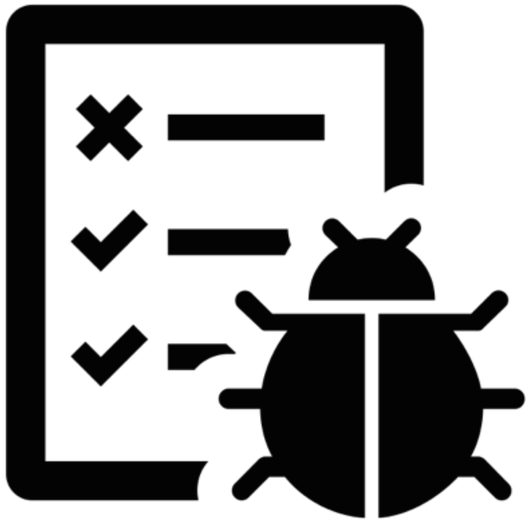
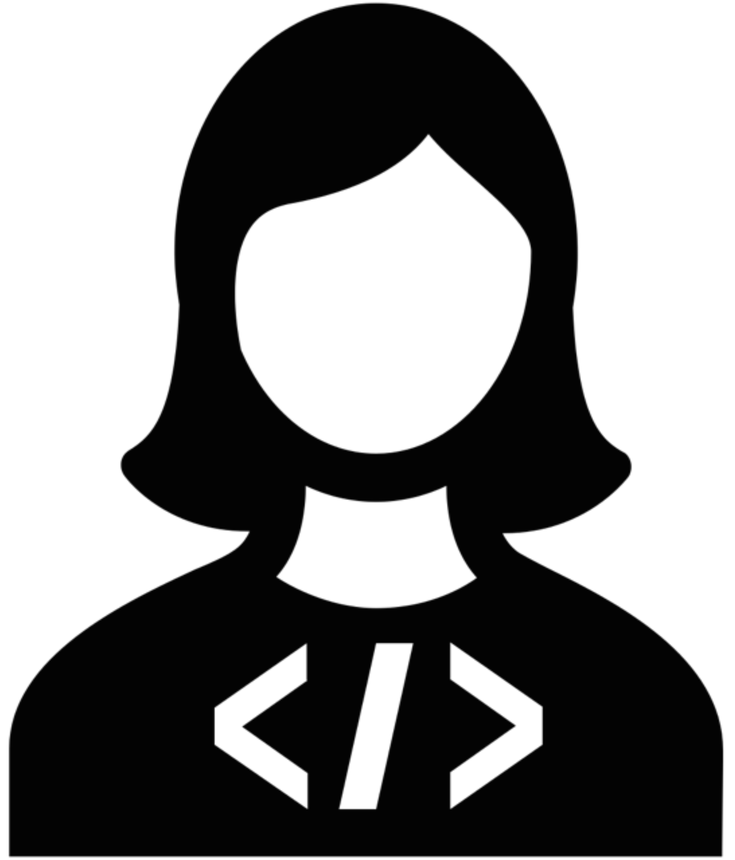
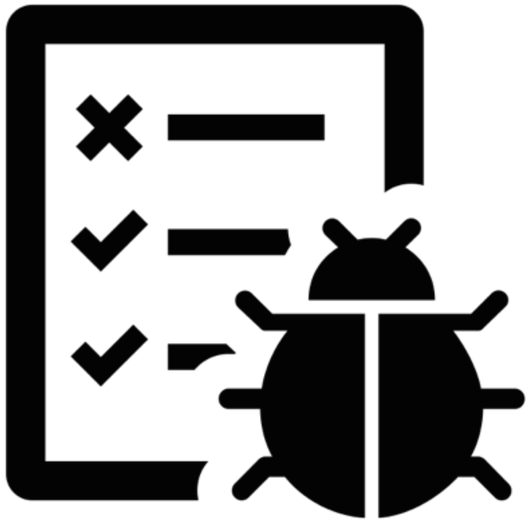
Minimizing Faulty Executions of Distributed Systems

Colin Scott, Aurojit Panda, Vjekoslav Brajkovic, George Necula,
Arvind Krishnamurthy, Scott Shenker





Software Developer



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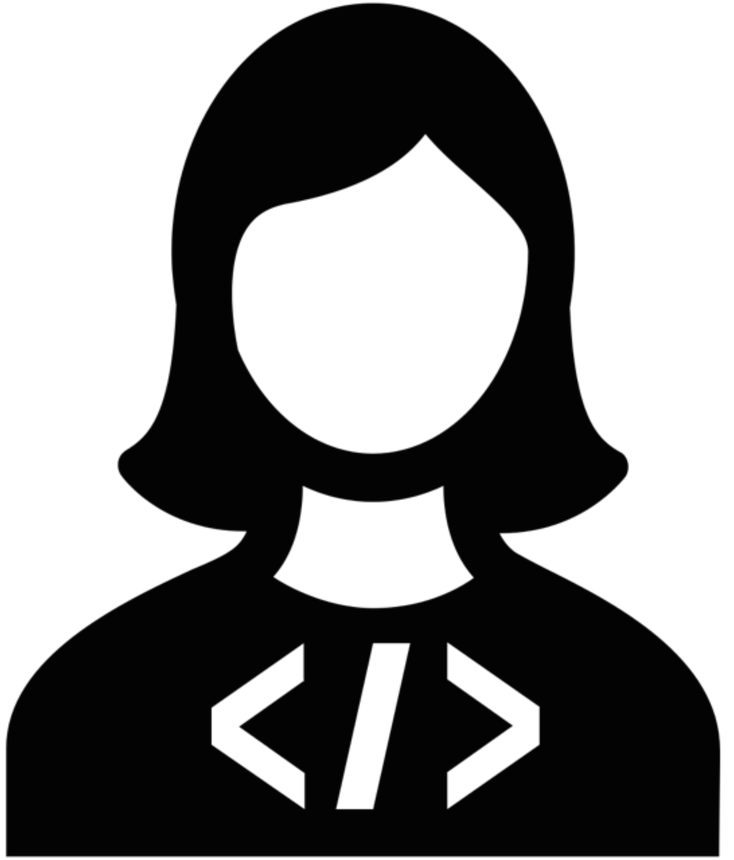

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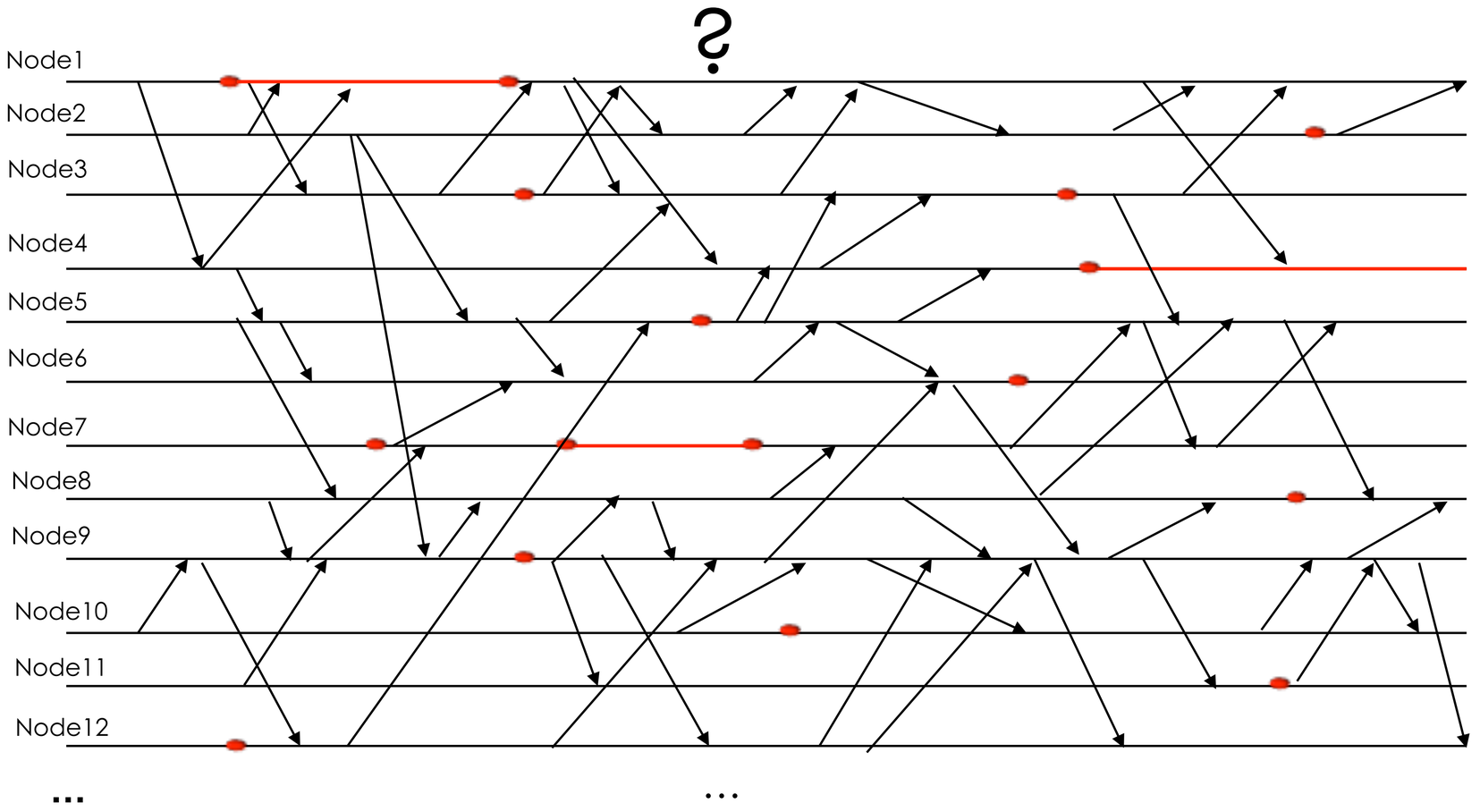
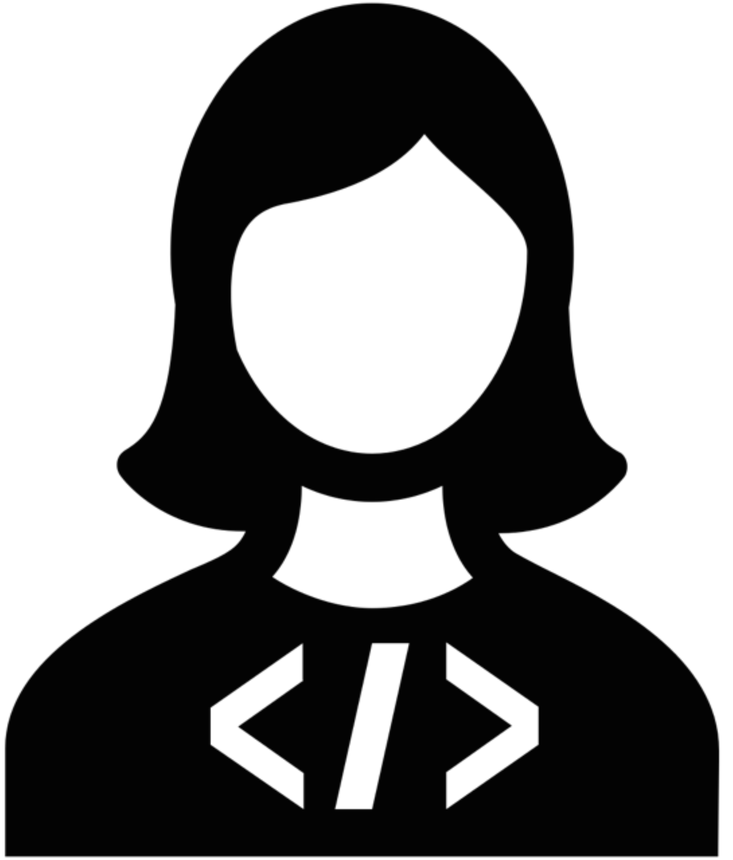
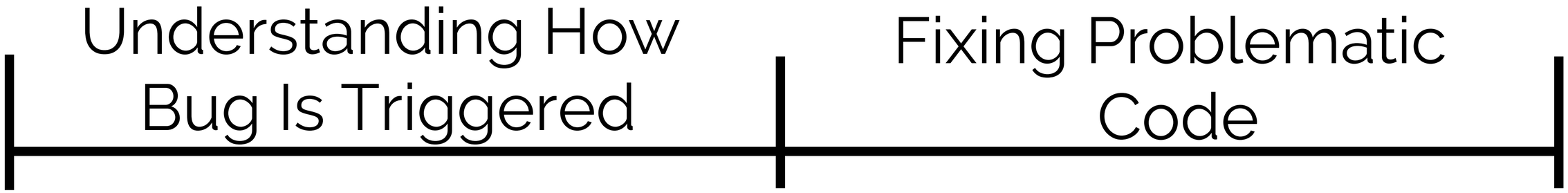




Software Developer

~49% of developers' time spent on debugging![1]



[1] LaToza, Venolia, DeLine, ICSE' 06

Our Goal

Allow Developers To Focus on Fixing the Underlying Bug

Problem Statement

Identify a **minimal causal sequence** of events that triggers the bug

Why Minimization?

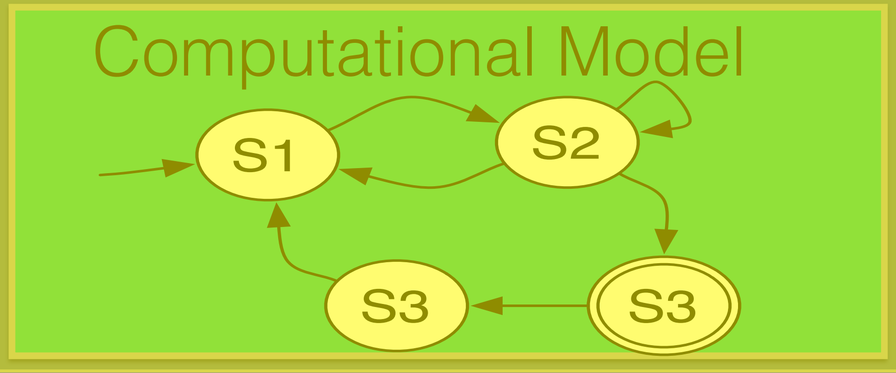
Smaller event traces are easier to understand

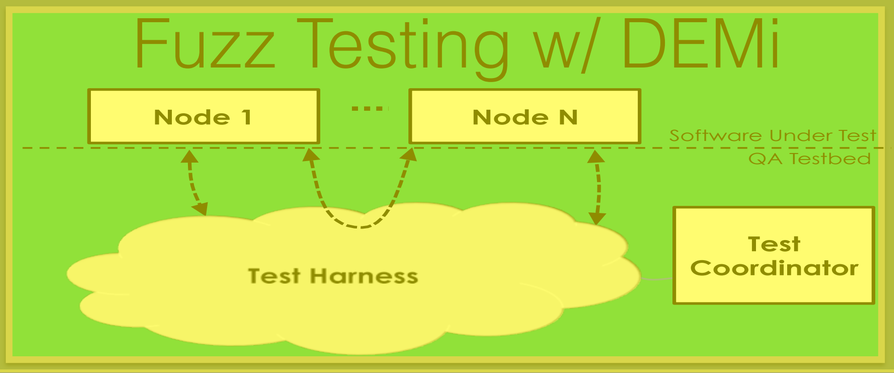
G. A. Miller. The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information. Psychological Review ’56.

