Diagnosing Distributed CPS with Timing Provenance

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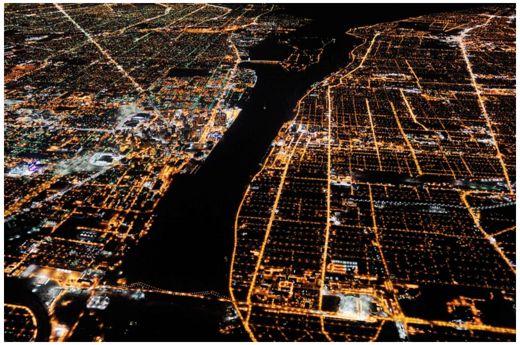
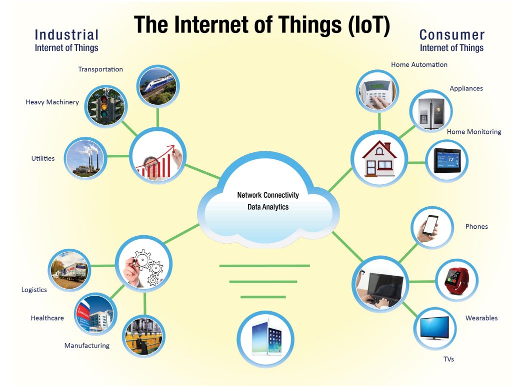
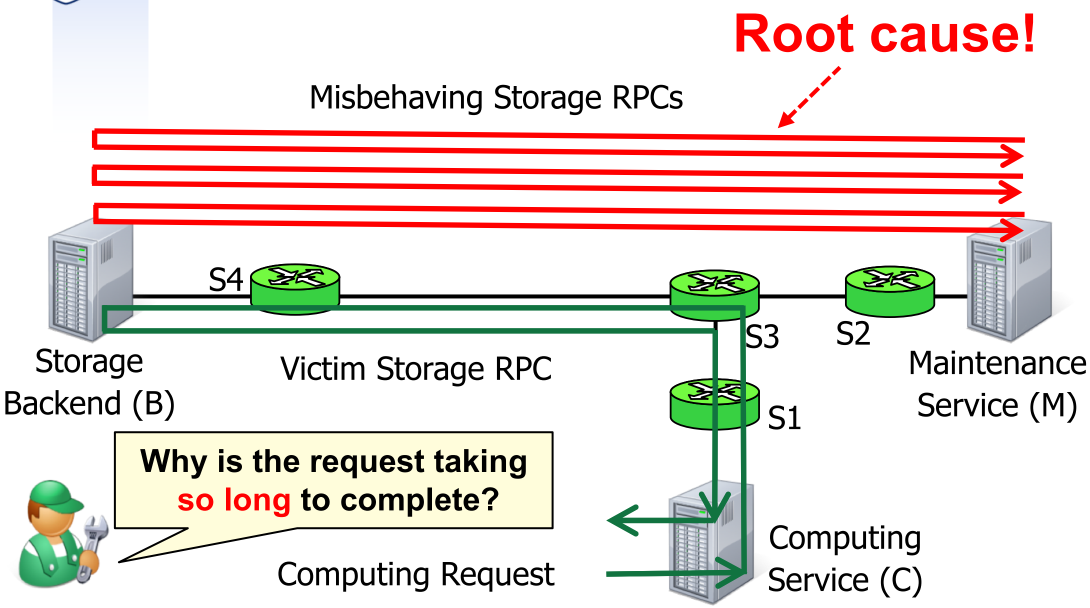
Problem: Timing faults

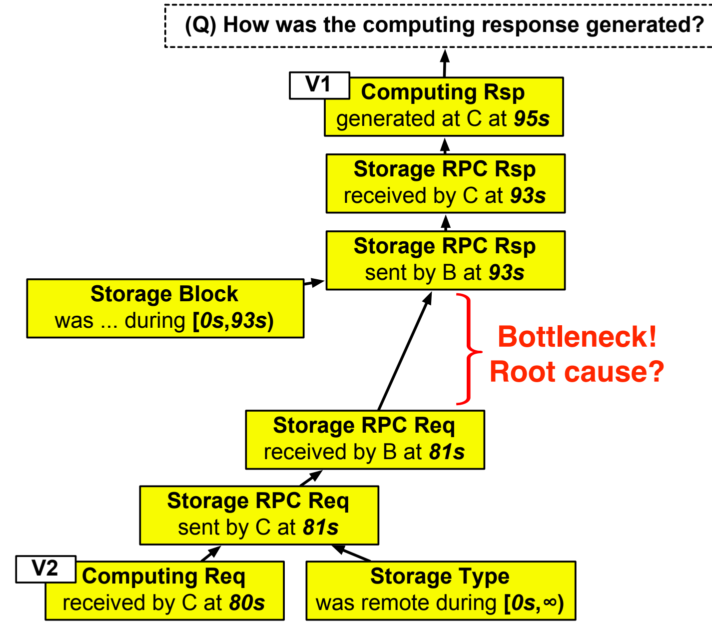
- Many CPS are time dependent
  - The "right thing" must happen at the "right time"!
- What if this goes wrong?
  - Reasons: attack, bug, misconfiguration, …
- Goal: A powerful diagnostic capability
  - Can we find the root cause of both functional and timing issues, such as low throughput, oscillations, high latencies, …?

