Software Verification using Predicate Abstraction and Iterative Refinement: Part 1

15-414 Bug Catching: Automated Program Verification and Testing

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Outline

Overview of Model Checking

Creating Models from C Code: Predicate Abstraction

Eliminating spurious behaviors from the model: Abstraction Refinement

Concluding remarks : research directions, tools etc.

Model Checking

Algorithm for answering queries about behaviors of state machines

- Given a state machine M and a query ϕ does $M \vDash \phi$?

Standard formulation:

- M is a Kripke structure
- ϕ is a temporal logic formula
  - Computational Tree Logic (CTL)
  - Linear Temporal Logic (LTL)

Discovered independently by Clarke & Emerson and Queille & Sifakis in the early 1980's

Scalability of Model Checking

Explicit statespace exploration: early 1980s

- Tens of thousands of states

Symbolic statespace exploration: millions of states

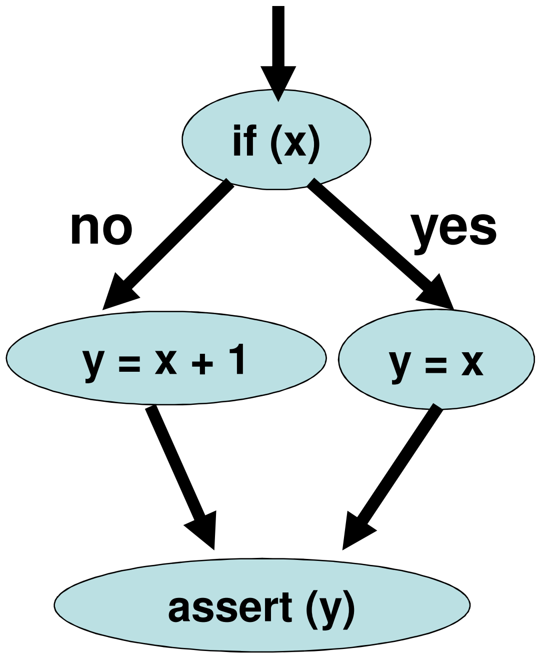
- Binary Decision Diagrams (BDD) : early 1990's
- Bounded Model Checking: late 1990's
  - Based on propositional satisfiability (SAT) technology

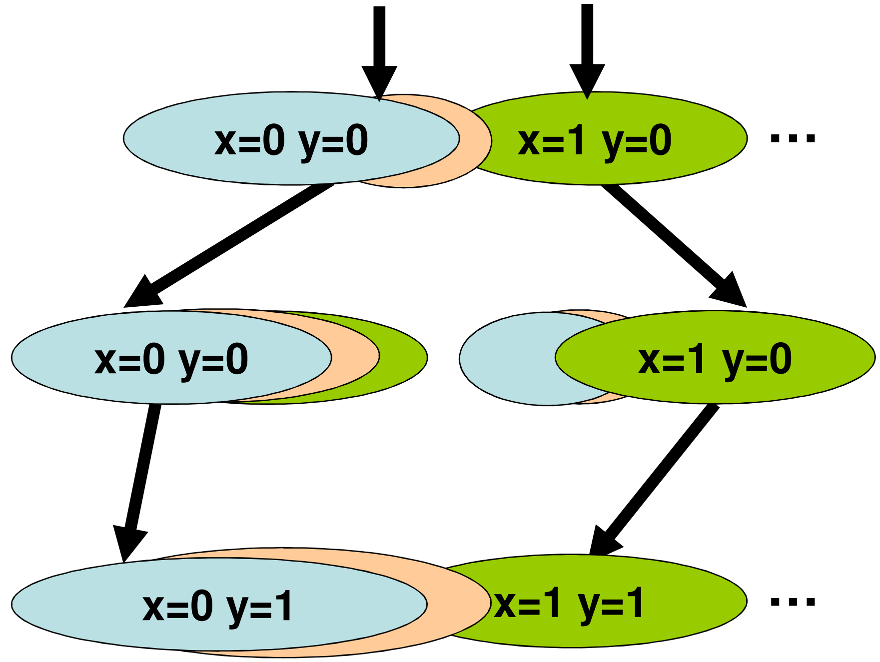
Abstraction and compositional reasoning

- 10^{120} to effectively infinite statespaces (particularly for software)

Models of C Code

```
if (x) {
  y = x;
} else {
  y = x + 1;
}
assert (y);
```





Program: Syntax **Control Flow Graph** **Model: Sem…**

Infinite State

Existential Abstraction

Partition concrete statespace into abstract states

- Each abstract state S corresponds to a set of concrete states s
- We write $\alpha(s)$ to mean the abstract state corresponding to s
- We define $\gamma(S) = \{ s \mid S = \alpha(s) \}$

Fix the transitions existentially

- $S \to S' \quad \Leftrightarrow \quad \exists\, s \in \gamma(S) \,.\, \exists\, s' \in \gamma(S') \,.\, s \to s'$
- $S \to S' \quad \Leftarrow \quad \exists\, s \in \gamma(S) \,.\, \exists\, s' \in \gamma(S') \,.\, s \to s'$

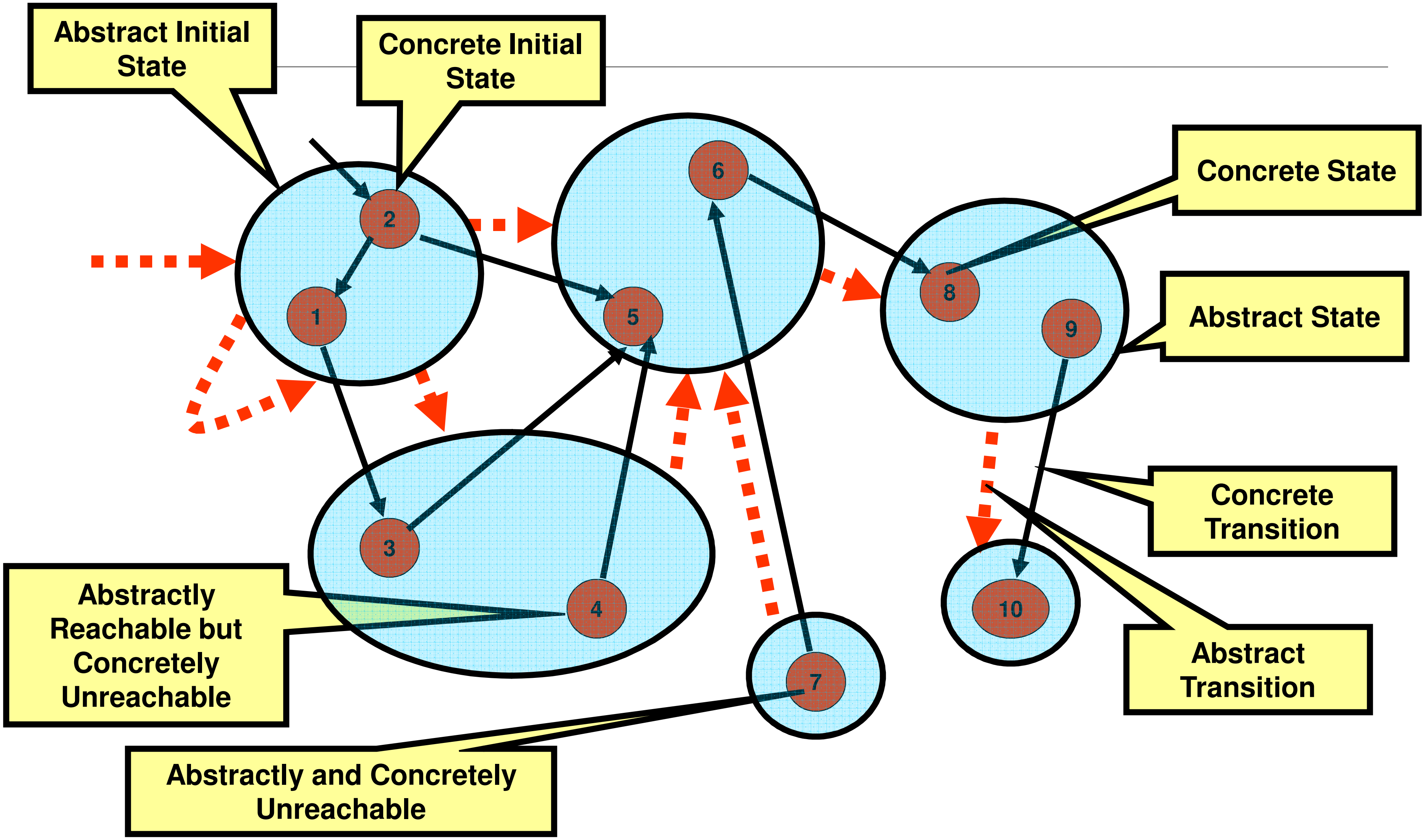
Strong & sometimes not computable

Weak: computable

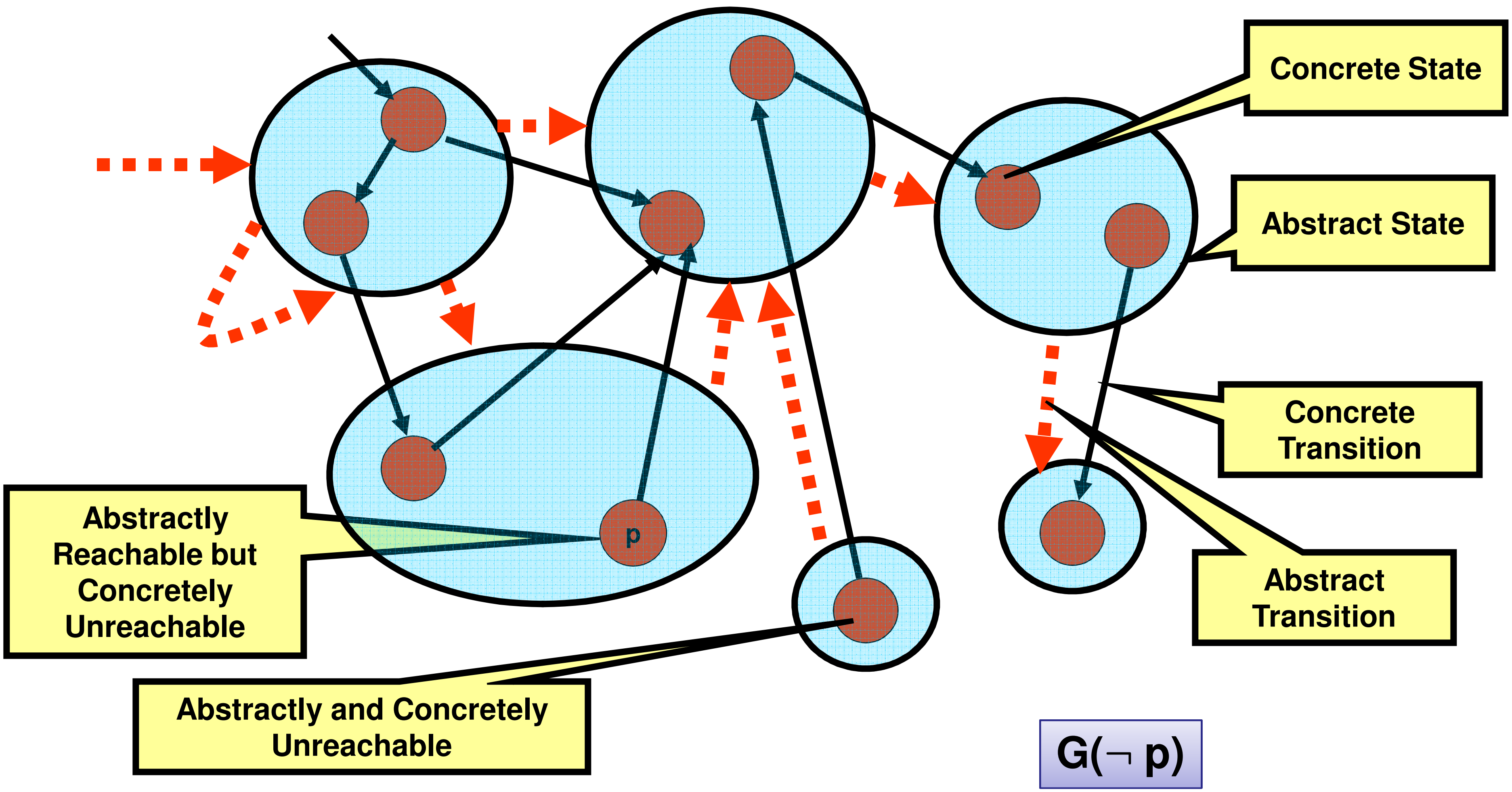
Existential Abstraction is conservative [ClarkeGrumbergLong94]

