Formal Verification of the Stellar Consensus Protocol

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Goals

- Formal specification of SCP
  - A formal version of the Internet Draft

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- Formal proofs that the SCP specification satisfies its intended properties

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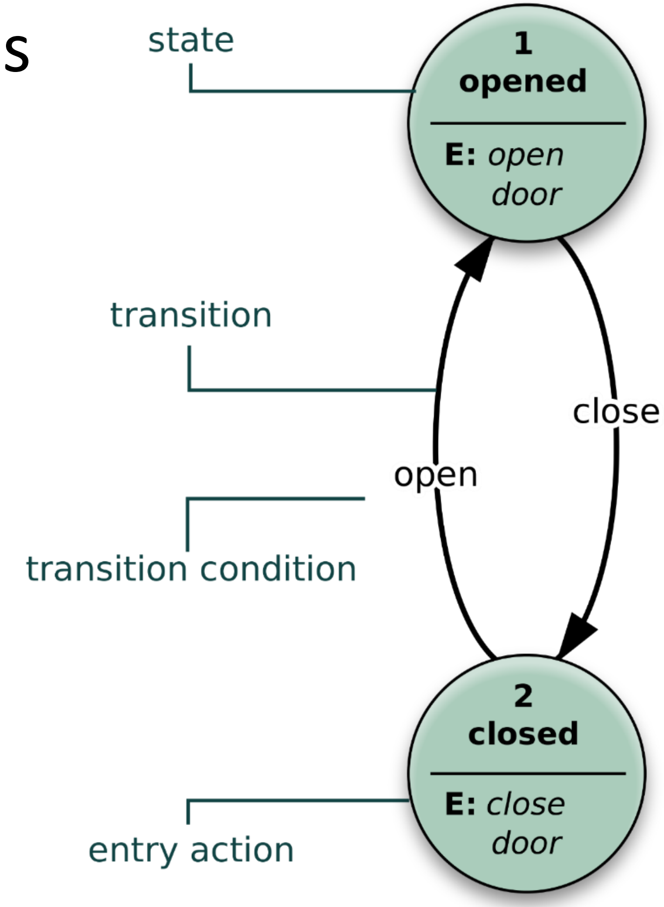
- Formally verified implementation

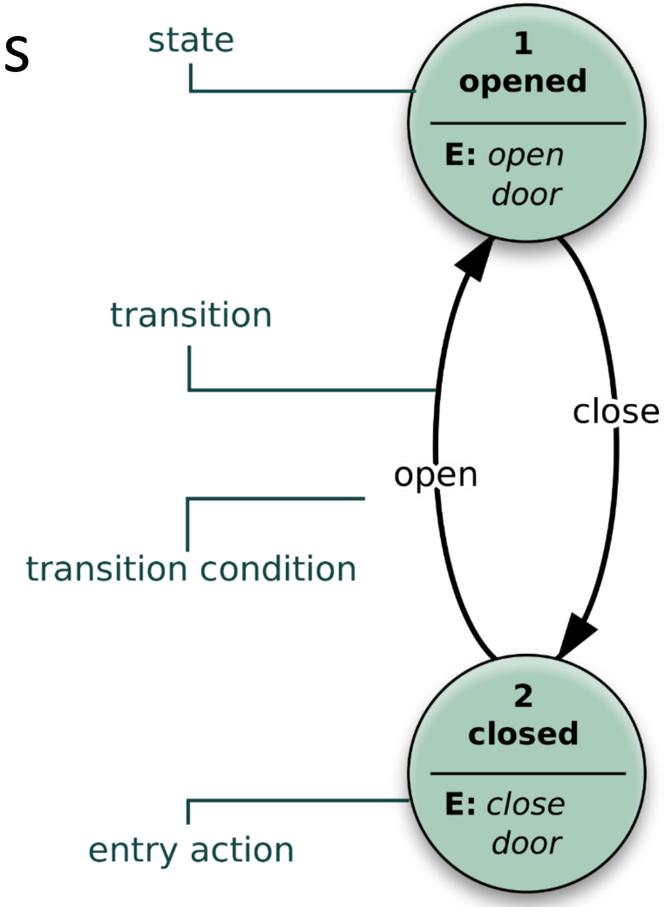
What is a formal specification?

- An abstract machine with states and transitions that specifies allowed behaviors



What is a formal specification?

- An abstract machine with states and transitions that specifies allowed behaviors
- A specification looks like a program, but
  - Has precise meaning
  - Is written for clarity
  - Specifies an envelope of allowed behaviors, leaving room for implementation choices



Why specify formally?

- Unambiguous protocol description
  - Given an API call trace, it is clear whether it satisfies the spec or not
- Advantages:
  - Communication between protocol designer and implementer: avoids interpretation errors
  - Can be used as test oracle
  - Intended properties of the specification can be formally verified
  - Can be used to formally verify implementations

Excerpts from the SCP specification in IVy

```
type statement = {commit, abort}
relation vote(V:node, B:ballot, S:statement)
relation accept(V:node, B:ballot, S:statement)
relation confirm(V:node, B:ballot, S:statement)
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action vote_commit(v:node, b:ballot) = {
       require b.n > 0;
       require forall C . C < b & C.x ≠ b.x -> confirm(v, C, abort);
       vote(v, b, commit) := true;
}
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}

action confirm(v:node, b:ballot, s:statement, q:nodeset) = {
       require is_quorum(q);
       require forall V . member(V,q) -> accept(V, b, s);
       confirm(v, b, s) := true;
}
```

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For SCP:

- Definitions: the quorums of <u>intertwined</u> nodes intersect at well-behaved nodes; <u>intact</u> nodes are intertwined nodes that are part of a quorum consisting only of intact nodes.

