Automated

I4: ~~Incremental Inference of Inductive Invariants for~~ Verification of Distributed Protocols

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Artifacts Evaluated Functional acm
Artifacts Available acm
Results Replicated acm

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Distributed Systems Are Subtle

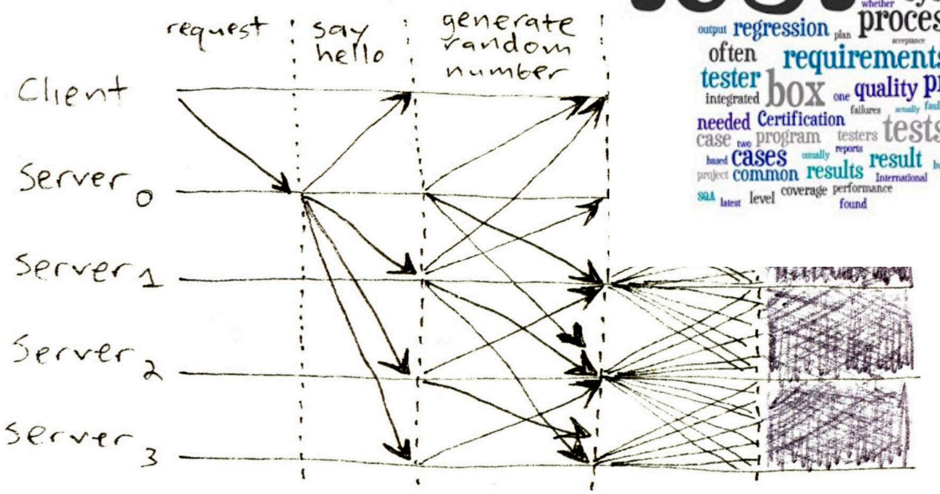
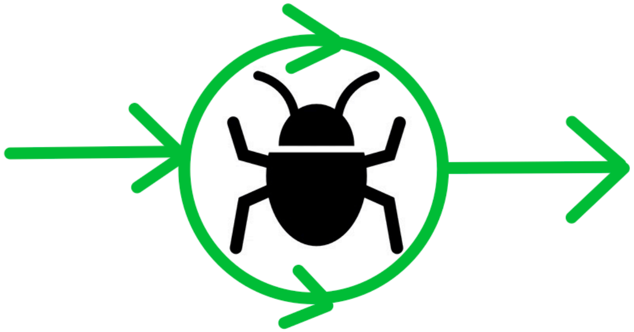


Figure 1: Typical Figure 2 from Byzantine fault paper: Our network protocol



[Mickens 2013]

The Alternative: Formal Verification

Existing Verification Approaches

Verdi(Coq)
[PLDI'15]

IronFleet(Dafny)
[SOSP'15]

Ivy
[PLDI'16]

I4

Person-years Person-months Person-days Person-hours Automated

Manual Effort

All existing approaches require the human to find an **inductive invariant**

We want to automatically find inductive invariants …
… by **combining the power of Ivy and model checking**

Preview of Results

Protocol	Traditional approach	Ivy	I4
Lock server	500 lines (Verdi)	<1 hour	Automated
Distributed lock	A few days (IronFleet)	A few hours	< 5 min

Numbers come from Ivy [PLDI 2016]

