

SMT Solver

Zhaoguo Wang

Adapted From:

ETH Zurich program verification, Lecture 2, 3

(<https://www.pm.inf.ethz.ch/education/courses/program-verification.html>)

<https://theory.stanford.edu/~nikolaj/programmingz3.html>

<<Solving SAT and SAT Modulo Theories: From an Abstract
Davis–Putnam–Logemann–Loveland Procedure to DPLL(T)>>

Predicate Logic (谓词逻辑)

1.1 Propositional Logic

Step 0. Proof.

Step 1. Convert program into mathematical formula.

Step 2. Ask the computer to solve the formula.

1.2 First Order Logic

Step 1. Convert it into first order logic formula.

Step 2. Ask the computer to solve the formula.

1.3 Auto-active Proof

Step 1. Axiom system

Step 2. Ask the computer to check the invariants

Outline – This Lecture

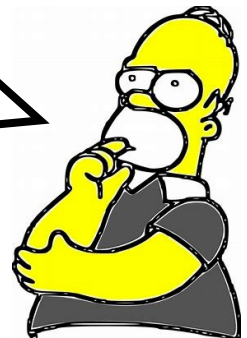
- SMT Solver
 - SMT
 - From DPLL to DPLL(T)
 - EUF

SMT

DEFINITION

The SMT problem (abbreviated satisfiability modulo theories) is the problem of determining if there exists an interpretation that satisfies a given predicate logic formula.

we can use SAT solvers to solve SAT problems automatically. Can we solve SMT problems automatically?





MathSAT 5

An SMT Solver for Formal Verification & More

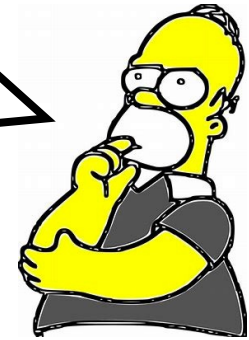
SMT solver can do it!

Z3

CVC3

CVC4

There are some powerful SAT solvers based on DPLL. Can we build SMT solvers based on these SAT solvers?



We only consider the case of *quantifier-free formulas*.

A Quick Recap

$$\emptyset \parallel \bar{1} \vee \bar{2}, 2 \vee 3, \bar{1} \vee \bar{3} \vee 4, 2 \vee \bar{3} \vee \bar{4}, 1 \vee 4 \implies (\text{Decide})$$

A Quick Recap

$$\begin{array}{llllllll} \emptyset & \parallel & \bar{1} \vee \bar{2}, & 2 \vee 3, & \bar{1} \vee \bar{3} \vee 4, & 2 \vee \bar{3} \vee \bar{4}, & 1 \vee 4 & \implies & \text{(Decide)} \\ 1^d & \parallel & \bar{1} \vee \bar{2}, & 2 \vee 3, & \bar{1} \vee \bar{3} \vee 4, & 2 \vee \bar{3} \vee \bar{4}, & 1 \vee 4 & \implies & \text{(UnitPropagate)} \end{array}$$

A Quick Recap

$$\begin{array}{llllllll} \emptyset & \parallel & \bar{1} \vee \bar{2}, & 2 \vee 3, & \bar{1} \vee \bar{3} \vee 4, & 2 \vee \bar{3} \vee \bar{4}, & 1 \vee 4 & \implies & \text{(Decide)} \\ 1^d & \parallel & \bar{1} \vee \bar{2}, & 2 \vee 3, & \bar{1} \vee \bar{3} \vee 4, & 2 \vee \bar{3} \vee \bar{4}, & 1 \vee 4 & \implies & \text{(UnitPropagate)} \\ 1^d \bar{2} & \parallel & \bar{1} \vee \bar{2}, & 2 \vee 3, & \bar{1} \vee \bar{3} \vee 4, & 2 \vee \bar{3} \vee \bar{4}, & 1 \vee 4 & \implies & \text{(UnitPropagate)} \end{array}$$

A Quick Recap

$\emptyset$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(Decide)
1^d	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(UnitPropagate)
$1^d \bar{2}$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(UnitPropagate)
$1^d \bar{2} 3$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(UnitPropagate)

