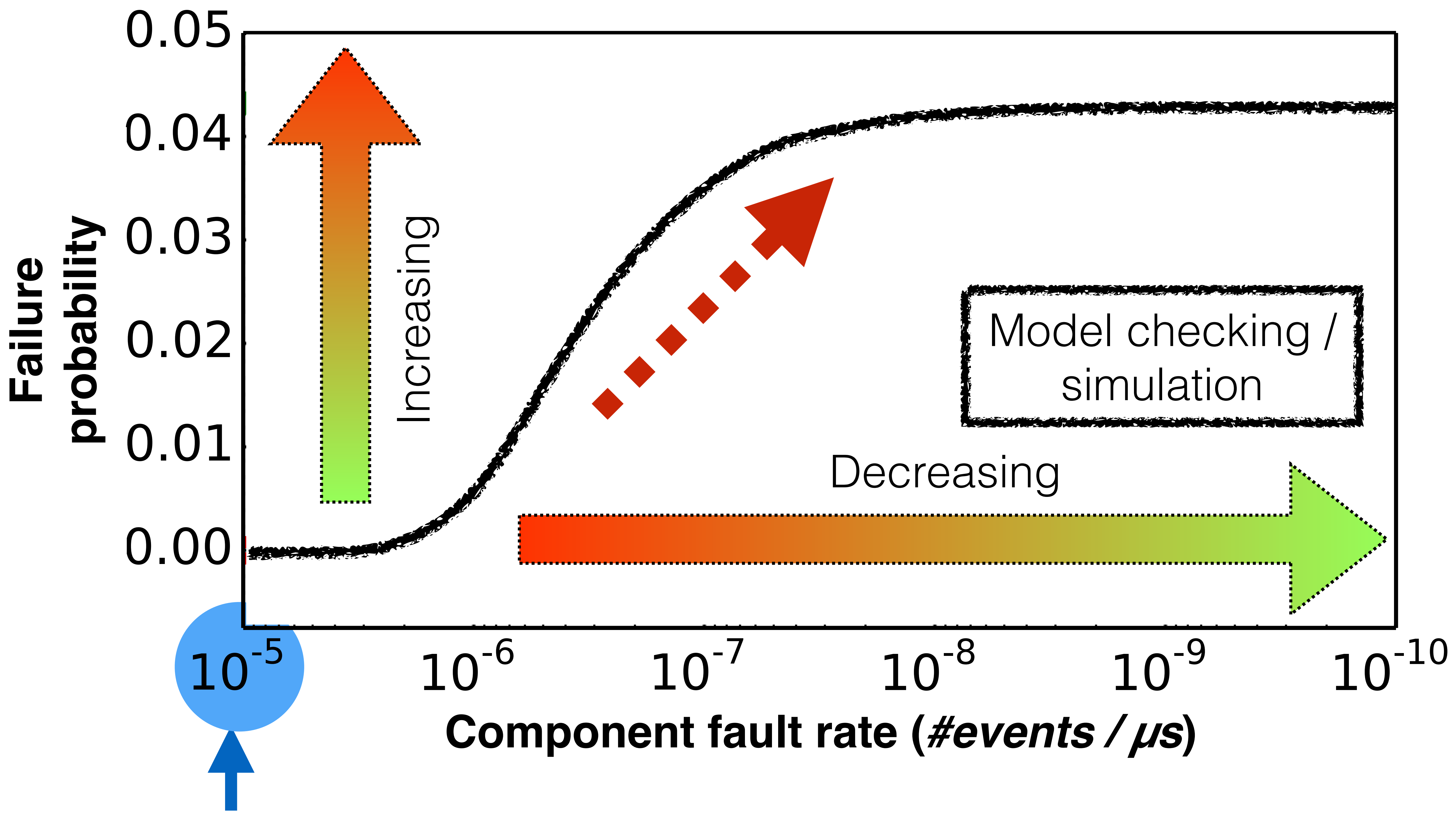

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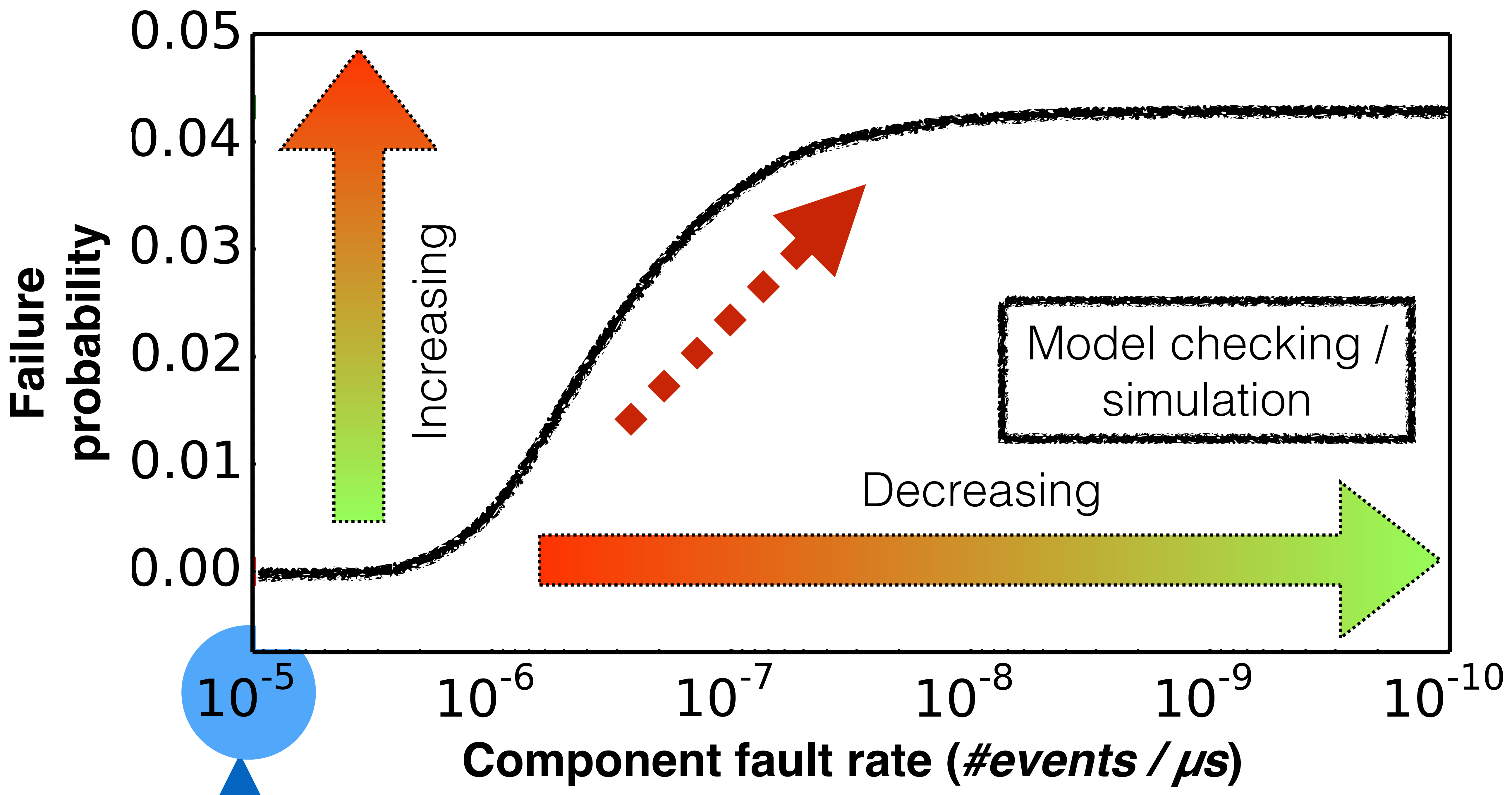

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Key idea 2: Ensure **monotonicity** to eliminate anomalies

Combinatorial analysis

$$P_{\text{UB}} = \begin{pmatrix} P_1 \cdot C_1 \\ +\overline{P_1} \cdot P_2 \cdot C_2 \\ +\overline{P_1} \cdot \overline{P_2} \cdot P_3 \cdot C_3 \\ +\overline{P_1} \cdot \overline{P_2} \cdot \overline{P_3} \cdot P_4 \cdot C_4 \\ +\overline{P_1} \cdot \overline{P_2} \cdot \overline{P_3} \cdot \overline{P_4} \cdot P_5 \cdot C_5 \\ +\overline{P_1} \cdot \overline{P_2} \cdot \overline{P_3} \cdot \overline{P_4} \cdot \overline{P_5} \cdot P_6 \cdot C_6 \\ +\overline{P_1} \cdot \overline{P_2} \cdot \overline{P_3} \cdot \overline{P_4} \cdot \overline{P_5} \cdot \overline{P_6} \cdot C_7 \end{pmatrix}$$

