Bounded Quantifier Instantiation for Checking Inductive Invariants

TACAS'17

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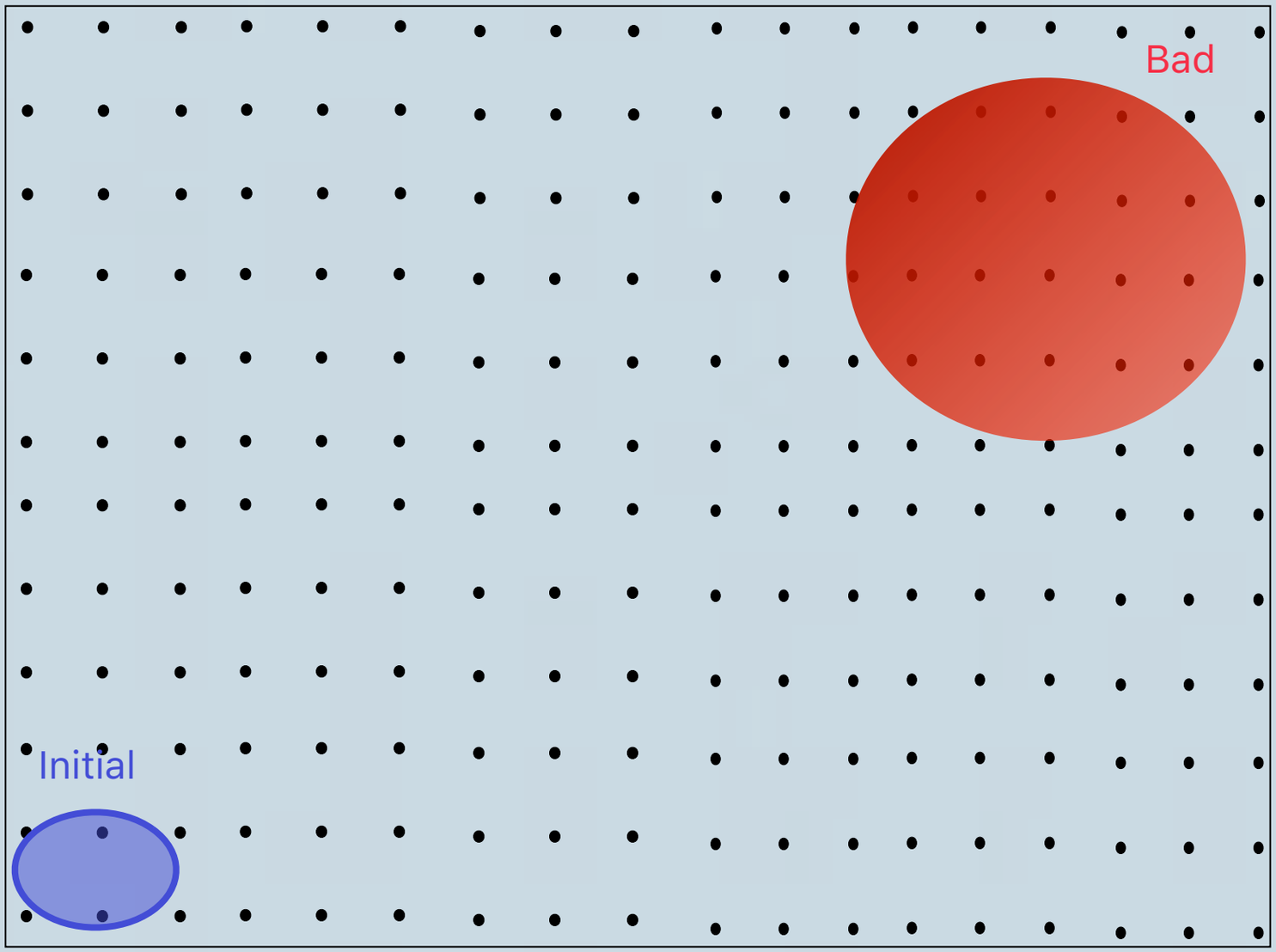
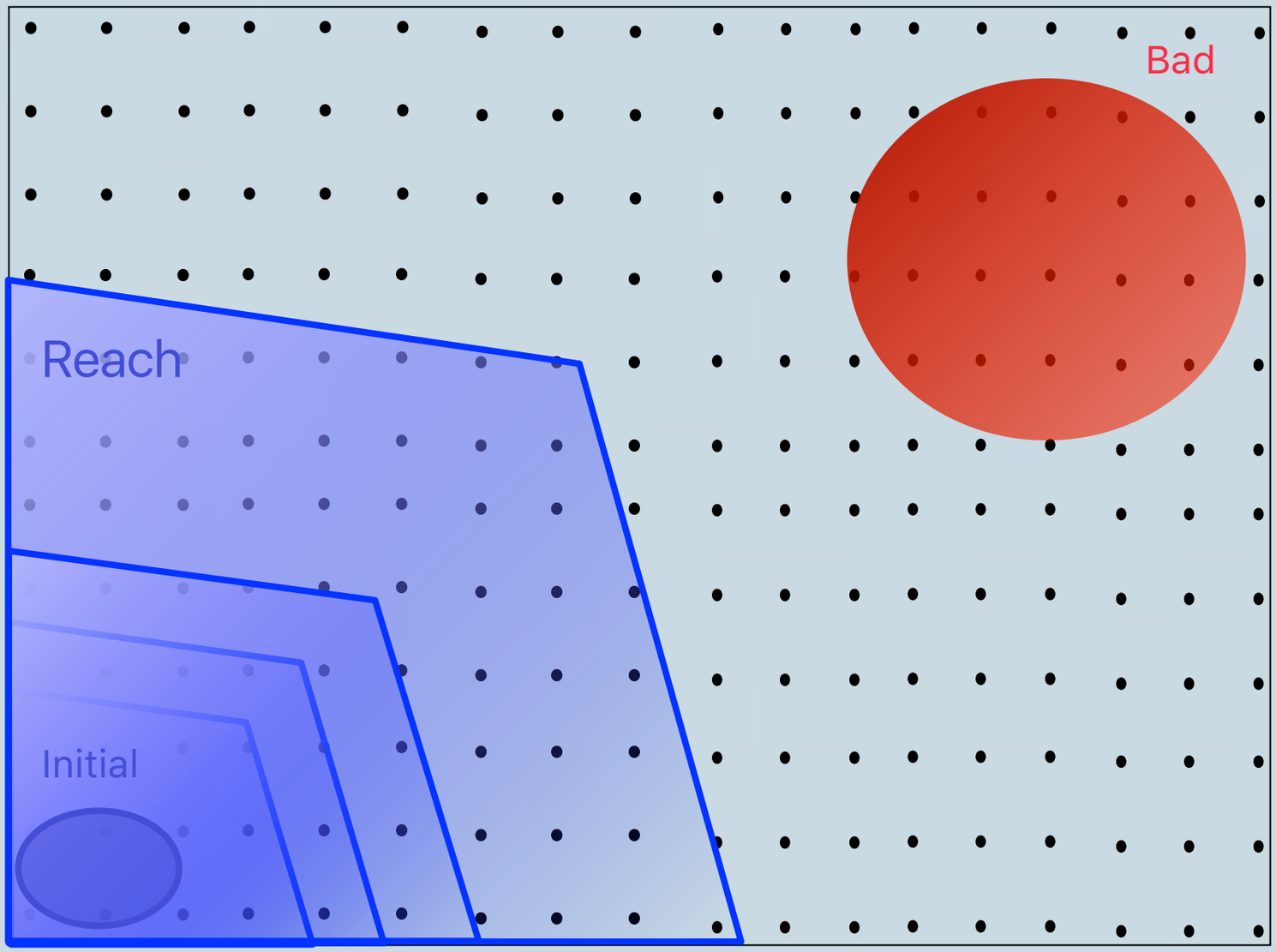
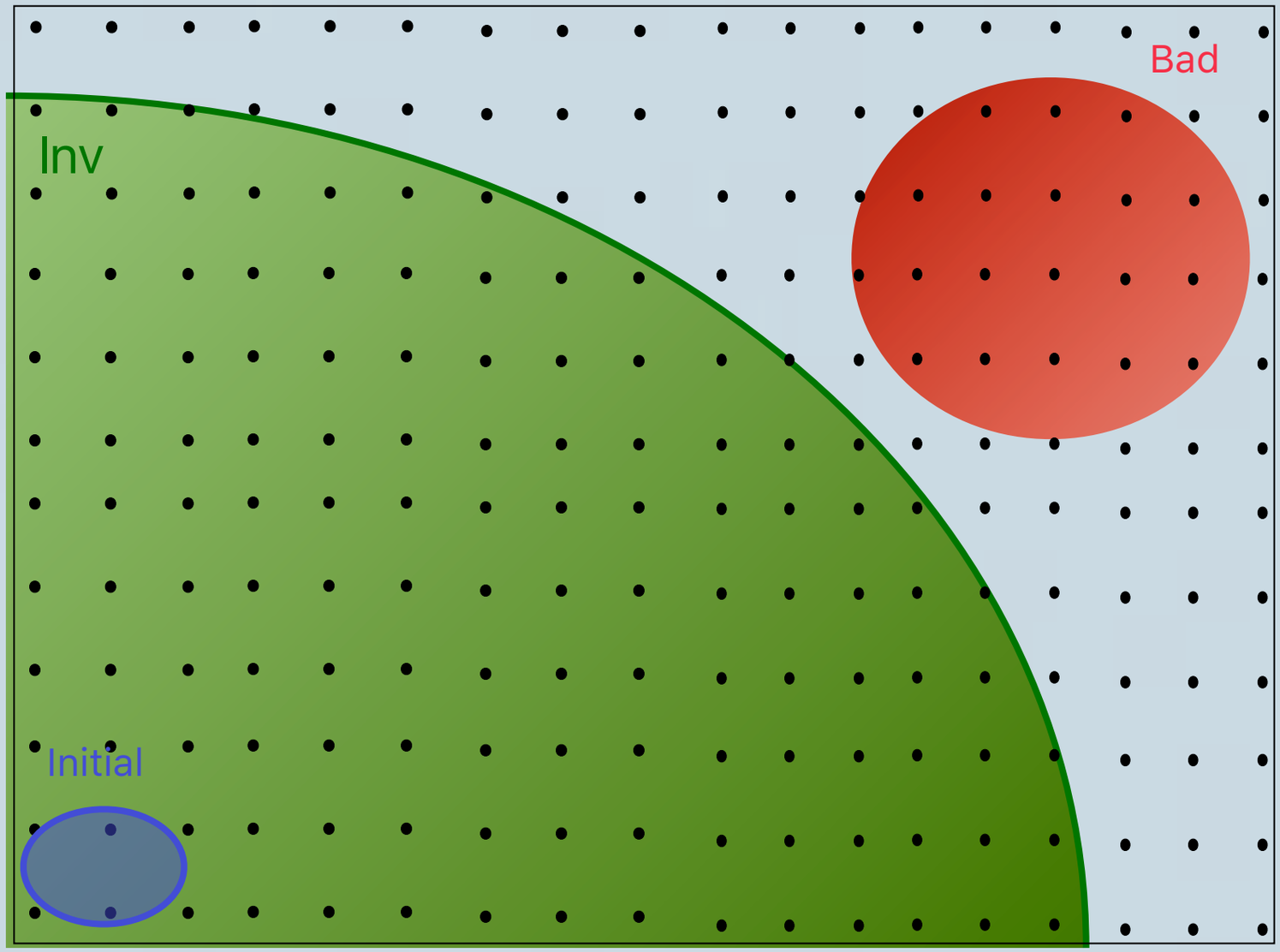
Safety of Infinite-State Systems



Safety of Infinite-State Systems



Inductive Invariants



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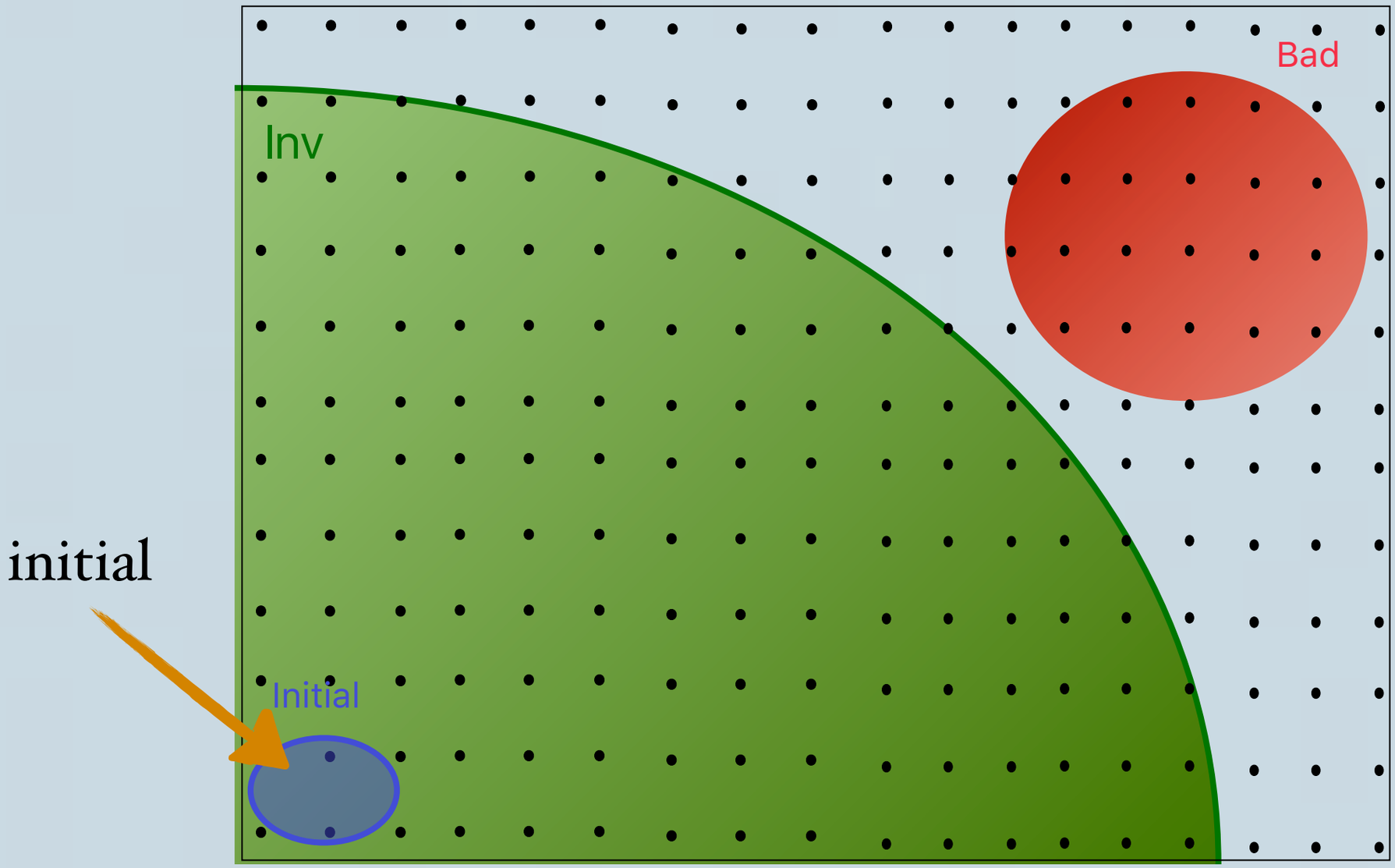
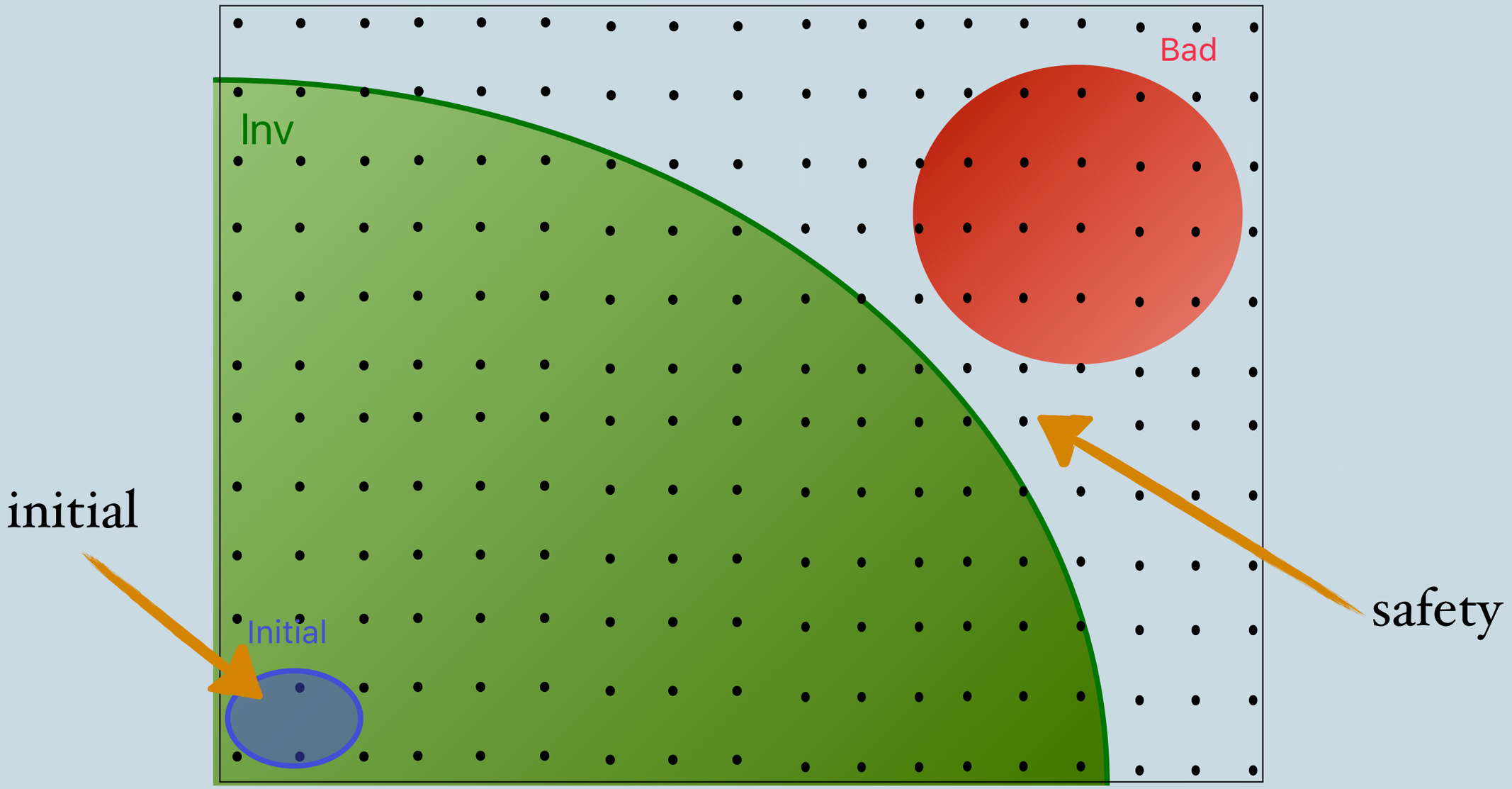


