Troubleshooting SDN Control Software with Minimal Causal Sequences

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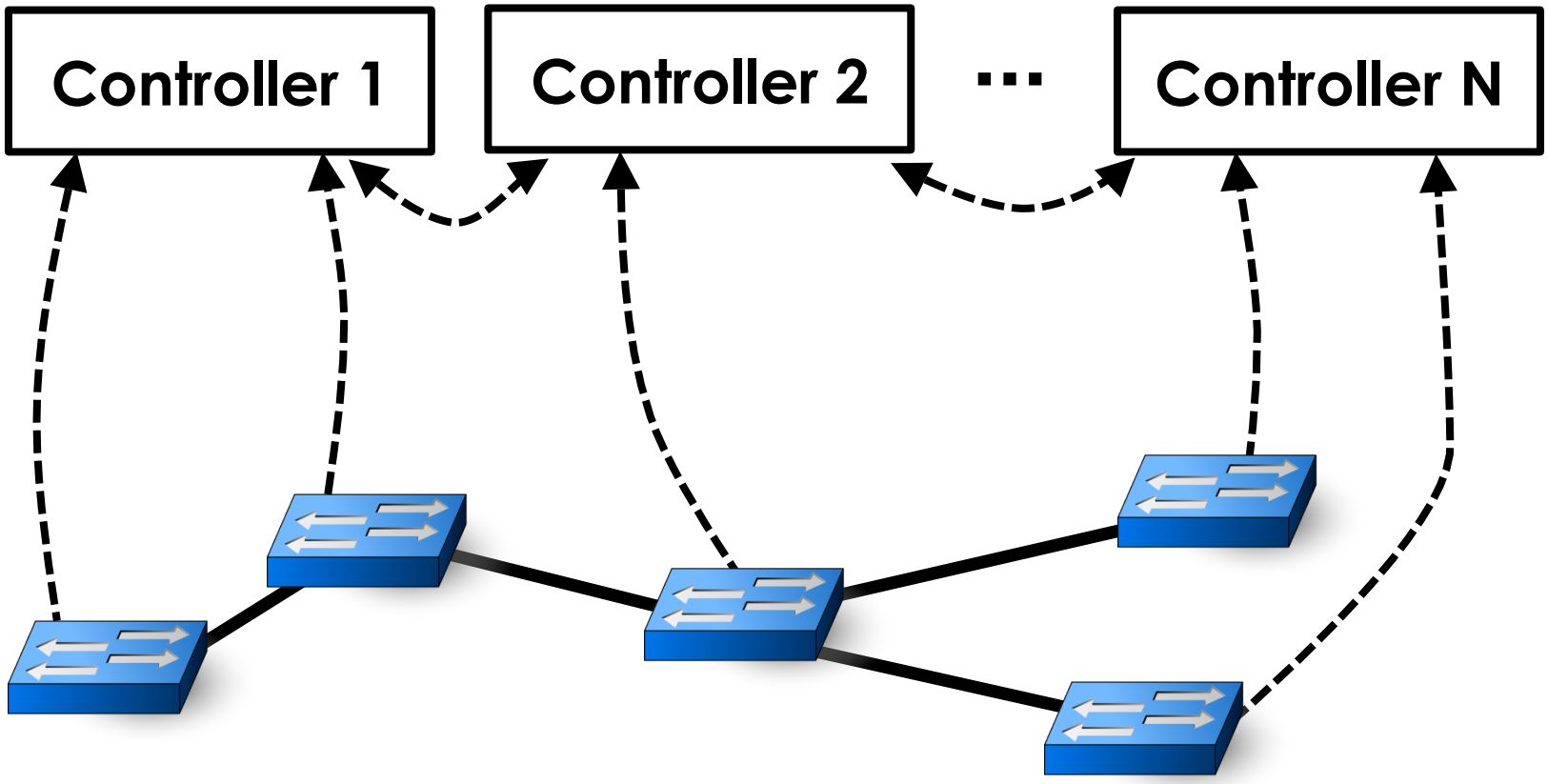
SDN is a Distributed System



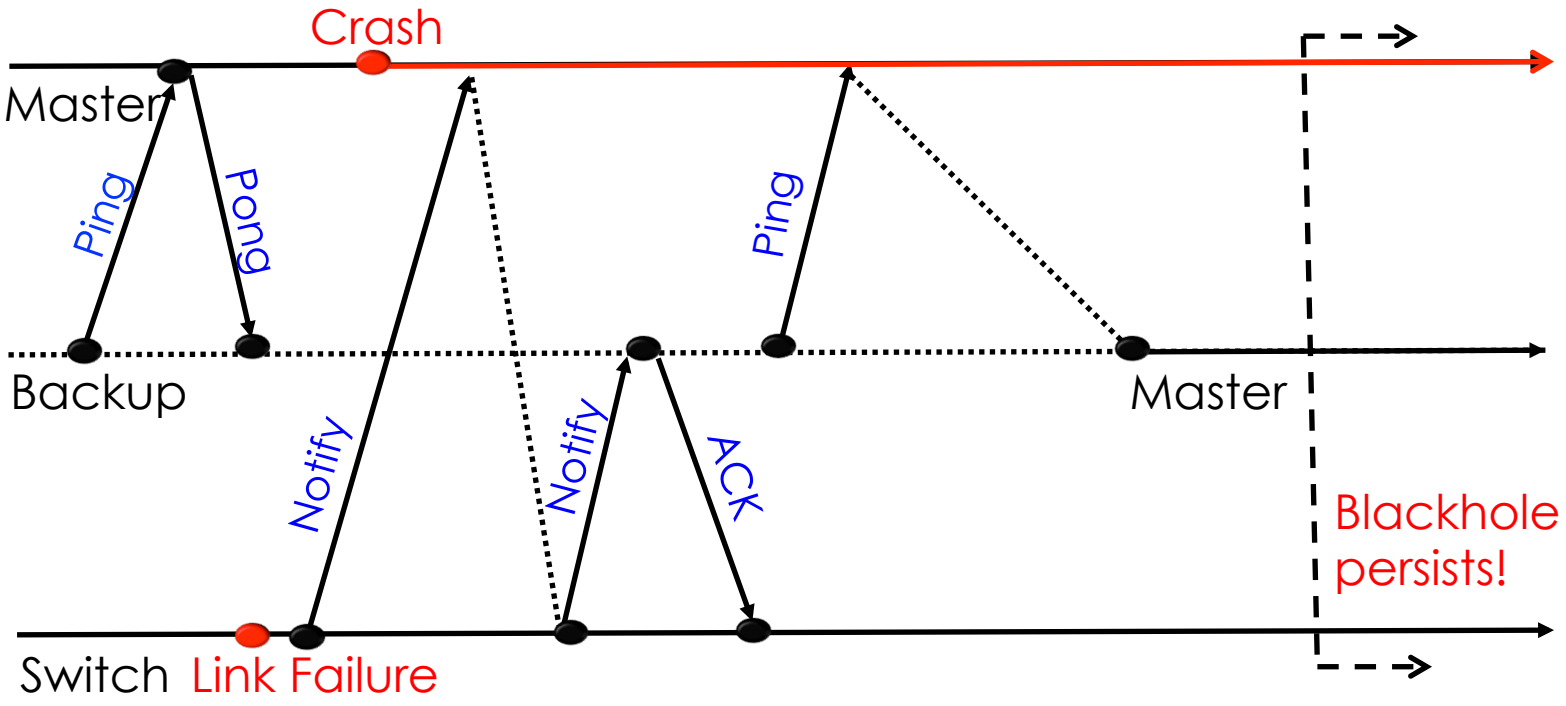
Distributed Systems are Bug-Prone

Distributed correctness faults:

- Race conditions
- Atomicity violations
- Deadlock
- Livelock
- …

+ Normal software bugs

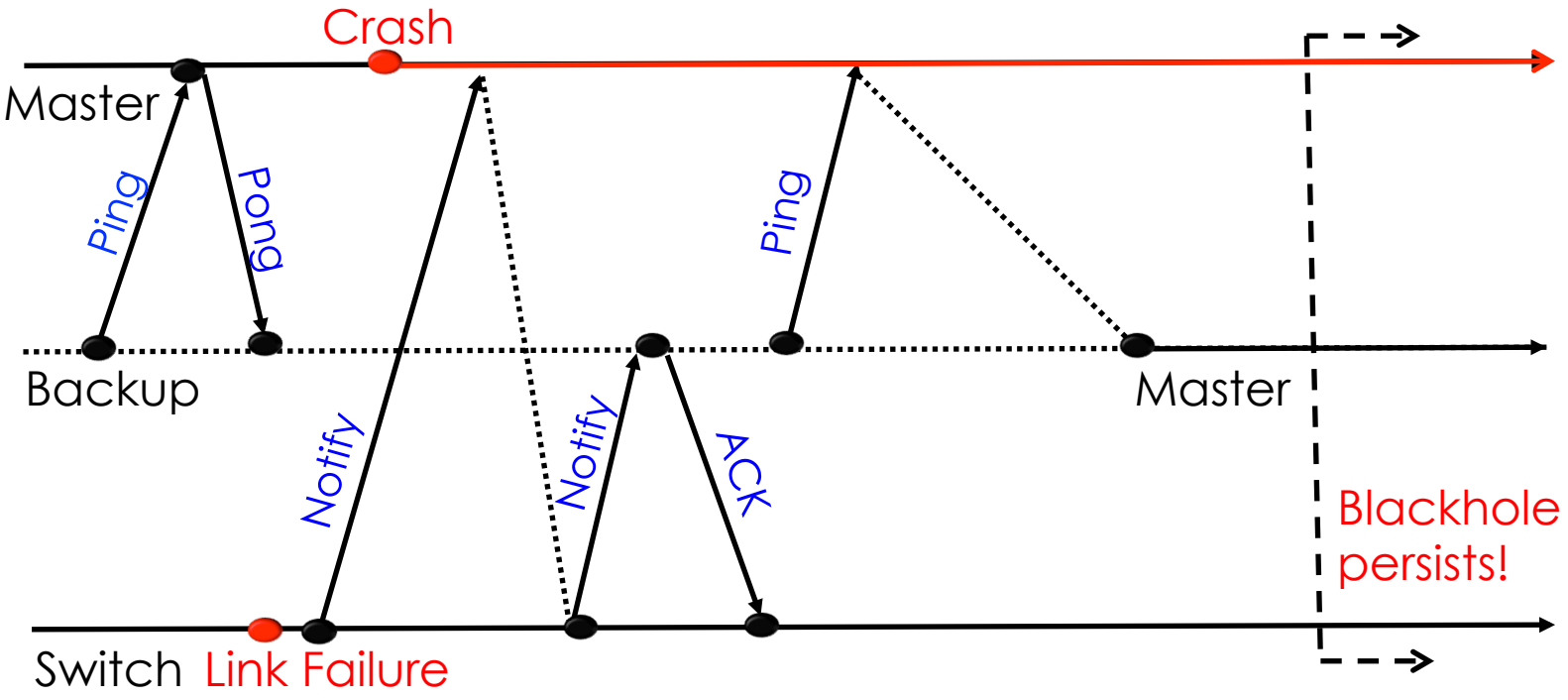
Example Bug (Floodlight, 2012)