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- Definitions: the quorums of intertwined nodes intersect at well-behaved nodes; intact nodes are intertwined nodes that are part of a quorum consisting only of intact nodes.
- SCP is Safe: no two intertwined nodes externalize different values for the same slot
- SCP is non-blocking: intact nodes always remain able to externalize a value

Why prove formally?

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Distributed protocol are notoriously hard to get right

Informal prose arguments do not suffice

~13000 citations

SIGCOMM 2001

Chord: A Scalable Peer-to-Peer Lookup Protocol for Internet Applications

Ion Stoica, Robert Morris, David Liben-Nowell, David R. Karger, M. Frans Kaashoek, Frank Dabek, and Hari Balakrishnan, *Member, IEEE*

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CCR 2012

Using Lightweight Modeling To Understand Chord

Pamela Zave
AT&T Laboratories—Research
Florham Park, New Jersey USA
pamela@research.att.com

Under the same assumptions made in the Chord papers, the [SIGCOMM] version of the protocol is not correct, and not one of the properties claimed invariant in [PODC] is actually invariantly true of it. The [PODC] version satisfies one invariant, but is still not correct. The results are presented by means of counterexamples to the invariants in Section 4. In preparation for the results, Section 2 gives a

Are formal proofs a realistic goal?

Yes; complex systems (even implementations) have been formally proved correct:

- CompCert: C compiler
- seL4: Hypervisor
- Project Everest: cryptography in Firefox
- GRAT toolchain: SAT solver
- FSCQ: journaling file system
- and many other examples…

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- Machine-checked

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$$(A \to B) \land (B \to C) \to (A \to C)$$

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$$\dfrac{\dfrac{\dfrac{\dfrac{}{A}\,{}^{1} \qquad A \to B}{B} \qquad B \to C}{C}}{A \to C}\,{}^{1}$$

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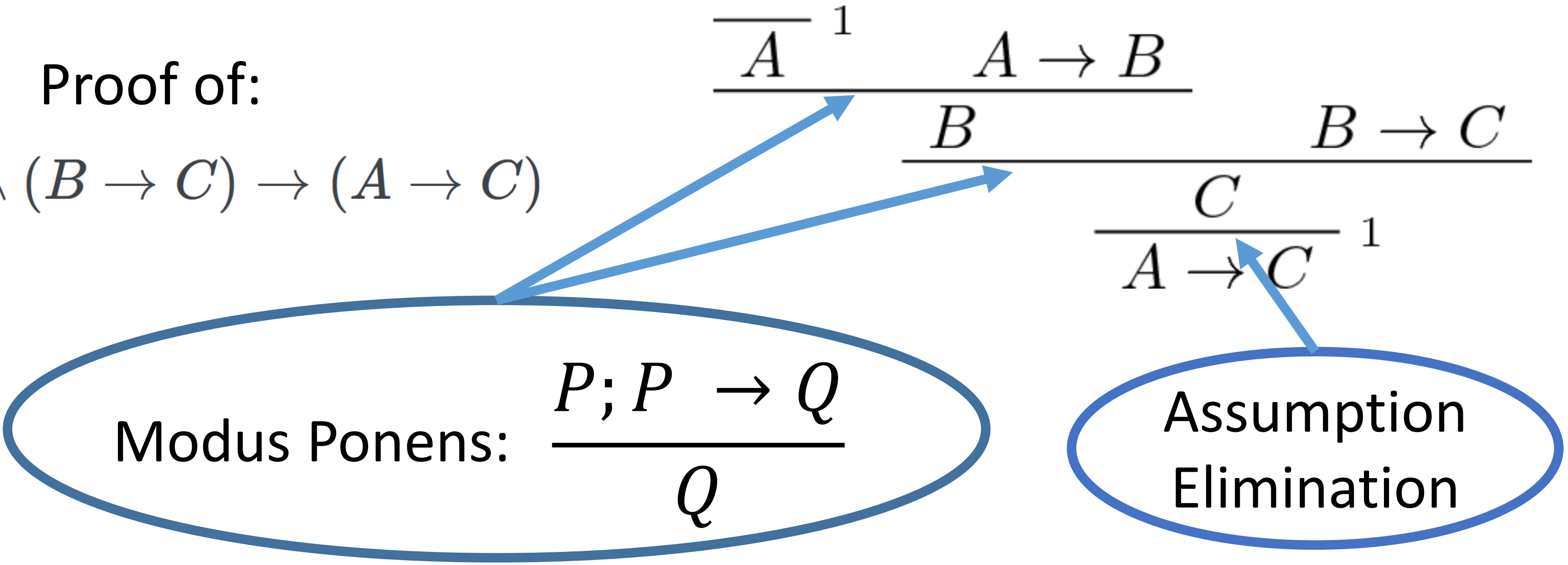
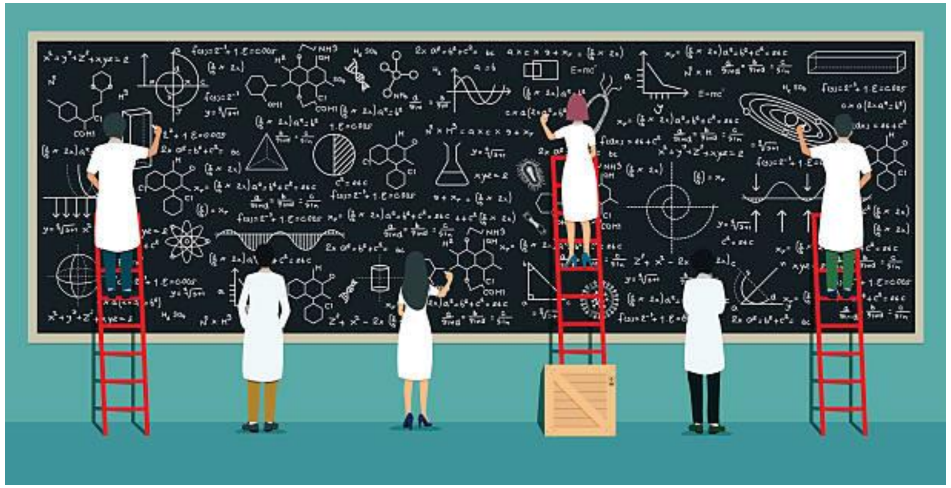


