Troubleshooting SDN Control Software with Minimal Causal Sequences

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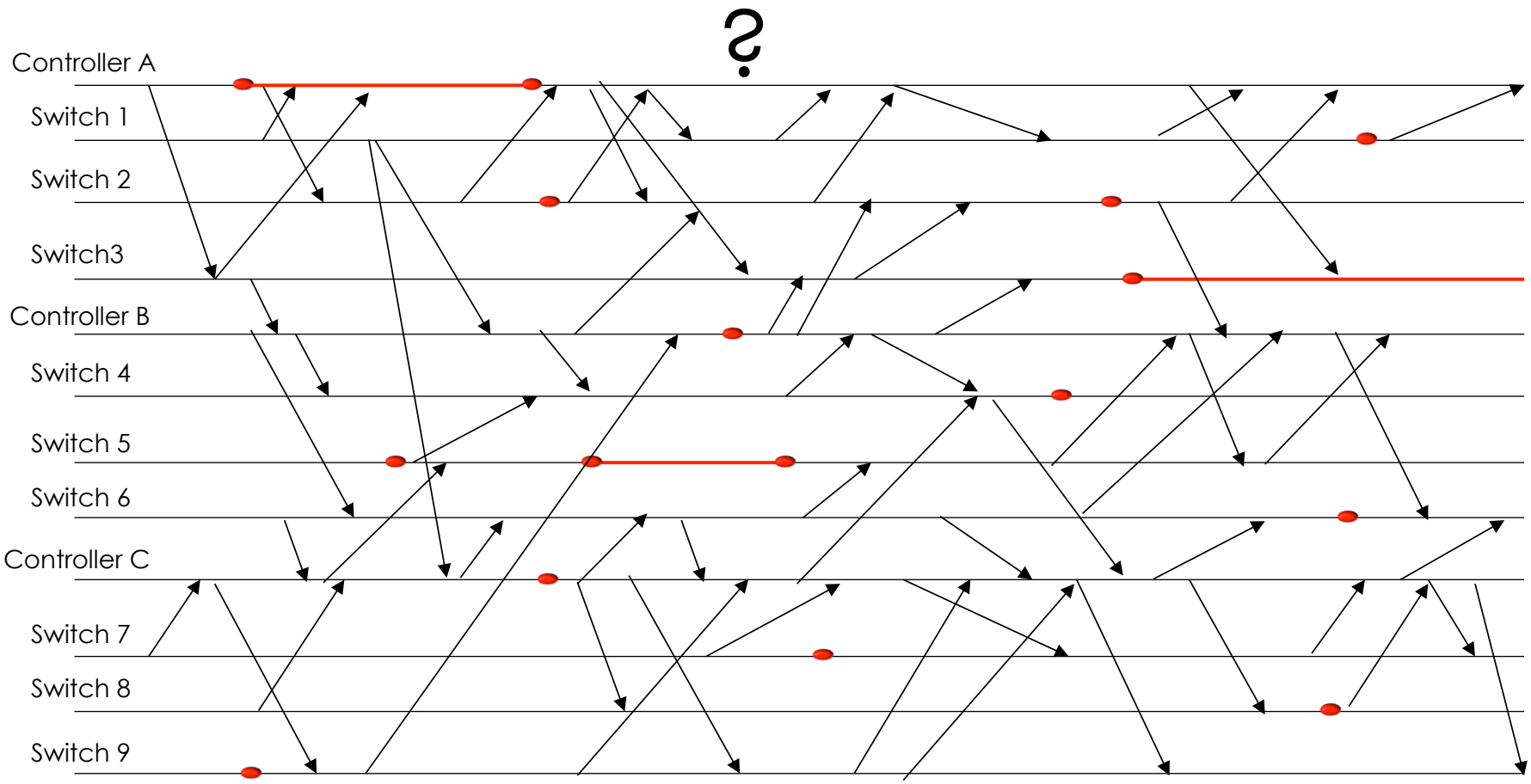
Something goes wrong!

- Loops, Blackholes, etc. found in:
  - Unit tests
  - Integration tests
  - Software QA testbeds
  - Hardware QA testbeds
  - Production

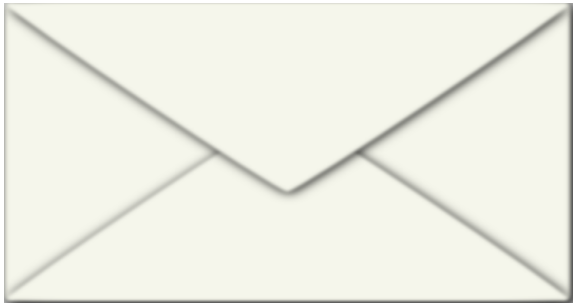
Best practice: Logs

Human analysis of log files

Best practice: Logs



How many events?



- 20,000 servers * 4 VMs / server = 80,000 VMs
- (6 migrations / day / VM) + (2 power up | down / day / VM) * 80,000 VMs = 640,000 VM events / day ~= **450 VM changes / minute** [1]
- **8.5 network error events / minute** [2]

How many events?

