Ivy: Safety Verification by Interactive Generalization

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PLDI 2016

http://microsoft.github.io/ivy/

Ivy: Safety Verification by Interactive Generalization

- Verification of distributed systems
- Modeling infinite-state systems in a way which allows decidable automated reasoning (EPR)
- Interactive discovery of inductive invariants

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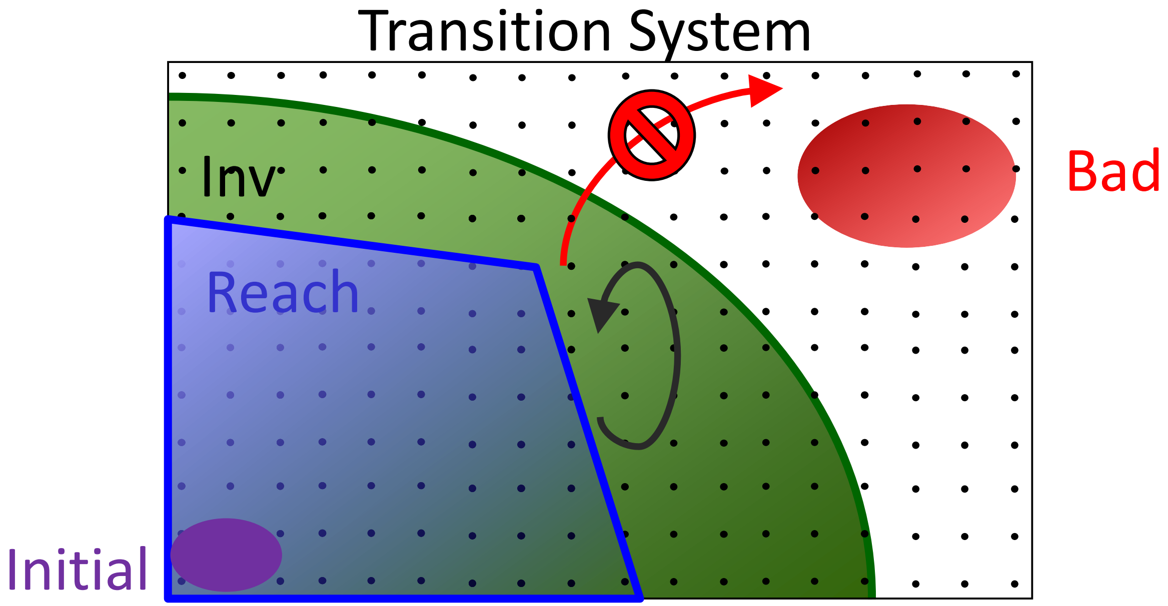
this talk (mostly)

Safety of Transition Systems



System S is safe if no bad state is reachable

System S is safe iff there exists an inductive invariant Inv s.t.:

> *Init* $\subseteq$ *Inv* *(Initiation)*
>
> *if* $\sigma \in$ *Inv and* $\sigma \rightarrow \sigma'$ *then* $\sigma' \in$ *Inv (Consecution)*
>
> *Inv* $\cap$ *Bad* $= \varnothing$ *(Safety)*

Challenges for Deductive Verification

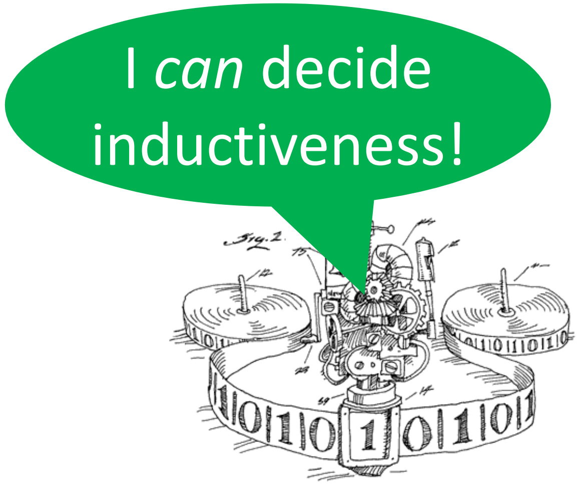
1. Formal specification:
    - Modeling the system
    - Formalizing the safety property
2. Inductive Invariants
    - Hard to specify manually
    - Hard to infer automatically
3. Deduction – Checking inductiveness
    - Undecidability of implication checking
        - Unbounded state, arithmetic, quantifier alternation

Existing Approaches for Verification of Infinite-State Systems

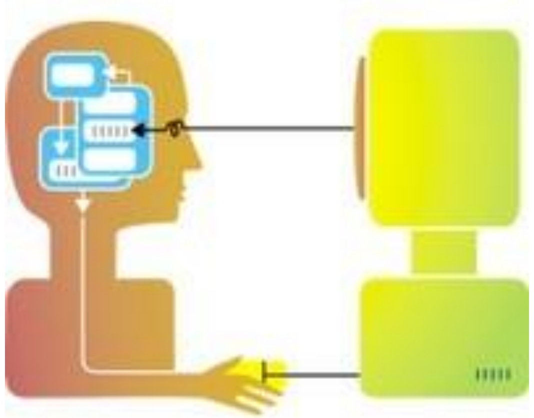
- Automated invariant inference
  - Abstract Interpretation
  - Ultimately limited due to undecidability
- Use SMT for deduction with manual program annotations (e.g. Dafny)
  - Requires programmer effort to provide inductive invariants
  - SMT solver may diverge (matching loops, arithmetic)
- Interactive theorem provers (e.g. Coq, Isabelle/HOL)
  - Programmer provides inductive invariant and proves it
  - Huge effort (10-100 lines of proof per line of code)

Usually opaque when failing

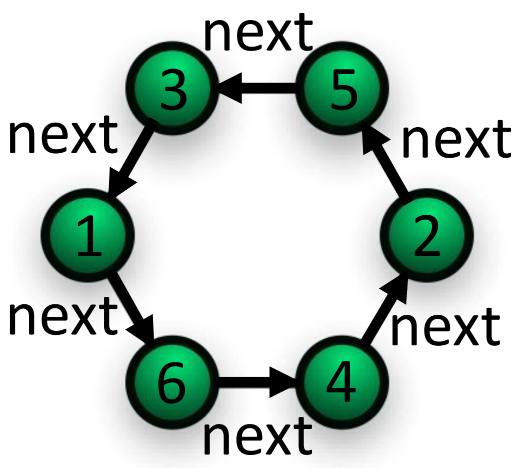
Our Approach in Ivy



- Restrict the specification language for decidability
  - Deduction is decidable with SAT solvers
  - Challenge: verify complex systems using a restricted language
    - Solution: domain specific axioms
- Finding inductive invariants (still undecidable):
  - Combine automated techniques with human guidance
  - Graphical user interaction
  - Key: generalization from counterexamples to induction
  - Decidability allows reliable automated checks



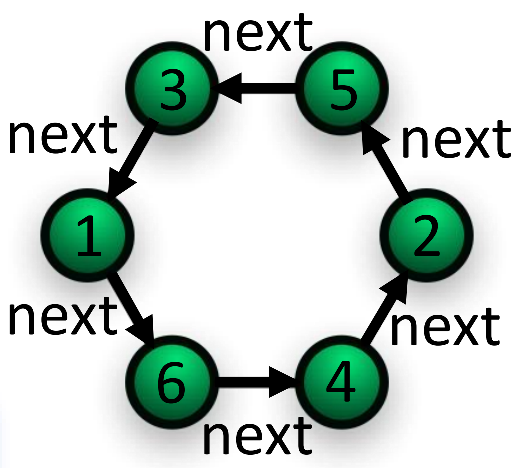
Example: Leader Election in a Ring



- Nodes are organized in a ring
- Each node has a unique numeric id
- Protocol:
  - Each node sends its id to the next
  - A node that receives a message passes it (to the next) if the id in the message is higher than the node's own id
  - A node that receives its own id becomes the leader
- Theorem:
  - The protocol selects at most one leader

[CACM'79] E. Chang and R. Roberts. *An improved algorithm for decentralized extrema-finding in circular configurations of processes*

Example: Leader Election in a Ring



- Nodes are organized in a ring
- Each node has a unique numeric id
- Protocol:
  - Each
  - A no ... if the id in the mes
  - A no
- Theore
  - The

Proposition: This algorithm detects one and only one highest number.

Argument: By the circular nature of the configuration and the consistent direction of messages, any message must meet all other processes before it comes back to its initiator. Only one message, that with the highest number, will not encounter a higher number on its way around. Thus, the only process getting its own message back is the one with the highest number.

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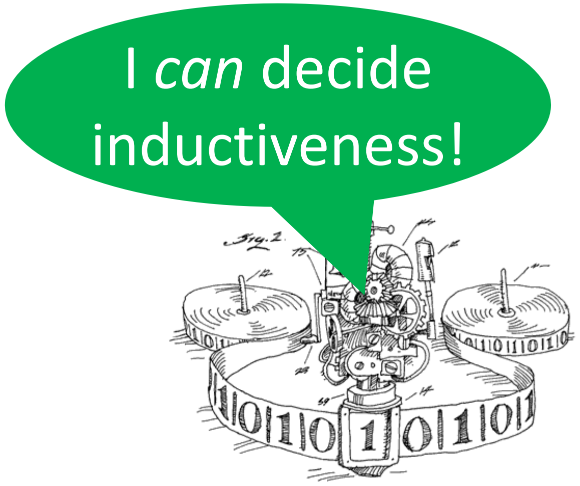
Relational Modeling Language (RML)



- Designed to make verification tasks decidable
  - Yet expressive enough to model systems
- Turing-Complete
- Universally quantified inductive invariants are decidable to check
- System state described by finite (unbounded) relations
- No numerics
- Simple (quantifier-free) updates
- Universally quantified axioms (domain specific)
  - Total orders, partial orders, lists, trees, rings, quorums, …

Leader Election Protocol (RML)

- ⩽ (ID, ID) – total order on node id’s
- **btw** (Node, Node, Node) – the ring topology
- **id**: Node → ID – relate a node to its unique id
- **pending**(ID, Node) – pending messages
- **leader**(Node) – leader(n) means n is the leader