Proving from first principles is hard

Example: safety proof of Raft implementation with Verdi: 50 000 lines of proof for 500 lines of code



Woos, Doug, et al. "Planning for change in a formal verification of the Raft consensus protocol." *Proceedings of the 5th ACM SIGPLAN Conference on Certified Programs and Proofs*. ACM, 2016.

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Automated Solvers

Z3

(and (or (and (= x0 y0) (= y0 x1)) ... z0 ... y1 ... (= ... z1 ... y2 x3)) (and (= x2 z2) ... z2 x3))) (not (= x0 x3)))

CVC4

SPASS

Amazing tools, but that can still fail…

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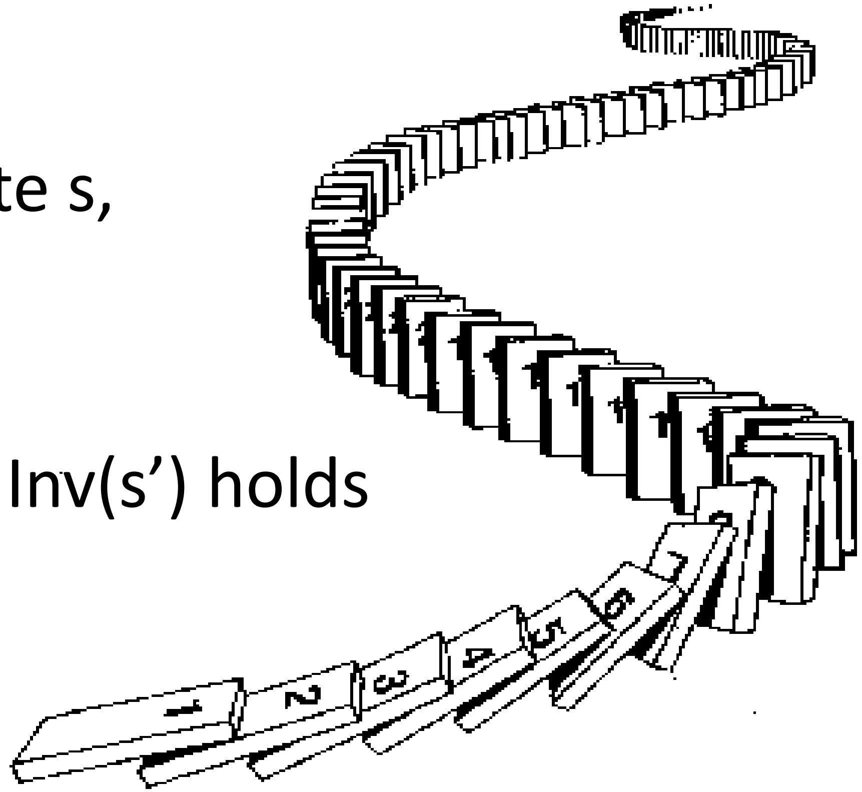
Inductive Invariants



To prove that P(s) holds for every reachable state s,
find predicate Inv(s) such that:

1. Initiation: Inv(s_0) holds in the initial state s_0
2. Consecution: If Inv(s) holds and s → s', then Inv(s') holds
3. Safety: Inv(s) implies P(s)