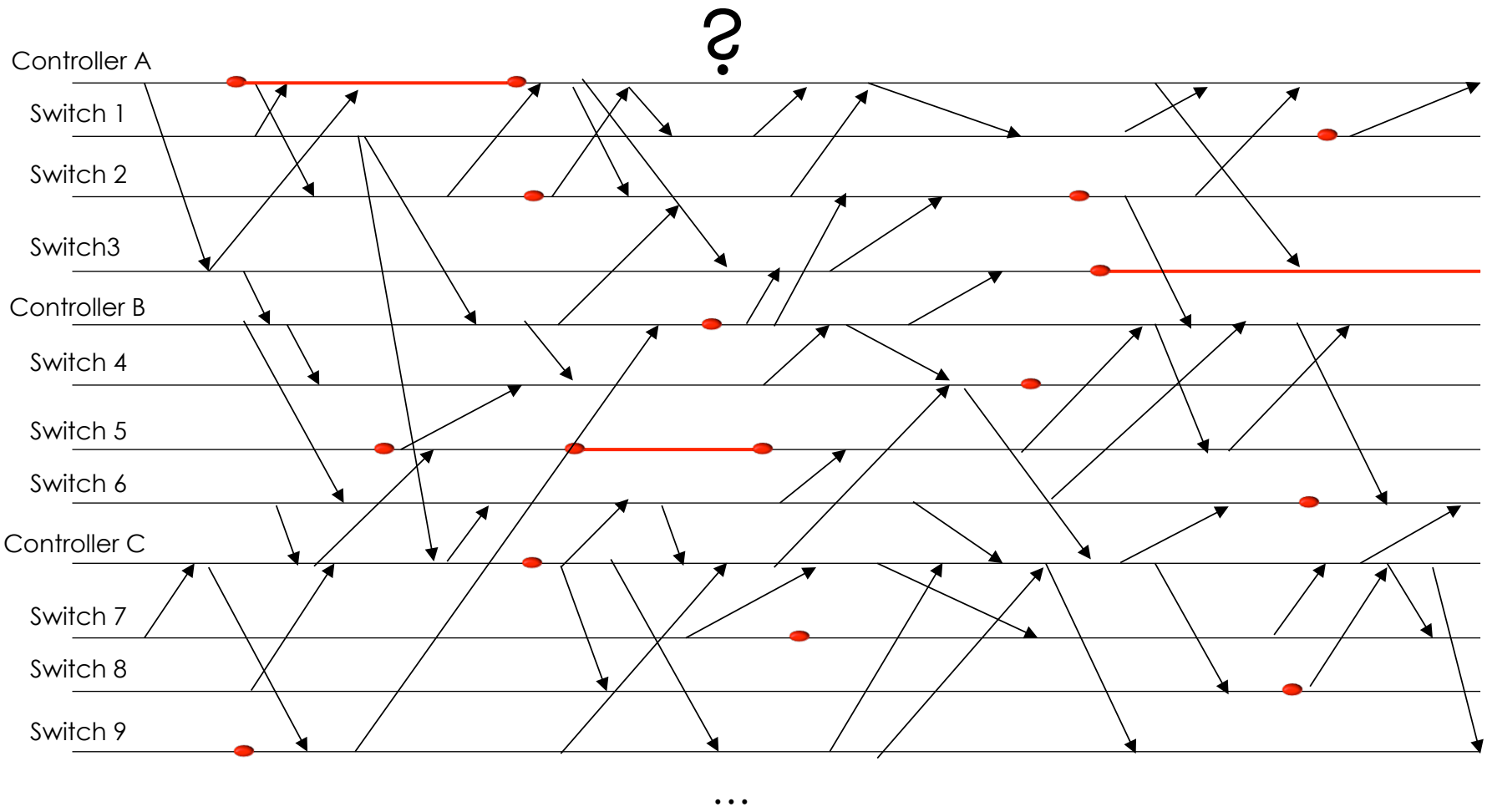
Best Practice: Logs

Human analysis of log files

Best Practice: Logs



Best Practice: Logs



Our Goal

Allow developers to focus on fixing the underlying bug

Problem Statement

Identify a **minimal** sequence of inputs that triggers the bug in a blackbox fashion

Why minimization?

Smaller event traces are easier to understand

G. A. Miller. The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information. Psychological Review '56.

Minimal Causal Sequence

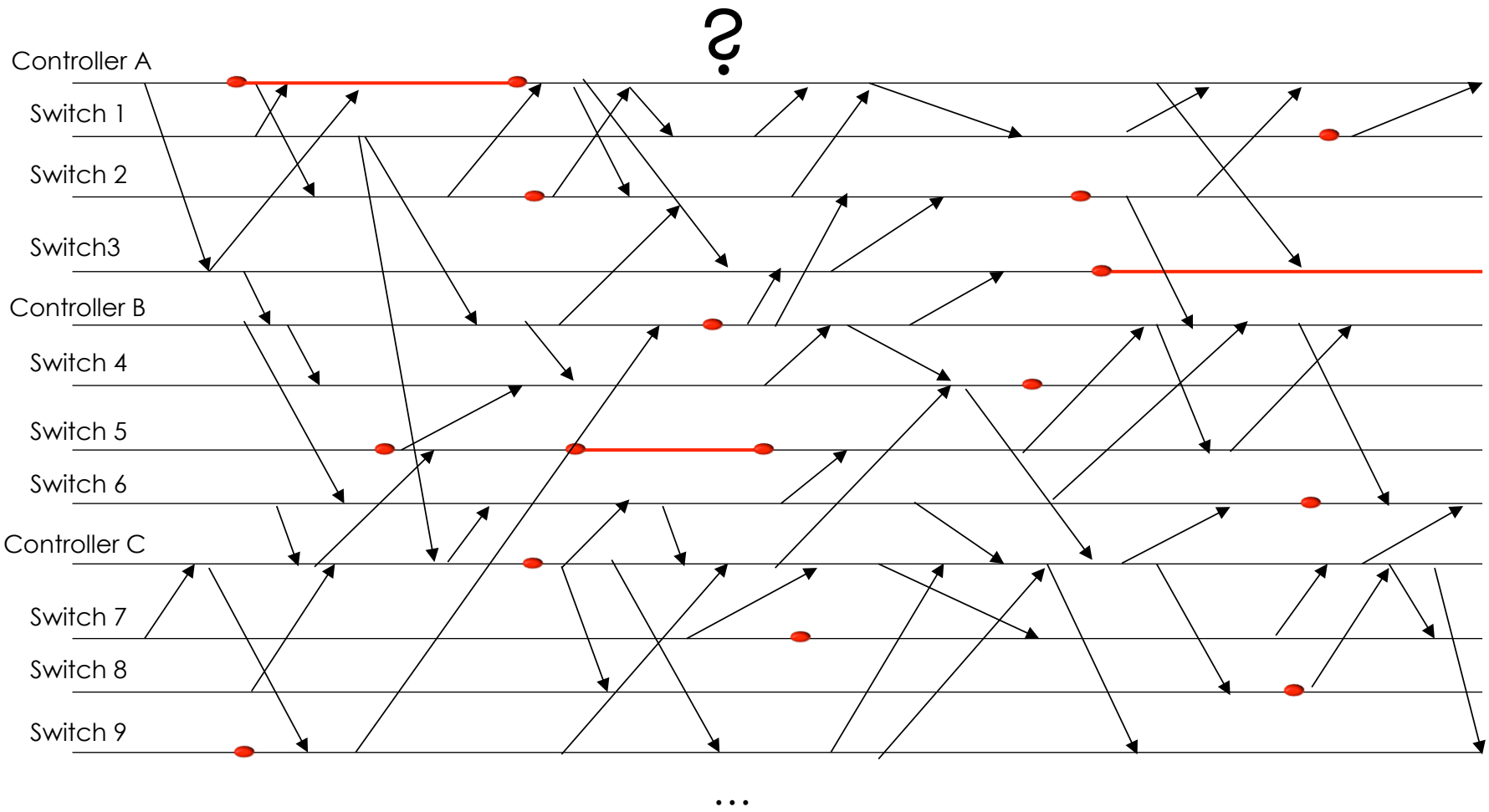
Output:

$$MCS \subset Trace \; s.t.$$

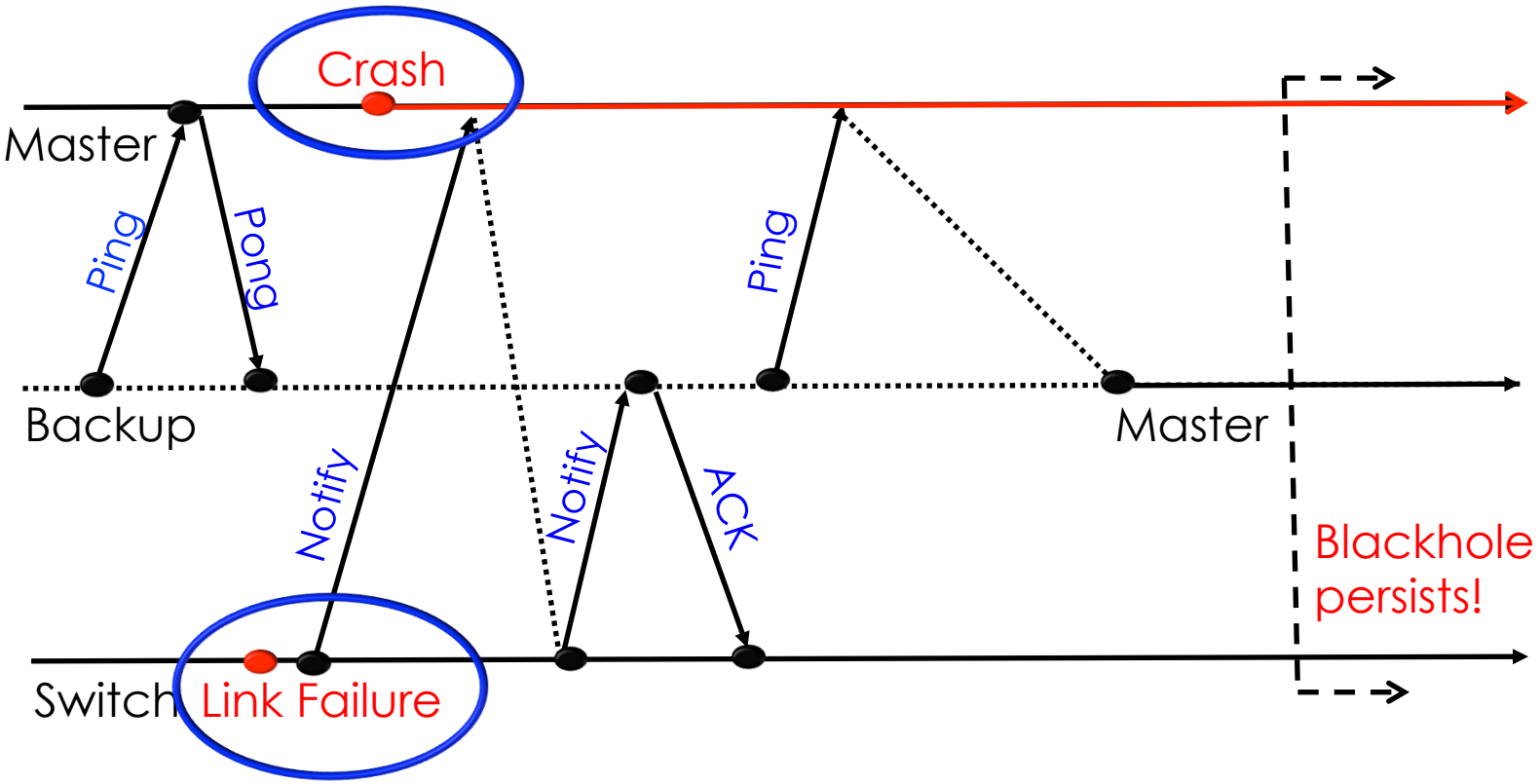
$$i.\; replay(MCS) \ni V$$ (i.e. violation occurs)

$$ii.\; \forall_{e \in MCS} replay(MCS - \{e\}) \not\ni V$$

Minimal Causal Sequence



Minimal Causal Sequence



Outline

- What are we trying to do?
- How do we do it?
- Does it work?

Where Bugs are Found

- Symptoms found:
  - On developer's local machine (unit and integration tests)

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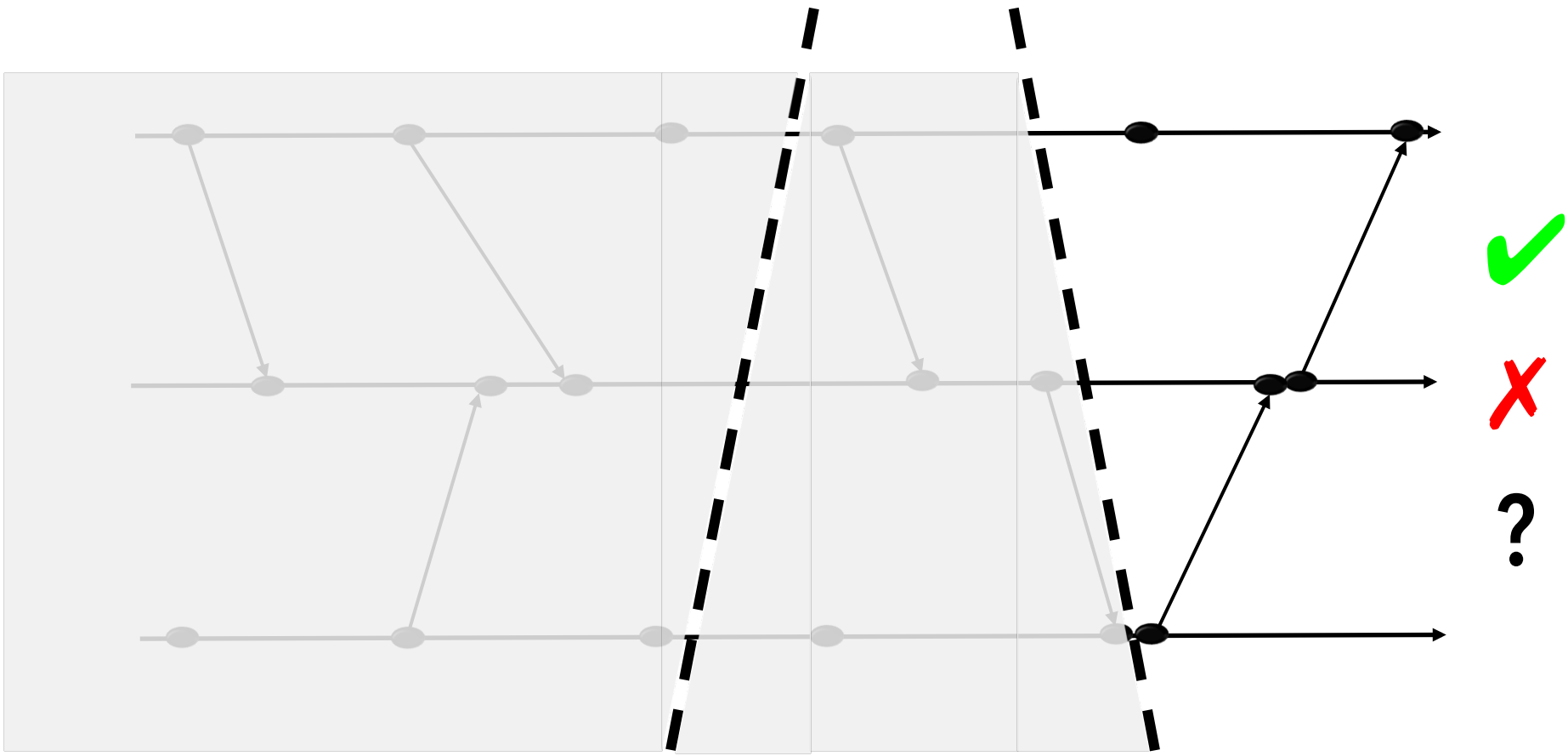
Where Bugs are Found