Inductive Invariants



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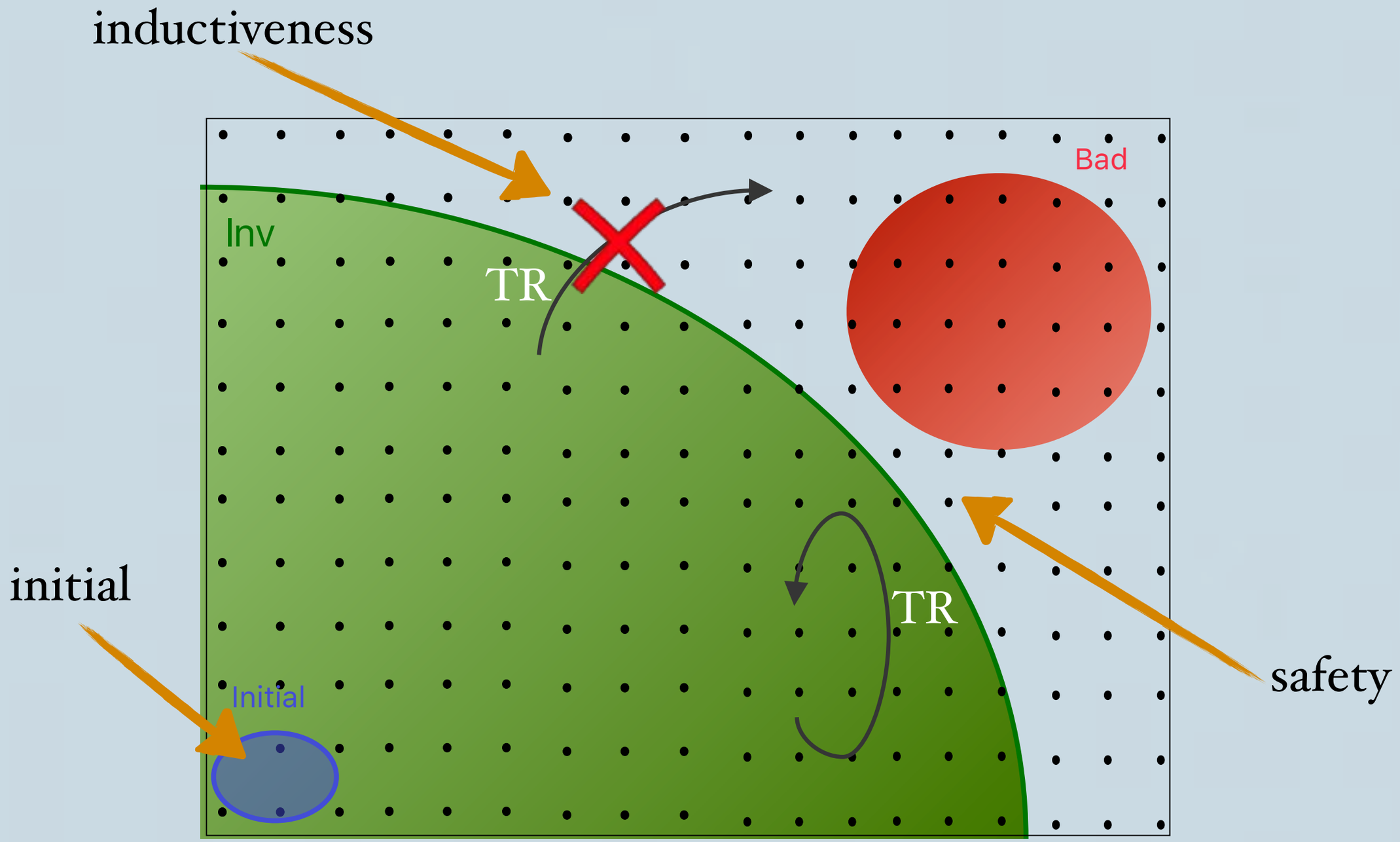

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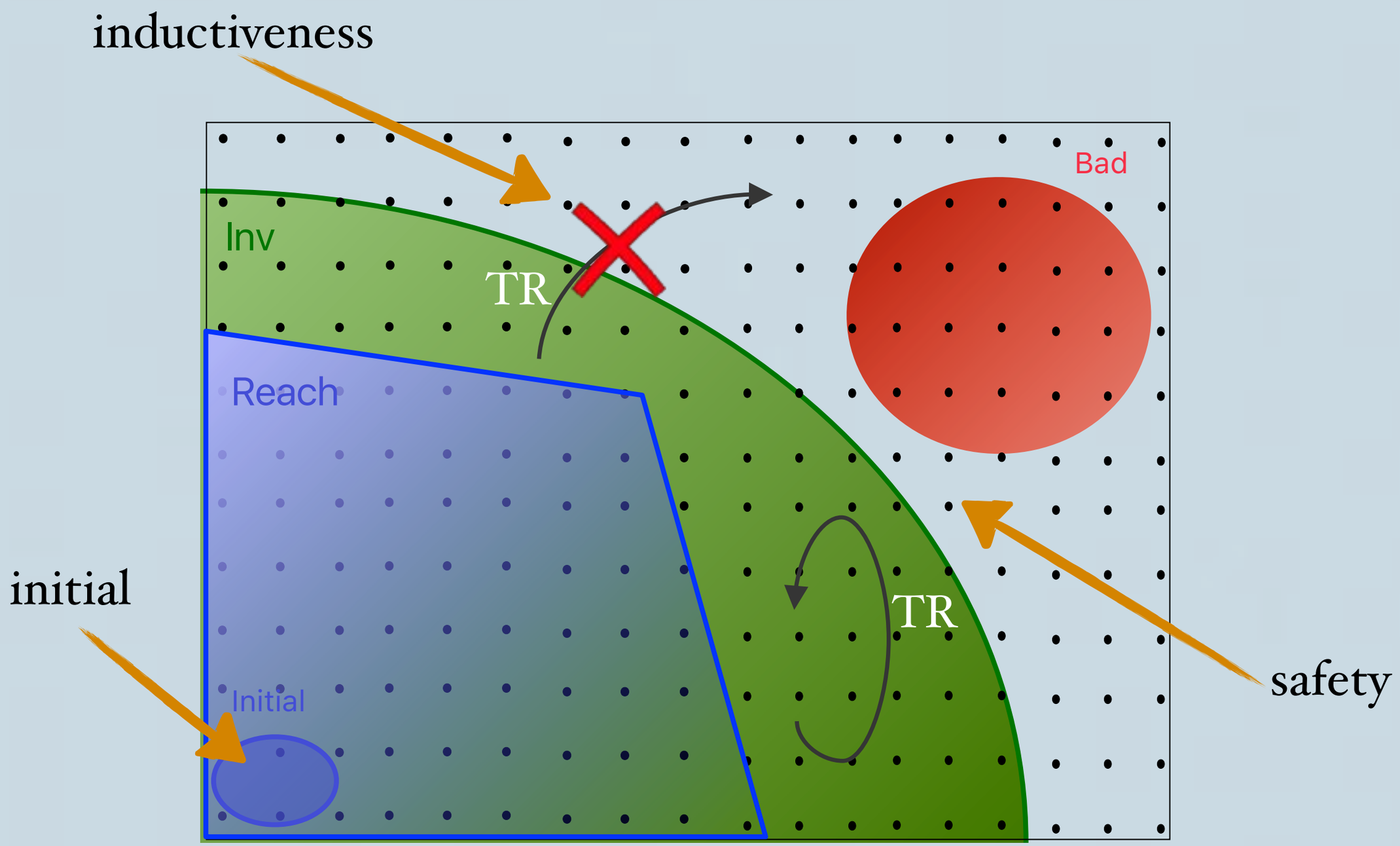
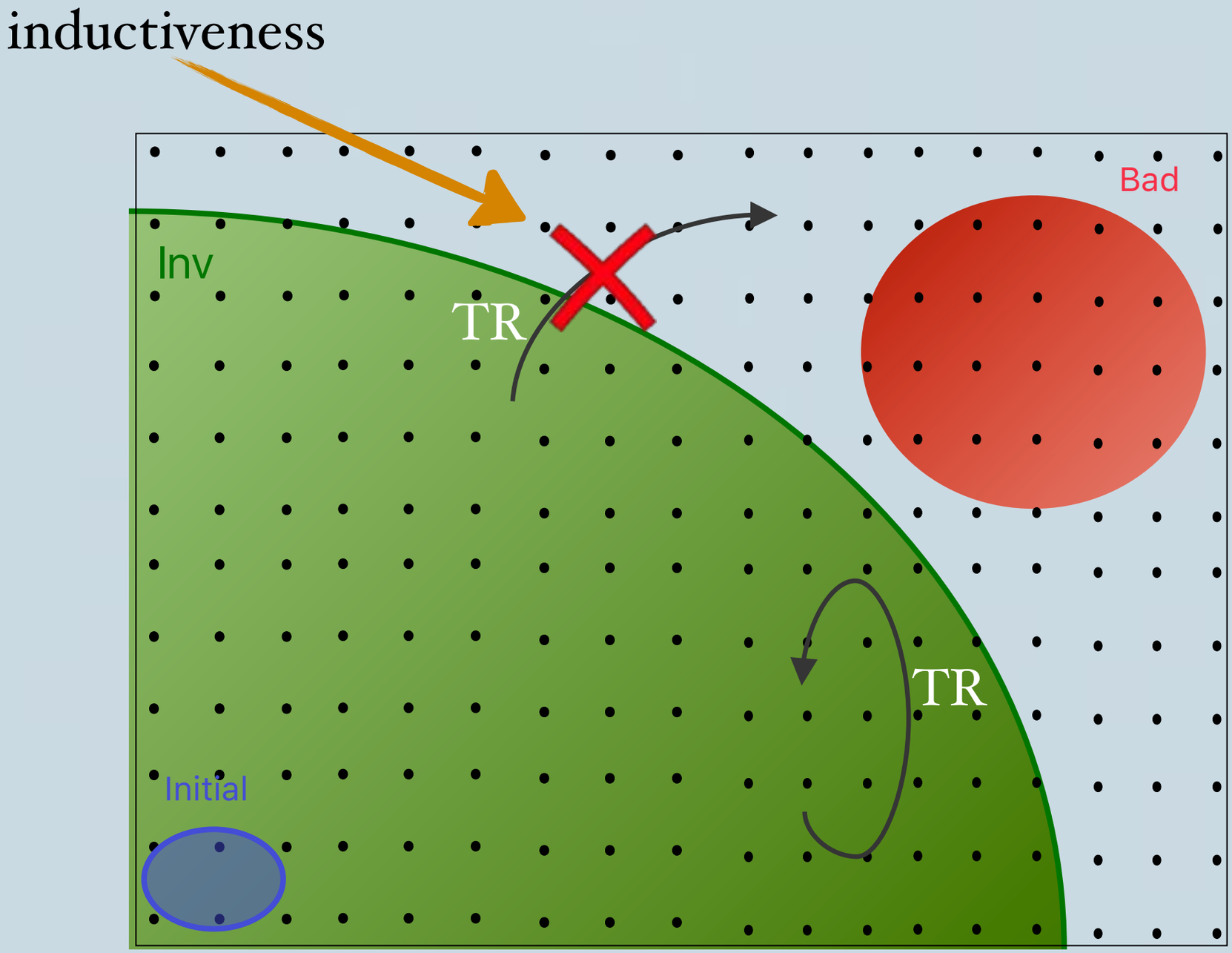


Checking Inductive Invariants



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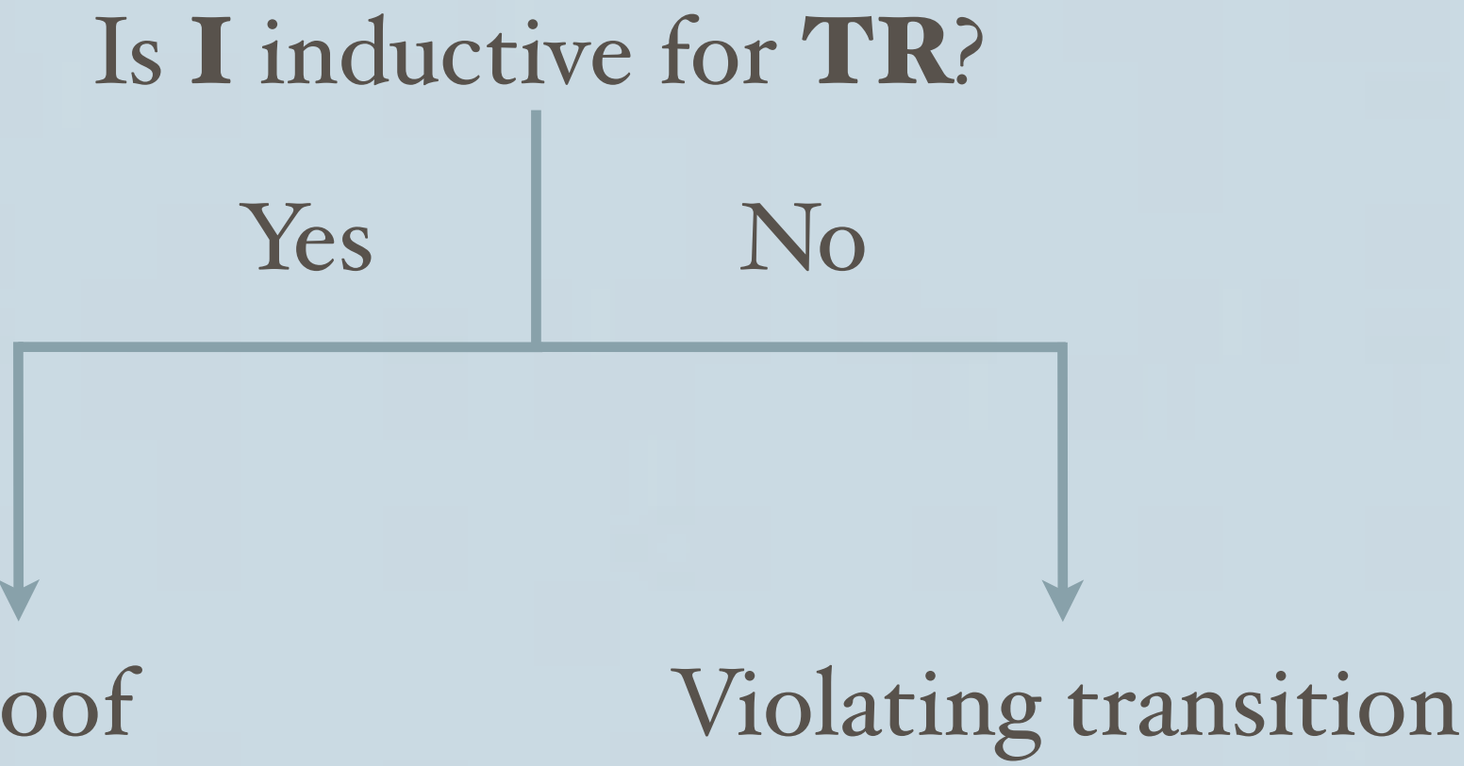
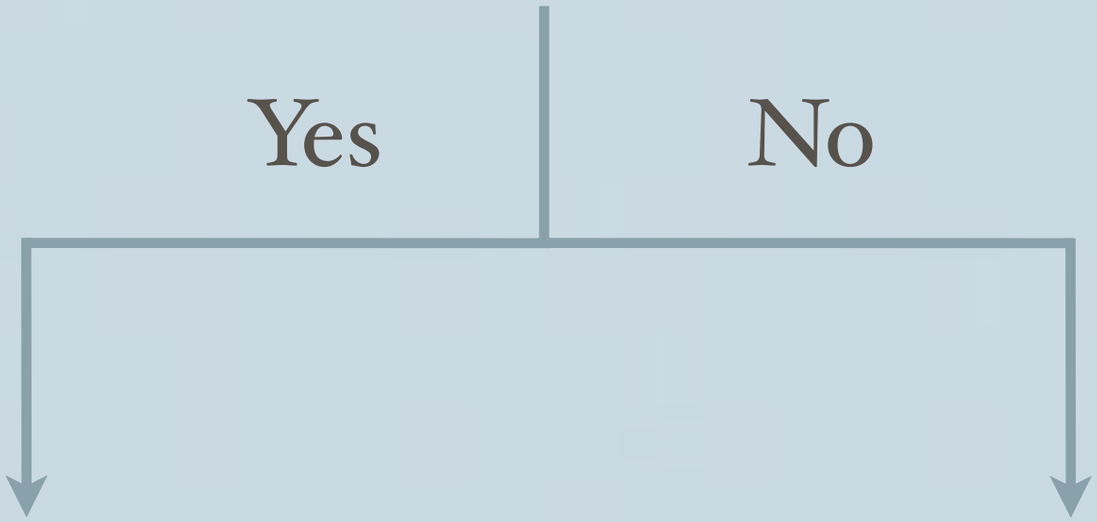


Checking Inductive Invariants

Is **I** inductive for **TR**?