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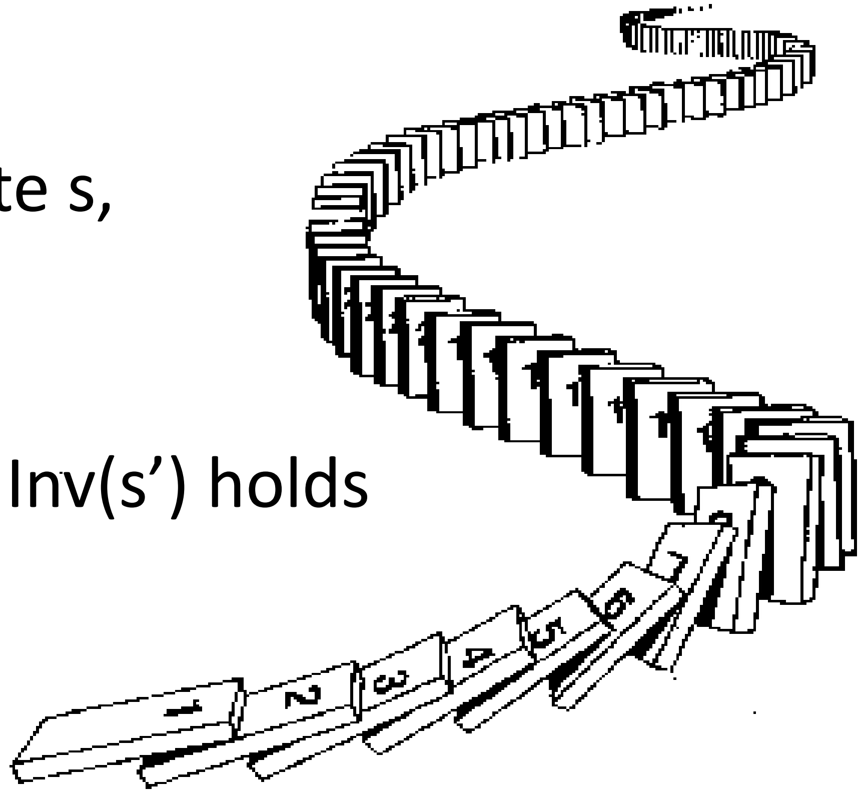
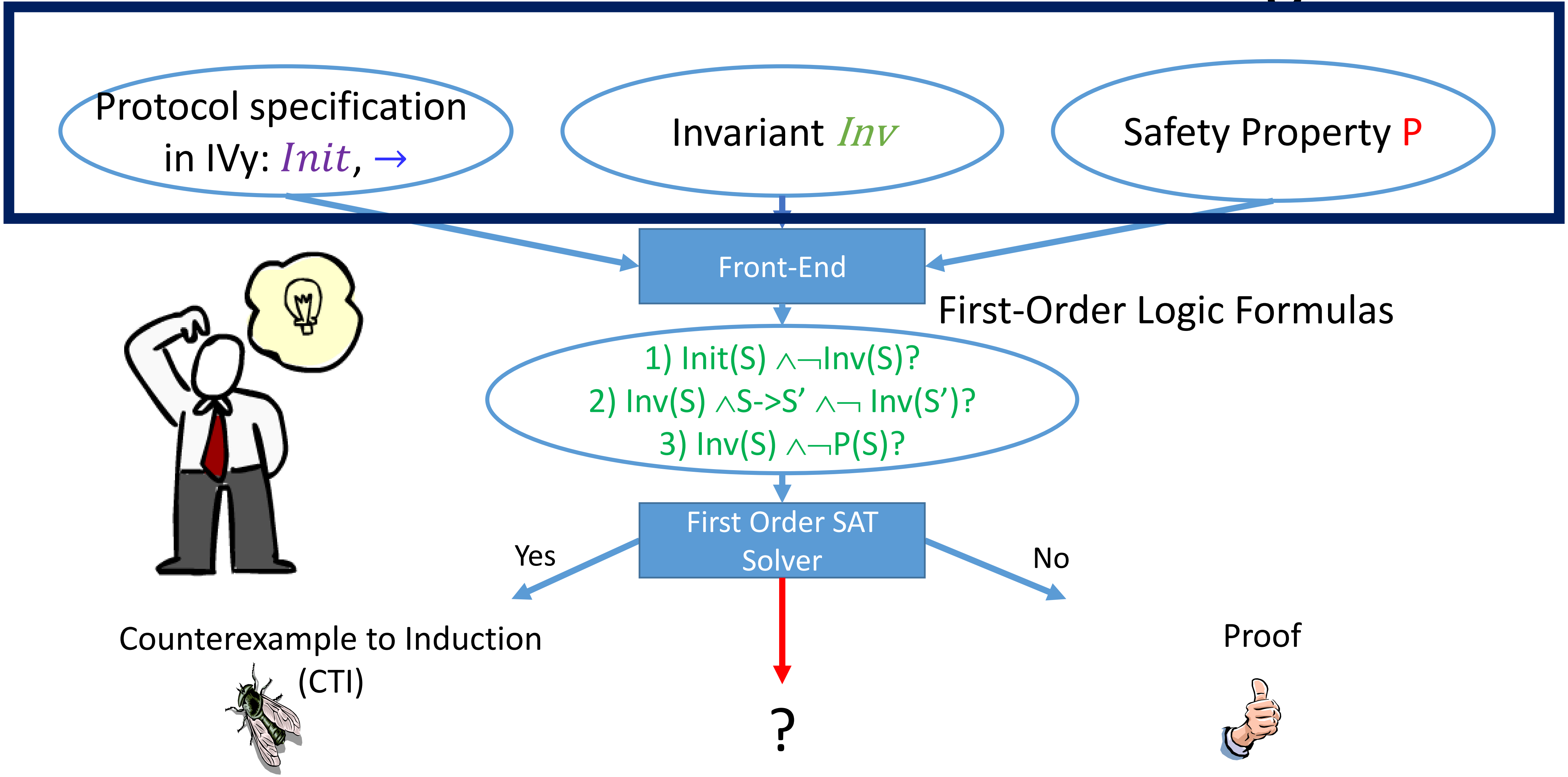


This is just proof by induction!

