Inferring and Asserting Distributed System Invariants

https://bitbucket.org/bestchai/dinv

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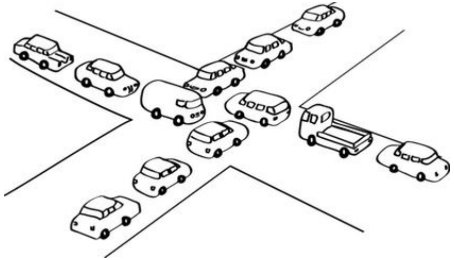
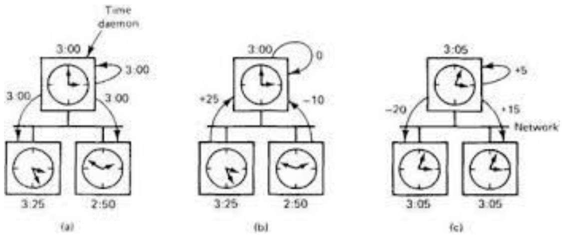
Distributed Systems are pervasive

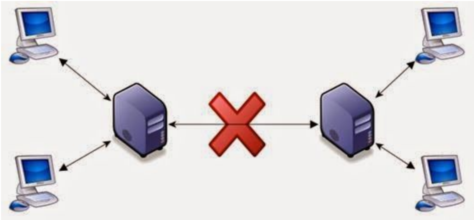
- Graph processing
- Stream processing
- Distributed databases
- Failure detectors
- Cluster schedulers
- Version control
- ML frameworks
- Blockchains
- KV stores
- ...

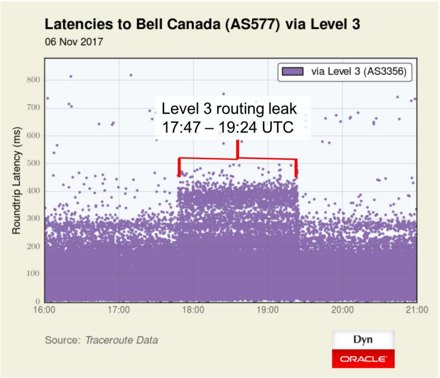
Distributed Systems are Notoriously Difficult to Build

- Concurrency
- No Centralized Clock
- Partial Failure
- Network Variance









Today's state of the art (building robust dist. sys)

Verification - [(verification) IronFleet SOSP'15, VerdiPLDI'15, Chapar POPL'16, (modeling), Lamport et.al SIGOPS'02, Holtzman IEEE TSE'97**]**

Bug Detection - [MODIST NSDI'09, Demi NSDI'16,**]**

Runtime Checkers - [D3S NSDI'18, **]**

Tracing - [PivotTracing SOSP'15, XTrace NSDI'07, Dapper TR'10, **]**

Log Analysis - [ShiViz CACM '16**]**

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←**Require Specifications**

Tracing - [PivotTracing SOSP’15, XTrace NSDI’07, Dapper TR’10, **]**

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Little work has been done to infer distributed specs

Some notable exceptions

- CSight ICSE'14
  - Communicatin finite state machines
- Avenger SRDS'11
  - Requires enormous manual effort
- Udon ICSE'15
  - Requires shared state

None of these can capture stateful properties like:

- Partitioned Key Space (Memcached):
  - ∀`nodes i,j keys_i != keys_j`
- Strong Leadership (raft)
  - ∀`followers i length(log_leader) >= length(log_follower_i)`

Design goal: handle **real** distributed systems

Wanted: distributed state invariants

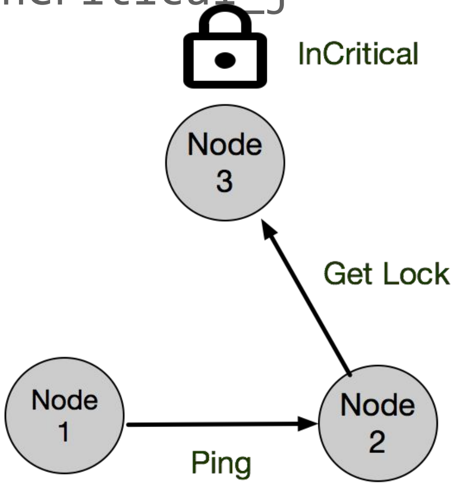
Make the fewest assumptions about the system as possible.

- N nodes
- Message passing
- Lossy, reorderable channels
- Joins and failures

Goal: Infer key correctness and safety properties

Mutual exclusion:

$\forall$ nodes i,j InCritical_i →¬InCritical_j



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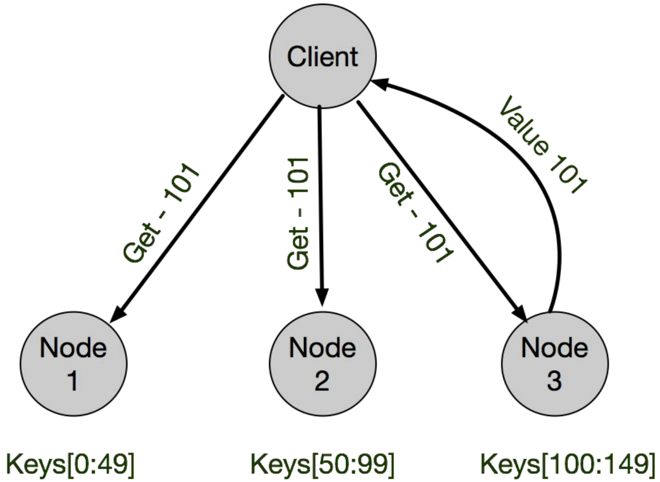

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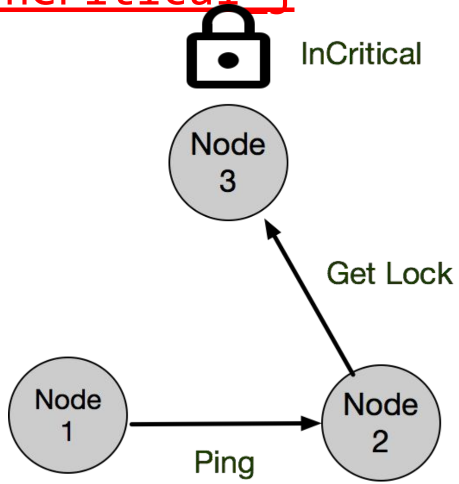

"Distributed State"

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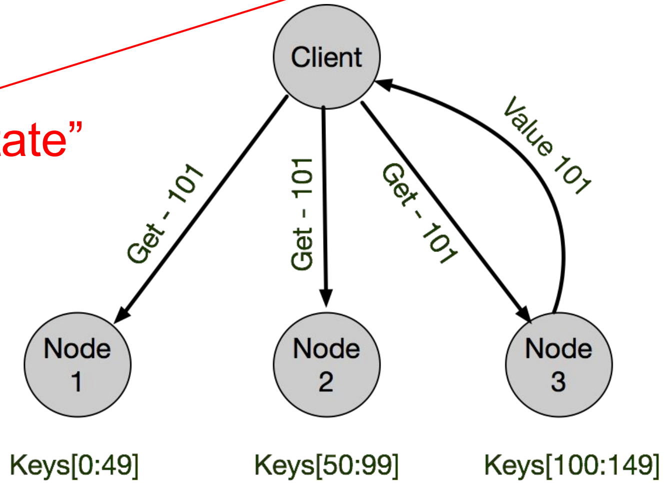

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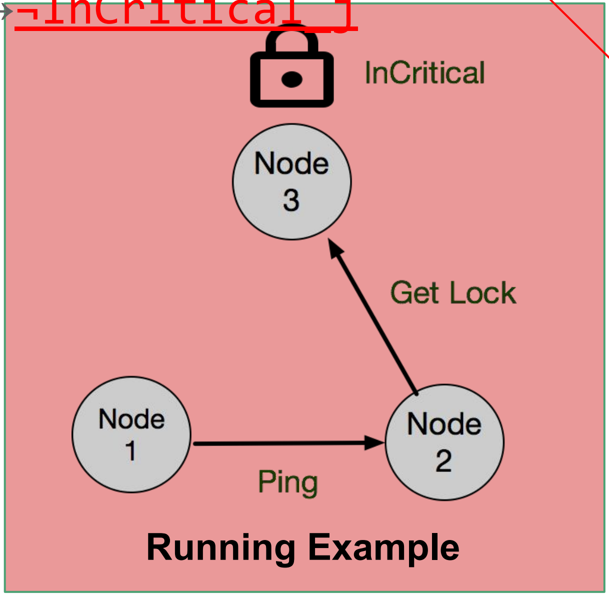

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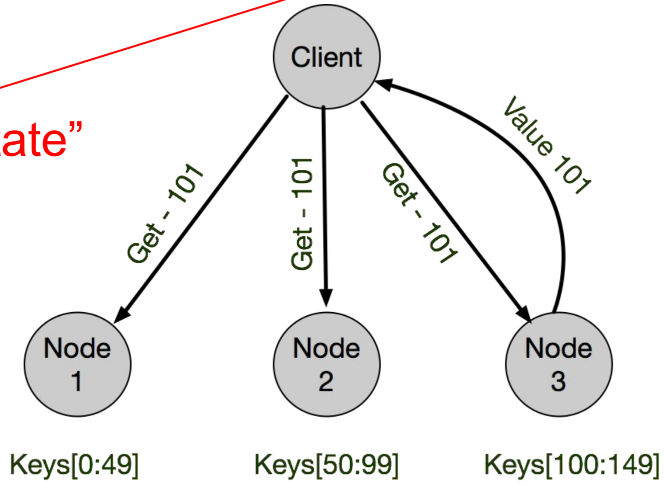
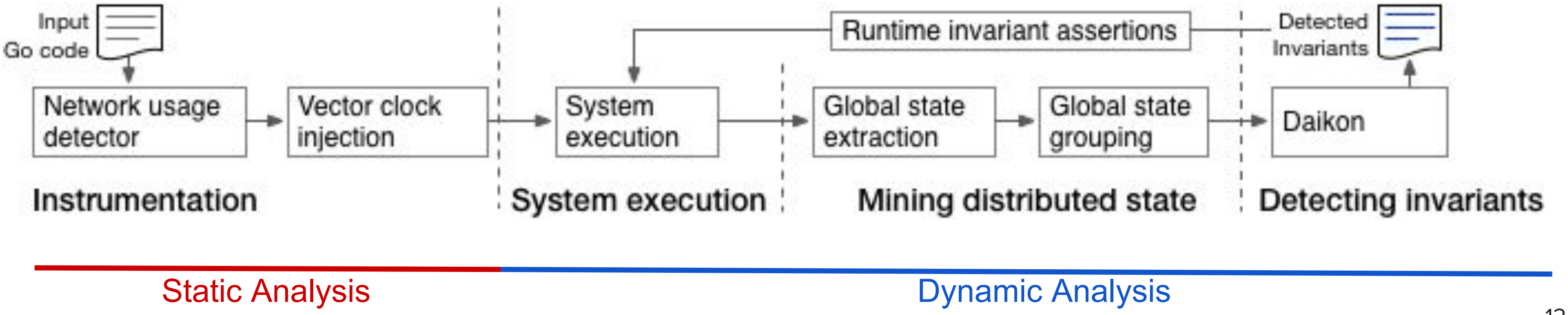


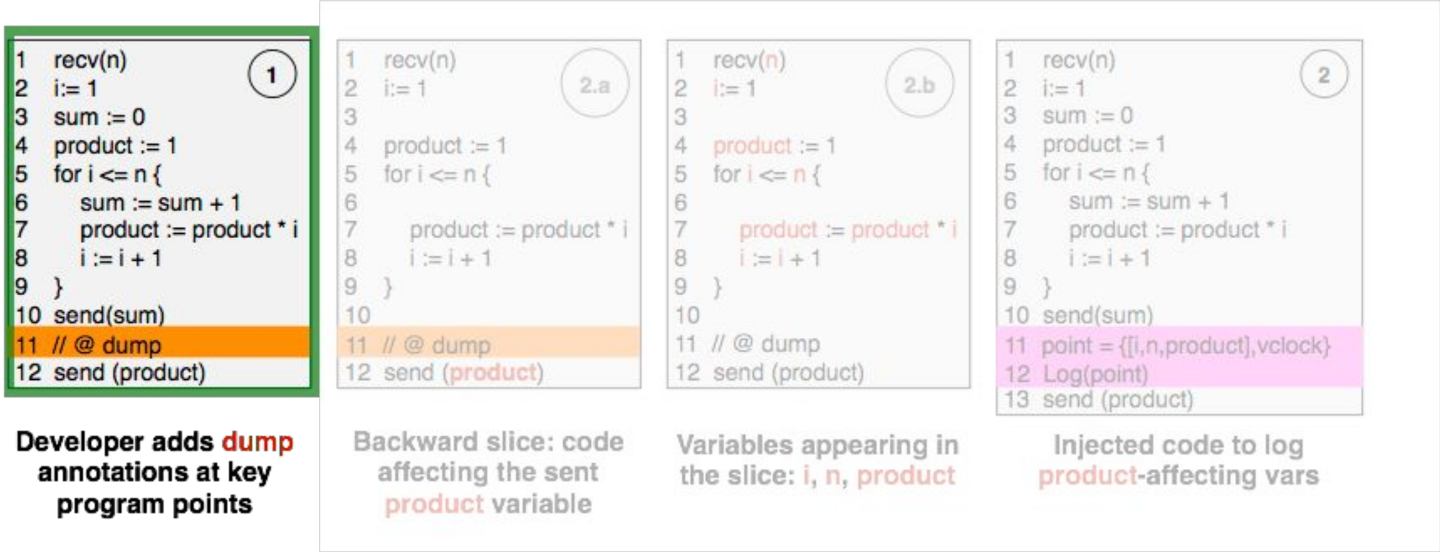
This talk: distributed invariants and Dinv