Goal: check automatically

Checking Inductive Invariants

$$\boldsymbol{I}(V) \wedge \boldsymbol{TR}(V, V') \wedge \neg \boldsymbol{I}(V')$$

invariant inductive iff formula unsat

Checking Inductive Invariants

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invariant inductive iff formula unsat

Pure First-Order Logic Modeling

+ Quantification - Arithmetic

- Shape Analysis [Itzhaky et al. CAV'13, POPL'14, CAV'14, CAV'15]
- Software-Defined Networks [Ball et al. PLDI'14]
- Distributed protocols [Padon et al. PLDI'16]
- Concurrent Modification Errors in Java programs [Frumkin et al. VMCAI'17]

Effectively Propositional Logic (EPR)

- No function symbols: constants + relations
- No arithmetic
- Restricted quantifier prefix: ∃*∀*
- Satisfiability is decidable

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$$\mathrm{TR} = \exists^*\forall^* \qquad\qquad \mathrm{Inv} = \forall^*$$

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$$\mathrm{TR} = \exists^*\forall^* \qquad\qquad \mathrm{Inv} = \forall^*$$

$$\mathrm{Inv} \wedge \mathrm{TR} \wedge \neg\mathrm{Inv}'$$
$$\forall^* \wedge \exists^*\forall^* \wedge \exists^*$$

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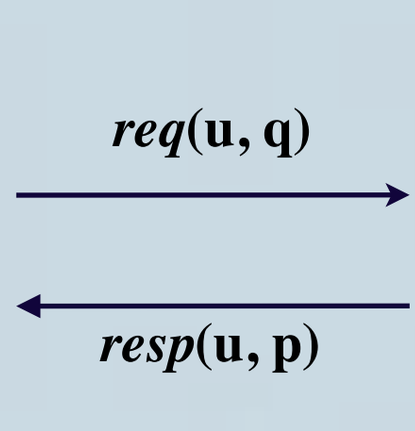
Example

```
req := ∅; resp := ∅; match := ∅;
action new_request(u) {
    q := new request;
    req := req ∪ {(u, q)}
}
```




```
action respond(u,q) {
    assume req(u , q);
    p := new response;
    match := match ∪ {(q, p)};
    resp := resp ∪ {(u, p)}
}

action check(u, p) {
     if resp(u, p) ∧ ¬(∃q. req(u, q) ∧ match(q, p))
        then abort
}
```

I = ∀u, p. *resp*(u, p) → ∃q. *req*(u, q) ∧ *match*(q, p)

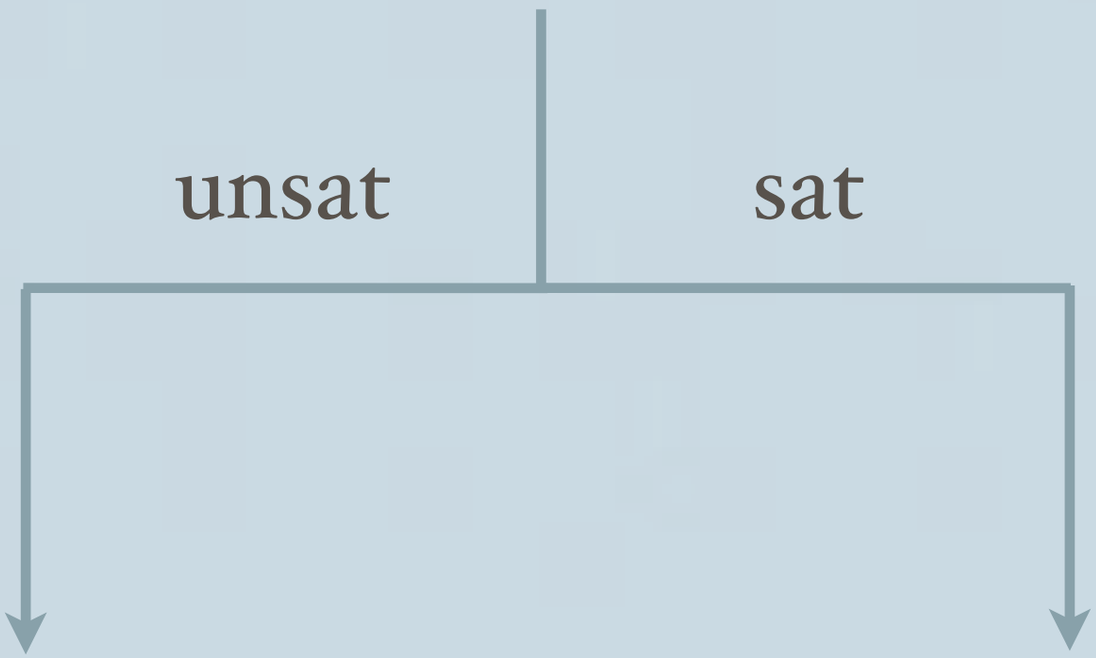
No Longer Decidable

$\text{Inv} = \forall^*$  $\text{Inv} = \forall^*\exists^*$

- Checking inductiveness of $\forall^*\exists^*$ invariants for EPR programs is **undecidable**.

Solving with Quantifier Alternation

$$I \wedge TR \wedge \neg I'$$



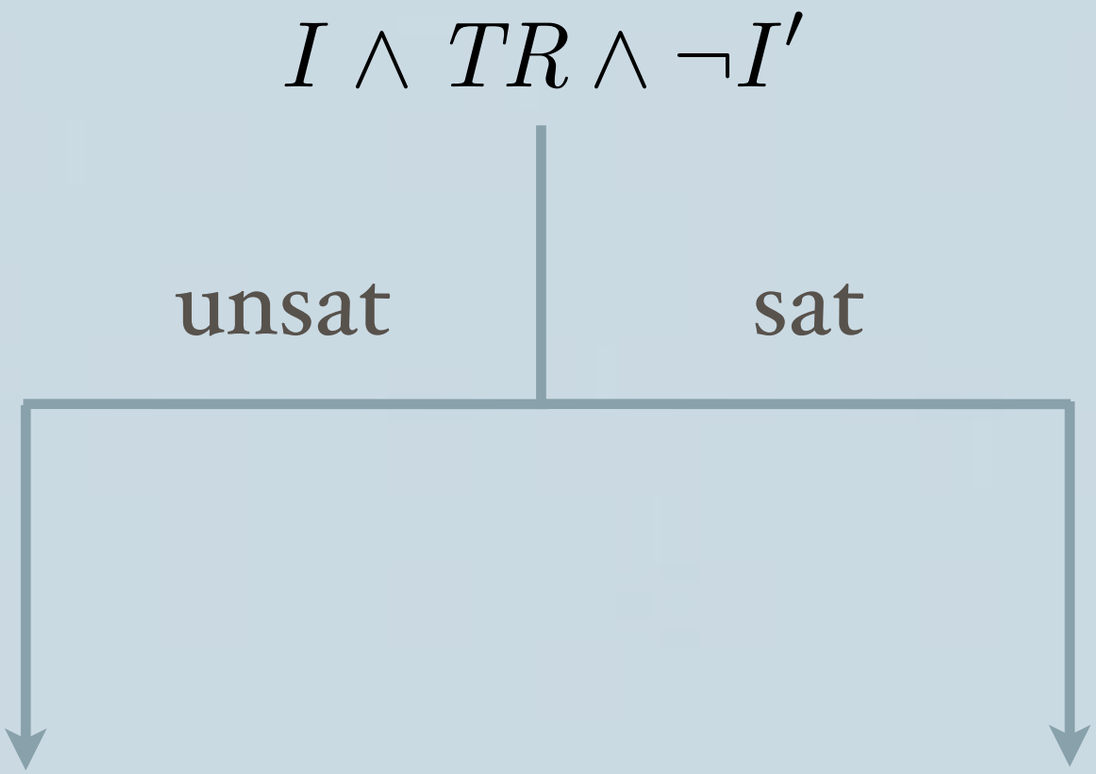
how to find
a proof?

matching loops

how to find
a cex?

infinite cex

Our Approach: Bounded-Horizon



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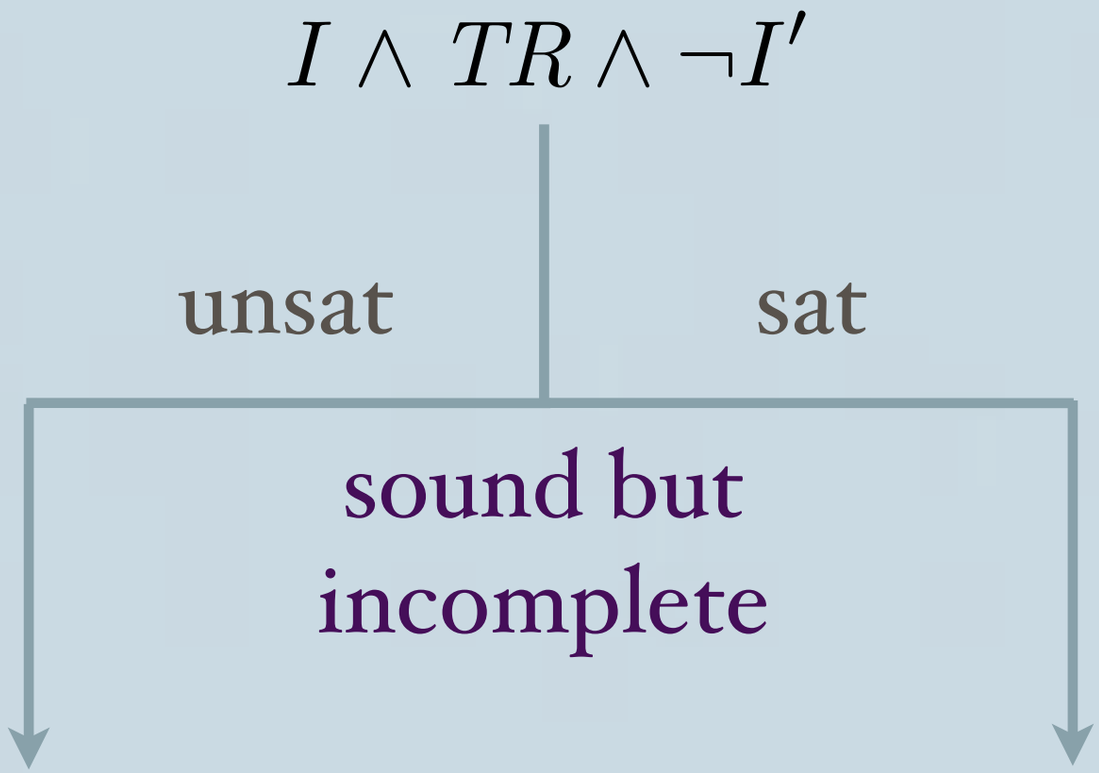

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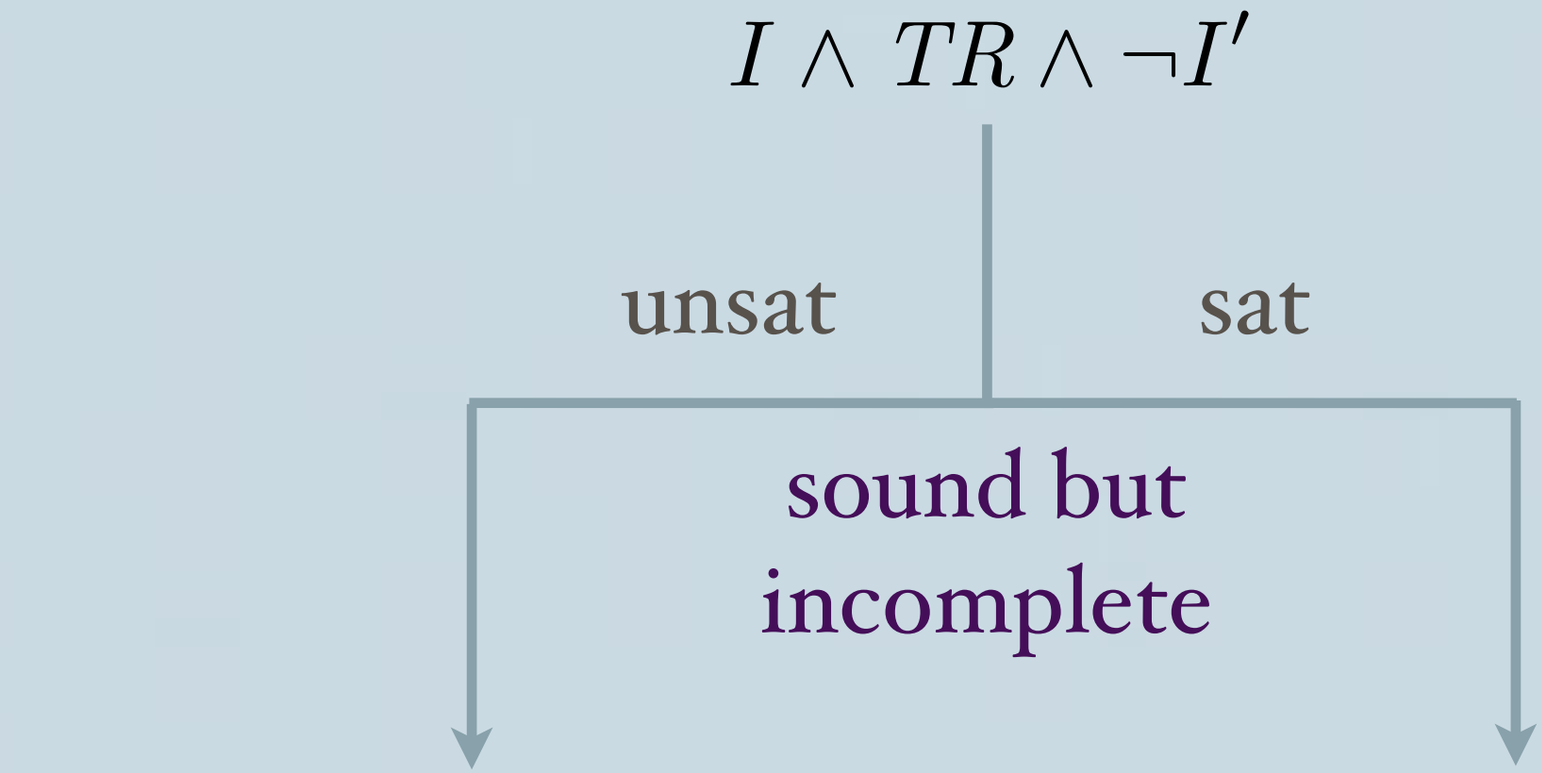