Deductive Verification

- The human provides insight in the form of an inductive invariant
- The automated prover “crunches the numbers” and automatically checks initiation, consecution, and safety

Deductive verification in First-Order Logic



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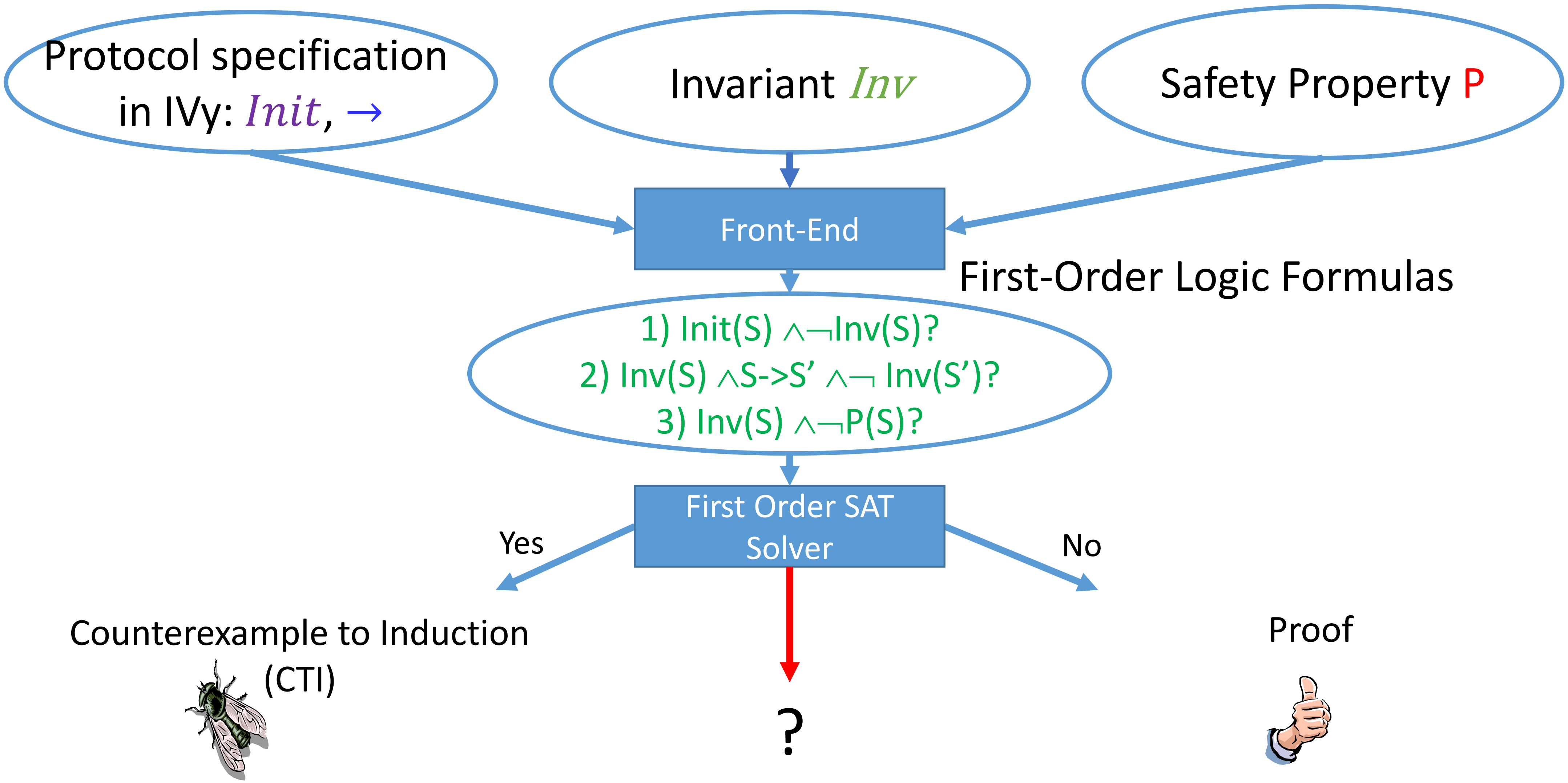