= ~500 inputs / minute

Our Goal

Identify a **minimal** sequence of inputs that triggers the bug

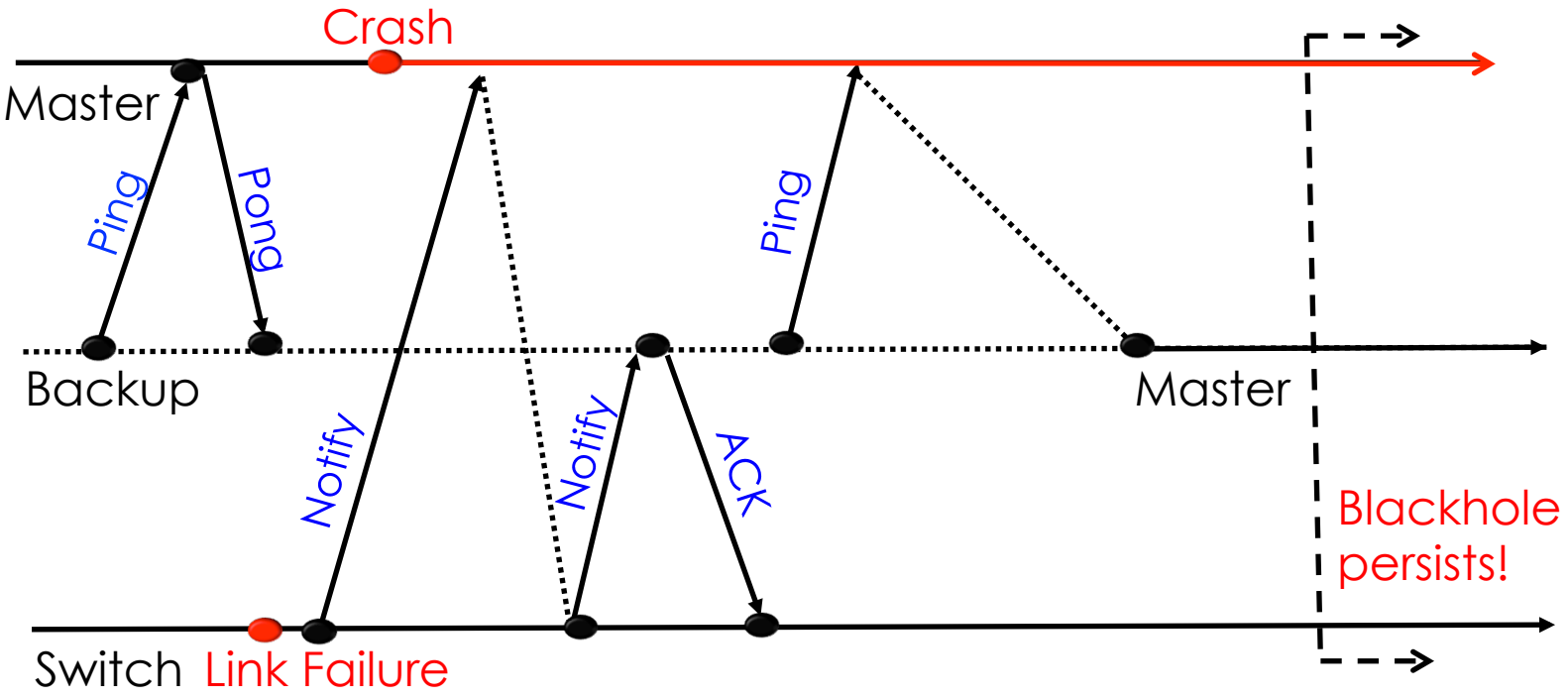
Minimal Causal Sequence

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

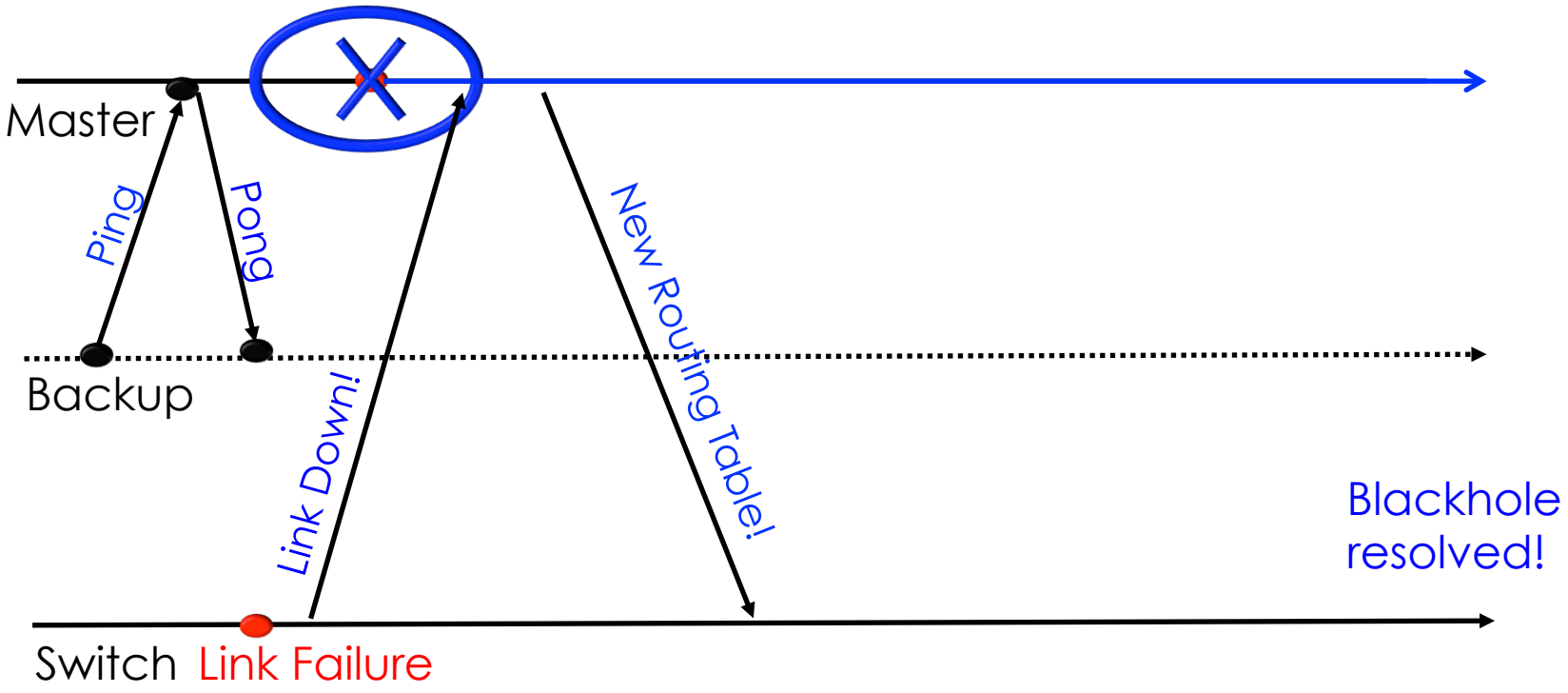
$$i.\; replay(MCS) = \chi$$

$$ii.\; \forall_{e \in MCS} replay(MCS - \{e\}) \neq \chi$$