- Automatic distributed invariant inference (techniques & challenges)
- Runtime checking: distributed assertions
- Evaluation: 4 large scale distributed systems



Capturing Distributed State Automatically

1. Interprocedural Program Slicing
2. Logging Code Injection



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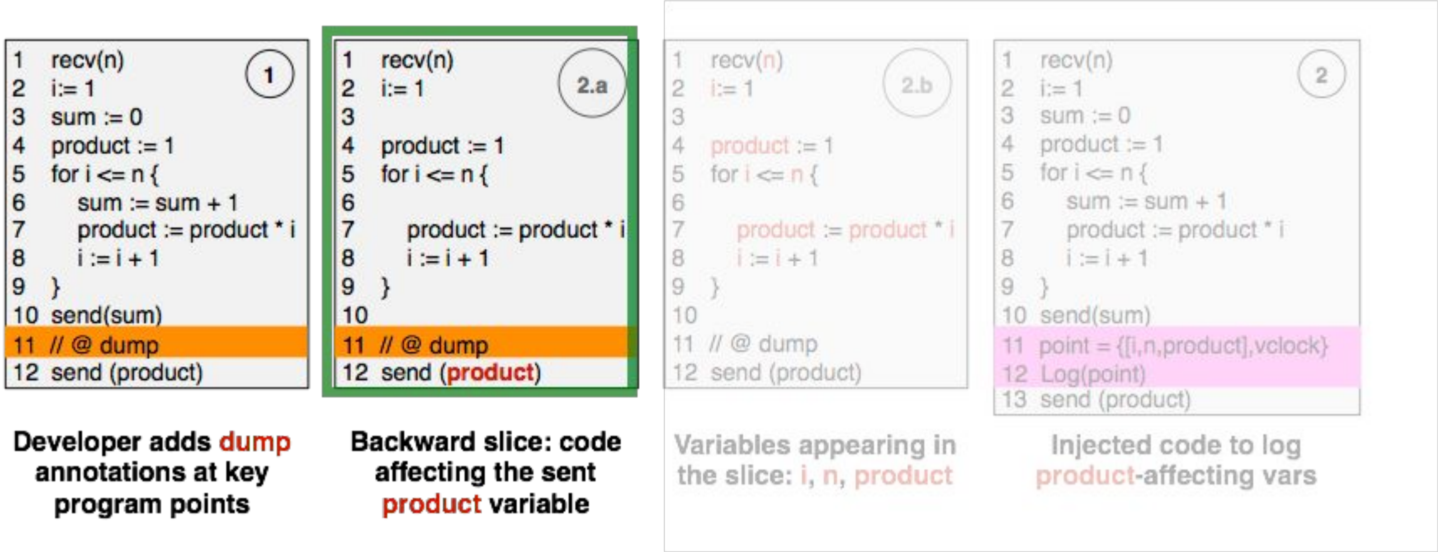

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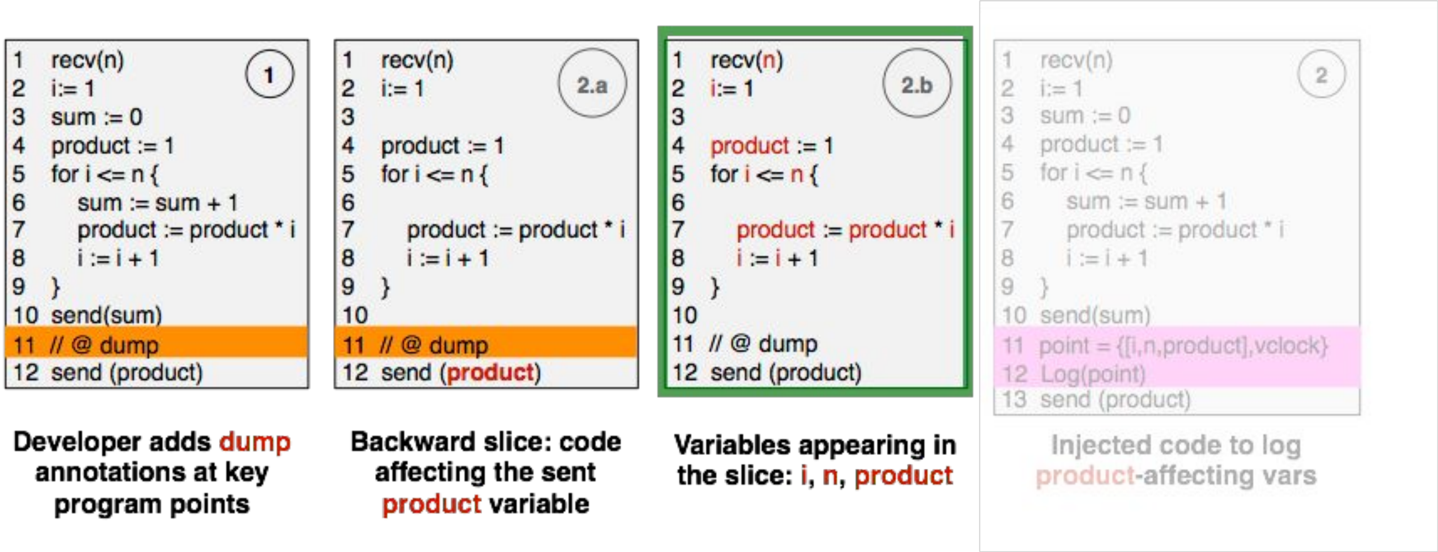

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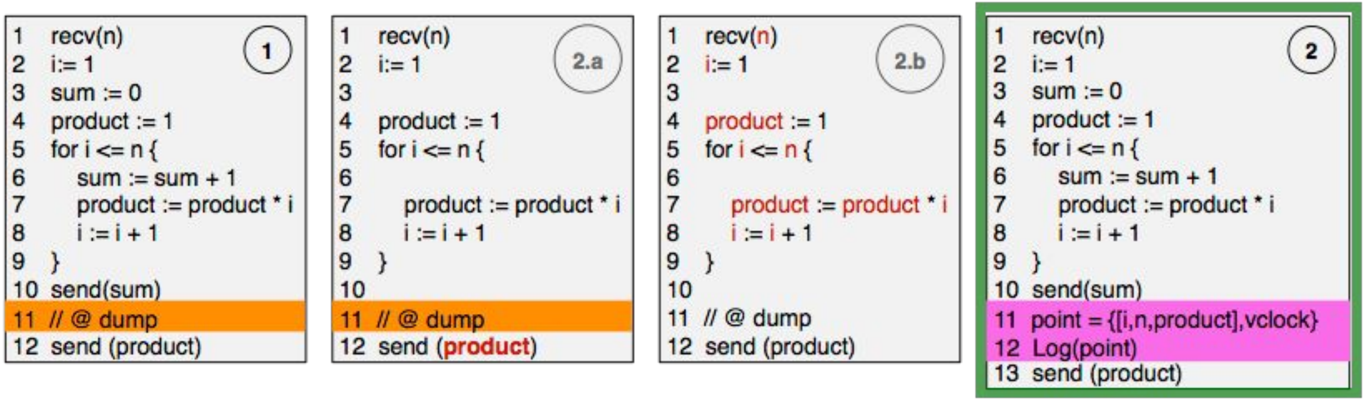

Developer adds dump annotations at key program points

Backward slice: code affecting the sent product variable

Variables appearing in the slice: i, n, product

Injected code to log product-affecting vars

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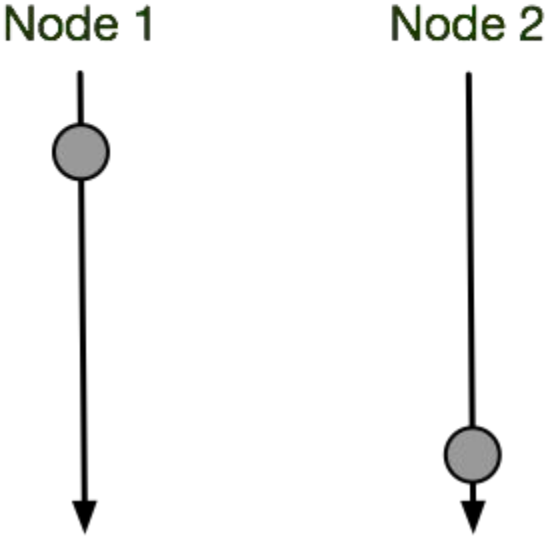

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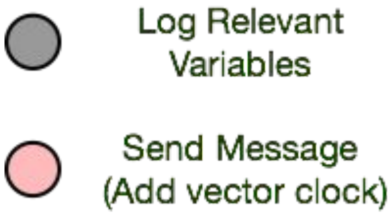
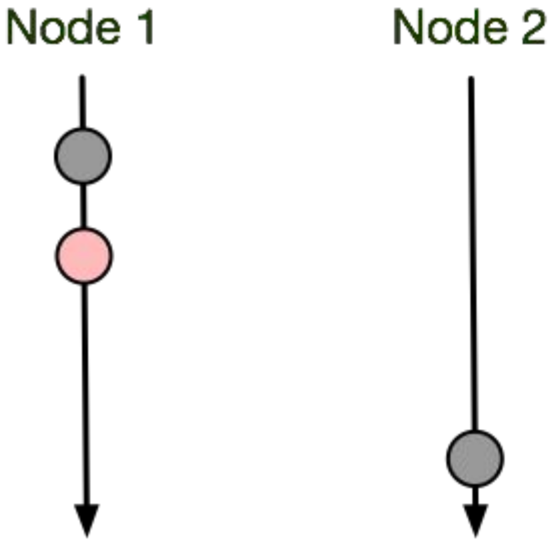
3. Vector Clock Injection





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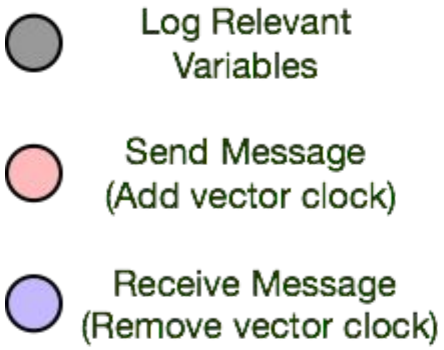

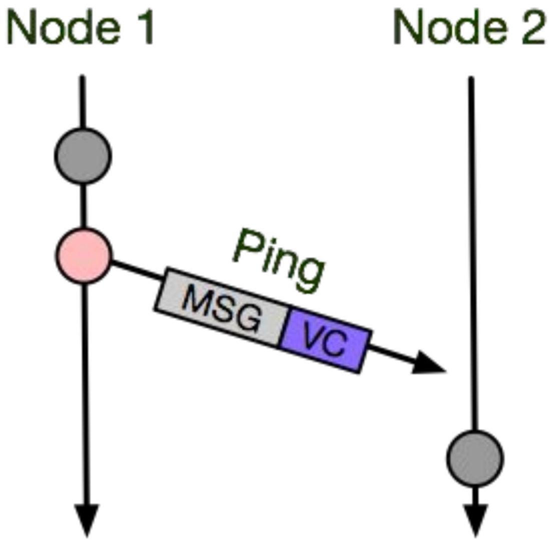

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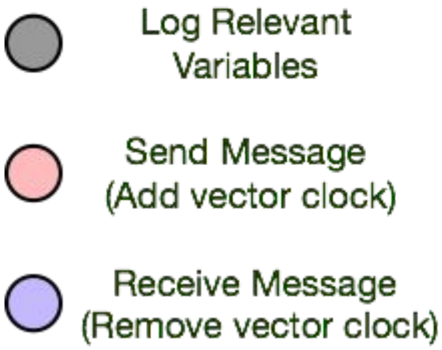