Outline

Motivation

Verification of distributed systems

I4: a new approach

Design of I4

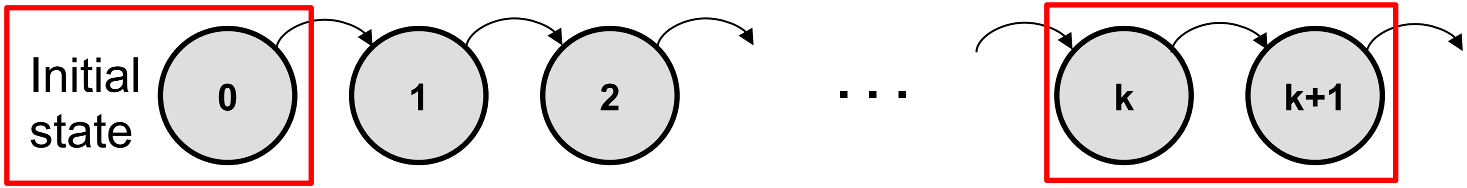
Evaluation

Conclusion

Induction on Distributed Protocol

Goal: prove that the safety property **always** holds

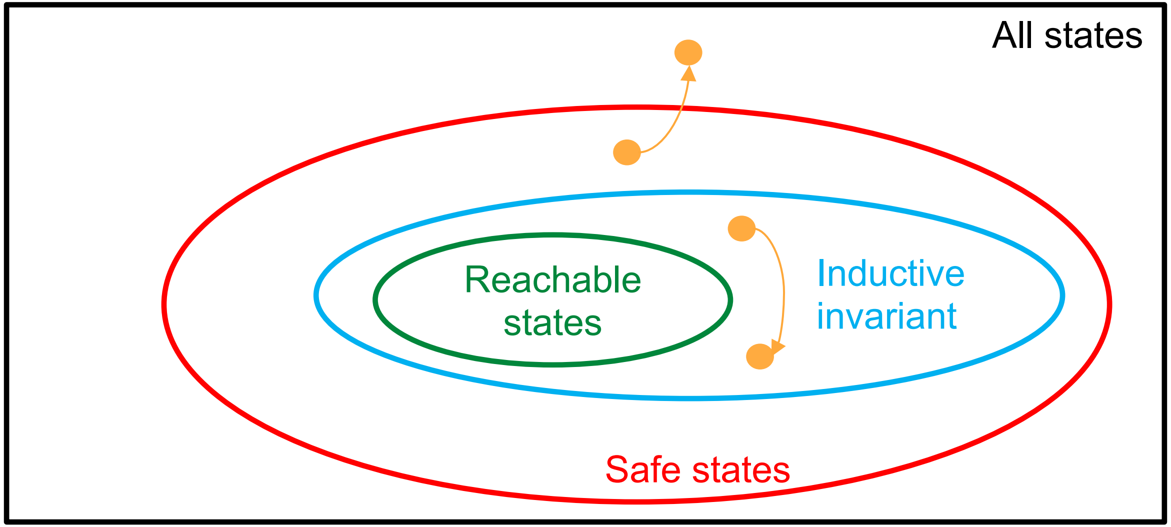
An execution:



Inductive proof

- Base case: prove initial state is safe
- Inductive step: if state **k** is safe, prove state **k+1** is safe

Safety Property vs. Inductive Invariant



Inductive Invariants Are Complex

$$\forall\ N_1, N_2 : node,\ \ E : epoch.$$
$$locked(E, N_1) \wedge locked(E, N_2) \implies N_1 = N_2$$

I.e. No tw… …e.

Existing approaches rely on manual effort and human intuition

$\wedge\ \ \forall\ N_1, N_2, E.\ held(N_1) \wedge trans(E, N_2) \implies le(E, ep(N_1))$

$\wedge\ \ \forall\ N_1, N_2, E.\ trans(E, N_1) \wedge \neg le(E, ep(N_1)) \implies$ …

$\wedge\ \ \forall\ N_1, N_2, E_1, E_2.\ (trans(E_1, N_1) \wedge \neg le(E_1, ep($ …

Strengthening Assertion

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Goal: Find an inductive invariant ***without*** relying on human intuition.

Insight: Distributed protocols exhibit ***regularity***.

- Behavior doesn’t fundamentally change as the size increases
- E.g. distributed lock, Chord DHT ring, …

Implication: We can use inductive invariants from small instances to infer a ***generalized*** inductive invariant that holds for all instances.

Leveraging Model Checking

☺ Fully automated

☹ Doesn't scale to distributed systems

I4 applies model checking to small, finite instances …

… and then generalizes the result to all instances.

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Protocol.ivy
Invariant generation on a **finite** instance
Invariant generalization
Increase Size