Outline

Introduction

Background



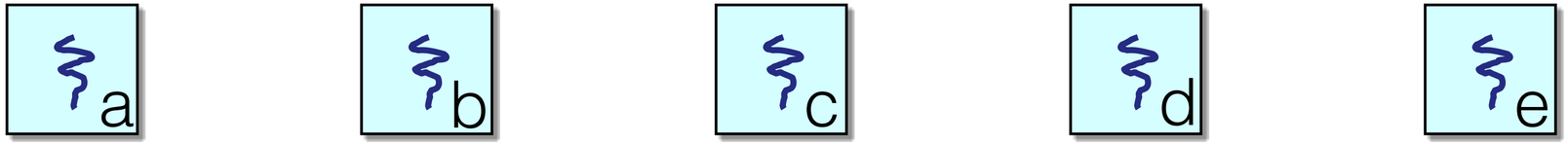


Minimization

Evaluation

Conclusion

Computational Model

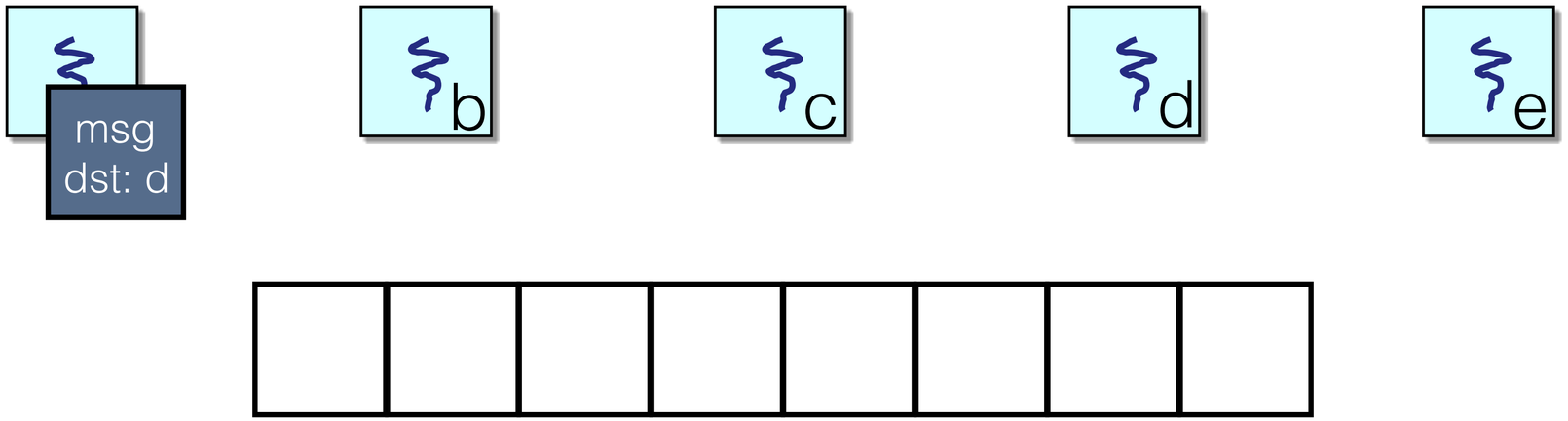


Distributed System: Collection of N processes

Each process p:

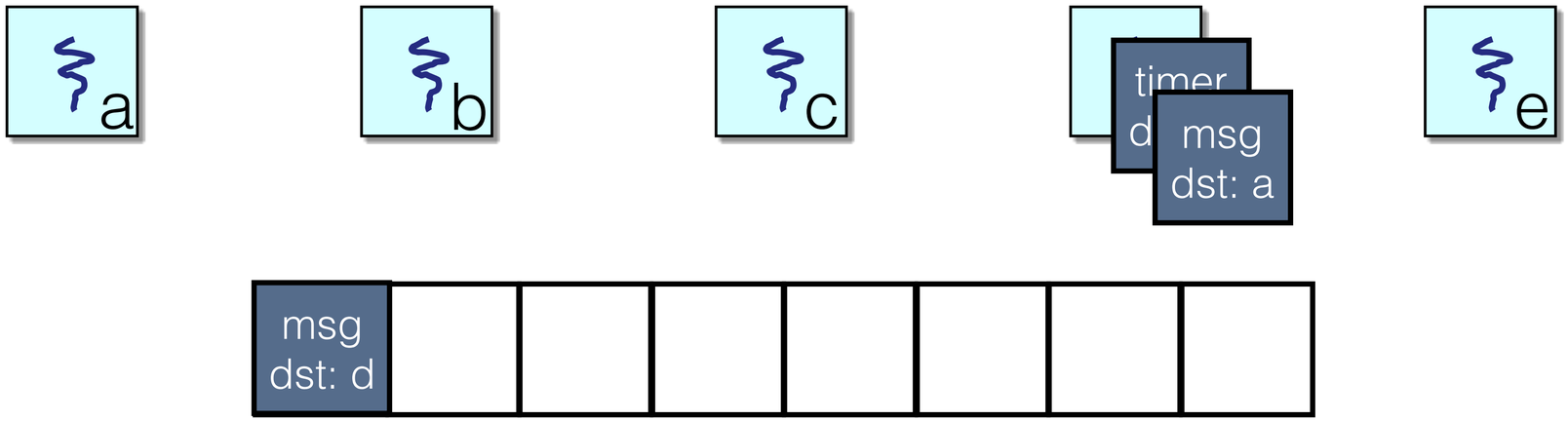
- Has unbounded memory
- Starts in a known initial state
- Changes states deterministically

Computational Model



The network maintains a buffer of sent but not yet delivered messages

Computational Model

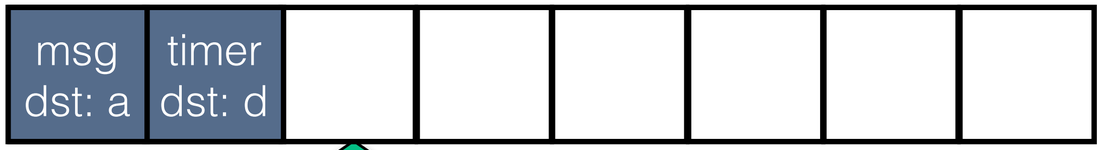


Message deliveries occur one at a time:

- destination enters a new state according to old state & message
- destination sends a finite set of messages to other processes*

*May include timer messages to be delivered to itself later

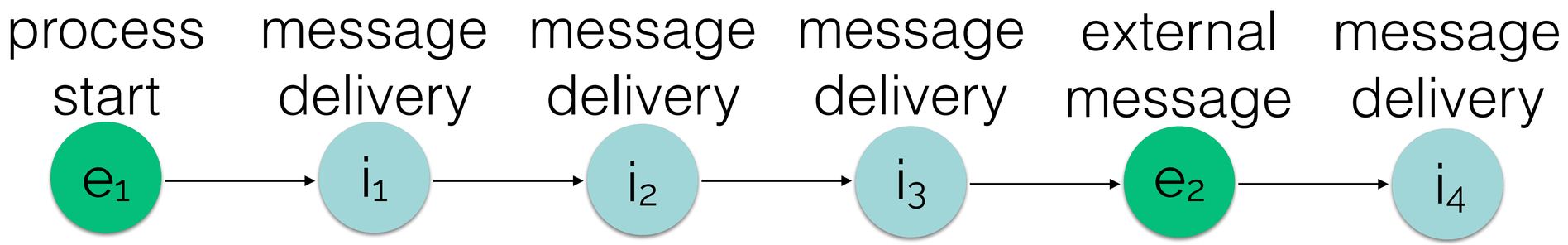
Computational Model



Steps may also be *external:*

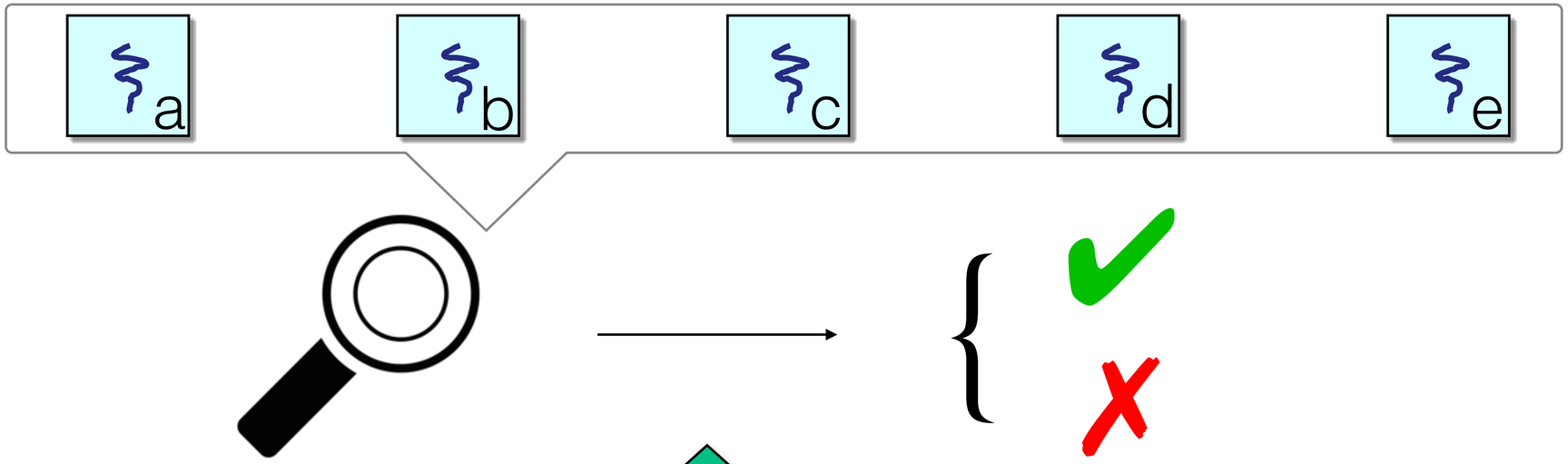
- External message is sent
- Process is created
- Process crash-recovers

Computational Model



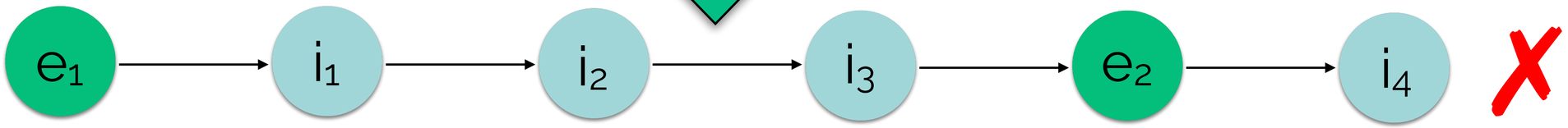
A schedule τ is a sequence of events (either external or internal message deliveries) that can be applied in turn starting from the initial configuration.

Invariant Checking



An invariant is a predicate *P* over the state of all processes.

A faulty execution is one that ends in an invariant violation.



Formal Problem Statement

Given: schedule τ that results in violation of P

Find: schedule τ' s.t.

- τ' violates P, $|\tau'| \leq |\tau|$
- τ' contains a subsequence of the external events of τ
- if we remove any external event e from τ',
- $\neg\exists\ \tau''$ containing same external events - e, s.t. τ'' violates P

Formal Problem Statement

After finding τ':

- remove extraneous message deliveries from τ'

Outline

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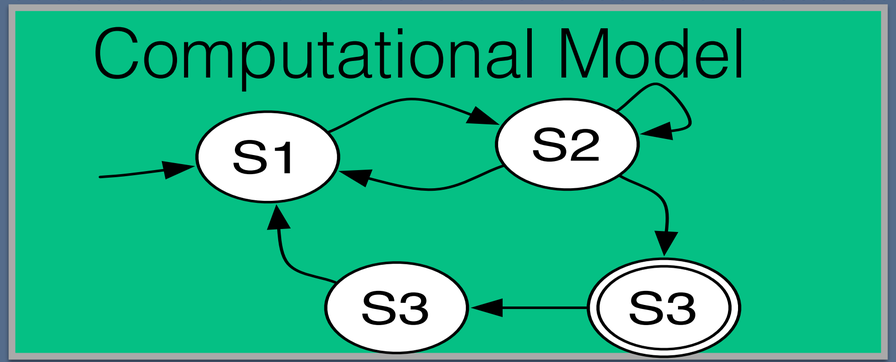
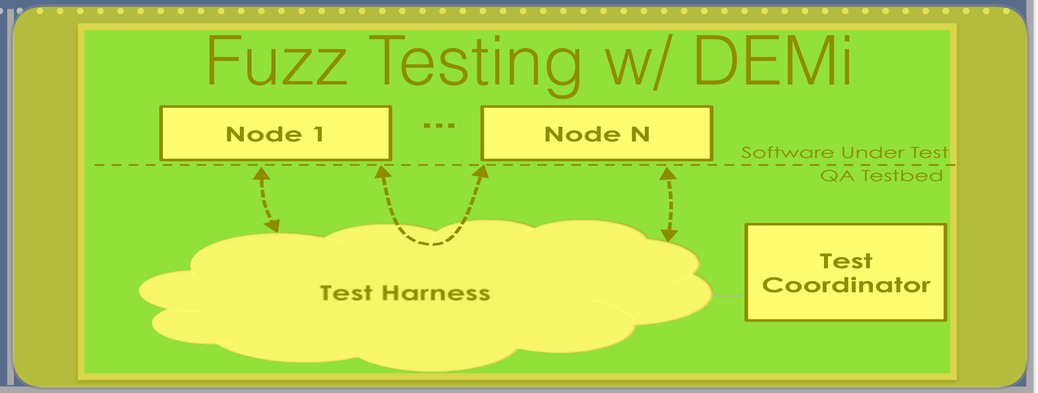
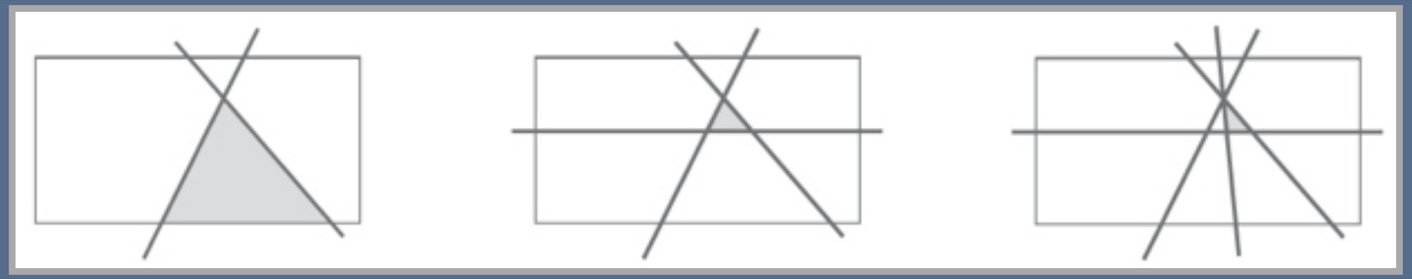
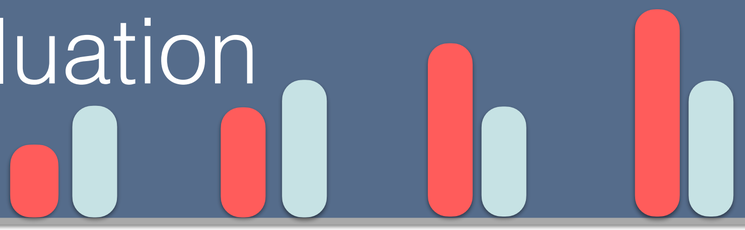




Minimization

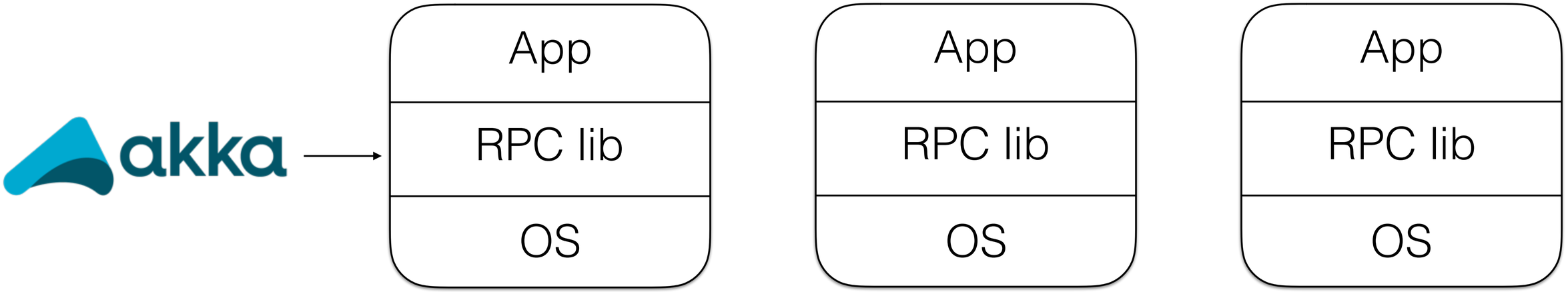


Evaluation



Conclusion

Fuzz Testing with DEMi



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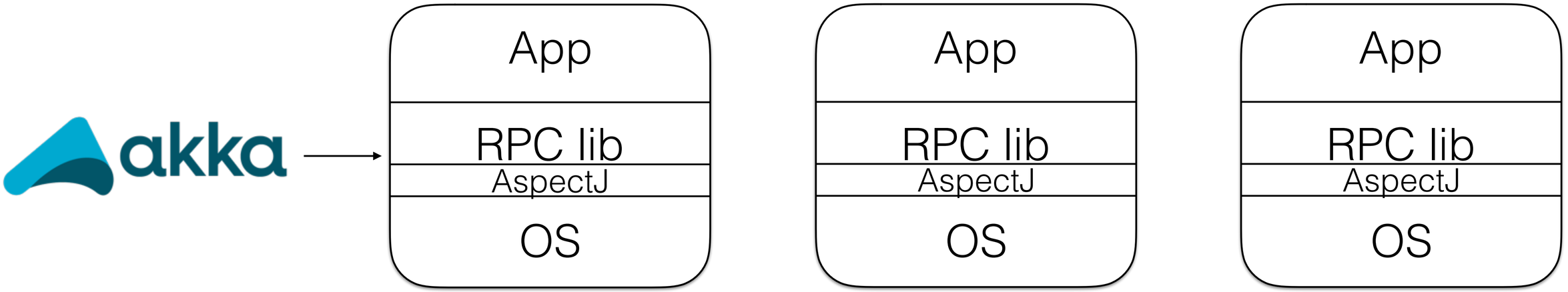

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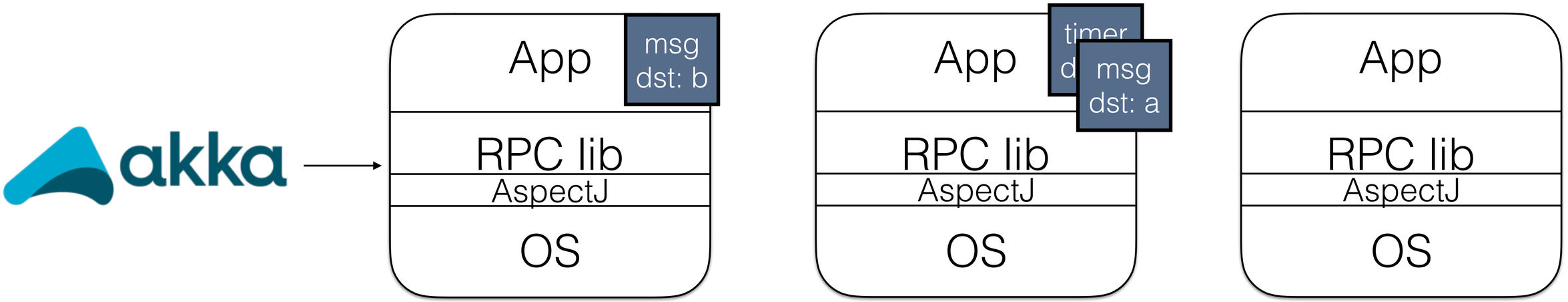