A Quick Recap

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1^d	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(UnitPropagate)
$1^d \bar{2}$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(UnitPropagate)
$1^d \bar{2} 3$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(UnitPropagate)
$1^d \bar{2} 3 4$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(Backtrack)

A Quick Recap

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1^d	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(UnitPropagate)
$1^d \bar{2}$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(UnitPropagate)
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$\bar{1}$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(UnitPropagate)

A Quick Recap

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$1^d \bar{2}$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(UnitPropagate)
$1^d \bar{2} 3$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(UnitPropagate)
$1^d \bar{2} 3 4$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(Backtrack)
$\bar{1}$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(UnitPropagate)
$\bar{1} 4$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(Decide)

A Quick Recap

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$1^d \bar{2} 3 4$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(Backtrack)
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$\bar{1} 4$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(Decide)
$\bar{1} 4 \bar{3}^d$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(UnitPropagate)

A Quick Recap

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1^d	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(UnitPropagate)
$1^d \bar{2}$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(UnitPropagate)
$1^d \bar{2} 3$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(UnitPropagate)
$1^d \bar{2} 3 4$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(Backtrack)
$\bar{1}$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(UnitPropagate)
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$\bar{1} 4 \bar{3}^d$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$	$\implies$	(UnitPropagate)
$\bar{1} 4 \bar{3}^d 2$	$\parallel$	$\bar{1} \vee \bar{2},$	$2 \vee 3,$	$\bar{1} \vee \bar{3} \vee 4,$	$2 \vee \bar{3} \vee \bar{4},$	$1 \vee 4$		

A Quick Recap

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1^d	$\parallel$	$\bar{1} \vee \bar{2}, 2 \vee 3, \bar{1} \vee \bar{3} \vee 4, 2 \vee \bar{3} \vee \bar{4}, 1 \vee 4$	$\implies$	(UnitPropagate)
$1^d \bar{2}$	$\parallel$	$\bar{1} \vee \bar{2}, 2 \vee 3, \bar{1} \vee \bar{3} \vee 4, 2 \vee \bar{3} \vee \bar{4}, 1 \vee 4$	$\implies$	(UnitPropagate)
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$\bar{1}$	$\parallel$	$\bar{1} \vee \bar{2}, 2 \vee 3, \bar{1} \vee \bar{3} \vee 4, 2 \vee \bar{3} \vee \bar{4}, 1 \vee 4$	$\implies$	(UnitPropagate)
$\bar{1} 4$	$\parallel$	$\bar{1} \vee \bar{2}, 2 \vee 3, \bar{1} \vee \bar{3} \vee 4, 2 \vee \bar{3} \vee \bar{4}, 1 \vee 4$	$\implies$	(Decide)
$\bar{1} 4 \bar{3}^d$	$\parallel$	$\bar{1} \vee \bar{2}, 2 \vee 3, \bar{1} \vee \bar{3} \vee 4, 2 \vee \bar{3} \vee \bar{4}, 1 \vee 4$	$\implies$	(UnitPropagate)
$\bar{1} 4 \bar{3}^d 2$	$\parallel$	$\bar{1} \vee \bar{2}, 2 \vee 3, \bar{1} \vee \bar{3} \vee 4, 2 \vee \bar{3} \vee \bar{4}, 1 \vee 4$		

The input of a SAT solver is CNF and it uses DPLL to solve the problem.