- If a ACTL* property holds on the abstraction, it also holds on the program
  - LTL is a subset of ACTL*
- However, the converse is not true: a property that fails on the abstraction may still hold on the program
- Existential abstraction can be viewed as a form of abstract interpretation

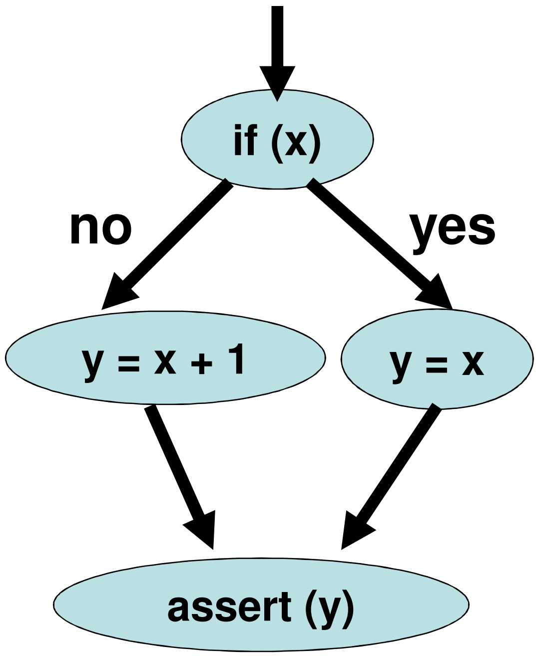
Example of Existential Abstraction



Example of Existential Abstraction

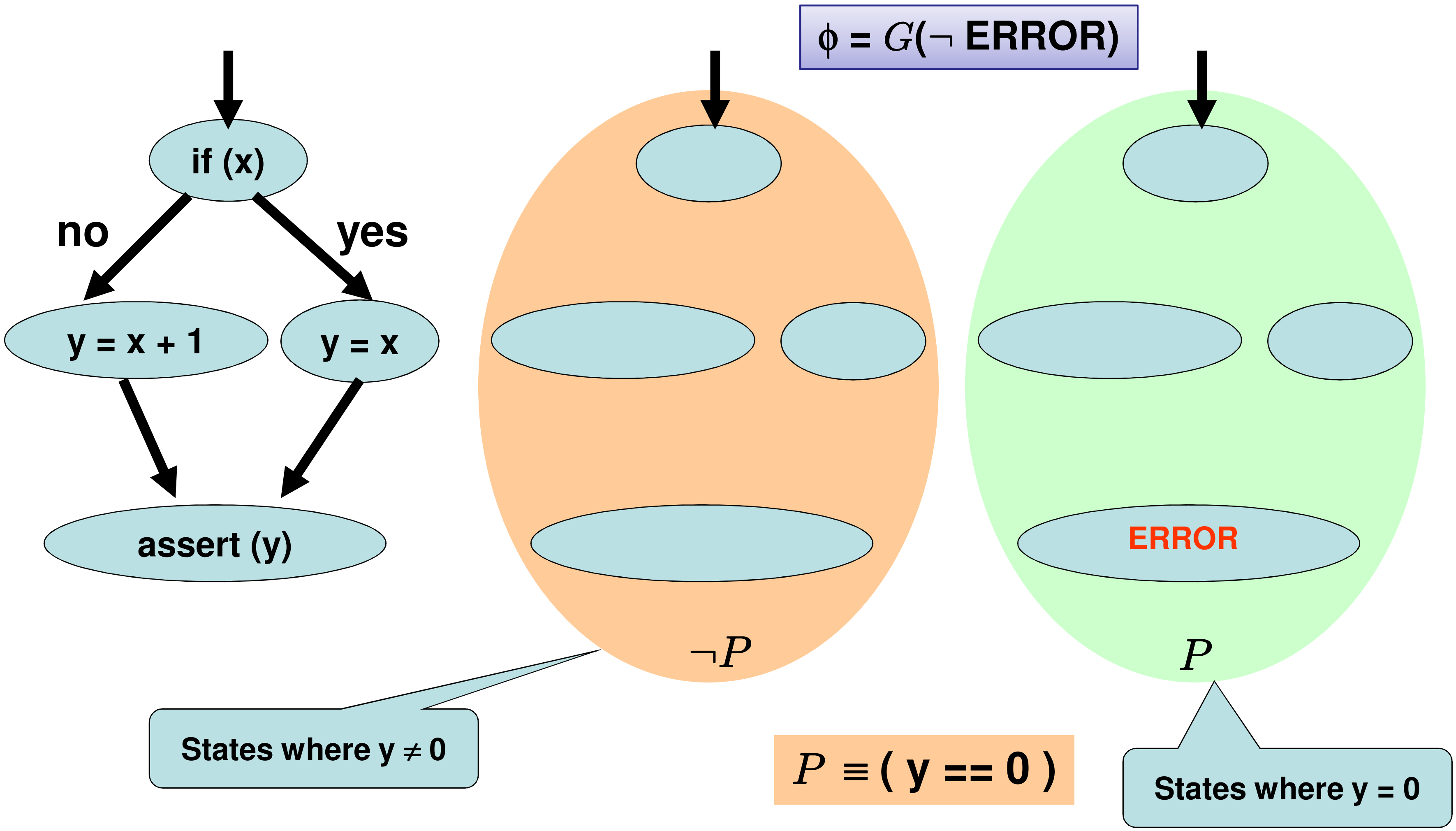


Predicate Abstraction

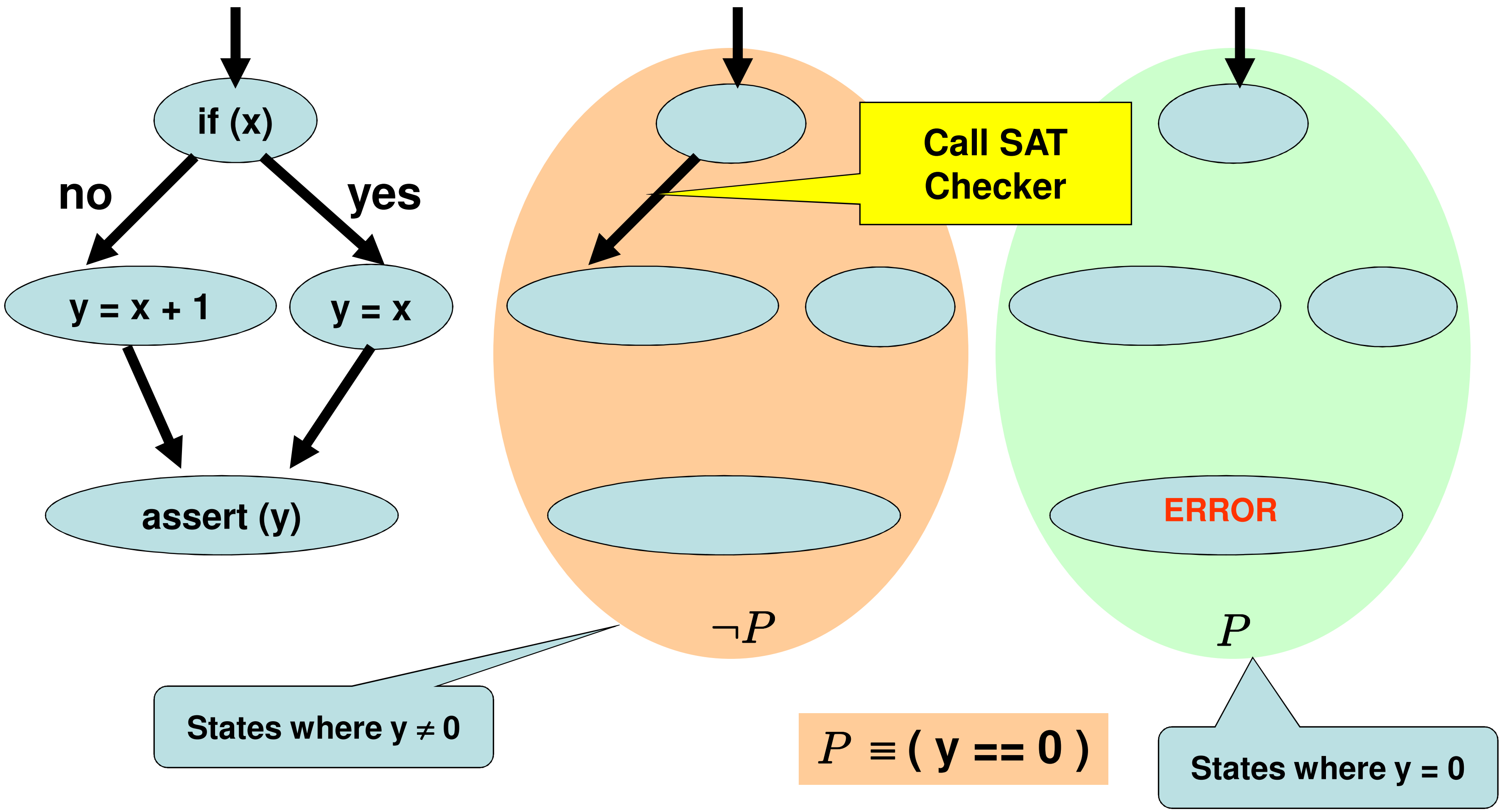


Partition the statespace based on values of a finite set of predicates on program variables