powerful as
manual reductions
to a decidable class
via **instrumentation**

Our Approach: Bounded-Horizon

$$I \wedge TR \wedge \neg I'$$

unsat

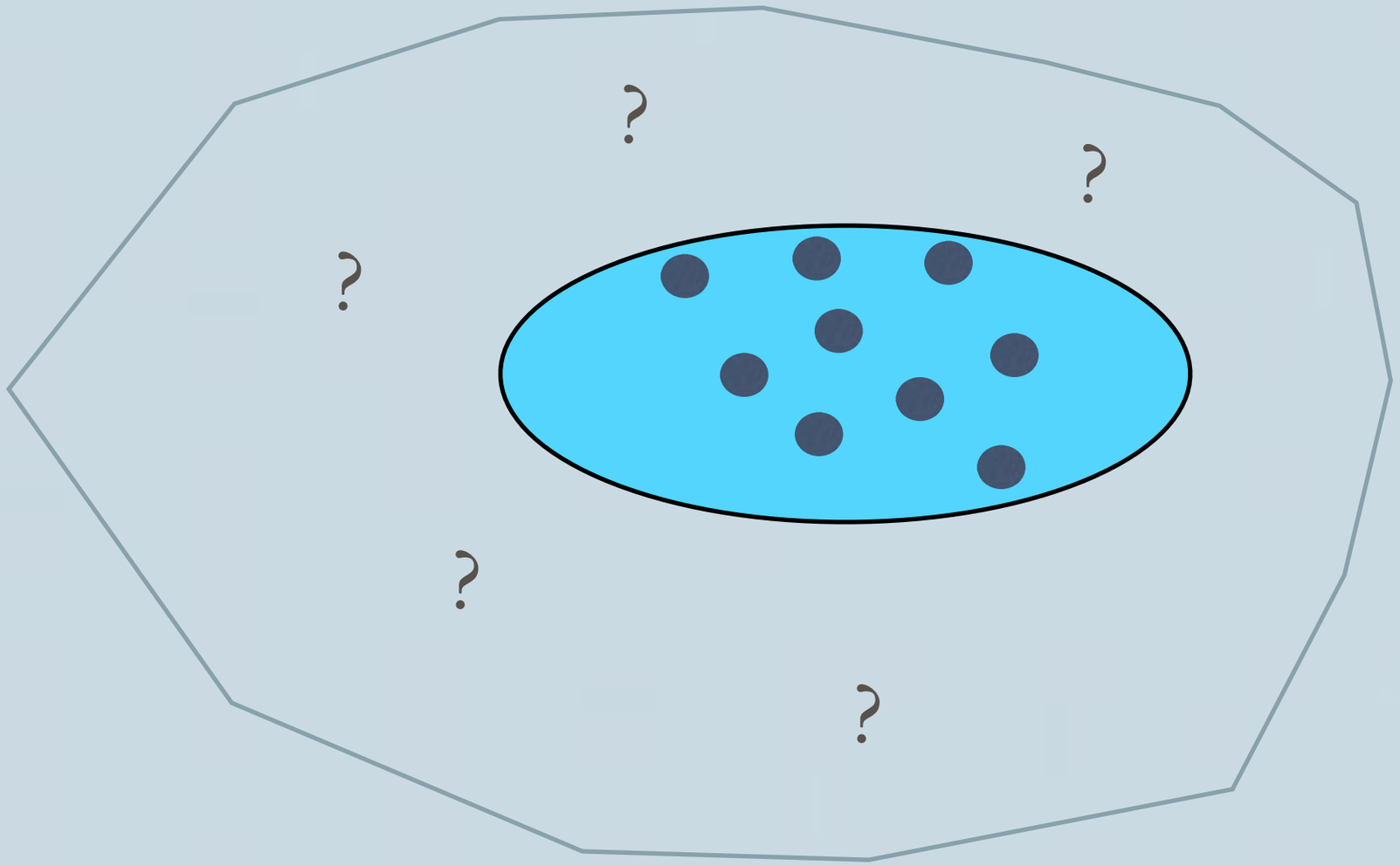
sat

sound but
incomplete

powerful as
manual reductions
to a decidable class
via **instrumentation**

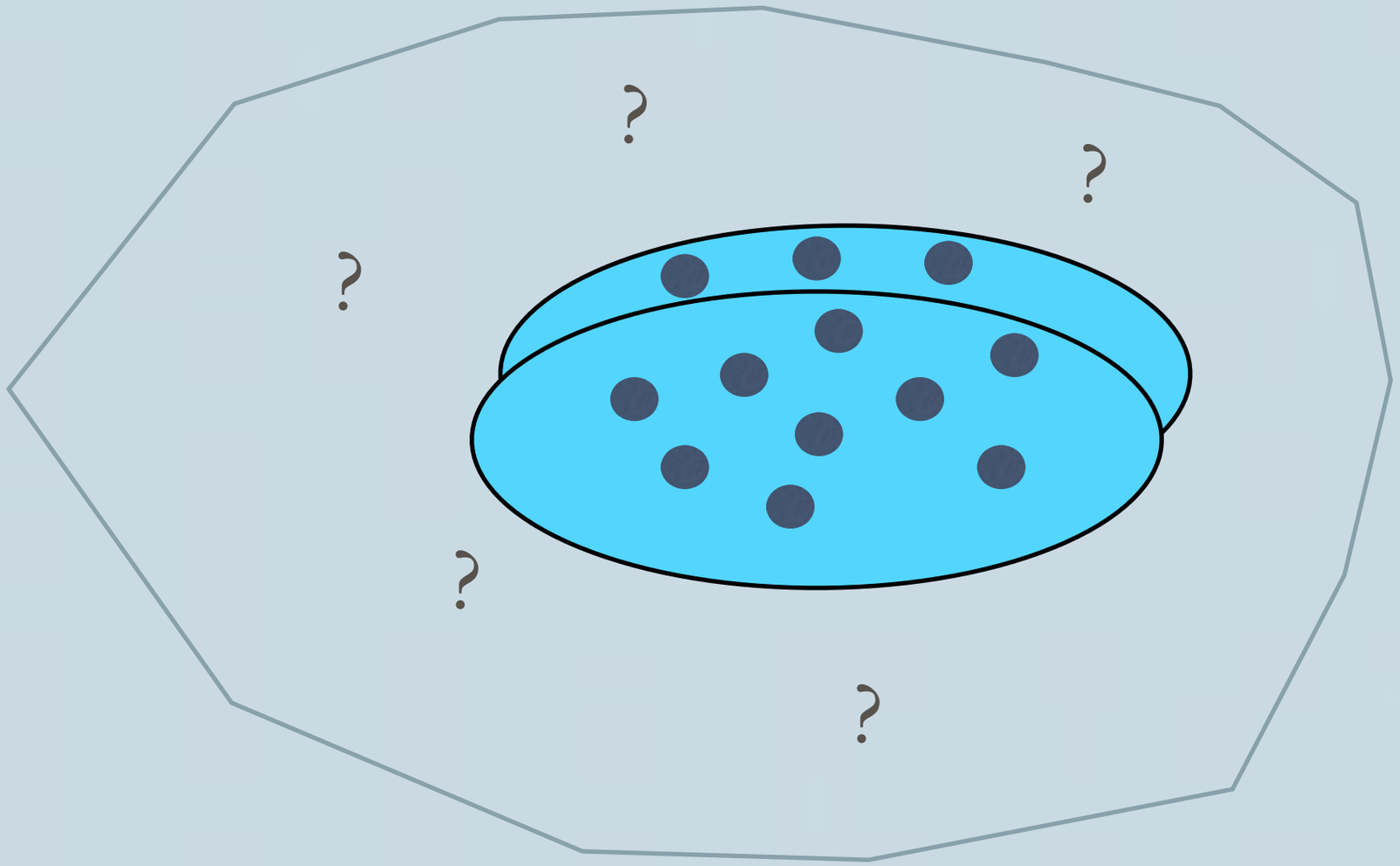
ability of producing
partial cexs
to overcome infinite cexs

Bounded-Horizon: Intuition



$I \wedge \mathrm{TR} \wedge \neg I'$ is unsat

Bounded-Horizon: Intuition



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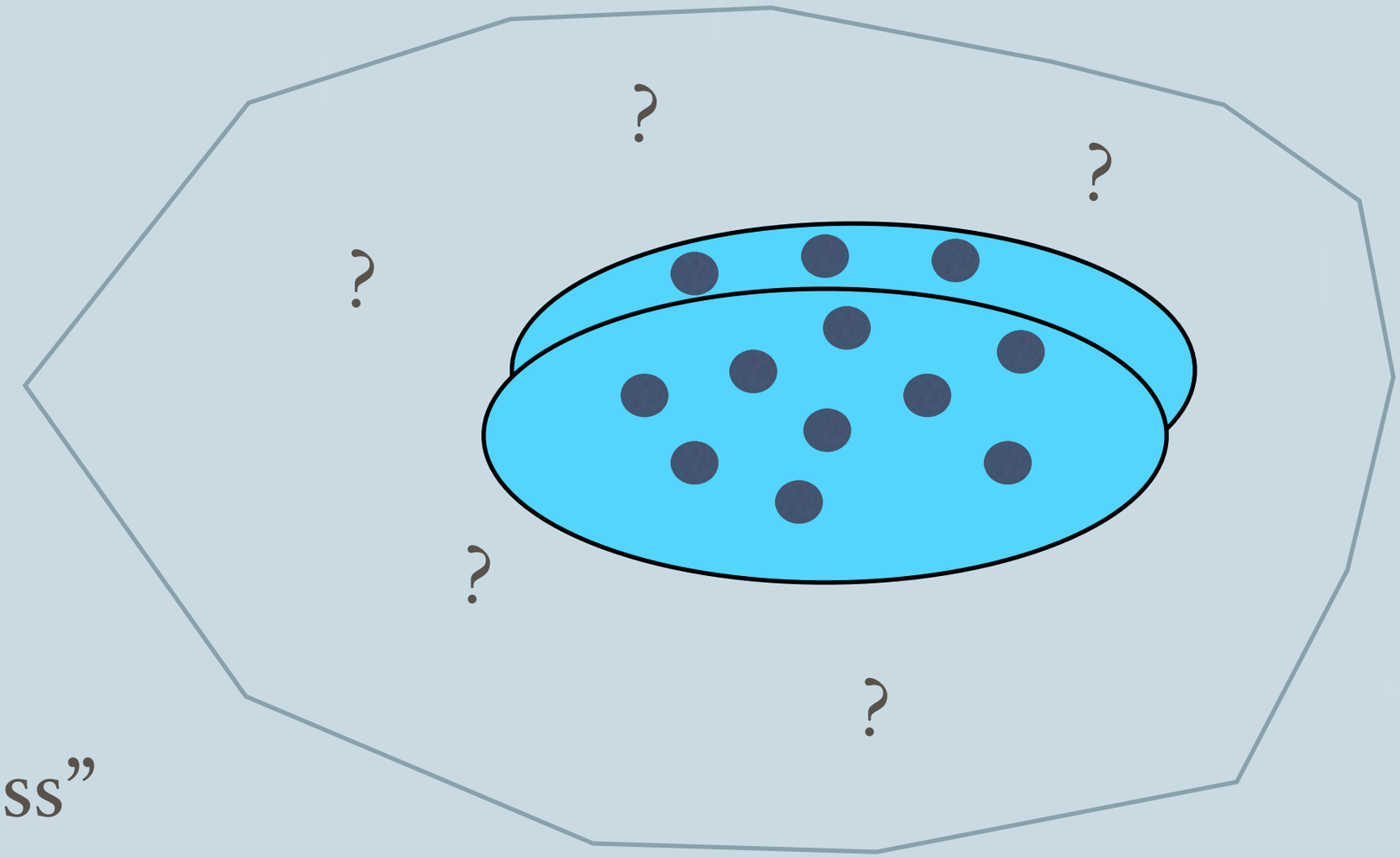
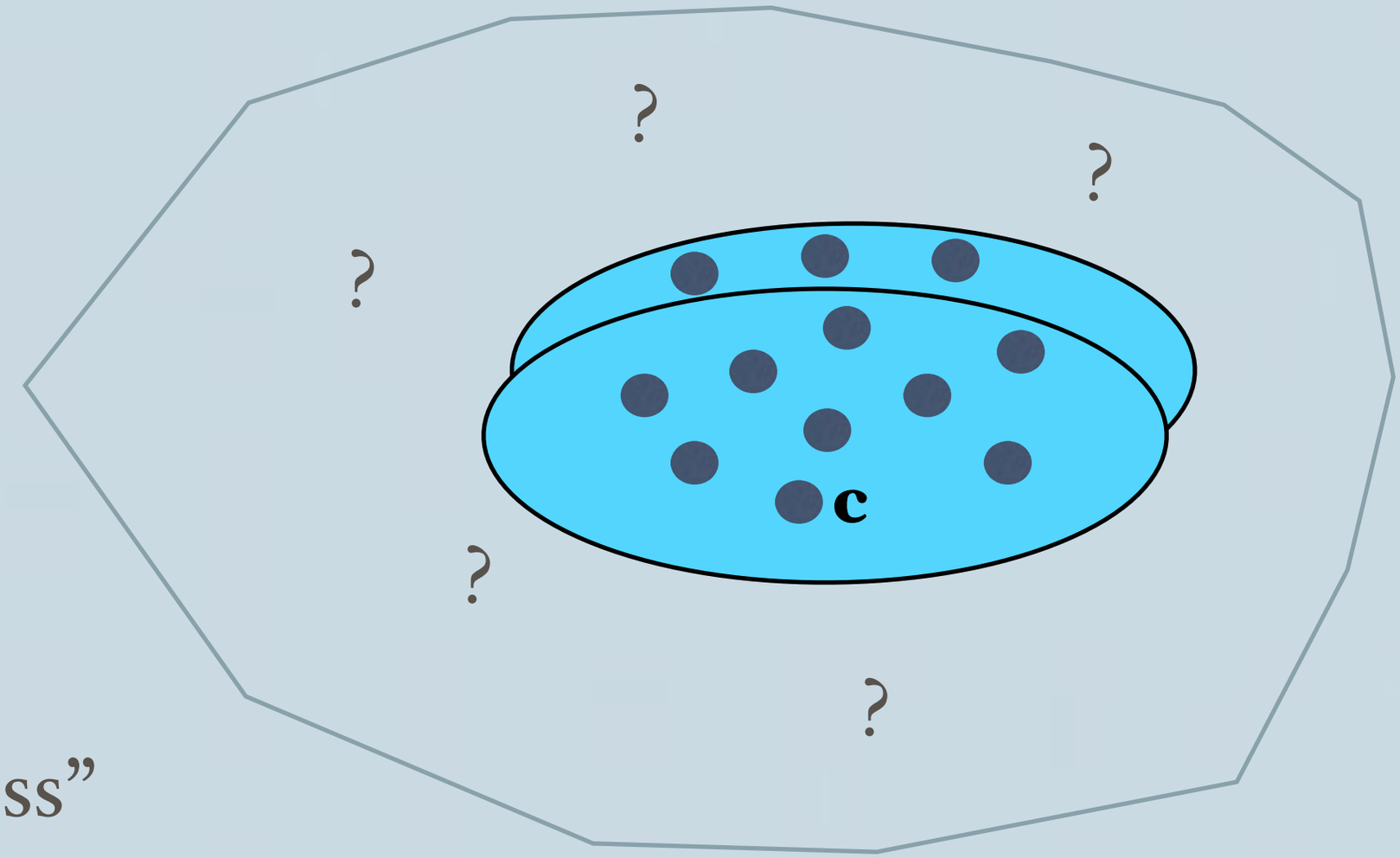


"witness"

$(\forall x.\, \exists y.\, \alpha(x, y)) \wedge \mathrm{TR} \wedge \neg I'$ is unsat