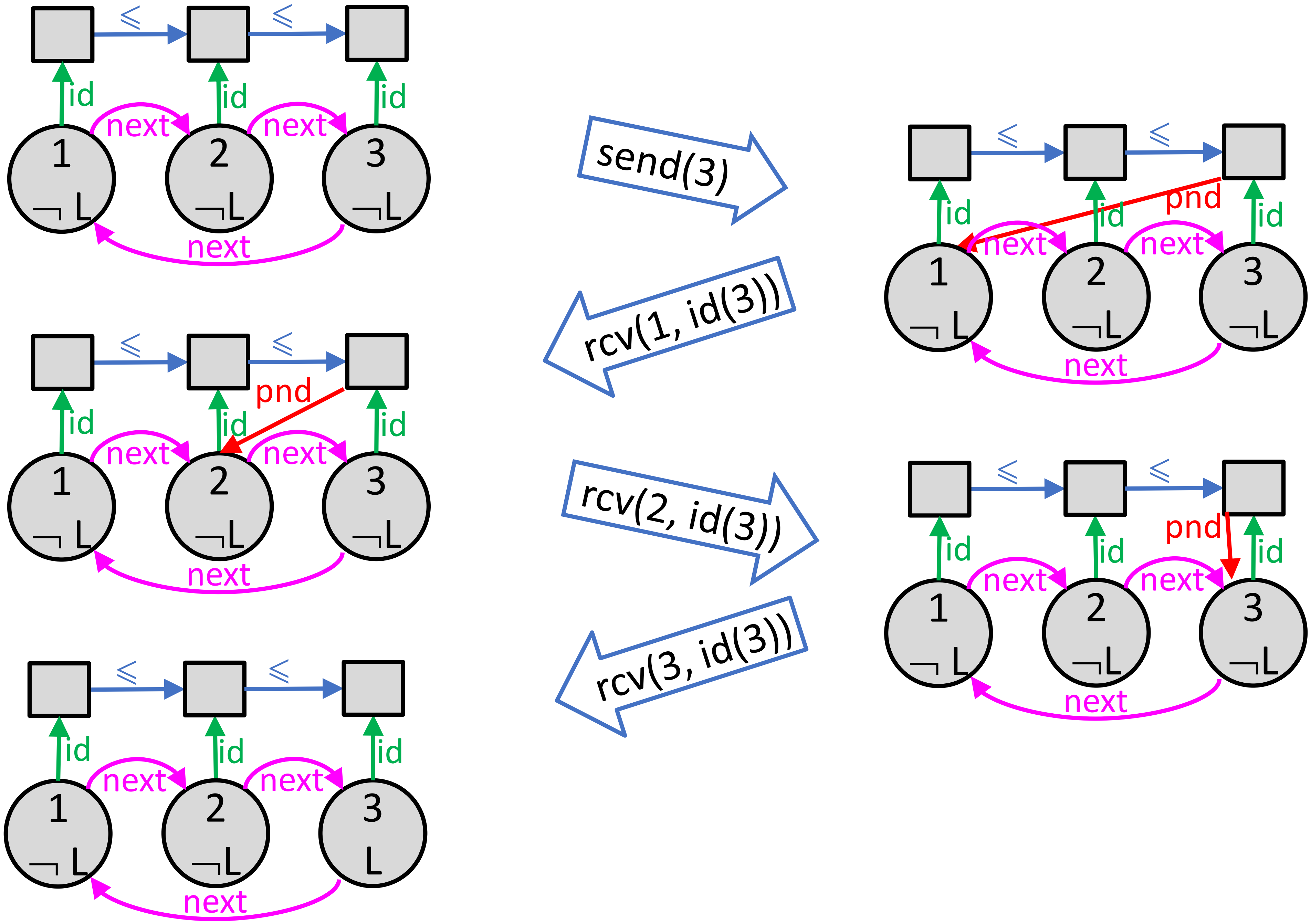
```
action send(n: Node) = {
  “s := next(n)”;
  pending(id(n),s) := true
}
```

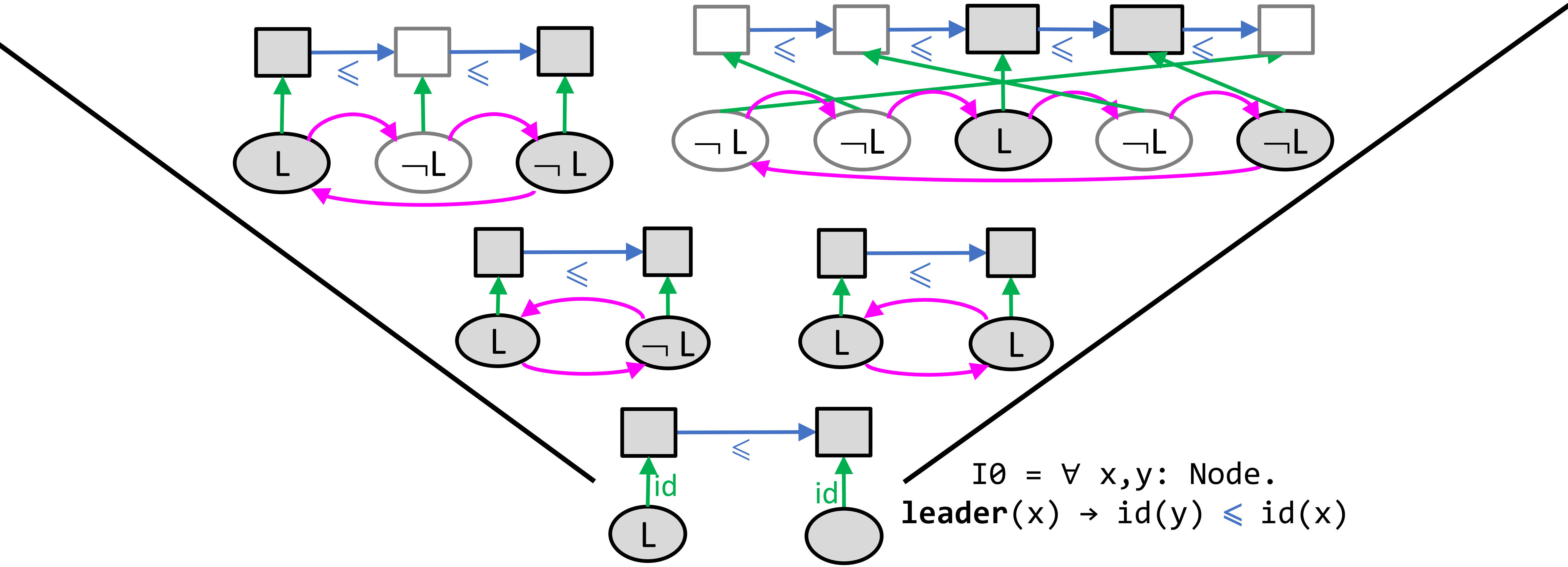
```
action receive(n: Node, m: ID) = {
  requires pending(m, n);
  pending(m, n) := false;
  if id(n) = m then
    // found leader
    leader(n) := true
  else if id(n) ⩽  m then
    // pass message
    “s := next(n)”;
    pending(m, s) := true
}
```

```
protocol = (send | receive)*
```

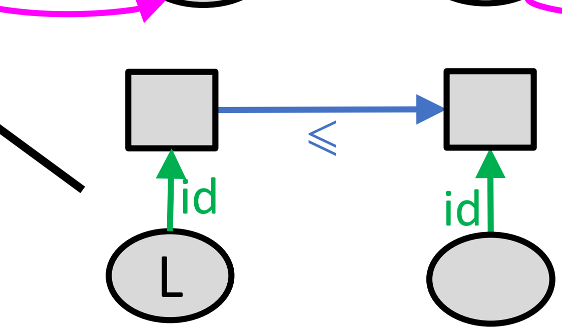
```
next(a)=b ↔ ∀x: Node. x=a ∨ x=b ∨ btw(a,b,x)
```

```
assert I0 = ∀ x,y: Node. leader(x) → id(y) ⩽ id(x)
```


send(3)
rcv(1, id(3))
rcv(2, id(3))
rcv(3, id(3))
pnd
next
id
⩽
¬L
L



I0 = ∀ x,y: Node.
leader(x) → id(y) ≤ id(x)



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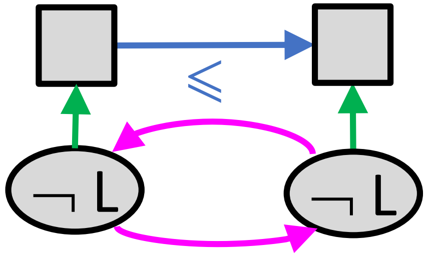

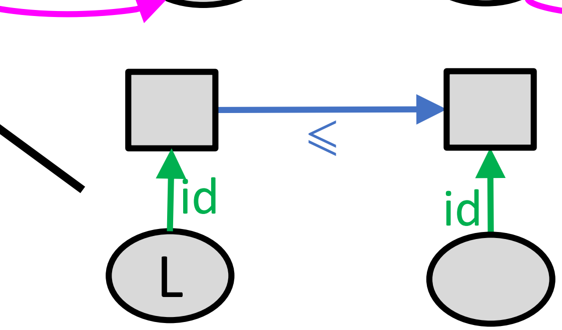

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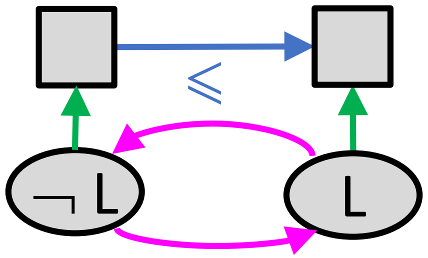

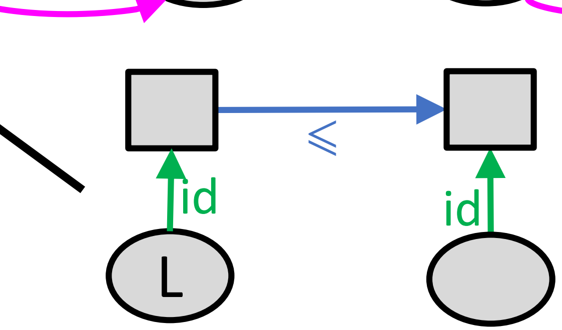

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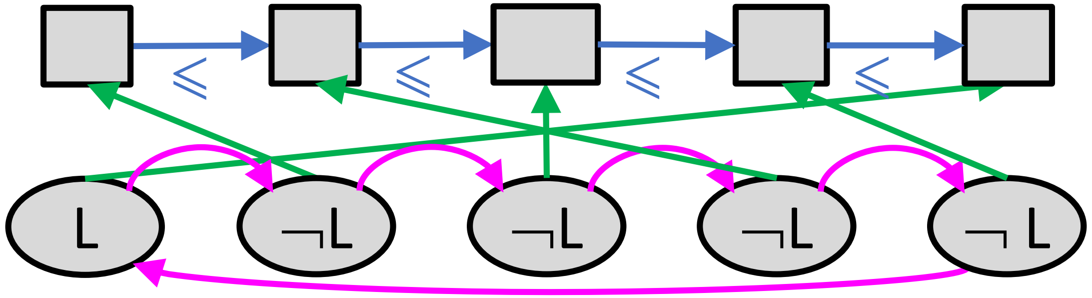

Inductive Invariant for Leader Election

- $\leqslant$ (ID, ID) – total order on node id's
- **btw** (Node, Node, Node) – the ring topology
- **id**: Node → ID – relate a node to its id
- **pending**(ID, Node) – pending messages
- **leader**(Node) – leader(n) means n is the leader

Safety property: I0

$$I0 = \forall\ x,y\colon \text{Node}.\ \mathbf{leader}(x) \rightarrow id(y) \leqslant id(x)$$

Inductive invariant: $Inv = I0 \land I1 \land I2$

$$I1 = \forall\ x,y\colon \text{Node}.\ \neg(\ pending(id(x),\ x) \land id(x) \neq id(y) \land id(x) \leqslant id(y)\ )$$

$$I2 = \forall\ x,y,z\colon \text{Node}.\ \neg(\ btw(x,\ y,\ z) \land pending(id(y),\ x) \land id(y) \leqslant id(z)\ )$$

Inductive Invariant for Leader Election

- $\leqslant$ (ID, ID) – total order on node id's
- **btw** (Node, Node, Node) – the ring topology
- **id**: Node → ID – relate a node to its id
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- **leader**(Node) – leader(n) means n is the leader

Safety property: `I0`

```
I0 = ∀ x,y: Node. leader(x) → id(y) ⩽ id(x)
```

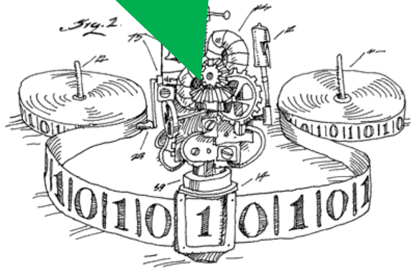
Inductive invariant: `Inv = I0 ∧ I1`

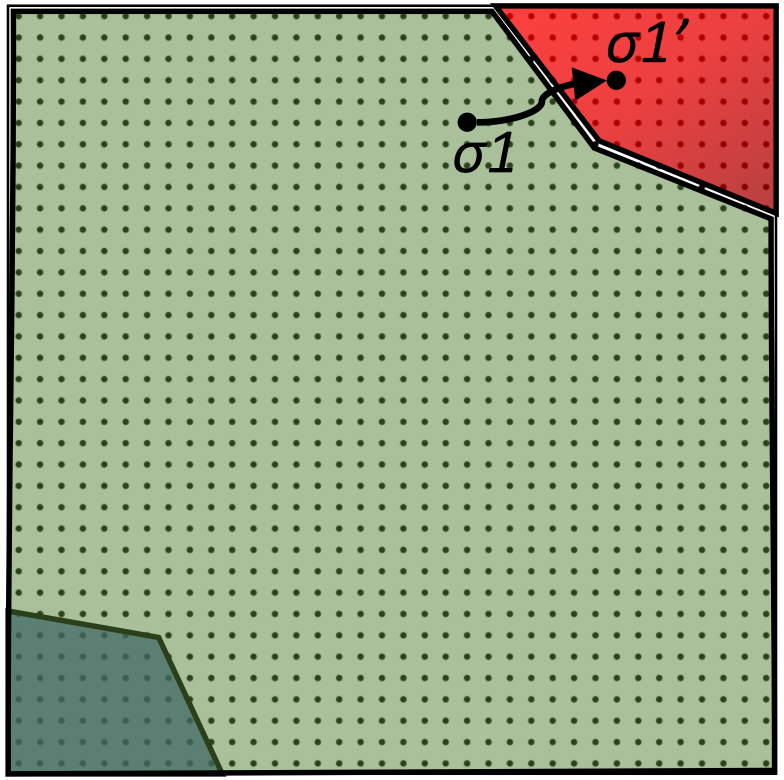
```
I1
I2
```

How can we find an inductive invariant without knowing it?