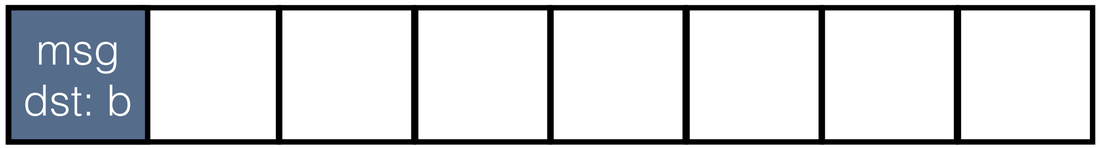

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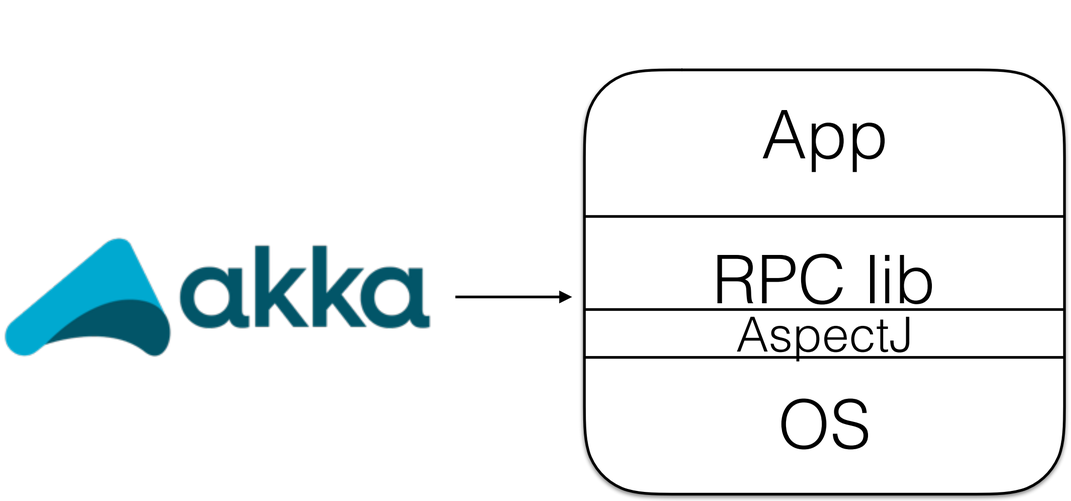

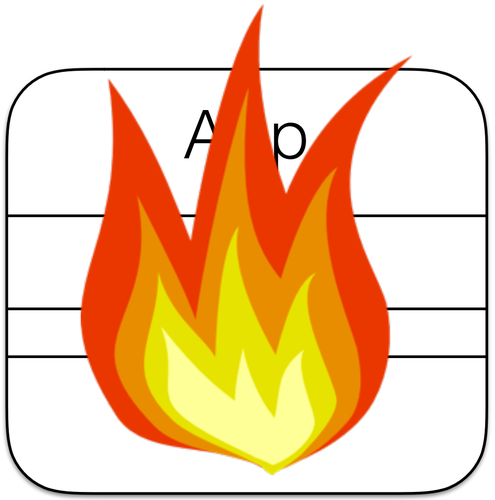

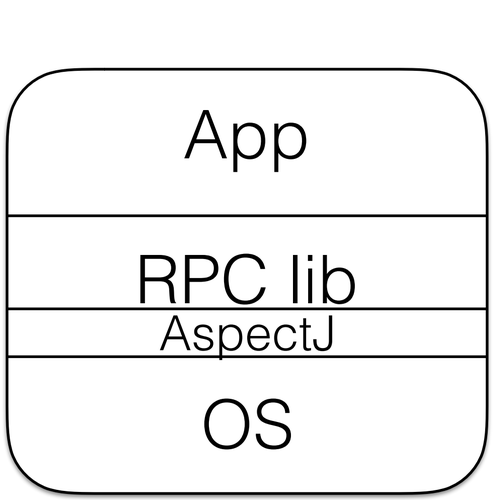

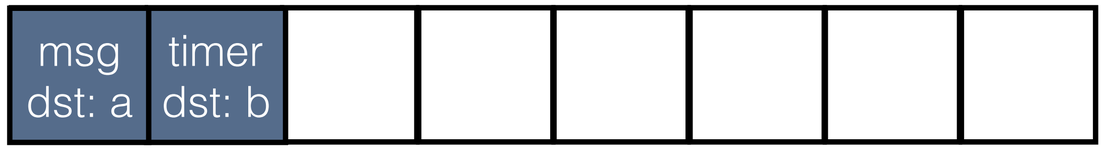

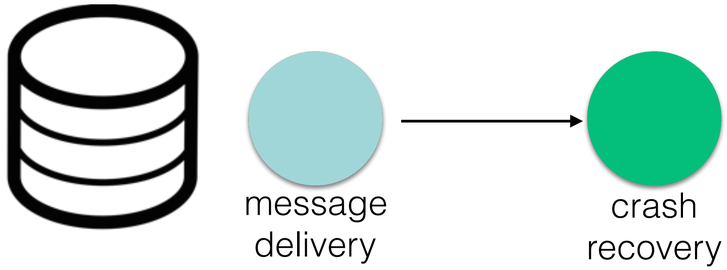

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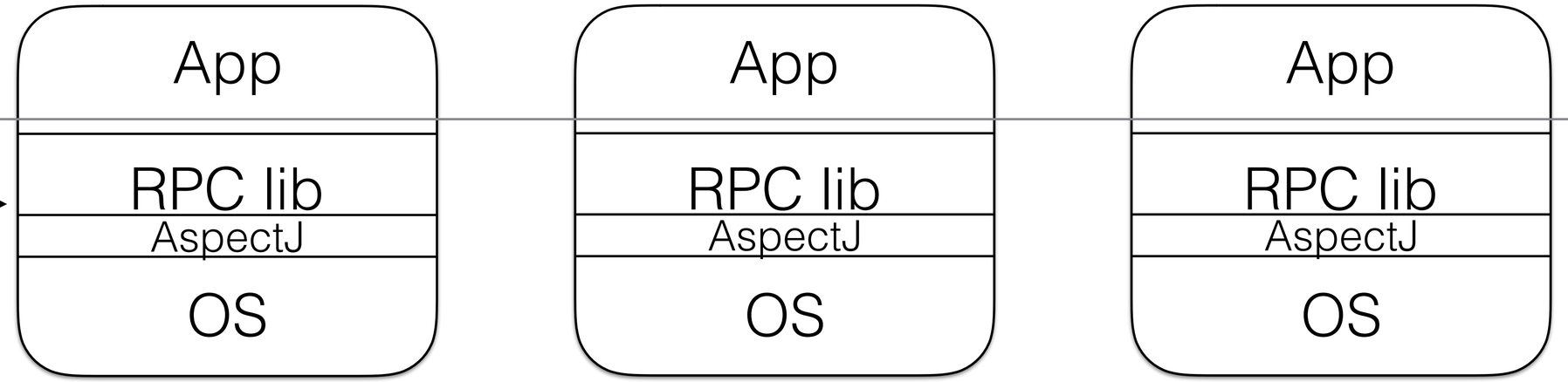

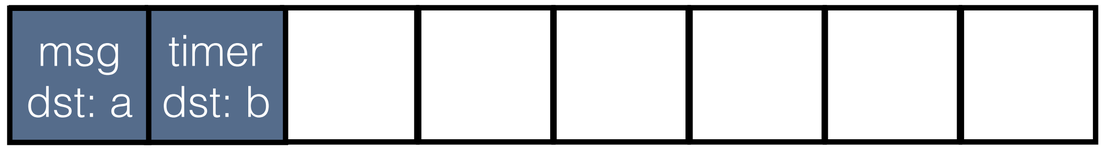

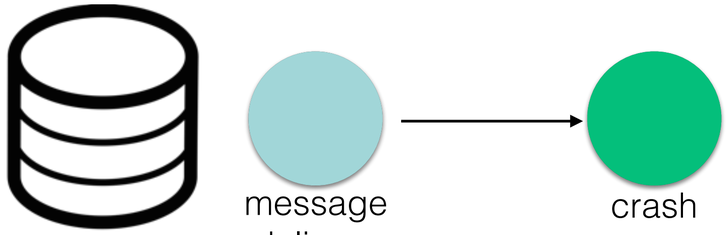

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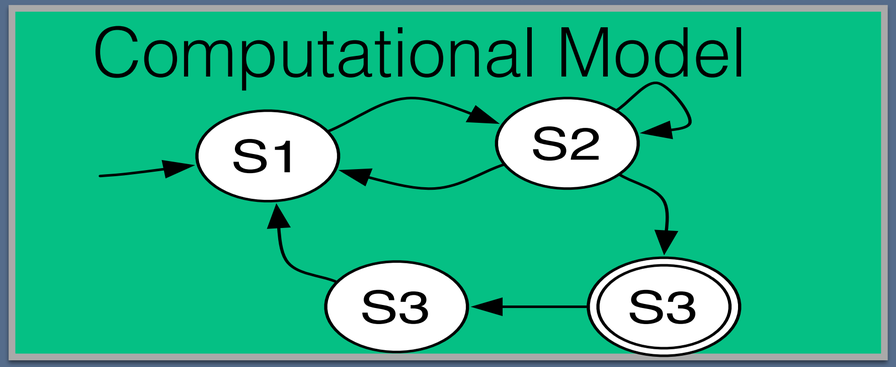

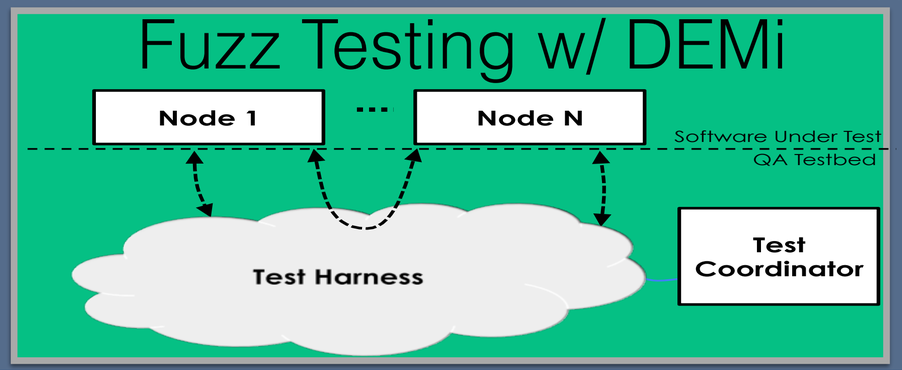

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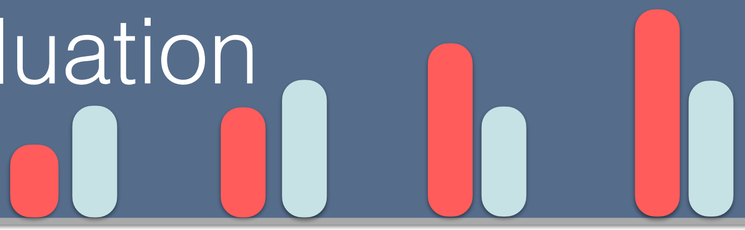


Conclusion

Running Example: Raft Consensus

client request

votes: {a,b,c}

client request

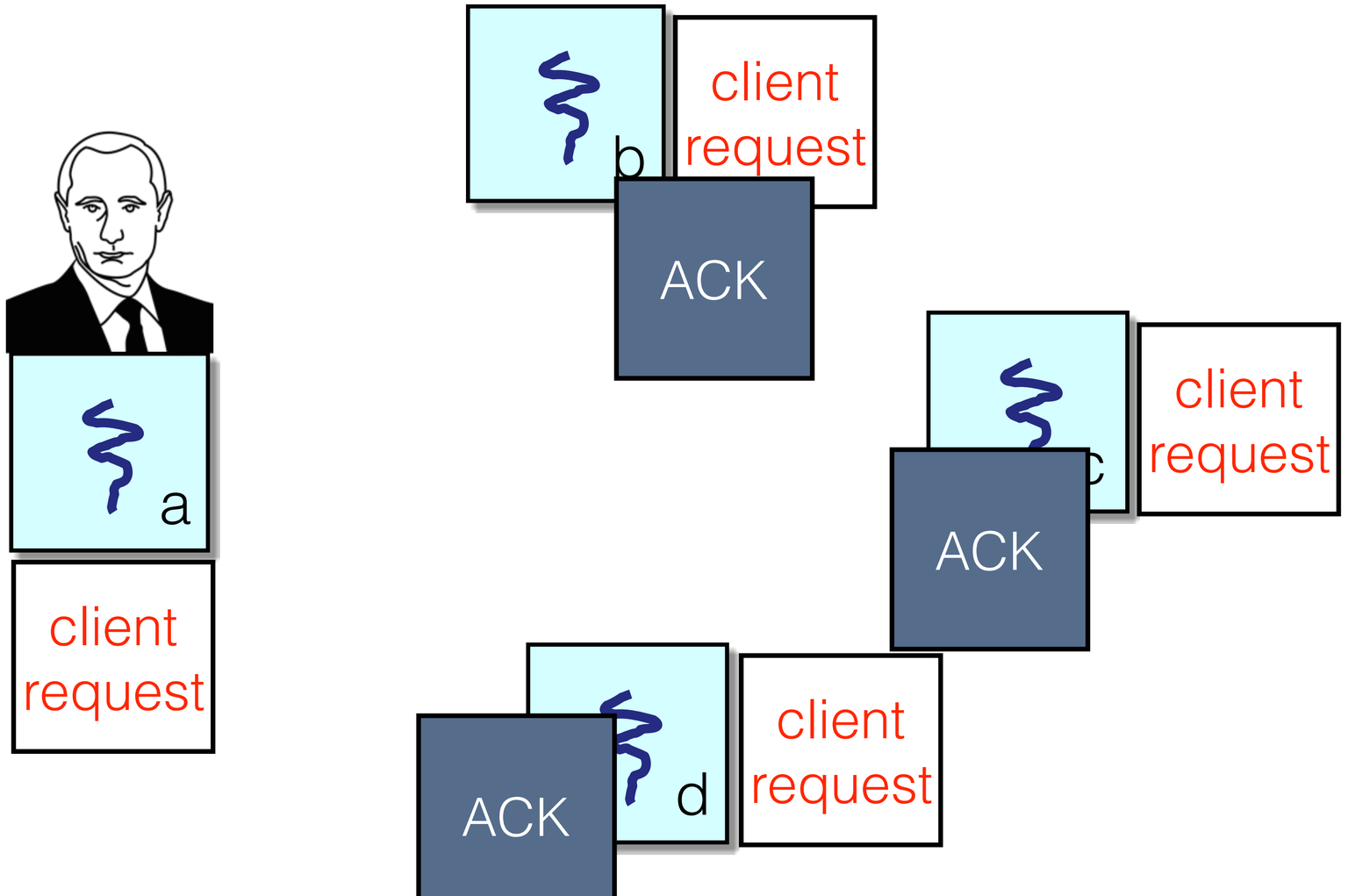
client request

b

c

d

Running Example: Raft Consensus



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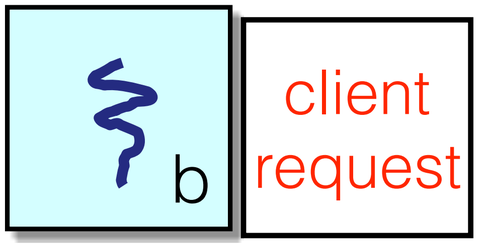

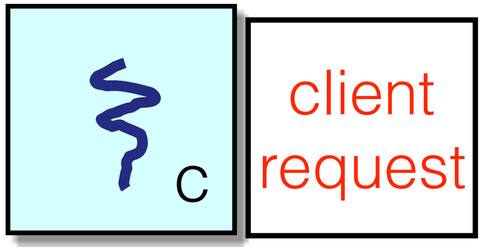

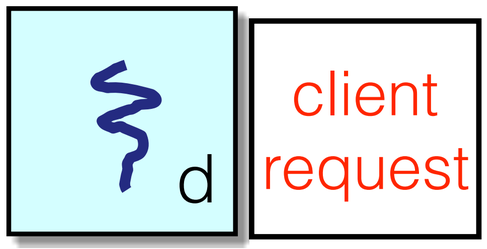

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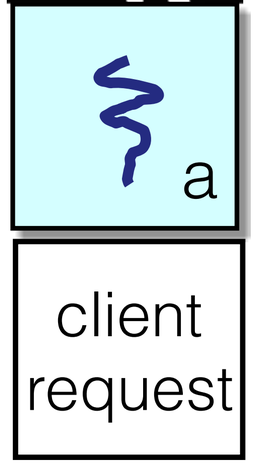