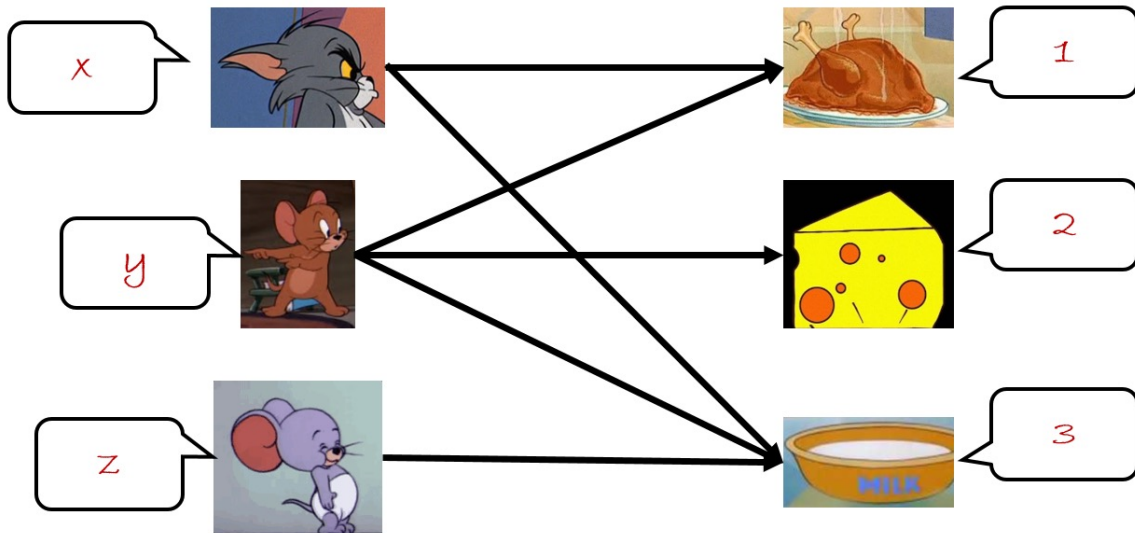


Lazy SMT integrates theory support
into the propositional search

Lazy SMT Techniques

DEFINITION

An atomic formula in predicate logic is a formula without propositional connectives or quantifiers.



$(x = 1 \vee x = 3) \wedge$
 $(y = 1 \vee y = 2 \vee y = 3) \wedge$
 $(z = 3) \wedge$
 $\neg(x = y) \wedge$
 $\neg(x = z) \wedge$
 $\neg(y = z)$

atom formulas

Lazy SMT Techniques

$(x = 1 \vee x = 3) \wedge$	$(p1 \vee p2) \wedge$
$(y = 1 \vee y = 2 \vee y = 3) \wedge$	$(p3 \vee p4 \vee p5) \wedge$
$(z = 3) \wedge$	$(p6) \wedge$
$\neg(x = y) \wedge$	$\neg p7 \wedge$
$\neg(x = z) \wedge$	$\neg p8 \wedge$
$\neg(y = z)$	$\neg p9$

Step1: replace atomic formulas with fresh propositional variables.

Lazy SMT Techniques

$(x = 1 \vee x = 3) \wedge$
 $(y = 1 \vee y = 2 \vee y = 3) \wedge$
 $(z = 3) \wedge$
 $\neg(x = y) \wedge$
 $\neg(x = z) \wedge$
 $\neg(y = z)$



$(p1 \vee p2) \wedge$
 $(p3 \vee p4 \vee p5) \wedge$
 $(p6) \wedge$
 $\neg p7 \wedge$
 $\neg p8 \wedge$
 $\neg p9$