Invariant Inference In Ivy

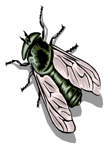
I *can* decide inductiveness!





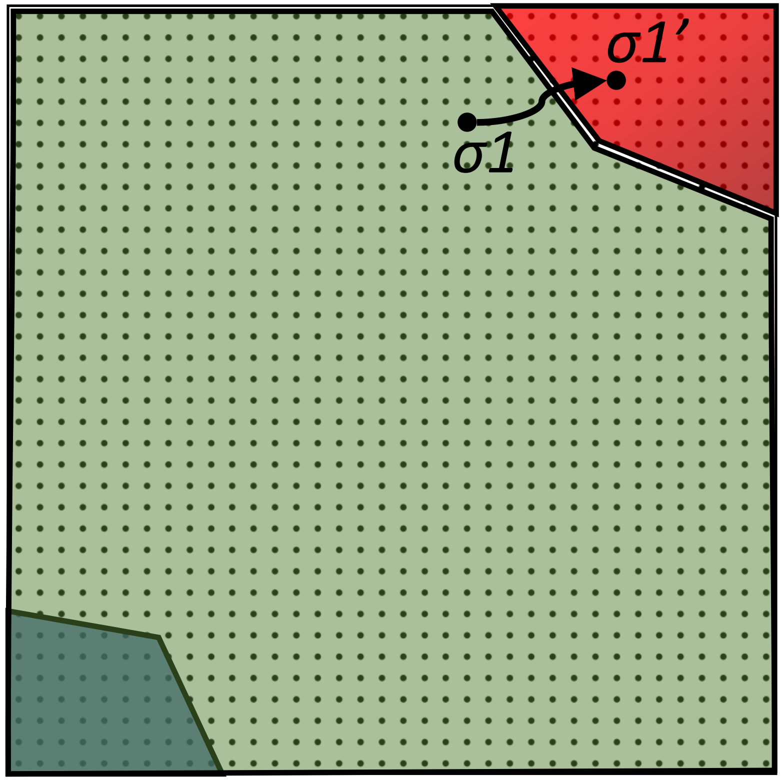
Inv = ¬Bad

Check Inductiveness



Counterexample To Induction (CTI)

Invariant Inference In Ivy



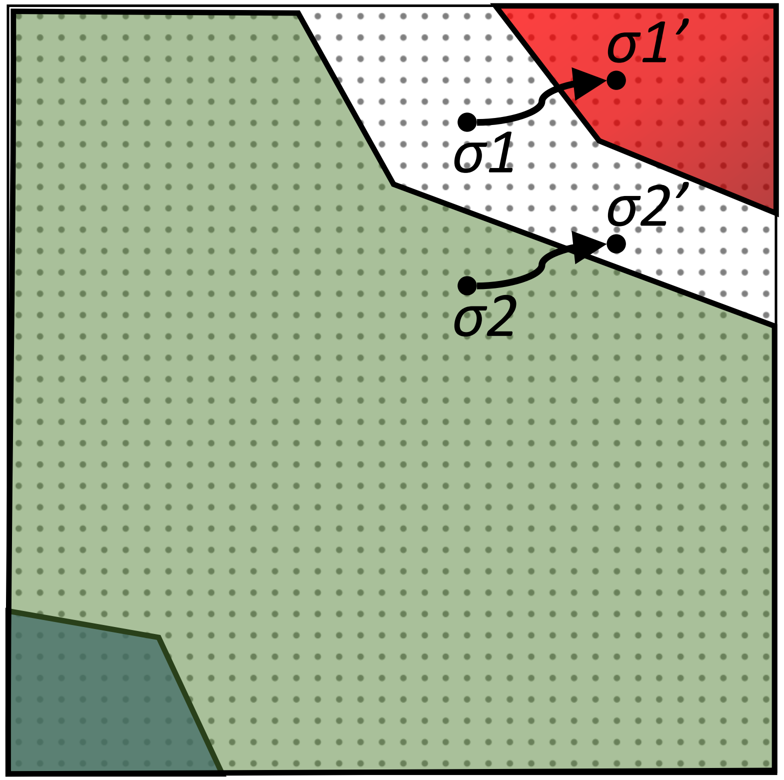
Inv = ¬Bad

σ1,σ1' – CTI

Generalize from CTI

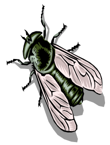
$\varphi(\sigma 1,\sigma 1')$

Invariant Inference In Ivy



$\mathrm{Inv} = \neg \mathrm{Bad} \wedge \varphi(\sigma 1, \sigma 1')$

Check Inductiveness



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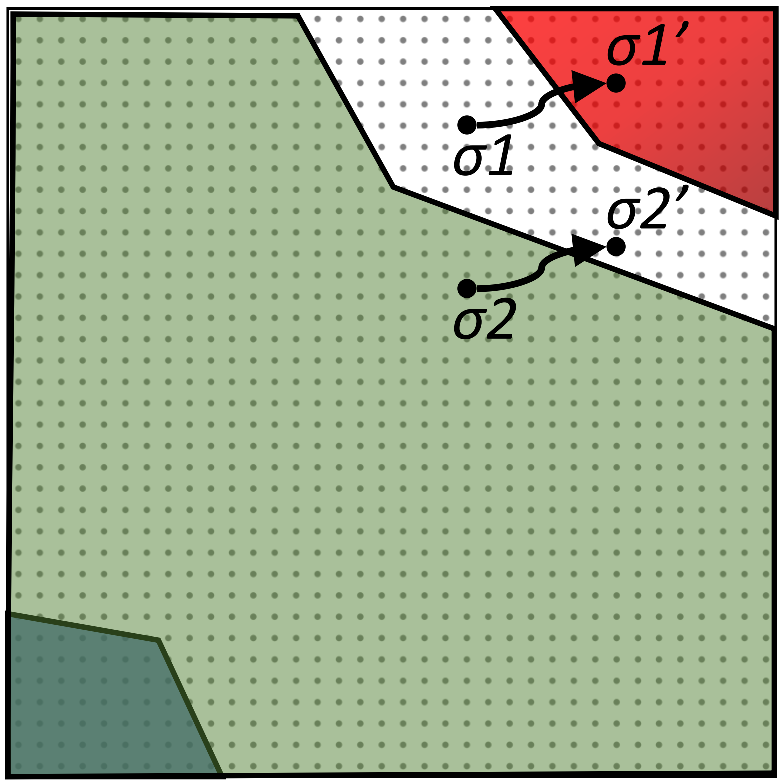
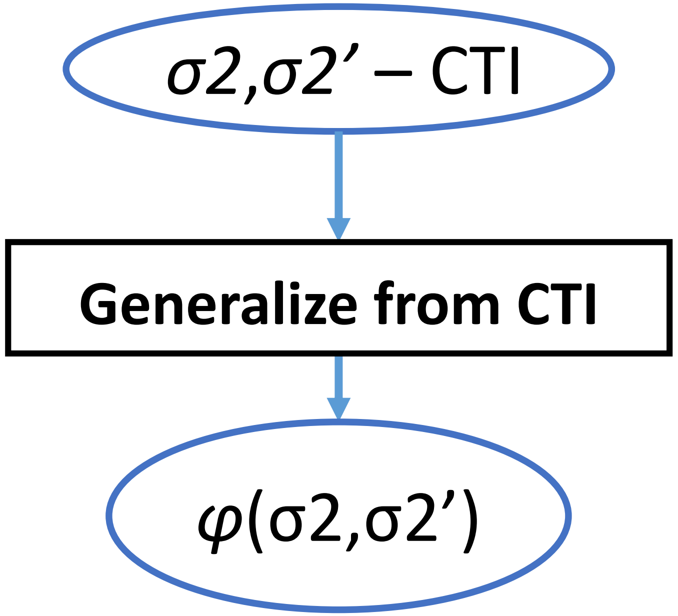


$Inv = \neg Bad \wedge \varphi(\sigma 1, \sigma 1')$



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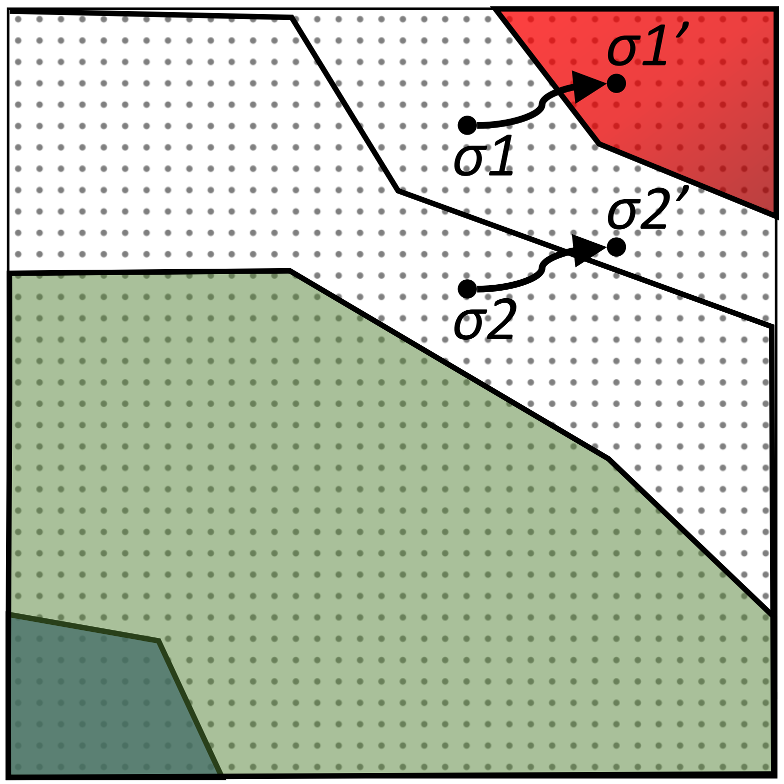
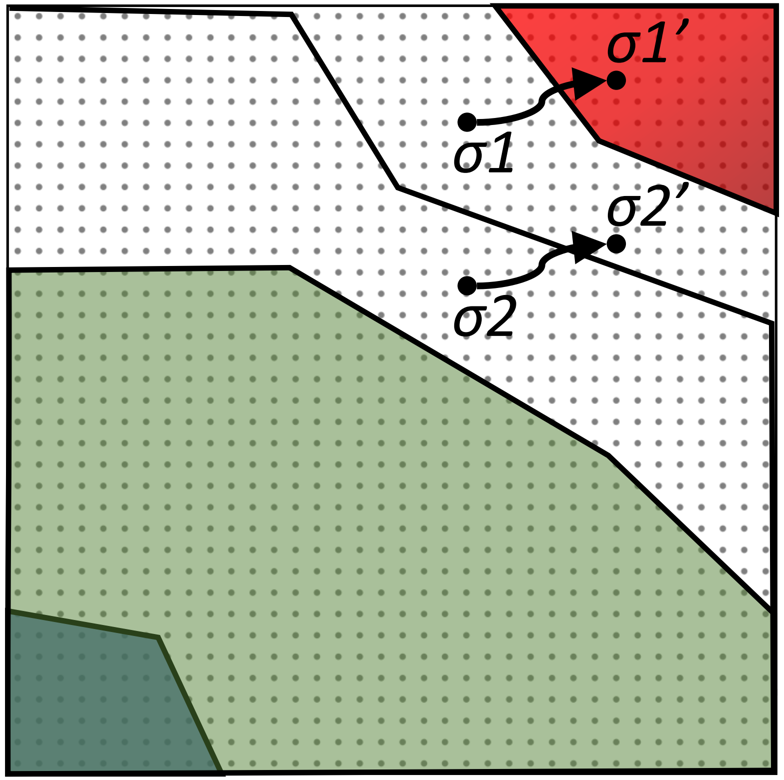