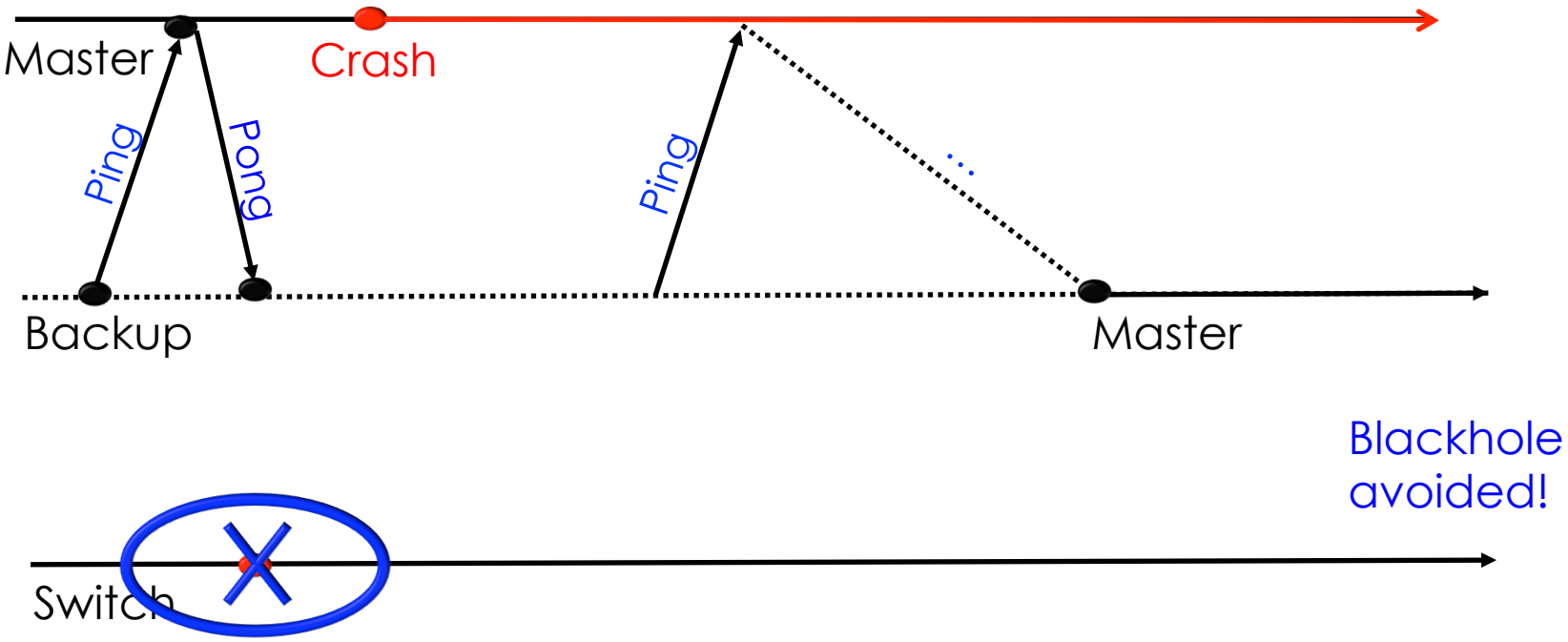
Minimal Causal Sequence



Minimal Causal Sequence

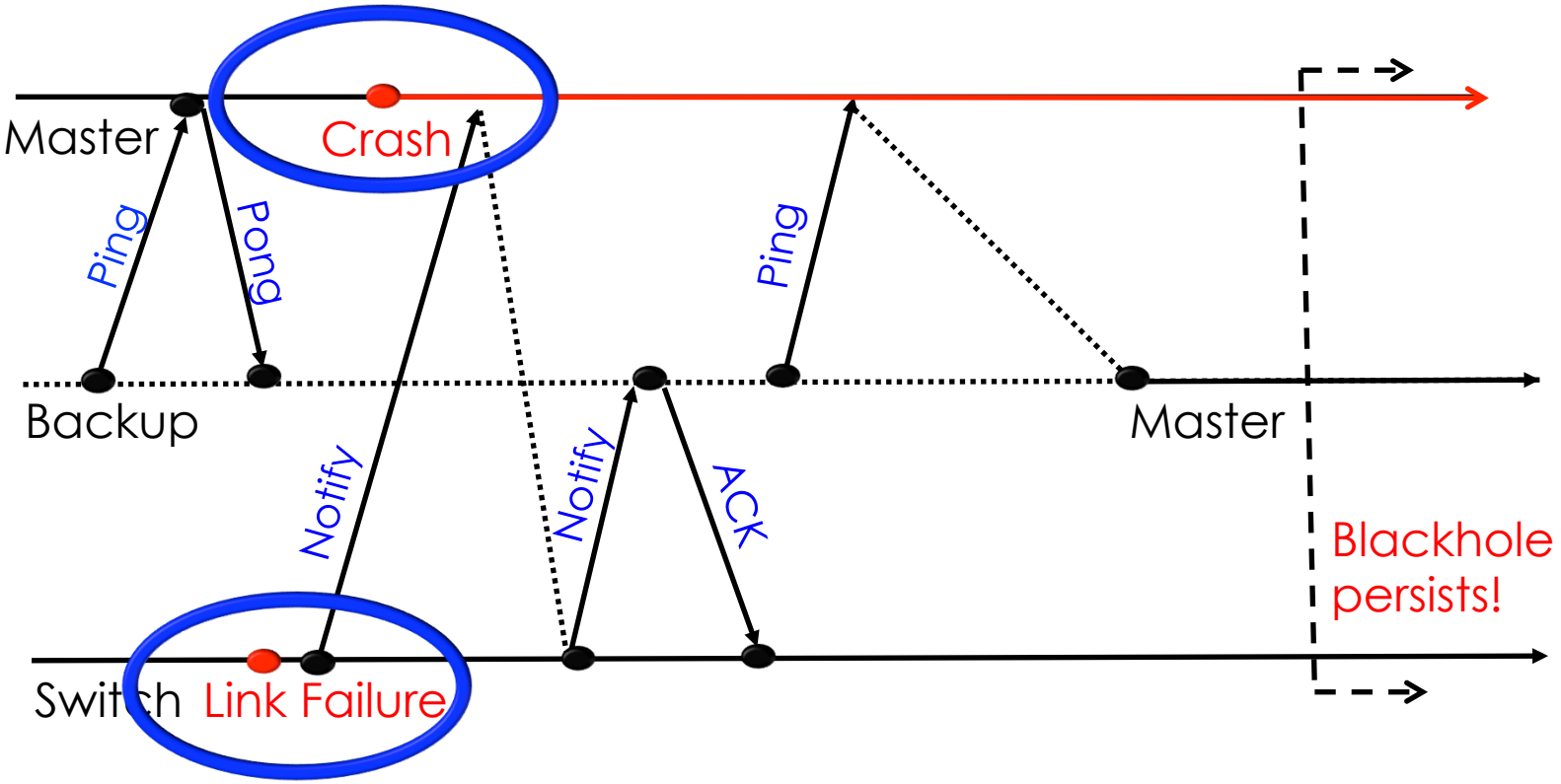


Minimal Causal Sequence

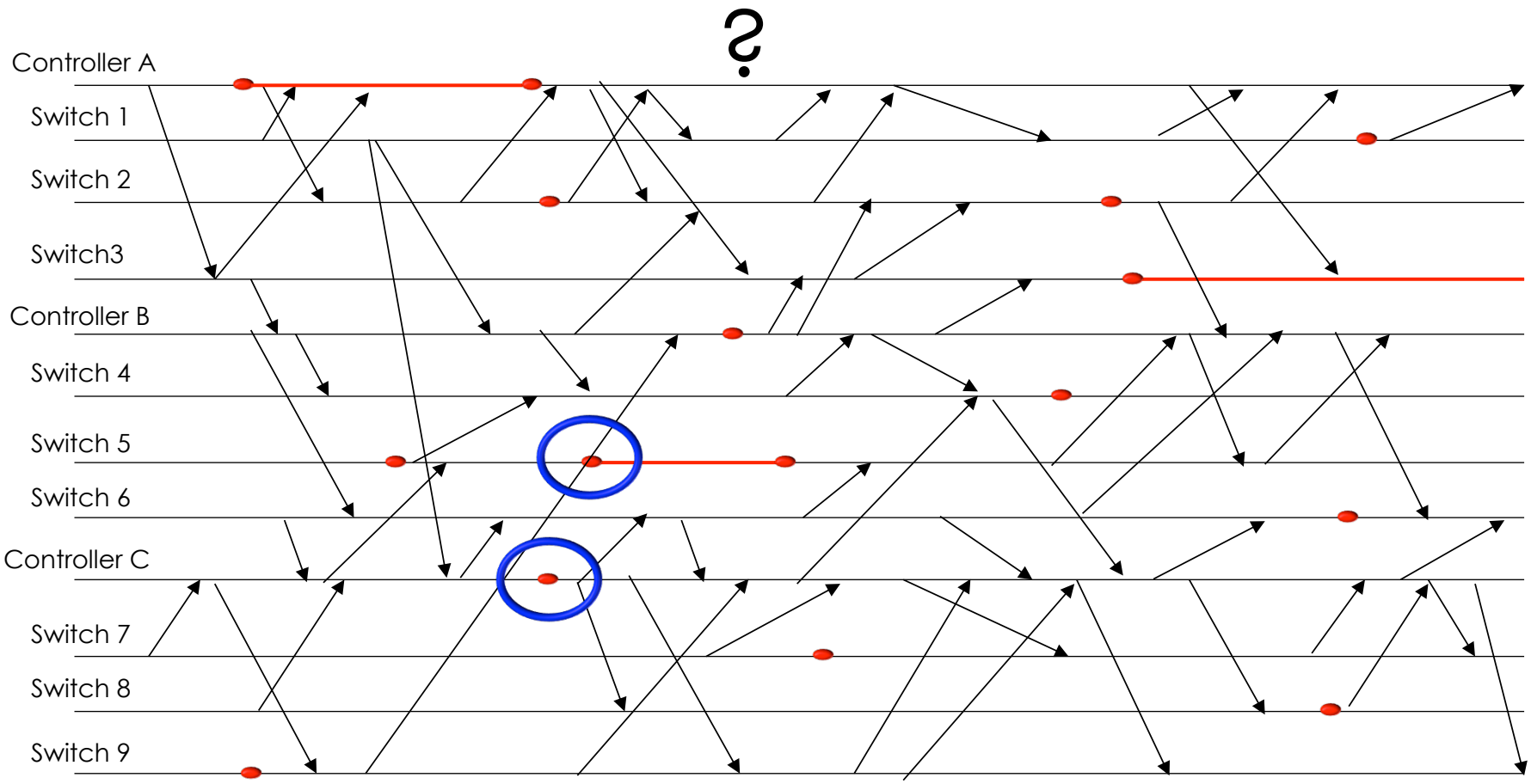


Minimal Causal Sequence

Both are necessary conditions!



Minimal Causal Sequence



Approach: Delta Debugging

Modify history!