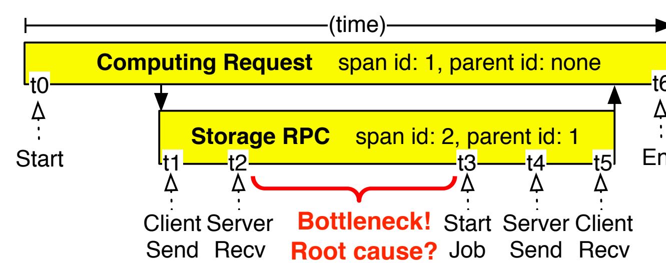




Challenge

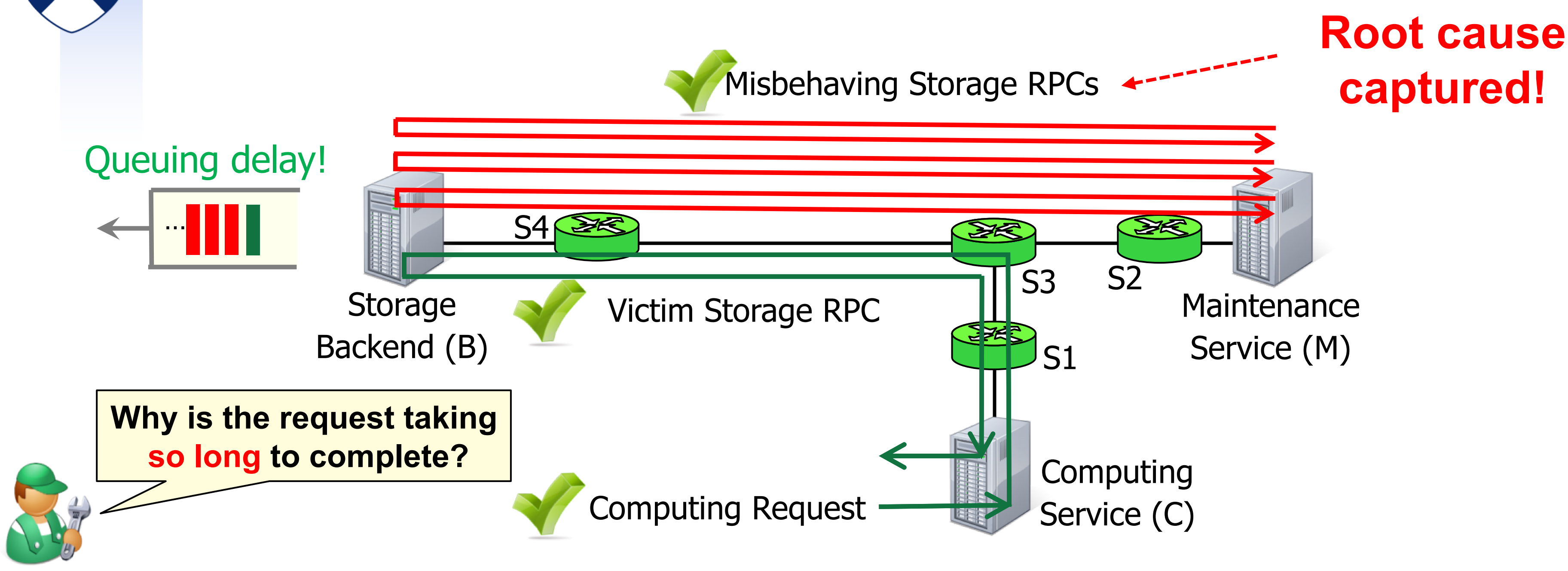






- State of the art
  - Distributed tracing: explain what was computed when, but not why
  - Network provenance: only reason about functional causality
- Cannot reason about timing

Approach: Timing provenance

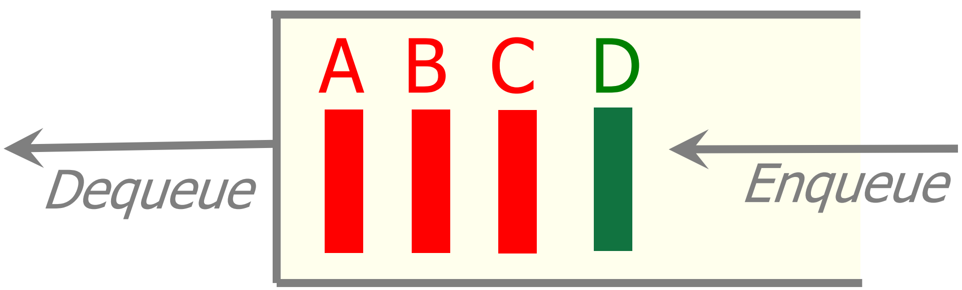


- A generalization of provenance that tracks both functional causality and temporal causality
  - i.e., causes that affect the timing of the observed symptom
  - may involve requests that are functionally independent
- Result: Can explain both the 'what' and the 'when'