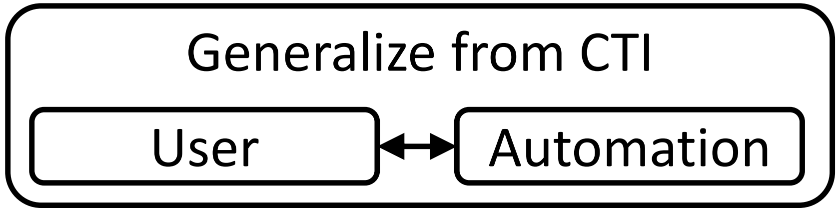
Inv = $\neg$Bad $\wedge$ φ(σ1,σ1') $\wedge$ φ(σ2,σ2')

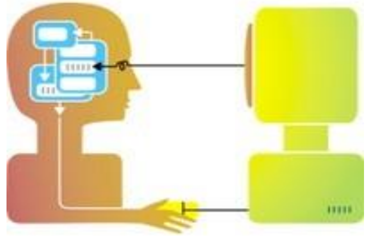
Invariant Inference In Ivy



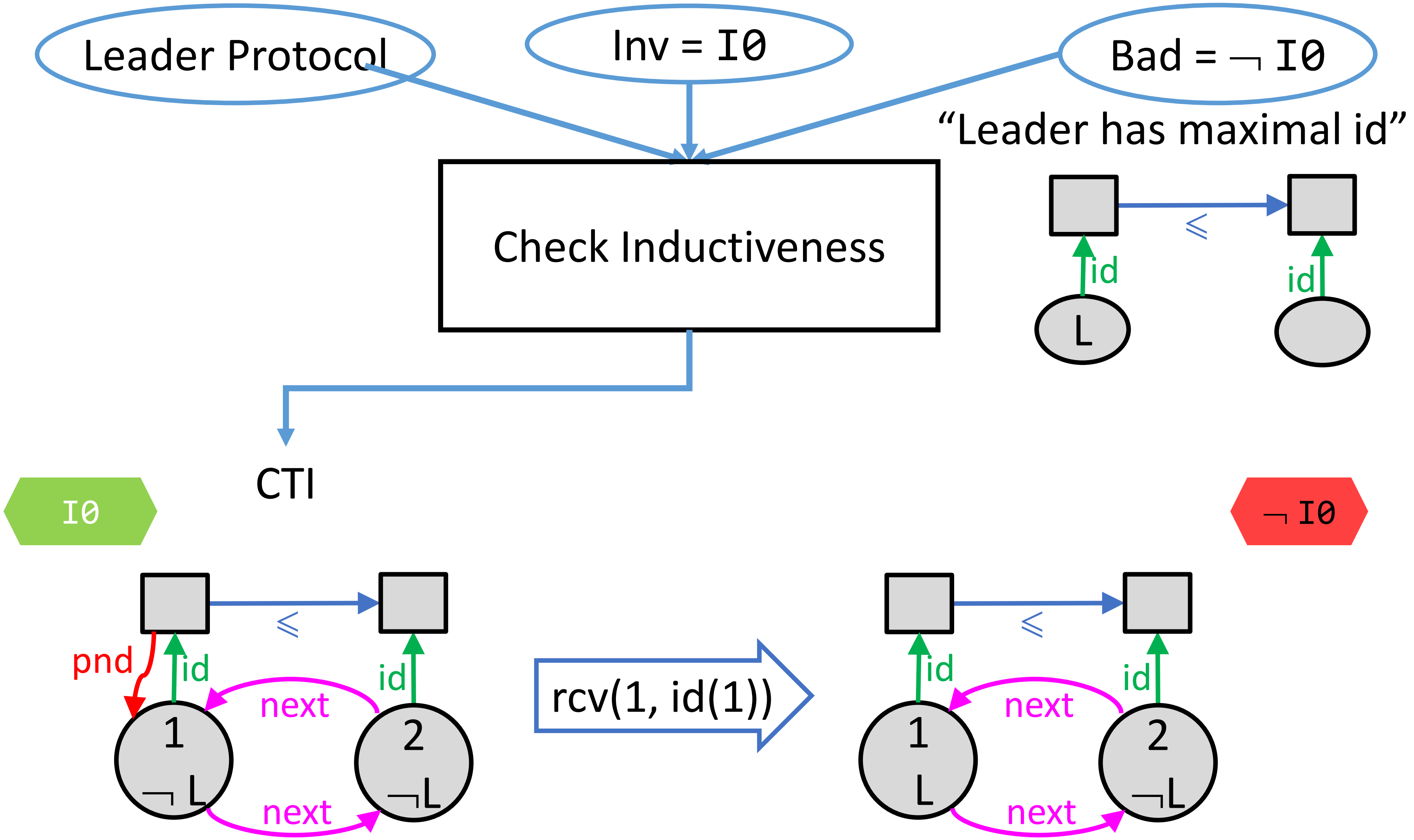
$Inv = \neg Bad \wedge \varphi(\sigma 1,\sigma 1') \wedge \varphi(\sigma 2,\sigma 2')$

- Key challenge for invariant inference: generalization
- Ivy's approach: put the user in the loop *interactive generalization*

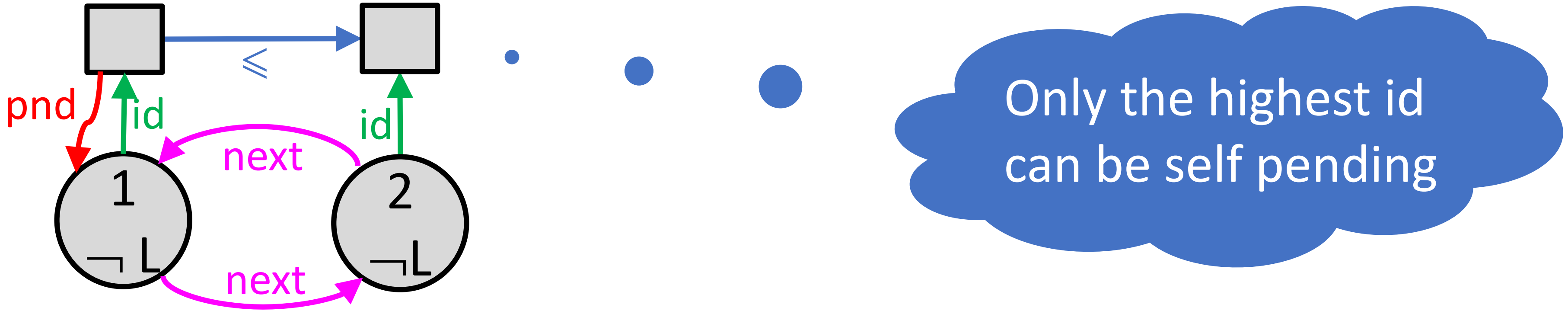




Ivy: Check Inductiveness (1)



Ivy: Generalize from CTI (1)



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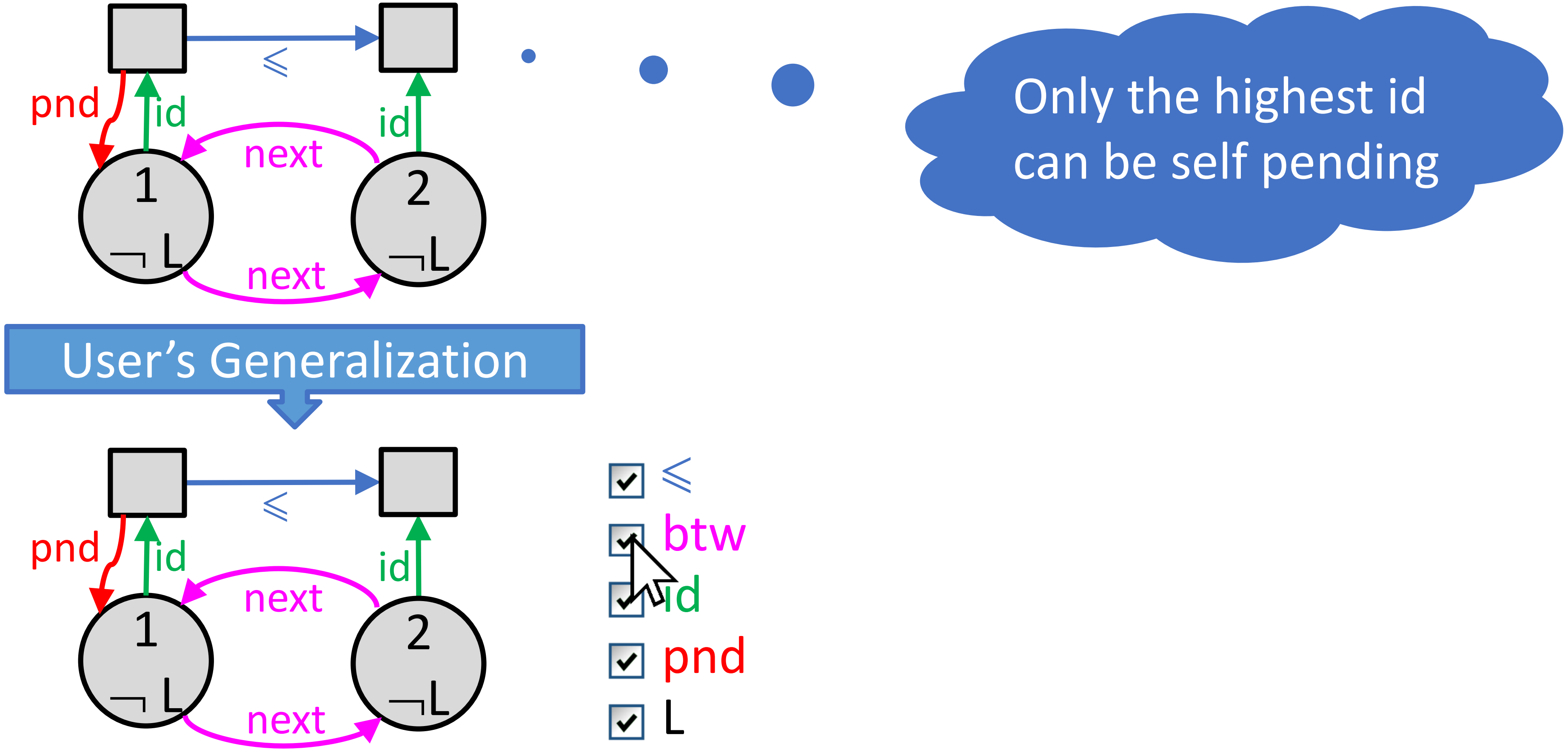