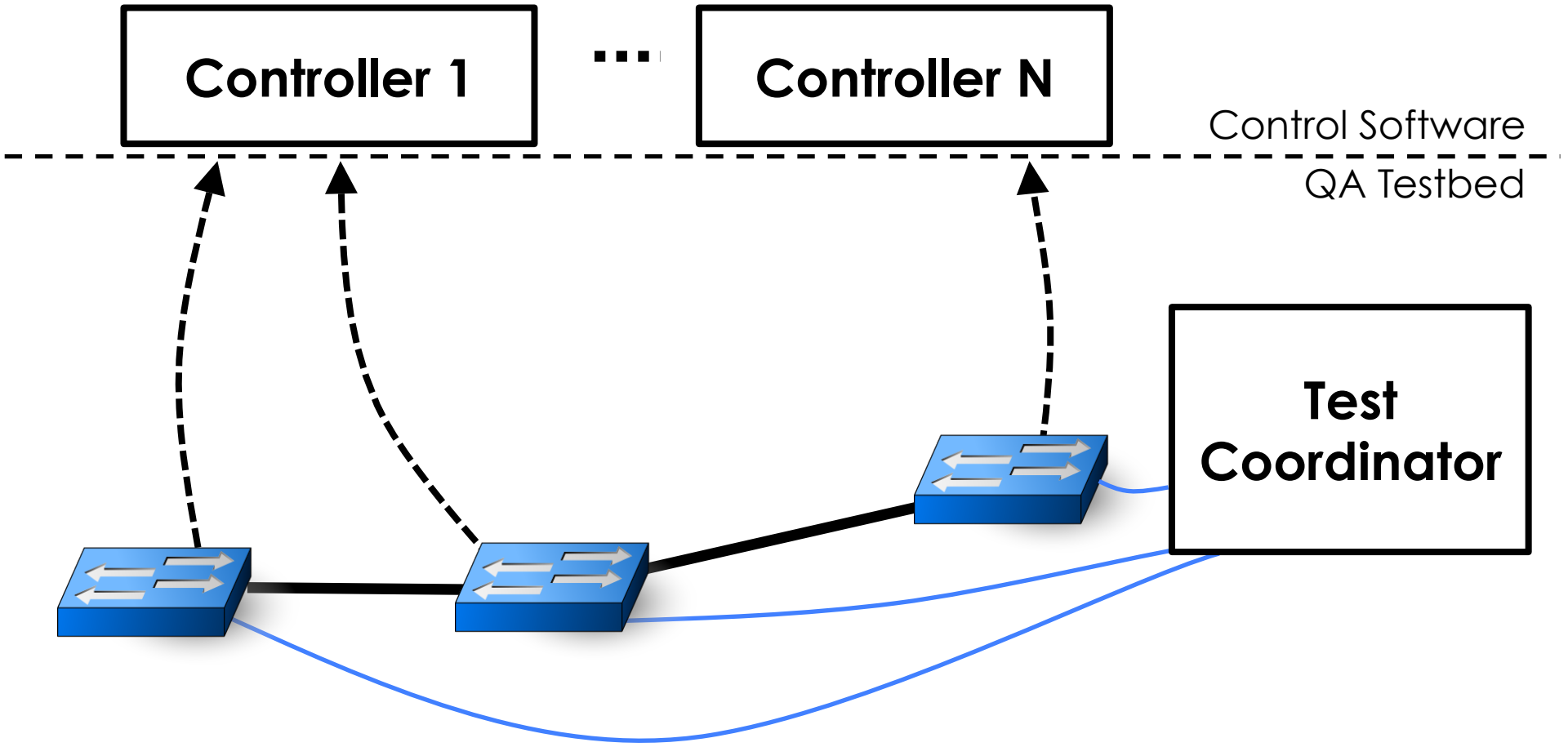
- Symptoms found:
  - On developer's local machine (unit and integration tests)
  - In production environment
  - On quality assurance testbed

Approach: Delta Debugging[1] Replay



1. A. Zeller et al. Simplifying and Isolating Failure-Inducing Input. IEEE TSE '02

Approach: Modify Testbed



Testbed Observables

- Invariant violation detected by testbed
- Event Sequence:

$$\tau_L = e_1 \rightarrow i_1 \rightarrow i_2 \rightarrow e_2 \rightarrow \cdots e_m \rightarrow \cdots i_p$$

  - External events (link failures, host migrations,..) injected by testbed

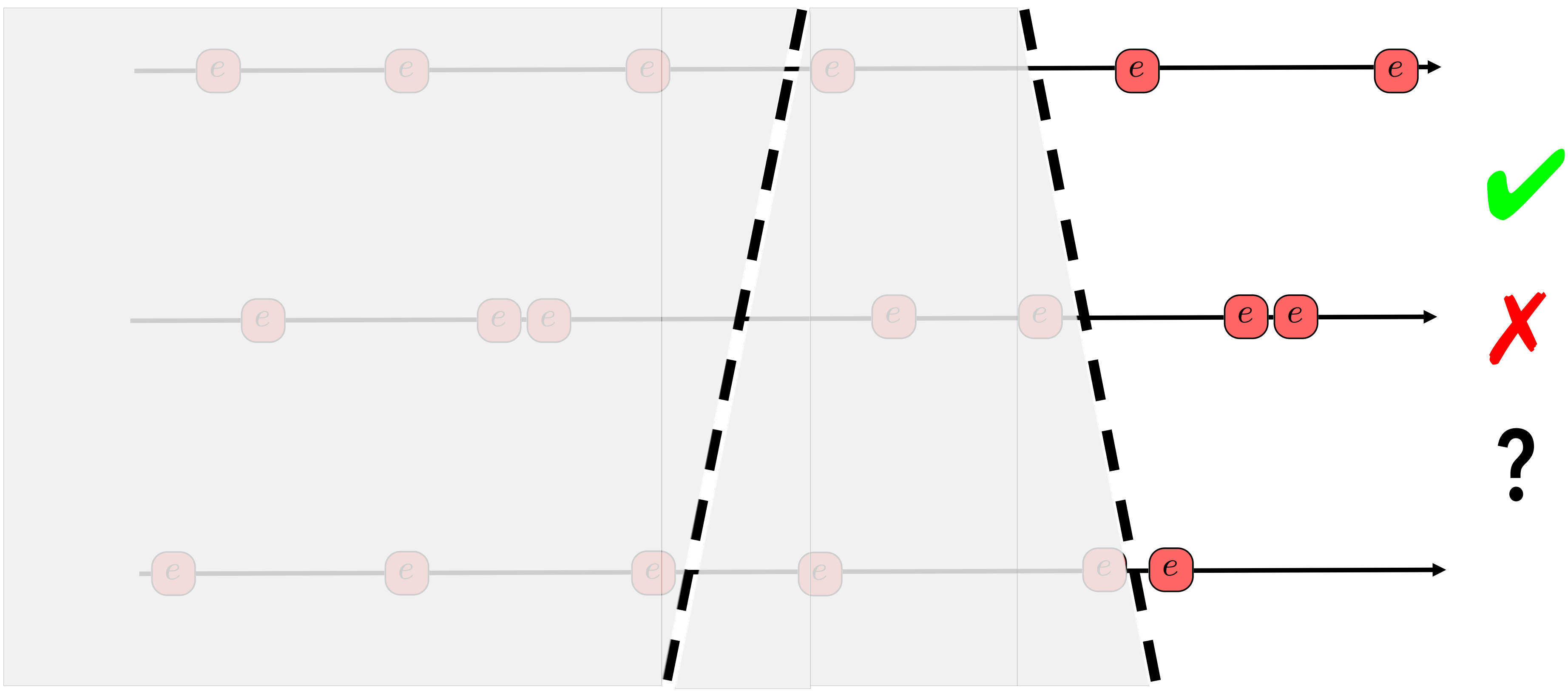
$$E_L = e_1, e_2 \cdots e_m$$

  - Internal events (message deliveries) observed by testbed (incomplete)

$$I_L = i_1, i_2 \cdots i_p$$

Approach: Delta Debugging[1] Replay

Events (link failures, crashes, host migrations) injected by test orchestrator



1. A. Zeller et al. Simplifying and Isolating Failure-Inducing Input. IEEE TSE '02

Key Point

Must Carefully Schedule Replay Events To Achieve Minimization!

Challenges

- Asynchrony
- Divergent execution
- Non-determinism

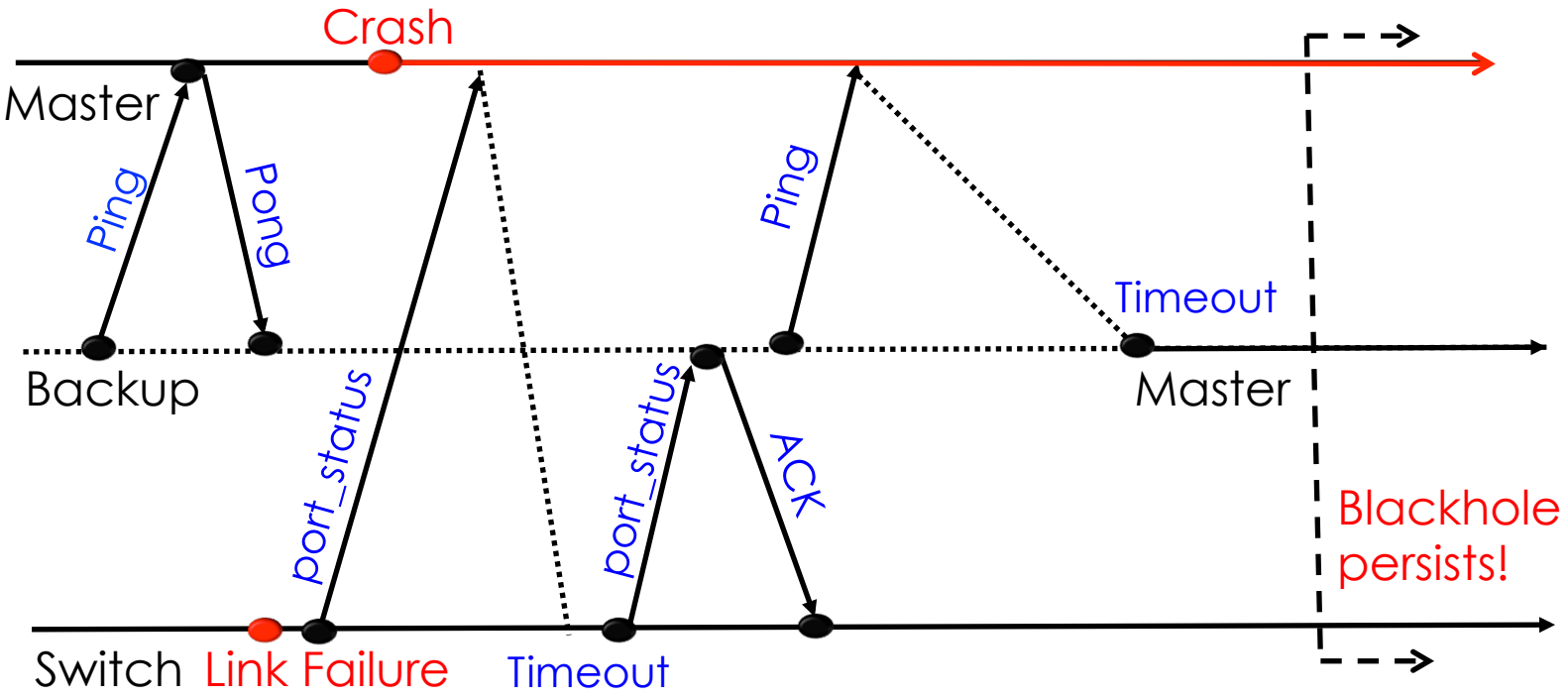
Challenge: Asynchrony

- Asynchrony definition:
  - No fixed upper bound on relative speed of processors
  - No fixed upper bound on time for messages to be delivered