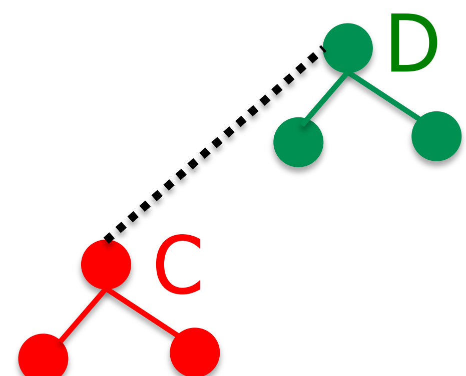
How to capture temporal causality?

- Intuition: Represent ordering relationship between exec.
  - We need to know not just what the system did, but also in what order (queuing and scheduling semantics)

- Extend critical-path analysis in a novel way for the analysis



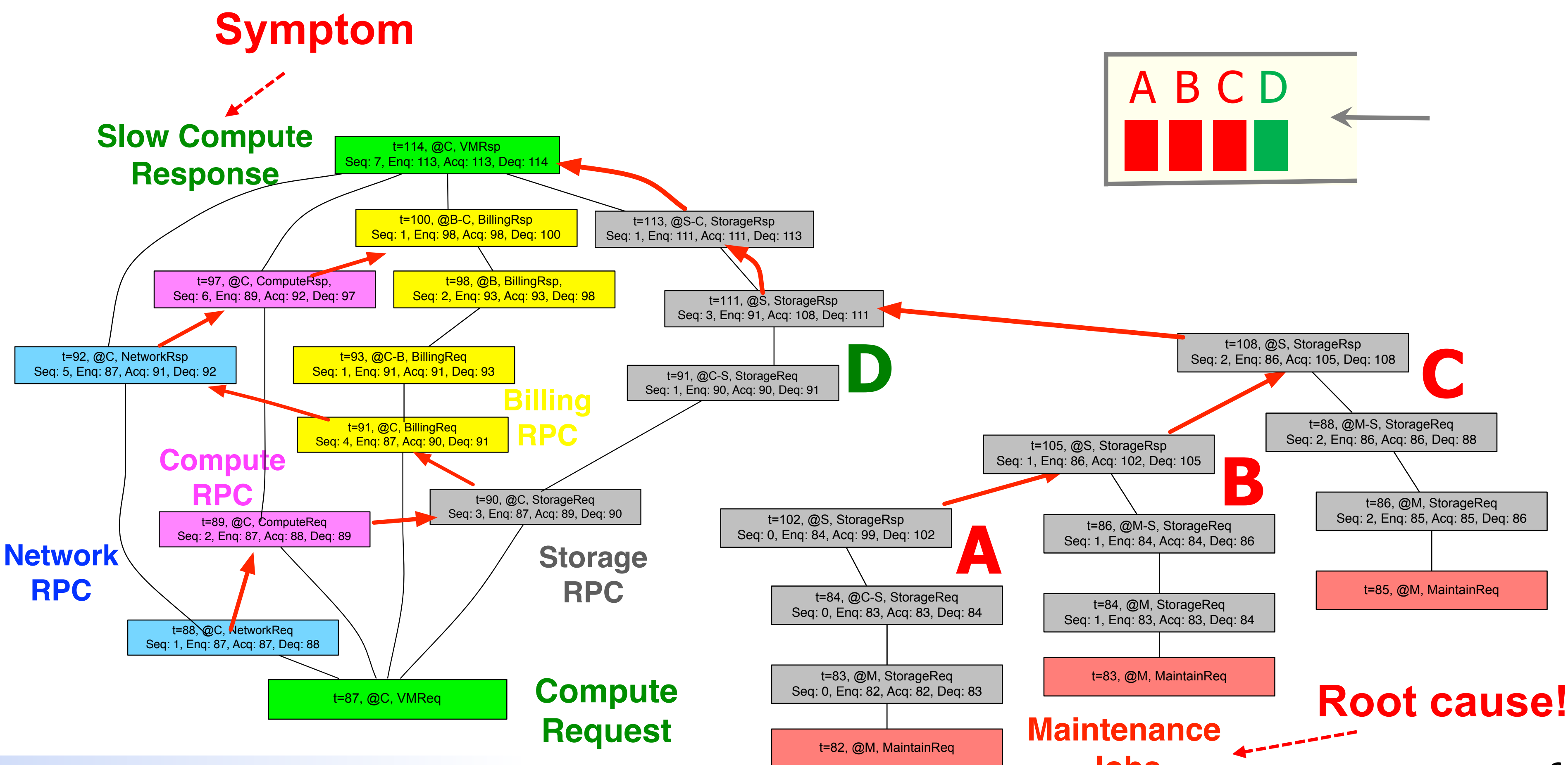
Request D can only be dequeued after C is dequeued and finished processing