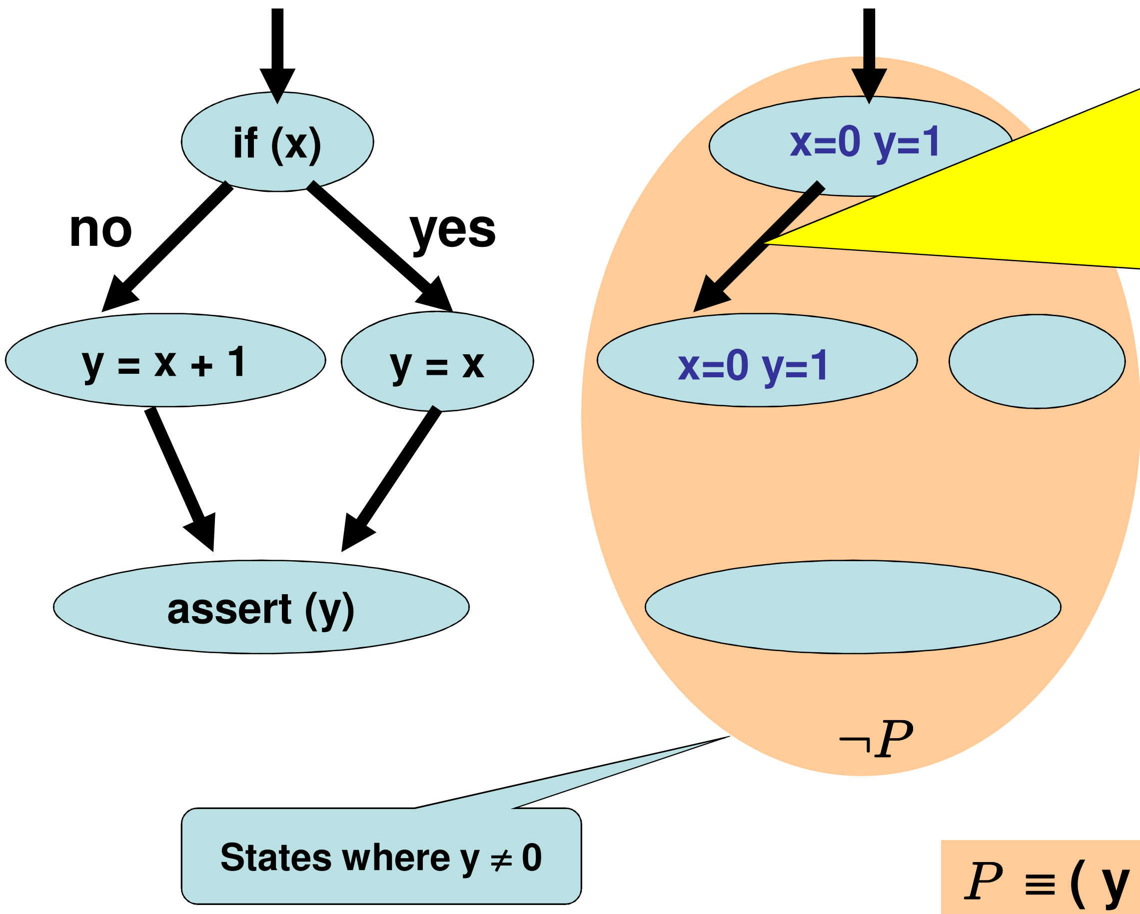
Predicate Abstraction



Predicate Abstraction



Predicate Abstraction



SAT Checker Query:

$y \neq 0 \wedge$

$x = 0 \wedge$

$x' = x \wedge$

$y' = y \wedge$

$y' \neq 0$

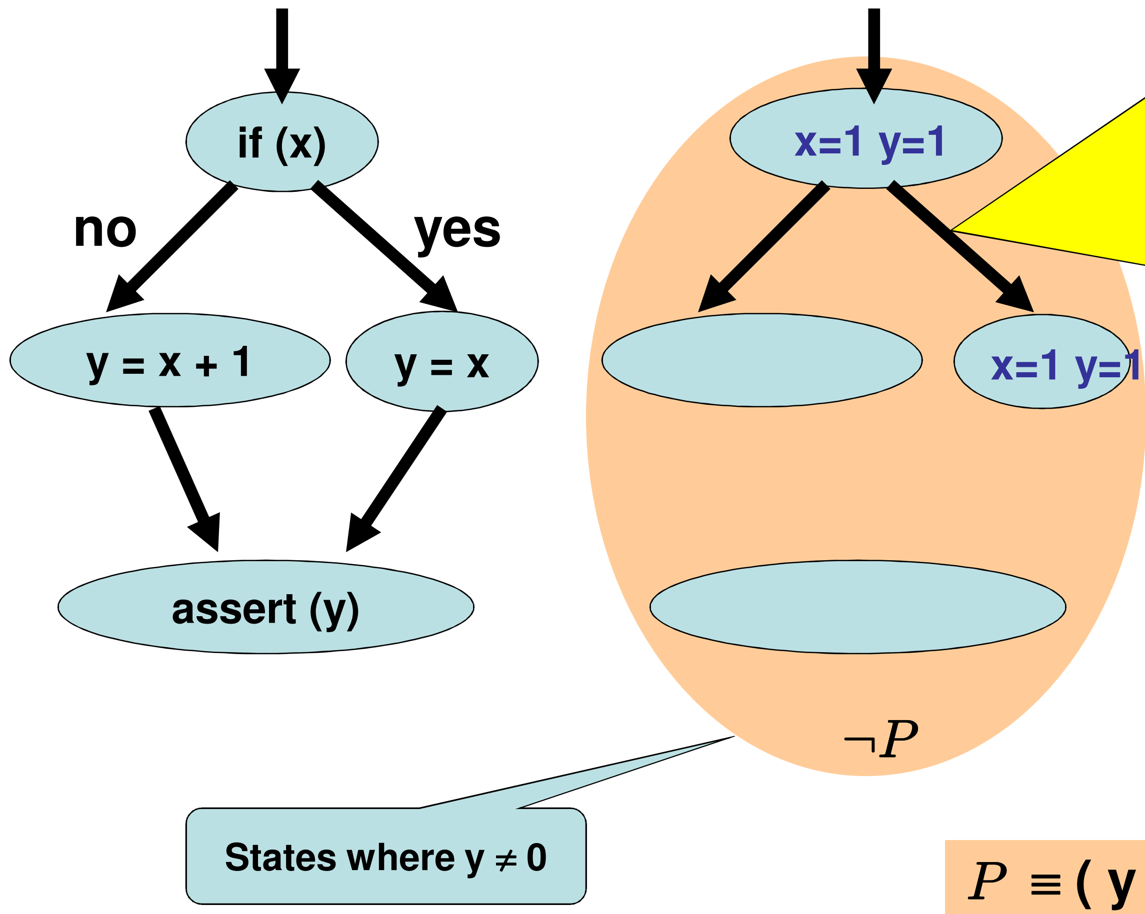
SAT Checker Answer:

SAT and here's a solution

x=0, y=1, x'=0, y'=1

$P \equiv (\, y == 0 \,)$

Predicate Abstraction



SAT Checker Query:

$y \neq 0 \wedge$

$x \neq 0 \wedge$

$x' = x \wedge$

$y' = y \wedge$

$y' \neq 0$

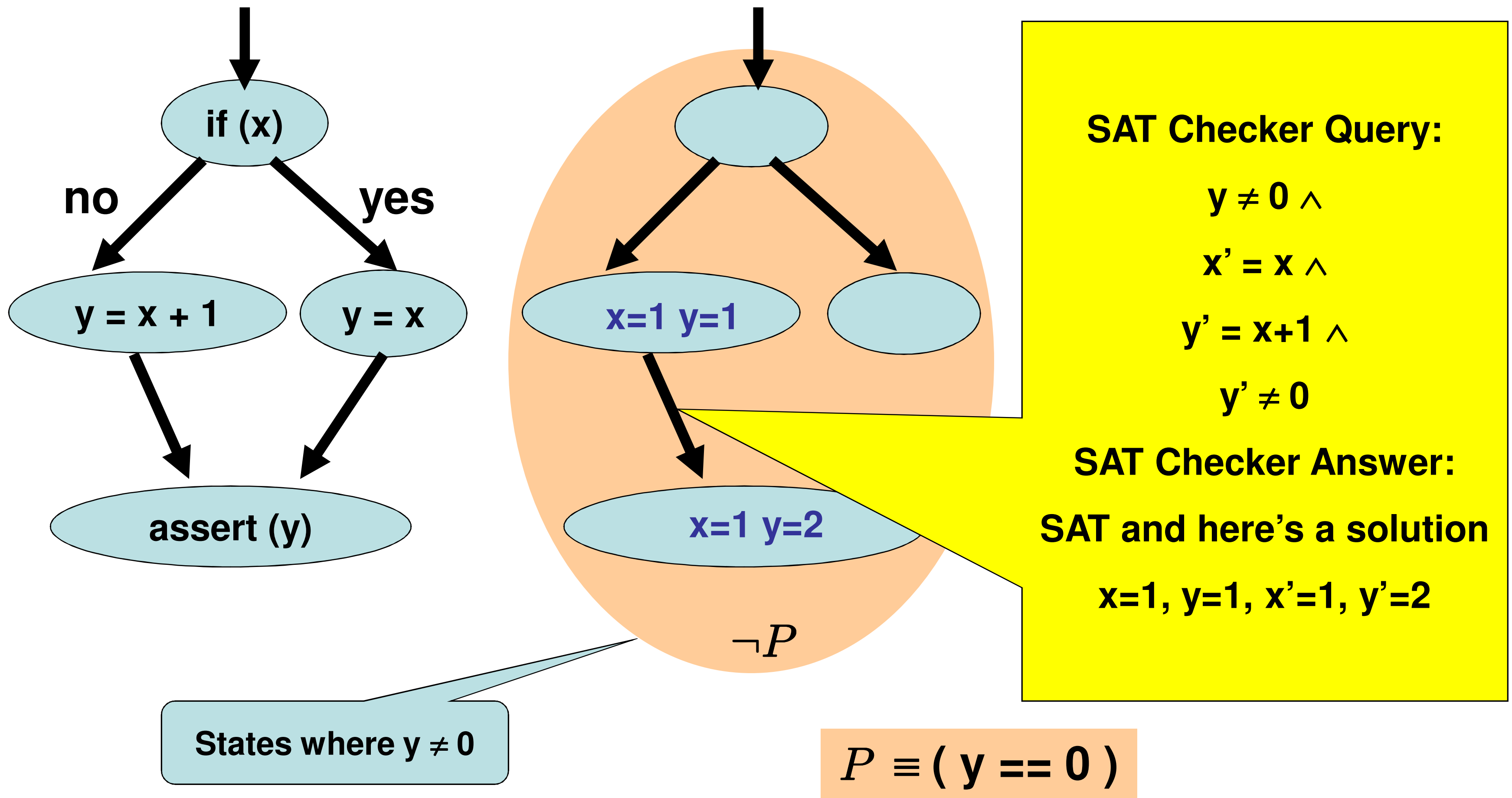
SAT Checker Answer:

SAT and here's a solution

x=1, y=1, x'=1, y'=1

$P \equiv (\, y == 0 \,)$

Predicate Abstraction



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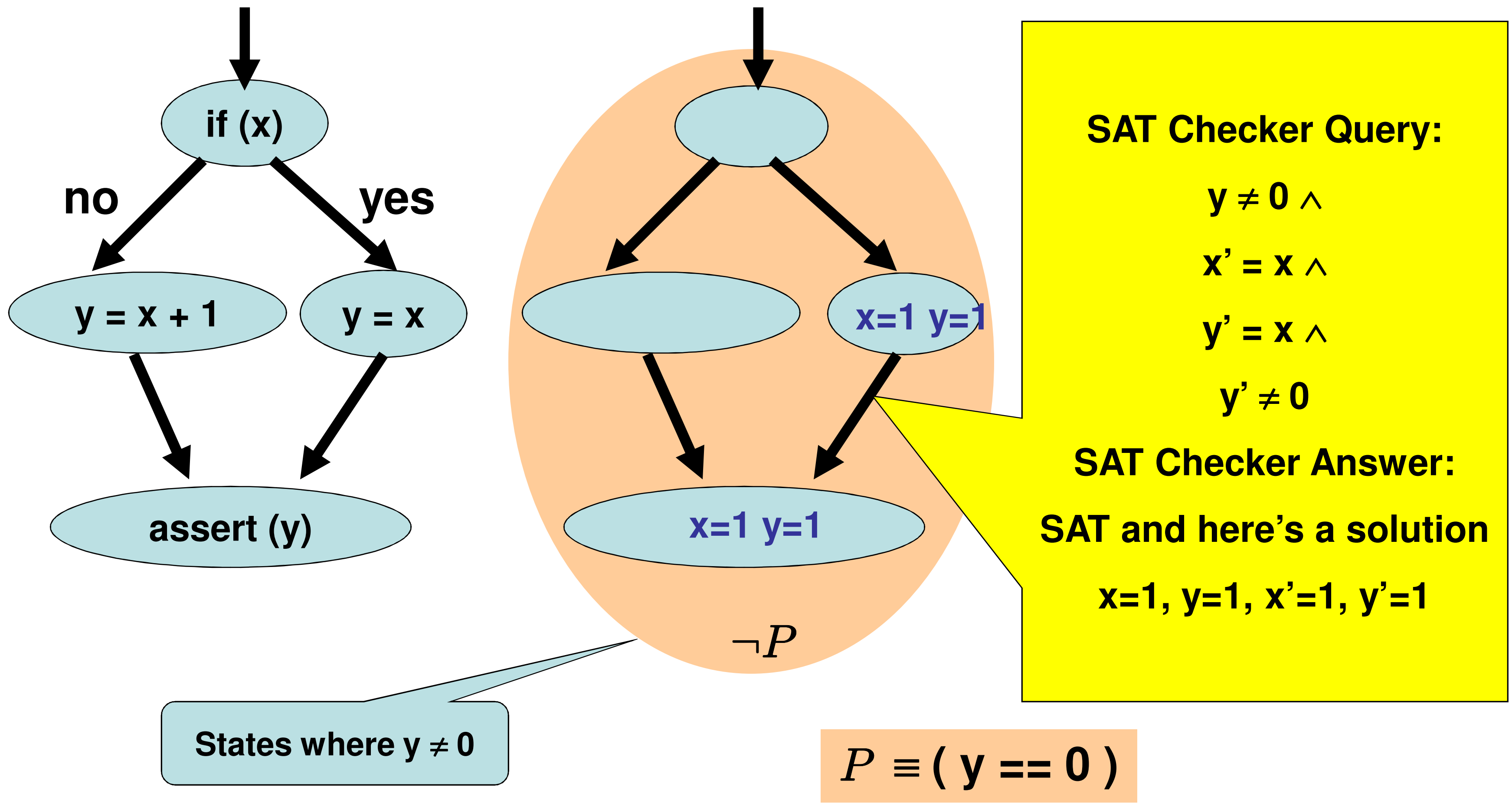
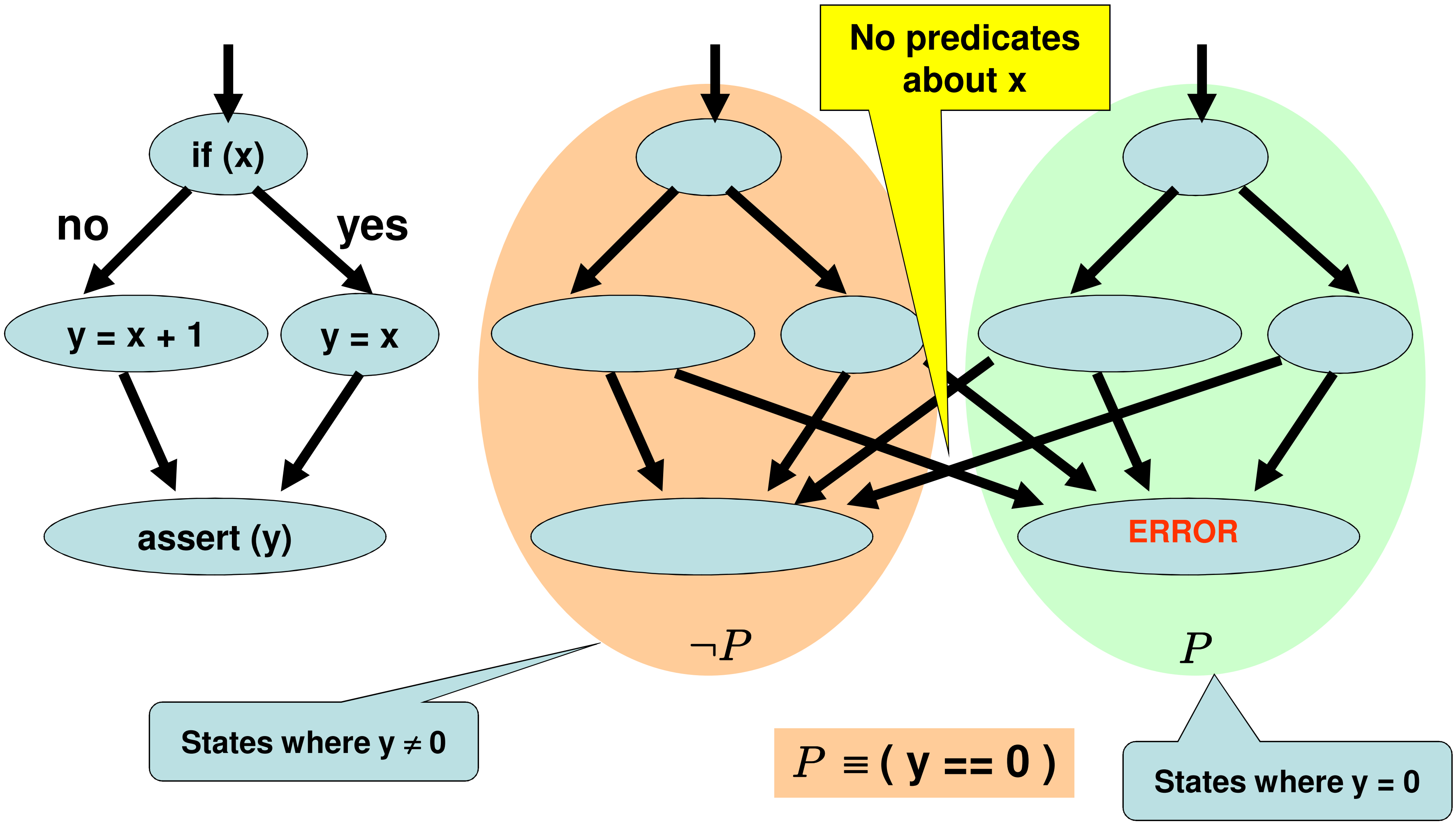


Predicate Abstraction



Imprecision due to Predicate Abstraction

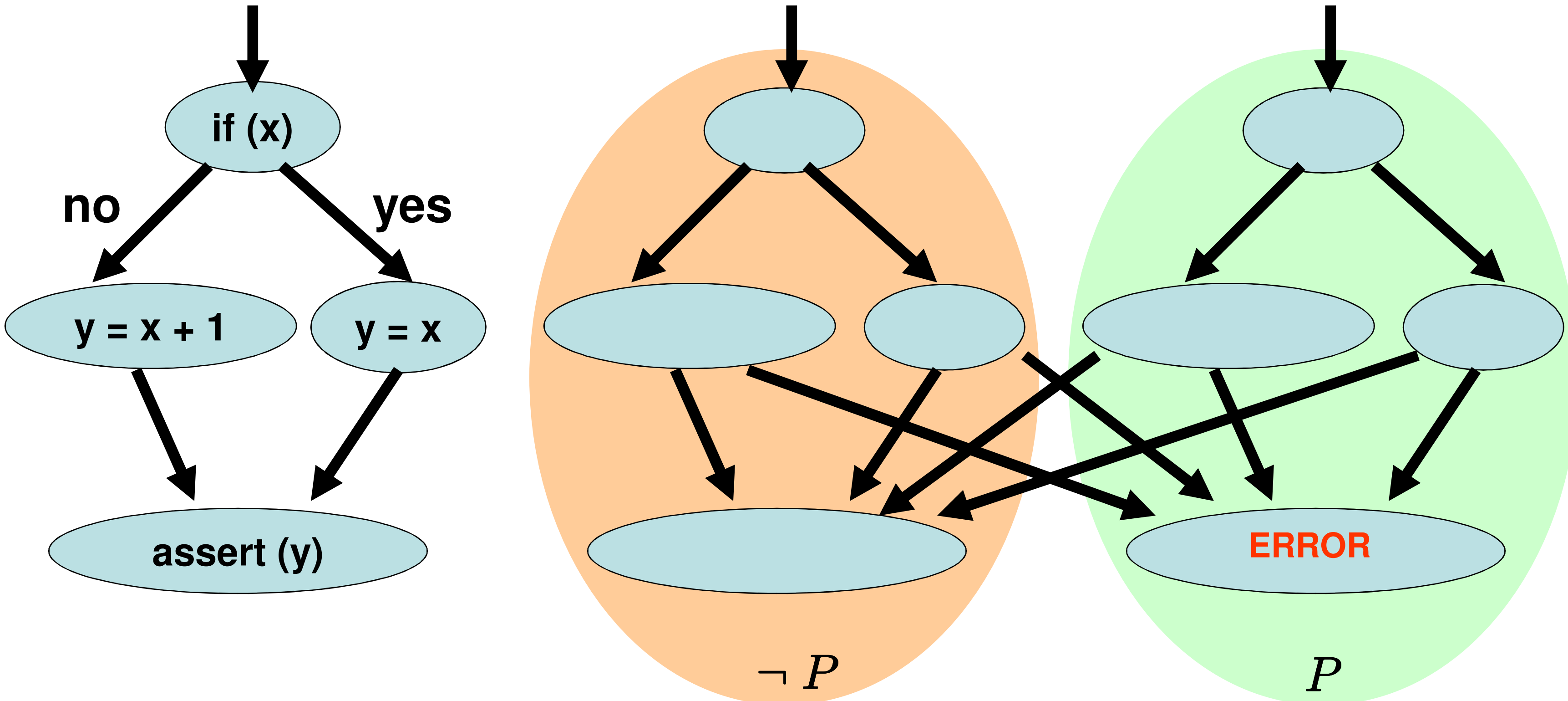
Counterexamples generated by model checking the abstract model may be spurious, i.e., not concretely realizable

Need to refine the abstraction iteratively by changing the set of predicates

Can infer new set of predicates by analyzing the spurious counterexample

- Lot of research in doing this effectively
- Counterexample Guided Abstraction Refinement (CEGAR)
- A.K.A. Iterative Abstraction Refinement
- A.K.A. Iterative Refinement