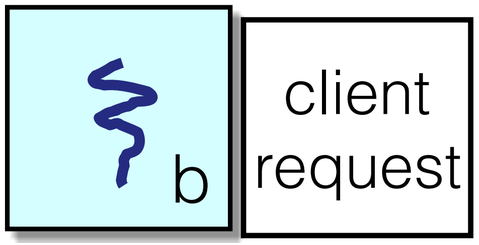

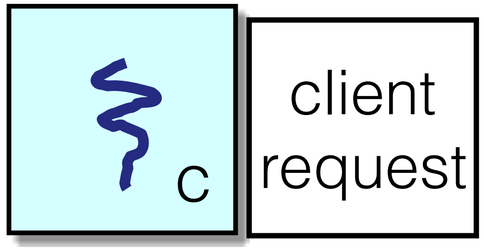

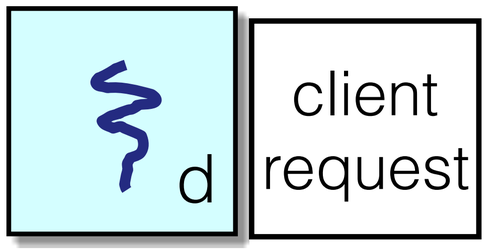

Log lines | Motifs

```
Sending to raft-member-4: RequestVote(Te
Sending to raft-member-2: BeginElection

Received message from raft-member-3: Req
Received timer: Timer(election-timer,Ele
Received message from raft-member-2: Beg

Sending to raft-member-3: VoteCandidate(
Sending to raft-member-3: BeginElection
Sending to raft-member-1: RequestVote(Te

Received message from raft-member-4: Vot
25 Received message from raft-member-2: R
   equestVote(Term(2),Actor[akka://new-sy
   stem-0/user/raft-member-2#-69475157
   3],Term(0),0)
Rec
Sending to raft-member-2: VoteCandidate(

Sending to raft-member-4: RequestVote(Te
Received message from raft-member-1: Vot
Received timer: Timer(election-timer,Ele

Received message from raft-member-3: Req
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Received message from raft-member-2: Req

Sending to raft-member-2: VoteCandidate(

Received message from raft-member-1: Vot
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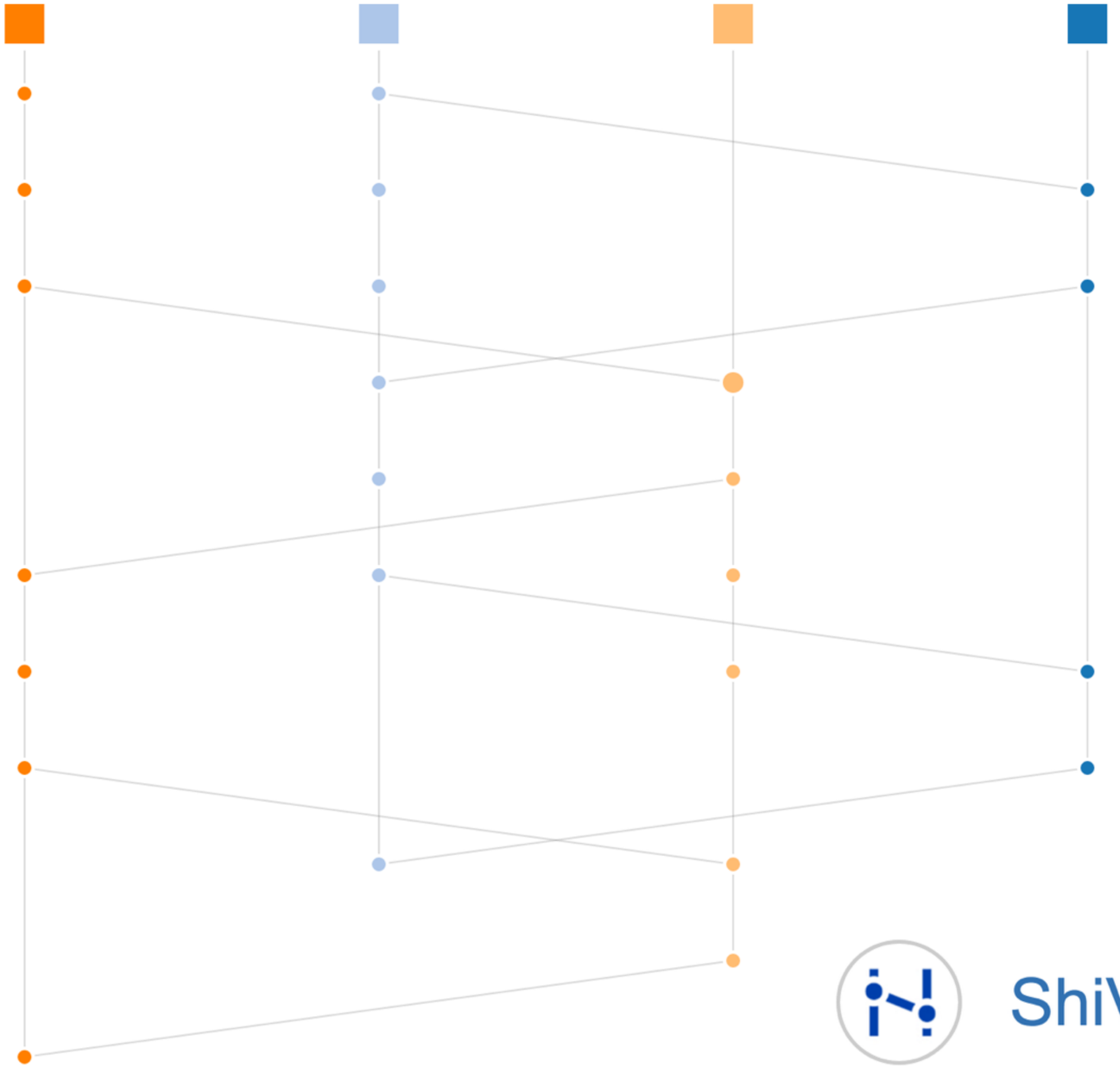
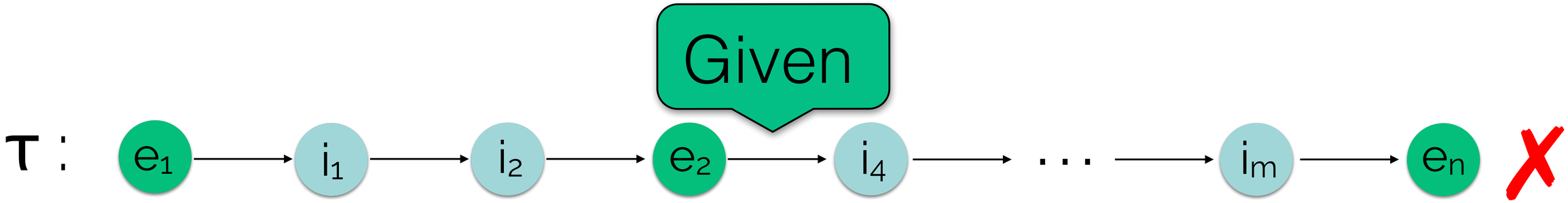


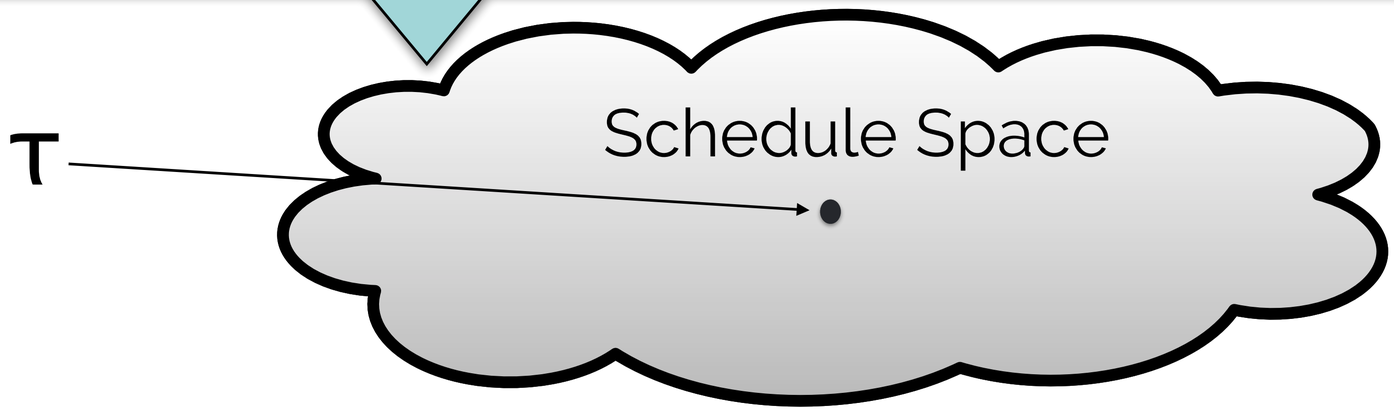
ShiViz

Minimization



Straightforward approach:

- Enumerate all schedules $|\tau'| \leq |\tau|$,
- Pick shortest sequence that reproduces ✗



$$O(n!)$$

Observation #1: many schedules are commutative

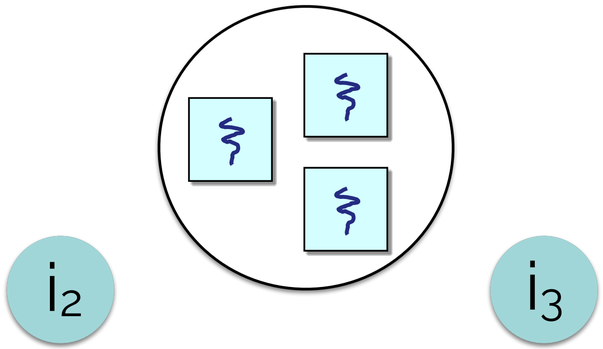
i_2

i_3

- $i_2 \nrightarrow i_3$
- $i_3 \nrightarrow i_2$