Timing provenance of D must include C

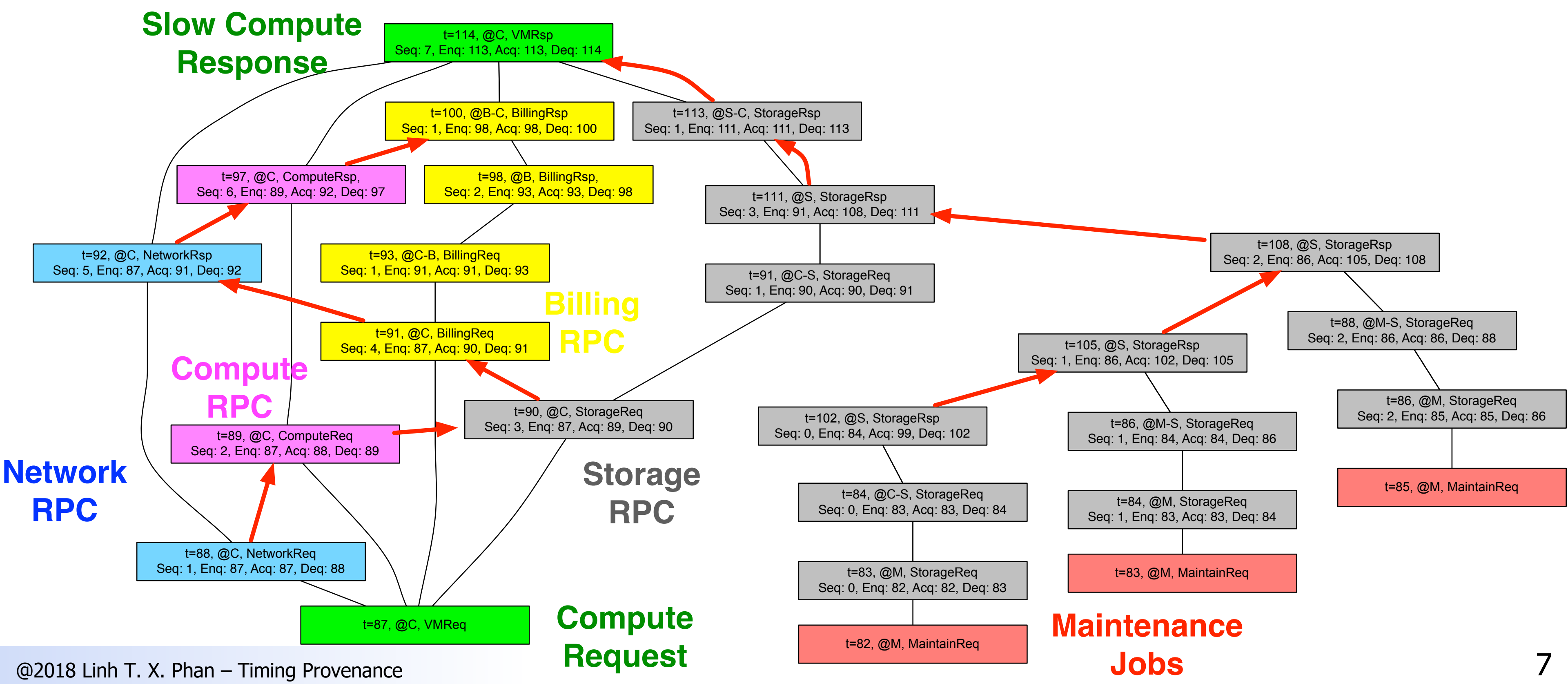
Insight #1: Sequencing edges

- Add a sequencing edge from execution X to execution Y if X immediately precedes Y in the queue