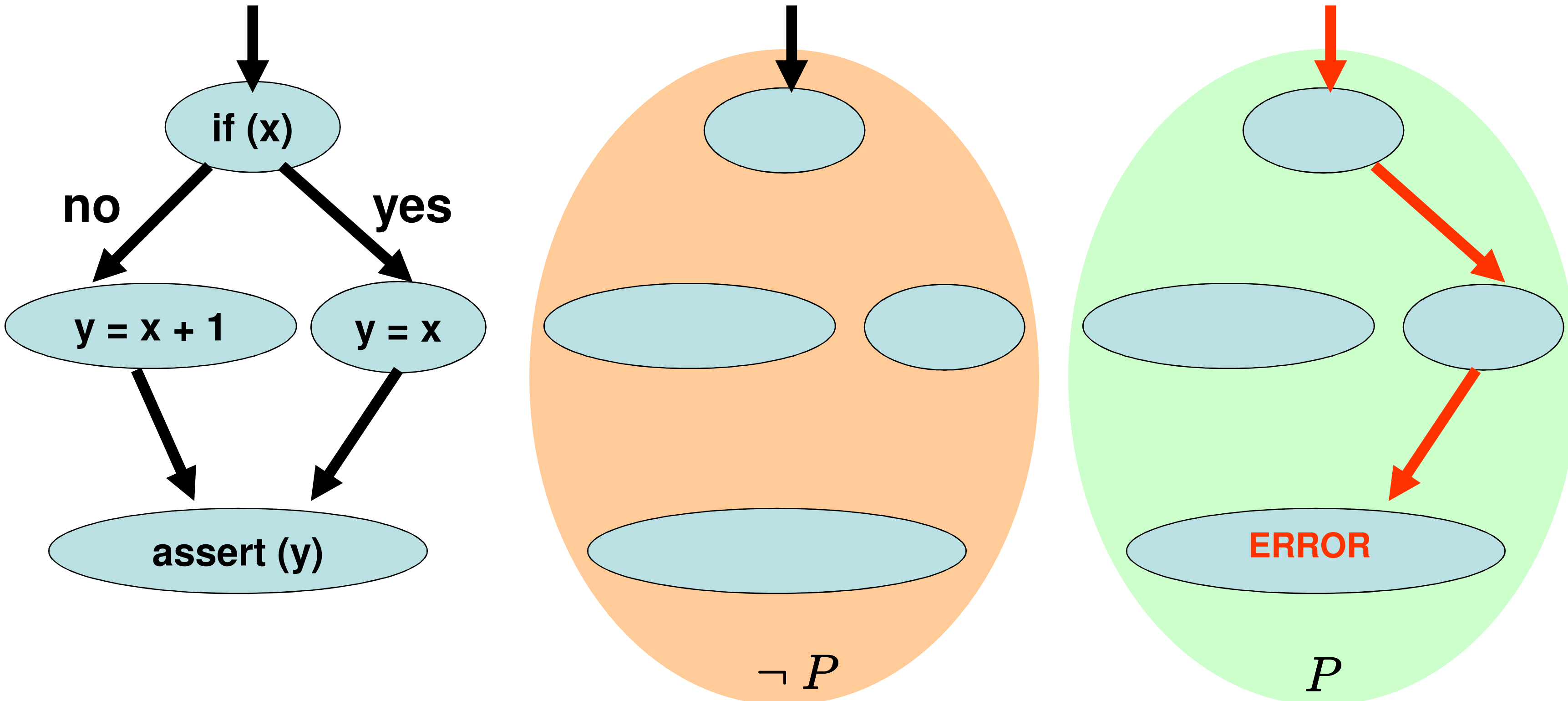
Model Checking



$\phi = G(\neg$ **ERROR**$)$

$P \equiv (\ y == 0\ )$

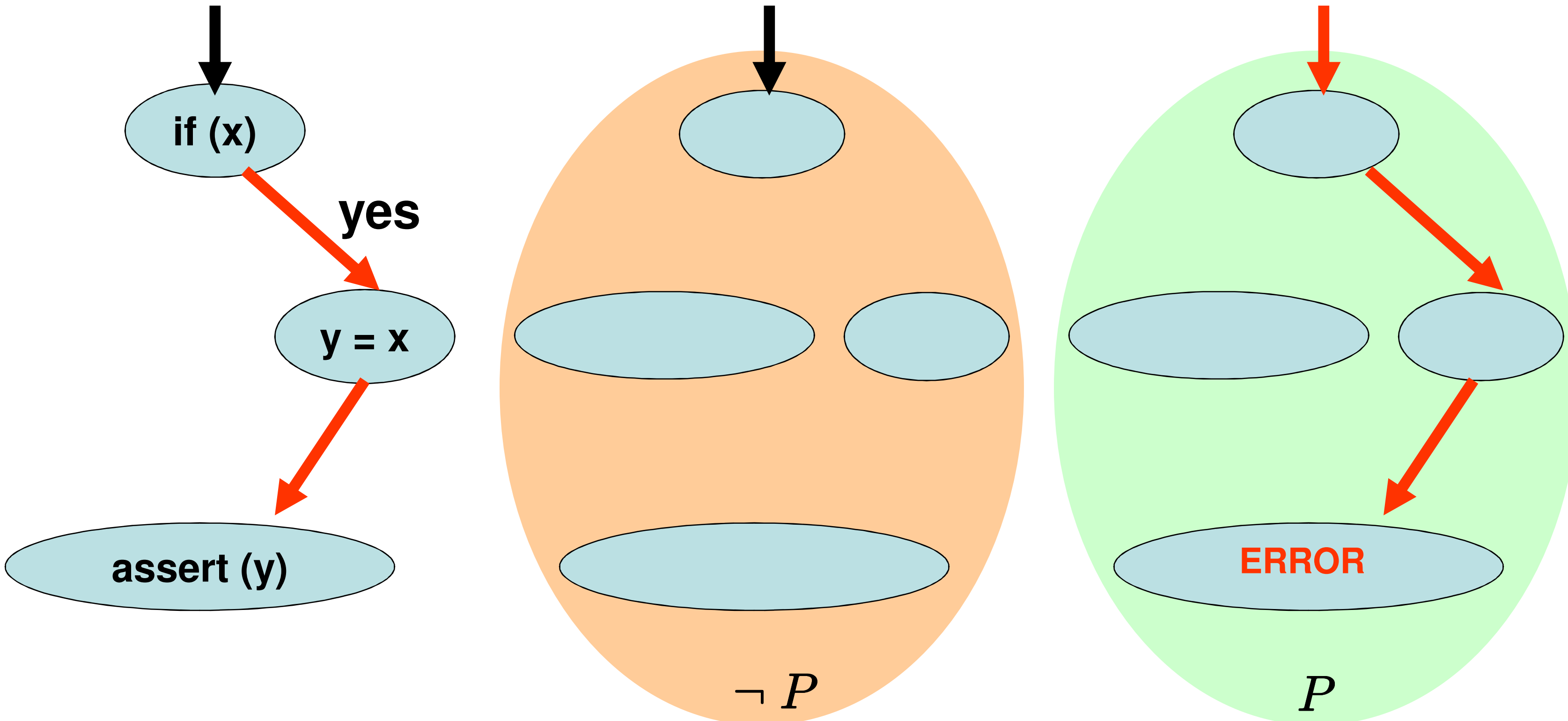
Model Checking



ϕ = $G(\neg$ ERROR)

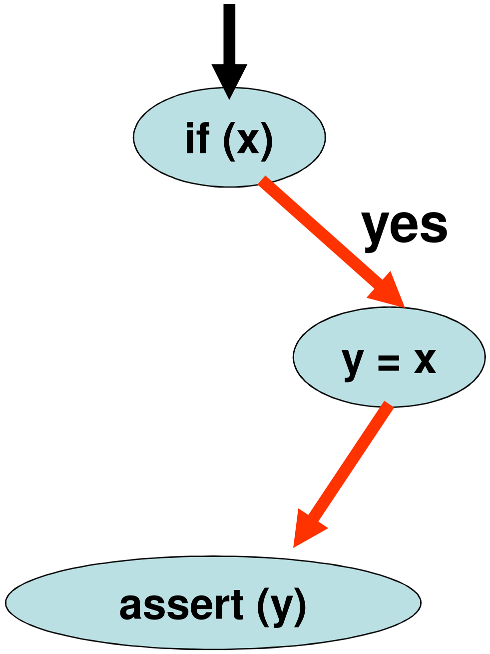
$P \equiv$ (y == 0)

Model Checking



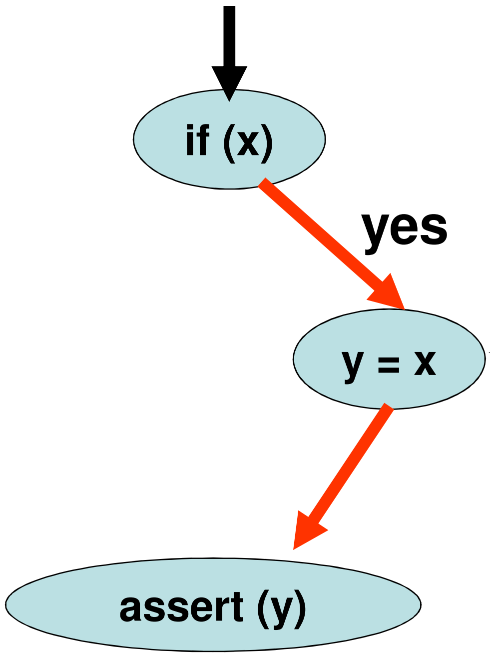
$P \equiv$ (y == 0)

Counterexample Validation



- Simulate counterexample symbolically
- Call SAT Checker to determine if the post-condition is satisfiable
- In our case, Counterexample is spurious
- New set of predicates {x==0,y==0}

Counterexample Validation



SAT Checker Query:

$x \neq 0 \wedge$

$y' = x \wedge$

$y' = 0$

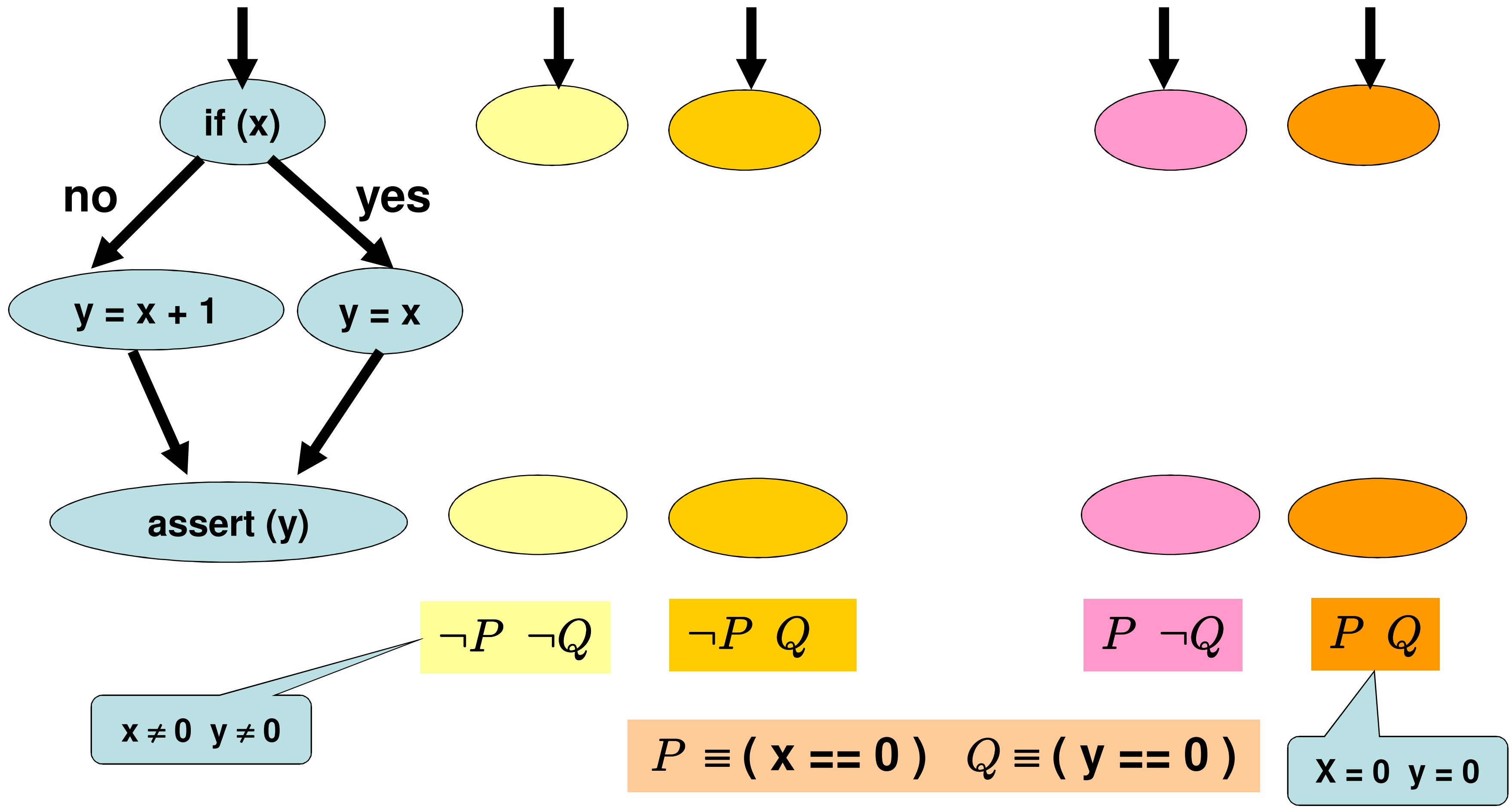
SAT Checker Answer:

UNSAT and here's an UNSAT core

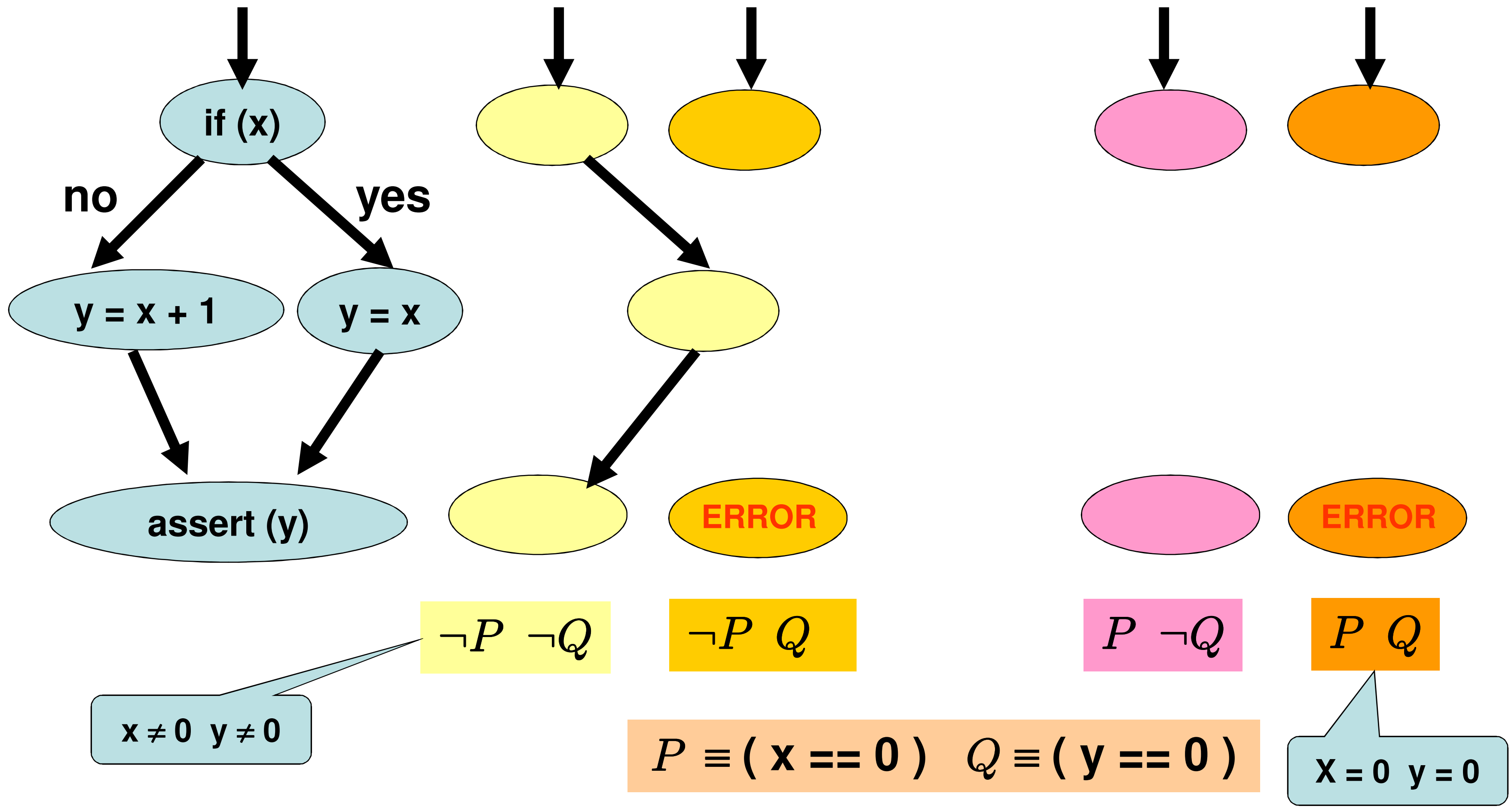
$\{x \neq 0 \,,\, y' = x \,,\, y' = 0\}$