- $dst(i_2) \neq dst(i_3)$

Observation #1: many schedules are commutative

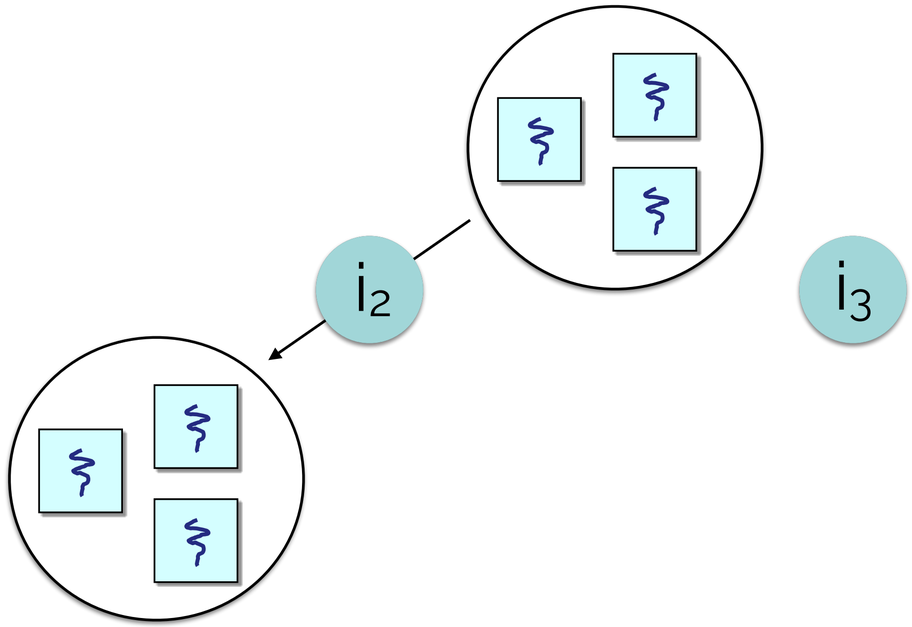
Step n:



- $i_2 \nrightarrow i_3$
- $i_3 \nrightarrow i_2$
- $dst(i_2) \neq dst(i_3)$

Observation #1: many schedules are commutative

Step n:



Step n+1:

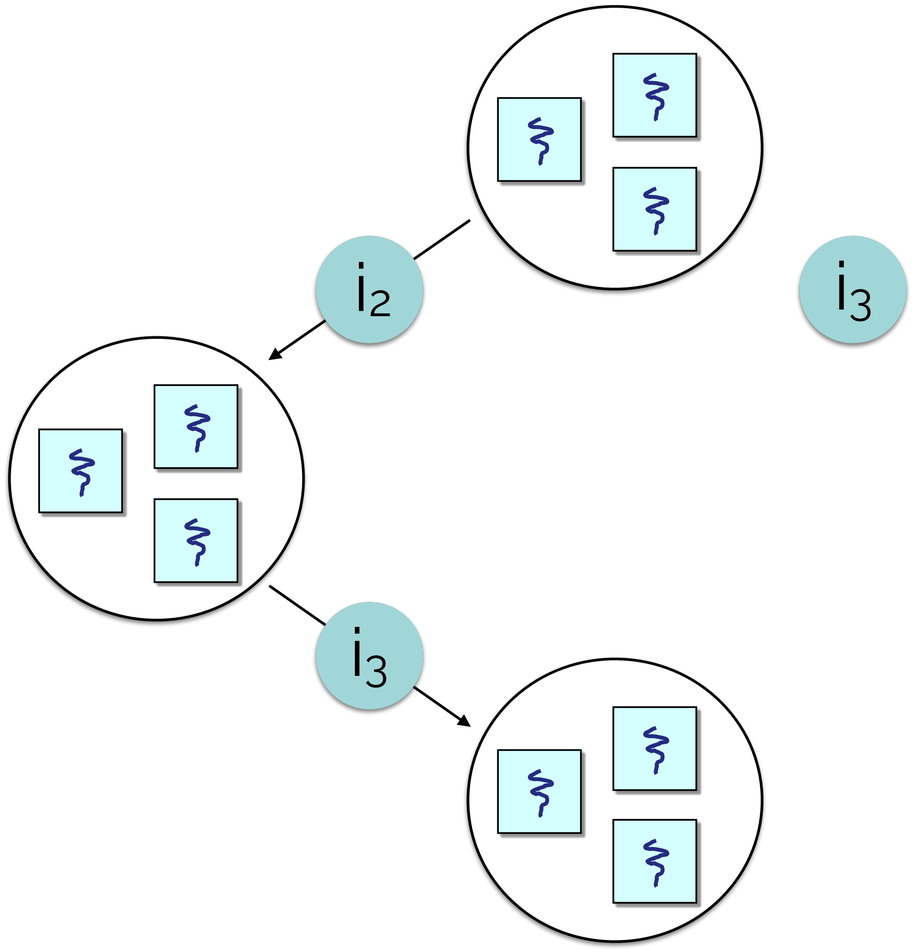
- $i_2 \nrightarrow i_3$
- $i_3 \nrightarrow i_2$
- $dst(i_2) \neq dst(i_3)$

Observation #1: many schedules are commutative

Step n:

Step n+1:

Step n+2:



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Step n:

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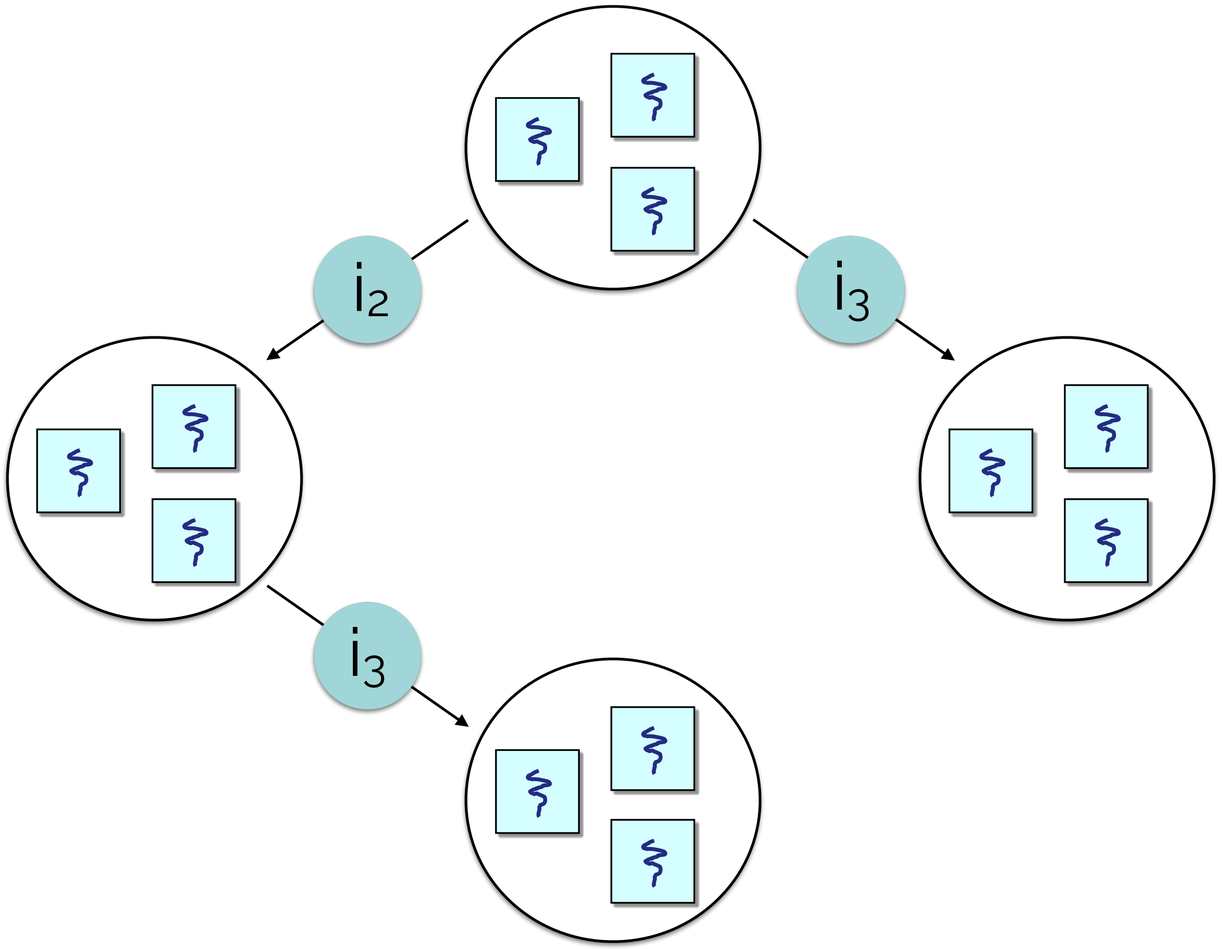

- $i_2 \nrightarrow i_3$
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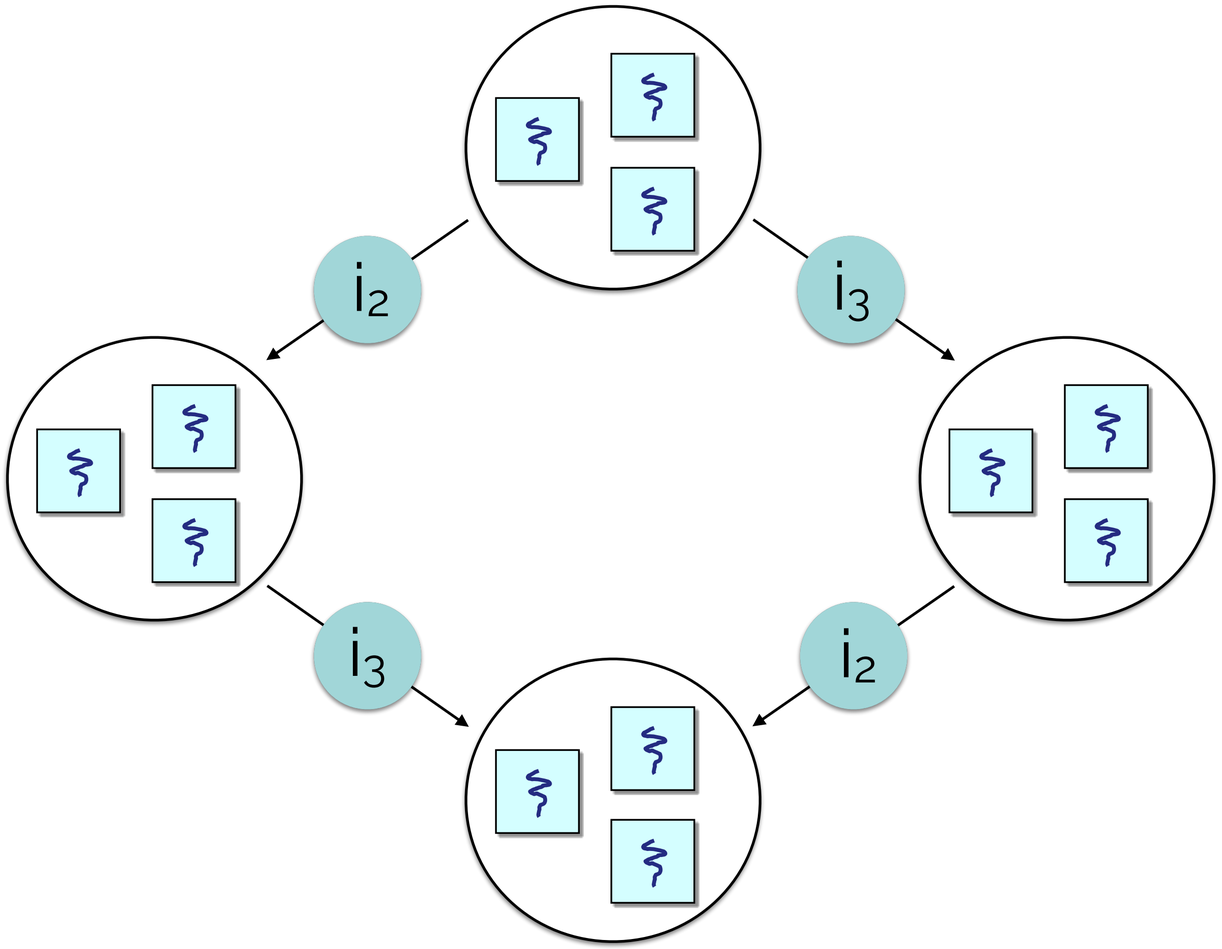
Observation #1: many schedules are commutative

Step n:

Step n+1:

Step n+2:

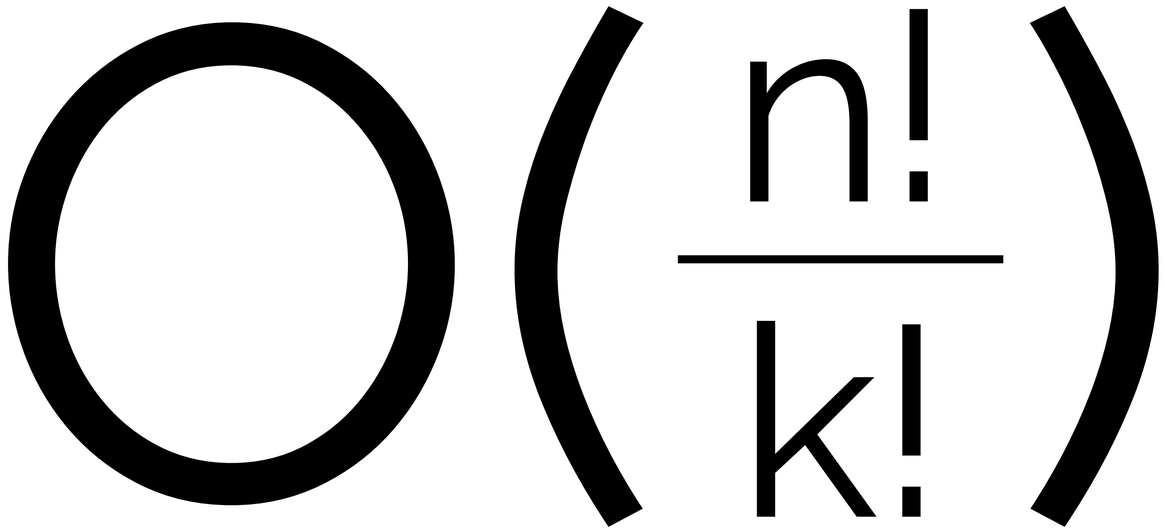


- $i_2 \nrightarrow i_3$
- $i_3 \nrightarrow i_2$
- $dst(i_2) \neq dst(i_3)$

Observation #1: many schedules are commutative

Adopt DPOR:
Dynamic **P**artial **O**rder **R**eduction

C. Flanagan, P. Godefroid, “Dynamic Partial-Order Reduction for Model Checking Software”, POPL ‘05


O(n!/k!)

Approach: prioritize schedule space exploration

Assume: fixed time budget
Objective: quickly find small failing schedules

Given:

- Prioritization function

Given:

- Prioritization function

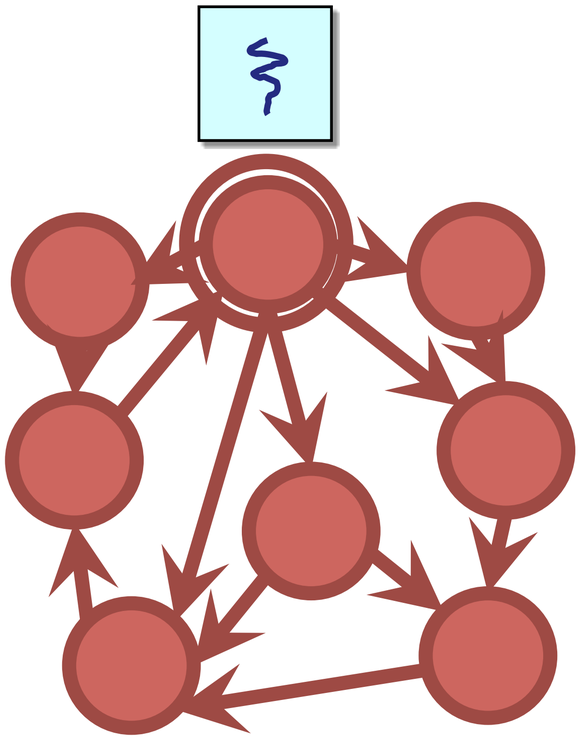
Produce:

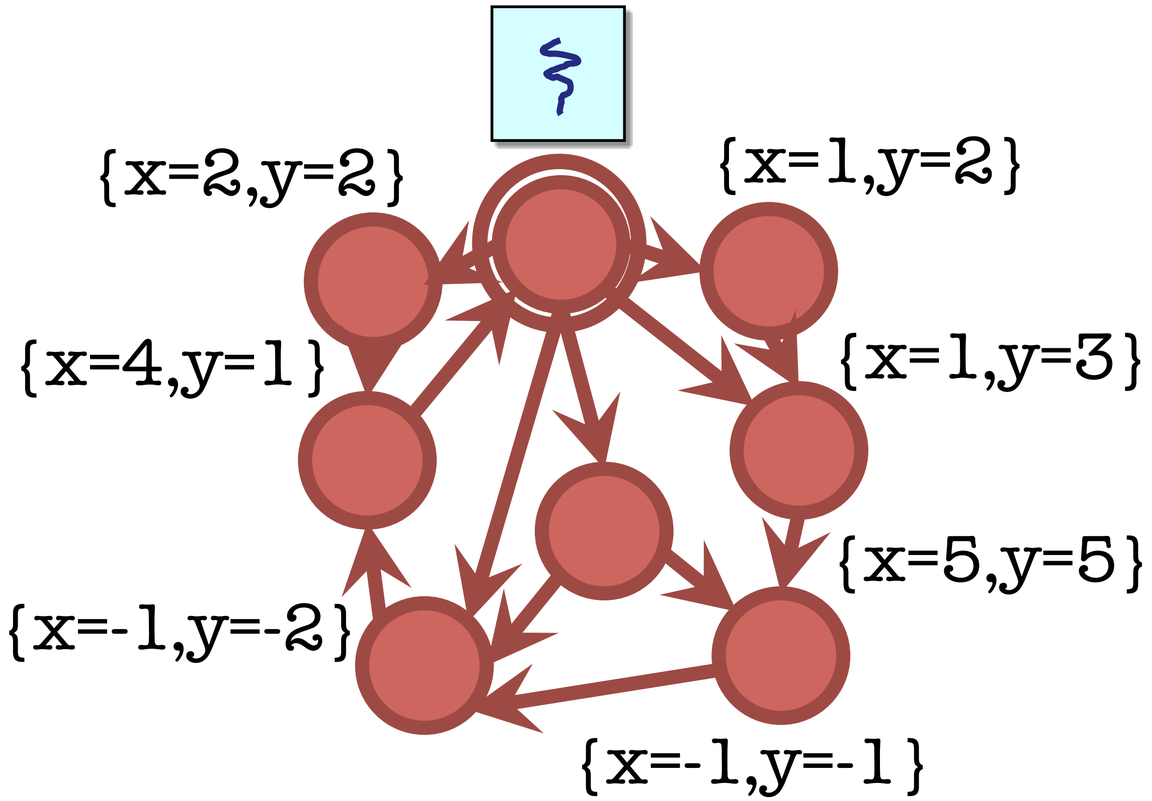
- Program under test
- Initial execution

s.t. prioritization makes scant progress