Dwork & Lynch. Consensus in the Presence of Partial Synchrony. JACM '88

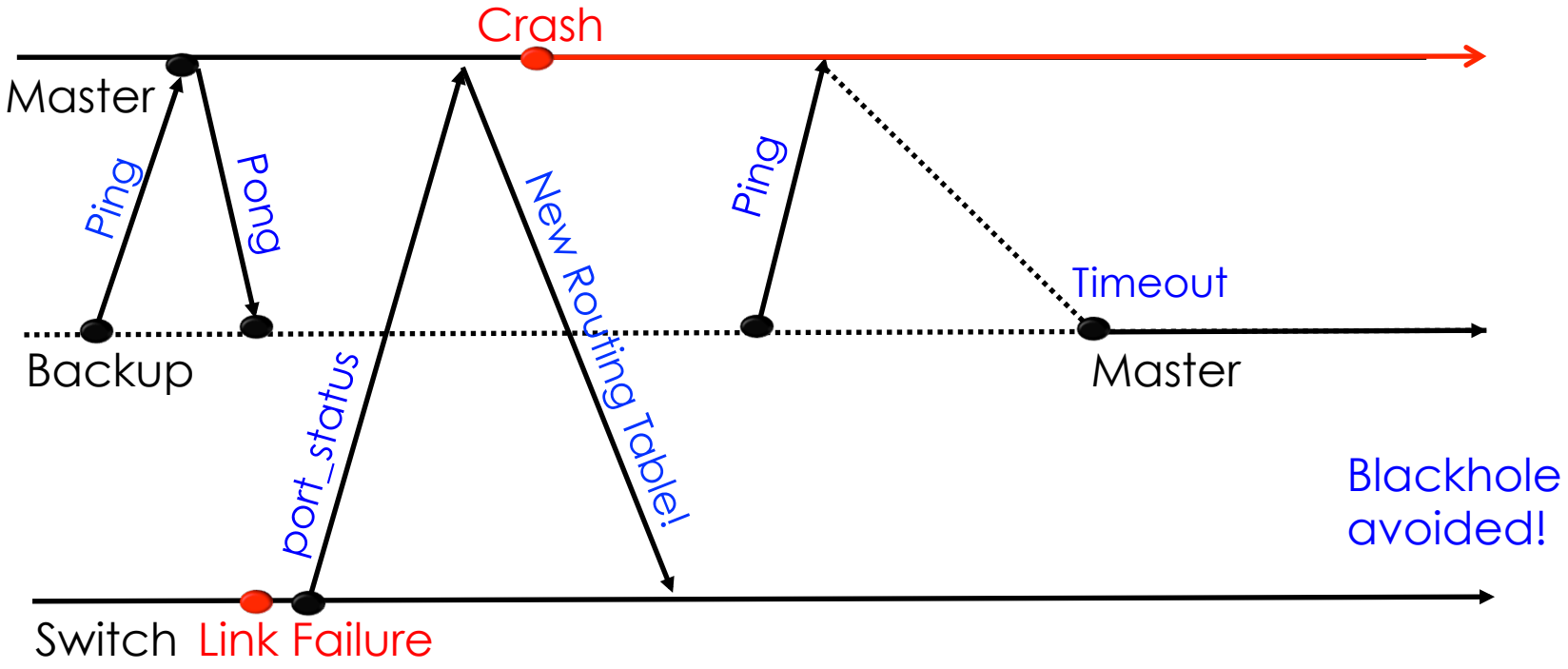
Challenge: Asynchrony

Need to maintain original event order

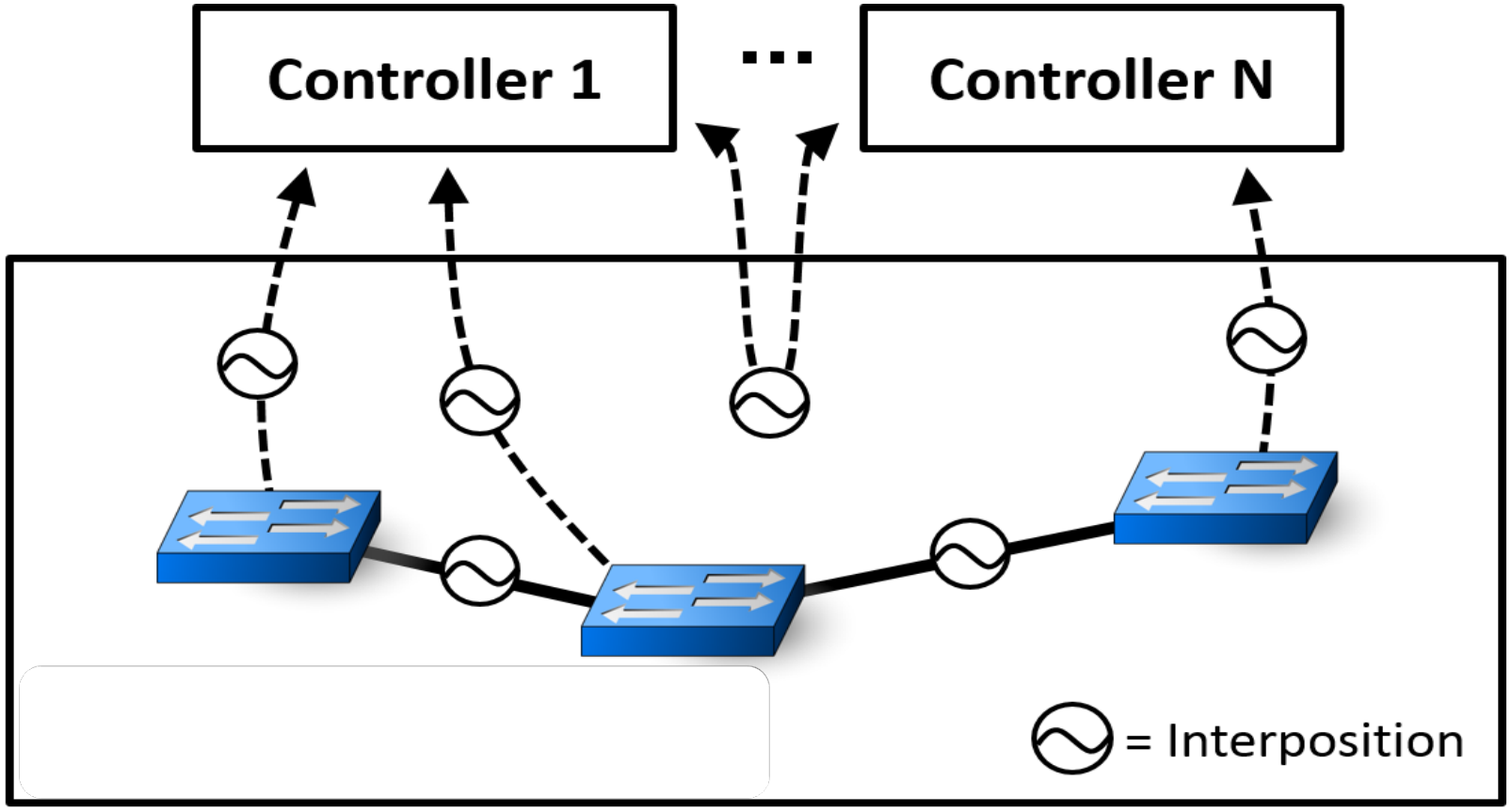


Challenge: Asynchrony

Need to maintain original event order



Coping with Asynchrony



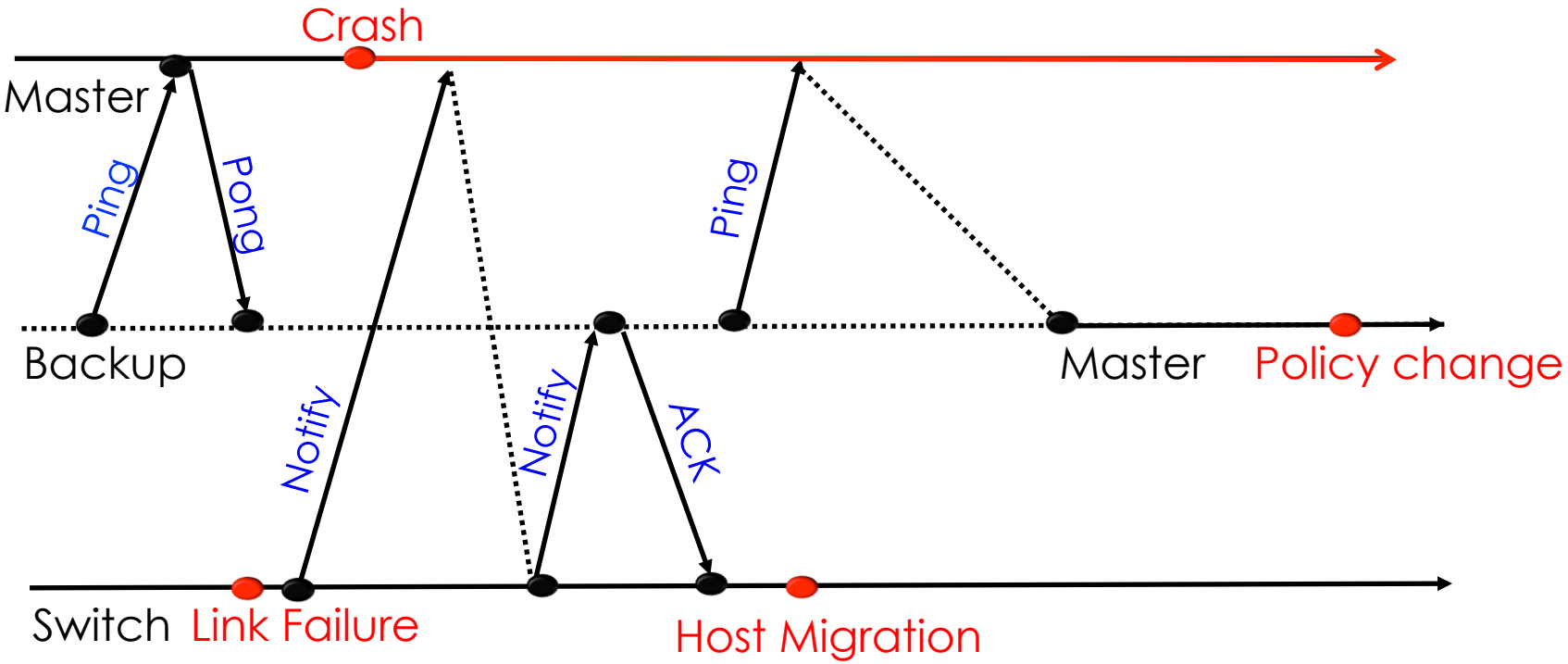
Use interposition to maintain causal dependencies

Challenge: Divergence

- Asynchrony
- Divergent execution
  - Syntactic Changes
  - Absent Events
  - Unexpected Events
- Non-determinism

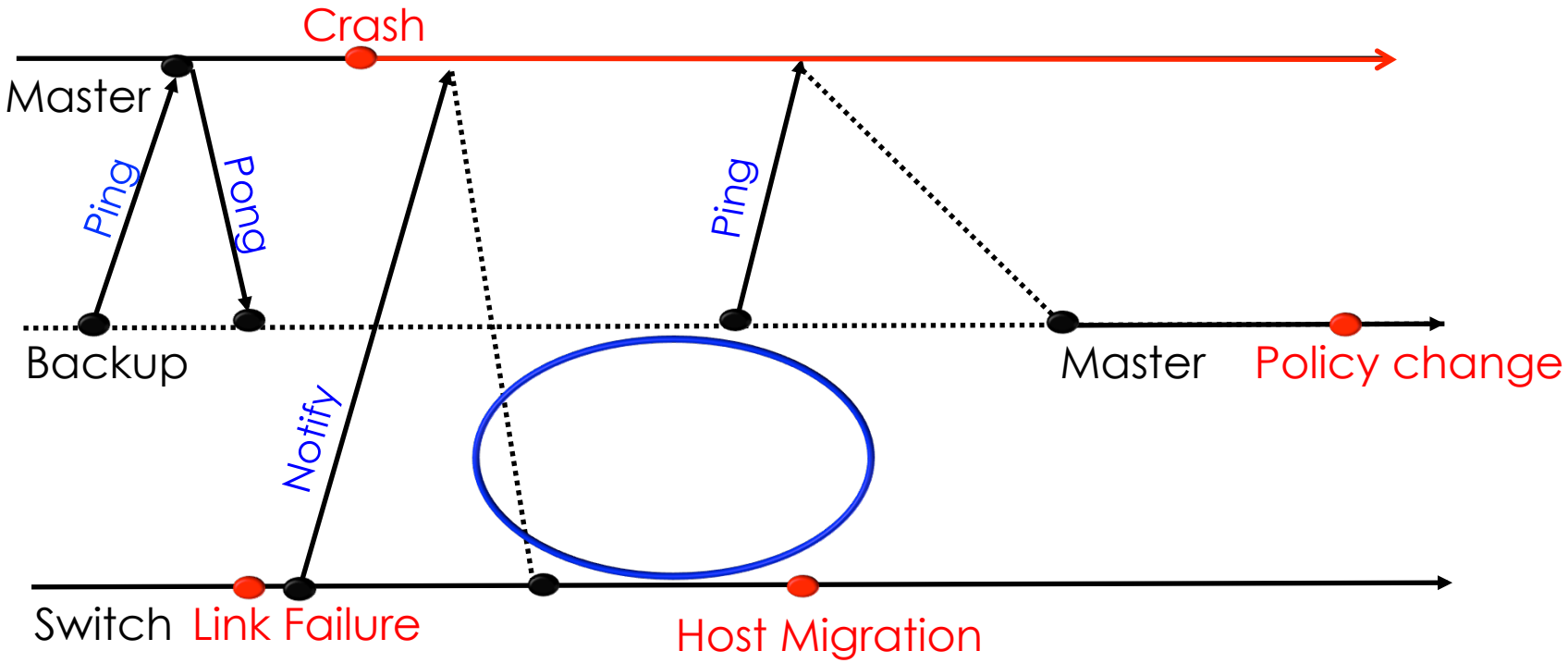
Divergence: Absent Internal Events

Prune Earlier Input..