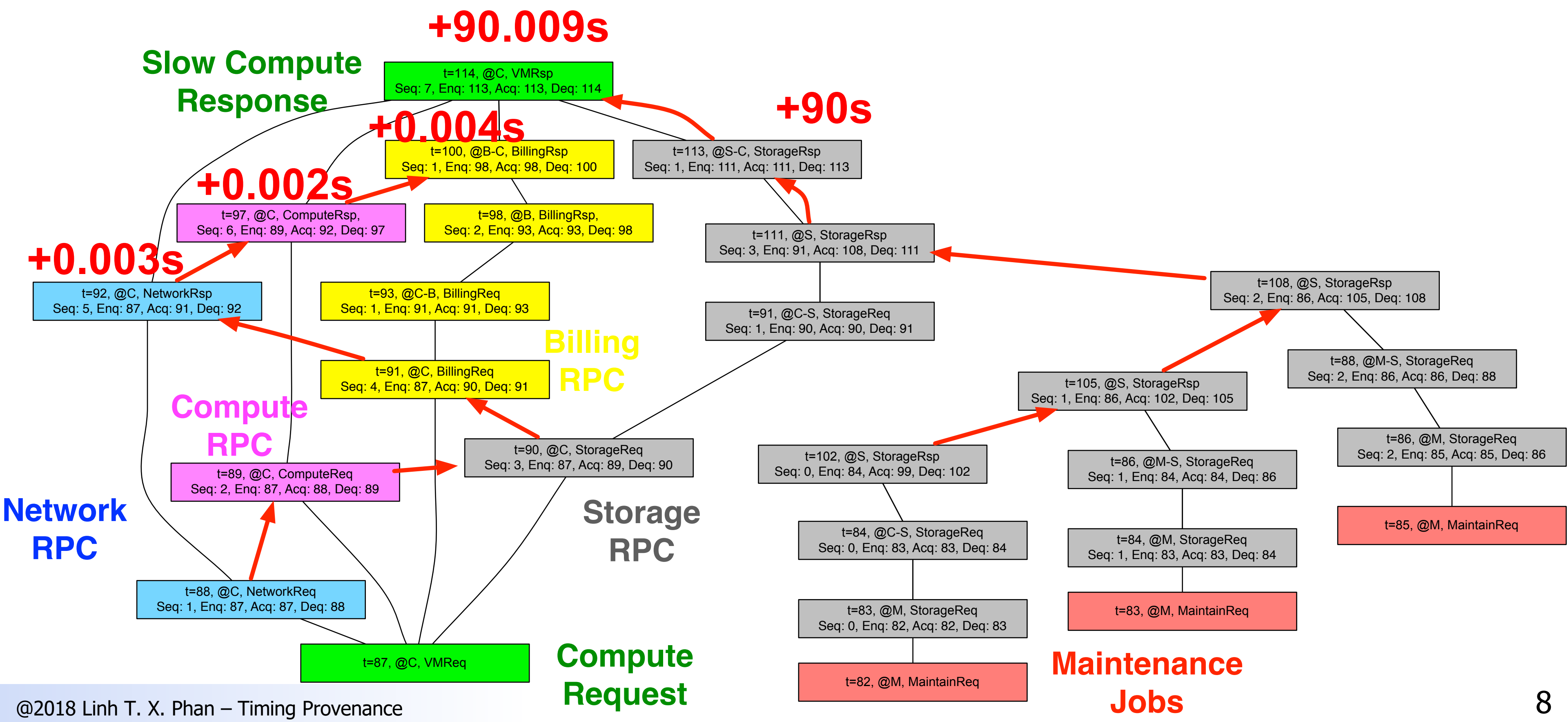
Challenge: Usability

- Not all executions are equally important
- How to isolate executions that contribute substantially to the overall delay?