Bounded-Horizon: Intuition



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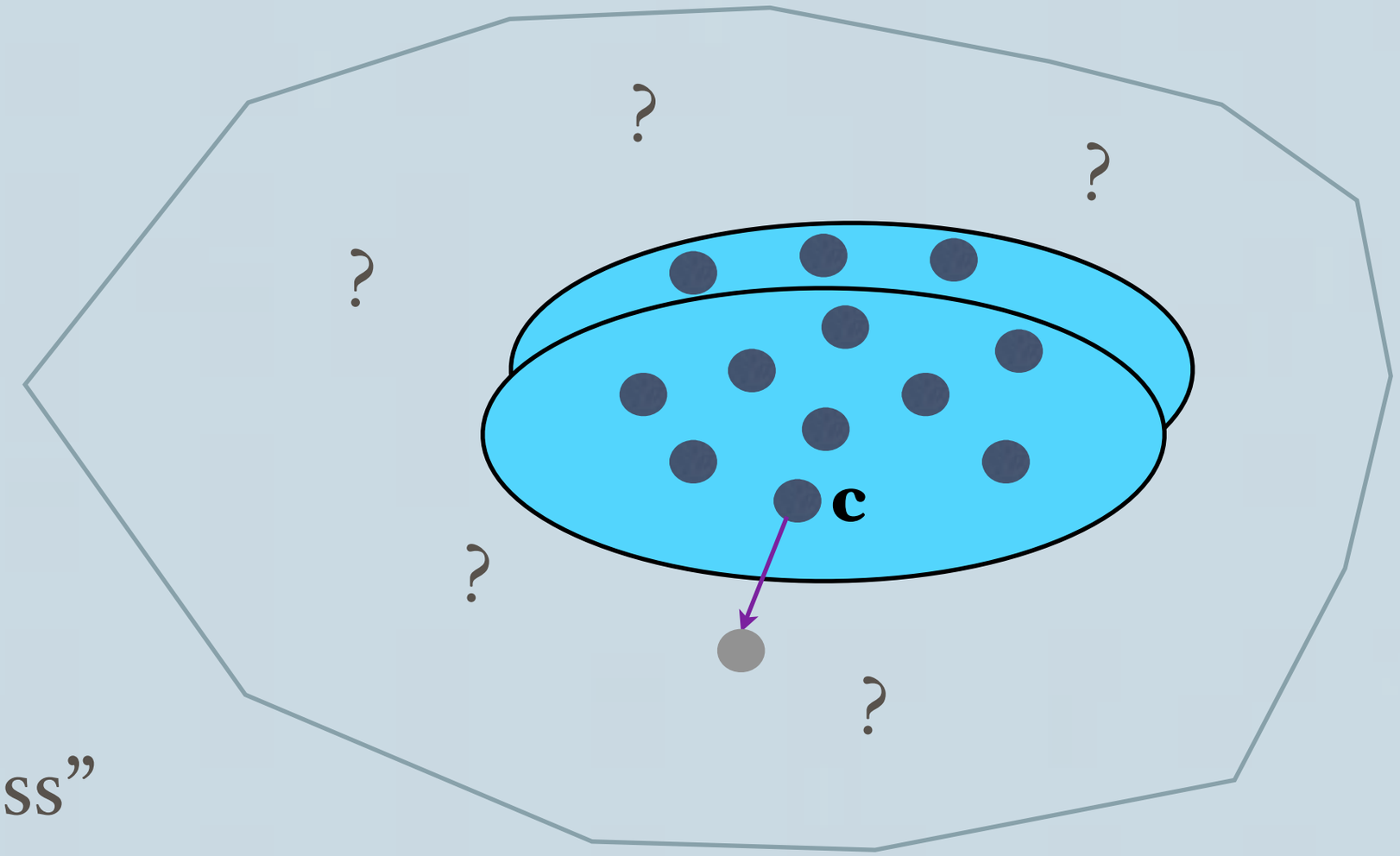

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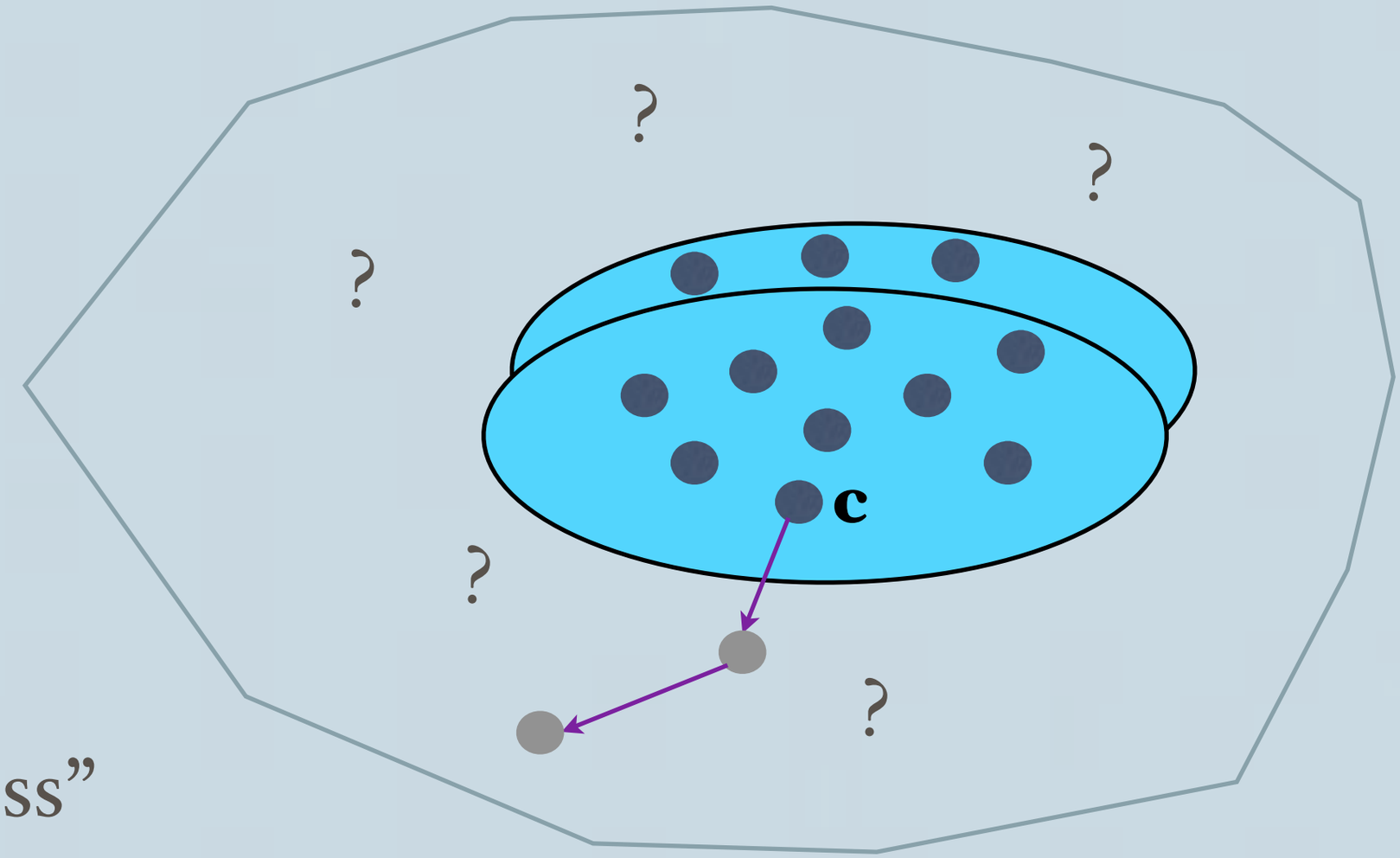

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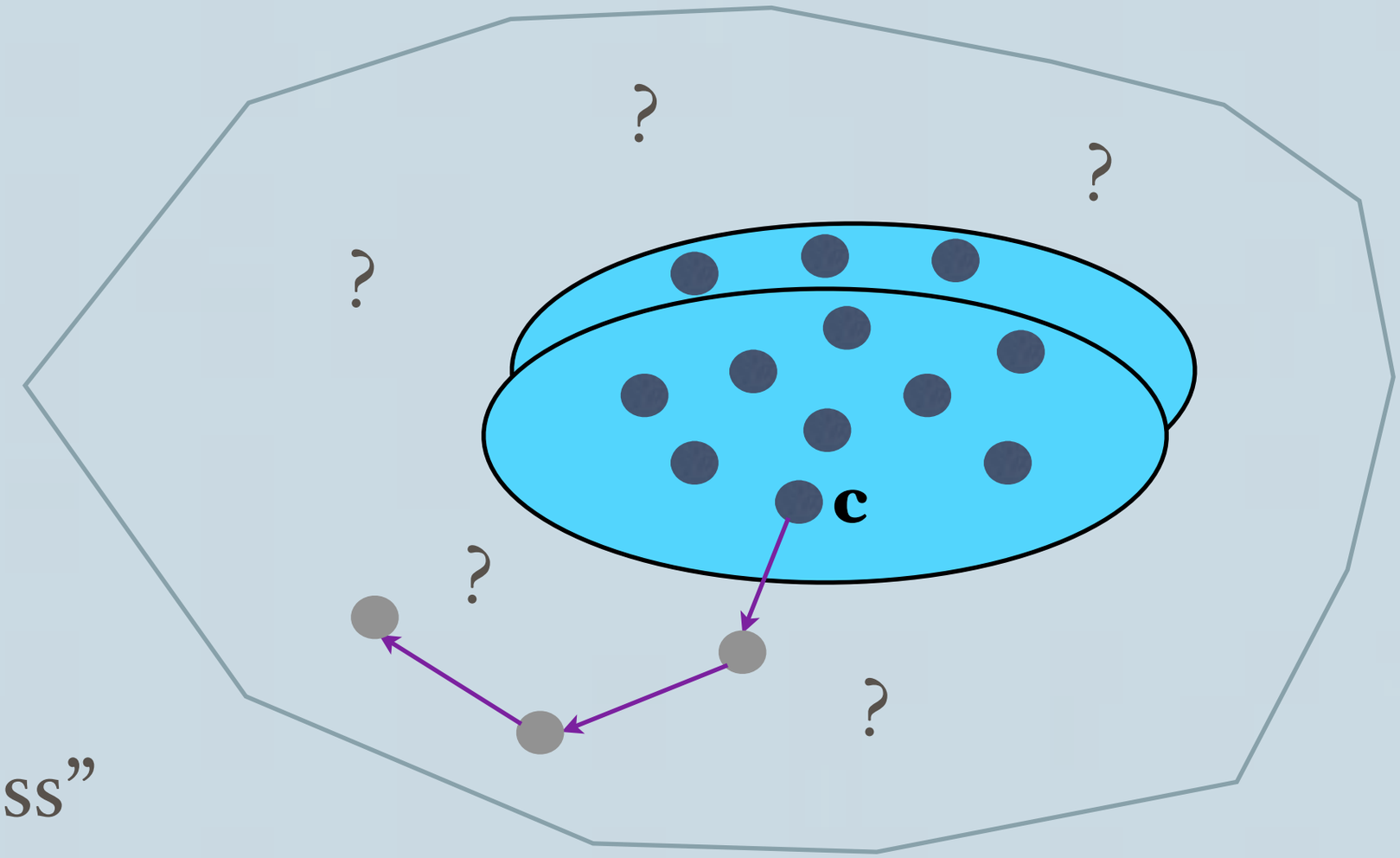

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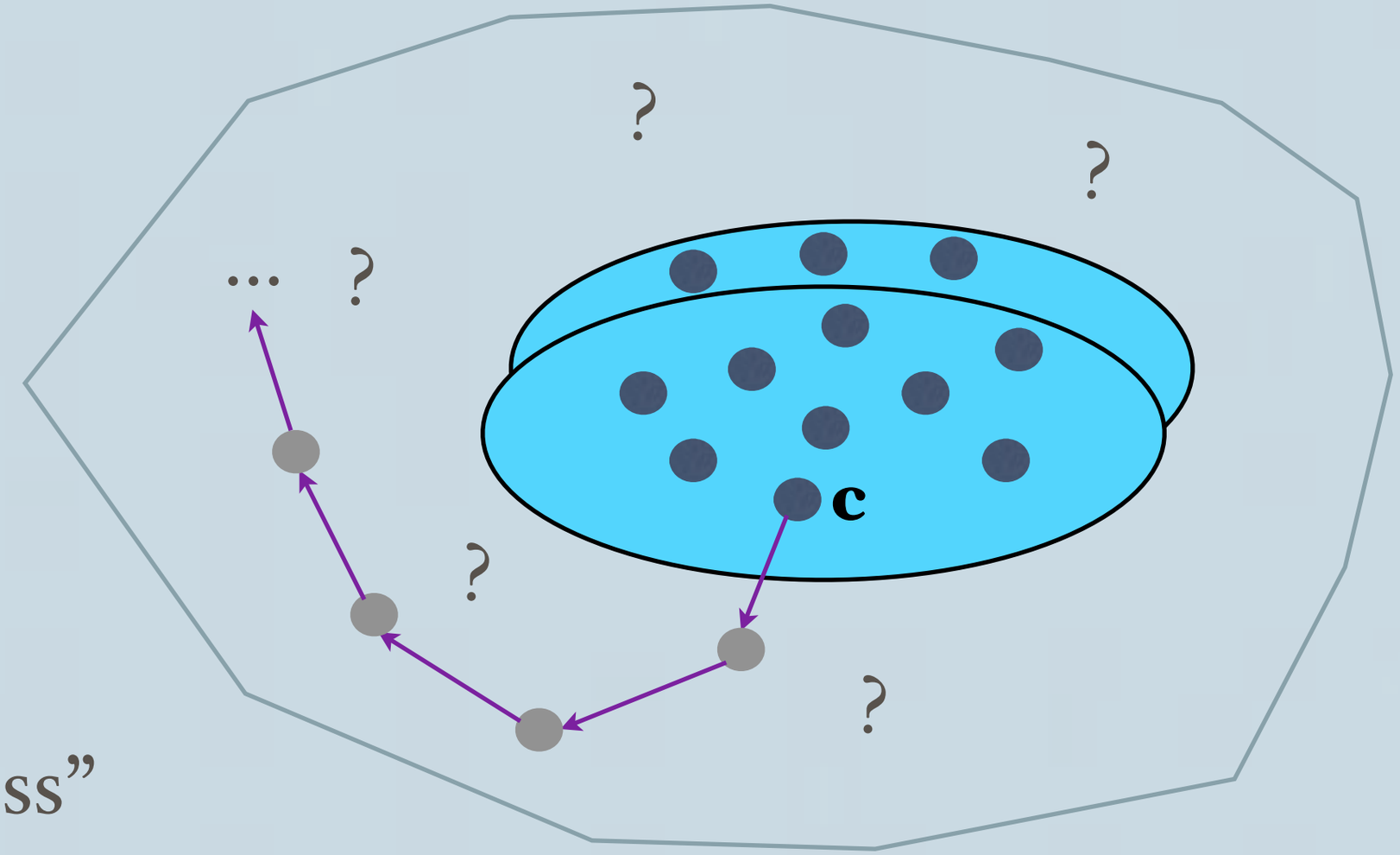

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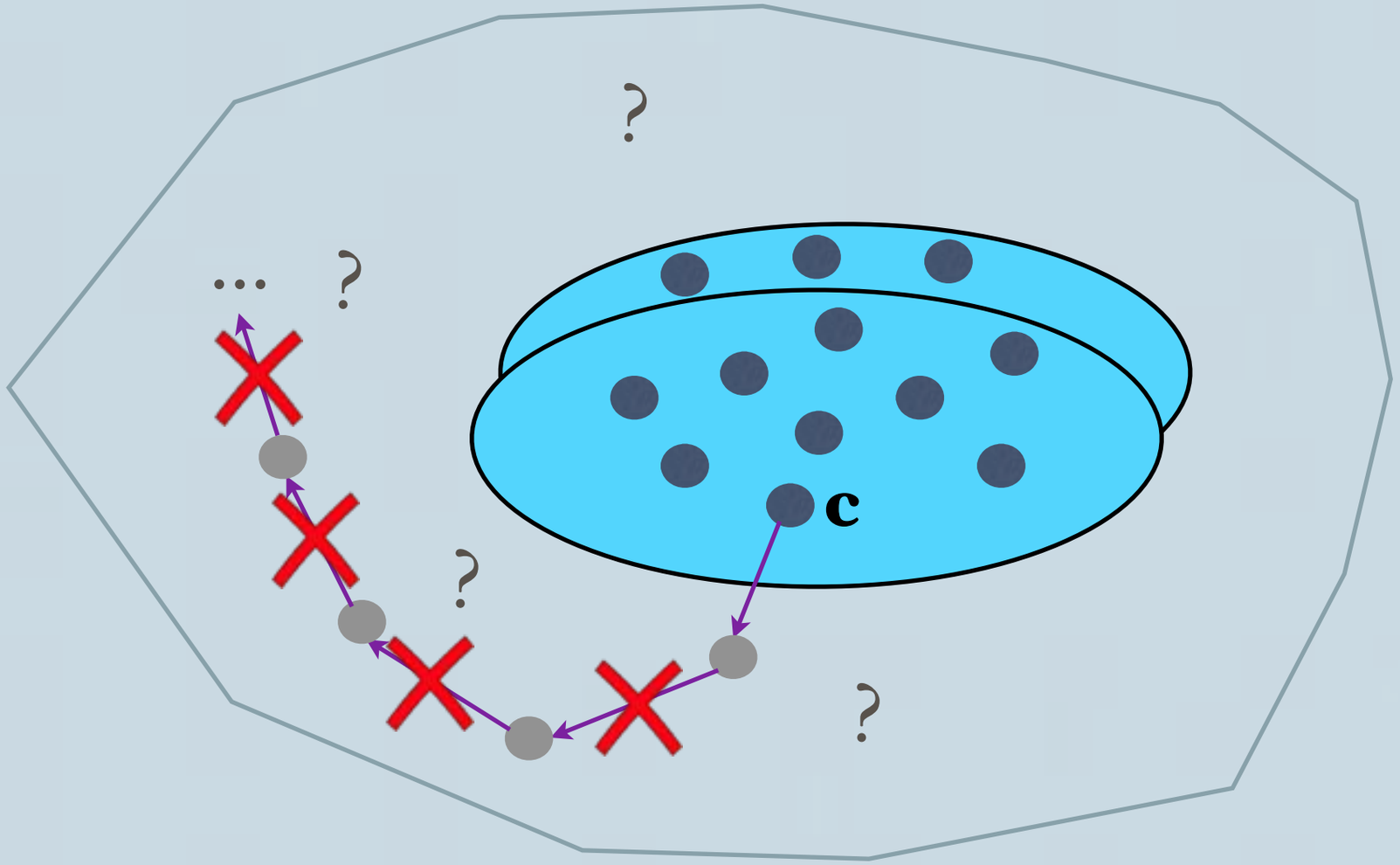