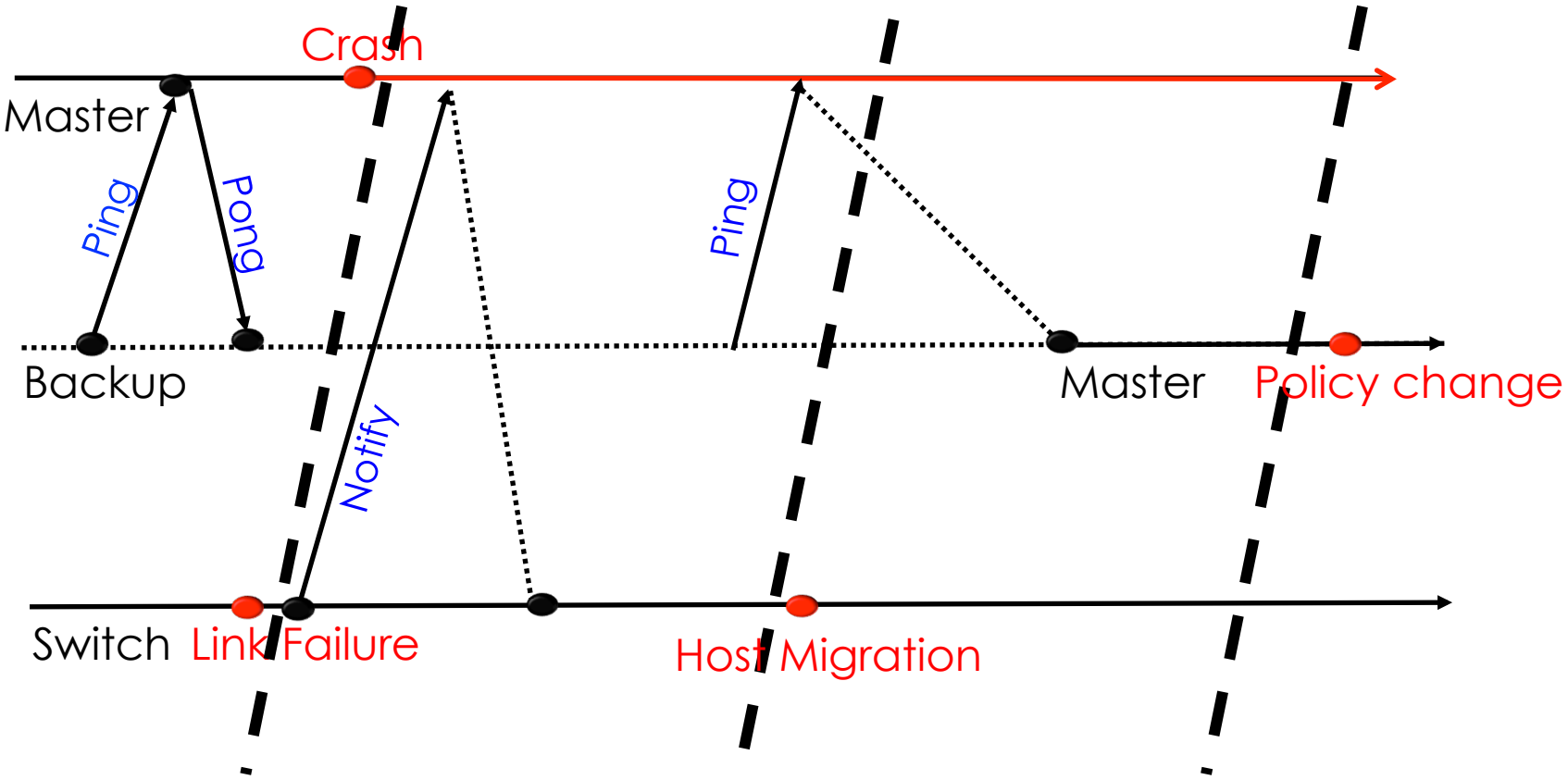
Divergence: Absent Internal Events

Some Events No Longer Appear



Solution: Peek Ahead

Infer which internal events will occur



Challenge: Non-determinism

- Asynchrony
- Divergent execution
- Non-determinism

Coping With Non-Determinism

- Replay multiple times per subsequence
- Assuming i.i.d., probability of not finding bug modeled by:

$$f(p,n) = (1-p)^n$$

- If not i.i.d., override gettimeofday(), multiplex sockets, interpose on logging statements

Approach Recap

- Replay events in QA testbed
- Apply delta debugging to inputs
- Asynchrony: interpose on messages
- Divergence: infer absent events
- Non-determinism: replay multiple times

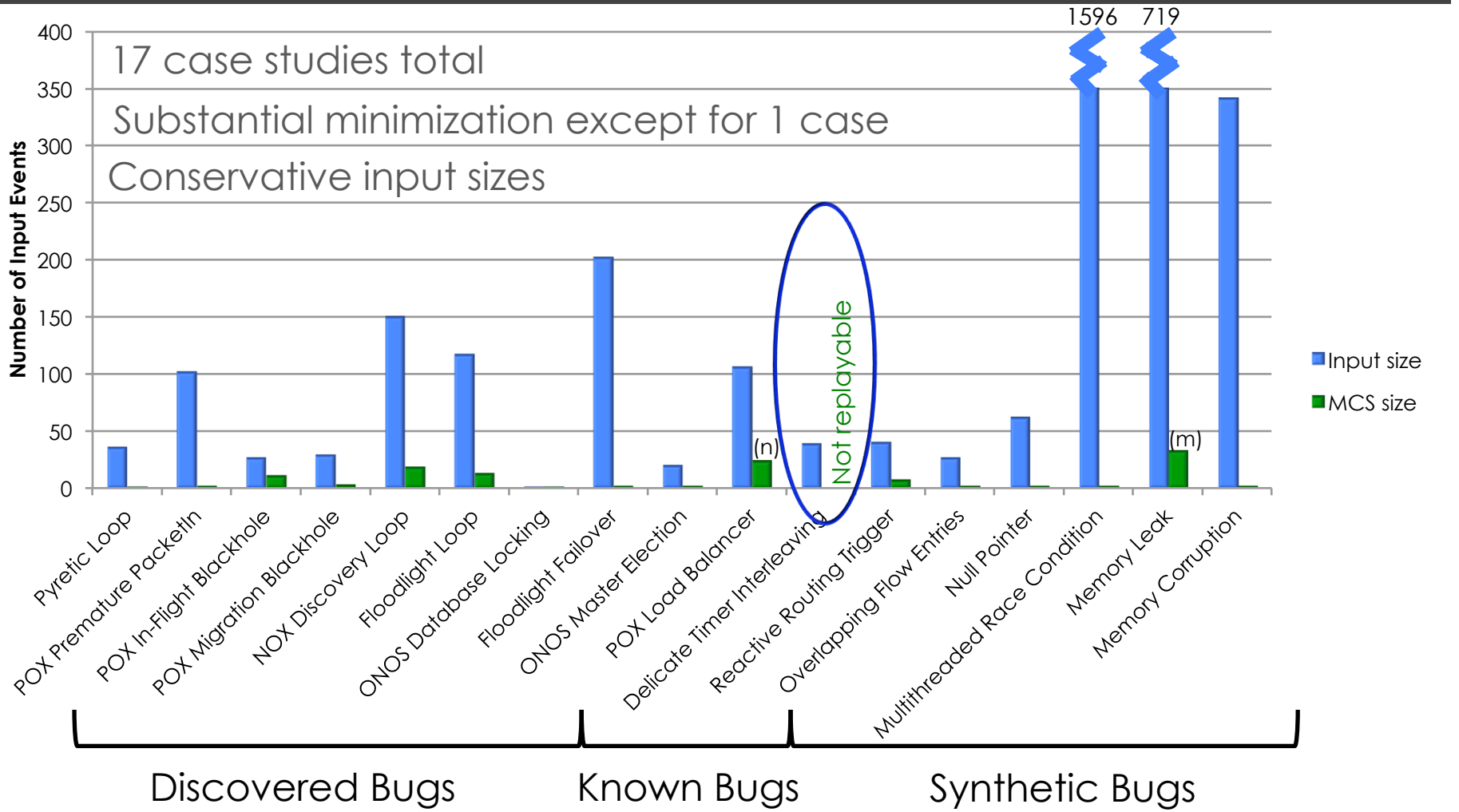
Outline

- What are we trying to do?
- How do we do it?
- Does it work?

Evaluation Methodology

- Evaluate on 5 open source SDN controllers (Floodlight, NOX, POX, Frenetic, ONOS)
- Quantify minimization for:
  - Synthetic bugs
  - Bugs found in the wild
- Qualitatively relay experience troubleshooting with MCSes

Case Studies



Comparison to Naïve Replay

- Naïve replay: ignore internal events
- Naïve replay often not able to replay at all
  - 5 / 7 discovered bugs not replayable
  - 1 / 7 synthetic bugs not replayable
- Naïve replay did better in one case
  - 2 event MCS vs. 7 event MCS with our techniques

Qualitative Results

- 15 / 17 MCSes useful for debugging
  - 1 non-replayable case (not surprising)
  - 1 misleading MCS (expected)

Related Work

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Conclusion

- Possible to automatically minimize execution traces for SDN control software
- System (23K+ lines of Python) evaluated on 5 open source SDN controllers (Floodlight, NOX, POX, Frenetic, ONOS) and one proprietary controller

ucb-sts.github.com/sts/

- Currently generalizing, formalizing approach

Backup

Related work

- Thread Schedule Minimization
  - Isolating Failure-Inducing Thread Schedules. SIGSOFT '02.
  - A Trace Simplification Technique for Effective Debugging of Concurrent Programs. FSE '10.
- Program Flow Analysis
  - Enabling Tracing of Long-Running Multithreaded Programs via Dynamic Execution Reduction. ISSTA '07.
  - Toward Generating Reducible Replay Logs. PLDI '11.
- Best-Effort Replay of Field Failures
  - A Technique for Enabling and Supporting Debugging of Field Failures. ICSE '07.
  - Triage: Diagnosing Production Run Failures at the User's Site. SOSP '07.