Possible failure causes

Set up first hypothesis

Test first hypothesis

Second hypothesis

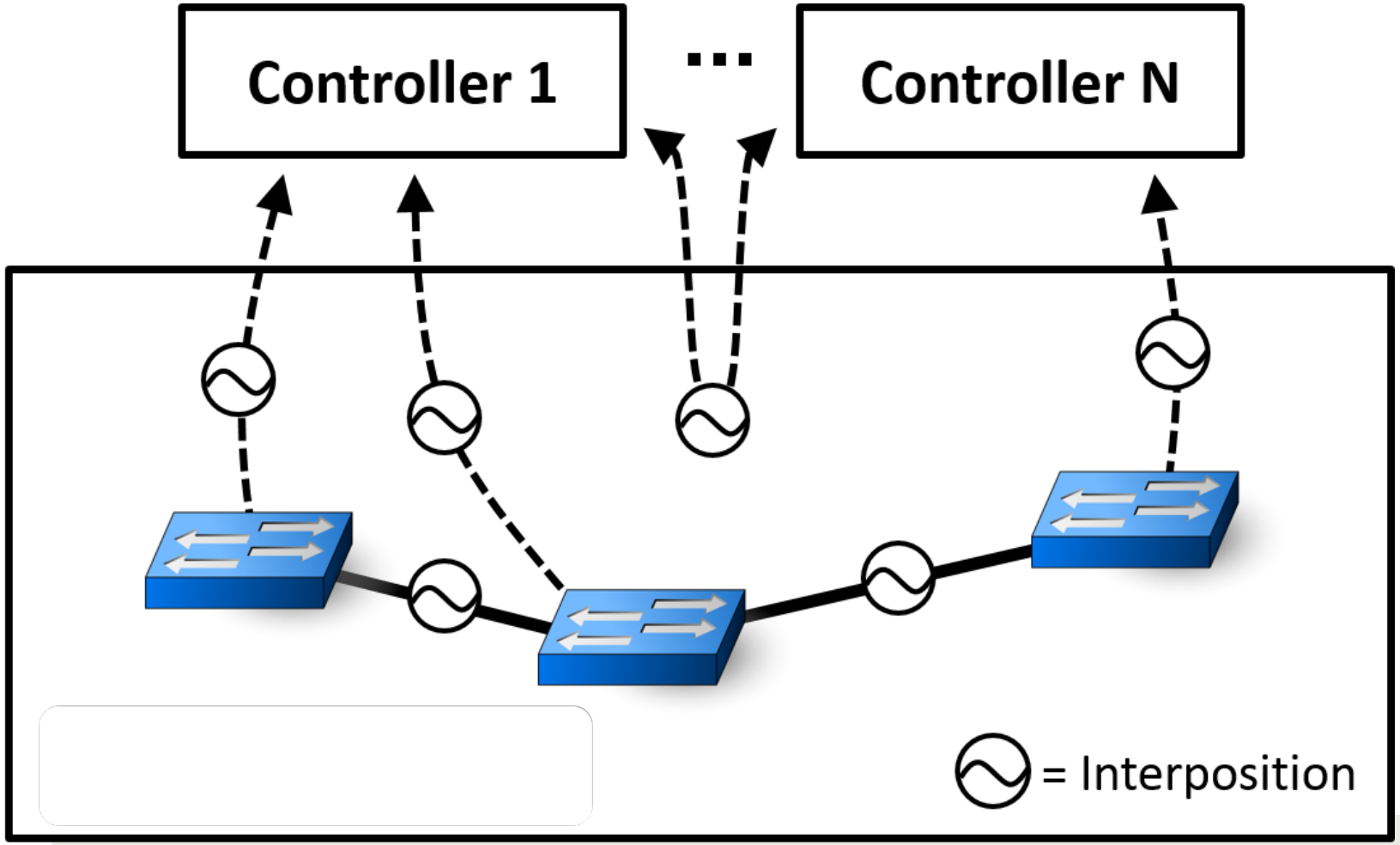
Third hypothesis

Fourth hypothesis...

Challenges

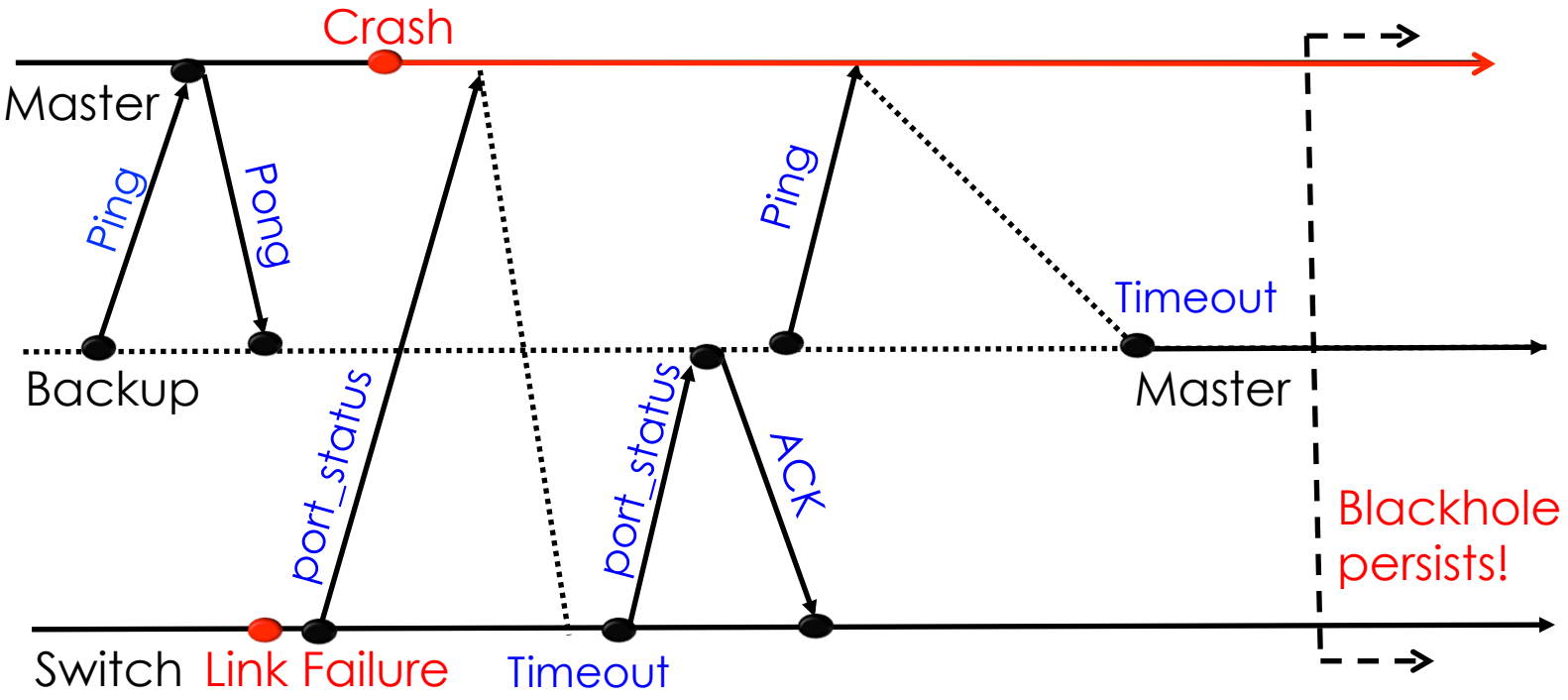
- Must carefully control timing of input events, despite
  - Modified history
  - Asynchrony
  - Non-determinism
- Without assuming language or instrumentation of control software