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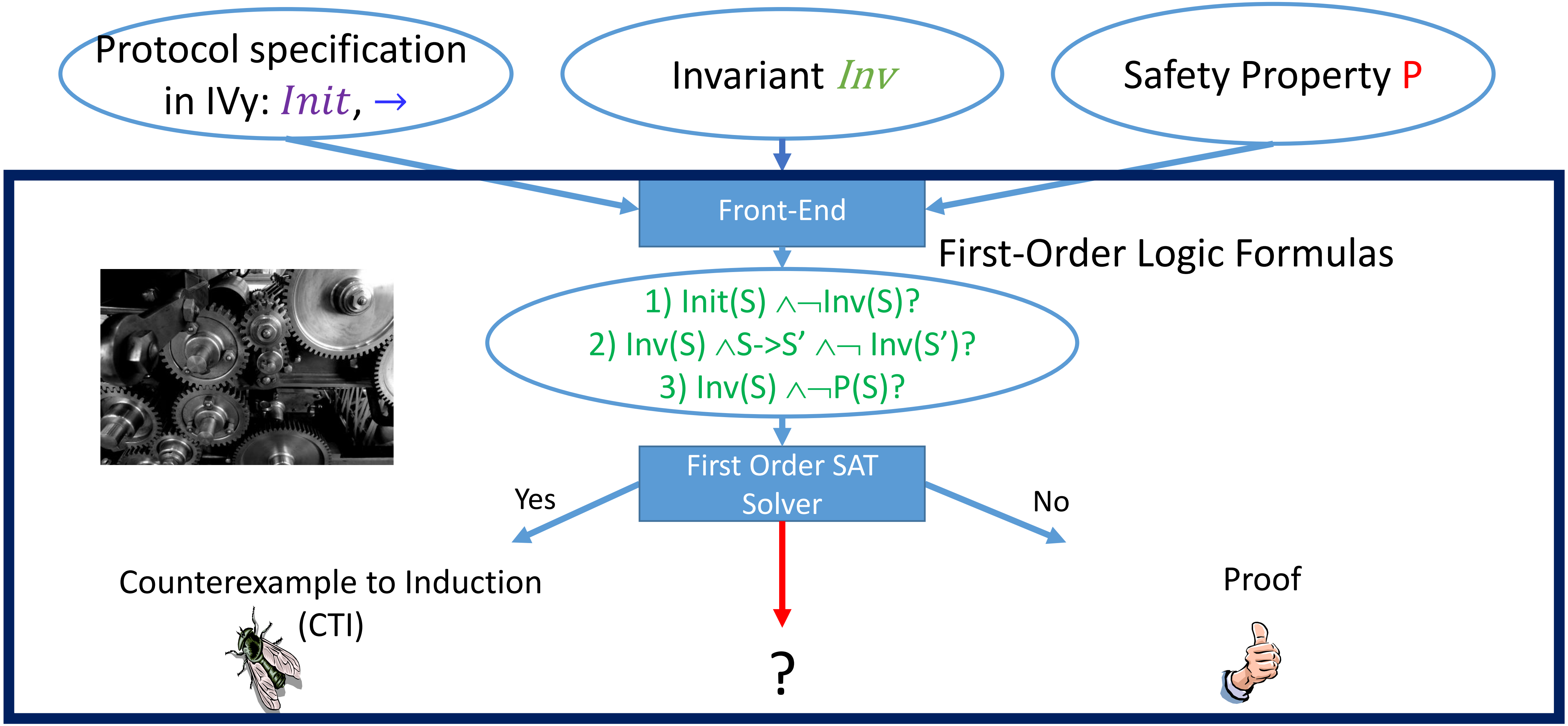

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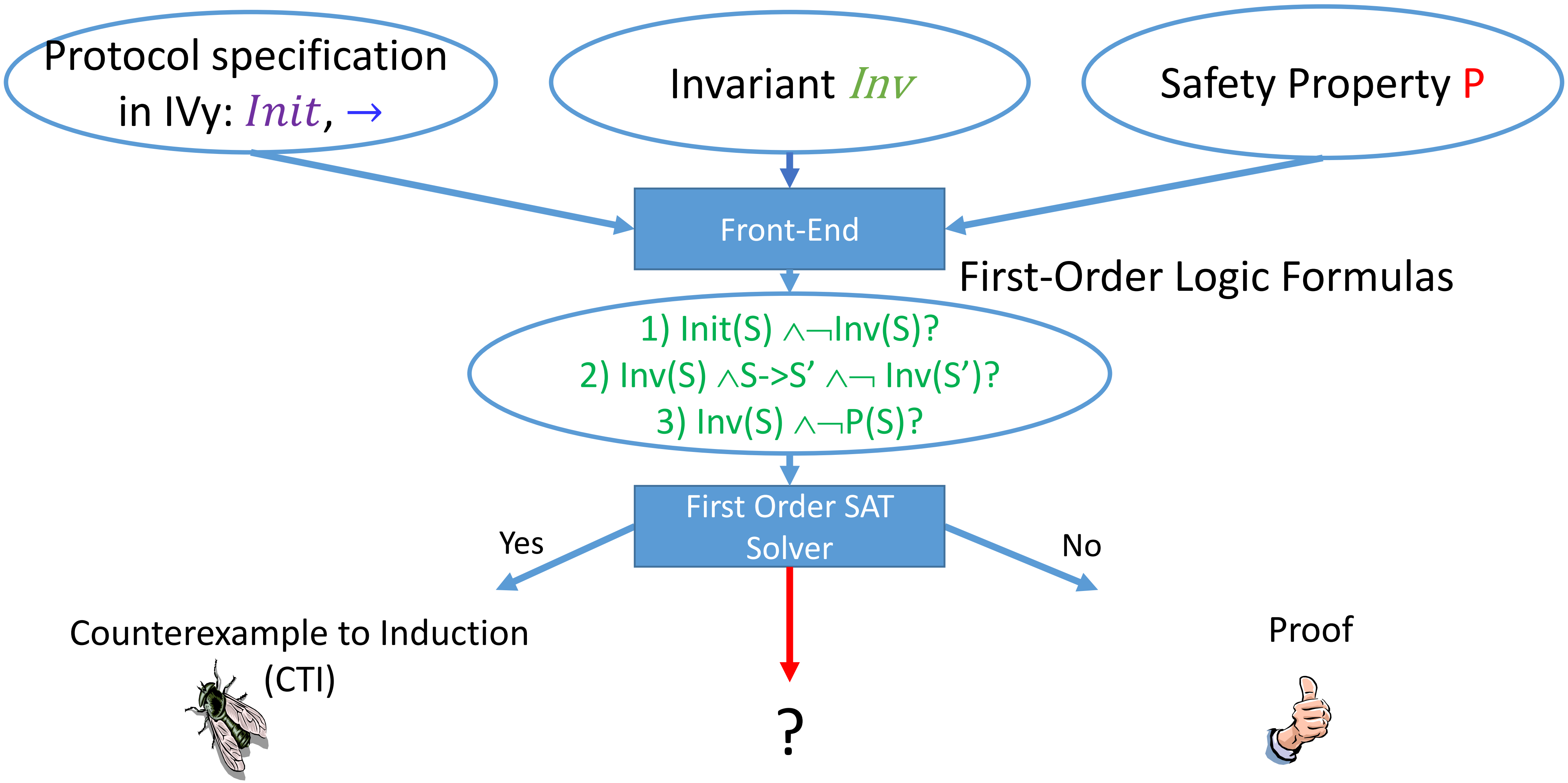