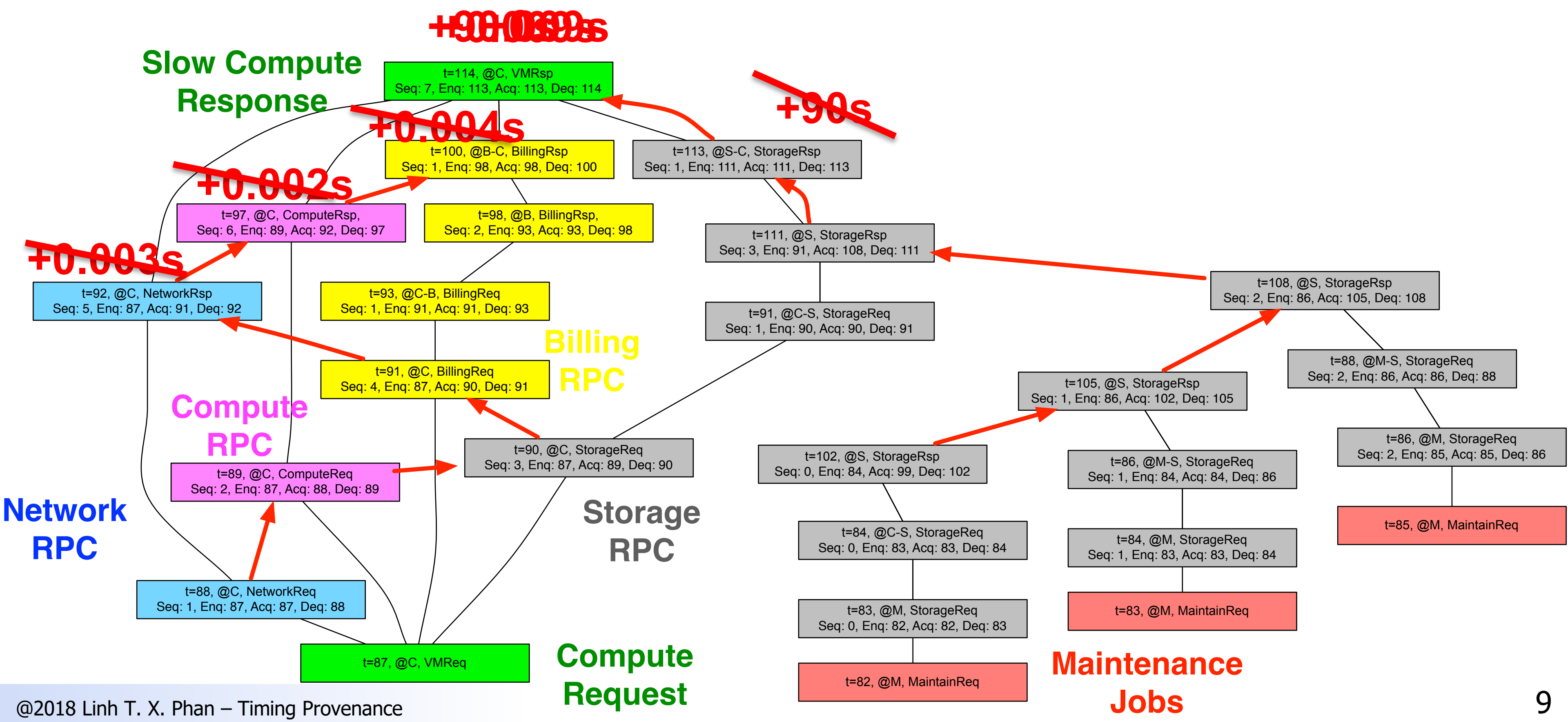
Insight #2: Delay annotations

- Annotate vertexes with the delays that they contribute



Insight #2: Delay annotations

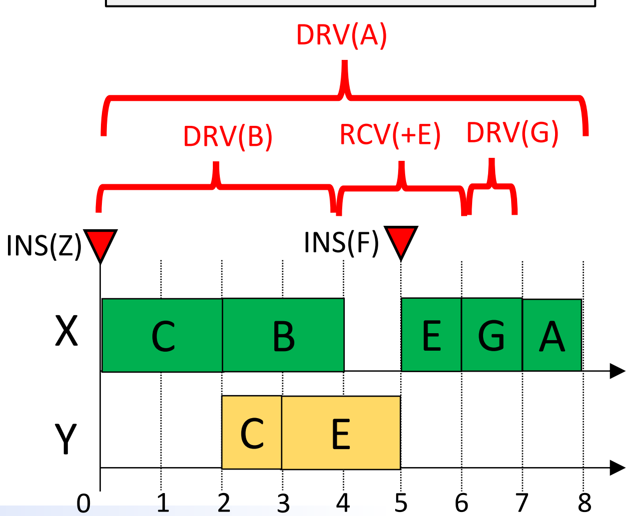
- Annotate vertexes with the delays that they contribute
- Goal: Delay annotations should correspond to “potential speedup”

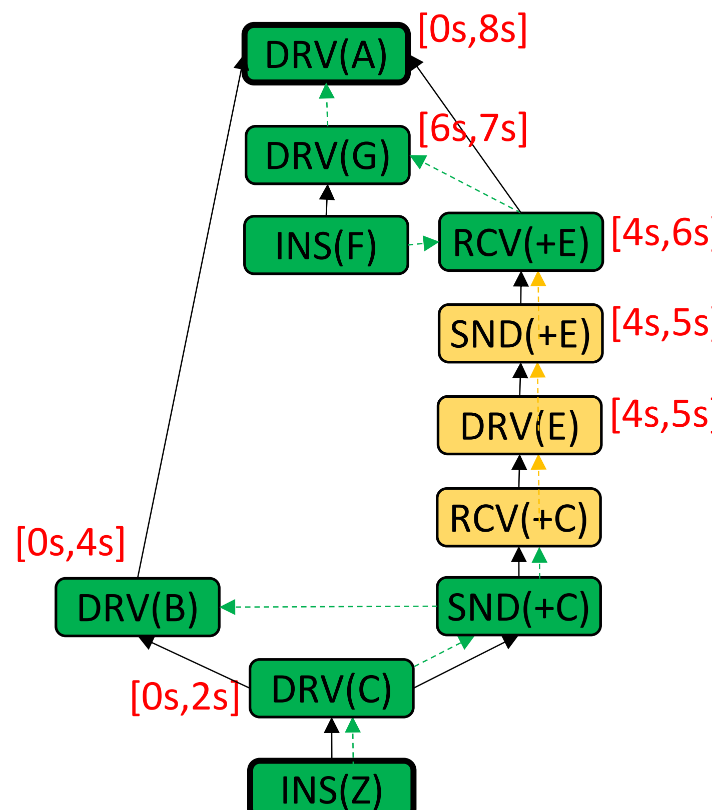


Delay annotations: How to compute?

- Rule 1: Subdivide delay among the preconditions in the order in which they are satisfied
- Rule 2: Attribute the remaining delay to predecessors along the sequencing edge