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Invariant generation on a **finite** instance
Invariant generalization
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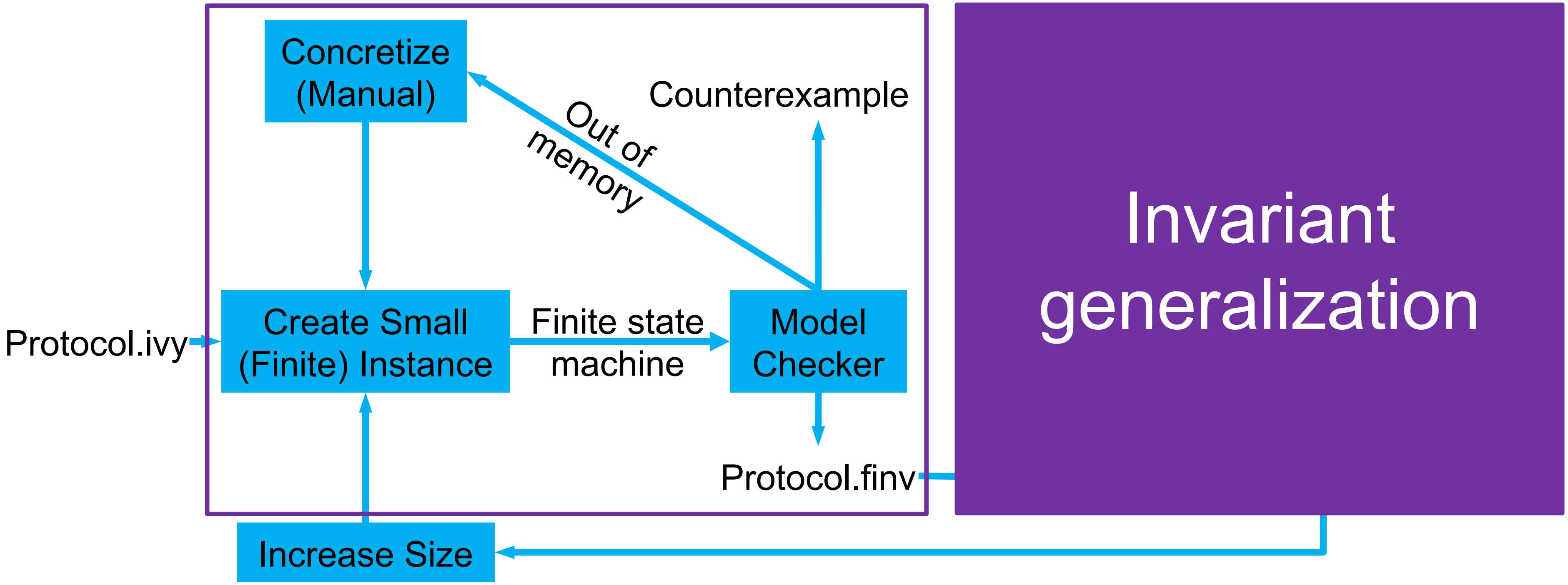
Making The Model Checking Problem Easier