Replay Infrastructure



Replaying Pruned Inputs is Hard

Must consider internal events



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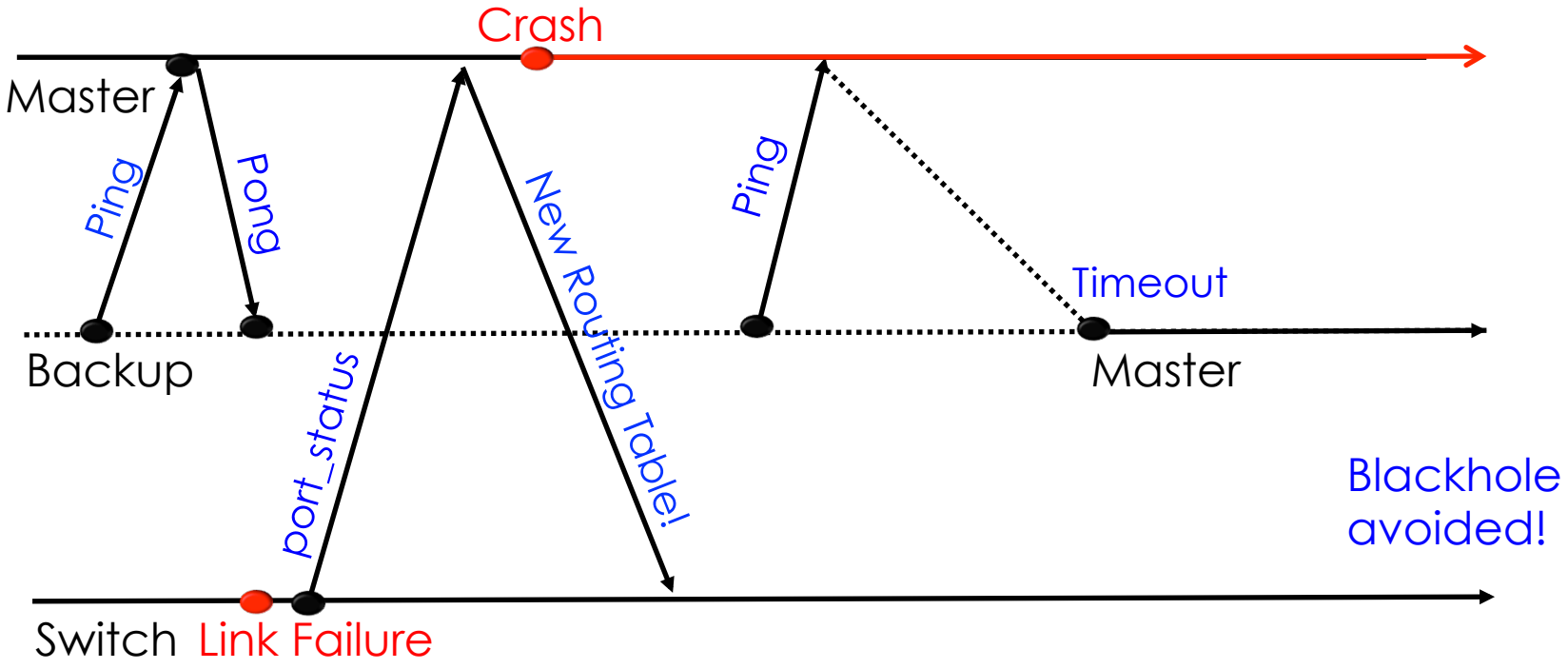
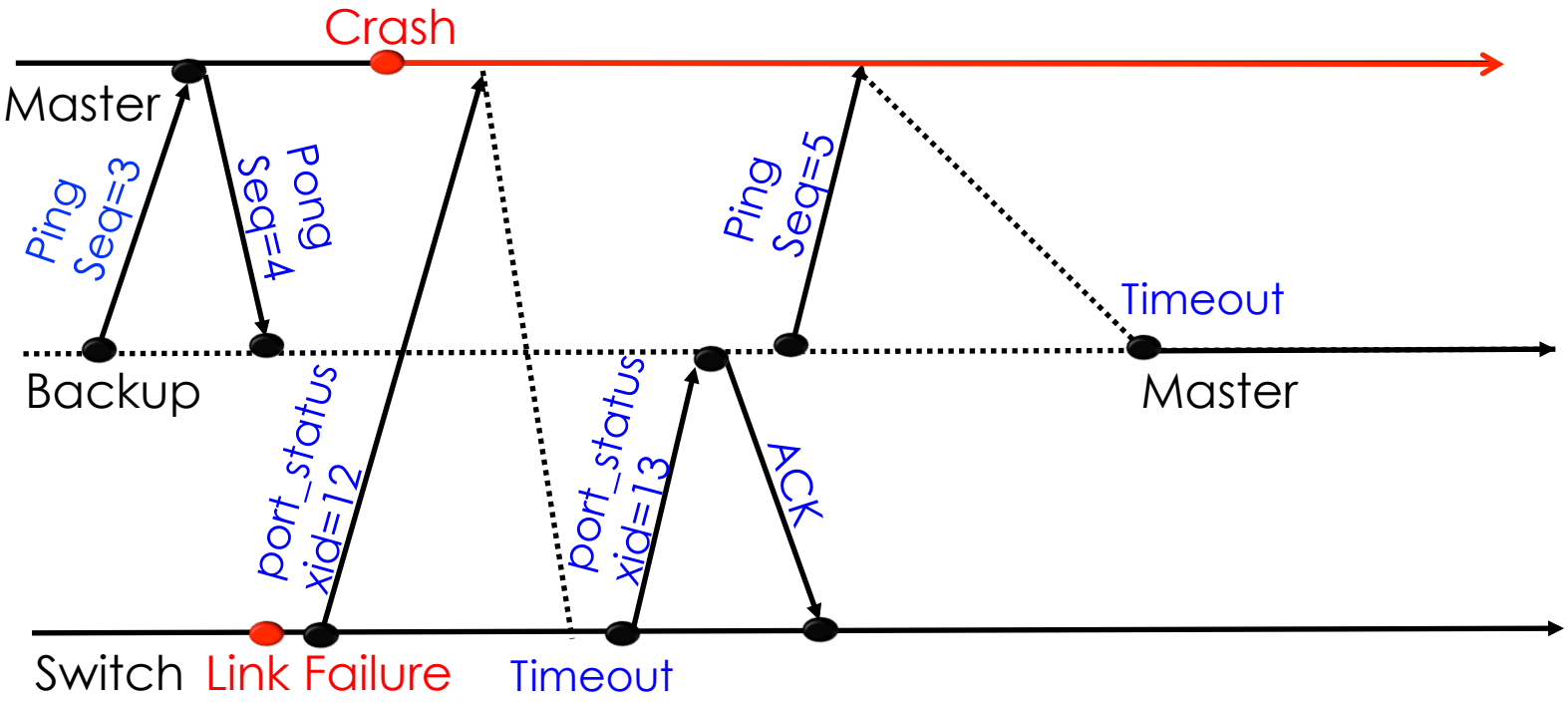


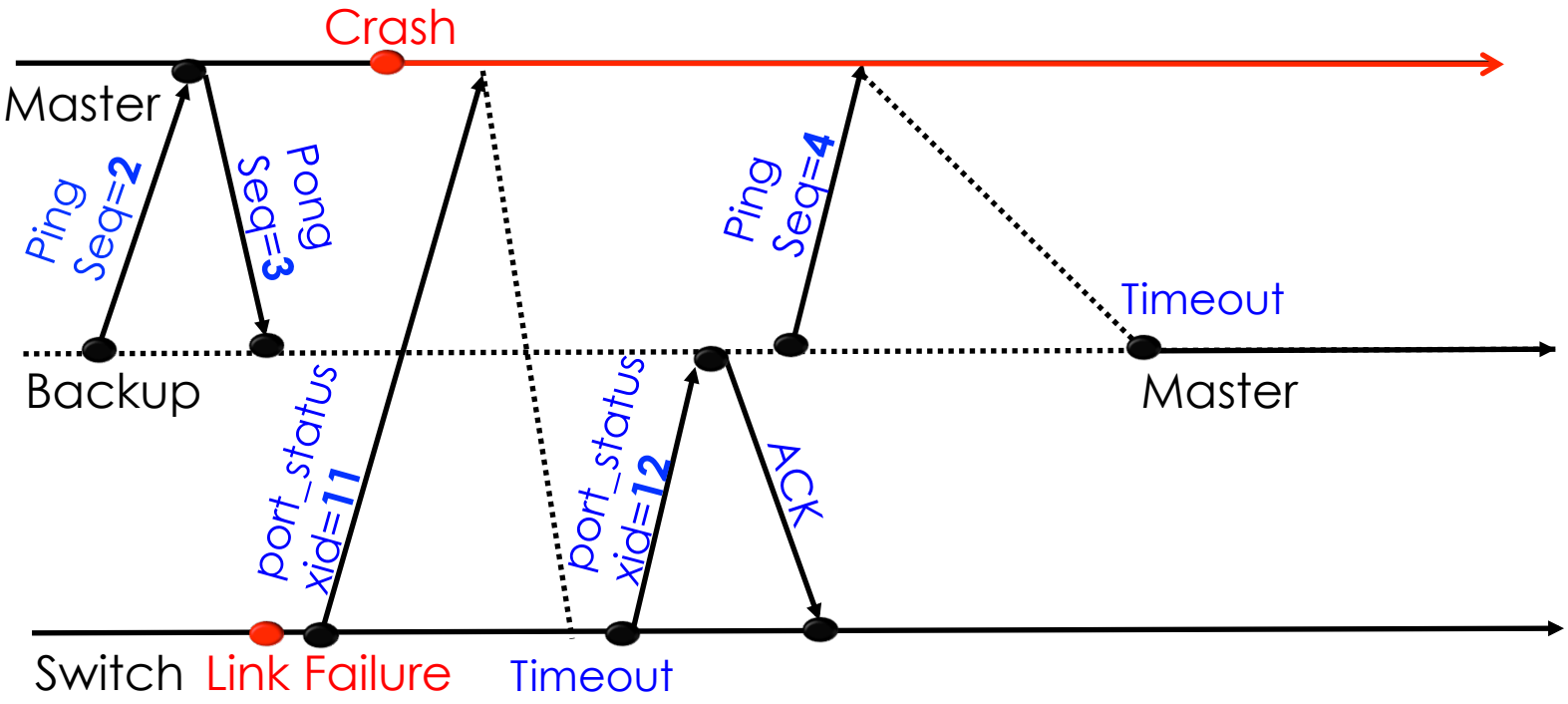
Pruning Alters Internal Events!

Prune Earlier Input..



Pruning Alters Internal Events!

Sequence Numbers Differ!