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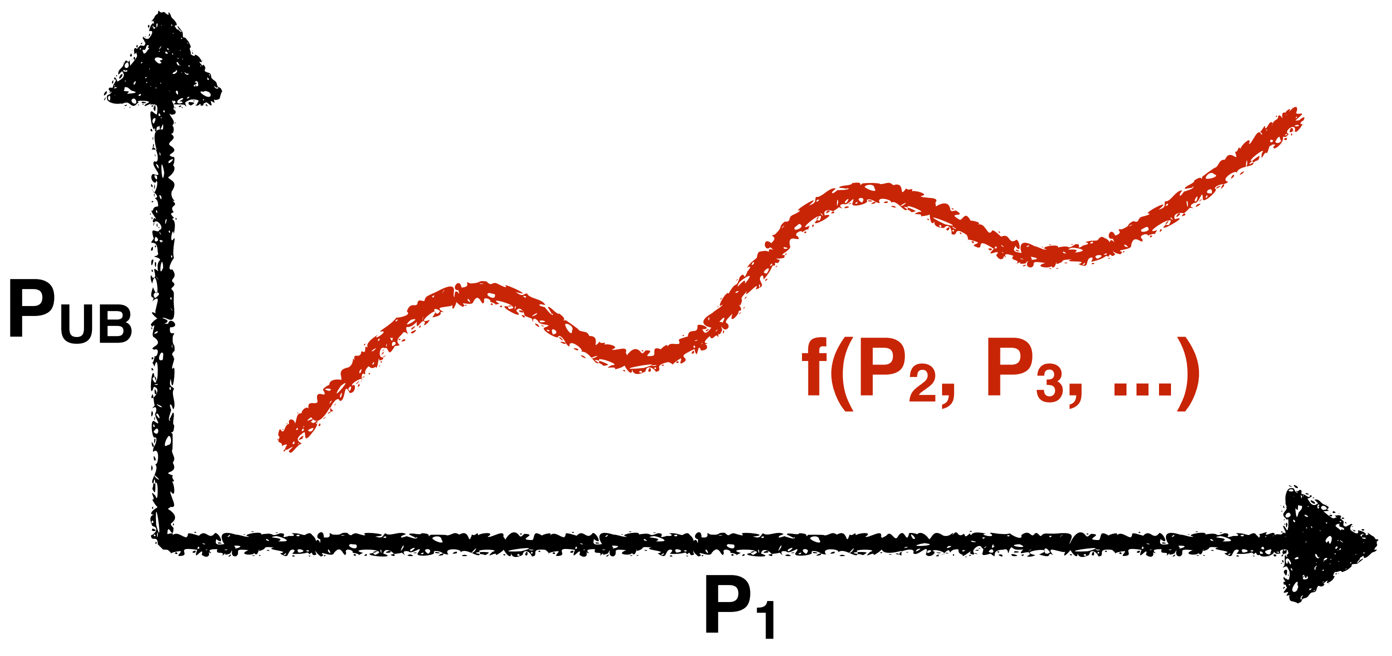
Root cause of reliability anomalies

P_{UB} may not monotonically increase with P_1, P_2, P_3, ...