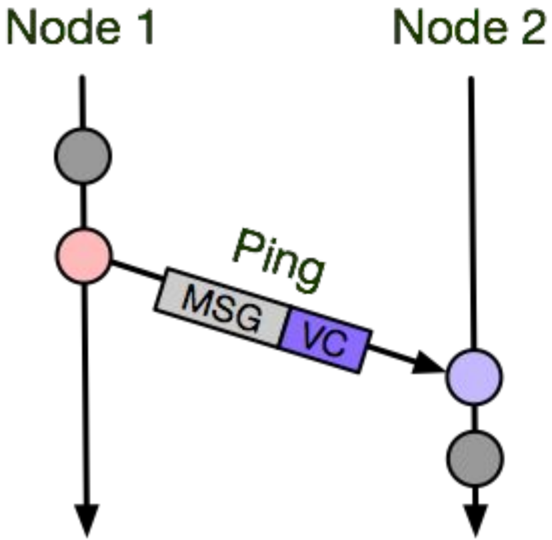

Consistent Cuts / Ground States

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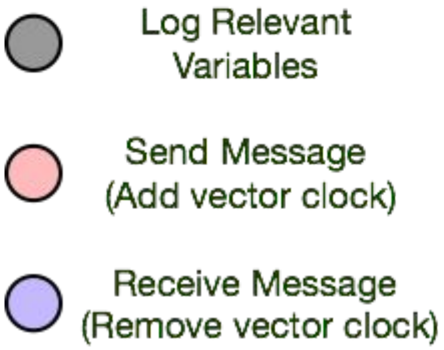
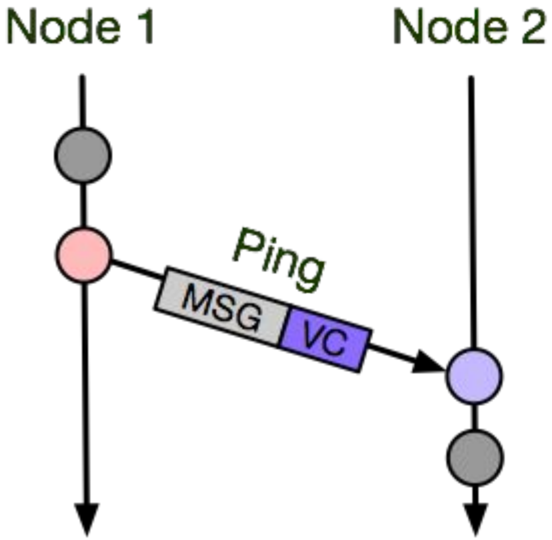
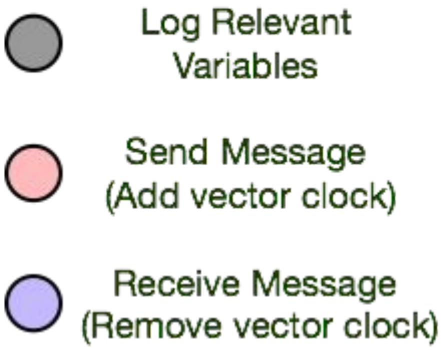
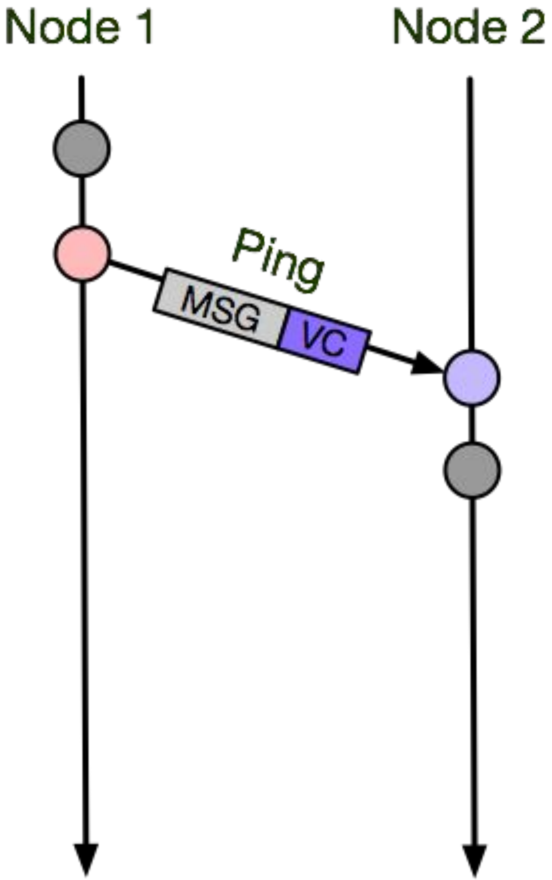




Consistent Cuts / Ground States

- Fast Forward





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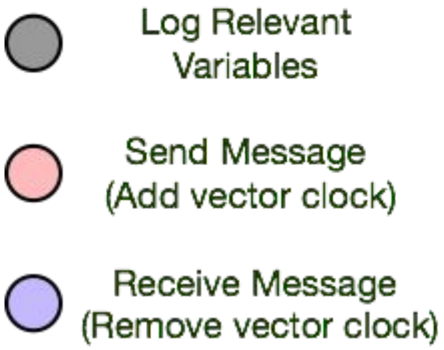

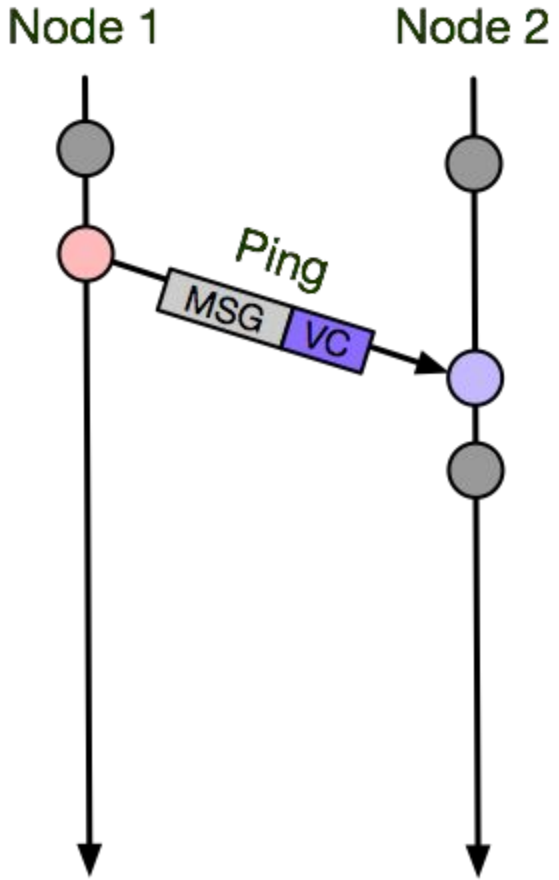

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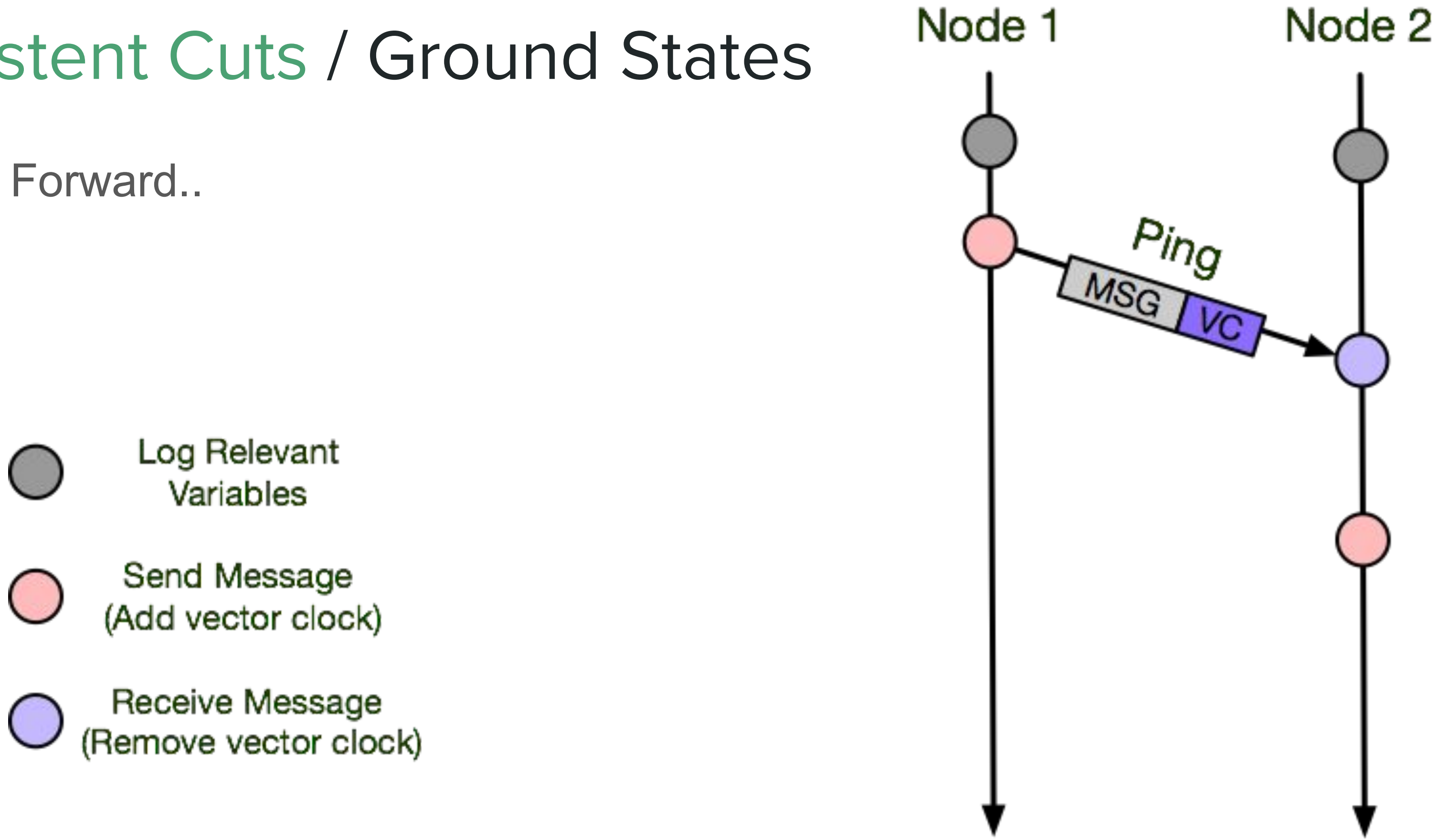

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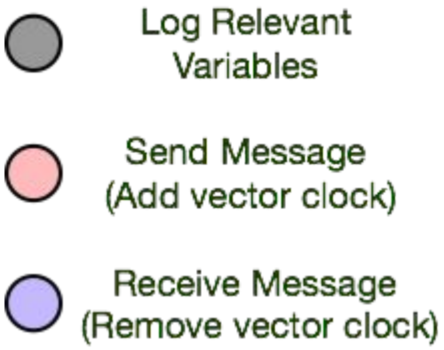

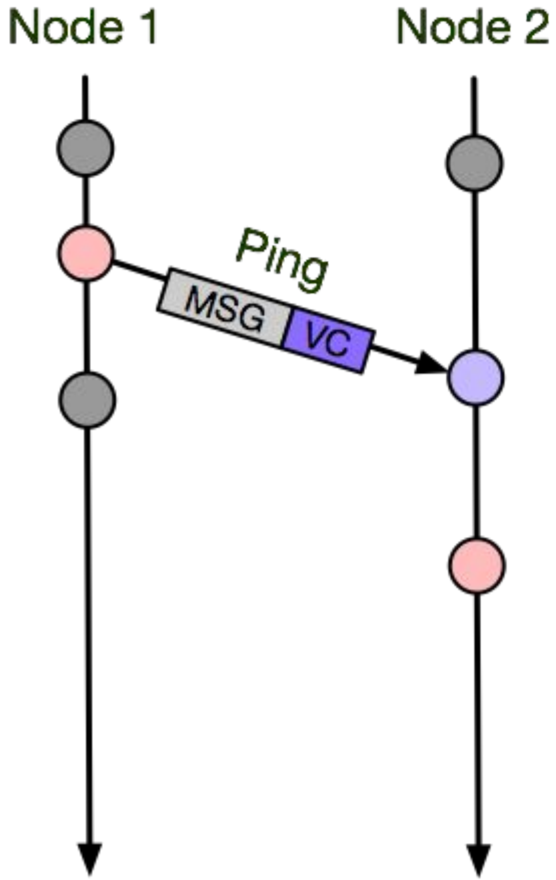

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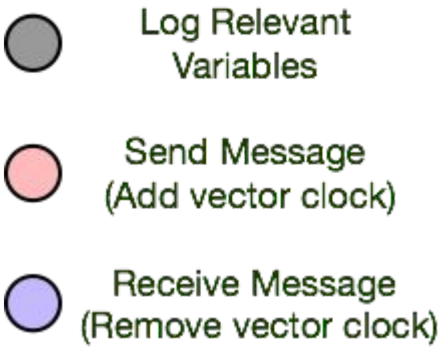

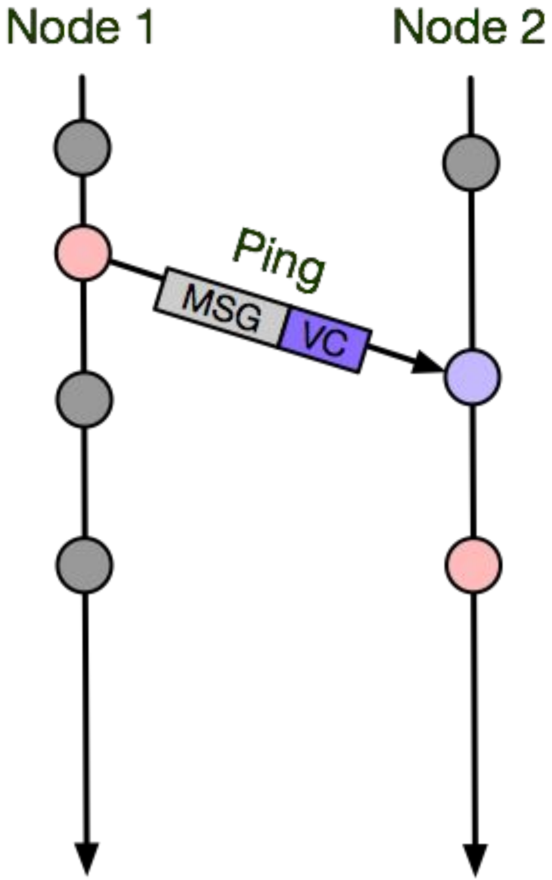

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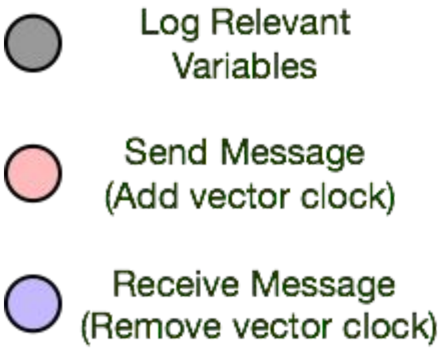