- Used to derive new predicate (x=0)
- Different heuristics used in practice

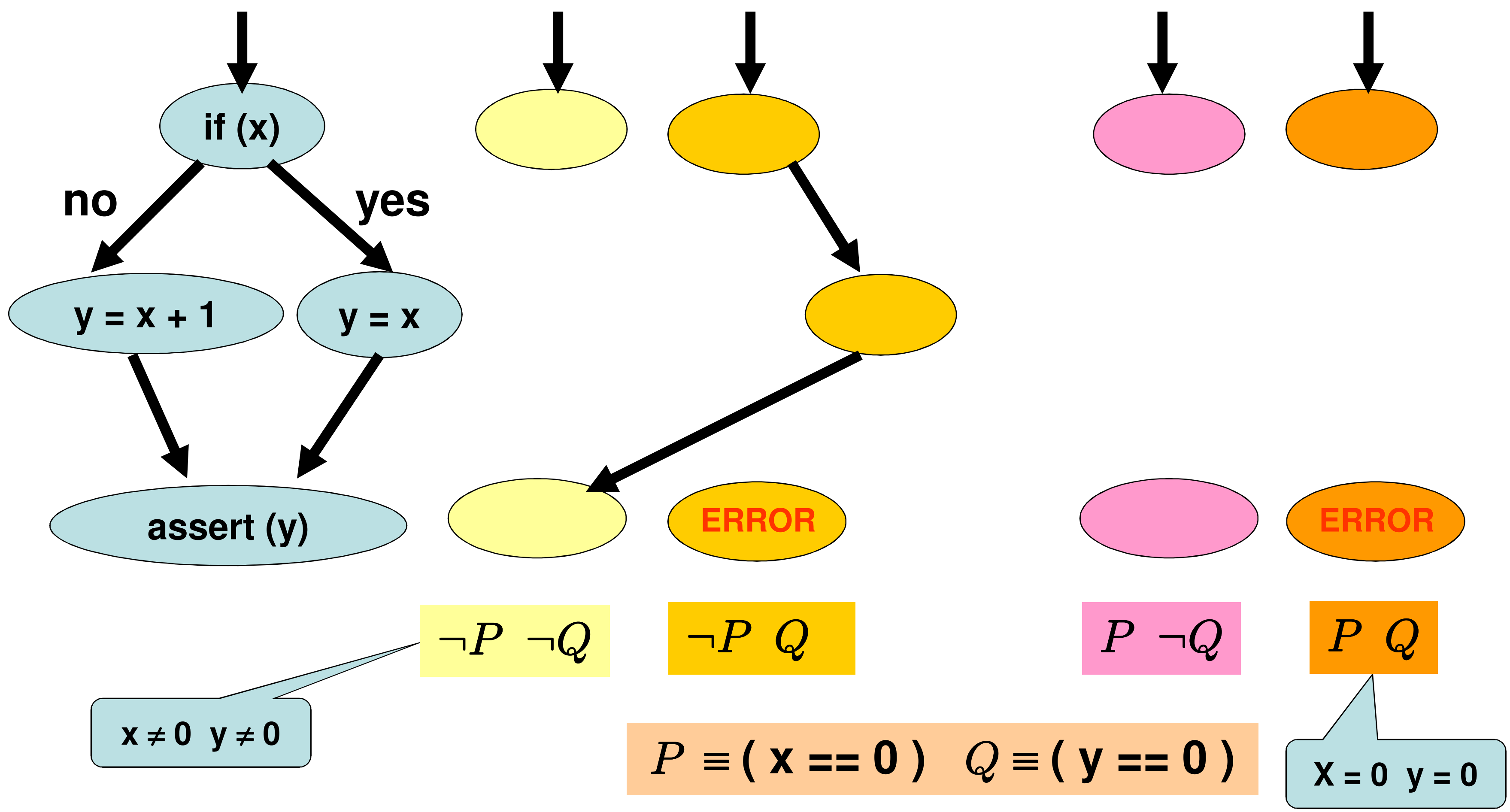
Predicate Abstraction: 2nd Iteration



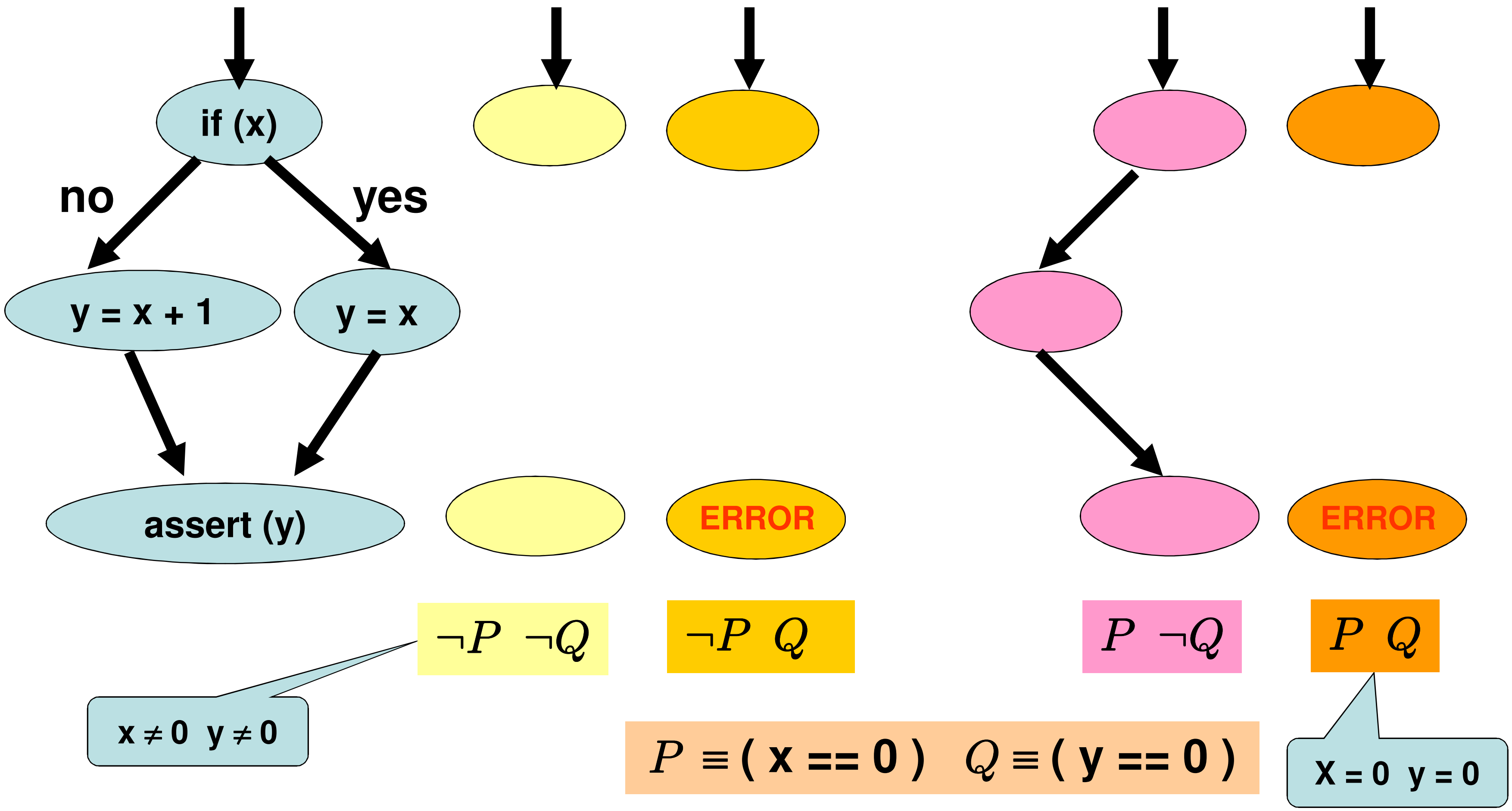
Predicate Abstraction: 2nd Iteration



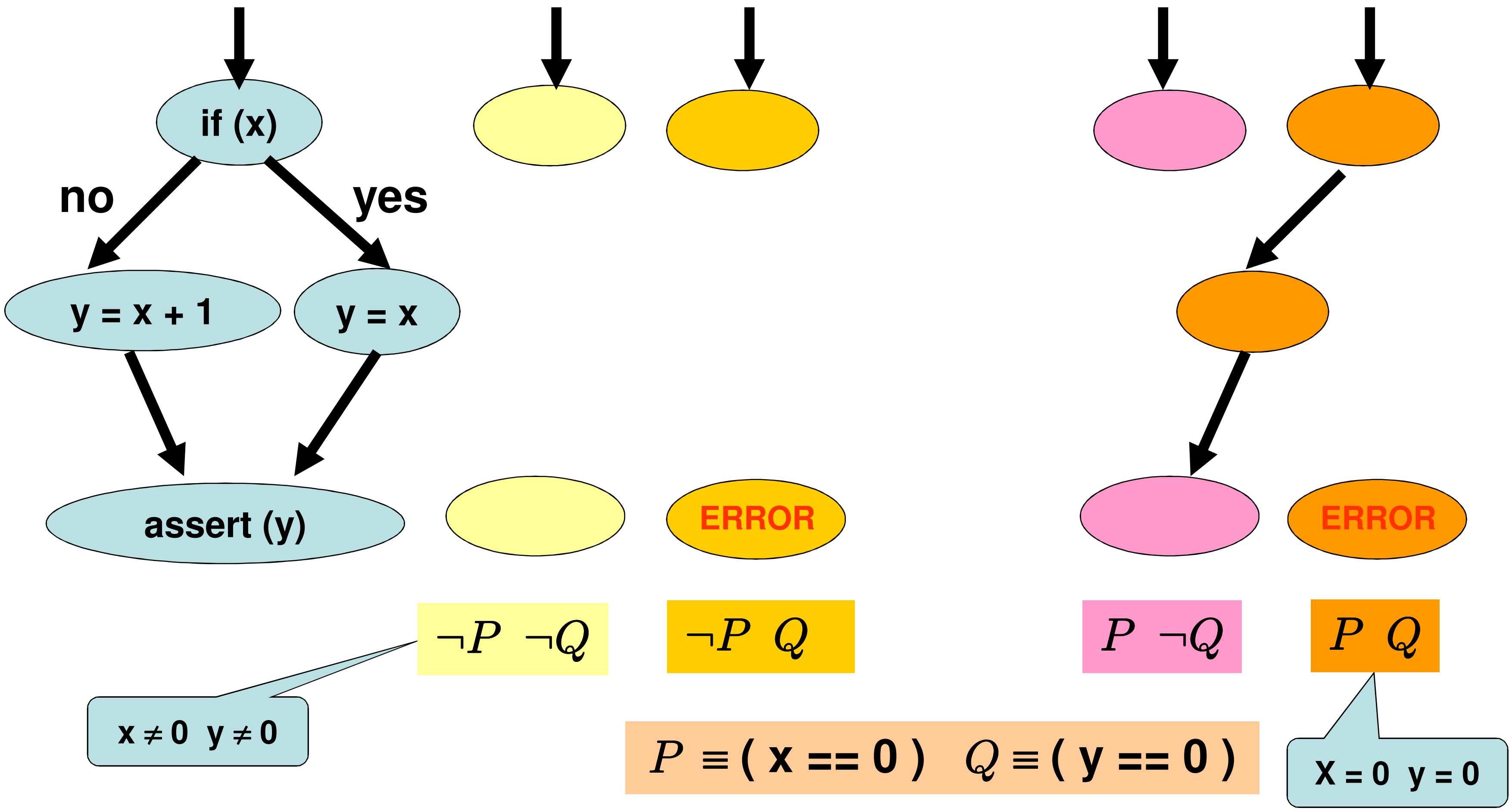
Predicate Abstraction: 2nd Iteration



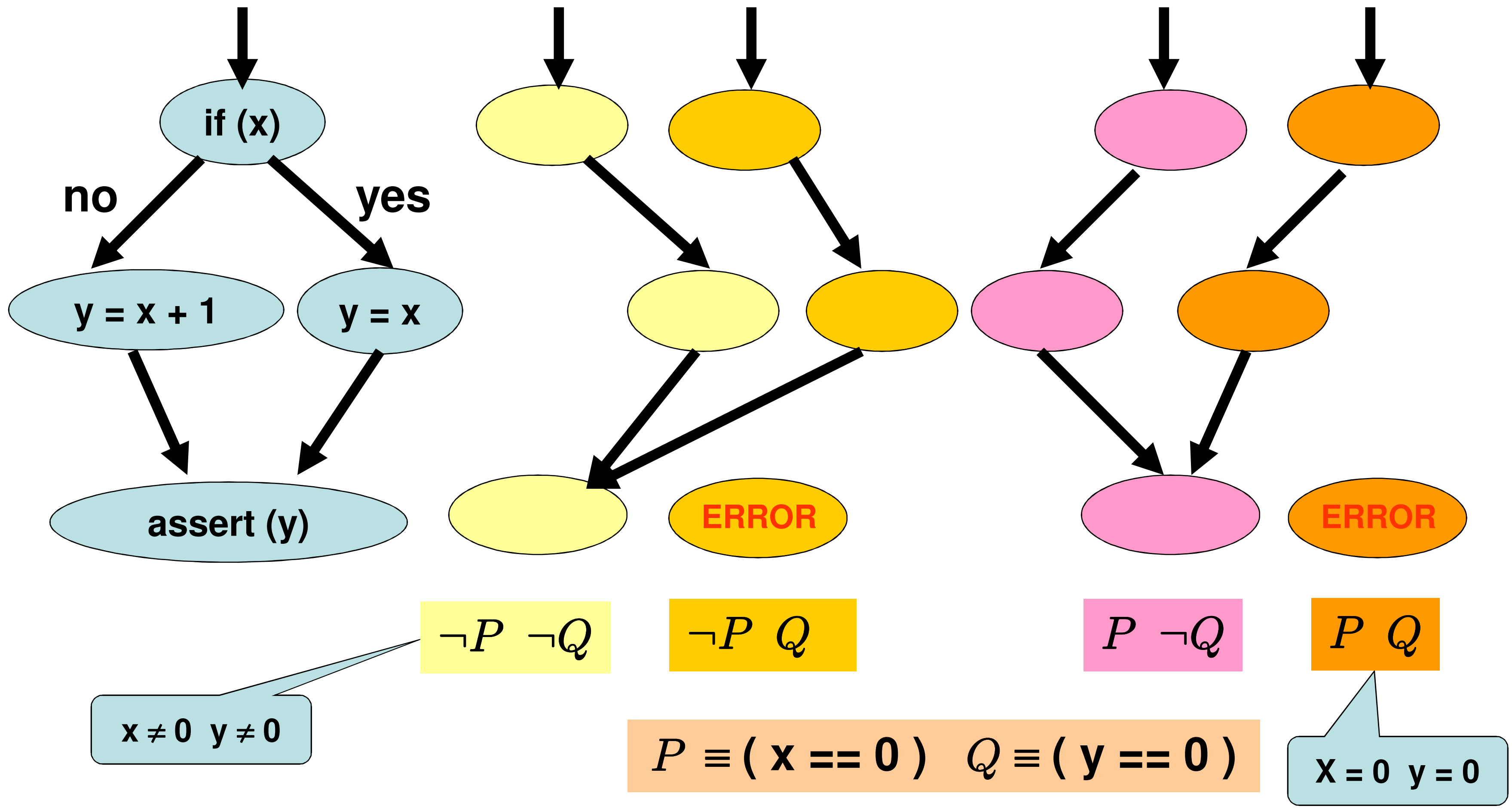
Predicate Abstraction: 2nd Iteration



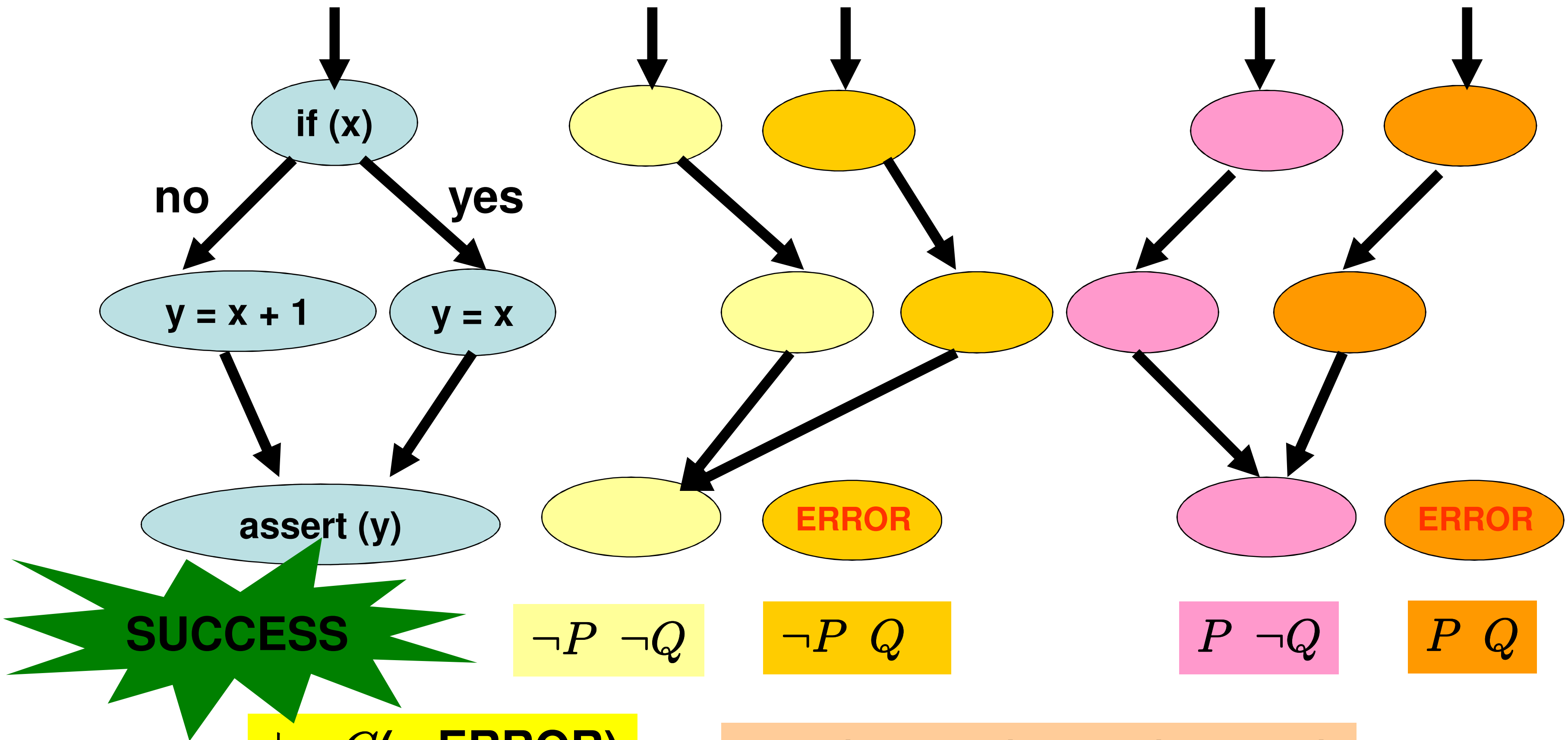
Predicate Abstraction: 2nd Iteration



Predicate Abstraction: 2nd Iteration



Model Checking: 2^{nd} Iteration



$\phi = G(\neg \text{ ERROR})$

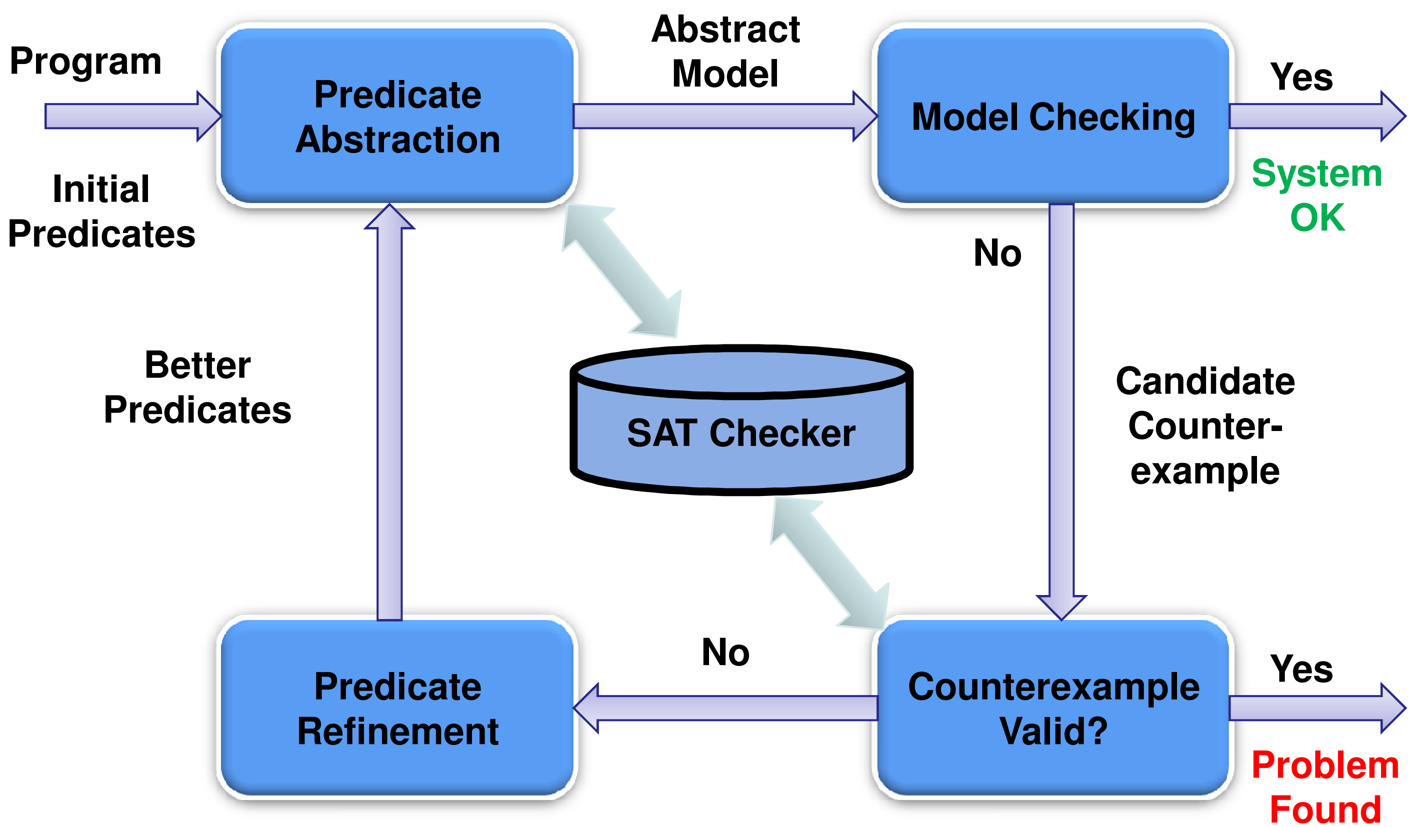
$P \equiv (\ \mathbf{x == 0}\ )\quad Q \equiv (\ \mathbf{y == 0}\ )$

Iterative Refinement: Summary

Choose an initial set of predicate, and proceed iteratively as follows:

1. **Abstraction:** Construct an abstract model M of the program using the predicate abstraction
2. **Verification:** Model check M. If model checking succeeds, exit with success. Otherwise, get counterexample CE.
3. **Validation:** Check CE for validity. If CE is valid, exit with failure.
4. **Refinement:** Otherwise, update the set of predicates and repeat from Step 1.