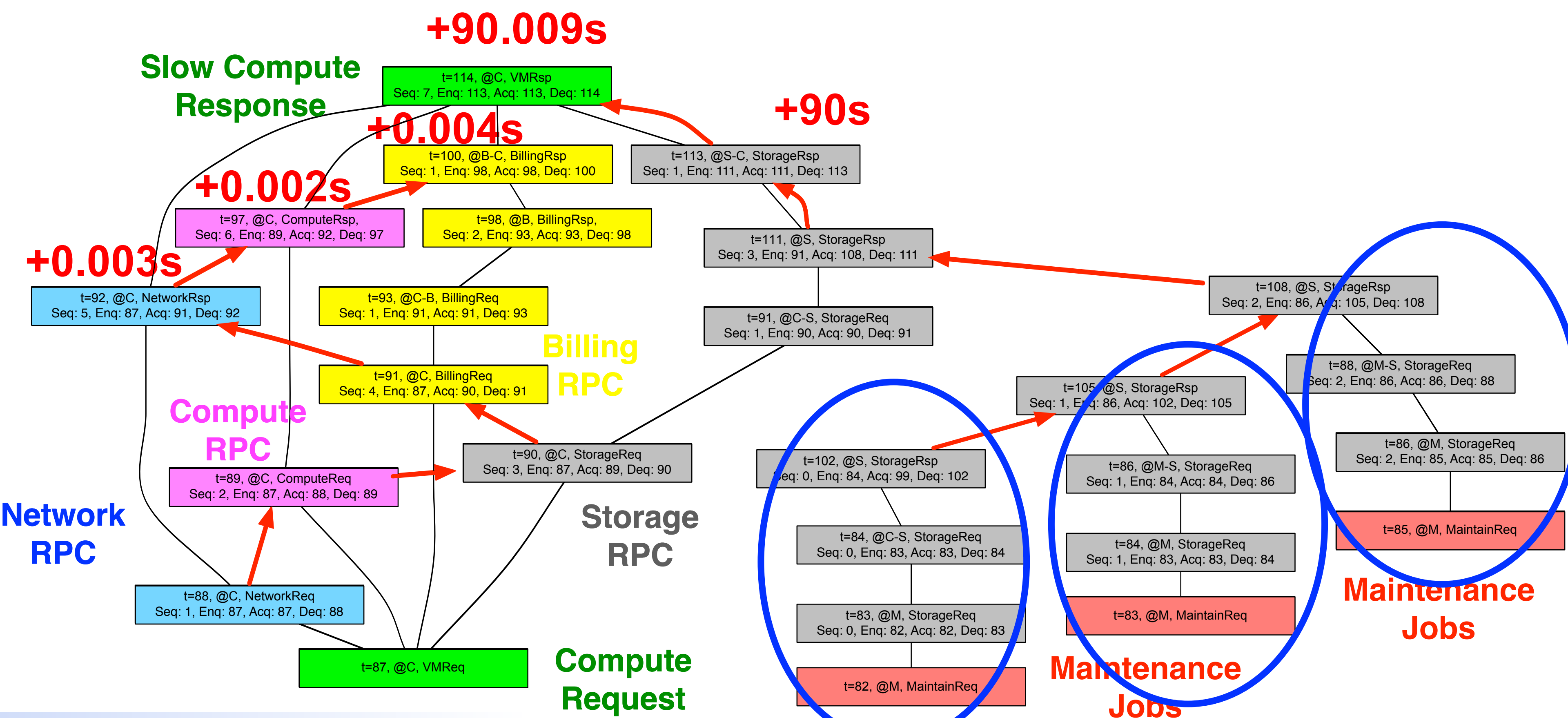
```
A@X :- B@X,E@Y
B@X :- C@X
E@Y :- C@X
C@X :- Z@X
G@X :- F@X
```