Conjecture:

Systems we care about exhibit **program properties** amenable with prioritization

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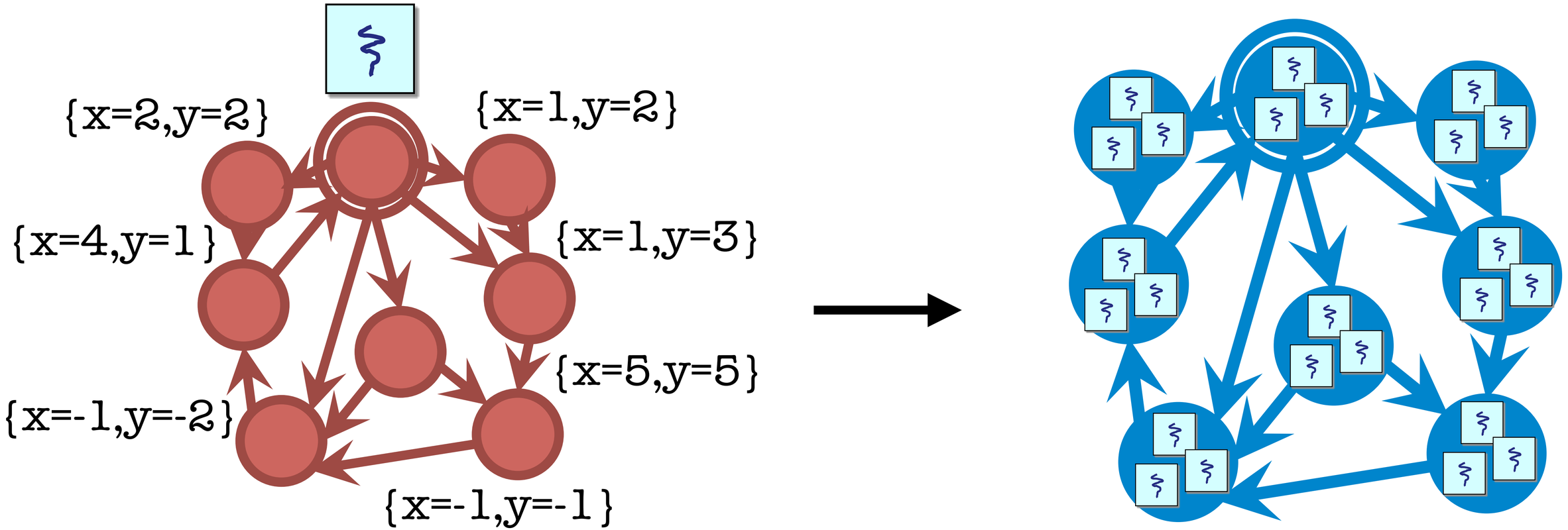
{x=1,y=2}
{x=4,y=1}
{x=1,y=3}
{x=5,y=5}
{x=-1,y=-2}
{x=-1,y=-1}


{x=2,y=2}
{x=1,y=2}
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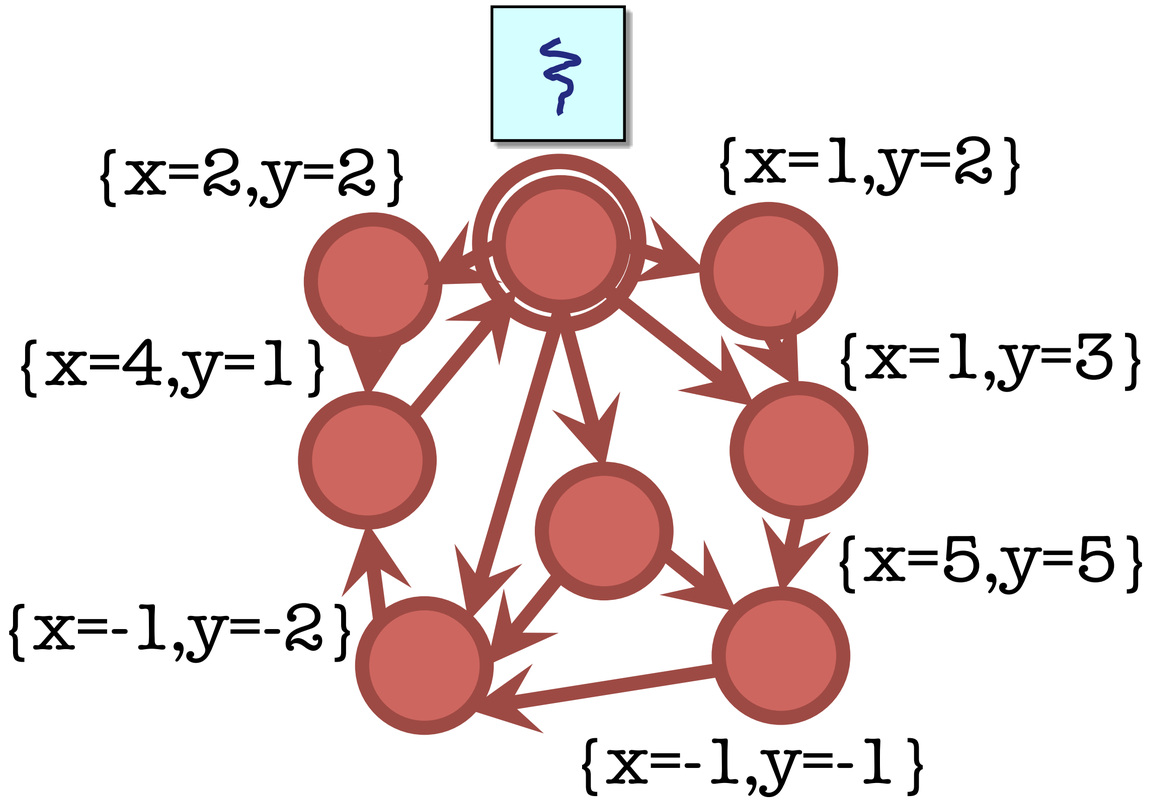
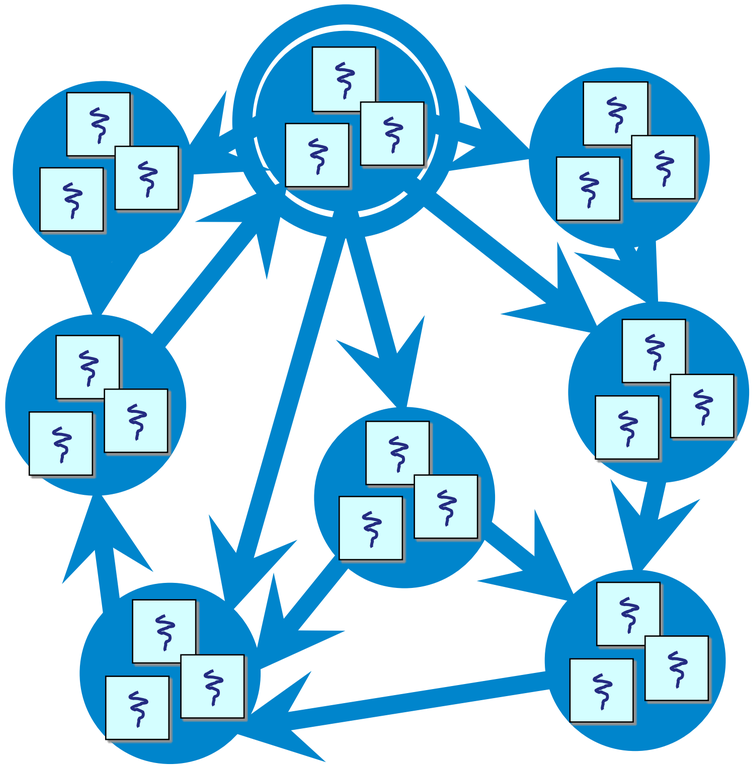
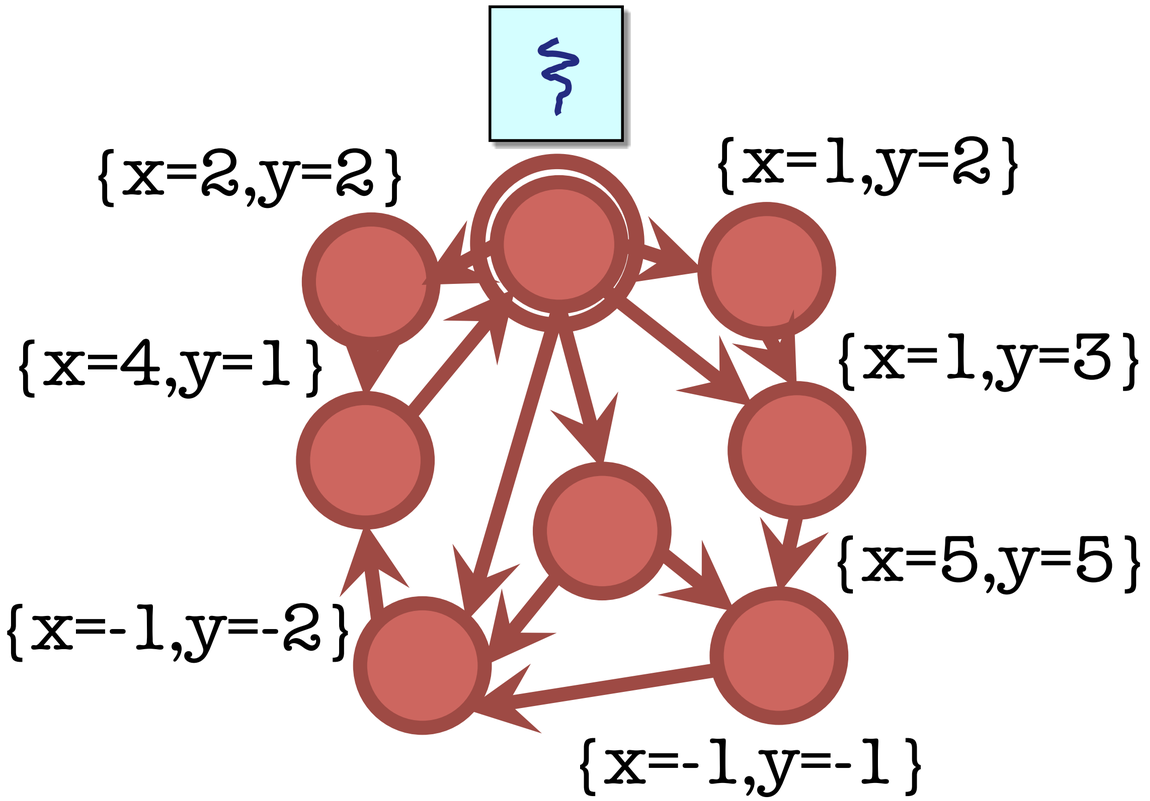
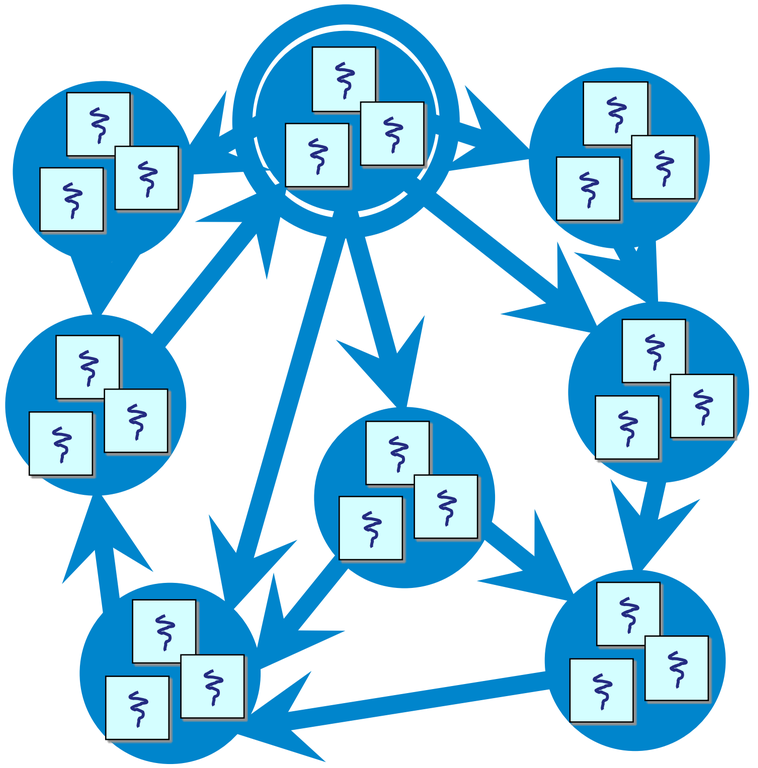


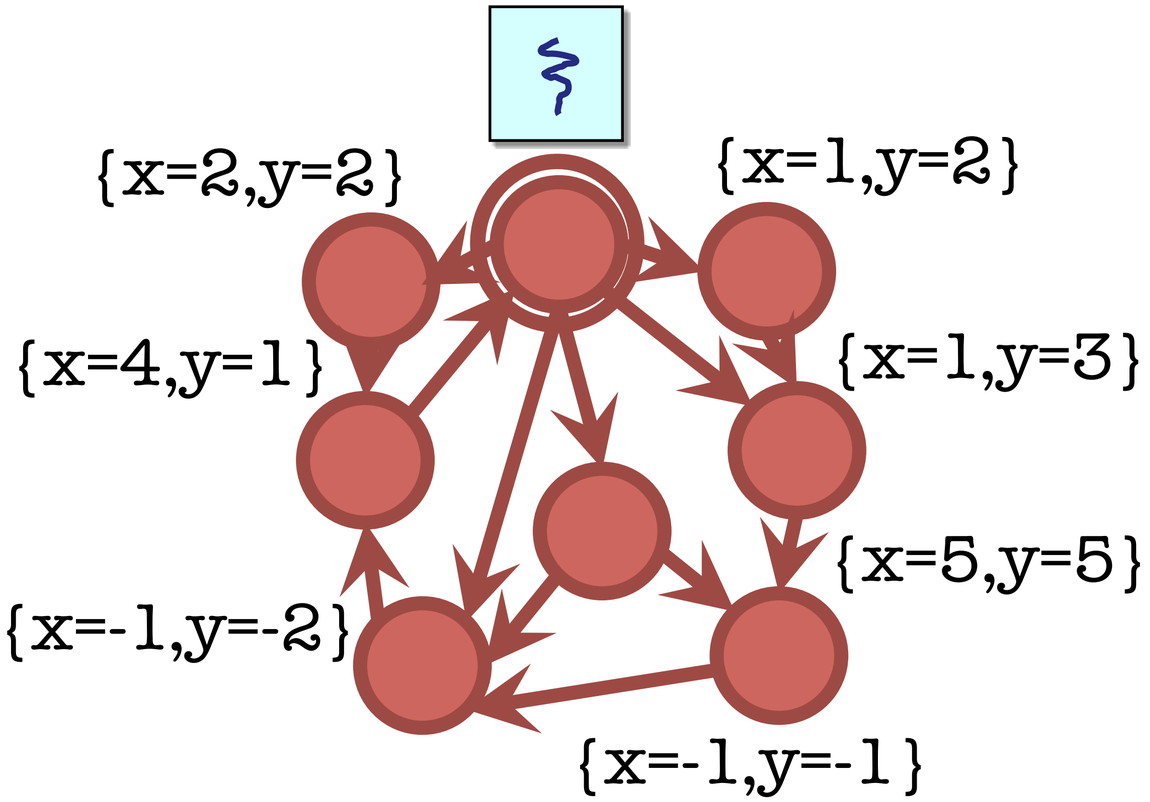


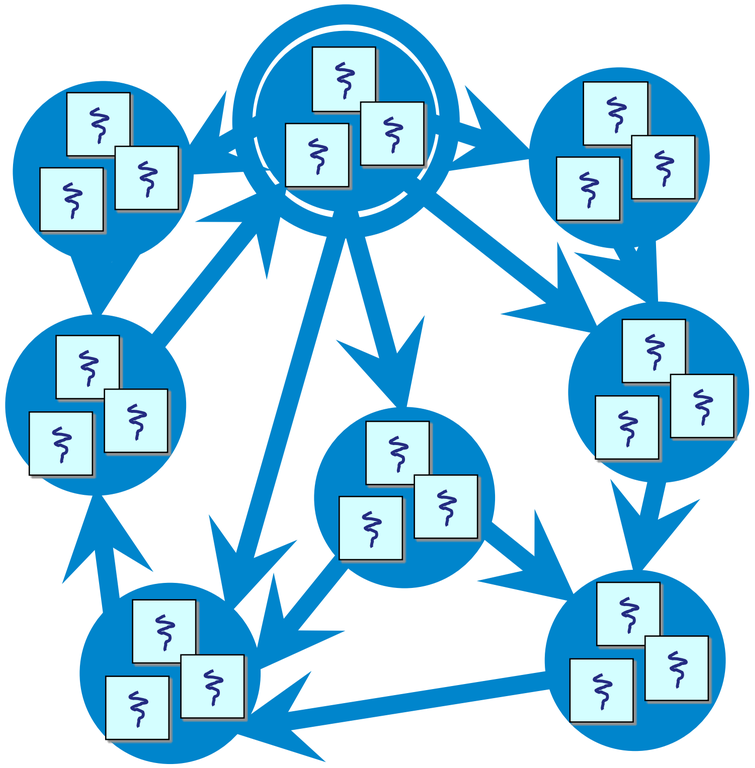
- Invariant defined over small subset of processes' variables





- Invariant defined over small subset of processes' variables
- Each event affects a small subset of receiver's variables





- Invariant defined over small subset of processes' variables
- Each event affects a small subset of receiver's variables

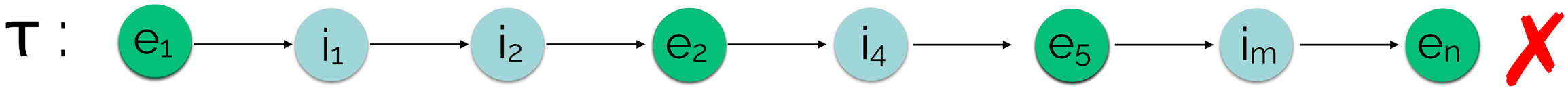
Initial execution contains events that don't affect invariant

Challenge:
Don't know which events are important

Approach:

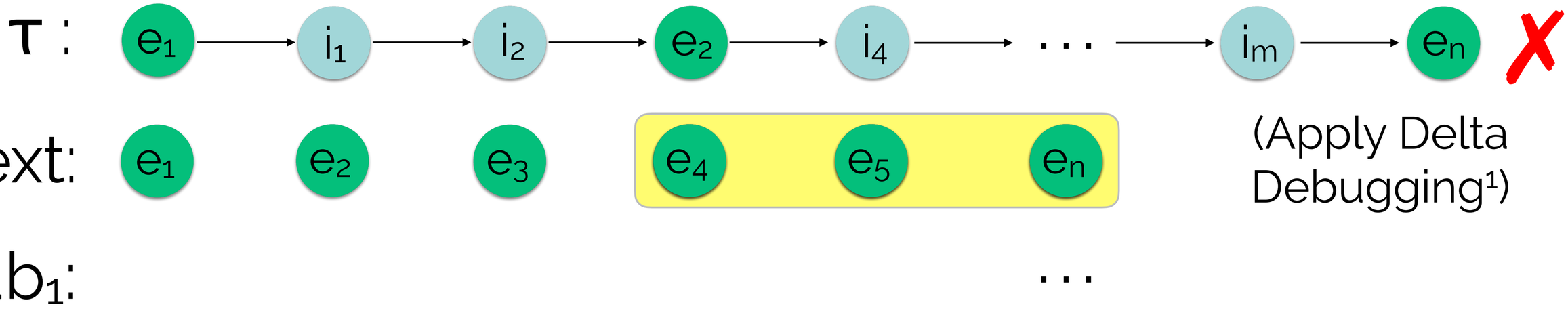
- experimentally "infer" important events
- stay close to the original execution

Observation #2: selectively mask original events



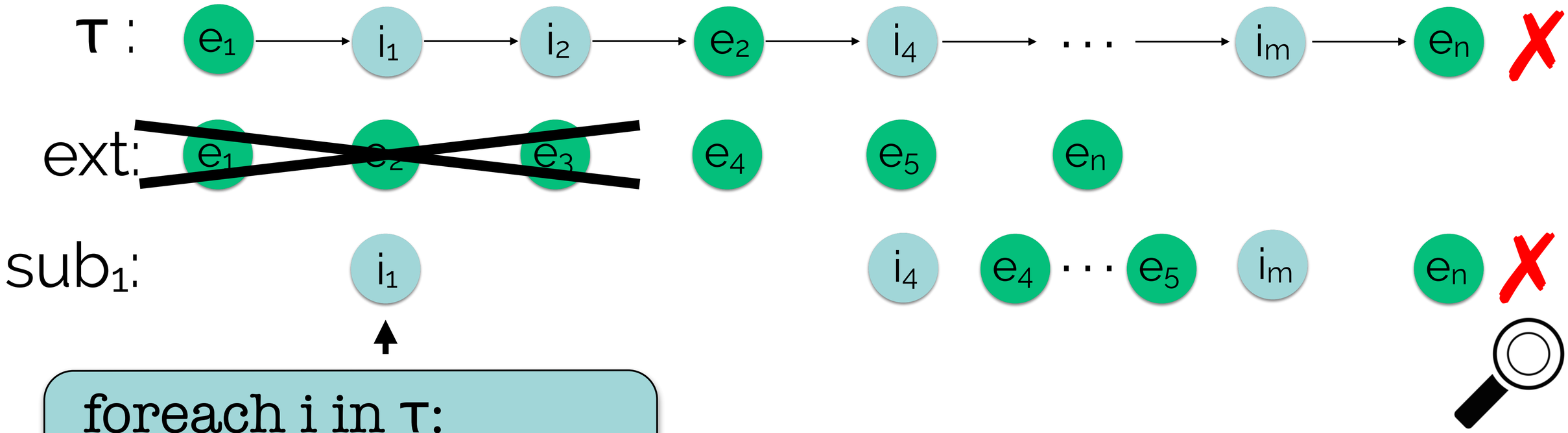
ext:

Observation #2: selectively mask original events



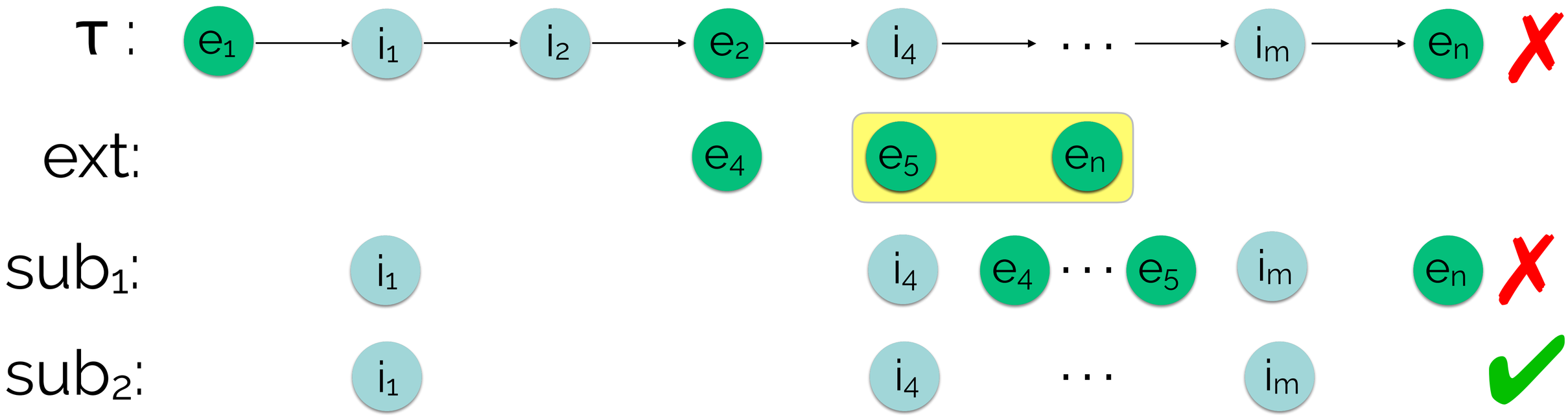
[1]A Zeller, R. Hildebrandt, “Simplifying and Isolating Failure-Inducing Input”, IEEE ‘02

Observation #2: selectively mask original events