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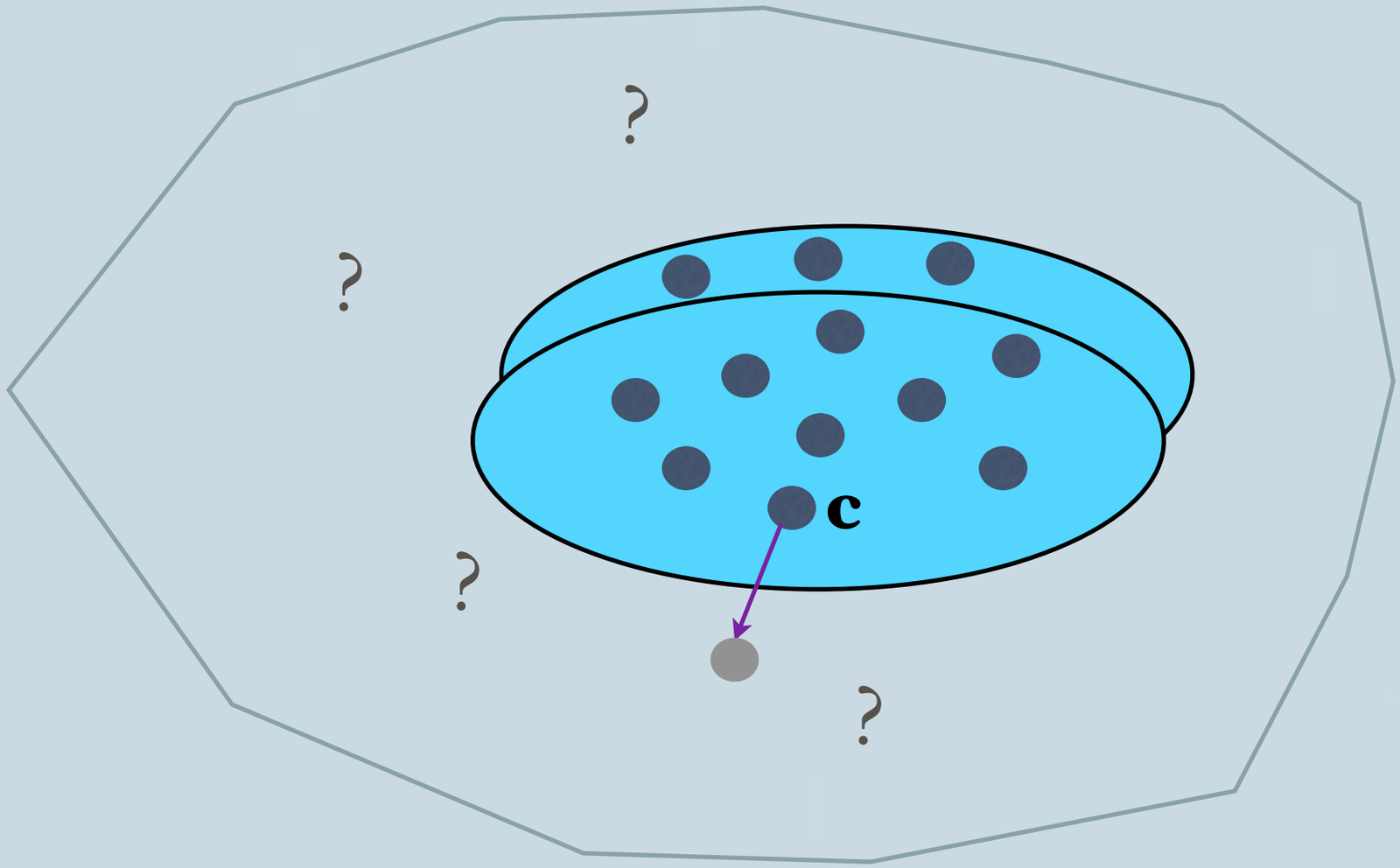

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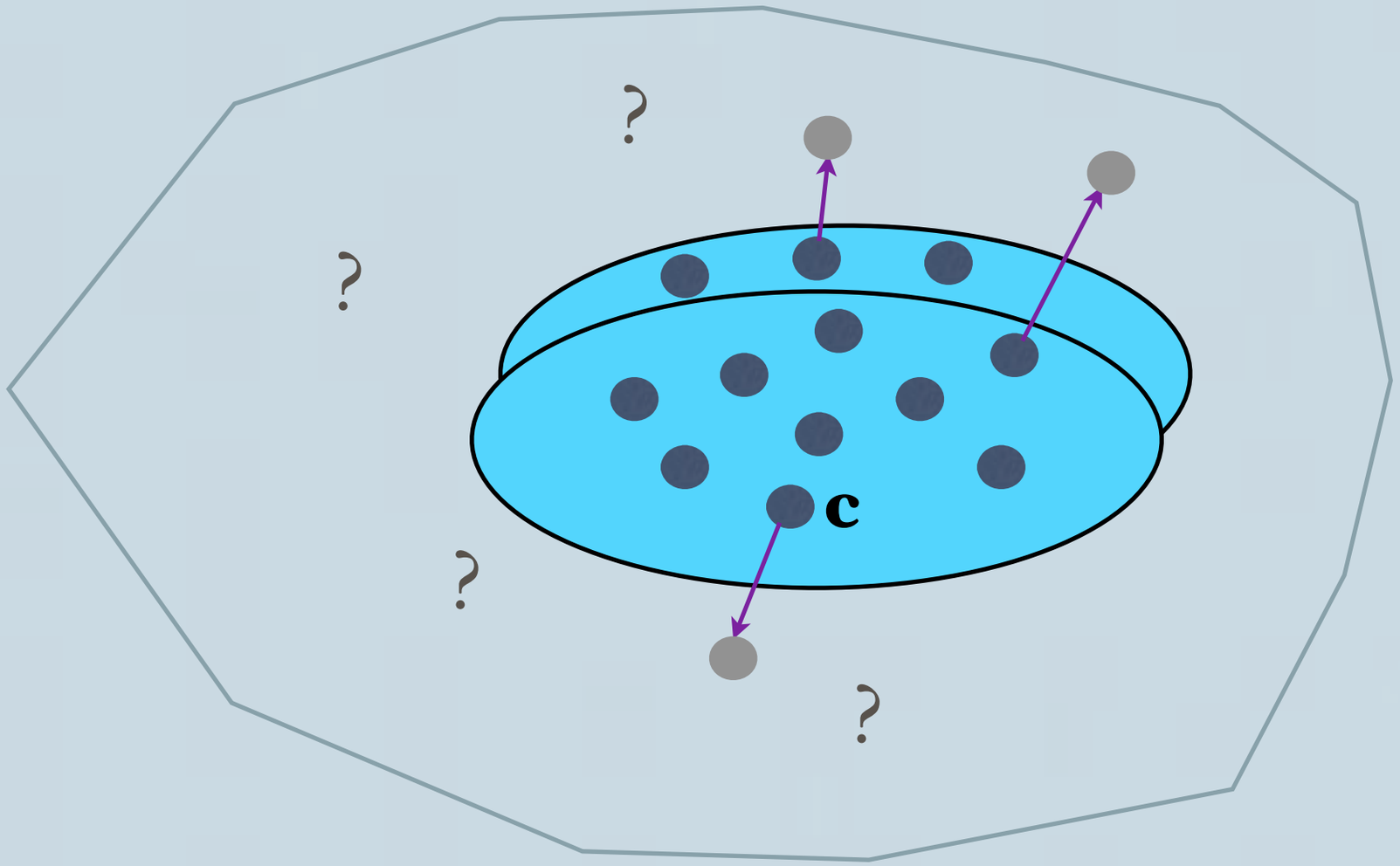

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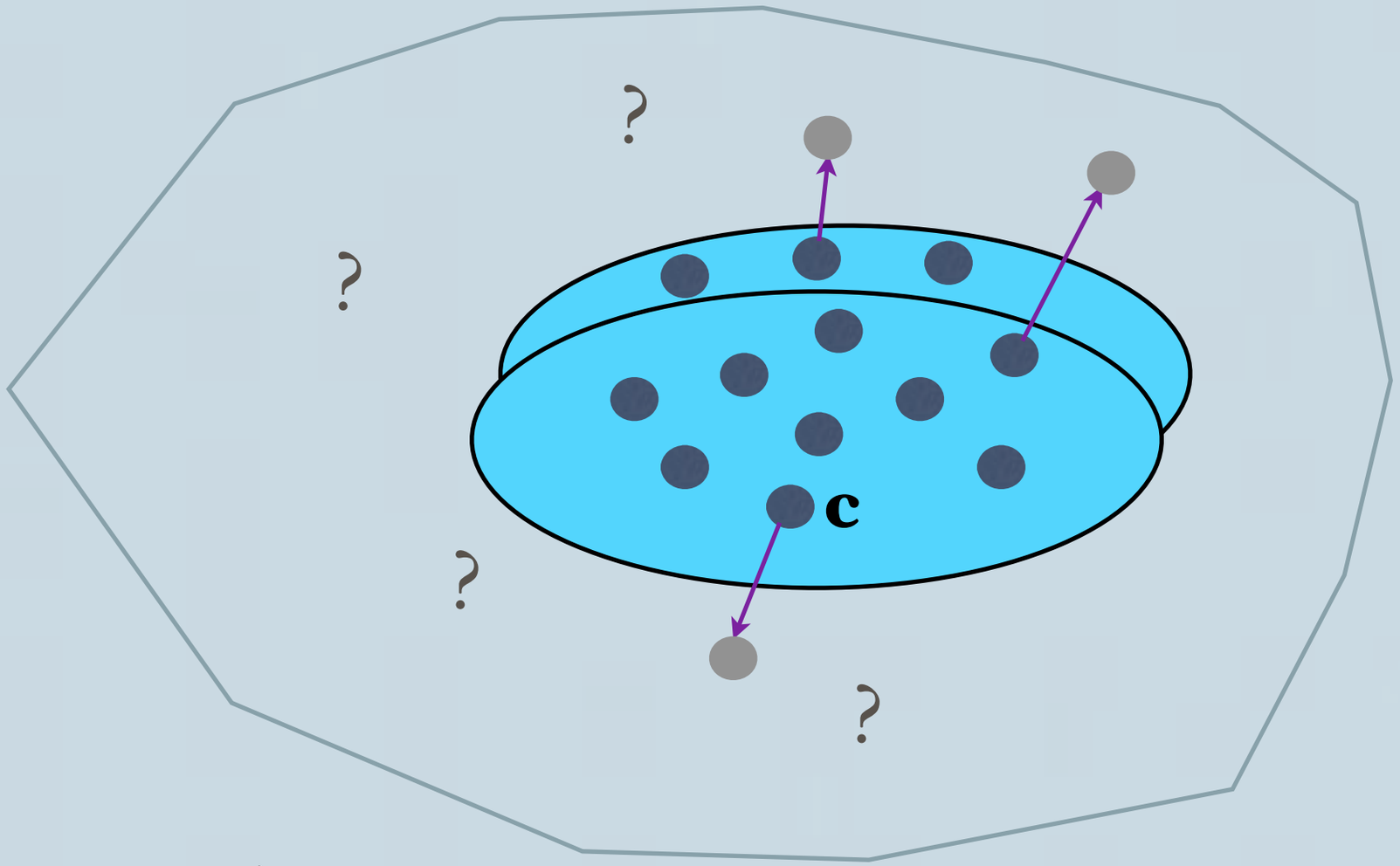
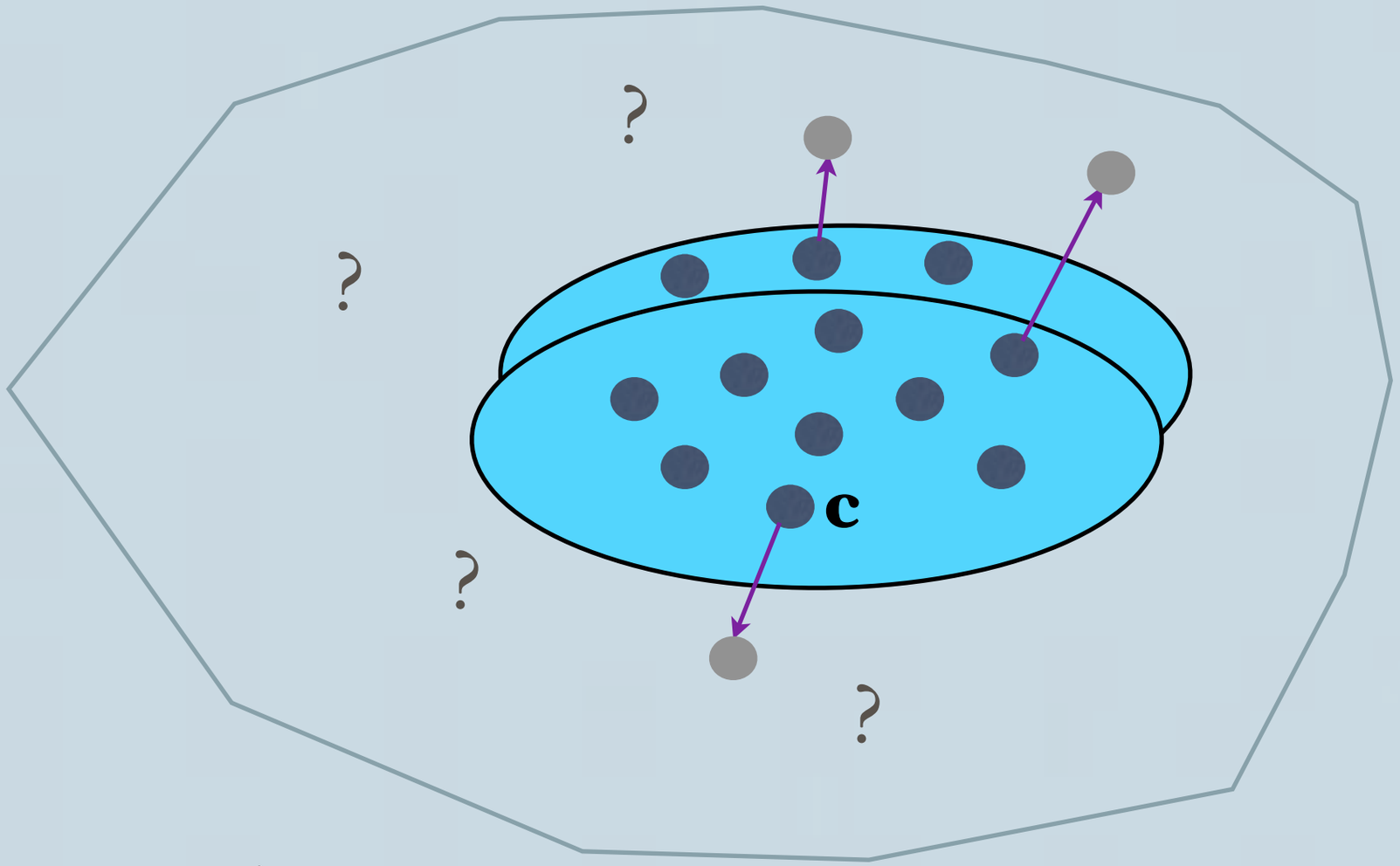


$$\left(\bigwedge_{c} \exists y.\, \alpha(c, y)\right) \wedge \mathrm{TR} \wedge \neg I' \text{ is unsat}$$

Bounded-Horizon: Intuition



$$\left(\bigwedge_{c} \exists y.\, \alpha(c, y)\right) \wedge \mathrm{TR} \wedge \neg I' \text{ is unsat}$$

decidable!

Quantifier Instantiation

Check SAT:

$$\forall x.\ \exists y.\ \alpha(x, y) \wedge \mathrm{TR} \wedge \neg I'$$

Quantifier Instantiation

Check SAT:

$$\forall x.\ \exists y.\ \alpha(x, y)$$

Quantifier Instantiation

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$$\forall x.\ \exists y.\ \alpha(x, y)$$

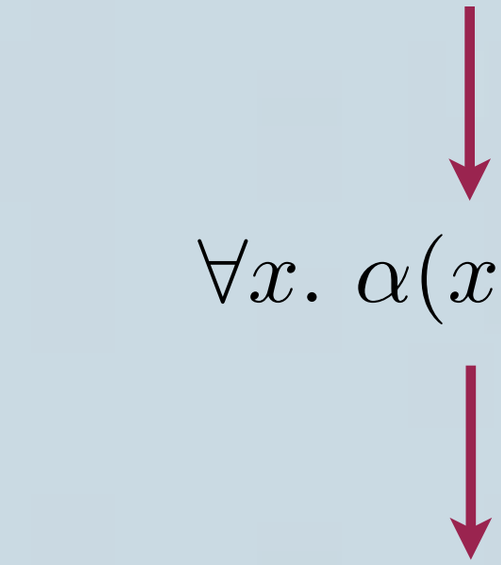
Skolemization

$$\forall x.\ \alpha(x, f(x))$$

Quantifier Instantiation

Check SAT:

$$\forall x.\ \exists y.\ \alpha(x, y)$$



Skolemization

$$\forall x.\ \alpha(x, f(x))$$

Herbrand's Theorem

$$\left\{\alpha(t, f(t)) \mid t \text{ ground term}\right\}$$

Bounded Instantiation

Check SAT:

$$\forall x.\ \exists y.\ \alpha(x, y)$$

Skolemization

$$\forall x.\ \alpha(x, f(x))$$

Herbrand's Theorem

$$\leq \mathbf{k}$$

decidable!