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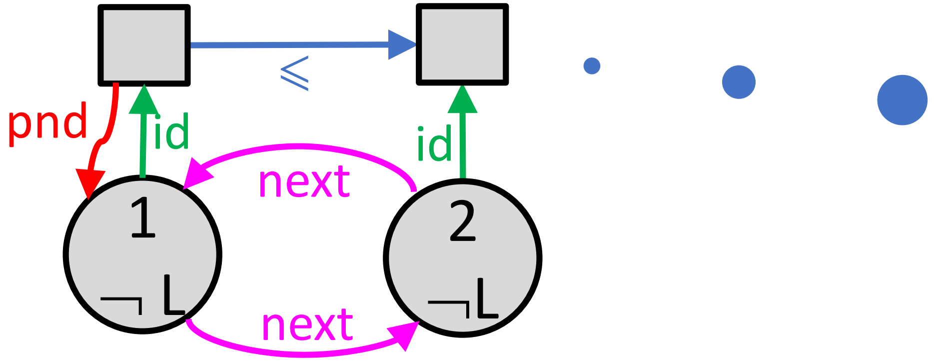
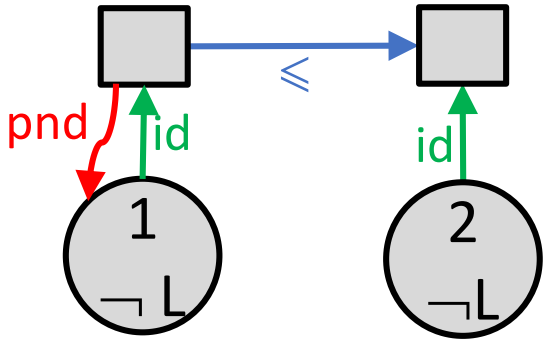
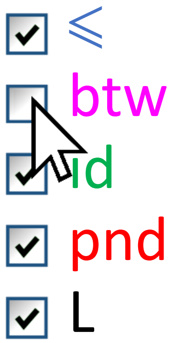


Only the highest id can be self pending

User’s Generalization





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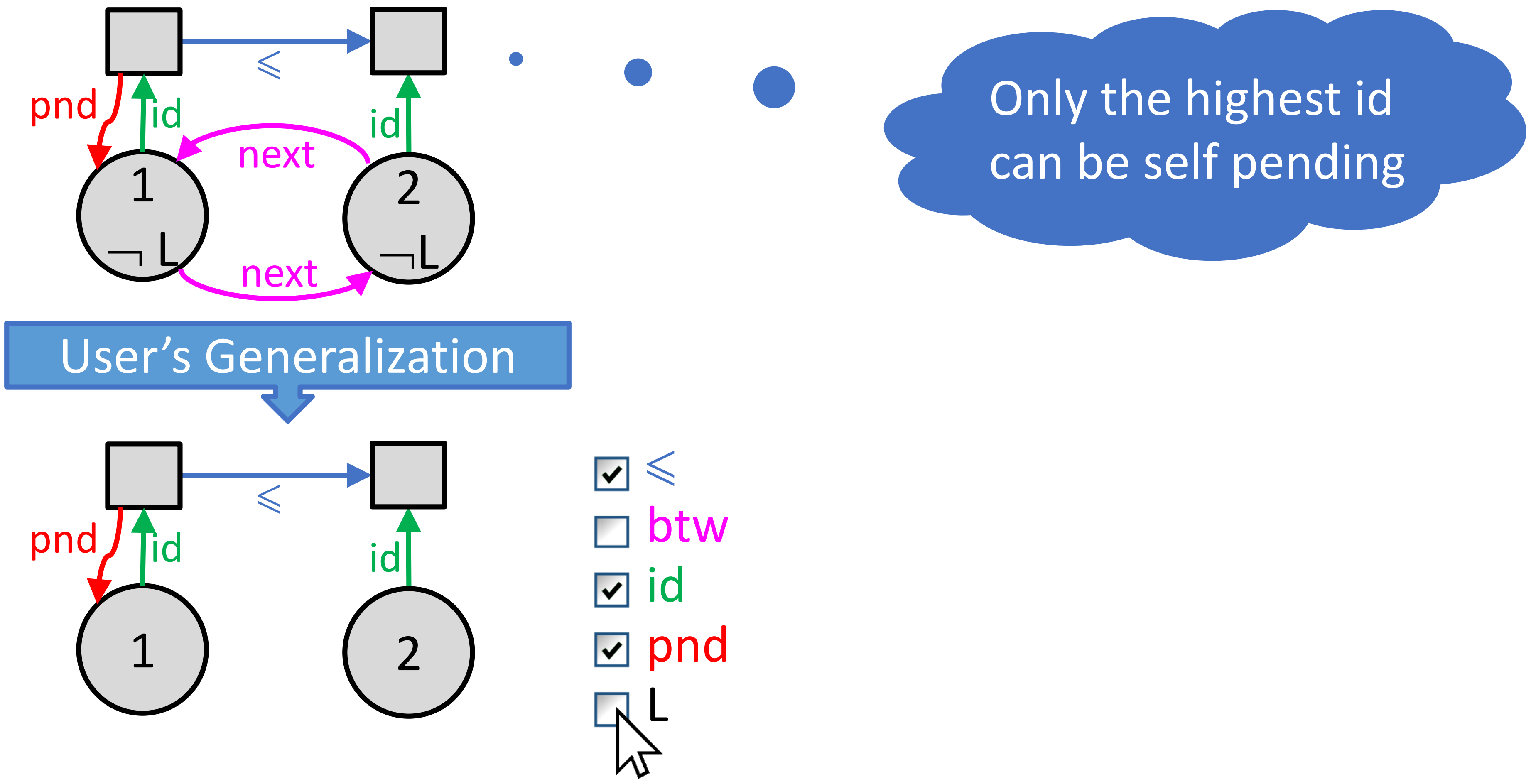

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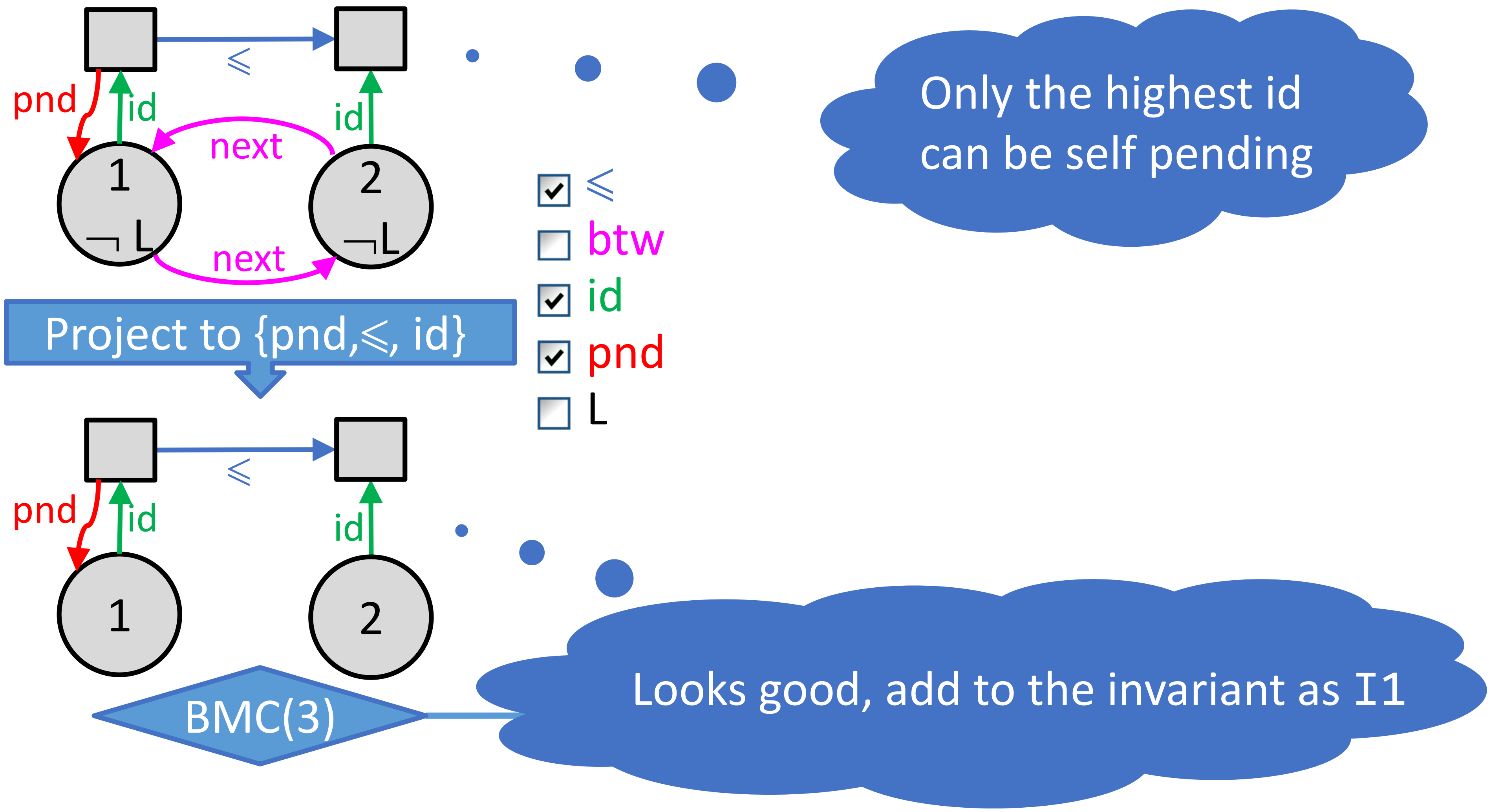
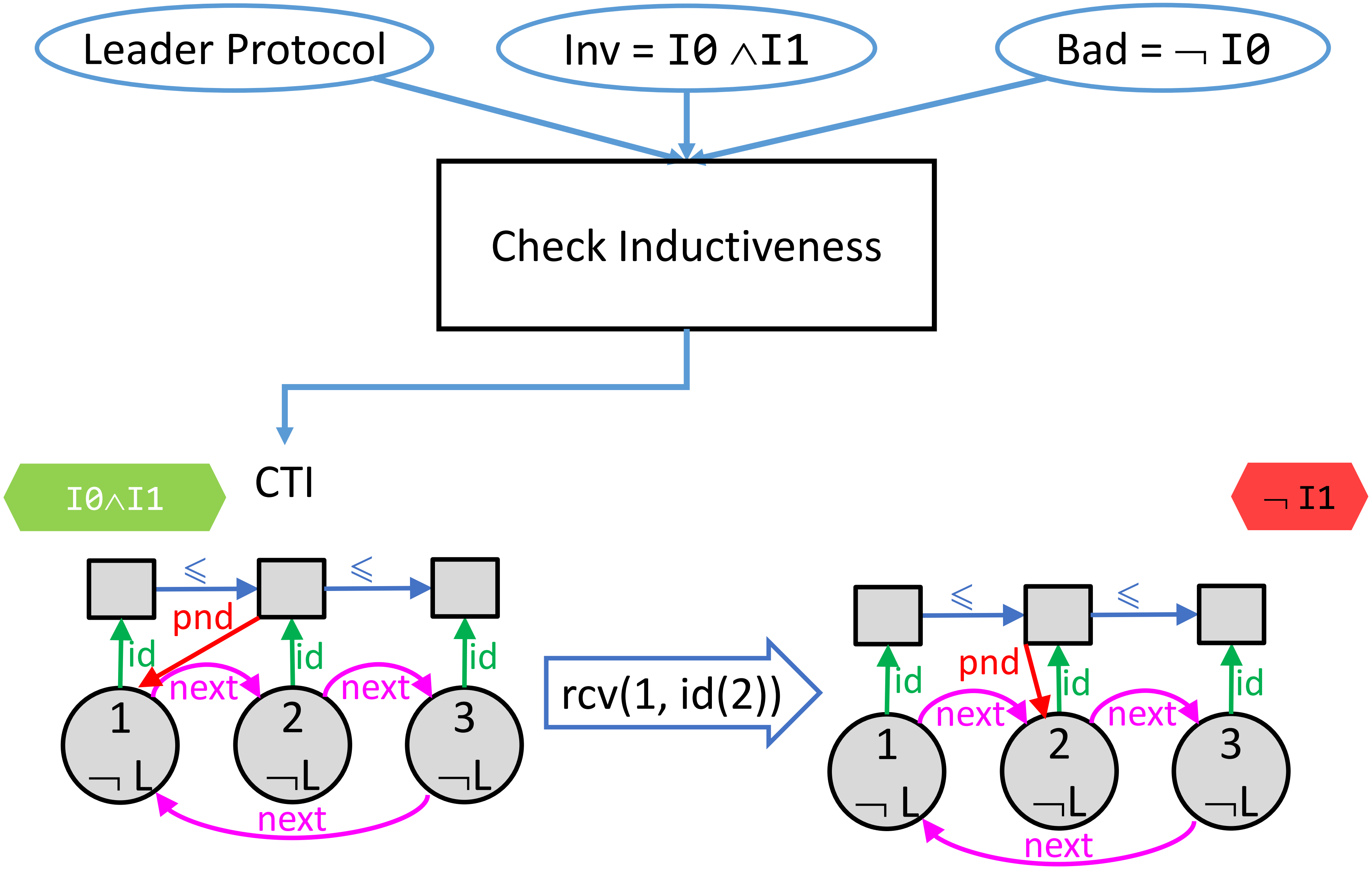