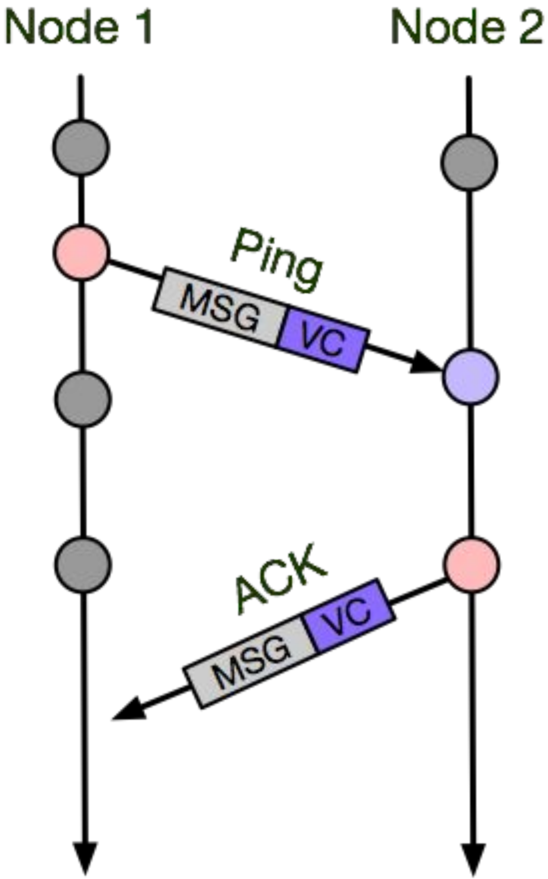

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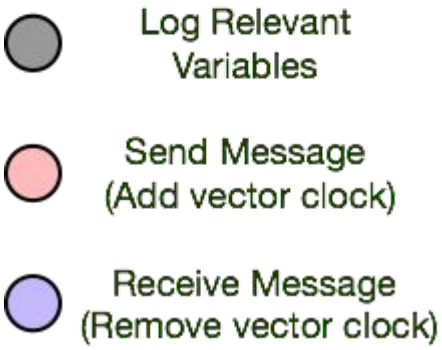

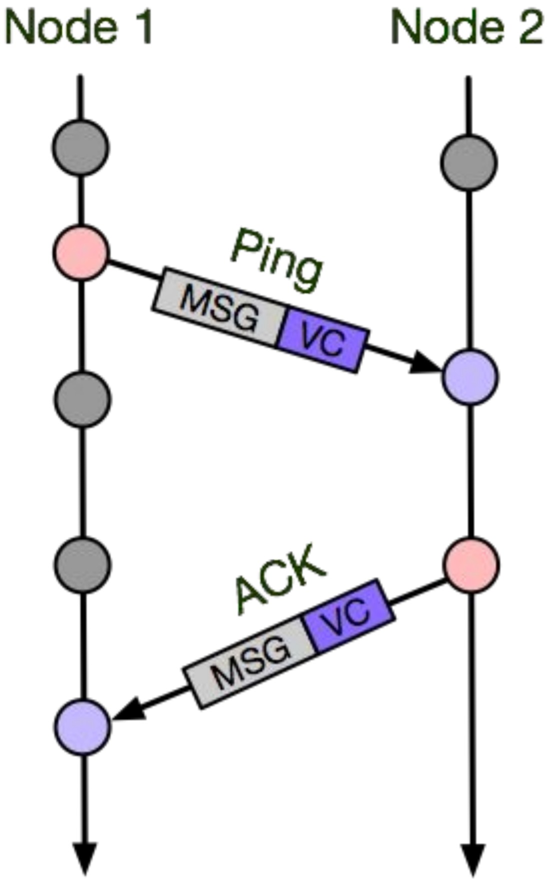

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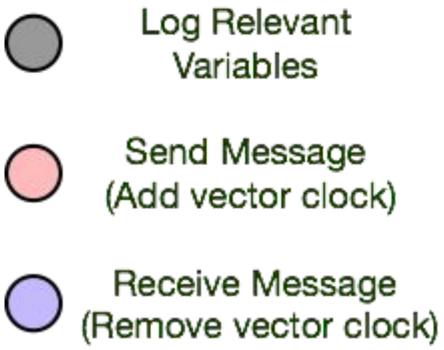
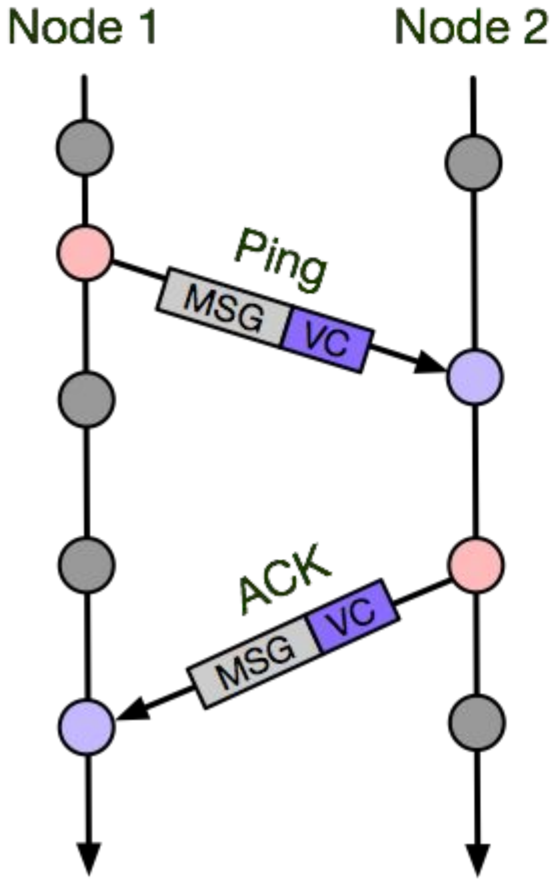
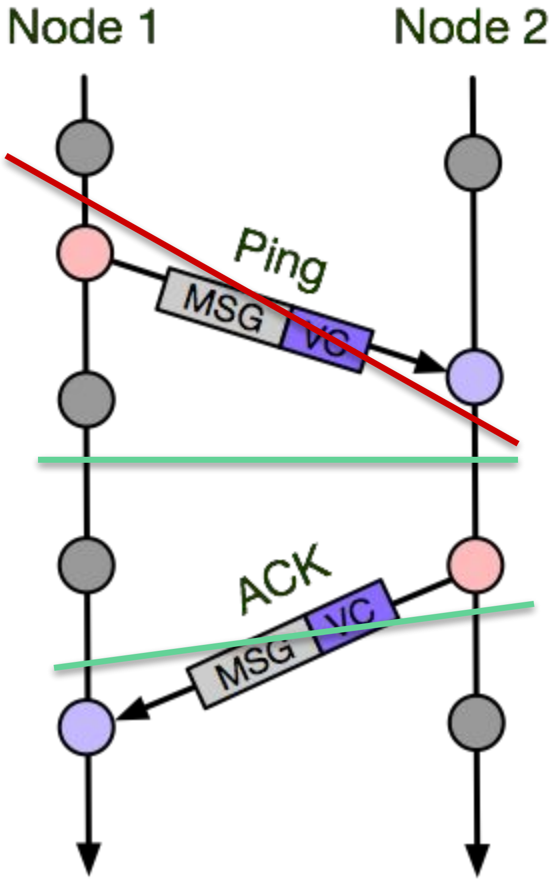




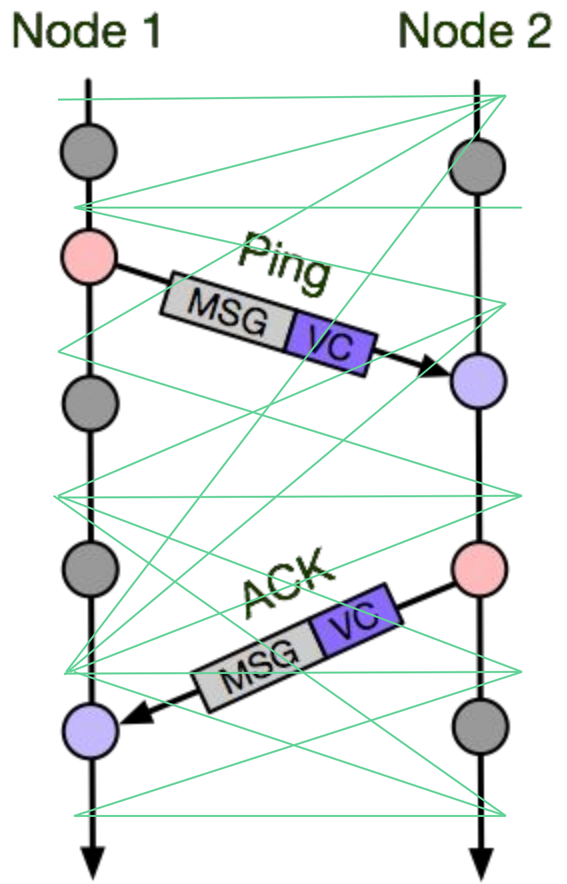
Consistent Cuts / Ground States

- Green lines mark consistent cuts
  - No messages are in flight
  - Message sent but not received
- The red line is not a consistent cut
  - The ping sent by Node 0 happened before the pings receipt on node 1.



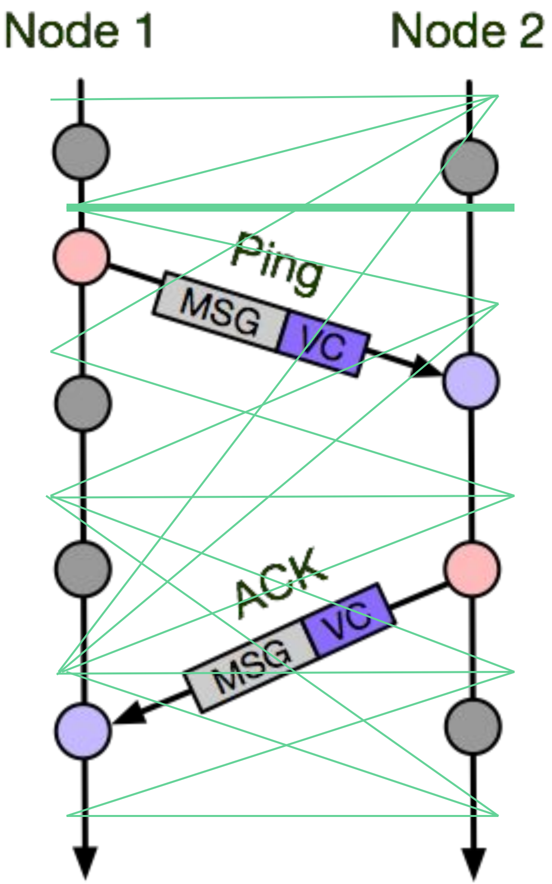
Consistent Cuts / Ground States

- Huge number of consistent cuts



Consistent Cuts / Ground States

- Huge number of consistent cuts
- Require sampling heuristic



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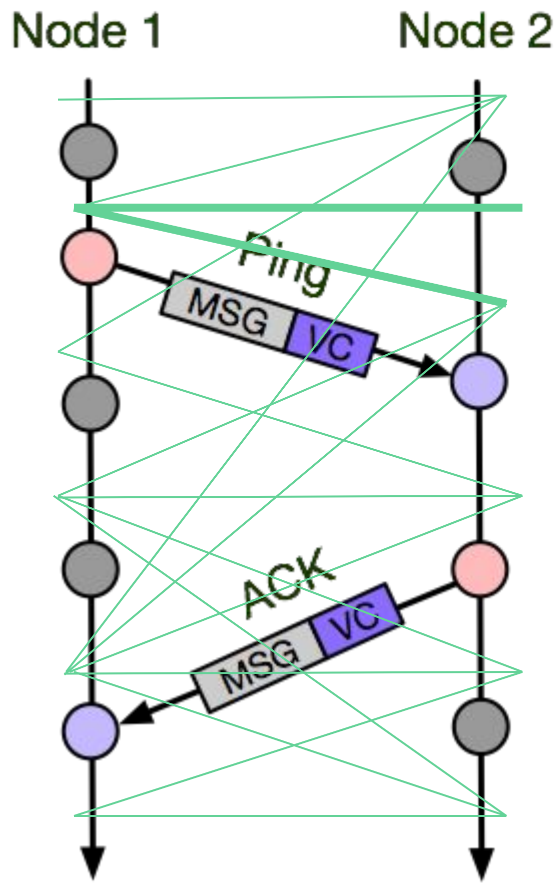