Iterative Refinement



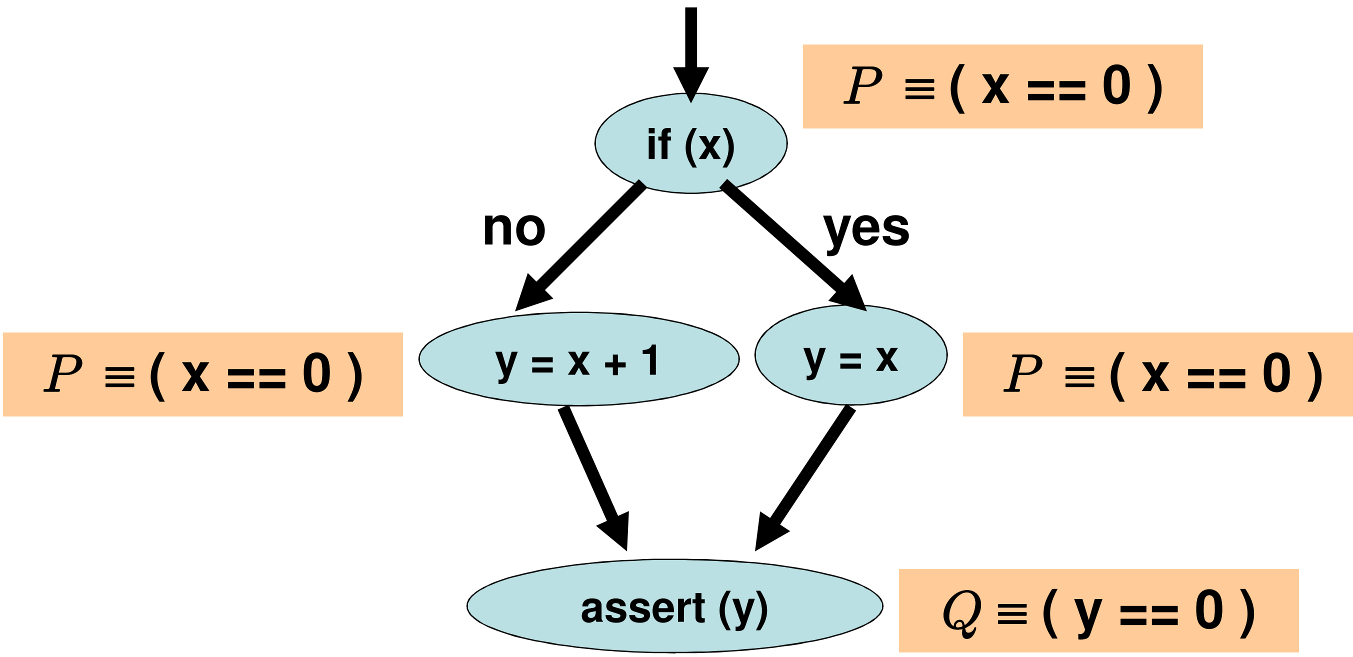
Localization Reduction, Kurshan, Bell Labs

Counterexample-guided Abstraction Refinement for Symbolic Model Checking, Clarke et al., CMU

Software Model Checking, SLAM Project, Microsoft, Ball & Rajamani

Predicate Abstraction: Optimizations

1. Construct transitions on-the-fly
2. Different set of predicates at different control locations



3. Avoid exponential number of theorem-prover calls

Research Areas

Finding “good” predicates

- Technically as hard as finding “good” loop invariants
- Complexity is linear in LOC but exponential in number of predicates

Combining with static analysis

- Alias analysis, invariant detection, constant propagation
- Inexpensive, and may make subsequent model checking more efficient

Bounded model checking

Software Model Checking Tools

Iterative Refinement

- SLAM, BLAST, MAGIC, Copper, SATABS, …

Next lecture

Bounded Model Checking

- CBMC, …

Following lecture

Others

- Engines: MOPED, BEBOP, BOPPO, …
- Java: Java PathFiner, Bandera, BOGOR, …
- C: CMC, CPAChecker, …

Bibliography

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