Ivy: Check Inductiveness (2)



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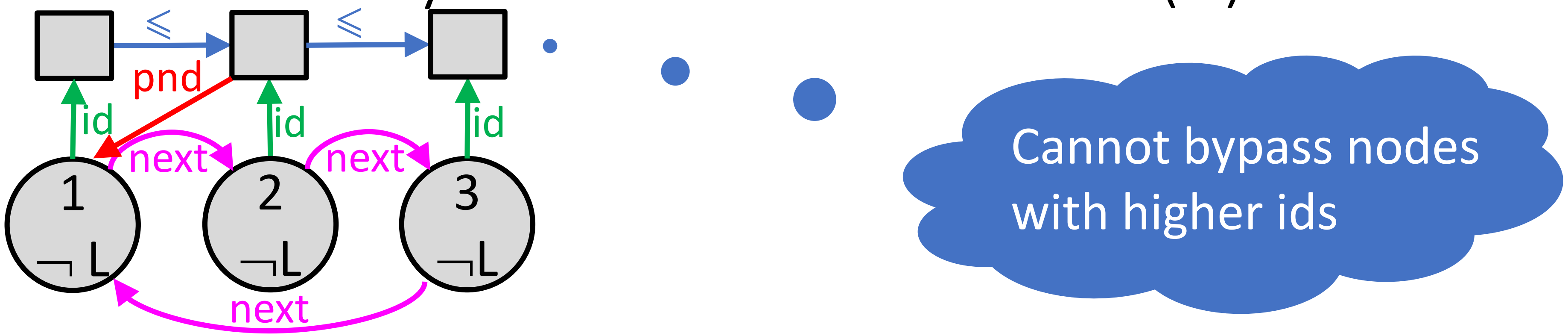

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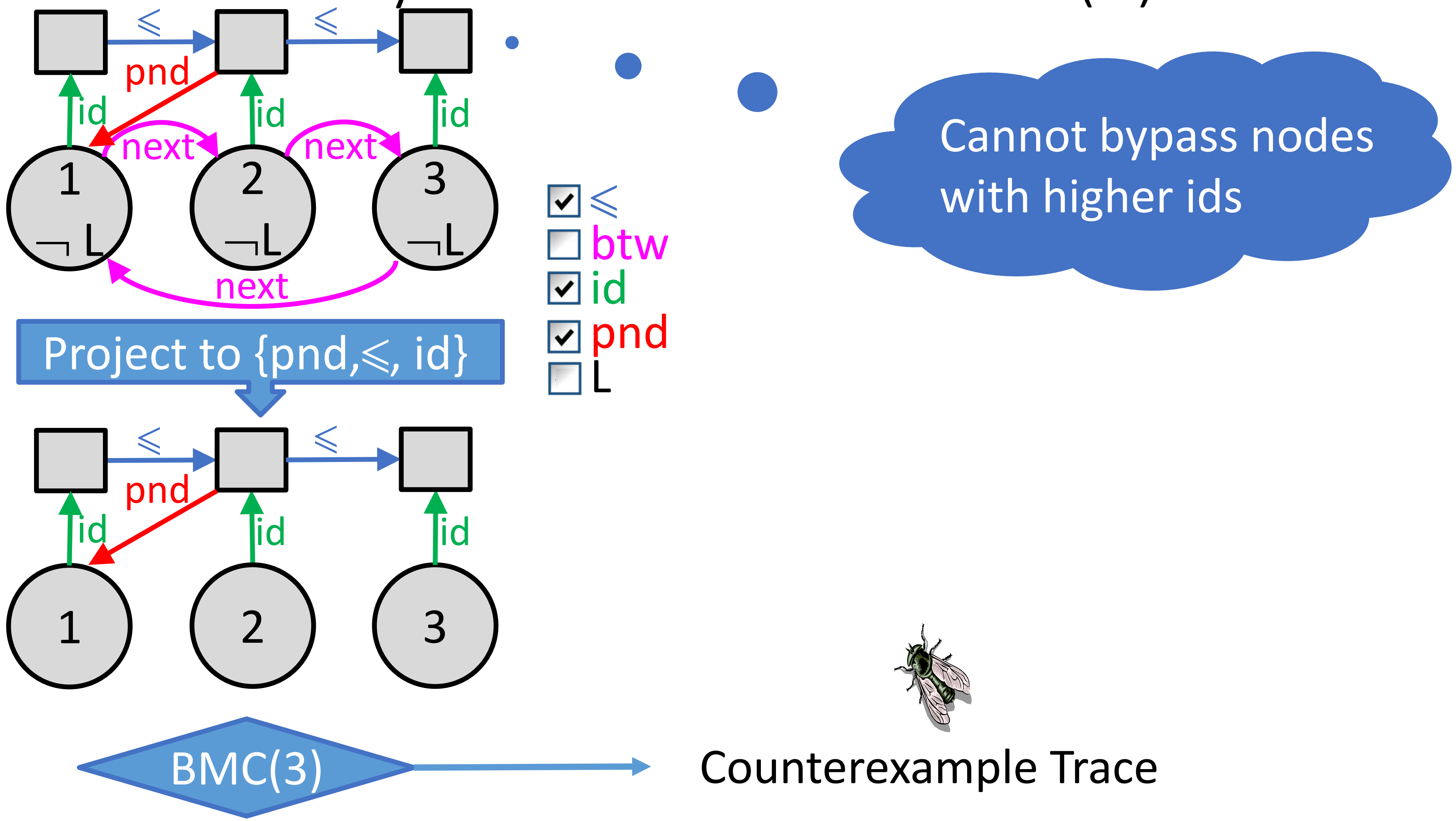

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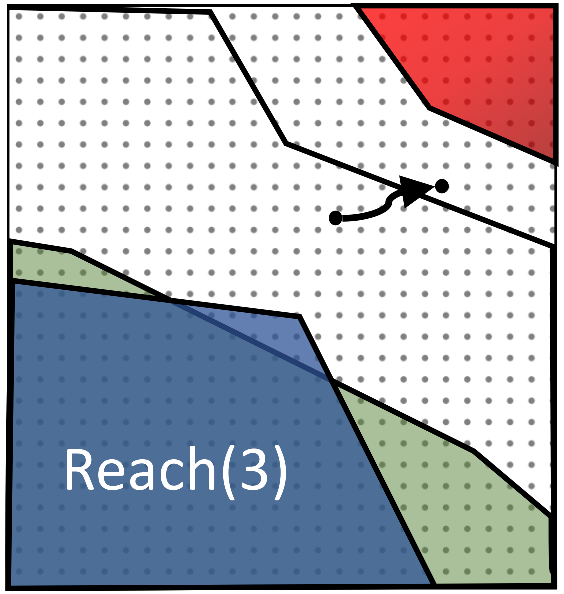
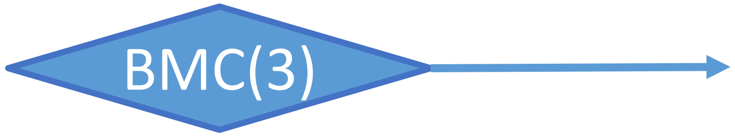
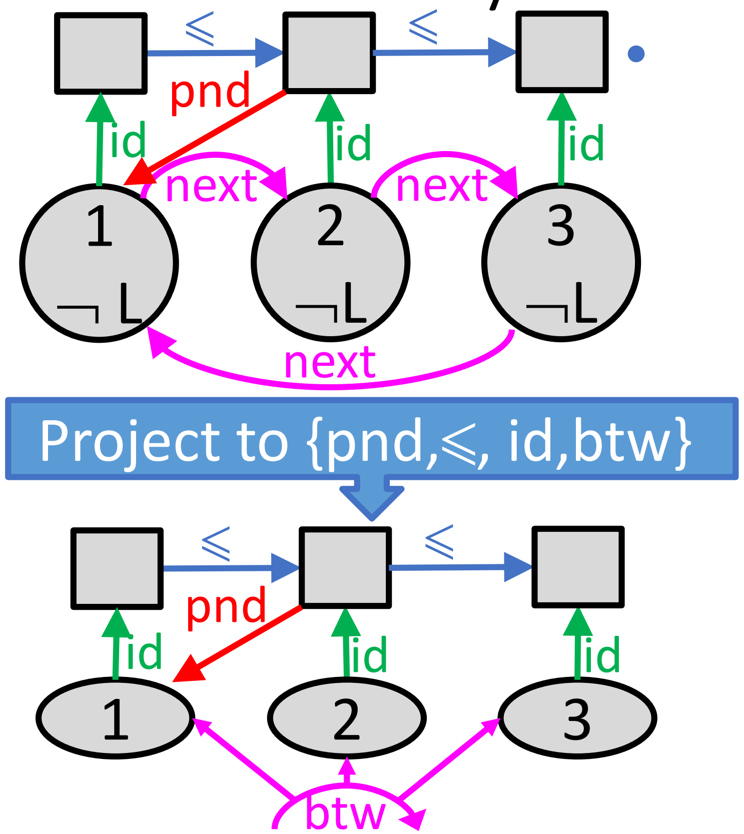