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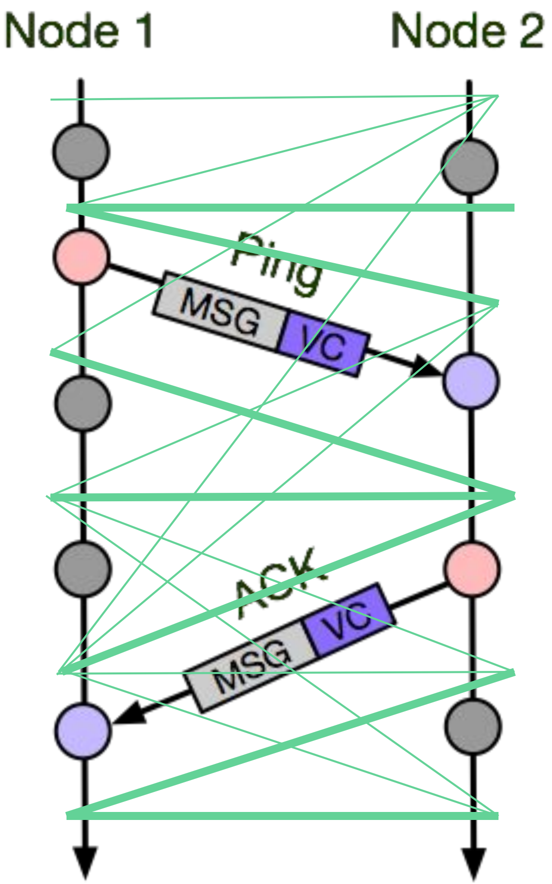
- Dramatically collapses search space



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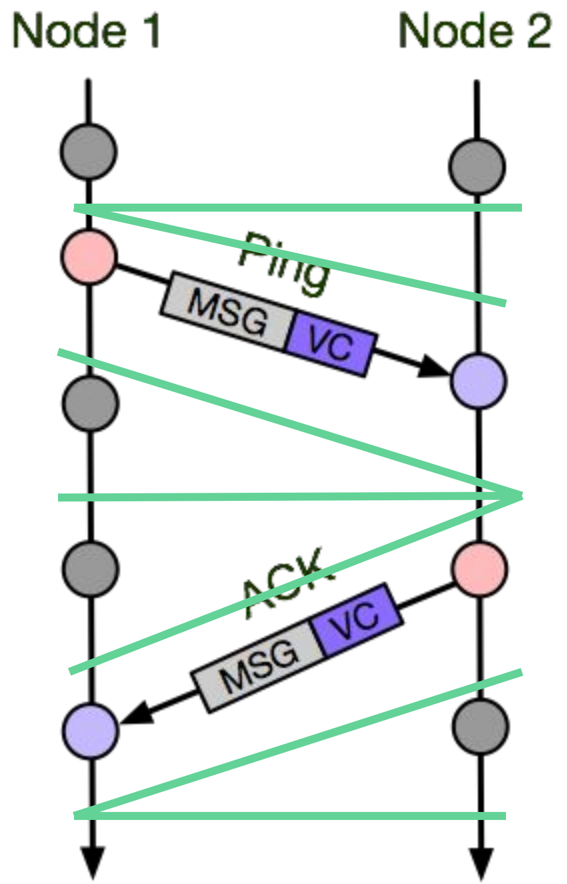
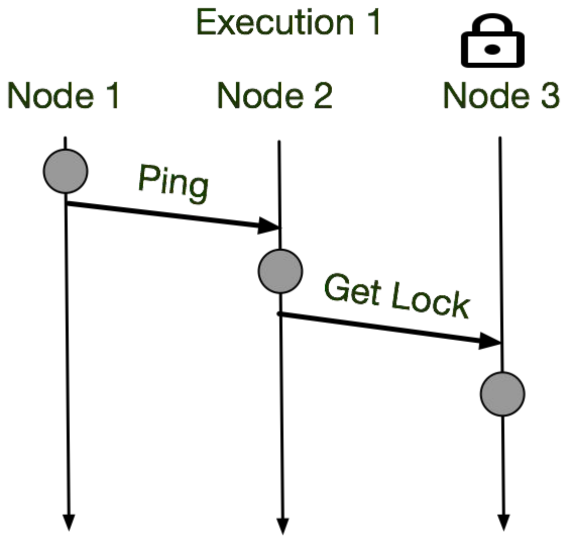
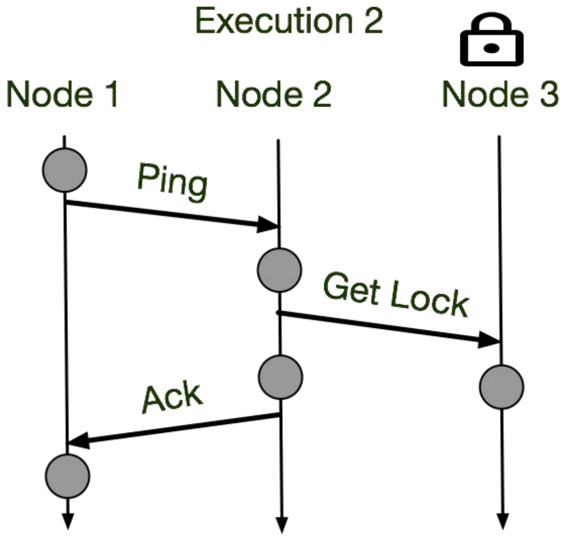
Ground State sampling used exclusively in evaluation



Reasoning About Global State: State Bucketing





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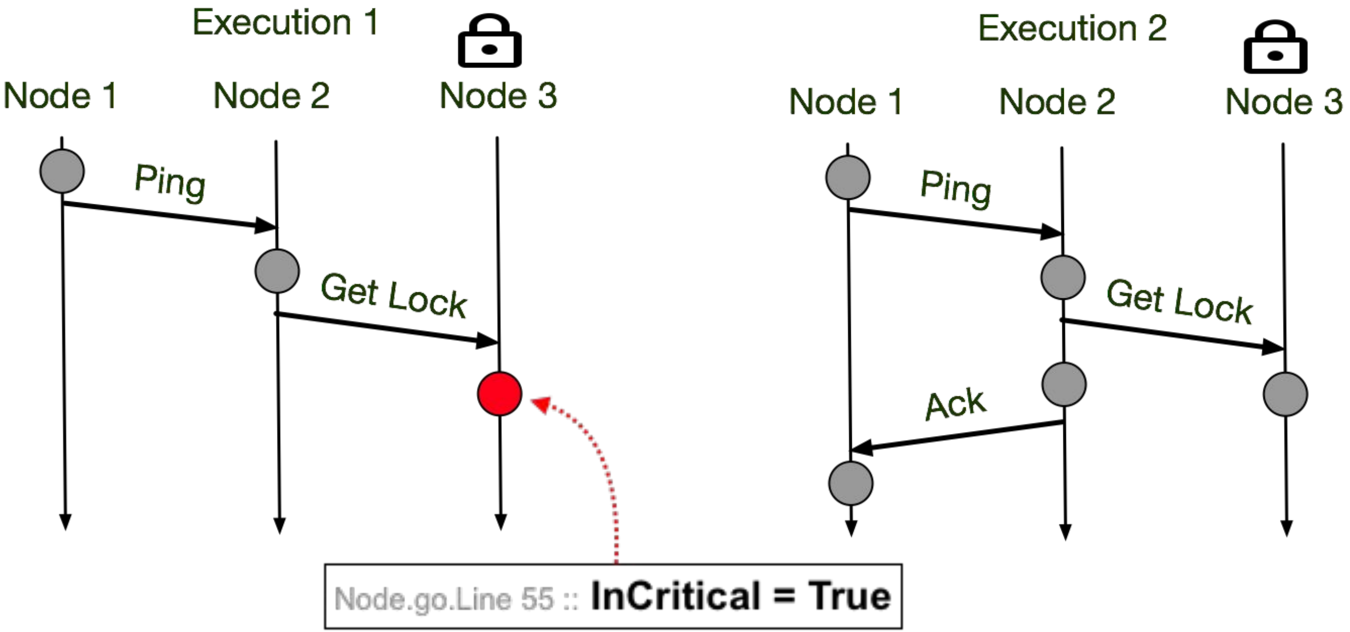

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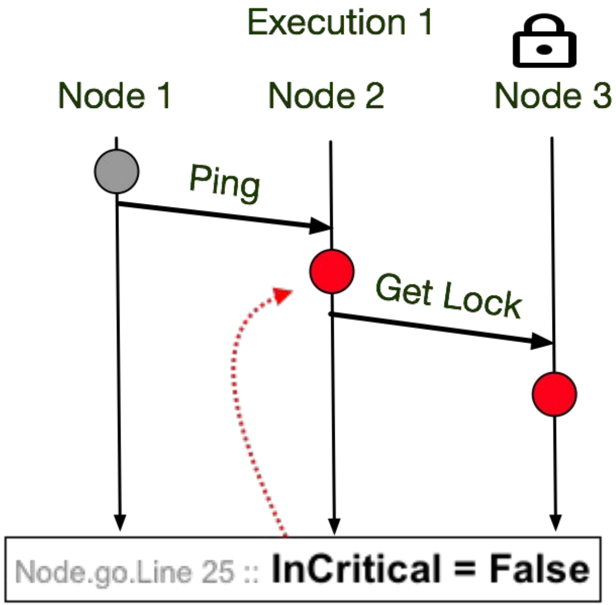

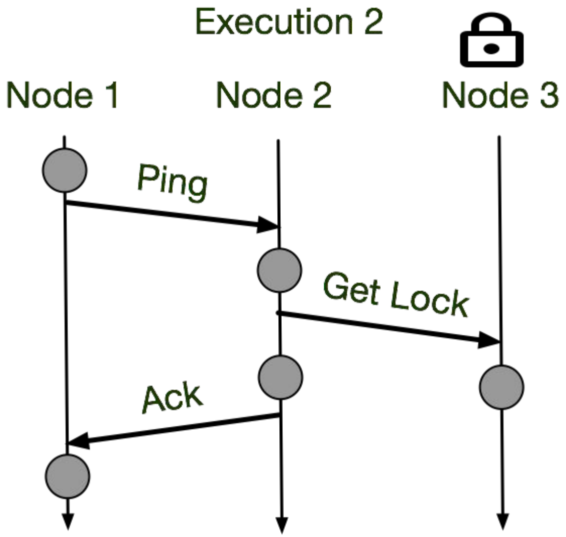

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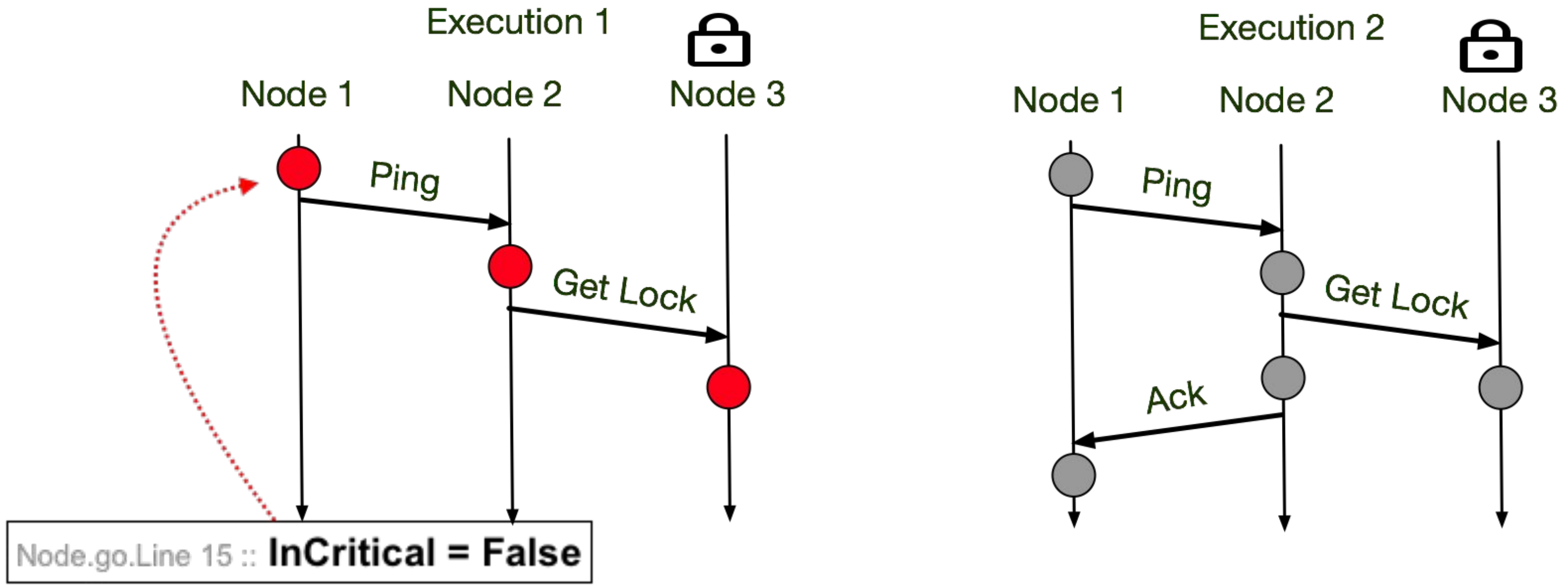