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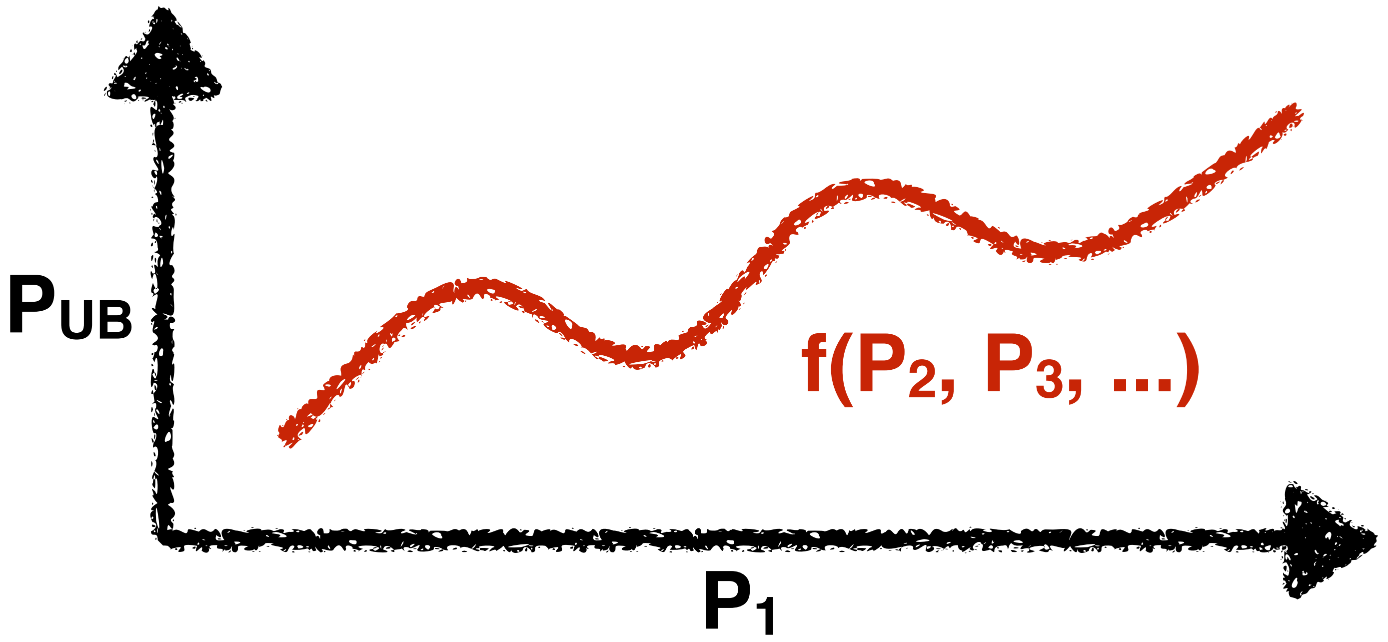
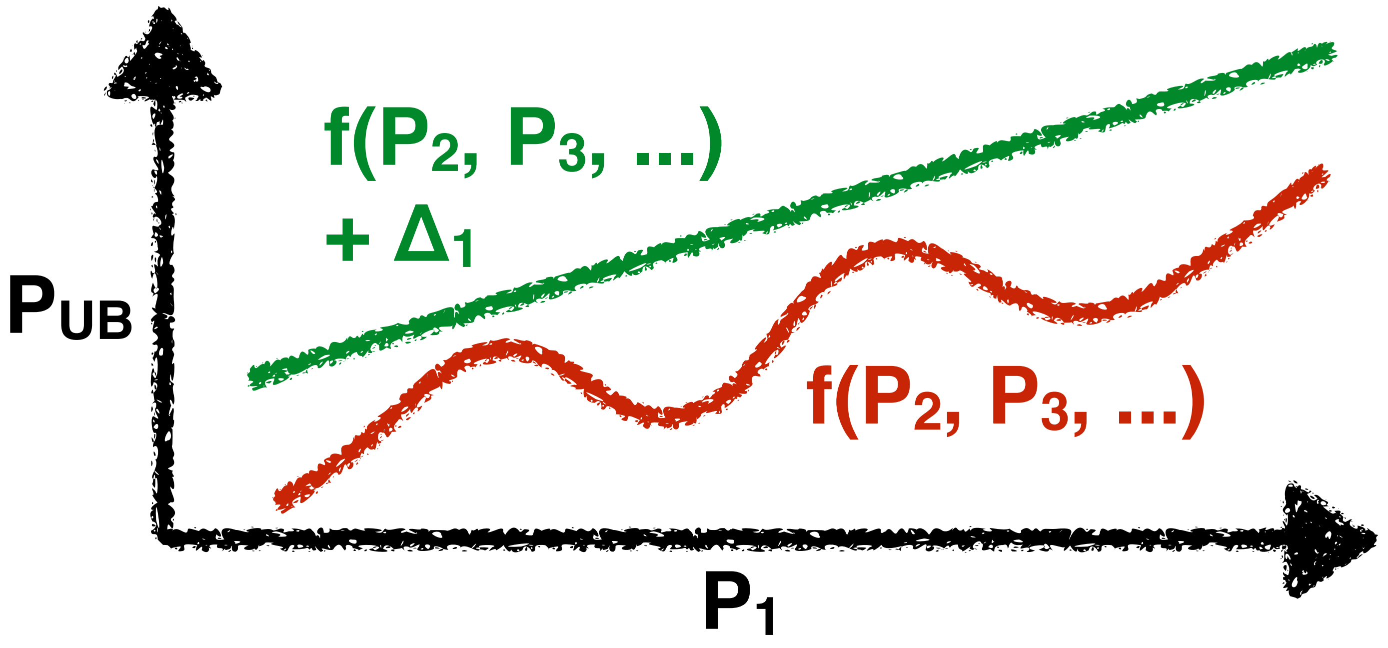


Eliminating reliability anomalies

A "fudge factor" Δ is added to P_{UB} to ensure that $P_{UB} + \Delta$ is monotonically increasing with P_1, P_2, P_3, ...