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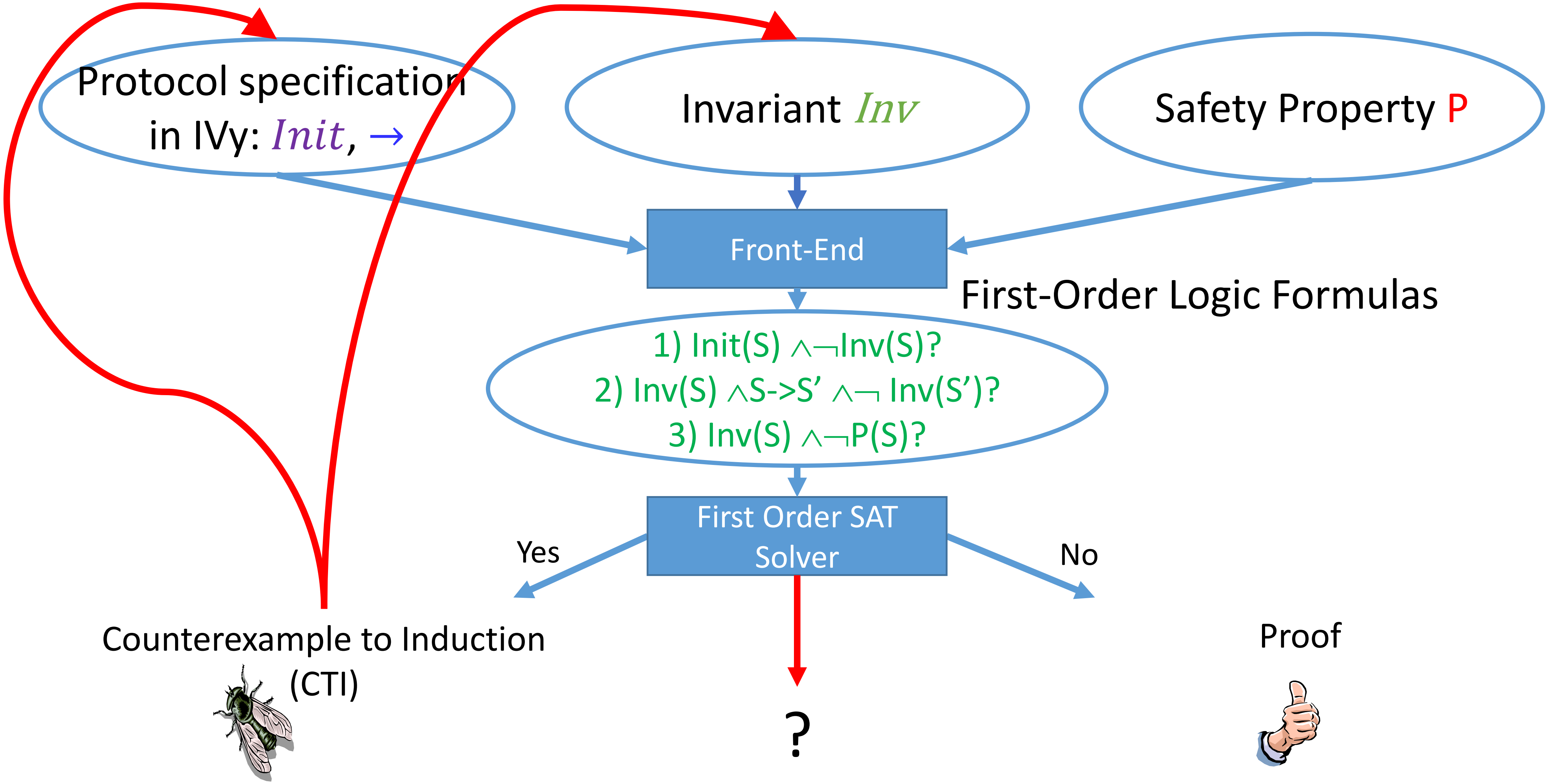