Bugs are costly and time consuming

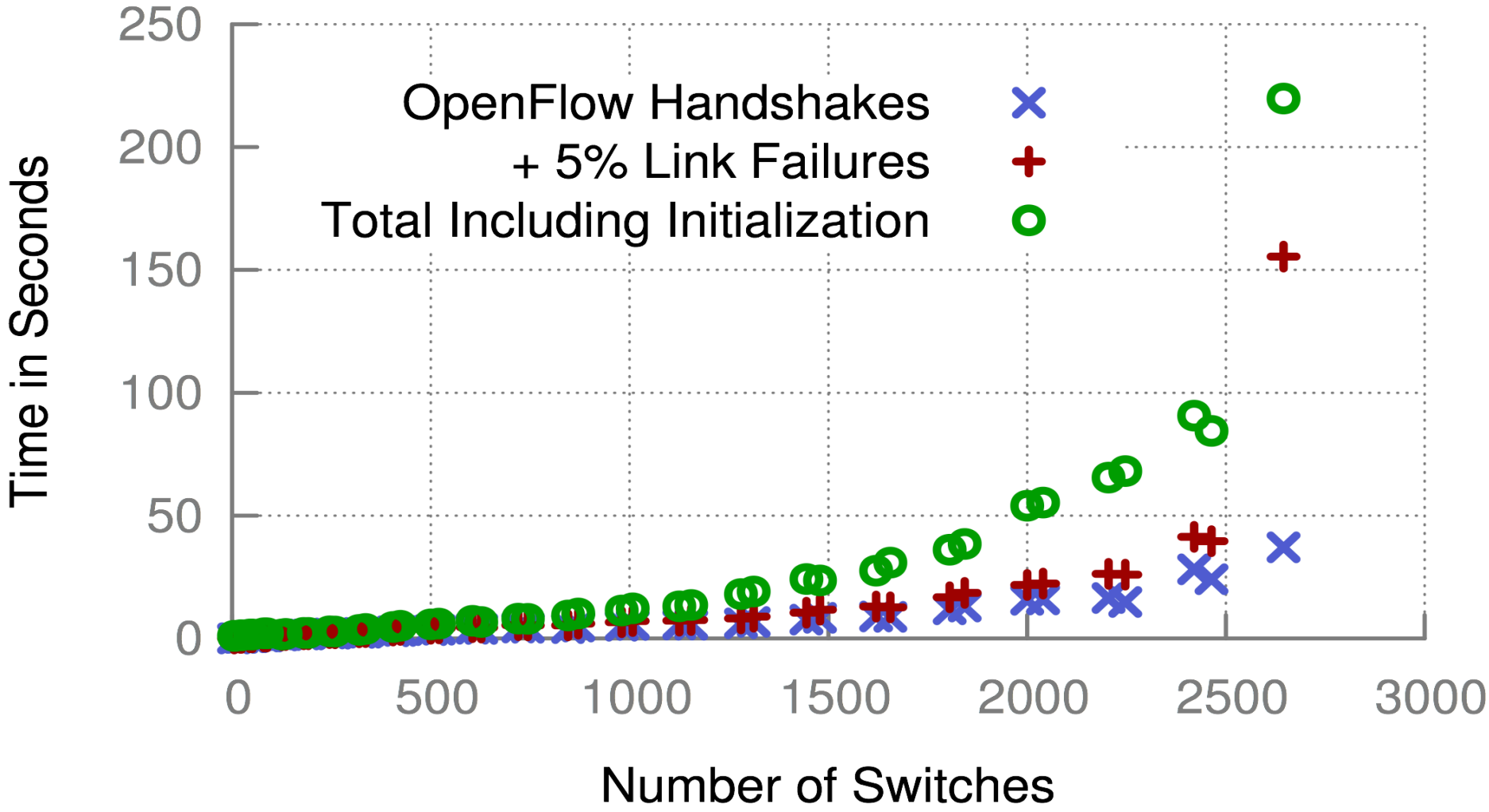
- Software bugs cost US economy $59.5 Billion in 2002 [1]
- Developers spend ~50% of their time debugging [2]
- Best developers devoted to debugging

1. National Institute of Standards and Technology 2002 Annual Report
2. P. Godefroid et al., Concurrency at Microsoft- An Exploratory Study. CAV '08

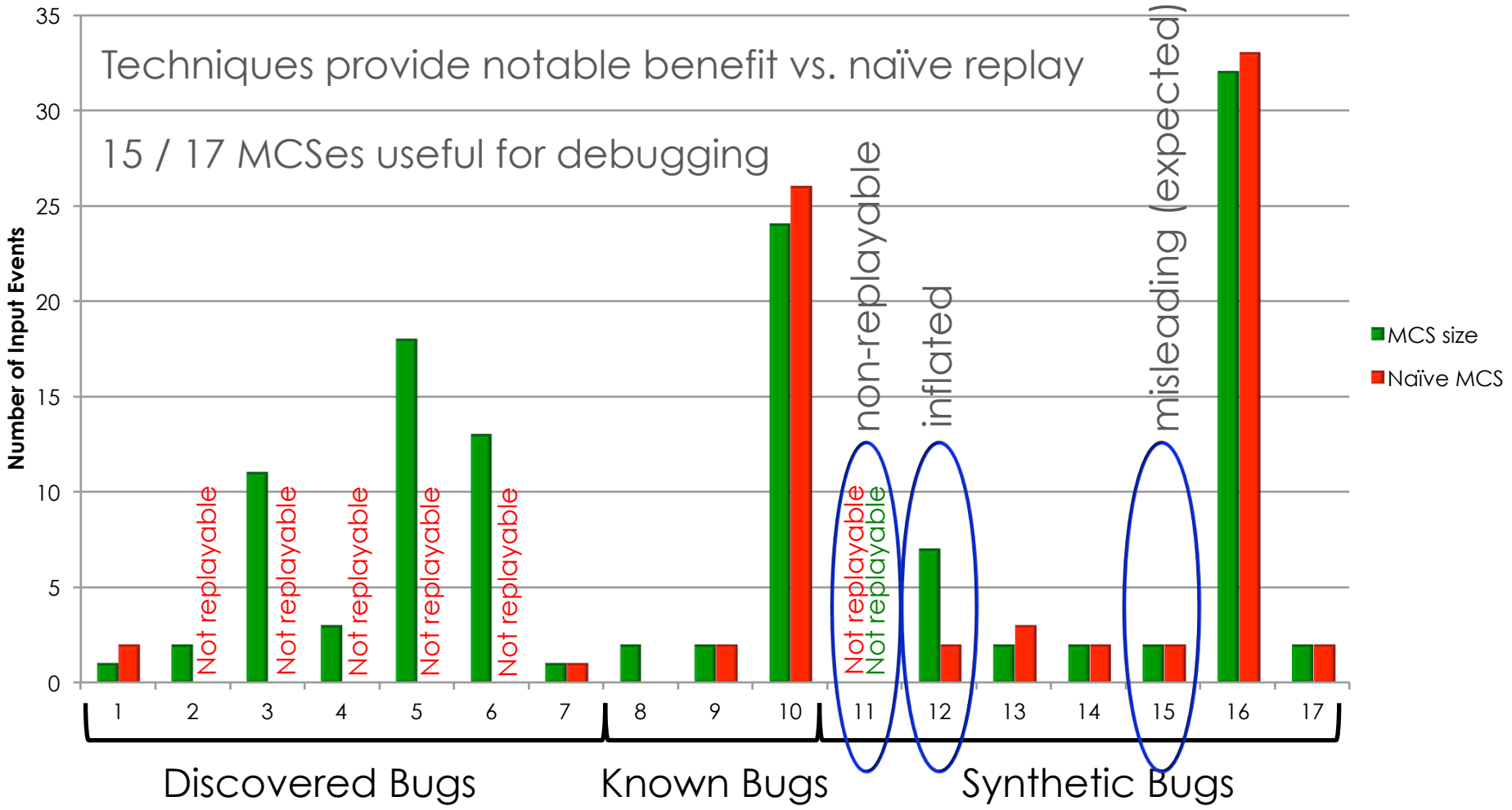
Ongoing work

- Formal analysis of approach
- Apply to other distributed systems (databases, consensus protocols)
- Investigate effectiveness of various interposition points
- Integrate STS into ONOS (ON.Lab) development workflow

Scalability



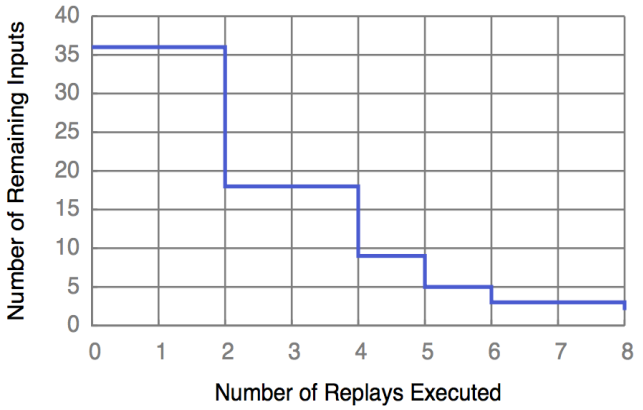
Case Studies



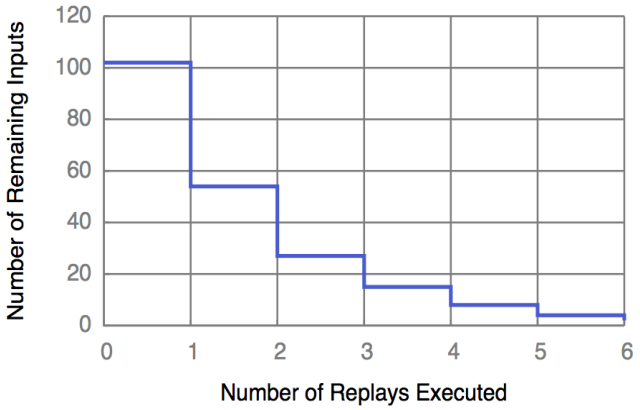
Case Studies

	Bug Name	Topology	Runtime (s)	Input Size	MCS Size	MCS WI	MCS Helpful?
Newly Found	Pyretic Loop	3 switch mesh	266.2	36	1	2	Yes
	POX Premature PacketIn	4 switch mesh	249.1	102	2	NR	Yes
	POX In-Flight Blackhole	2 switch mesh	1478.9	27	11	NR	Yes
	POX Migration Blackhole	4 switch mesh	1796.0	29	3	NR	Yes
	NOX Discovery Loop	4 switch mesh	4990.9	150	18	NR	Indirectly
	Floodlight Loop	3 switch mesh	27930.6	117	13	NR	Yes
	ONOS Database Locking	2 switch mesh	N/A	1	1	1	N/A
Known	Floodlight Failover	2 switch mesh	-	202	2	-	Yes
	ONOS Master Election	2 switch mesh	2746.0	20	2	2	Yes
	POX Load Balancer	3 switch mesh	2396.7	106	24 (N+1)	26	Yes
Synthetic	Delicate Timer Interleaving	3 switch mesh	N/A	39	NR	NR	No
	Reactive Routing Trigger	3 switch mesh	525.2	40	7	2	Indirectly
	Overlapping Flow Entries	2 switch mesh	115.4	27	2	3	Yes
	Null Pointer	20 switch FatTree	157.4	62	2	2	Yes
	Multithreaded Race Condition	10 switch mesh	36967.5	1596	2	2	Indirectly
	Memory Leak	2 switch mesh	15022.6	719	32 (M+2)	33	Indirectly
	Memory Corruption	4 switch mesh	145.7	341	2	2	Yes

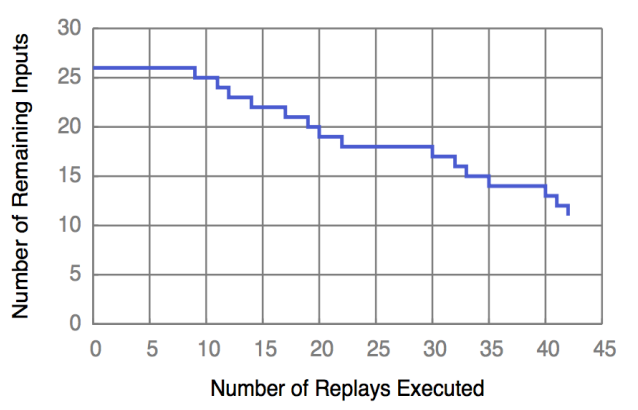
Runtime



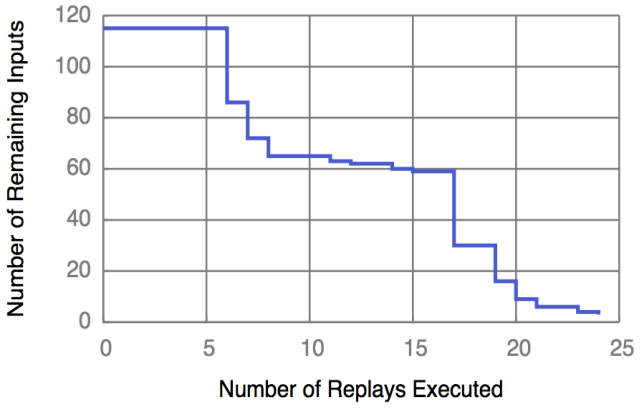
(a) Pyretic Loop.



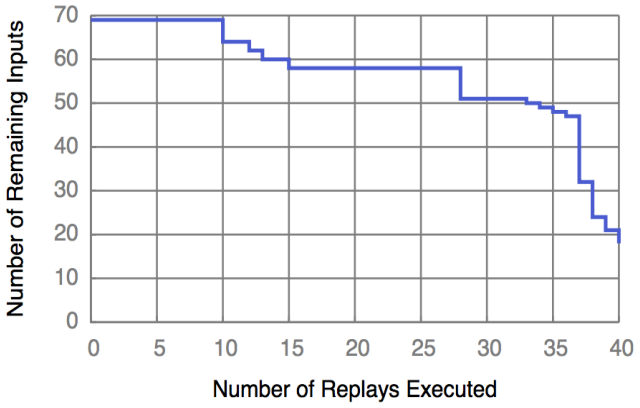
(b) POX Premature PacketIn.