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Bounded Instantiation

Check SAT:

$$\forall x.\ \exists y.\ \alpha(x, y)$$

Skolemization

$$\forall x.\ \alpha(x, f(x))$$

Herbrand's Theorem

$\leq \mathbf{k}$

decidable!

$$\left\{ \alpha(t, f(t)) \;\middle|\; t \text{ ground term} \right\}$$

sound but incomplete

Our Approach: Bounded-Horizon

$$I \wedge TR \wedge \neg I'$$

unsat

how to find
a proof?

**at least as powerful
as instrumentation**

sat

how to find
a cex?

ability of producing
partial cexs

Reduction by Instrumentation

TR $\qquad\qquad$ $\widehat{\mathrm{TR}}$

$\mathrm{Inv} = \forall^*\exists^* \longrightarrow \widehat{\mathrm{Inv}} = \forall^*$

S. Sagiv, T. W. Reps, and R. Wilhelm. Parametric Shape Analysis via 3-Valued Logic (TOPLAS'02)
S. Itzhaky, A. Banerjee, N. Immerman, A. Nanevski, and M. Sagiv. Effectively-Propositional Reasoning About Reachability in Linked Data Structures (CAV'13)
A. Karbyshev, N. Bjørner, S. Itzhaky, N. Rinetzky, and S. Shoham. Property-Directed Inference of Universal Invariants or Proving their Absence (CAV'15)
O. Padon, K. L. McMillan, A. Panda, M. Sagiv, and S. Shoham. Ivy: Safety Verification by Interactive Generalization (PLDI'16)

Reduction by Instrumentation

TR — auxiliary state for derived relation → $\widehat{\mathrm{TR}}$

$\mathrm{Inv} = \forall^*\exists^*$ ⟶ $\widehat{\mathrm{Inv}} = \forall^*$

"$r(x) \equiv \psi(x)$"

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Instrumentation Example

```
req := ∅; resp := ∅; match := ∅;
action new request(u) {
    q := new request;
    req := req ∪ {(u, q)}

}
```

I = ∀u, p. *resp*(u, p) → ∃**q. *req*(u, q)** ∧ ***match*(q, p)**

```
action respond(u,q) {
    assume req(u , q);
    p := new response;
    match := match ∪ {(q, p)};

    resp := resp ∪ {(u, p)}
}

action check(u, p) {
    if resp(u, p) ∧ ¬(∃q. req(u, q) ∧ match(q, p))
        then abort
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r(u, p) "≡" ∃q. *req*(u, q) ∧ *match*(q, p)

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I = ∀u, p. *resp*(u, p) → **∃q. *req*(u, q) ∧ *match*(q, p)**

I = ∀u, p. *resp*(u, p) → **r(u, p)**

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r(u, p) "≡" ∃q. *req*(u, q) ∧ *match*(q, p)

I = ∀u, p. *resp*(u, p) → ∃**q. *req*(u, q)** ∧ ***match*(q, p)**

I = ∀u, p. *resp*(u, p) → **r(u, p)**

Instrumentation Example

```
req := ∅; resp := ∅; match := ∅;
action new request(u) {
    q := new request;
    req := req ∪ {(u, q)}
    r := r ∪ {(u,y) | match(q,y)}
}

action respond(u,q) {
    assume req(u , q);
    p := new response;
    match := match ∪ {(q, p)};
    r := r ∪ {(x,p) | req(x,q)};
    resp := resp ∪ {(u, p)}
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I = ∀u, p. *resp*(u, p) → ∃**q. *req*(u, q) ∧ *match*(q, p)**

I = ∀u, p. *resp*(u, p) → **r(u, p)**

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action new request(u) {
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    req := req ∪ {(u, q)}
    r := r ∪ {(u,y) | match(q,y)}
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action respond(u,q) {
    assume req(u , q);
    p := new response;
    match := match ∪ {(q, p)};
    r := r ∪ {(x,p) | req(x,q)};
    resp := resp ∪ {(u, p)}
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action check(u, p) {
    if resp(u, p) ∧ ¬(∃q. req(u, q) ∧ match(q, p))
        then abort
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Possibly unsound!

if resp(u, p) ∧ ¬r(u, p)

Instrumentation for Verification

Given TR, $I \in \forall^*\exists^*$

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$\mathrm{TR}, \widehat{\mathrm{TR}}$ have the same existentials

then

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Bounded-Horizon vs. Instrumentation

Given TR, $I \in \forall^*\exists^*$ **if exists** sound instrumentation without additional existentials

$I = \widehat{I}[\psi/r]$ $\quad$ $\widehat{I} \in \forall^*$ $\quad$ $\widehat{I}$ is inductive for $\widehat{\mathrm{TR}}$

Then

- Theorem:
  For ψ that is a Boolean combination of ∀* and ∃*,
  for proving that I is inductive for TR it suffices to use **Bounded-Horizon with bound=2**.

Bounded-Horizon vs. Instrumentation

Given TR, $I \in \forall^*\exists^*$ **if exists** sound instrumentation without additional existentials

$I = \widehat{I}[\psi/r]$ $\quad$ $\widehat{I} \in \forall^*$ $\quad$ $\widehat{I}$ is inductive for $\widehat{\mathrm{TR}}$

Then

- Theorem:
  For $\psi \in \exists^*$ and r appears only positively in the invariant
  (or $\psi \in \forall^*$ and r appears only negatively in the invariant),
  Bounded-Horizon with bound=1 suffices.

- Invariants that are combinations of $\forall^*\exists^*$ and $\exists^*\forall^*$ also handled

Our Approach: Bounded-Horizon

$$I \wedge TR \wedge \neg I'$$

unsat

how to find
a proof?

at least as powerful
as instrumentation

sat

how to find
a cex?

**ability of producing
partial cexs**

Infinite Counterexample

$$I \wedge \mathrm{TR} \wedge \neg I'$$

has **infinite** model

but **no finite** models

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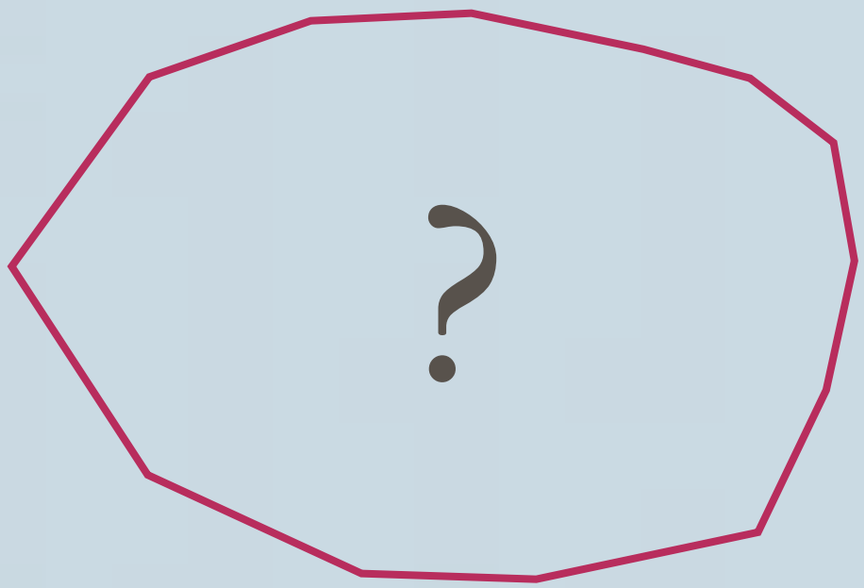
$$I \wedge \mathrm{TR} \wedge \neg I'$$