Counterexample Trace

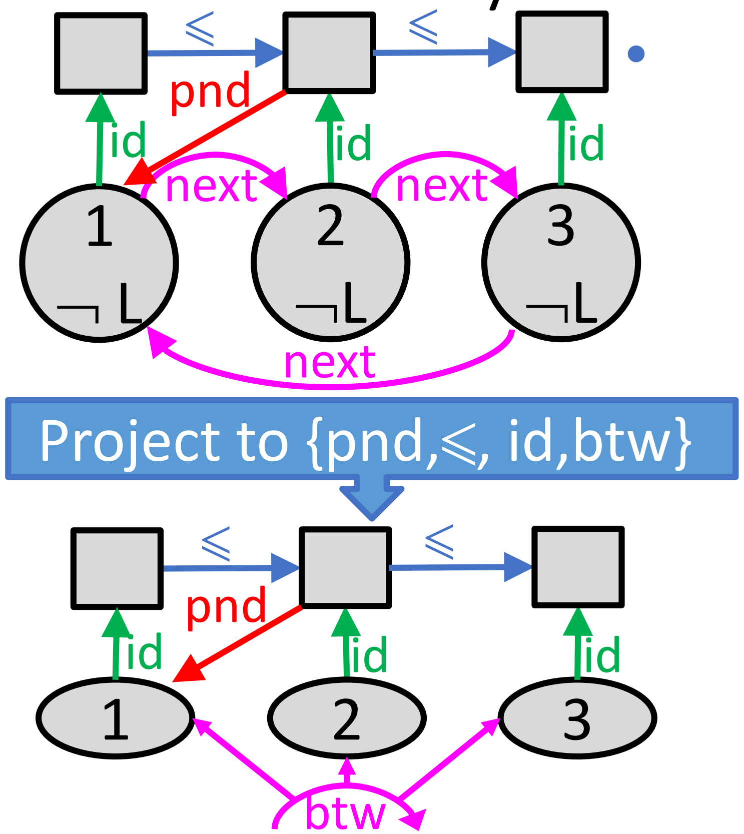
Ivy: Generalize from CTI (2)



- ☑ ⩽
- ☑ btw
- ☑ id
- ☑ pnd
- ☐ L

Cannot bypass nodes with higher ids

Ivy: Generalize from CTI (2)

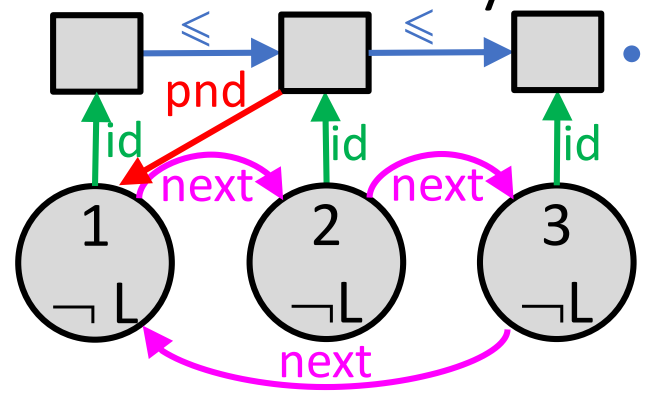


- [x] ⩽
- [x] btw
- [x] id
- [x] pnd
- [ ] L

Cannot bypass nodes with higher ids

BMC(3) → Proof + UNSAT CORE

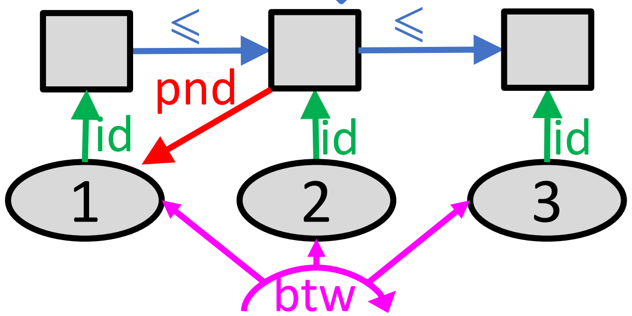
Ivy: Generalize from CTI (2)



Cannot bypass nodes with higher ids

- [x] ⩽
- [x] btw
- [x] id
- [x] pnd
- [ ] L

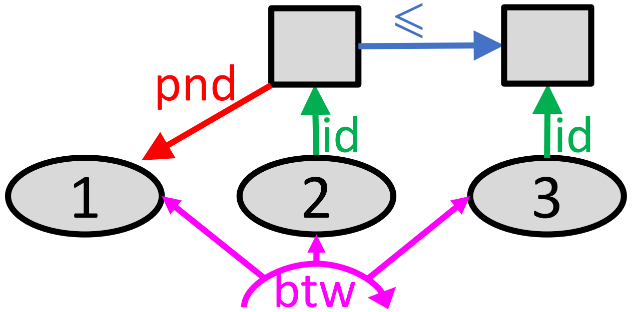
Project to {pnd,⩽, id,btw}



Interp(3)

Proof +

UNSAT CORE



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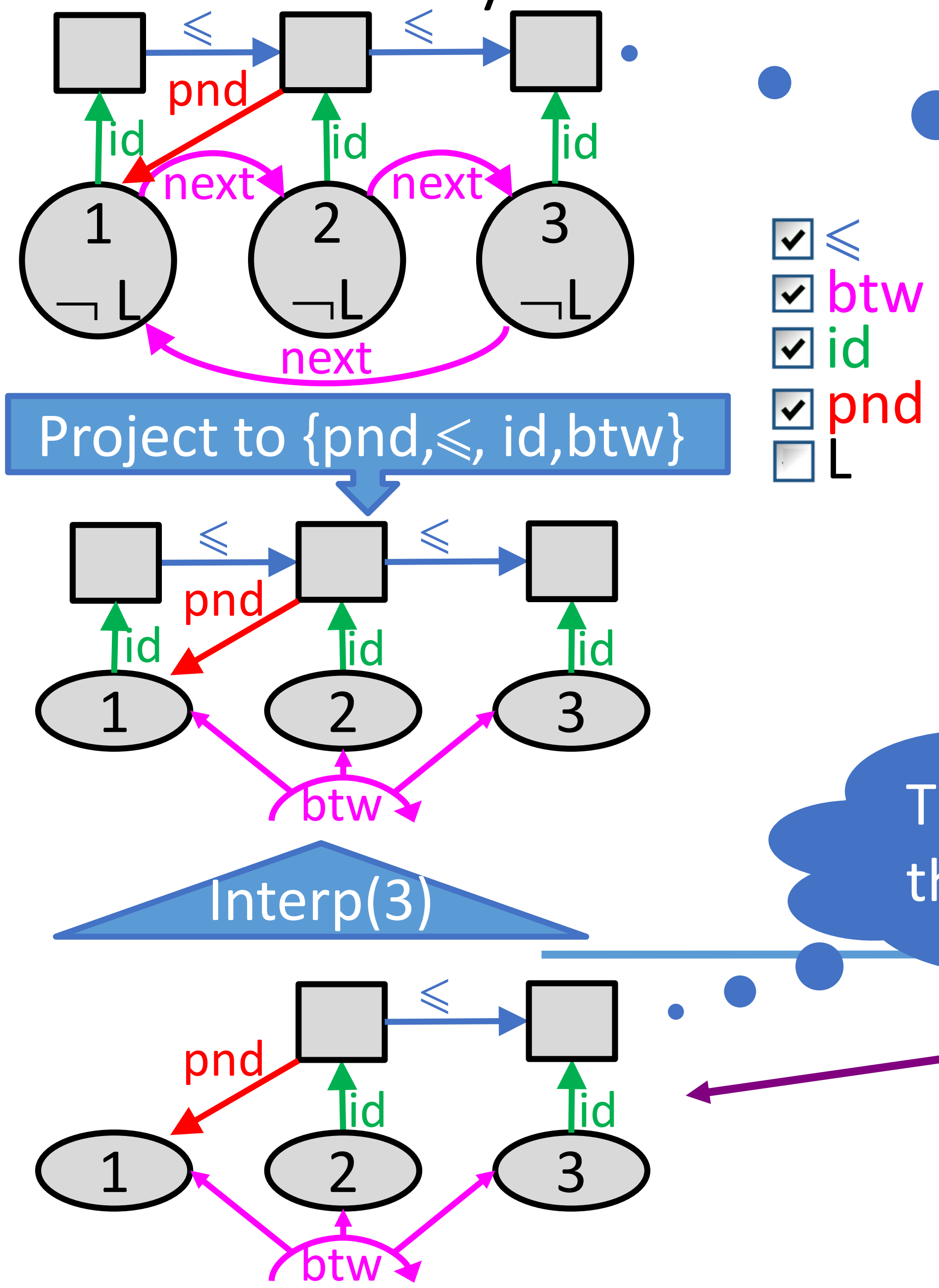
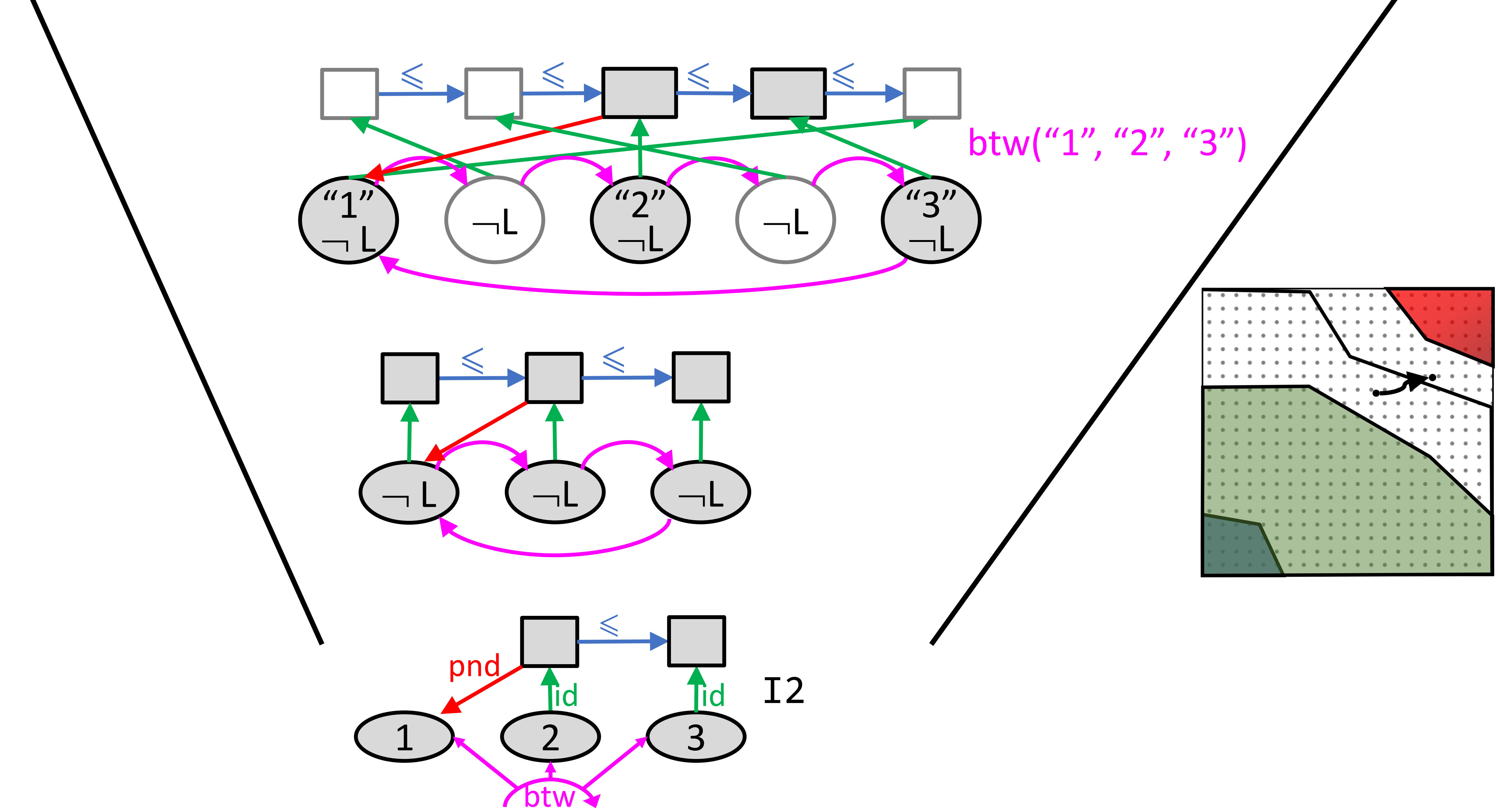