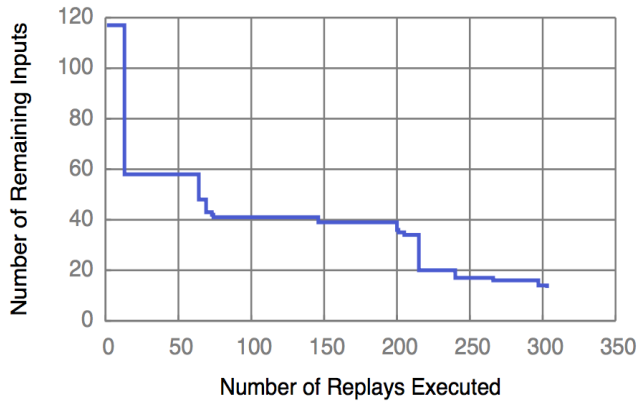
(c) POX In-Flight Blackhole.



(d) POX Migration Blackhole.

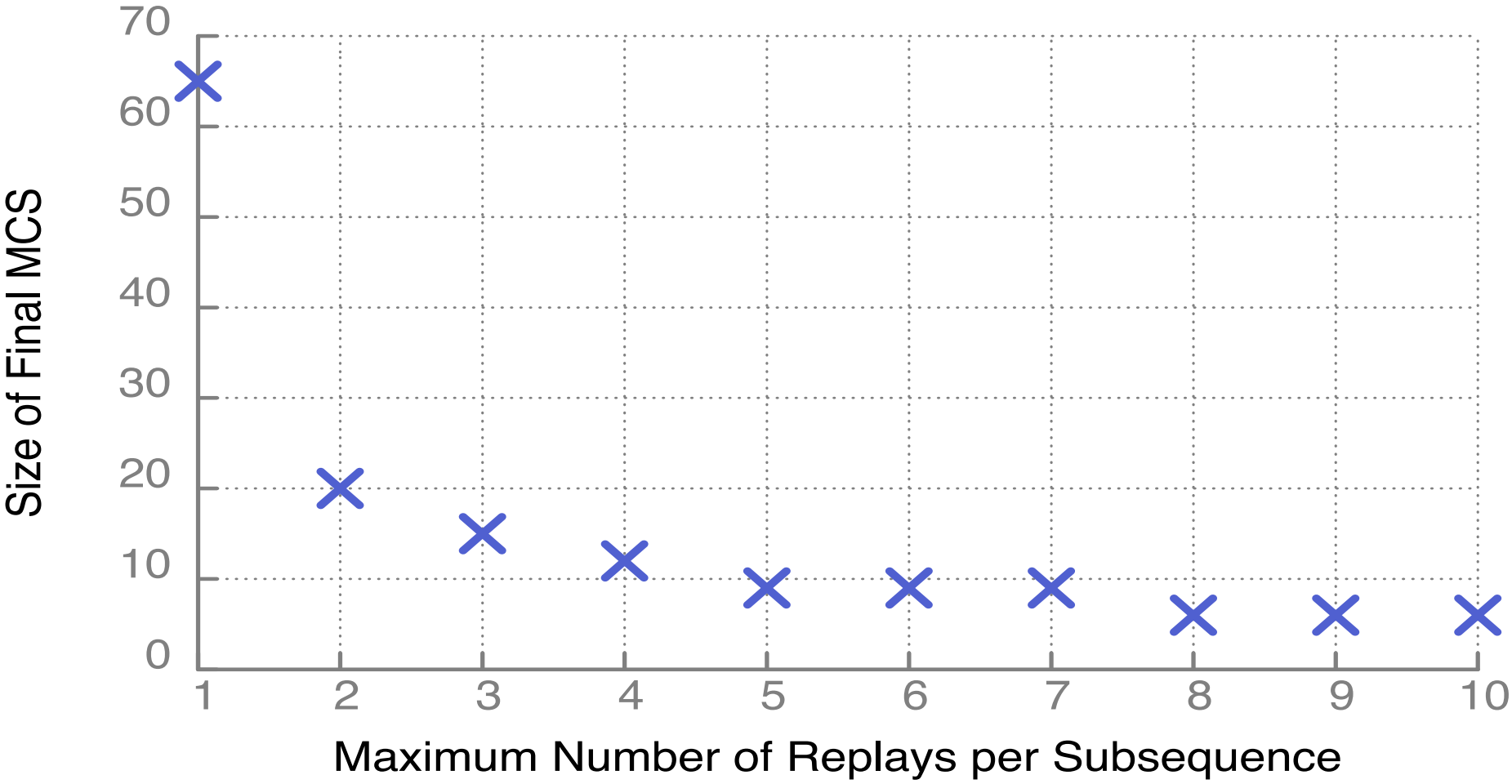


(e) NOX Discovery Loop.



(f) Floodlight Loop.

Coping with Non-Determinism

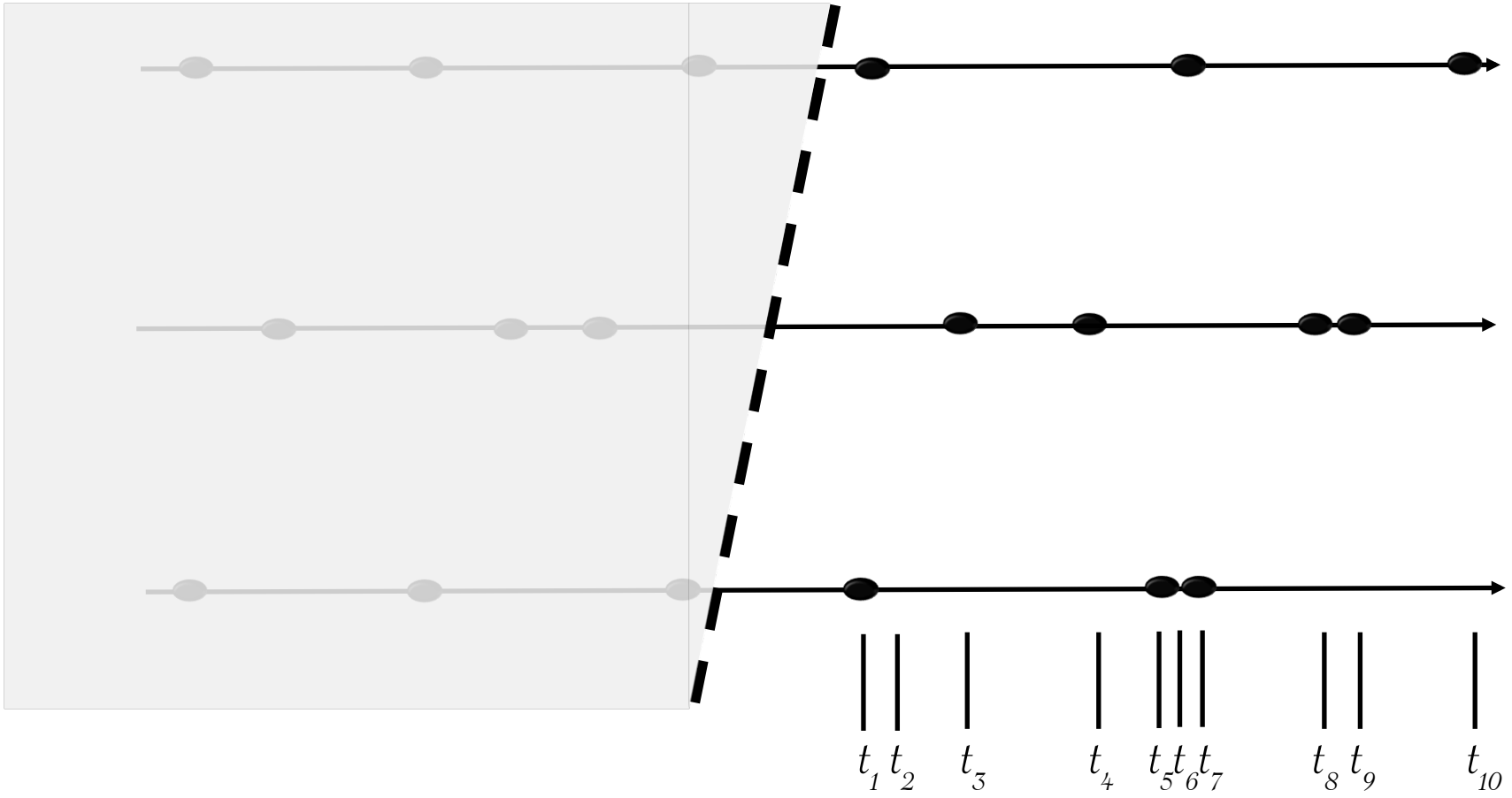


Replay Requirements

- Need to maintain original happens-before relation
- Includes internal events
  - Message Deliveries
  - State Transitions

Naïve Replay Approach

Schedule events according to wall-clock time



Complexity

Best Case	**Worst Case**
- Delta Debugging: Ω(log n) replays - Each replay: O(n) events - Total: Ω(nlog n)	- Delta Debugging: O(n) replays - Each replay: O(n) events - Total: $O(n^2)$

Assumptions of Delta Debugging

- *Monotonic:*

$$P \oplus C = \chi \Rightarrow P \oplus (C \cup C') \neq \checkmark$$

- *Unambiguous:*

$$P \oplus C = \chi \wedge P \oplus C' = \chi \Rightarrow P \oplus (C \cap C') \neq \checkmark$$

- *Consistent*

$$P \oplus C \neq ?$$

Local vs. Global Minimality

Definition 8 (Global minimum). *A set* $c \subseteq c_\chi$ *is called the* global minimum *of* c_χ *if:* $\forall c' \subseteq c_\chi \cdot \left(|c'| < |c| \Rightarrow test(c') \neq \chi\right)$ *holds.*

Definition 10 (n-minimal test case). *A test case* $c \subseteq c_\chi$ *is* n-minimal *if:* $\forall c' \subset c \cdot |c| - |c'| \leq n \Rightarrow \left(test(c') \neq \chi\right)$ *holds. Consequently,* c *is 1-minimal if* $\forall \delta_i \in c \cdot test\left(c - \{\delta_i\}\right) \neq \chi$ *holds.*

Forensic Analysis of Production Logs

- Logs need to capture causality: Lamport Clocks or accurate NTP
- Need clear mapping between input/internal events and simulated events
- Must remove redundantly logged events
- Might employ causally consistent snapshots to cope with length of logs

Instrumentation Complexity

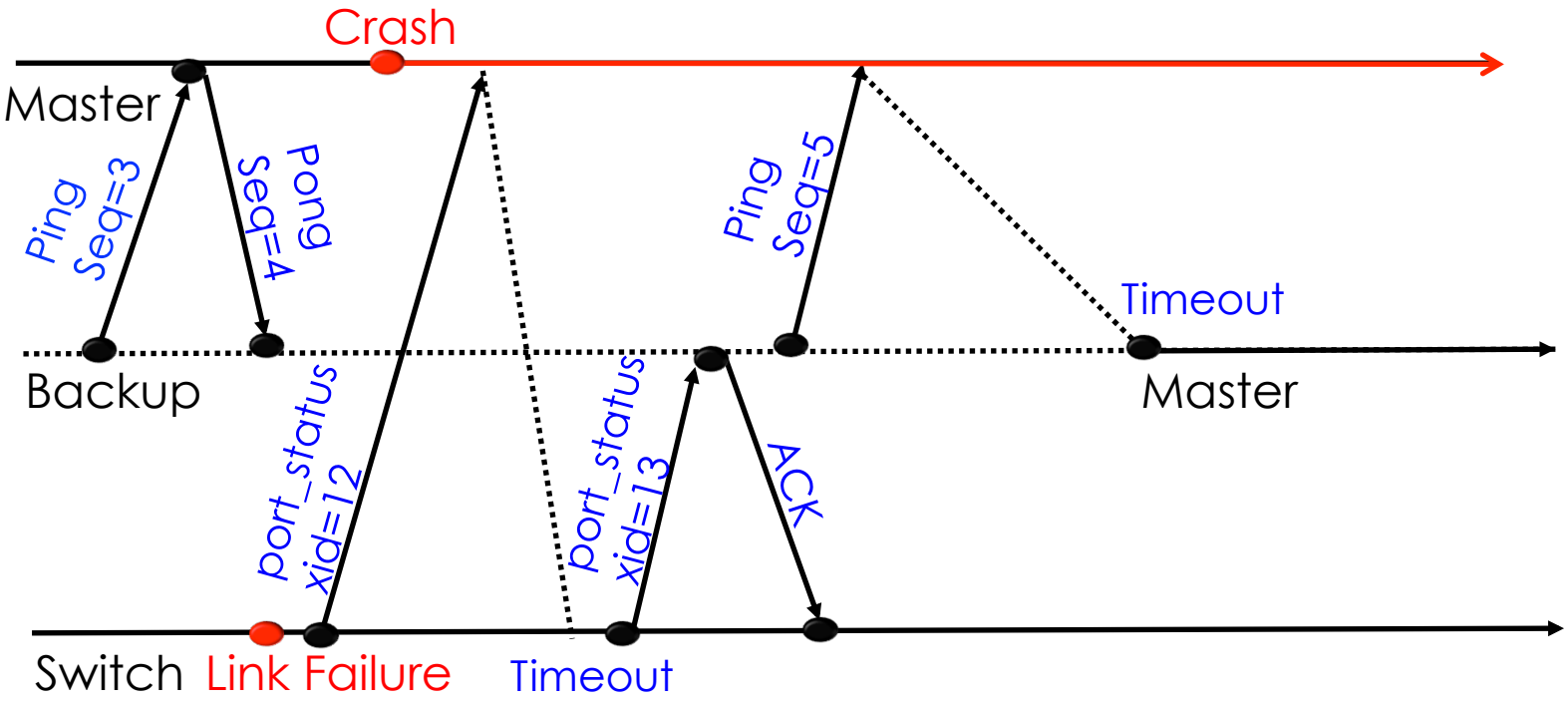
- Code to override gettimeofday(), interpose on logging statements, and multiplex sockets:
  - 415 LOC for POX (Python)
  - 722 LOC for Floodlight (Java)