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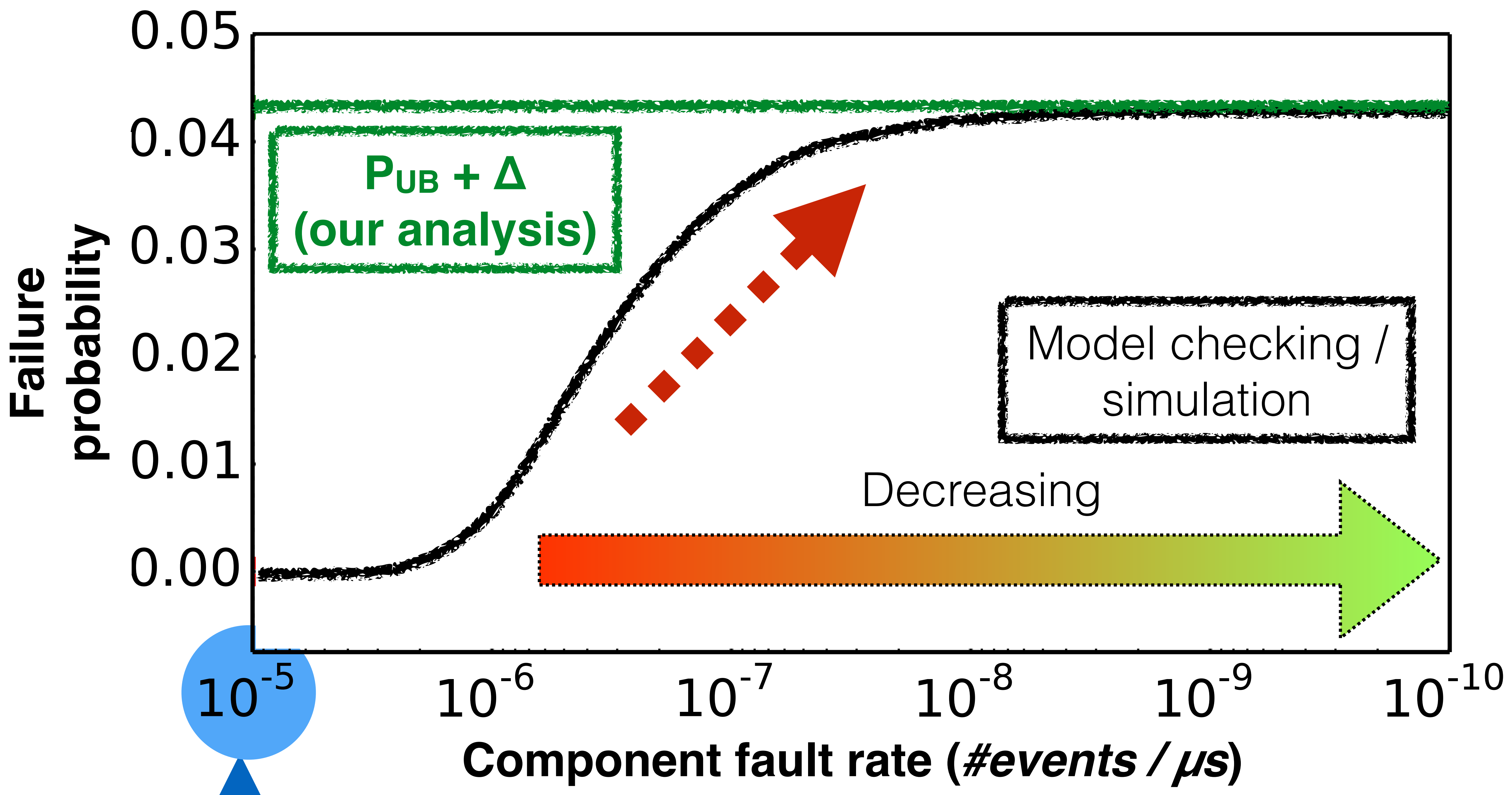