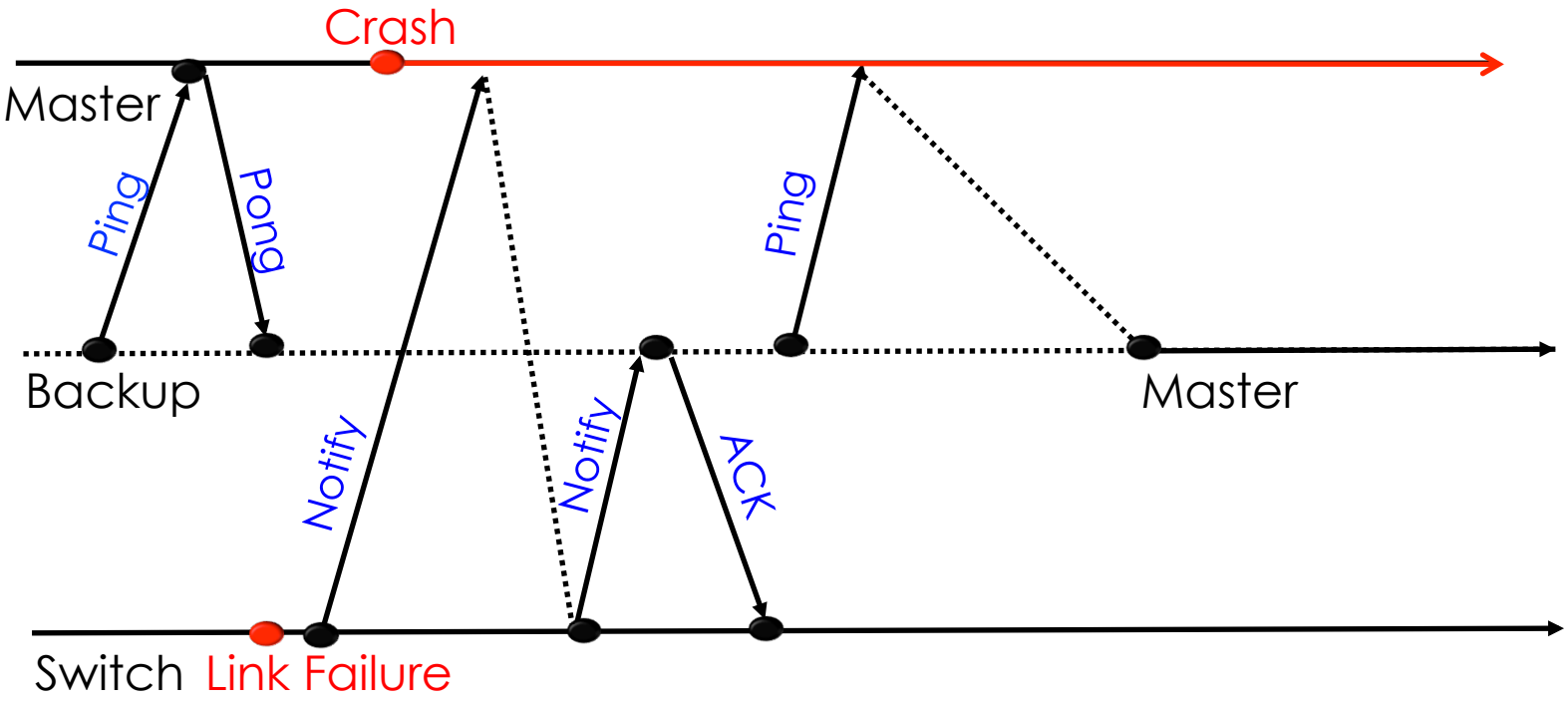
Solution: Equivalence Classes

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

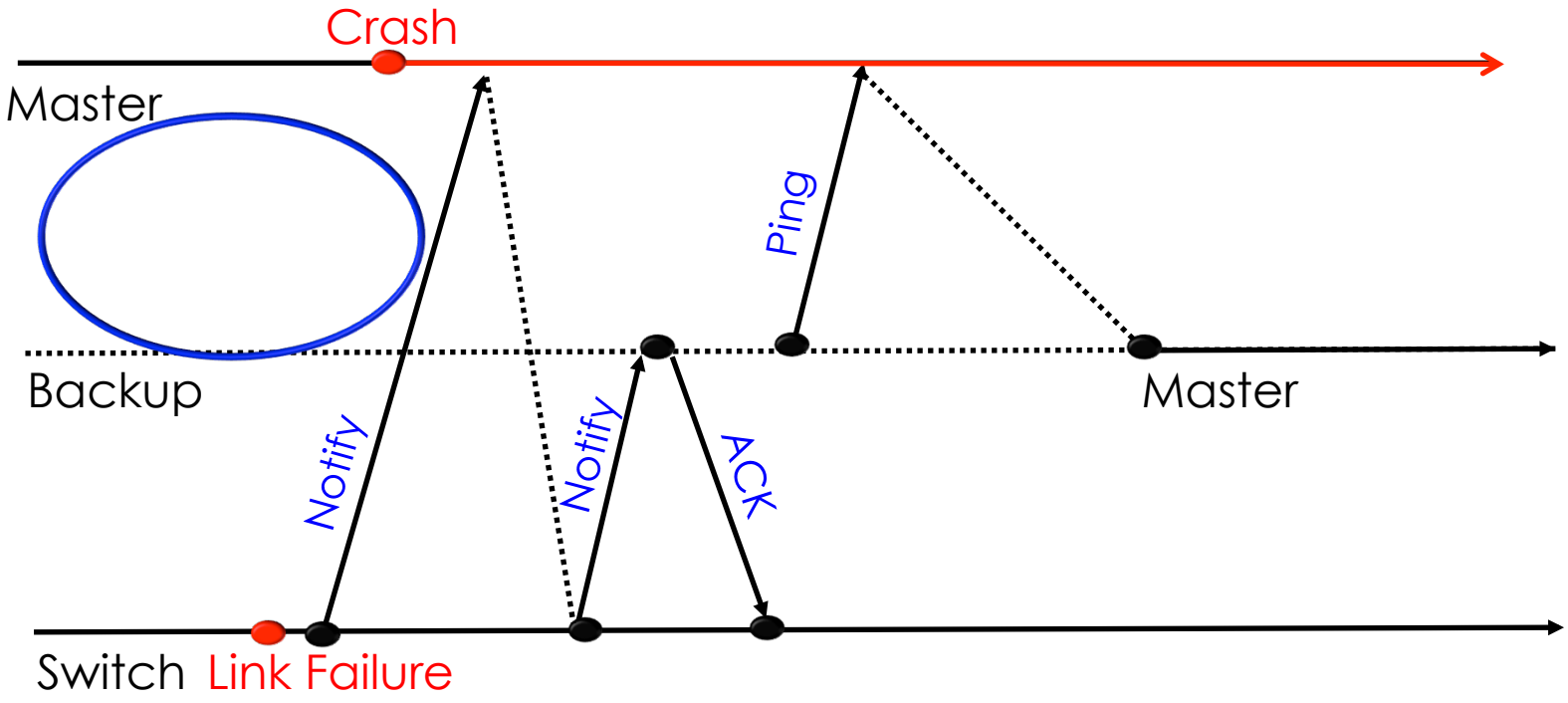
Pruning Alters Internal Events!

Prune Earlier Input..



Pruning Alters Internal Events!

Some Events No Longer Appear



Solution: Peek ahead

procedure PEEK(*input subsequence*)