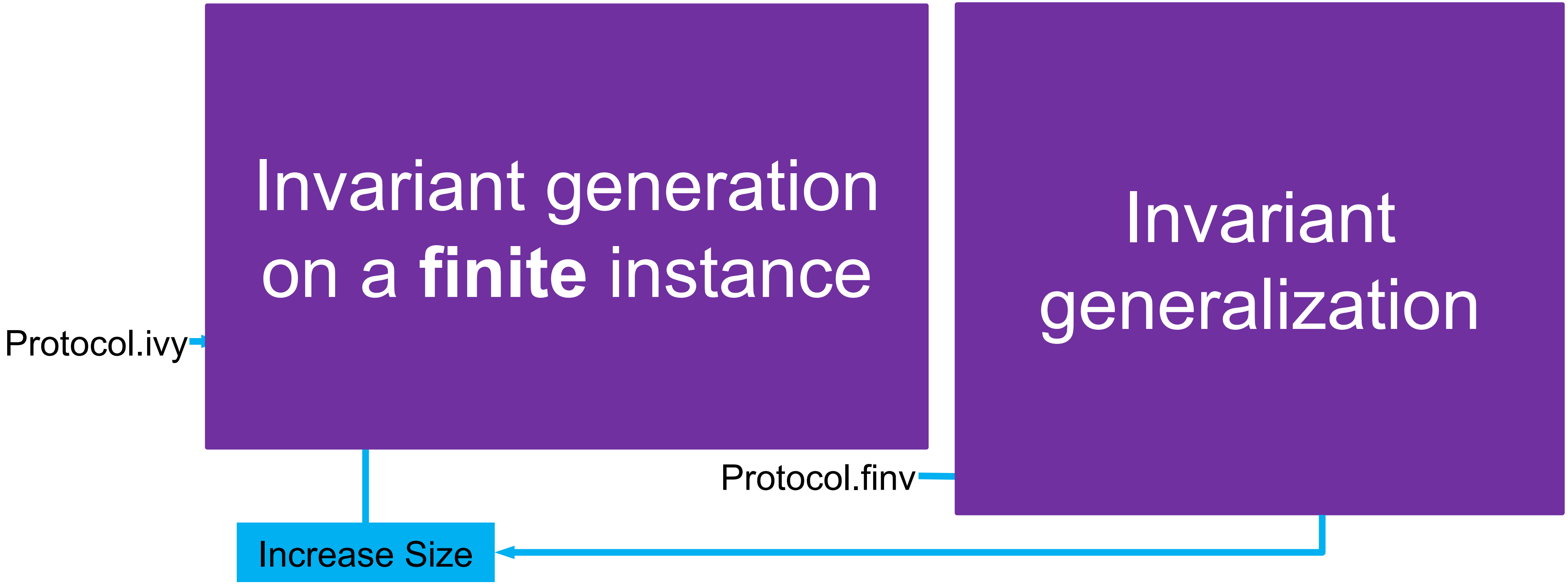
Symmetry

E.g. FIRST is the node that sends the first message

FIRST = Node1

Invariant Generation on a Finite Instance




Invariant generation on a **finite** instance
Invariant generalization
Protocol.ivy
Protocol.finv
Increase Size

Generalizing The Inductive Invariant

$P(N_1, N_2)$

$$\forall N_1, N_2. N_1 \neq N_2 \implies P(N_1, N_2)$$

Invariant generation on a finite instance

$P(N_1, N_2)$ $\quad N_1 = first$

Protocol.ivy

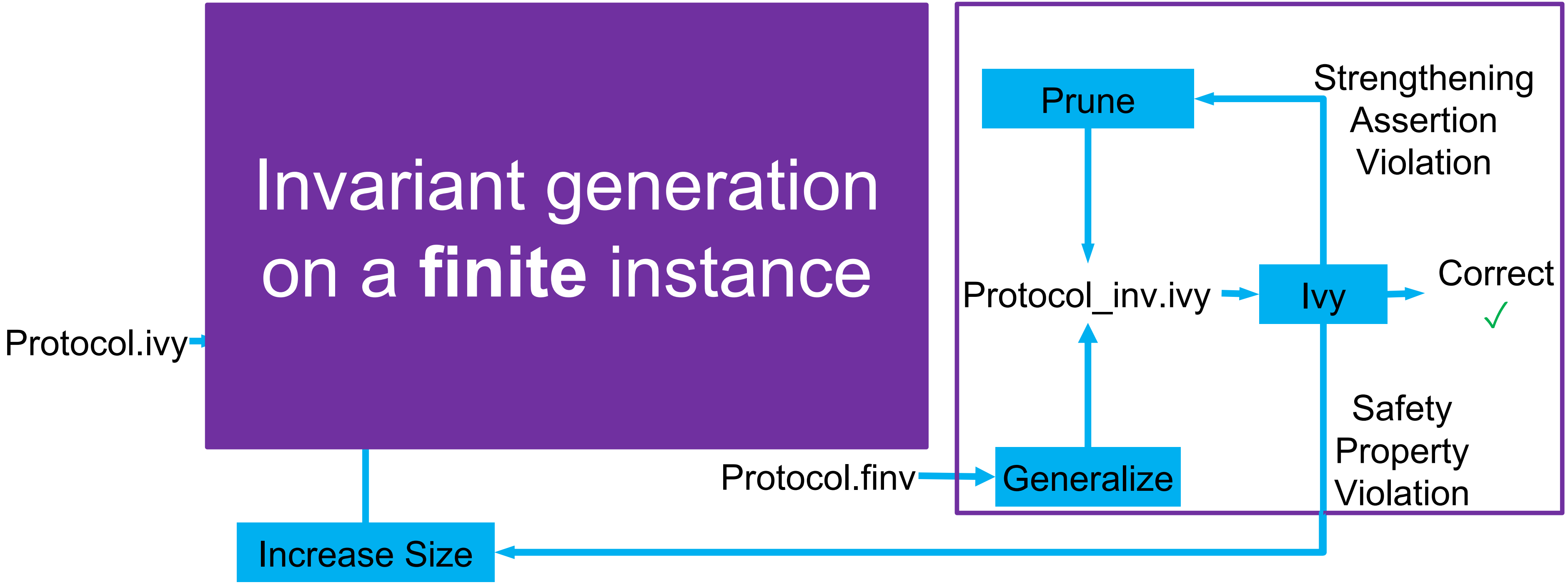
$$\forall N_1, N_2. (N_1 \neq N_2) \wedge (N_1 = first) \wedge (N_2 \neq first) \implies P(N_1, N_2)$$