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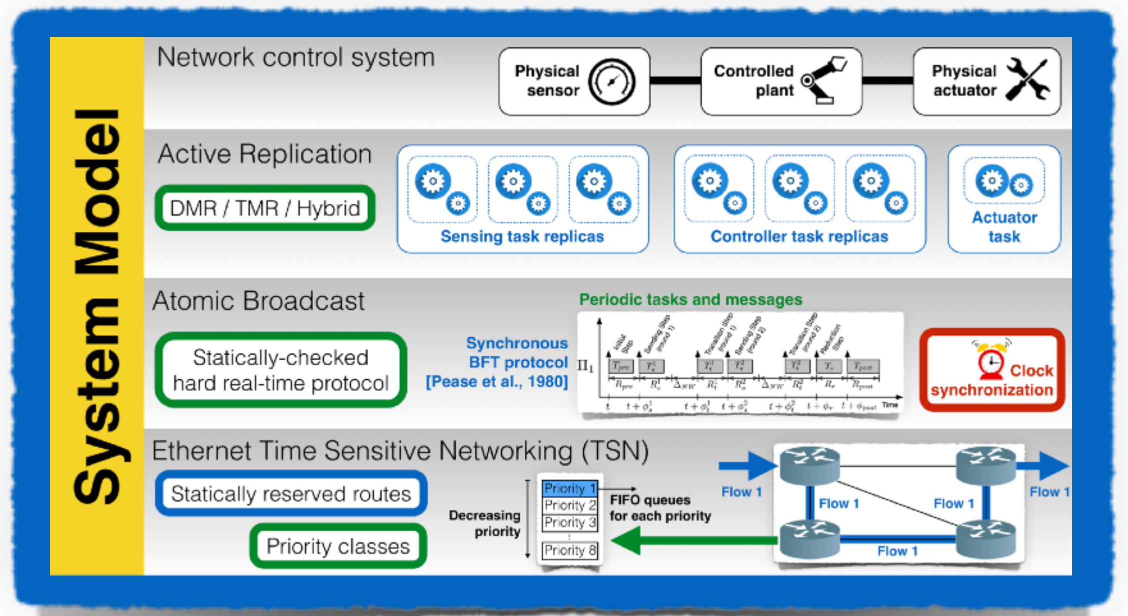