$inferred \leftarrow [\,]$

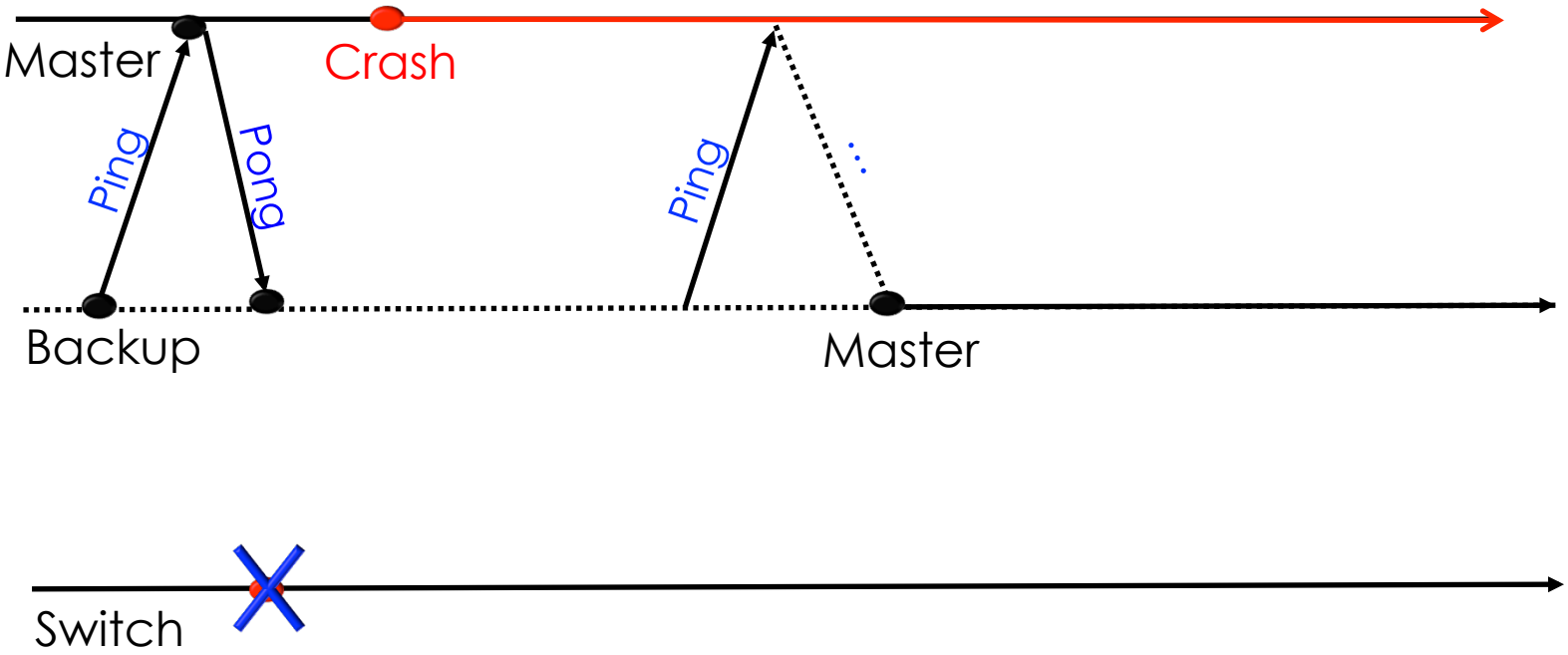
for e_i *in subsequence*

- $checkpoint\ system$
- $inject\ e_i$
- $\Delta \leftarrow |e_{i+1}.time - e_i.time| + \epsilon$
- $record\ events\ for\ \Delta\ seconds$
- $matched \leftarrow original\ events\ \&\ recorded\ events$
- $inferred \leftarrow inferred + [e_i] + matched$
- $restore\ checkpoint$

return $inferred$

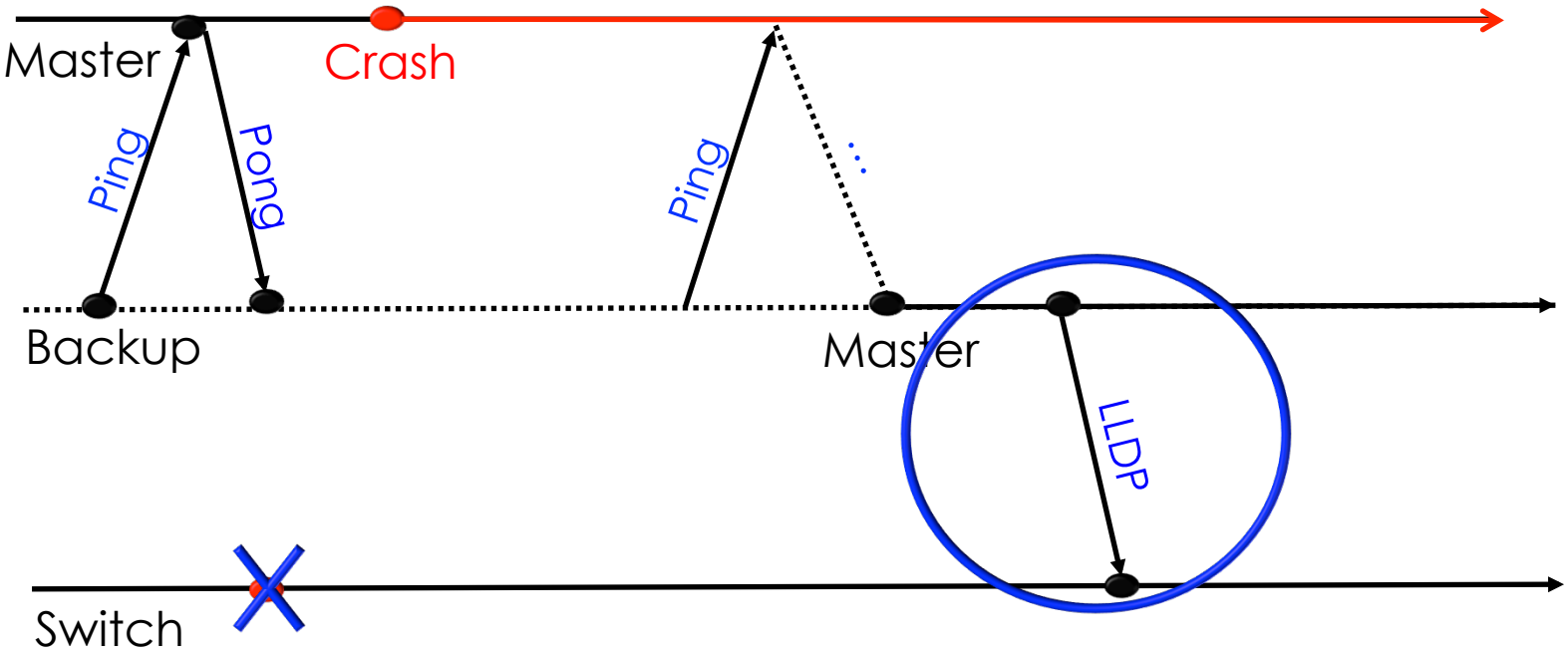
Pruning Alters Internal Events!

Prune Input..



Pruning Alters Internal Events!

Unexpected Events Appear



Dealing with unexpected events

Theory:

- Divergent paths → Exponential possibilities

Practice:

- Allow unexpected events through

Coping With Non-Determinism

- Replay multiple times per subsequence
- Probability of not finding bug modeled by:

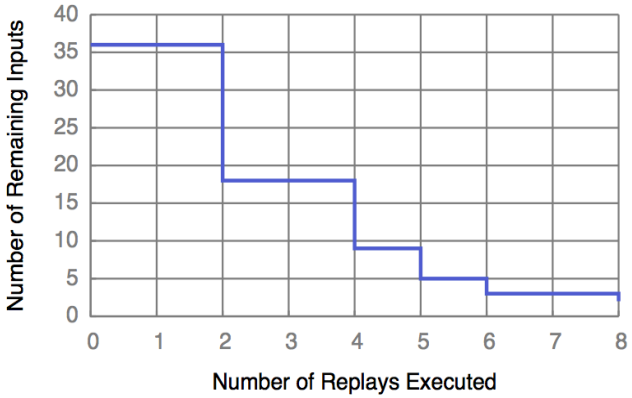
$$f(p,n) = (1-p)^n$$

- Optionally override gettimeofday(), multiplex sockets, interpose on logging statements

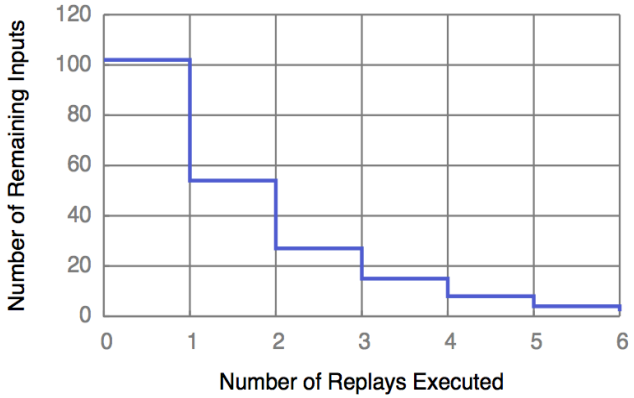
It Works!

	Bug Name	Topology	Runtime (s)	Input Size	MCS Size	MCS helpful?
Newly Found	Pyretic loop	3 switch mesh	266.2	36	2	Yes
	POX premature PacketIn	4 switch mesh	249.1	102	2	Yes
	POX in-flight blackhole	2 switch mesh	641.1	46	7	Yes
	POX migration blackhole	4 switch mesh	1796.0	29	3	Yes
	NOX discovery loop	4 switch mesh	4990.9	150	18	Indirectly
	Floodlight loop	3 switch mesh	27930.6	117	13	Yes
	ONOS distributed database locking	2 switch mesh	N/A	1	1	N/A
Known	Floodlight failover bug	2 switch mesh	-	202	2	Yes
	ONOS master election	2 switch mesh	6325.2	30	3	Yes
	POX load balancer error checking	3 switch mesh	2396.7	106	24 (N+1)	Yes
Synthetic	Null pointer on rarely used codepath	20 switch FatTree	2396.7	365	2	Yes
	Overlapping flow entries	2 switch mesh	115.4	27	2	Yes
	Delicate timer interleaving	3 switch mesh	N/A	39	39	No
	Algorithm misimplementation	3 switch mesh	525.2	40	7	Indirectly
	Multithreaded race condition	10 switch mesh	36967.5	1596	2	Indirectly
	Memory leak	2 switch mesh	15022.6	719	30 (M)	Indirectly
	Memory corruption	4 switch mesh	145.7	341	2	Yes

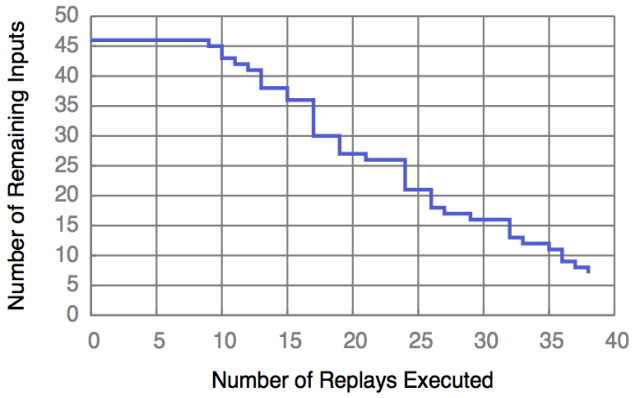
It Works!