has **infinite** model

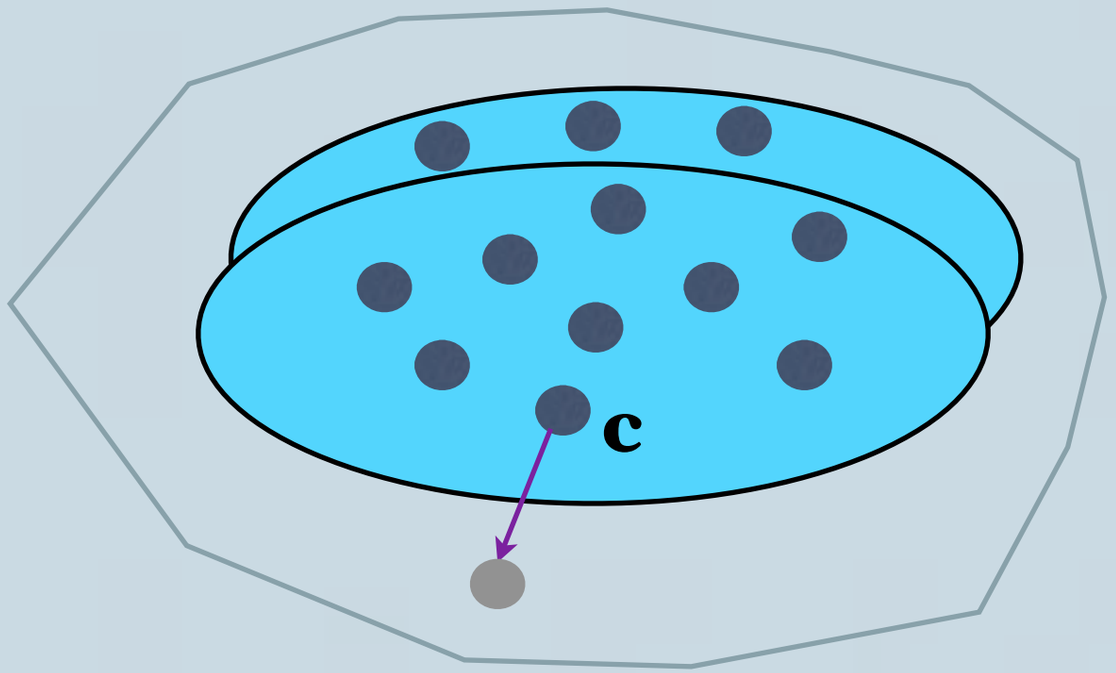
but **no finite** models

usually **no support** for **infinite cexs**

in general first-order logic

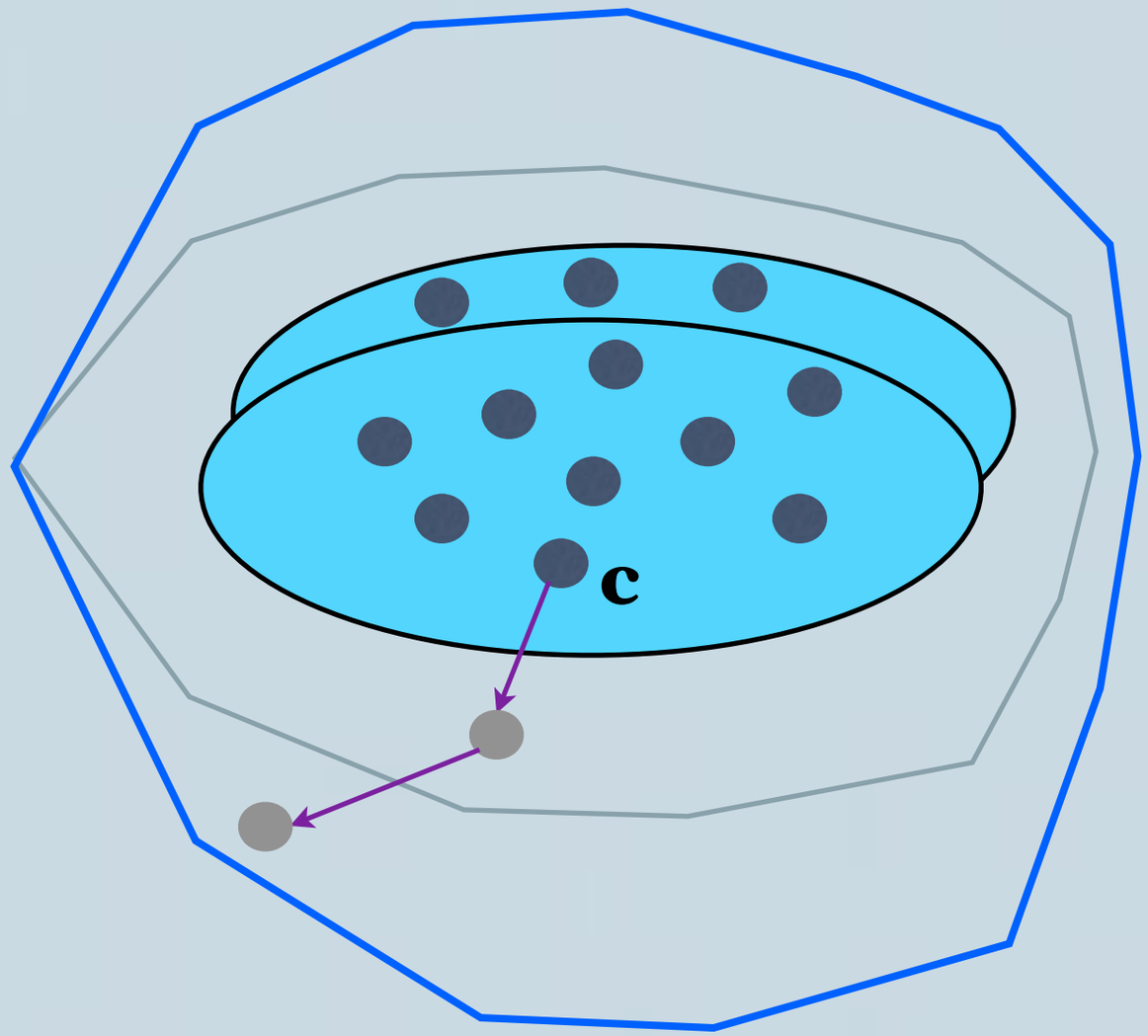


Partial Models



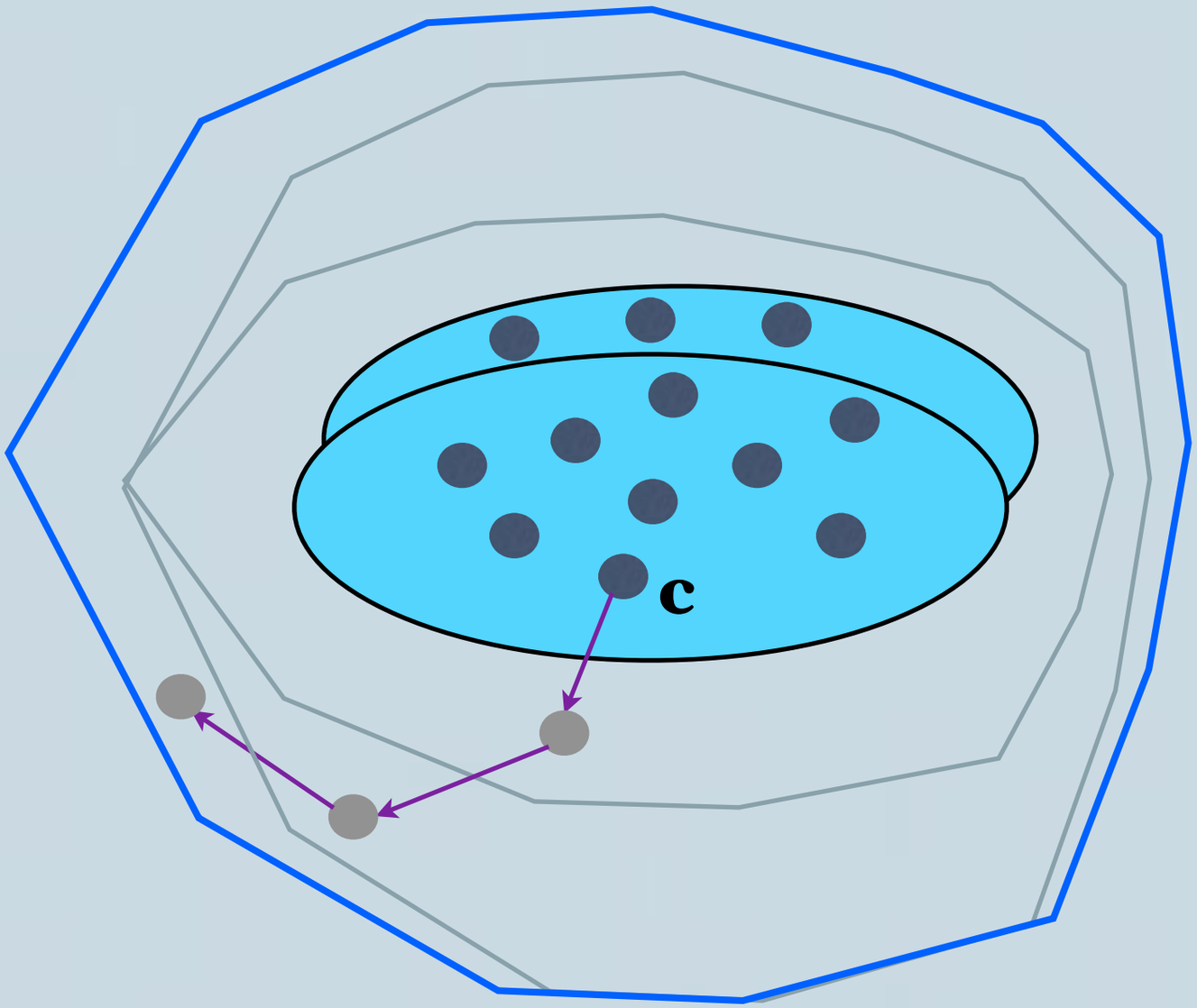
Bound 1

Partial Models



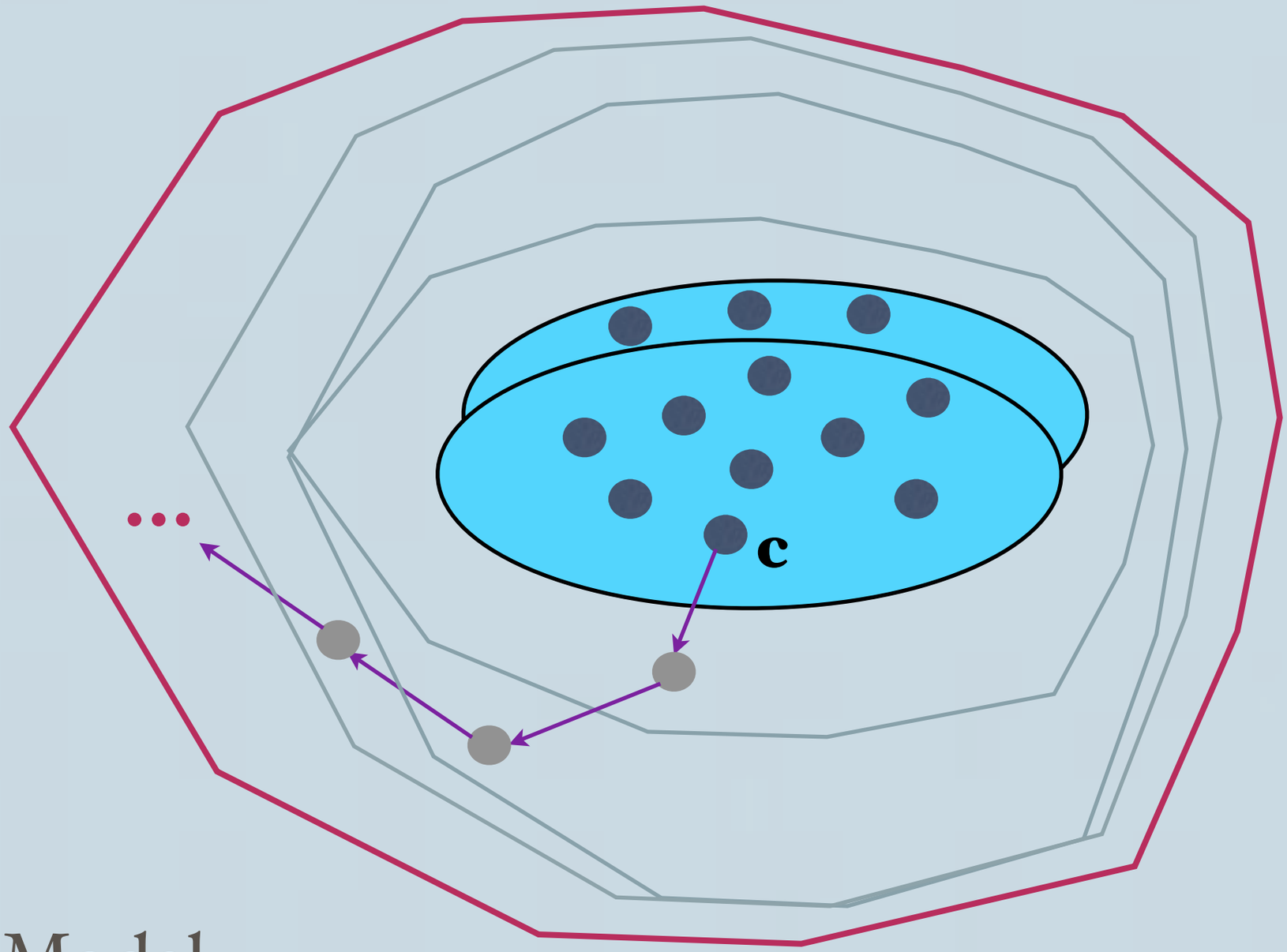
Bound 2

Partial Models



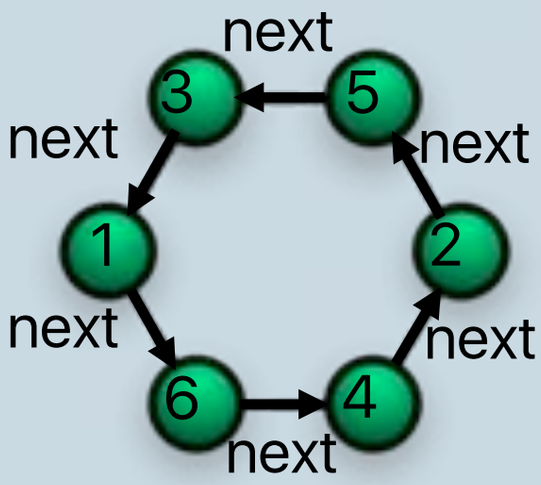
Bound 3

Partial Models



Total Model

Example: Leader Election in a Ring



E. Chang and R. Roberts. An improved algorithm for decentralized extrema-finding in circular configurations of processes, CACM’79

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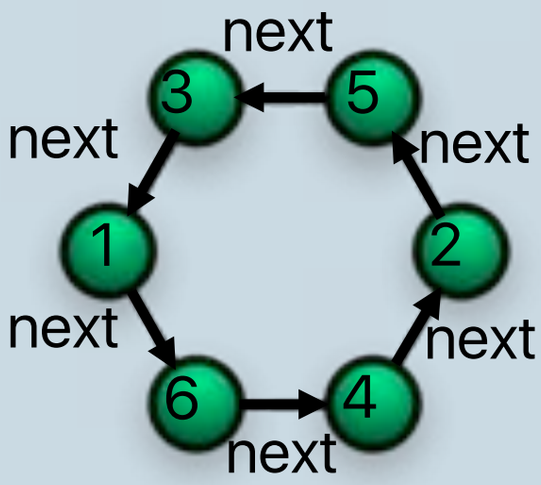

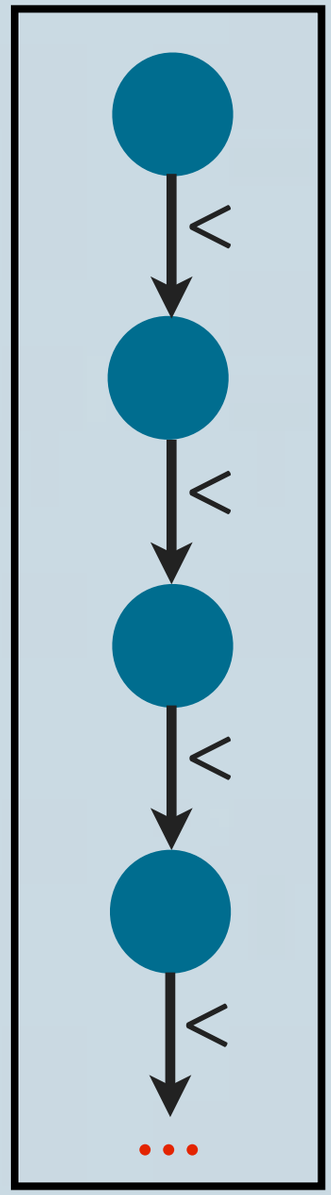

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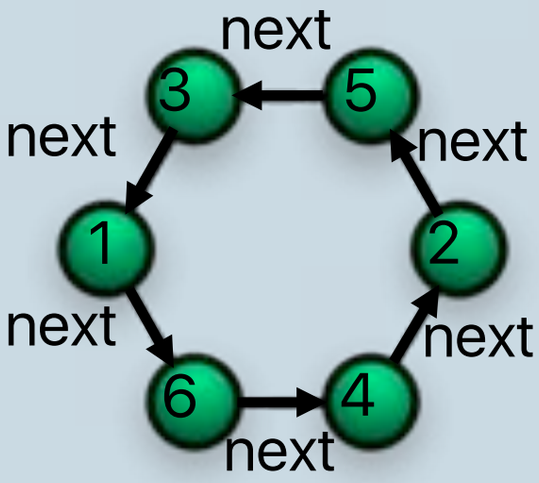

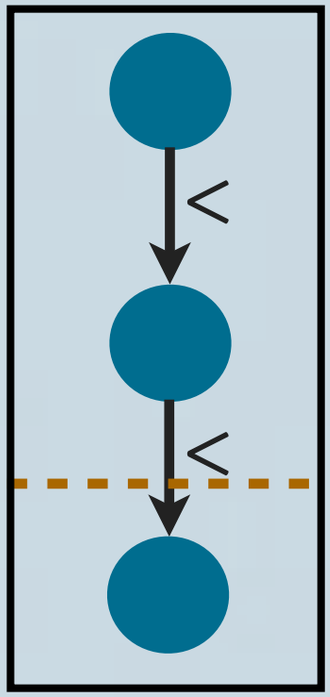

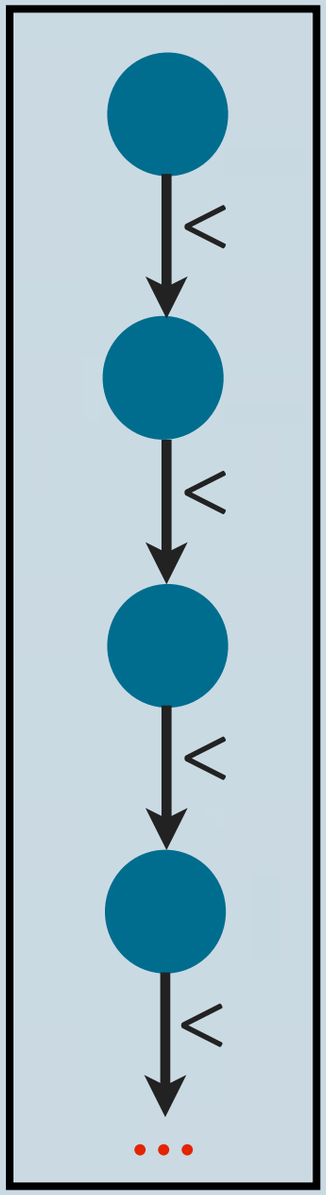

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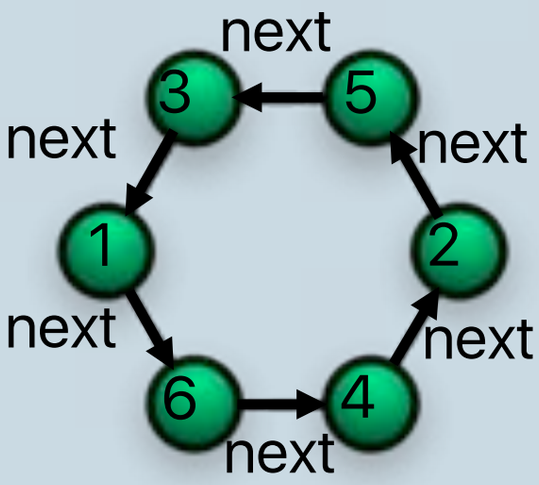

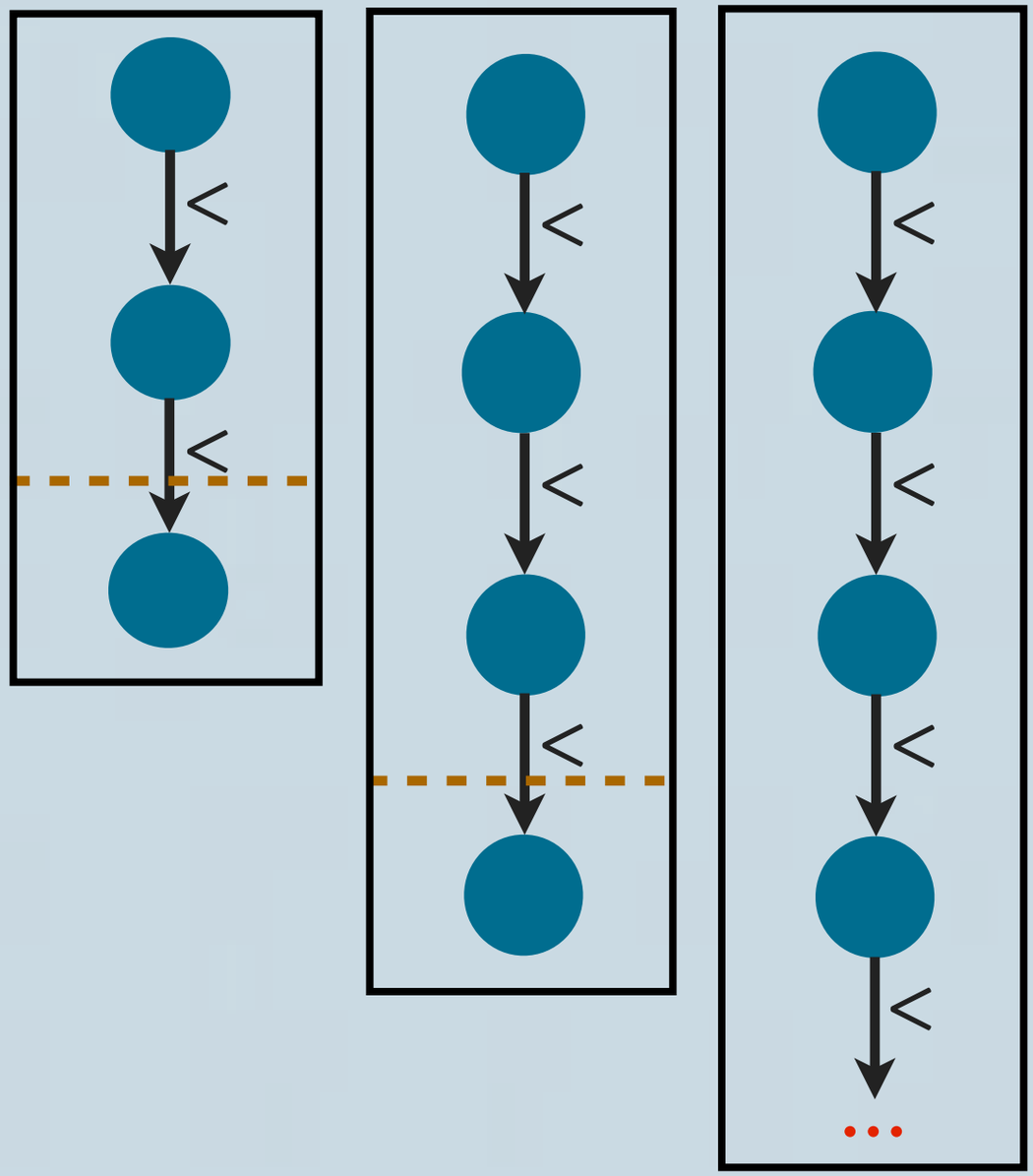

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Implementation of Bound 1

$$\forall x.\ \theta_S$$

$$\downarrow$$

$$\forall x.\left(\bigvee_{c} x = c\right) \rightarrow\ \theta_S$$

$$\downarrow$$

Z3: sat?

Evaluation

Program	#∀	#f-sk	#Consts	B1 Total	B1 Solve	Baseline Z3
Client-server	14	1	15	58 ms	3 ms	3 ms
List reverse	47	3	15	319 ms	211 ms	50 ms
Learning switch	70	1	7	245 ms	65 ms	33 ms
Hole-punching firewall with ghost	15	1	18	75 ms	4 ms	4 ms
Hole-punching firewall ∃ time	32	2	21	102 ms	4 ms	4 ms
Leader-election in a ring (correct)	41	1	21	113 ms	36 ms	27 ms
Leader-election in a ring (incorrect)	40	1	20	1112 ms	1008 ms	—

Summary

Checking $\forall^*\exists^*$ Inductive Invariants

Proof

sound but incomplete

powerful as certain **manual reductions** to a decidable class

Cex

sound but incomplete

ability of producing **partial cexs** to facilitate **progress**