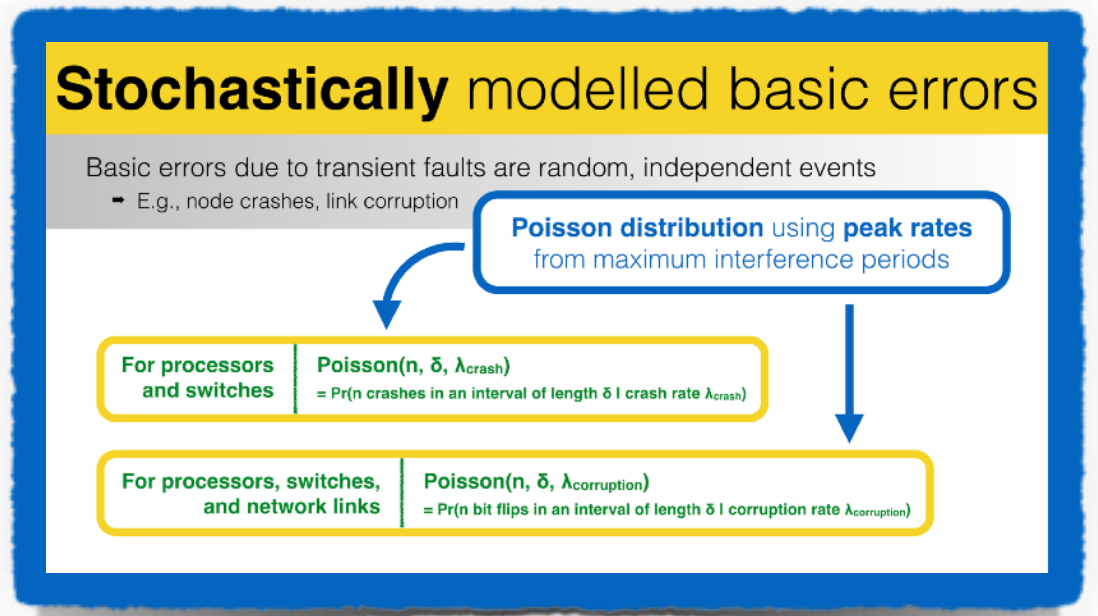

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Summary

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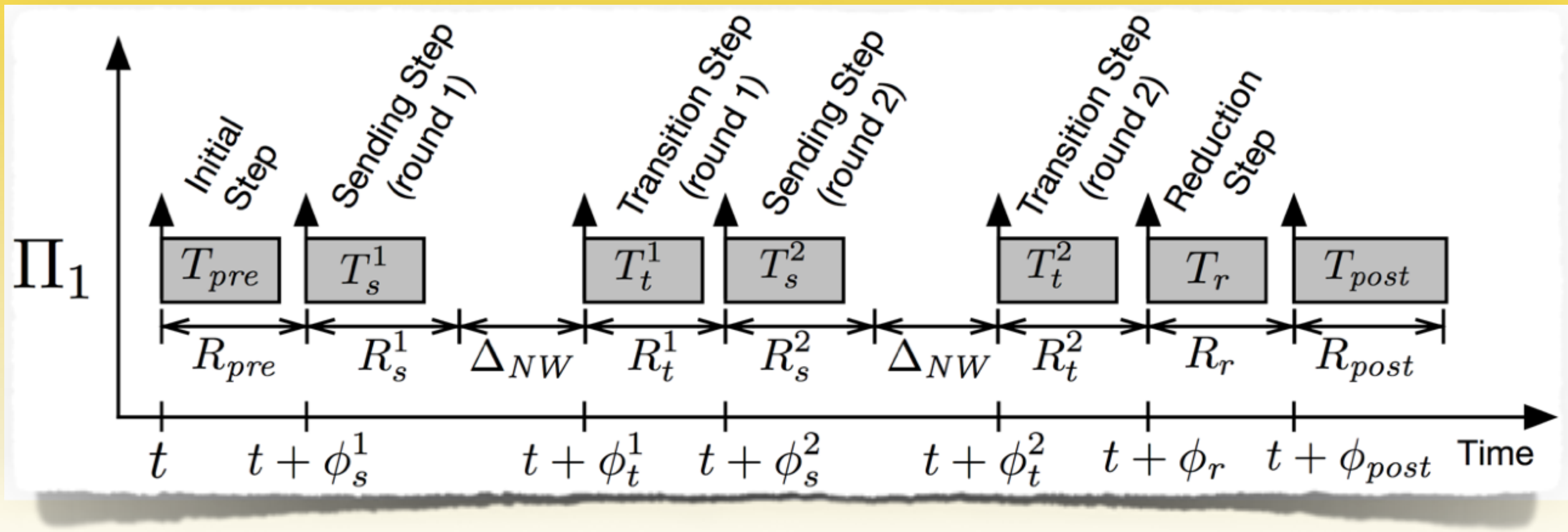
Statically-checked hard real-time protocol

Synchronous BFT protocol [Pease et al., 1980]

Periodic tasks and messages



Details in the paper!

Clock synchronization

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Ethernet frame corruptions / omissions

Transient fault-induced errors

Omission / incorrect computation at nodes and switches

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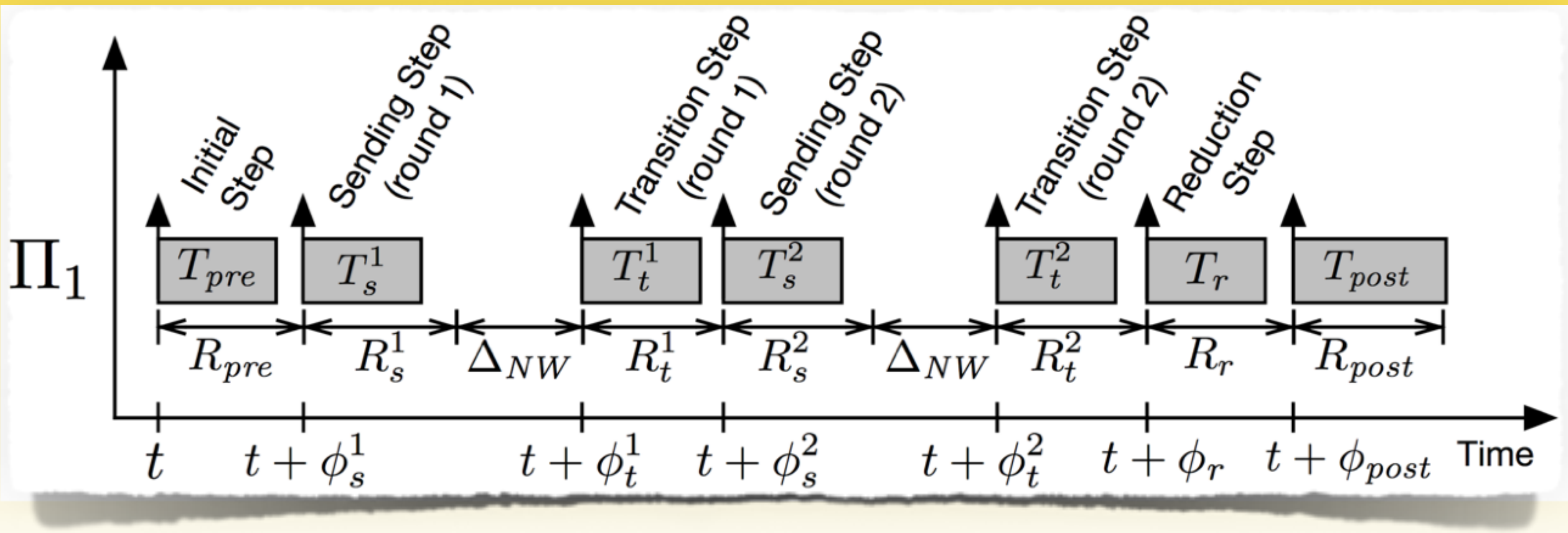