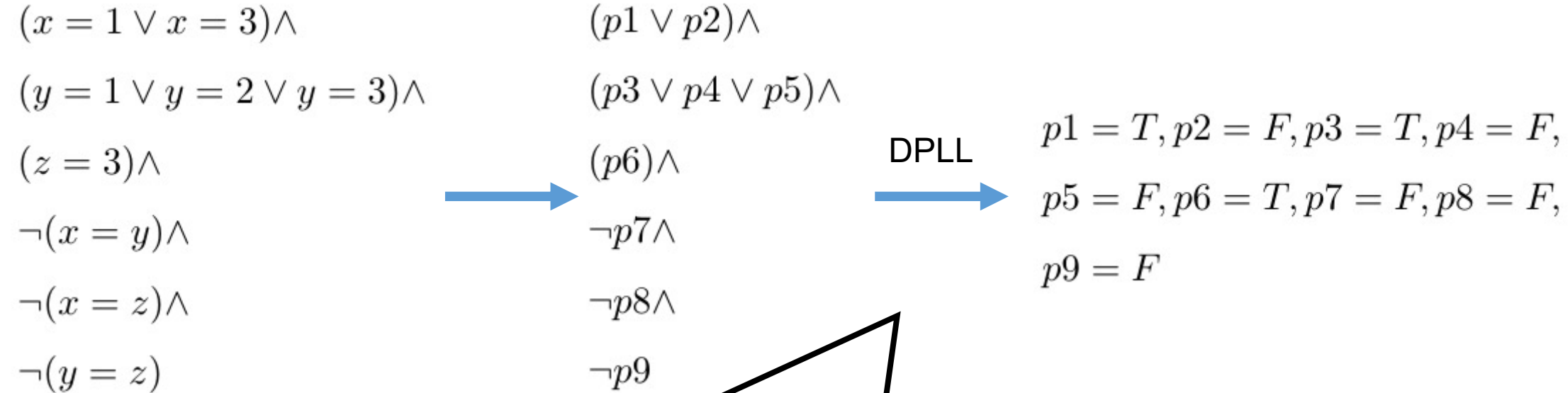
DPLL

UNSAT

If it is unsatisfiable,
the original formula is
also unsatisfiable.

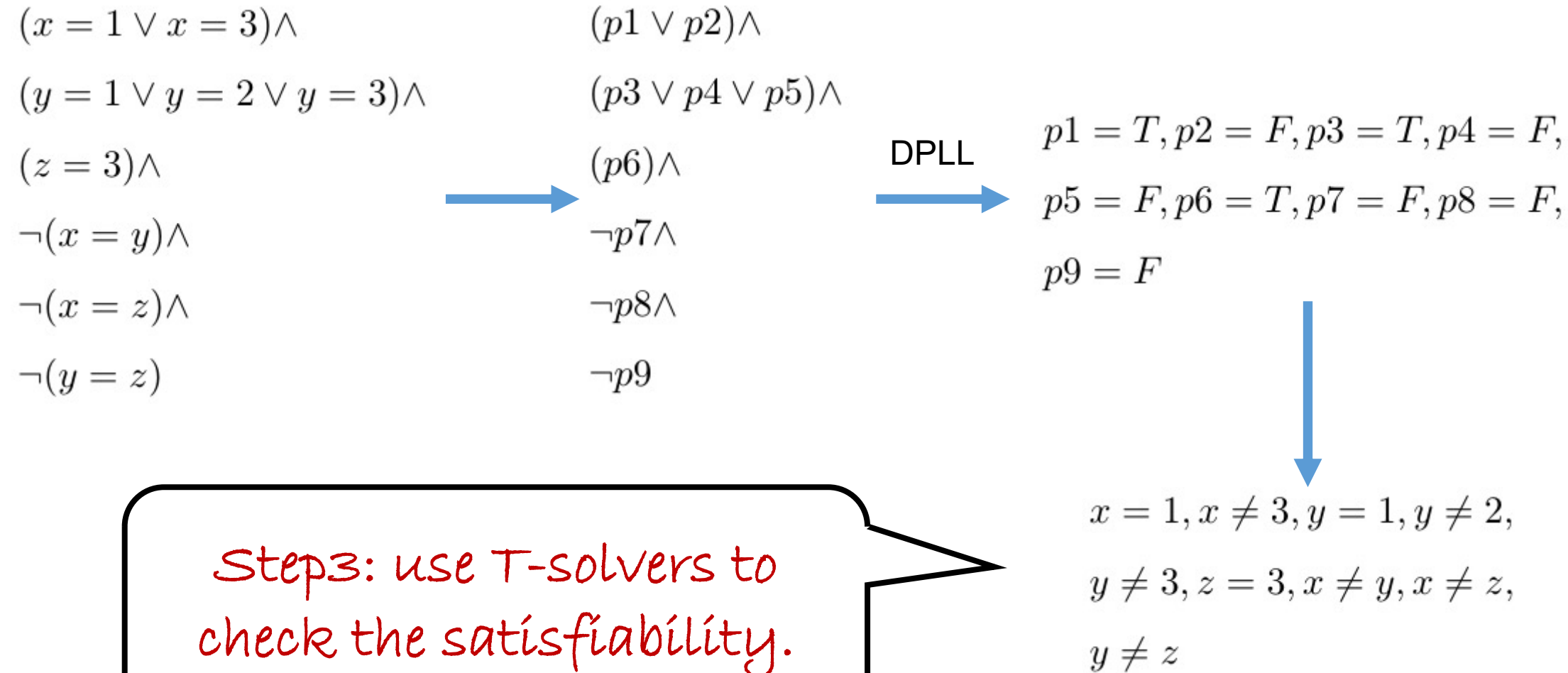
Step2: use SAT solvers to
get assignments.