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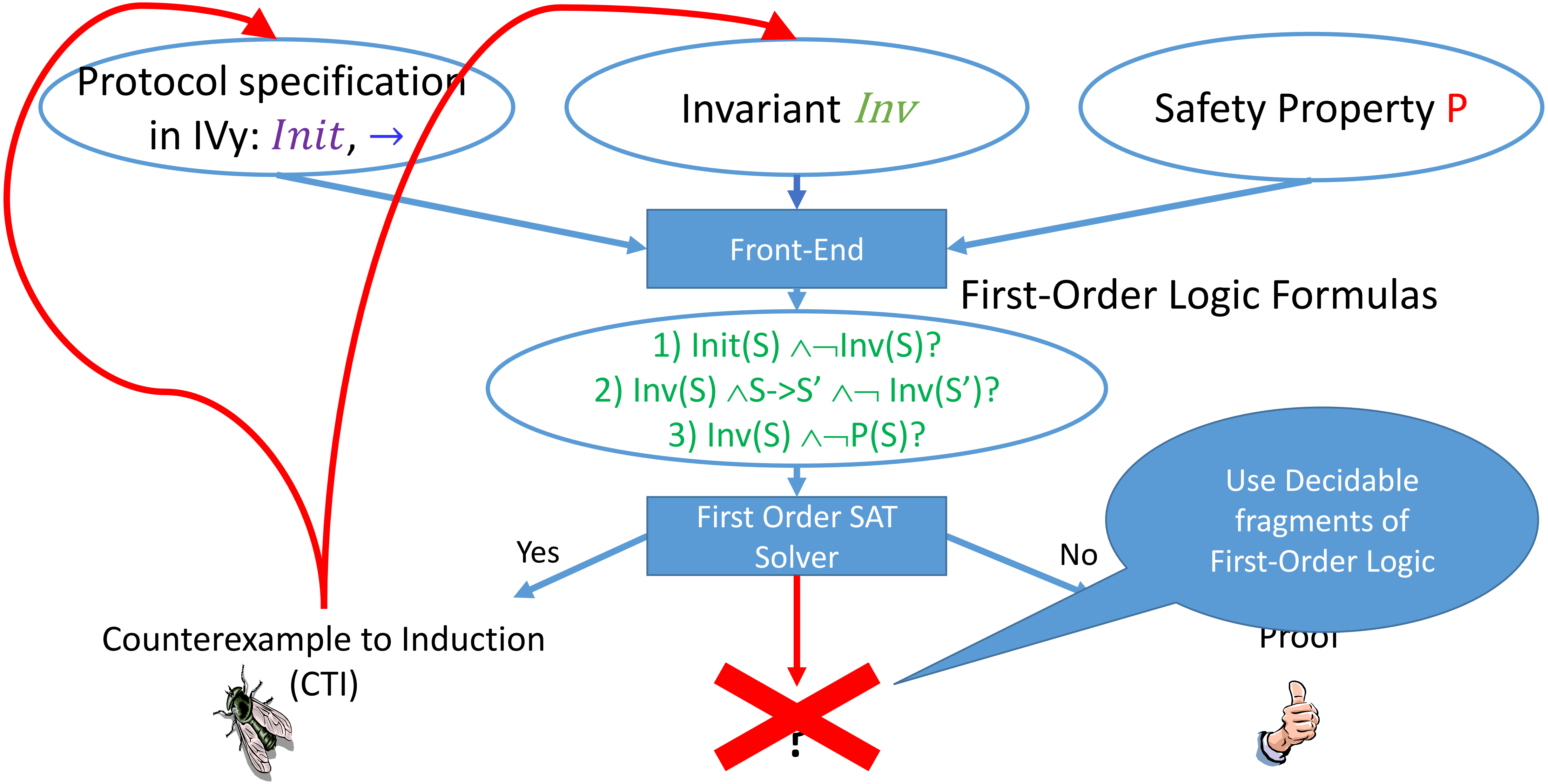

Example: SCP’s inductive invariant

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invariant forall V1,V2,B1,B2 .
      confirm(V1,B1,commit) & confirm(V2,B2,commit) -> B1.x = B2.x
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invariant forall V,B,S . confirm(V,B,S) -> (exists Q . is_quorum(Q) &
      forall V2 . member(V2,Q) -> accept(V2,B,S))
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invariant forall V, B2 . accept(V,B2,commit) -> (
      (forall B1 . B1 < B2 & B1.x ≠ B2.x ->
            exists Q . is_quorum(Q) & (forall V . member(V,Q) -> accept(N,B1,abort))
      |
      (exists B1 . B1 < B2 & B1.x = B2.x & accept(V,B1,commit)) )
```

Current Status

- High-level specification of the ballot protocol has been proved safe
  https://github.com/nano-o/SCP-Verification
- Next
  - Produce a formal document that is readable along with the Internet Draft
  - Proof of non-blocking property
  - Verified (reference) implementation

More information on IVy and its verification techniques

- https://microsoft.github.io/ivy/
- Padon, Oded, et al. "Paxos made EPR: decidable reasoning about distributed protocols.“ OOPSLA 2017
- Padon, Oded, et al. "Reducing liveness to safety in first-order logic.“ POPL 2018
- Taube, Marcelo, et al. "Modularity for decidability of deductive verification with applications to distributed systems.“ PLDI 2018