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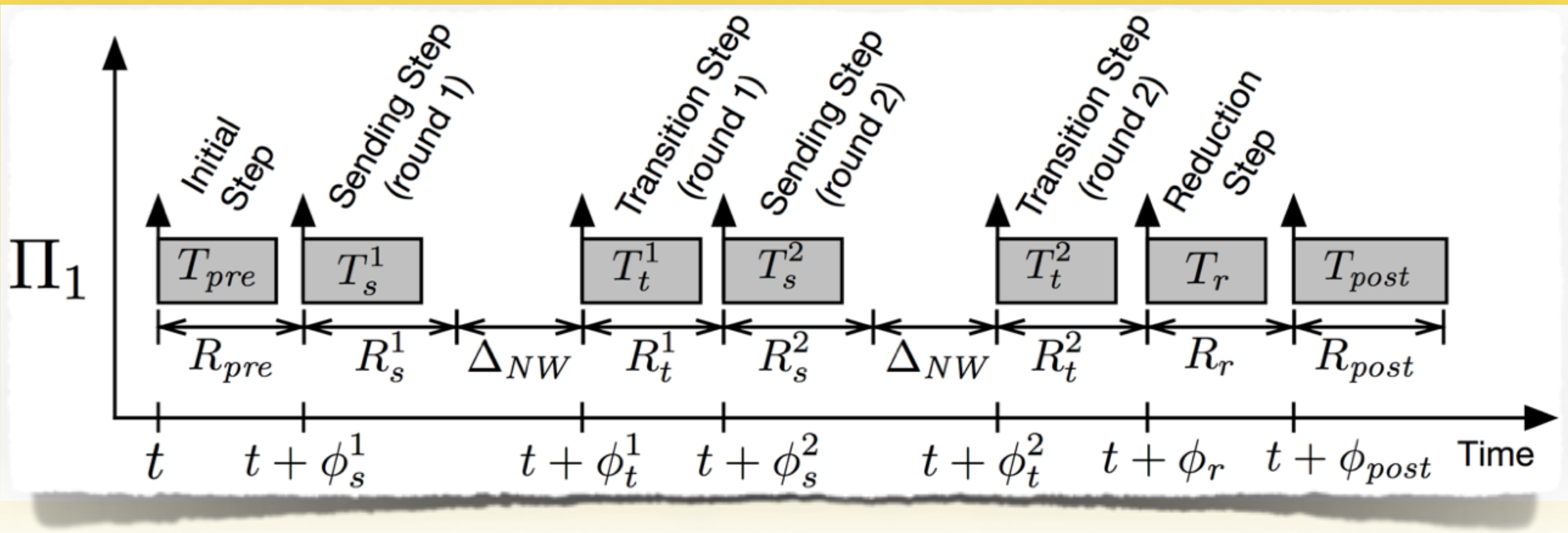

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Clock synchronization

Building safety-critical real-time applications

- COTS-based distributed systems with **quantifiably negligible** failure rates
- Byzantine errors with **non-uniform fault rates** resulting from transient faults
- Formalize and eliminate **reliability anomalies**

In the paper ...

Parameterized BFT interactive consistency protocol

Time-aware correctness criteria

Reliability anomalies formalization for arbitrary configurations

Analysis versus simulation experiments

Case studies with varying network topologies and protocol parameters

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Thank you!

arpanbg@mpi-sws.org