```
foreach i in τ:
   if i is pending:
     deliver i
# ignore unexpected
```

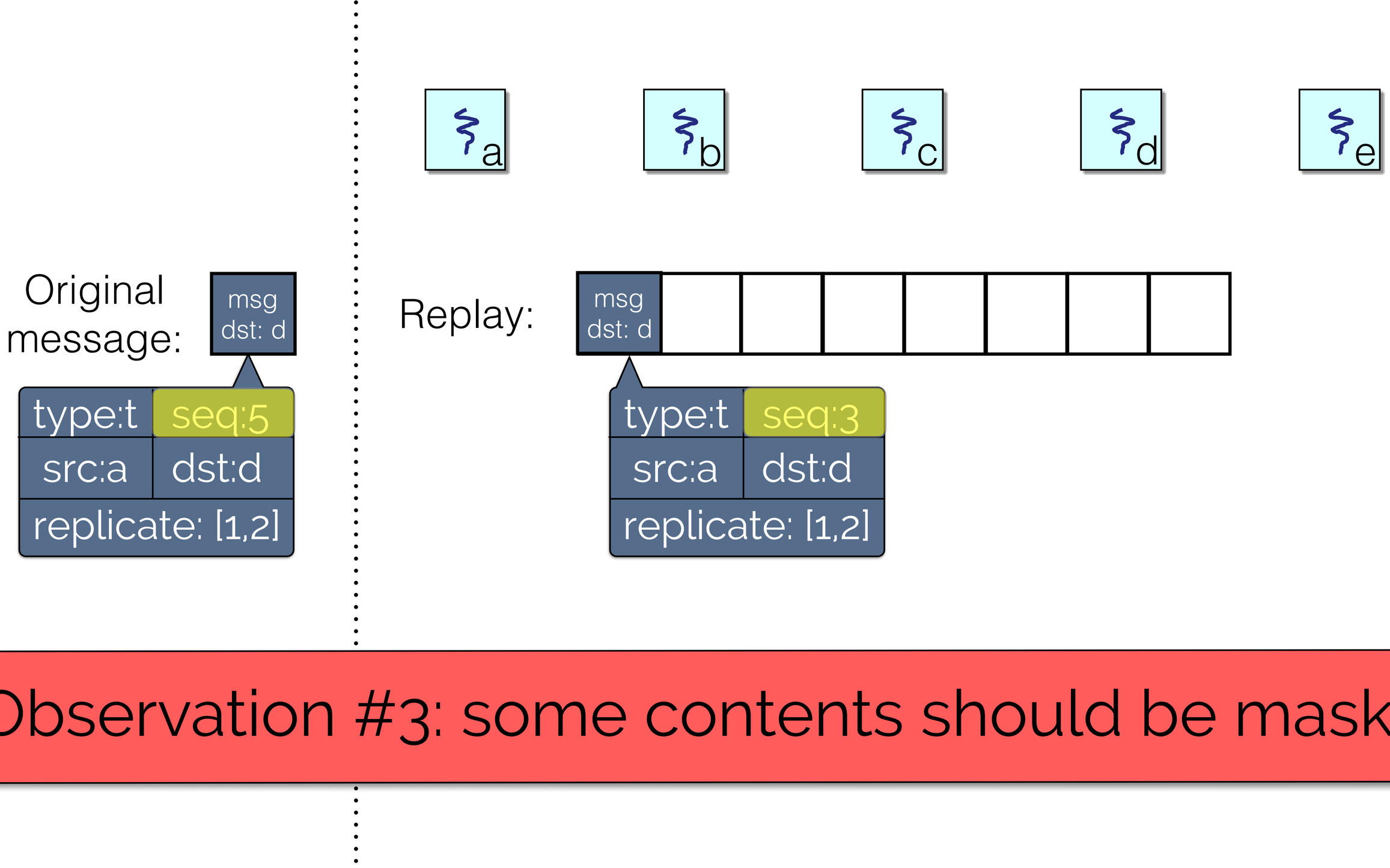
Observation #2: selectively mask original events



Explore backtrack points until (i) ✗ or (ii) time budget for sub_2 expired

. . .

Message contents may differ across executions!



Observation #3: some contents should be masked

Observation #3: some contents should be masked

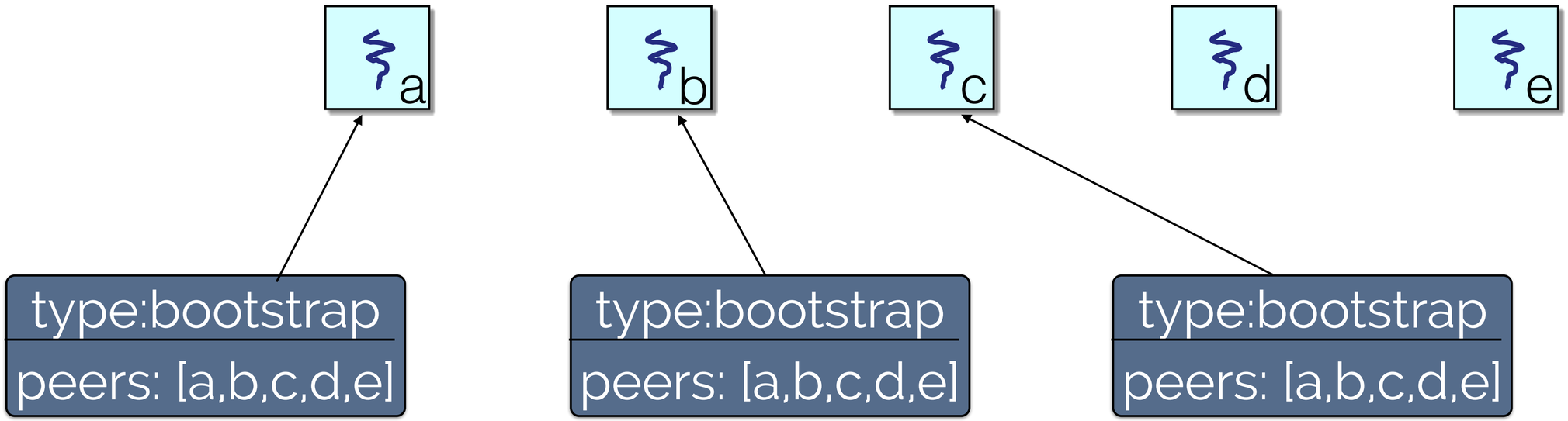
Phase 1: choose initial schedule

- Match messages by user-defined “fingerprint”

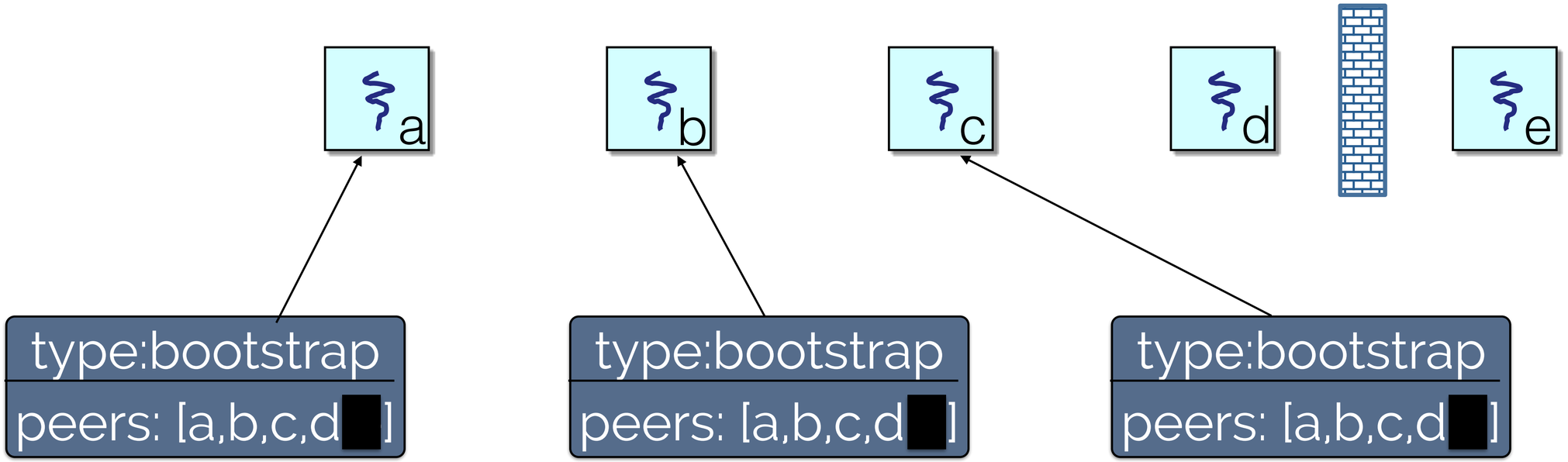
Phase 2: prioritize backtrack points

- Match messages by type only
- Backtrack whenever multiple pending messages match by type

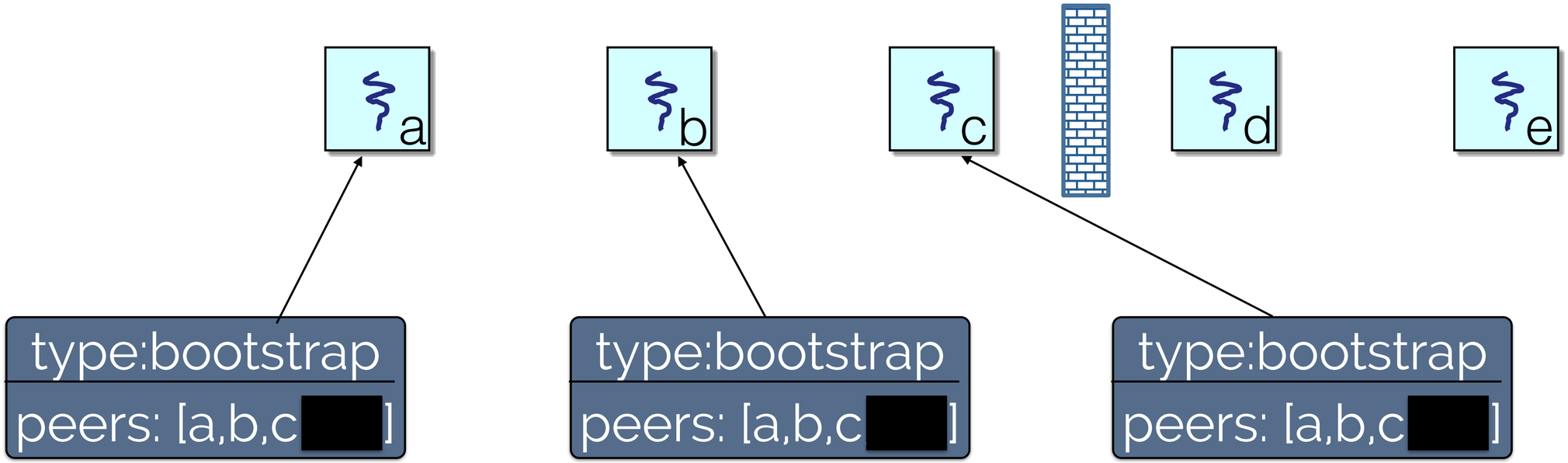
Observation #4: shrink external message contents



Observation #4: shrink external message contents



Observation #4: shrink external message contents



Goal: find minimal schedule that produces violation

Observation #1: many schedules are commutative

Approach: prioritize schedule space exploration

Observation #2: selectively mask original events

Observation #3: some contents should be masked

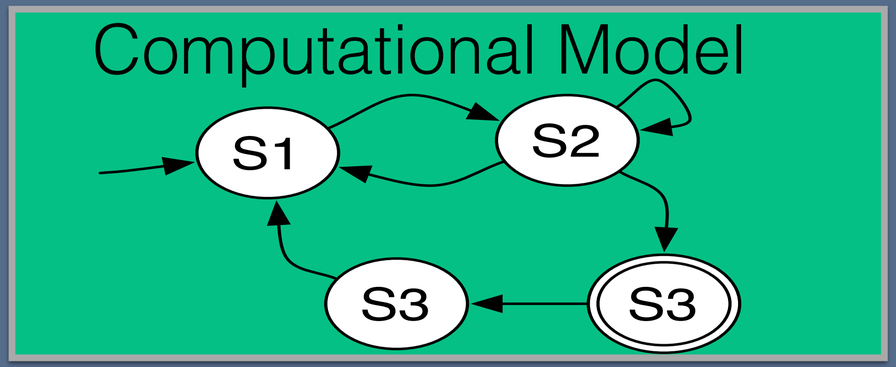
Observation #4: shrink external message contents

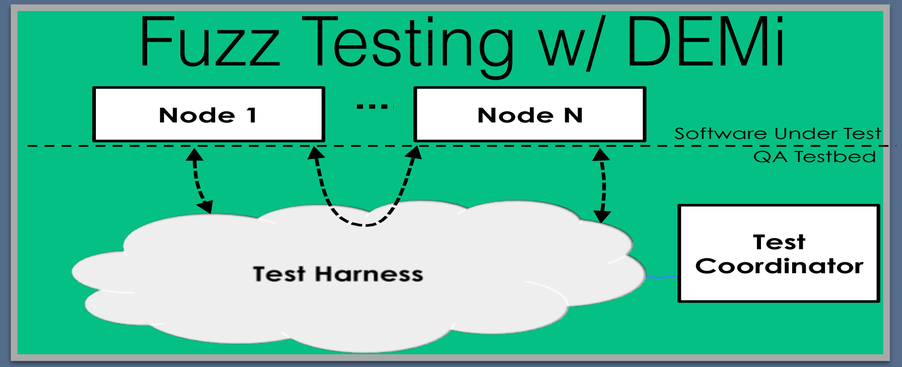
Minimize internal events after externals minimized

Outline

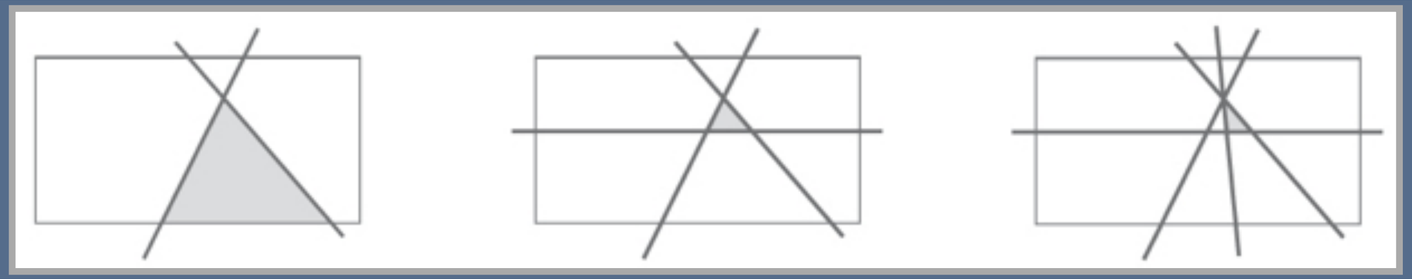
Introduction

Background





Minimization

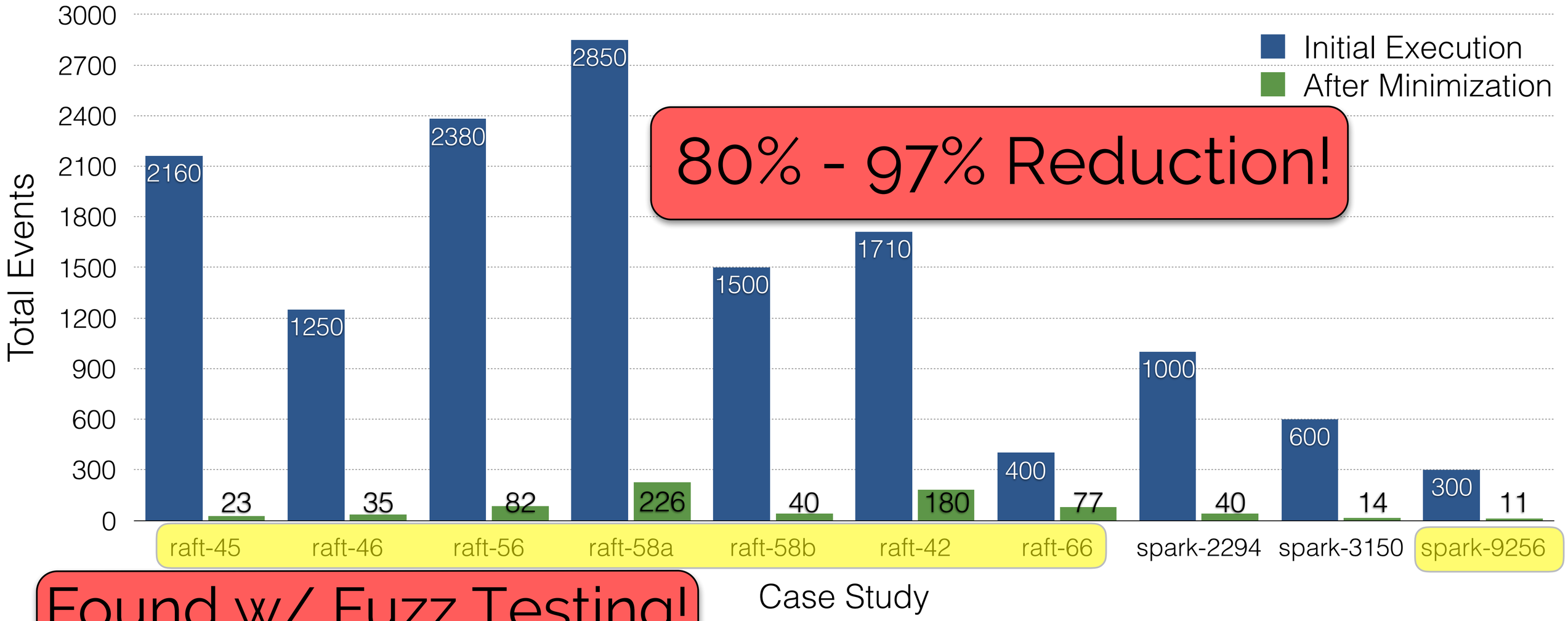


Evaluation

Conclusion

Target Systems

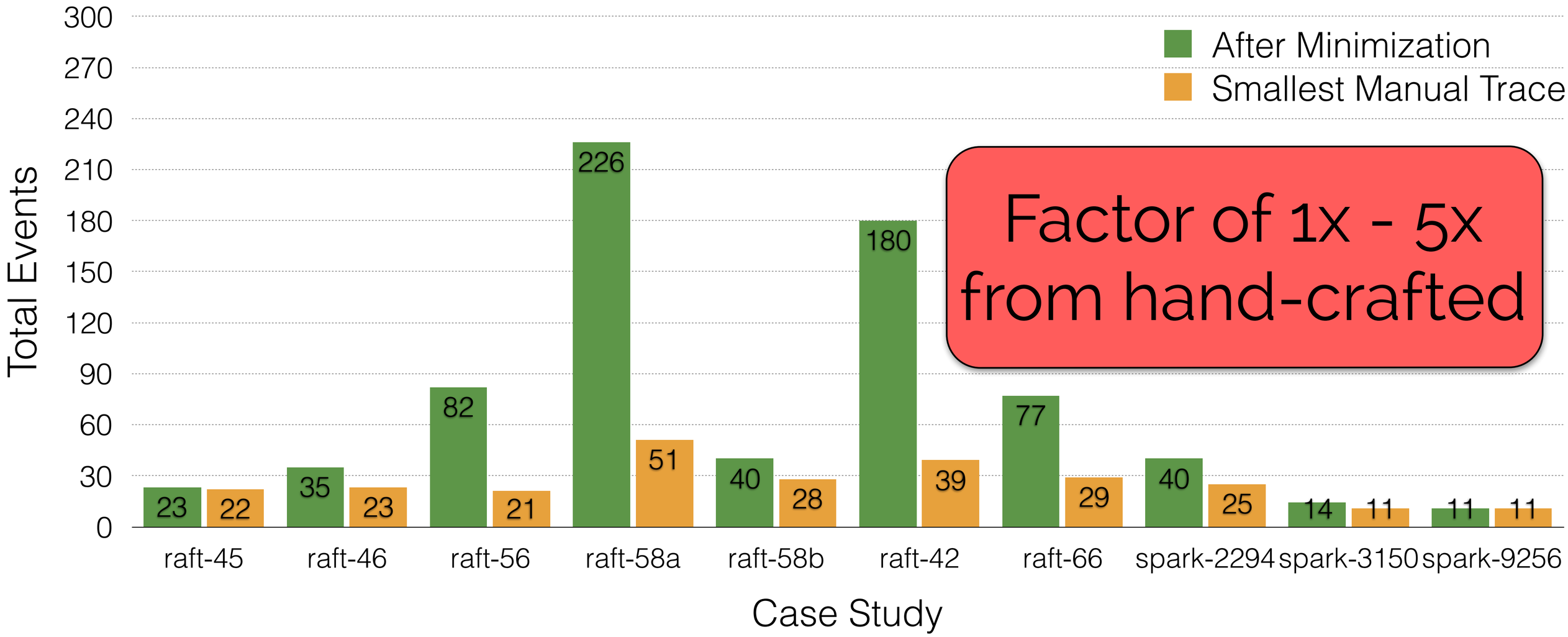
How well does DEMi work?



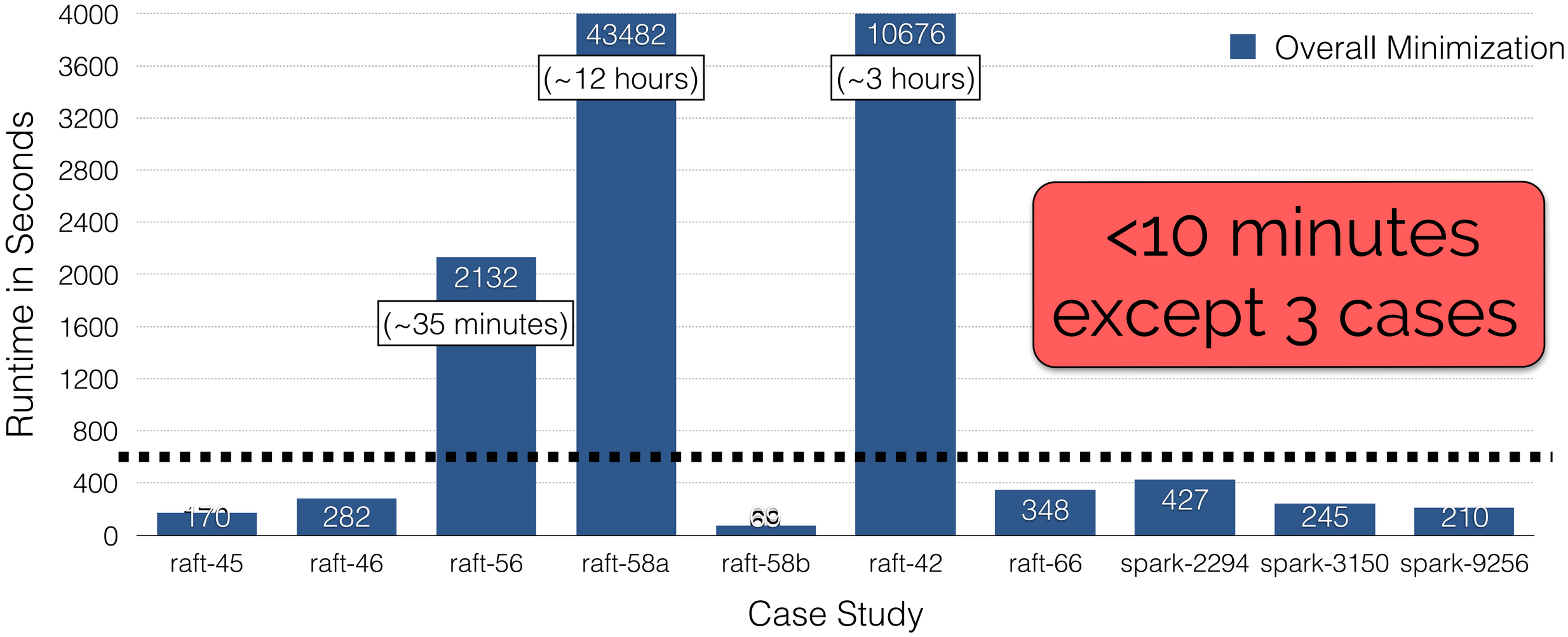
80% - 97% Reduction!

Found w/ Fuzz Testing!

How well does DEMi work?



How quickly does DEMi work?



See the paper for…

- How we handle non-determinism
- Handling multithreaded processes
- Supporting other RPC libraries
- Sketch for minimizing production traces
- More in-depth evaluation
- Related work
- …

Conclusion

Optimistic that these techniques can be successfully applied more broadly

Open source tool: github.com/NetSys/demi

Read our paper!
eecs.berkeley.edu/~rcs/research/nsdi16.pdf

Contact me! cs@cs.berkeley.edu

Thanks for your time!

Attributions

Inspiration for slide design: Jay Lorch's IronFleet slides

Graphic Icons: thenounproject.org

logfile: mantisshrimpdesign

magnifying glass: Ricardo Moreira

disk: Anton Outkine

hook: Seb Cornelius

bug report: Lemon Liu

devil: Mourad Mokrane

Putin: Remi Mercier

Production Traces

Model: feed partially ordered log into single machine DEMi

Require:

- Partial ordering of all message deliveries
- All crash-recoveries logged to disk

Instrumentation Complexity

	akka-raft	Spark
Message Fingerprint	59	56
Non-Determinism	2	~250

Table 4: Instrumentation complexity (lines of code) needed to define message fingerprints, and to mitigate non-determinism.

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.

DDmin in more detail

Input: $T_{\text{✘}}$ s.t. $T_{\text{✘}}$ is a trace and $\mathit{test}(T_{\text{✘}}) = \text{✘}$. Output: $T'_{\text{✘}} = \mathit{ddmin}(T_{\text{✘}})$ s.t. $T'_{\text{✘}} \subseteq T_{\text{✘}}$, $\mathit{test}(T'_{\text{✘}}) = \text{✘}$, and $T'_{\text{✘}}$ is minimal.