Cannot bypass nodes with higher ids

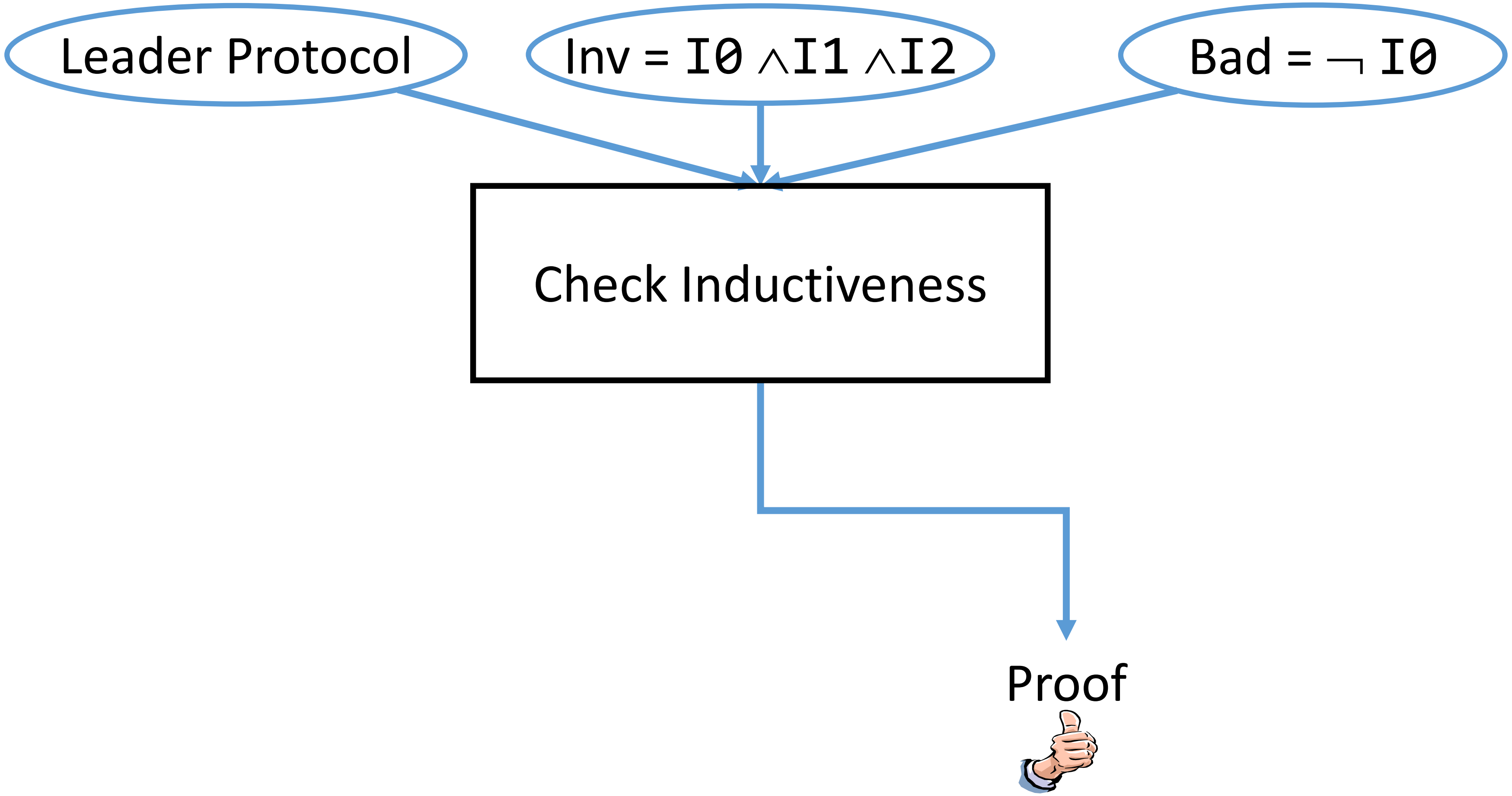
This looks good, add to the invariant as I2

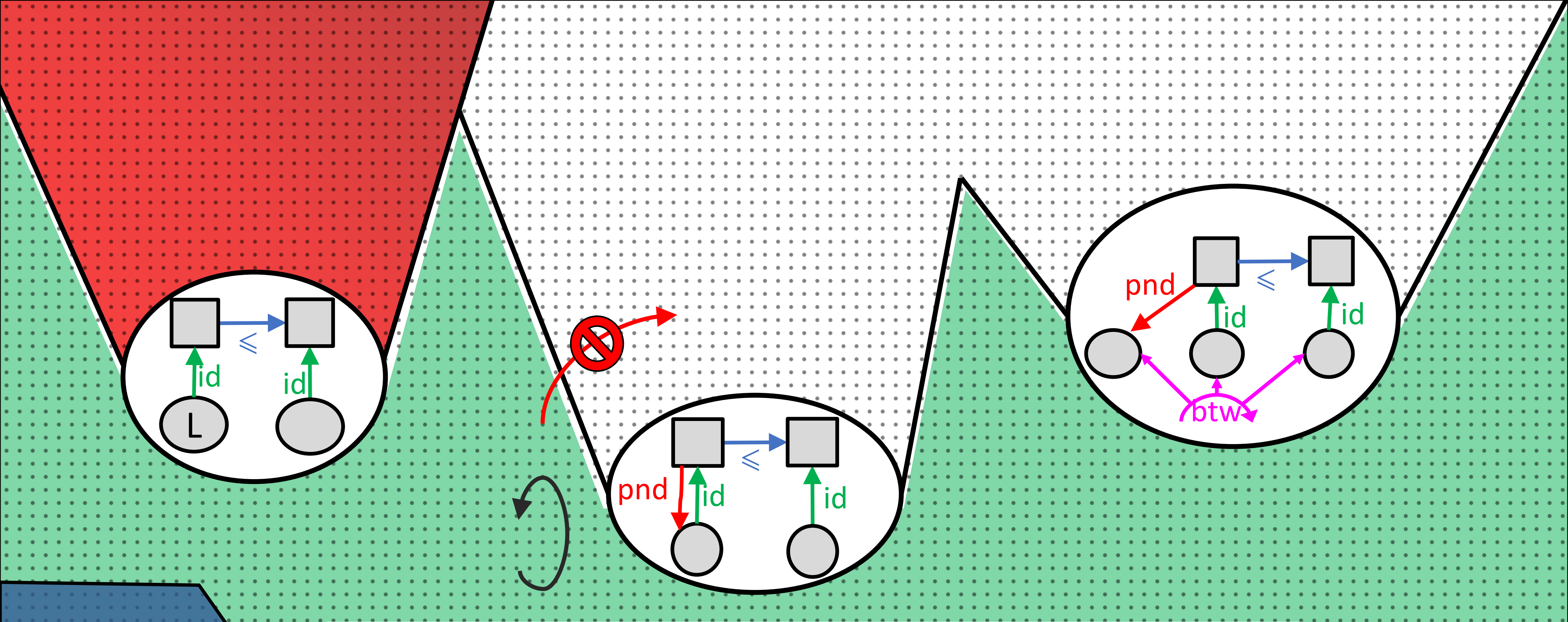
UNSAT CORE

Generalization with btw



Ivy: Check Inductiveness (3)





Init $\subseteq$ *Inv* (*Initiation*)

if $\sigma \in$ *Inv and* $\sigma \rightarrow \sigma'$ *then* $\sigma' \in$ *Inv* (*Consecution*)

Inv $\cap$ *Bad* $= \varnothing$ (*Safety*)

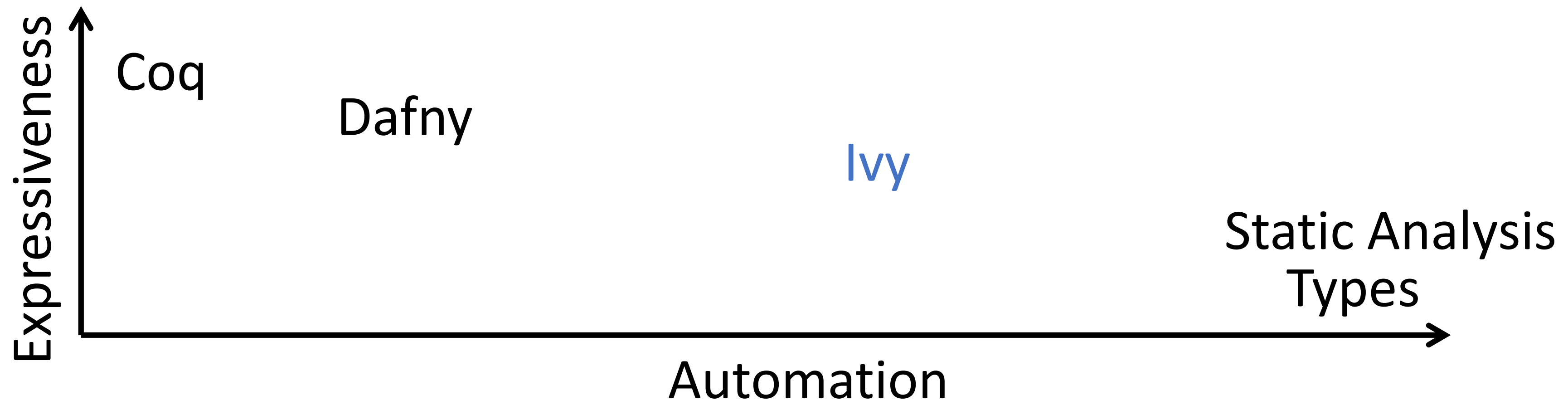
Completeness and Interaction Complexity

- Any generalization from CTI adds one universally quantified clause
- A universally quantified invariant in CNF with N clauses, can be obtained by the user in N generalization steps
  - Assuming the user is optimal
- If the user is sub-optimal, backtracking (weakening) may be needed

Verified Protocols

Protocol	Model Types	Relations & Functions	Property (# Literals)	Invariant (# Literals)	CTI Gen. Steps
Leader in Ring	2	5	3	12	3
Learning Switch	2	5	11	18	3
DB Chain Replication	4	13	11	35	7
Chord	1	13	35	46	4
Lock Server 500 Coq lines [Verdi]	5	11	3	21	8 (1h)
Distributed Lock 1 week [IronFleet]	2	5	3	26	12 (1h)
Paxos	Work in progress				
Raft					

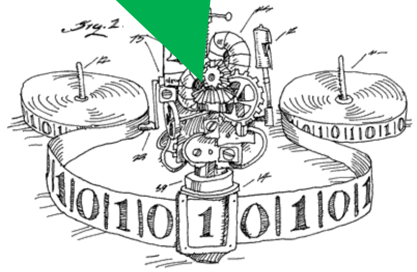
Expressiveness vs. Automation



	Coq	Dafny	Ivy	Fully Automatic Static Analysis
Invariant	User	User	User + System	System
Deduction	User	System (Z3) + "User"	System (EPR Z3)	System

Summary

I *can* decide inductiveness!



- RML – modeling language that makes deduction decidable
  - Many systems can be verified (axioms for orders, trees, rings, …)
- Interactive generalization for finding inductive invariants
- Application to the domain of distributed protocols
- User intuition and machine heuristics complement each other:
  - User has intuition that leads to *better generalizations*
  - Machine is better at finding bugs and corner cases
- Interactive process assists user to gain intuition about the protocol