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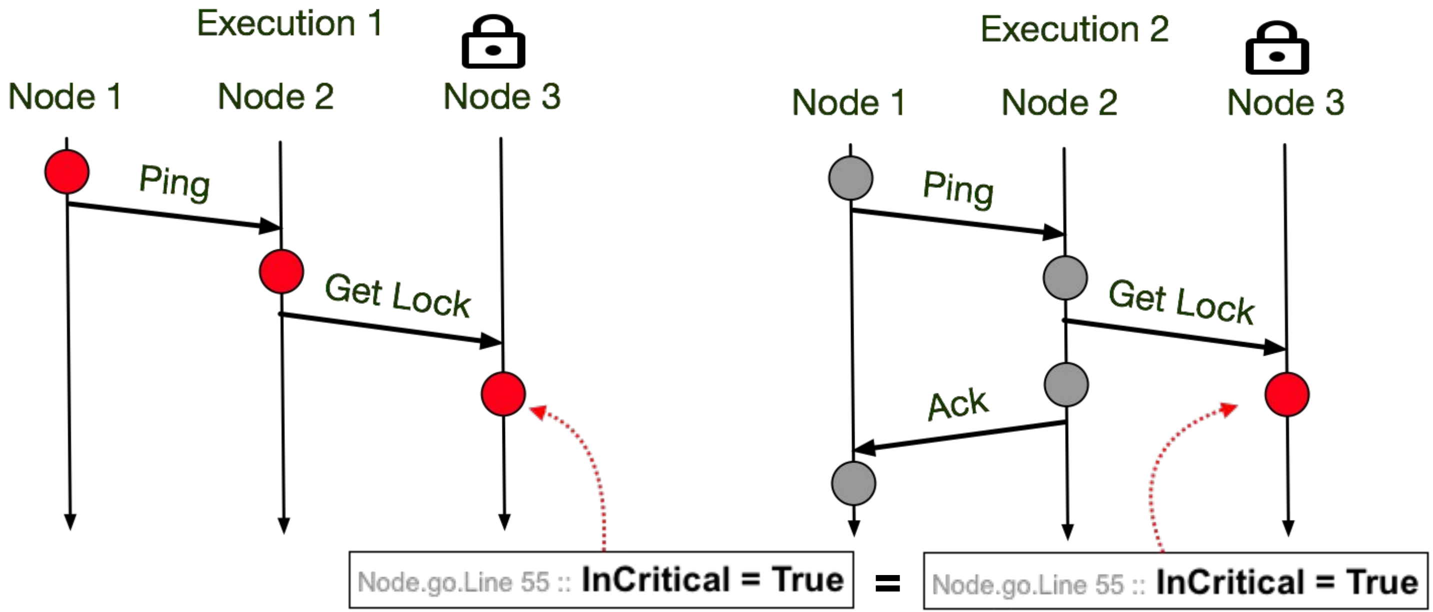

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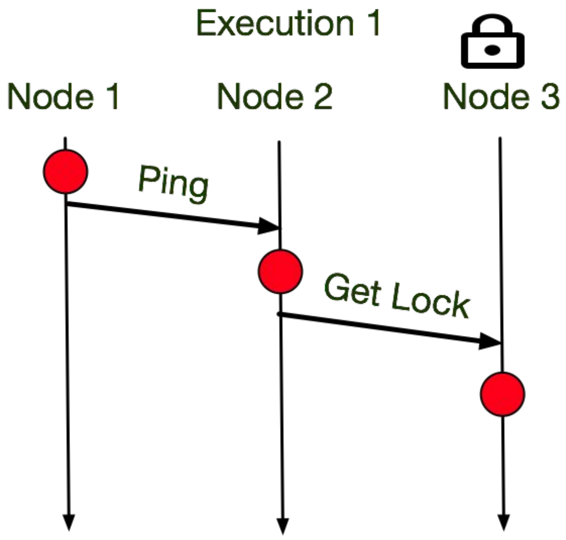

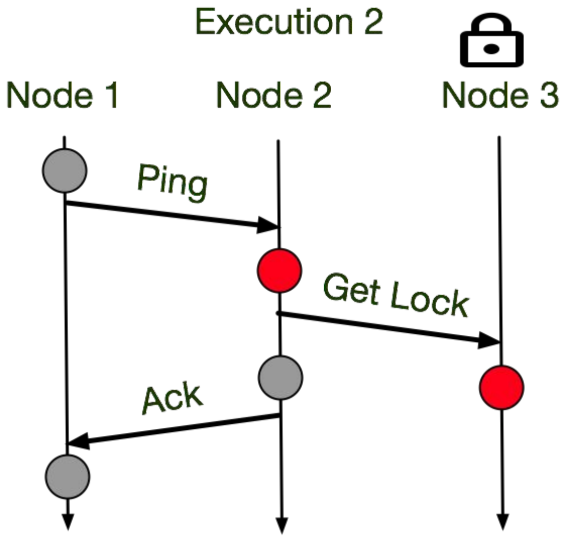

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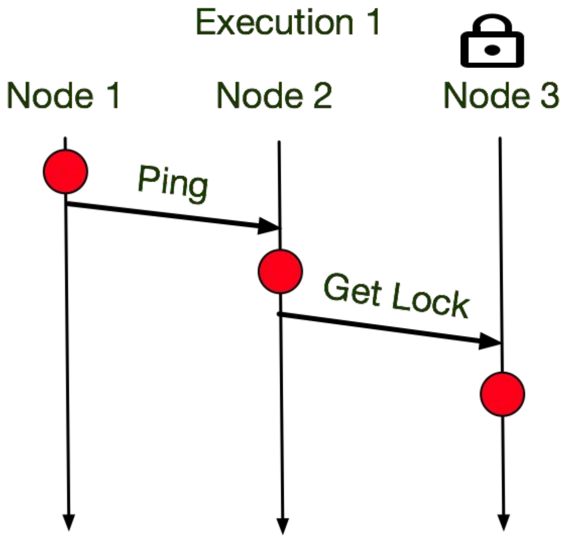

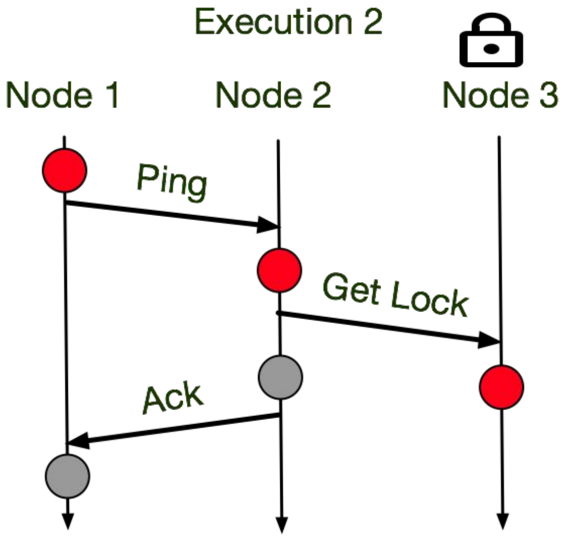

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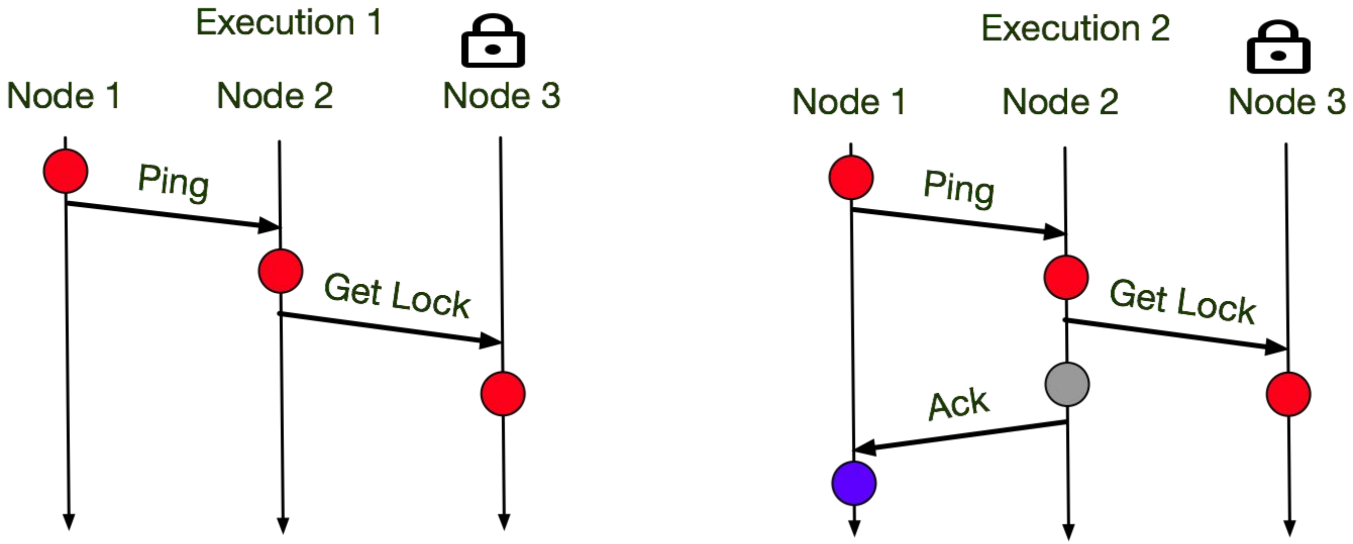

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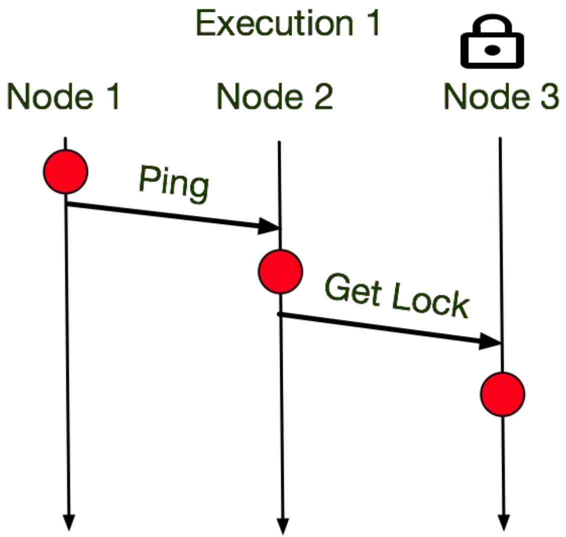

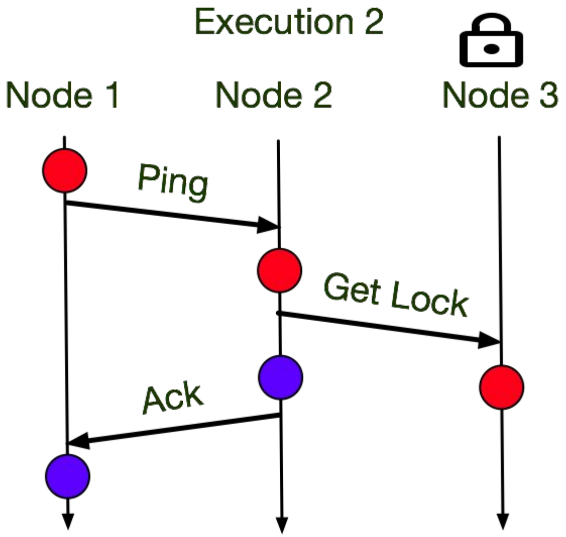

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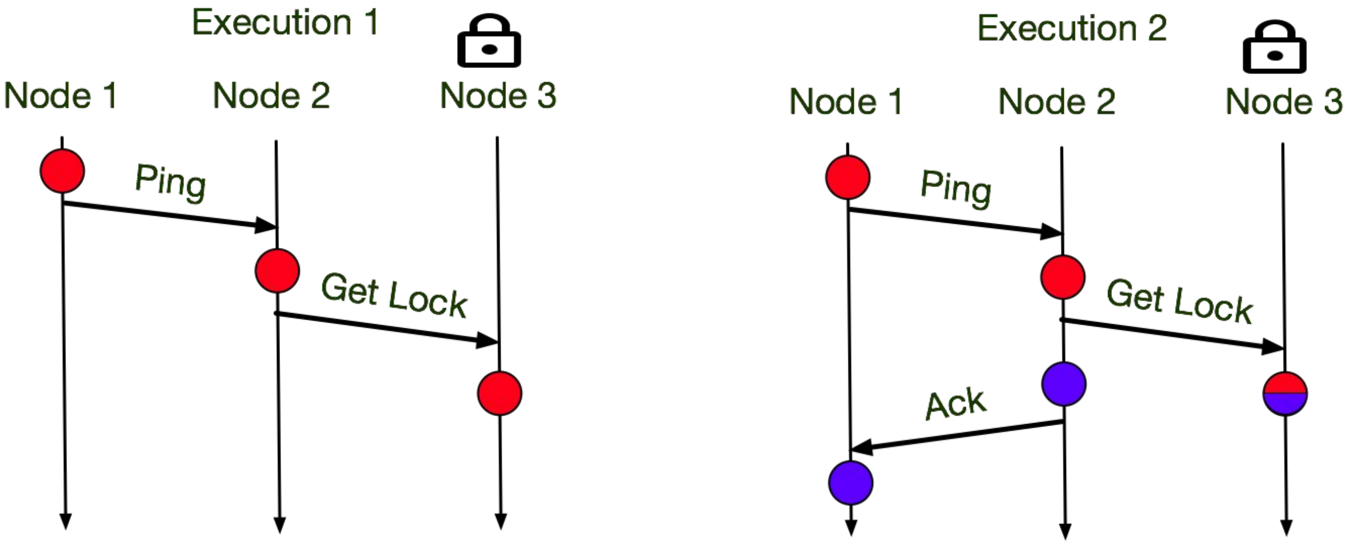