$$\mathit{ddmin}(T_{\text{✘}}) = \mathit{ddmin}_2(T_{\text{✘}}, \emptyset) \quad \text{where}$$

$$\mathit{ddmin}_2(T'_{\text{✘}}, R) = \begin{cases} T'_{\text{✘}} & \text{if } |T'_{\text{✘}}| = 1 \text{ (“base case”)} \\ \mathit{ddmin}_2(T_1, R) & \text{else if } \mathit{test}(T_1 \cup R) = \text{✘} \text{ (“in } T_1\text{”)} \\ \mathit{ddmin}_2(T_2, R) & \text{else if } \mathit{test}(T_2 \cup R) = \text{✘} \text{ (“in } T_2\text{”)} \\ \mathit{ddmin}_2(T_1, T_2 \cup R) \cup \mathit{ddmin}_2(T_2, T_1 \cup R) & \text{otherwise (“interference”)} \end{cases}$$

where $\mathit{test}(T)$ denotes the state of the system after executing the trace T, ✘ denotes an invariant violation, $T_1 \subset T'_{\text{✘}}$, $T_2 \subset T'_{\text{✘}}$, $T_1 \cup T_2 = T'_{\text{✘}}$, $T_1 \cap T_2 = \emptyset$, and $|T_1| \approx |T_2| \approx |T'_{\text{✘}}|/2$ hold.

DDmin assumptions

- *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 minima

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

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

Minimization Pace

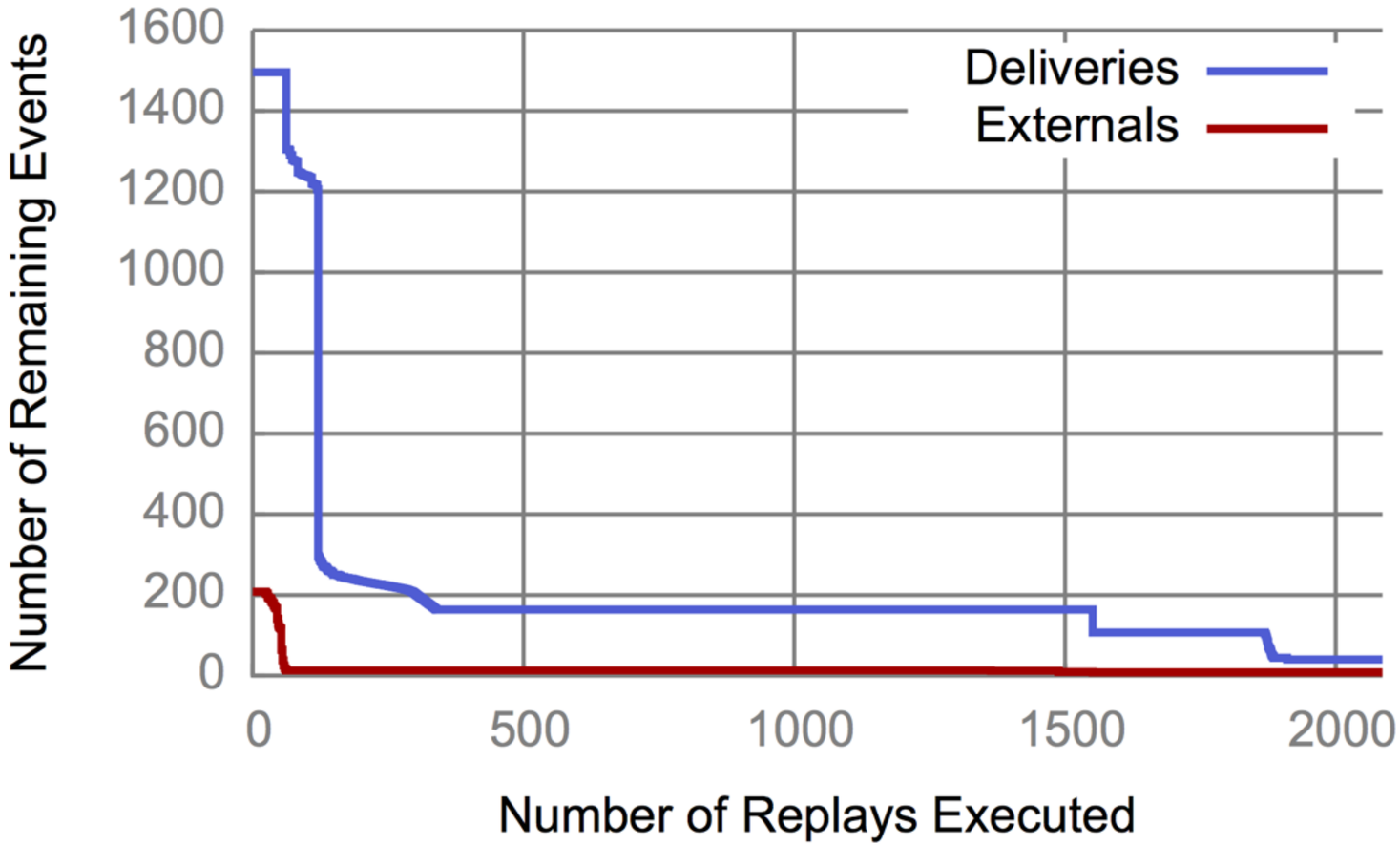


Figure 2: Minimization pace for raft-58b. Significant progress is made early on, then progress becomes rare.

Dealing With Threads

If you're lucky: threads are largely independent (Spark)
If you're unlucky: key insight:
A write to shared memory is equivalent to a message delivery

Approach:

- interpose on virtual memory, thread scheduler
- pause a thread whenever it writes to shared memory / disk

Cf. "Enabling Tracing Of Long-Running Multithreaded Programs Via Dynamic Execution Reduction", ISSTA '07

Dealing With Non-Determinism

Interpose on:

- Timers
- Random number generators
- Unordered hash values
- ID allocation

Stop-gap: replay each schedule multiple times

Complete Results

Bug Name	Bug Type	Initial	Provenance	STSSched	TFB	Optimal	NoDiverge
raft-45	Akka-FIFO, reproduced	2160 (E:108)	2138 (E:108)	1183 (E:8)	23 (E:8)	22 (E:8)	1826 (E:11)
raft-46	Akka-FIFO, reproduced	1250 (E:108)	1243 (E:108)	674 (E:8)	35 (E:8)	23 (E:6)	896 (E:9)
raft-56	Akka-FIFO, found	2380 (E:108)	2376 (E:108)	1427 (E:8)	82 (E:8)	21 (E:8)	2064 (E:9)
raft-58a	Akka-FIFO, found	2850 (E:108)	2824 (E:108)	953 (E:32)	226 (E:31)	51 (E:11)	2368 (E:35)
raft-58b	Akka-FIFO, found	1500 (E:208)	1496 (E:208)	164 (E:13)	40 (E:8)	28 (E:8)	1103 (E:13)
raft-42	Akka-FIFO, reproduced	1710 (E:208)	1695 (E:208)	1093 (E:39)	180 (E:21)	39 (E:16)	1264 (E:43)
raft-66	Akka-UDP, found	400 (E:68)	392 (E:68)	262 (E:23)	77 (E:15)	29 (E:10)	279 (E:23)
spark-2294	Akka-FIFO, reproduced	1000 (E:30)	886 (E:30)	43 (E:3)	40 (E:3)	25 (E:1)	43 (E:3)
spark-3150	Akka-FIFO, reproduced	600 (E:20)	536 (E:20)	18 (E:3)	14 (E:3)	11 (E:3)	18 (E:3)
spark-9256	Akka-FIFO, found (rare)	300 (E:20)	256 (E:20)	11 (E:1)	11 (E:1)	11 (E:1)	11 (E:1)

Runtime Breakdown

Bug Name	STSSched	TFB
raft-45	56s (594)	114s (2854)
raft-46	73s (384)	209s (4518)
raft-56	54s (524)	2078s (31149)
raft-58a	137s (624)	43345s (834972)
raft-58b	23s (340)	31s (1747)
raft-42	118s (568)	10558s (176517)
raft-66	14s (192)	334s (10334)
spark-2294	330s (248)	97s (78)
spark-3150	219s (174)	26s (21)
spark-9256	96s (73)	0s (0)

Integrating with other RPC libs