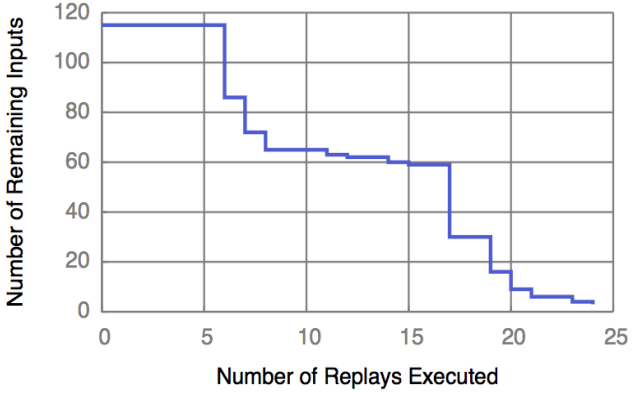
(a) Pyretic loop.



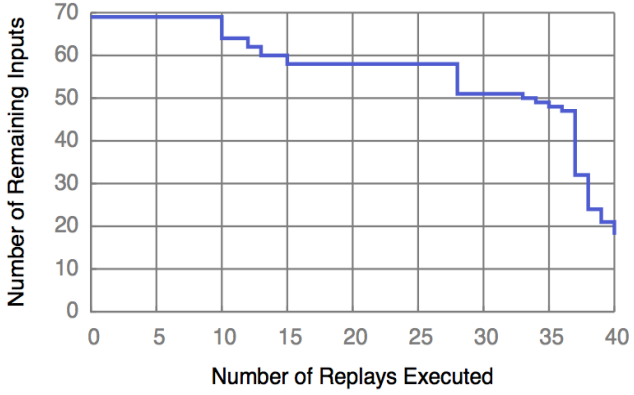
(b) POX Premature Packet-In Failure.



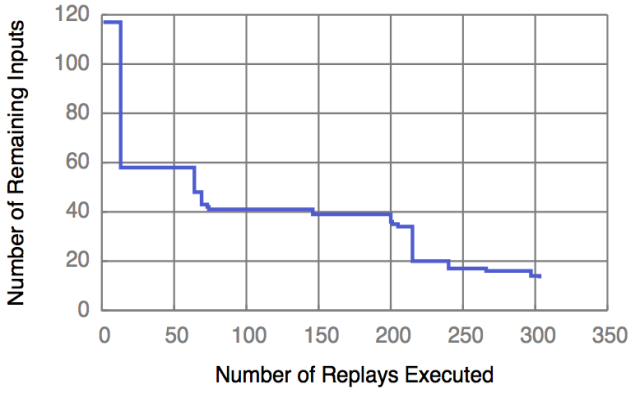
(c) POX in-flight blackhole.



(d) POX migration blackhole.



(e) NOX discovery loop.



(f) Floodlight loop.

Summary

- Goal: isolate minimal causal sequences
- We built a real system (21K+ lines of Python) that works on real controllers (Floodlight, NOX, POX, Frenetic, ONOS) including one proprietary controller
- Check us out:

ucb-sts.github.com/sts/

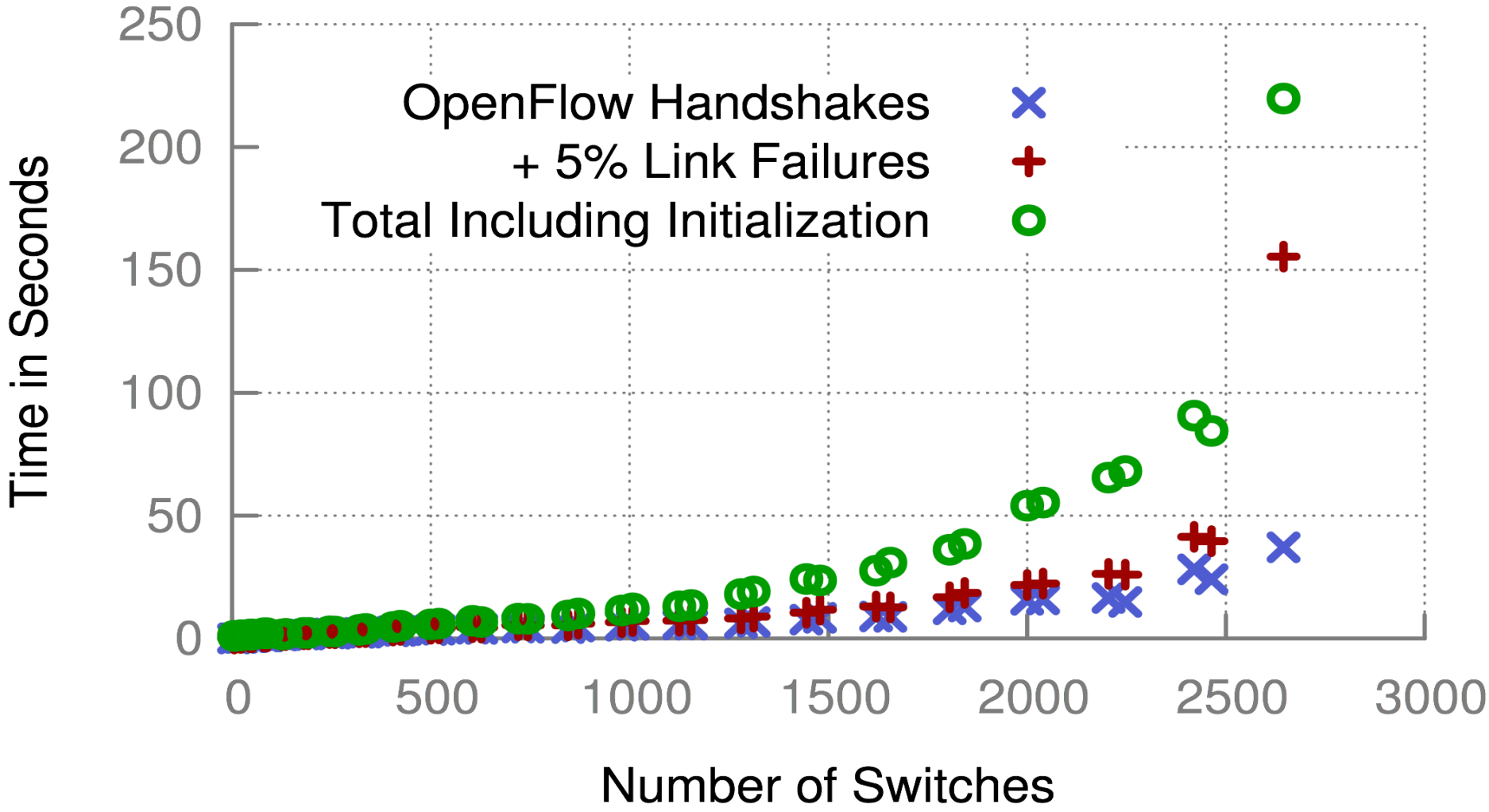
References

- [1] V. Soundararajan and K. Govil. Challenges in building scalable virtualized datacenter management. SIGOPS Operating Systems Review '10.

- [2] A. Greenberg, J. R. Hamilton, N. Jain, S. Kandula, C. Kim, P. Lahiri, D. A. Maltz, P. Patel, and S. Sengupta. VL2: a scalable and flexible data center network, Sec. 3.4. SIGCOMM '09.

Backup

Scalability



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*

$$P \oplus C \neq ?$$

Coping With Non-determinism

Results for synthetic multithreading bug in Floodlight

Max replays per subsequence	**Size of final MCS**	**Total hours**
1	65	6.10
2	20	6.37
3	15	7.78
4	12	9.59
5	9	6.38
6	9	11.20
7	9	11.83
8	6	12.35
9	6	11.13
10	6	12.86

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

Related Work

- Delta Debugging
- Program Flow Analysis
- Instrumentation (Tracing)
- Bug Detection (Invariant Checking, Model Checking)
- Replay
- Root Cause Analysis

Instrumentation Complexity

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

Future Work

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