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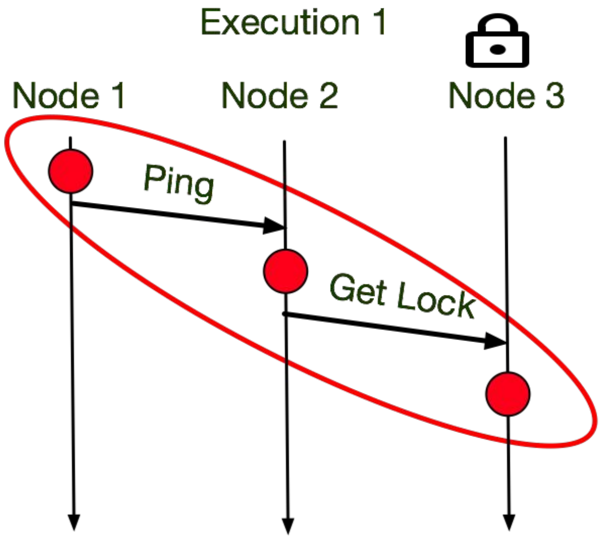

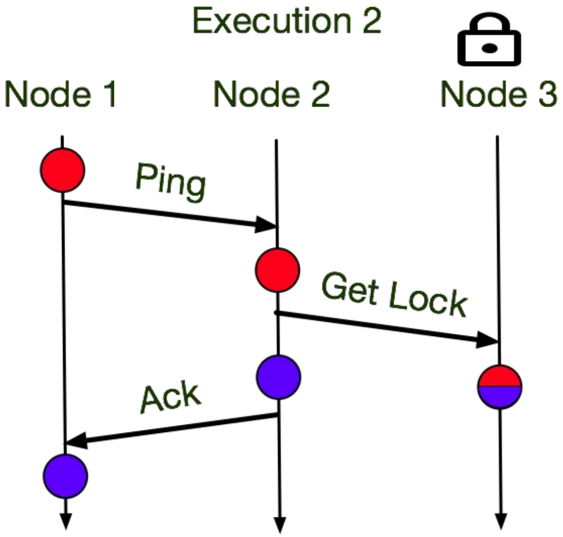

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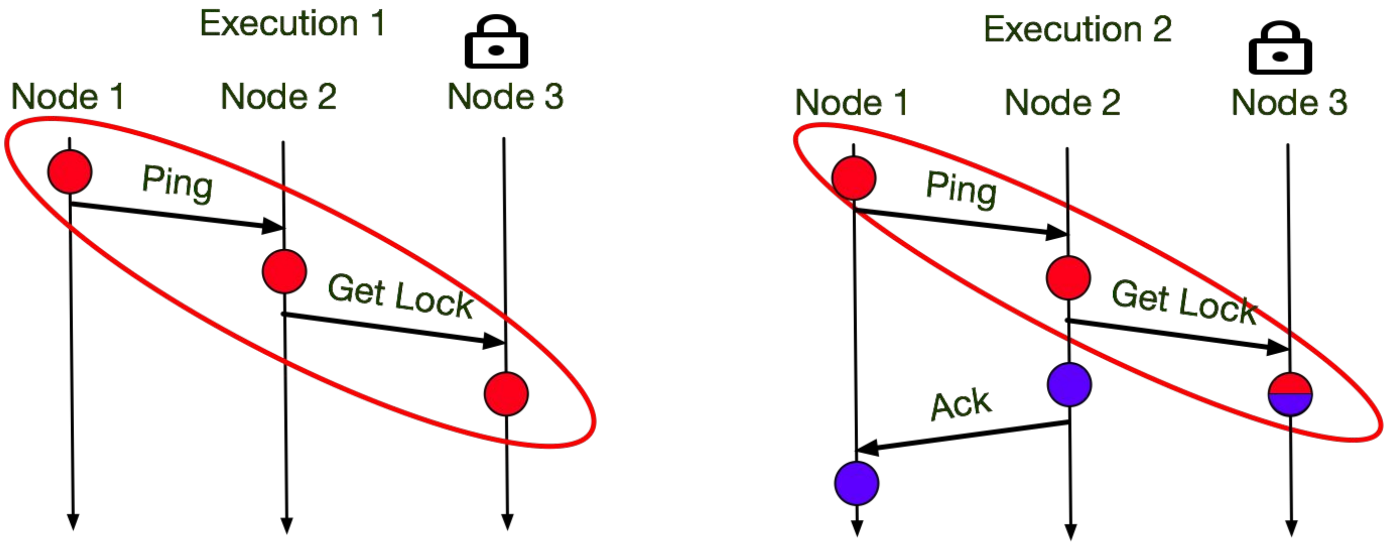

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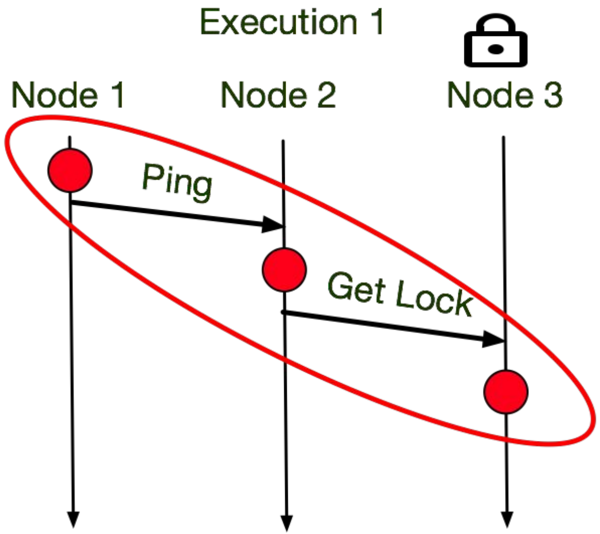

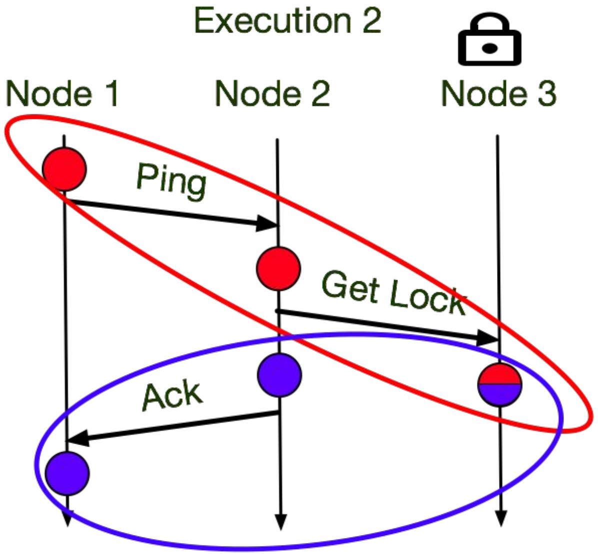

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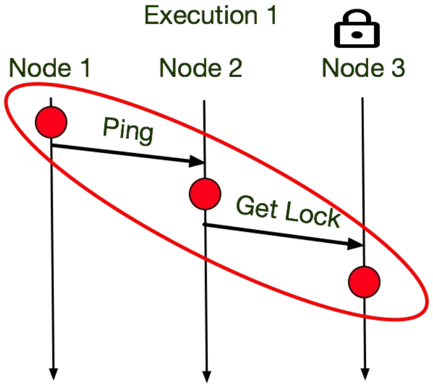
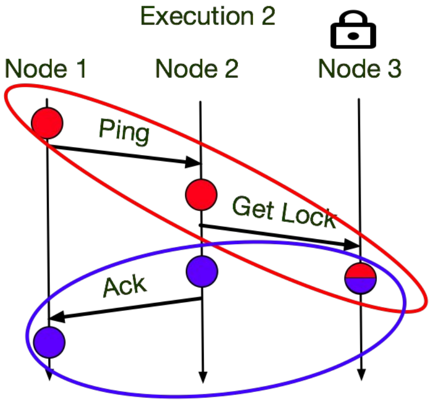
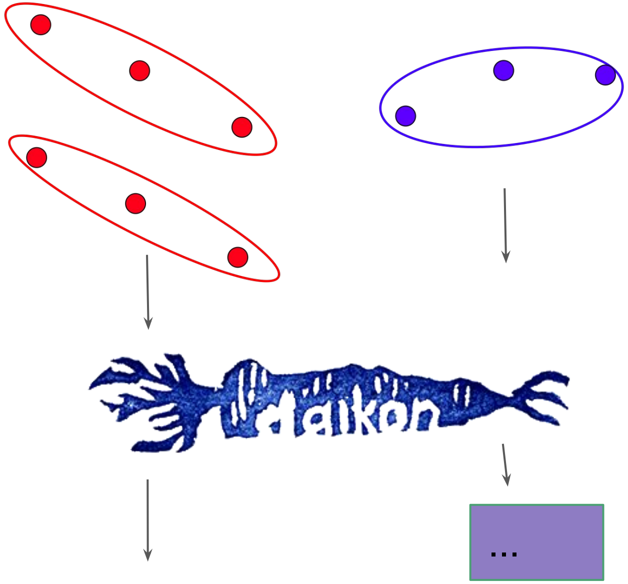




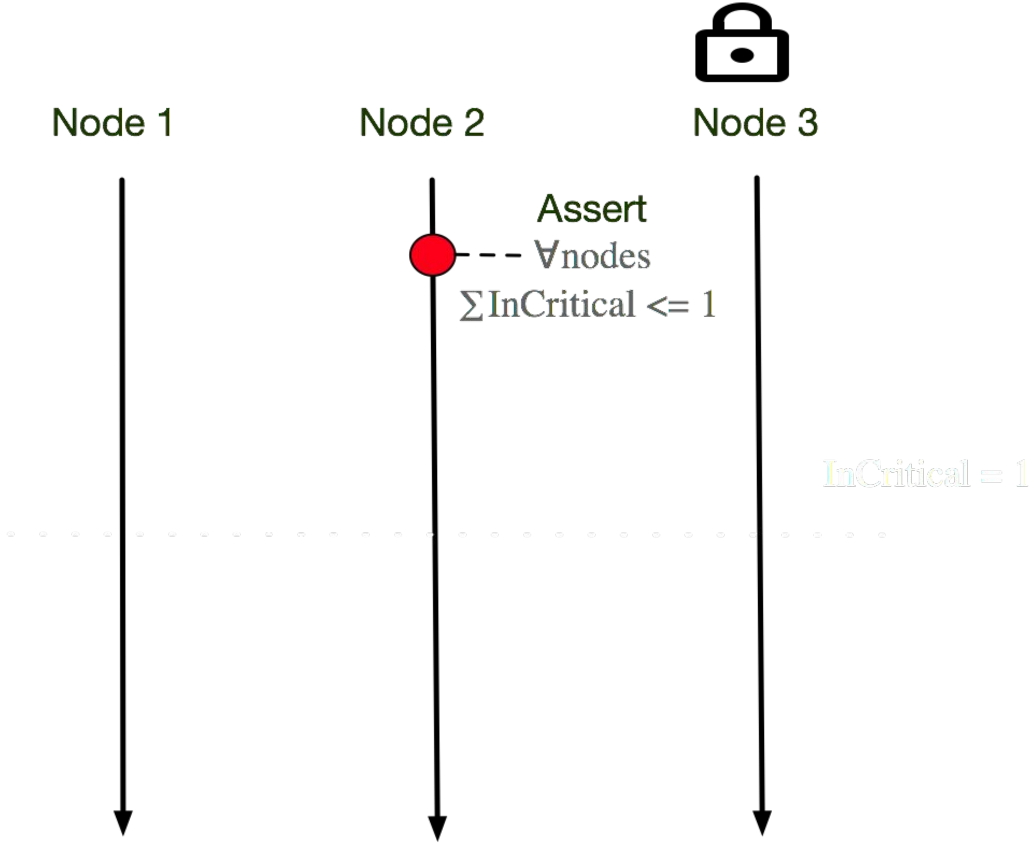


“Likely” Invariants

Node_**3**_InCritical == **True**
Node_**2**_InCritical != Node_**3**_InCritical
Node_**2**_InCritical == Node_**1**_InCritical