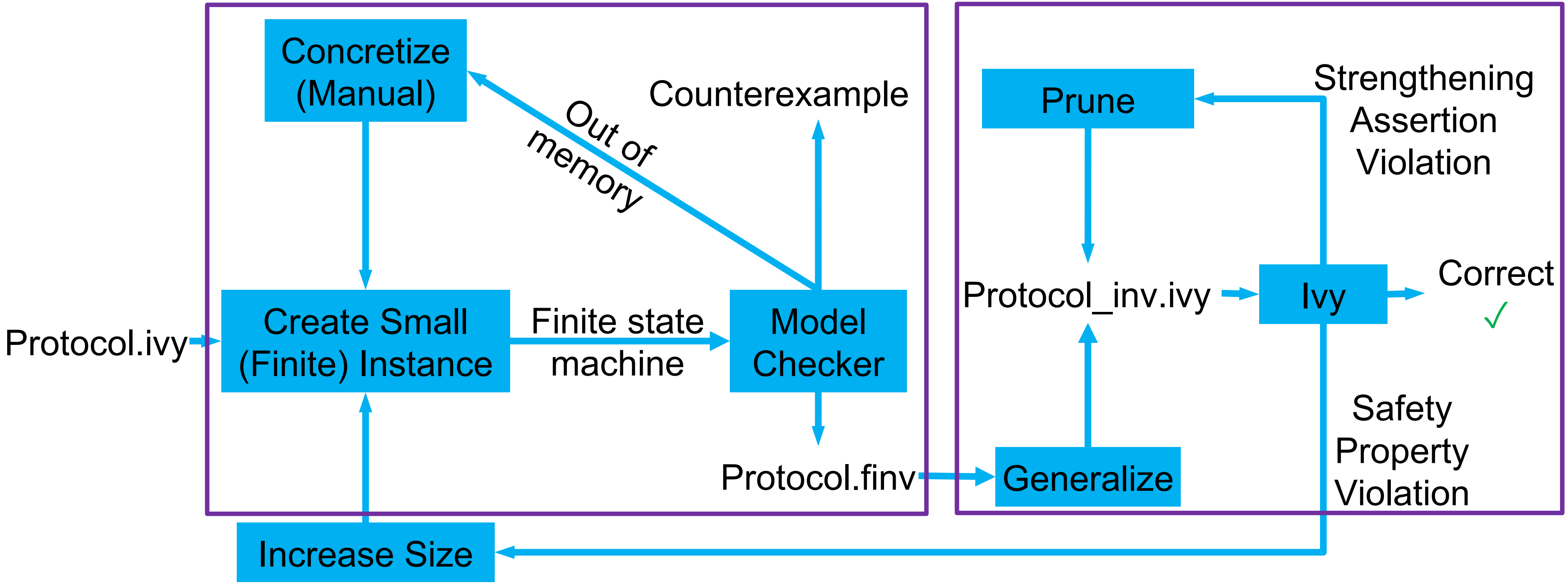
Protocol.finv

Generalize

Increase Size

Invariant Generalization




Concretize
(Manual)
Out of
memory
Counterexample
Protocol.ivy
Create Small
(Finite) Instance
Finite state
machine
Model
Checker
Protocol.finv
Increase Size
Prune
Strengthening
Assertion
Violation
Protocol_inv.ivy
Ivy
Correct
✓
Generalize
Safety
Property
Violation

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Evaluation

Lock Server
Leader Election
Distributed lock

Blind Tests {
Chord Ring
Learning Switch
Database Chain Consistency
Two-Phase Commit

Result Summary

Protocol	Manual Effort	Total time (sec)	Minimal instance size
Lock server	None	0.9	2 clients, 1 server
Leader election in ring	<5min	6.2	3 nodes, 3 ids
Distributed lock	<5min	159.6	2 nodes, 4 epochs
Chord ring	<5min	628.9	4 nodes
Learning switch	None	10.7	3 nodes, 1 packets
Database chain Consistency	None	12.6	3 transactions, 3 operations, 1 key, 2 node
Two-Phase Commit	None	4.3	6 nodes

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Thanks

Regularity of distributed protocols makes it possible to automatically infer inductive invariants of distributed protocols from small instances.

By combining the power of **model checking** and **Ivy**, I4 can verify a number of interesting protocols with little to no manual effort.

https://github.com/GLaDOS-Michigan/I4

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I’m looking for a research intern for next summer. If you’re interested, just contact me.

```
type node
type epoch

relation le(E:epoch, E:epoch)
relation locked(E:epoch, N:node)
relation transfer(E:epoch, N:node)
relation held(N:node)

individual zero : epoch
individual e : epoch
function ep(N:node) : epoch
individual first : node
```

```
after init {
        held(X) := X:node = first;
        ep(N) := zero;
        ep(first) := e;
        transfer(E,N) := false;
        locked(E,N) := false
}
```