Improvements

- Many improvements:
  - Parallelize delta debugging
  - Smarter delta debugging time splits
  - Apply program flow analysis to further prune
  - Compress time (override gettimeofday)

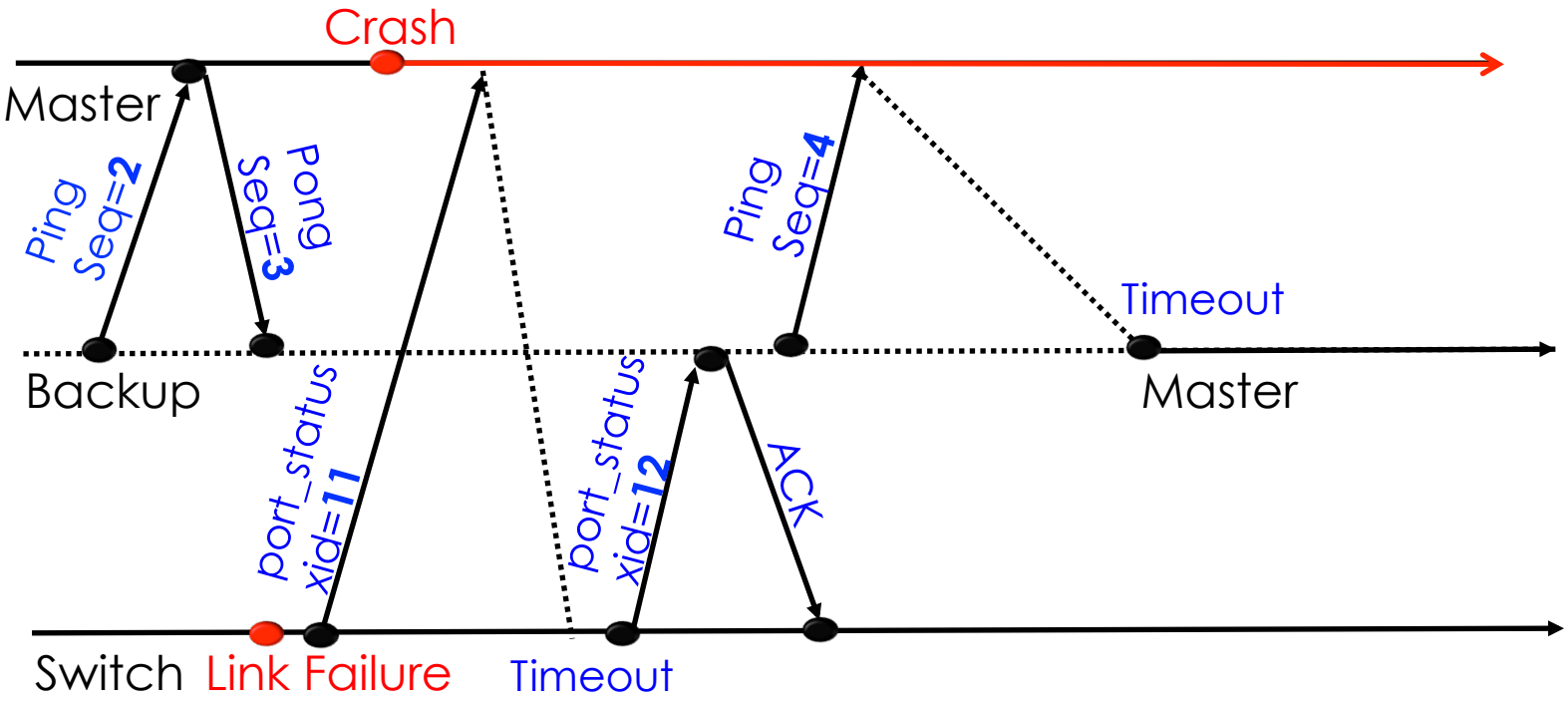
Divergence: Syntactic Changes

Prune Earlier Input..



Divergence: Syntactic Changes

Sequence Numbers Differ!



Solution: Equivalence Classes

Mask Over Extraneous Fields

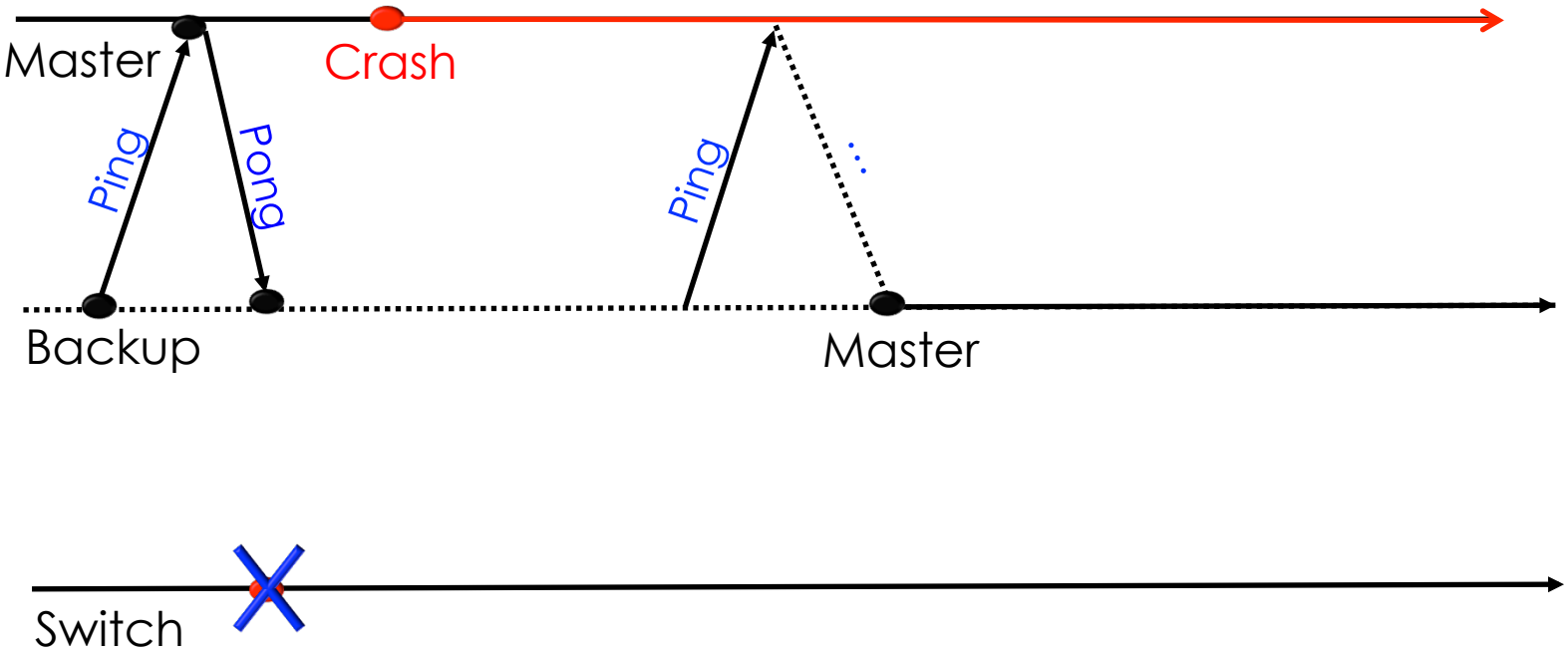
Internal message	**Masked values**
OpenFlow messages	xac id, cookie, buffer id, stats
packet_out/in payload	all values except src, dst, data
Log statements	varargs parameters to printf

Solution: Peek ahead

procedure PEEK(*input subsequence*)
 $inferred \leftarrow [\,]$
 for e_i *in subsequence*
  $checkpoint\ system$
  $inject\ e_i$
  $\Delta \leftarrow |e_{i+1}.time - e_i.time| + \epsilon$
  $record\ events\ for\ \Delta\ seconds$
  $matched \leftarrow original\ events\ \&\ recorded\ events$
  $inferred \leftarrow inferred + [e_i] + matched$
  $restore\ checkpoint$
 return $inferred$

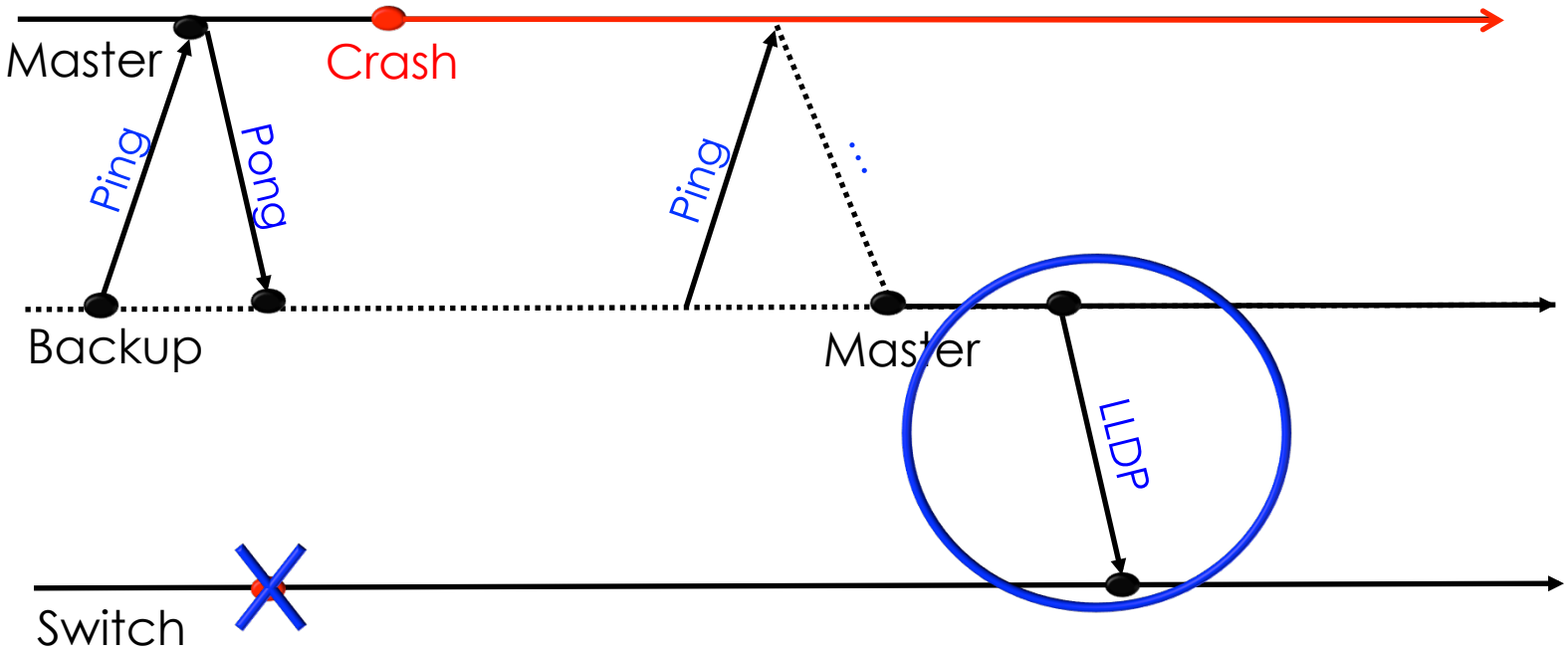
Divergence: Unexpected Events

Prune Input..



Divergence: Unexpected Events

Unexpected Events Appear



Solution: Emperical Heuristic

Theory:

- Divergent paths → Exponential possibilities

Practice:

- Allow unexpected events through