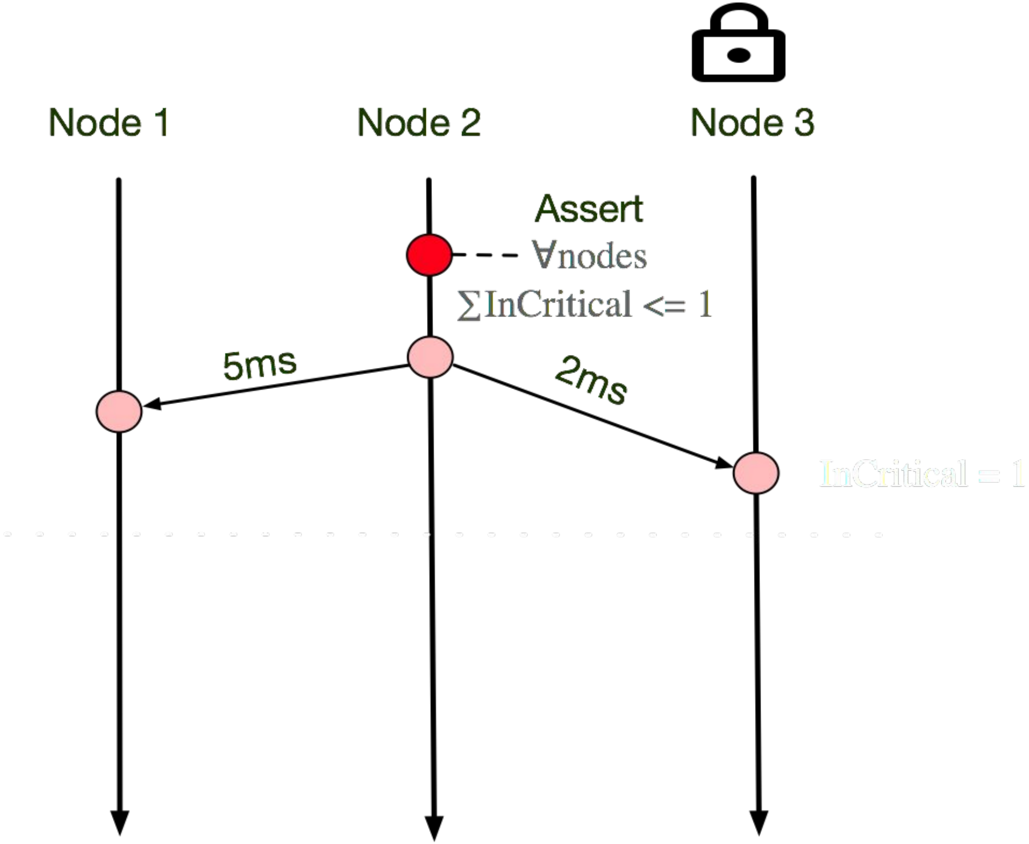
Distributed Asserts

- Distributed asserts enforce invariants at runtime



Distributed Asserts

- Distributed asserts enforce invariants at runtime
- Snapshots are constructed using approximate synchrony



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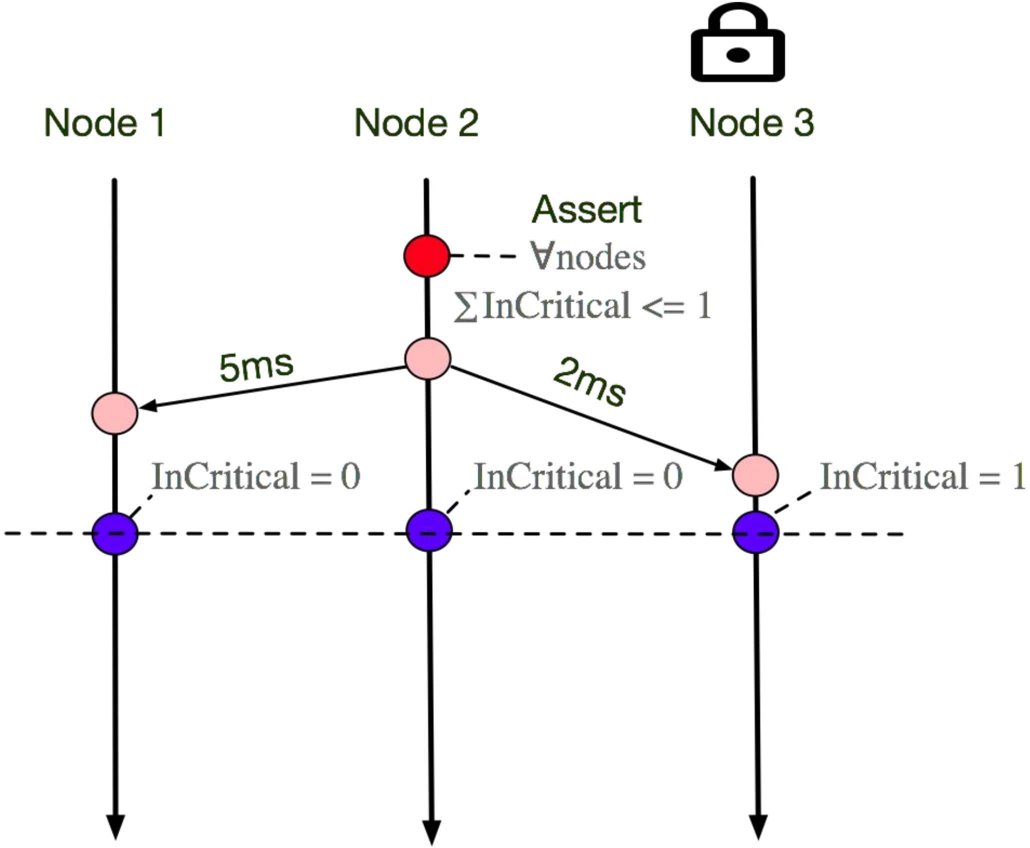

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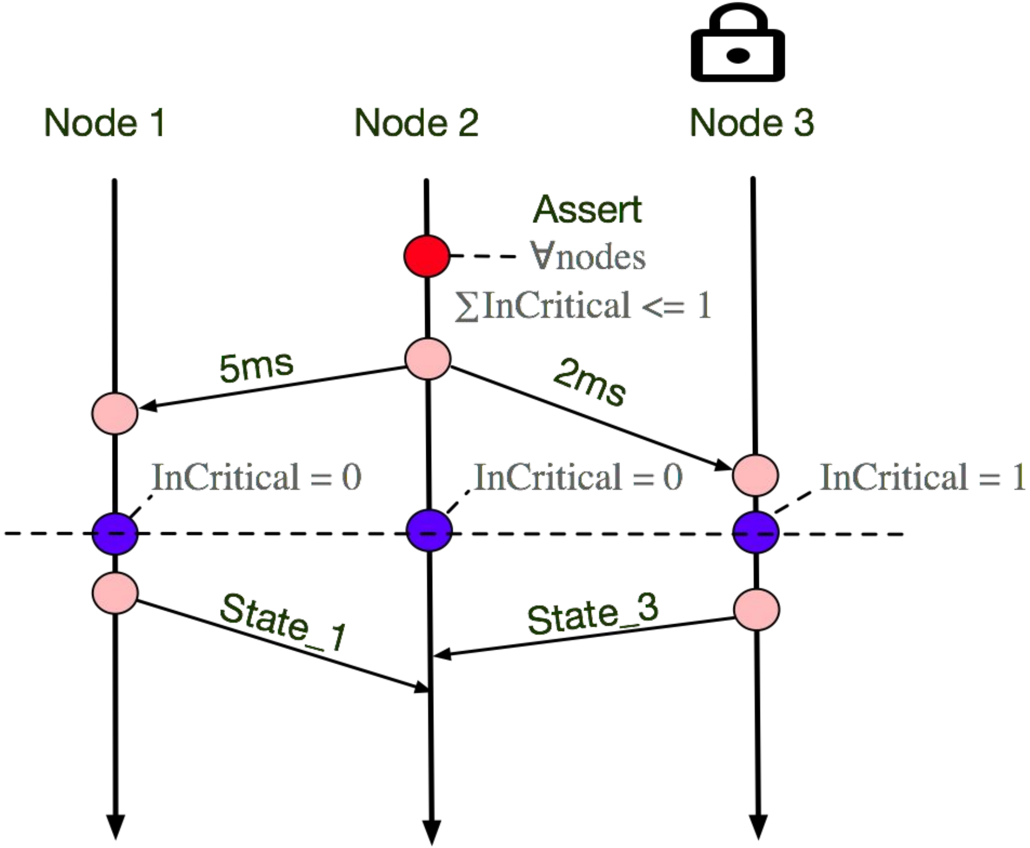

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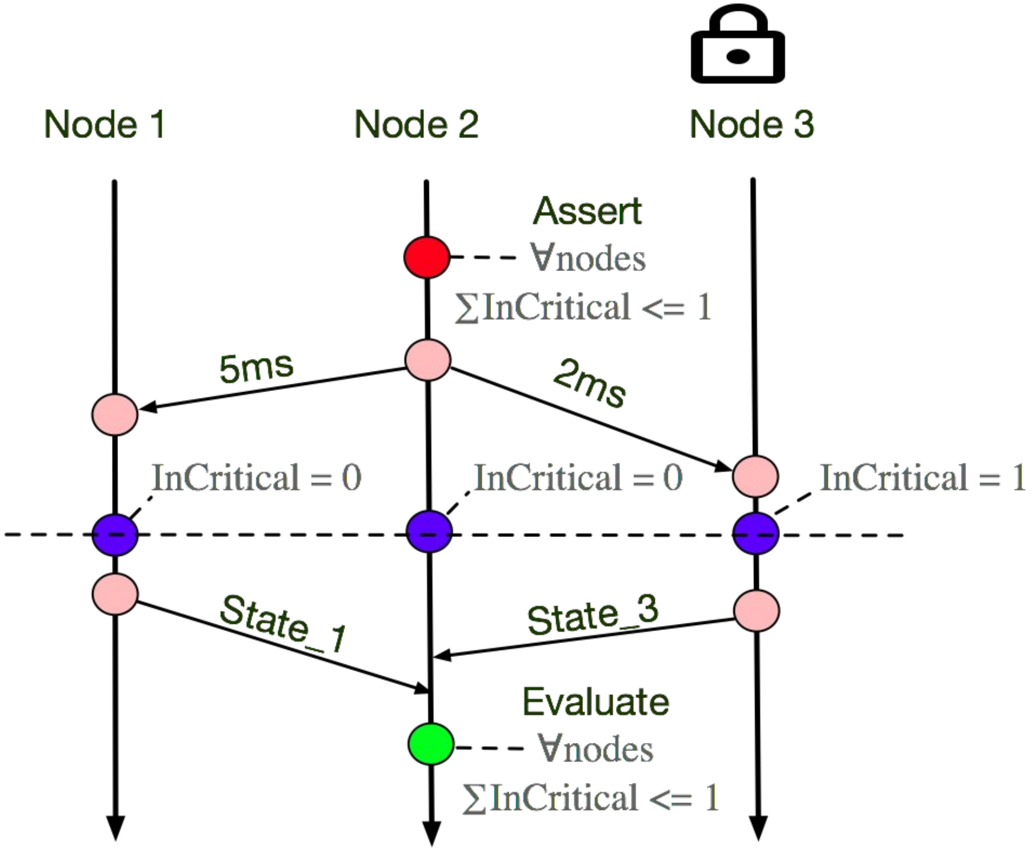

Evaluated Systems

Etcd: Key-Value store running Raft - 120K LOC

Serf: large scale gossiping failure detector - 6.3K LOC

Taipei-Torrent: Torrent engine written in Go - 5.8K LOC

Groupcache: Memcached written in Go - 1.7K LOC

Etcd ~ 120K Lines of Code

System and Targeted property	Dinv-inferred invariant	Description
Raft **Strong Leader principle**	**∀ follower *i*, len(leader log) ≥ len(*i*'s log)**	**All appended log entries must be propagated by the leader**
Raft Log matching	∀ nodes *i, j* if *i*-log[*c*] = *j*-log[*c*] → ∀(*x* ≤ *c*), *i*-log[*x*] = *j*-log[*x*]	If two logs contain an entry with the same index and term, then the logs are identical on all previous entries.
Raft Leader agreement	If ∃ node *i*, s.t *i* leader, than ∀ *j* ≠ *i, j* follower	If a leader exists, then all other nodes are followers.

*Raft: In search of an understandable consensus algorithm, D.Ongaro et. al

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Injected Bugs for each invariant caught with assertions

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See the paper for full system evaluation

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Limitations and future work

Limitations

- Dinv’s dynamic analysis is incomplete
- Ground state sampling is poor on loosely coupled systems
- Large number of generated invariants

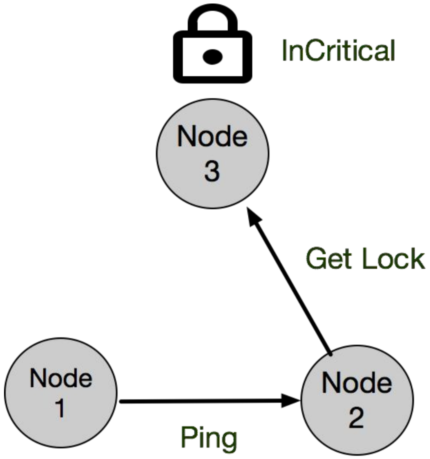
Future work

- Extend analysis to temporal invariants
- Bug Isolation
- Distributed test case generation
- Mutation testing/analysis based on mined invariants

Dinv: Contributions

Analysis for distributed Go systems

- Automatic **distributed state** invariant inference
  - Static identification of distributed state
  - Automatic static instrumentation
  - Post-execution merging of distributed states
- Runtime checking: distributed assertions



∀nodes InCritical <= 1

Repo: https://bitbucket.org/bestchai/dinv

Demo: https://www.youtube.com/watch?v=n9fH9ABJ6S4