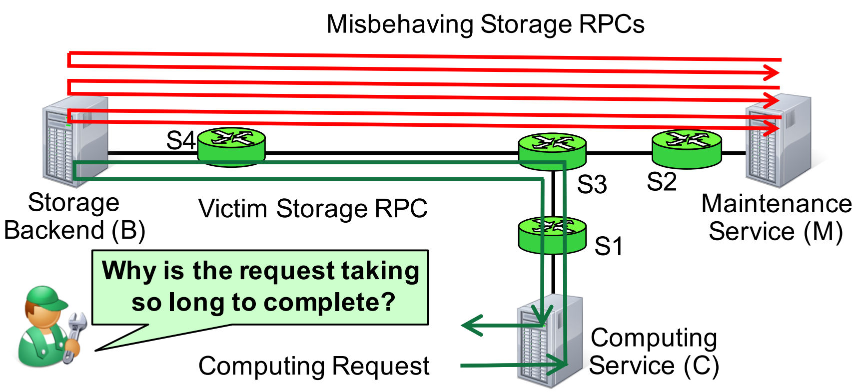


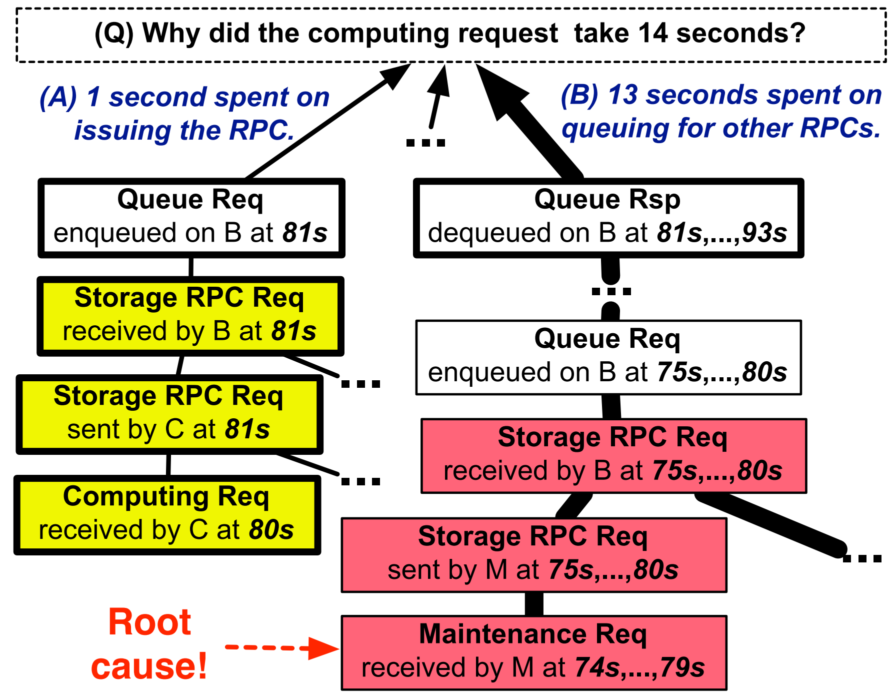
Insight #3: Provenance aggregation

- Aggregating subgraphs that are structurally similar
- Pruning zero-delay subgraphs



Putting everything together





- Detailed and weighted causal explanation of the delay
- Can find off-path root causes!

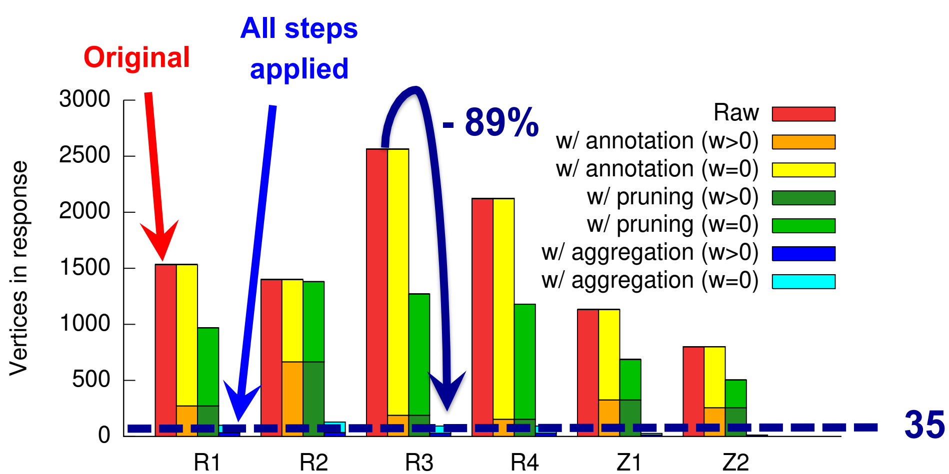
Implementation, experimental setup

- Zeno, a debugger for timing-related faults
- Support for declarative + imperative systems
  - Interfaces with NDlog and Zipkin
  - Gathers data from switches w/P4
- Evaluation
  - Evaluated with 9 realistic bugs from Google Cloud platform*
  - Used networks that contained 8-700 nodes
  - Results are promising

Evaluation results

- Correctly identifies 11-28 relevant events

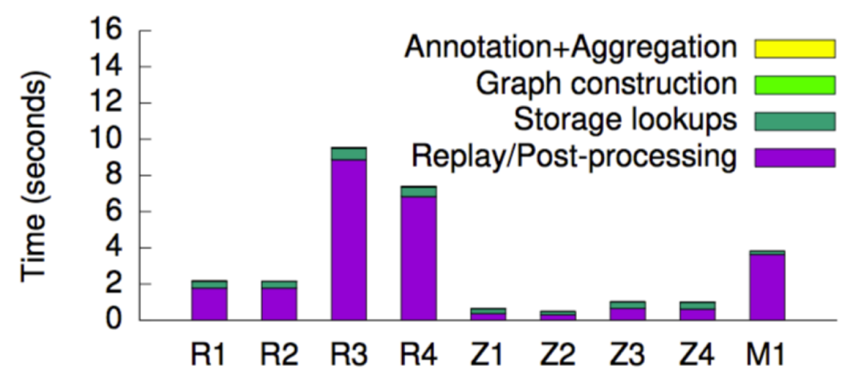
11-35 vertexes contributing delay



Size of the provenance for different example scenarios

Produces readable explanations

Diagnosis in less than 10s



Turnaround time for provenance queries

Low run-time overhead

Timing provenance is useful, compact and efficient!

Summary: Timing Provenance

- A generalization of provenance to explicit represent temporal causality
  - The provenance tracks both functional and temporal causality through sequencing edges
  - Delay annotations + provenance aggregation improves usability
  - Applied to RapidNet and Zipkin: Can find off-path root causes
- Benefit: Precise reasoning of both functional <u>and</u> timing faults
  - This will be useful for CPS diagnostics where time matters!
- On-going work
  - Generalize to more complex scheduling policies