Lazy SMT Techniques

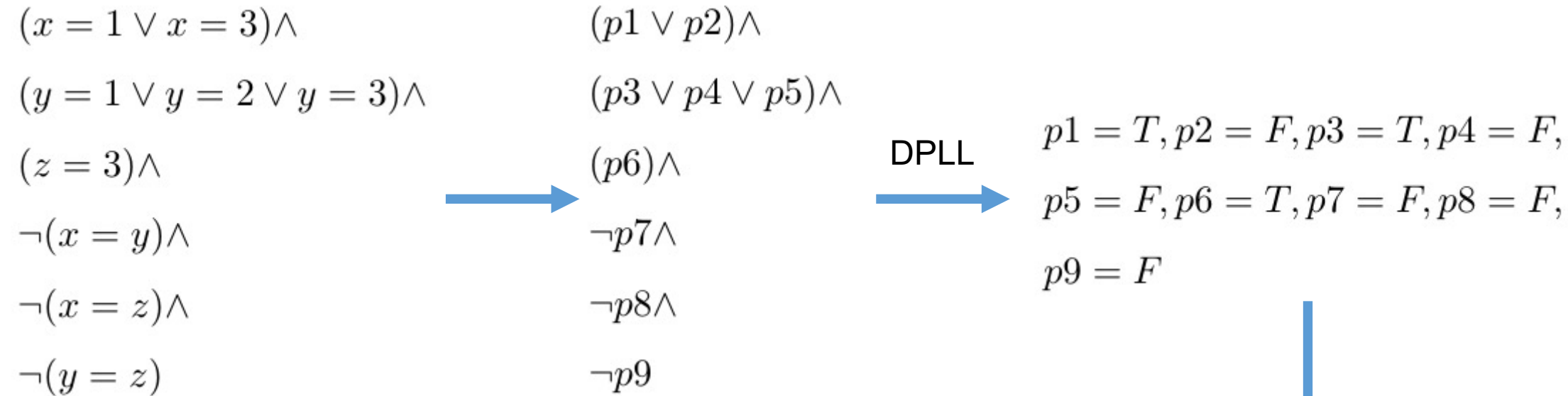


Step2: use SAT solvers to
get assignments.

Lazy SMT Techniques



Lazy SMT Techniques



Step3: use T-solvers to check the satisfiability.

$x = 1, x \neq 3, y = 1, y \neq 2,$
 $y \neq 3, z = 3, x \neq y, x \neq z,$
 $y \neq z$

FALSE

Lazy SMT Techniques

$(x = 1 \vee x = 3) \wedge$	$(p1 \vee p2) \wedge$
$(y = 1 \vee y = 2 \vee y = 3) \wedge$	$(p3 \vee p4 \vee p5) \wedge$
$(z = 3) \wedge$	$(p6) \wedge$
$\neg(x = y) \wedge$	$\neg p7 \wedge$
$\neg(x = z) \wedge$	$\neg p8 \wedge$
$\neg(y = z)$	$\neg p9$

DPLL

$p1 = T, p2 = F, p3 = T, p4 = F,$
 $p5 = F, p6 = T, p7 = F, p8 = F,$
 $p9 = F$

$x = 1, x \neq 3, y = 1, y \neq 2,$
 $y \neq 3, z = 3, x \neq y, x \neq z,$
 $y \neq z$

If it is unsatisfiable,
tell SAT solver to give
another assignment.

FALSE

Lazy SMT Techniques

$$\begin{array}{ll} (x = 1 \vee x = 3) \wedge & (p1 \vee p2) \wedge \\ (y = 1 \vee y = 2 \vee y = 3) \wedge & (p3 \vee p4 \vee p5) \wedge \\ (z = 3) \wedge & (p6) \wedge \\ \neg(x = y) \wedge & \neg p7 \wedge \\ \neg(x = z) \wedge & \neg p8 \wedge \\ \neg(y = z) & \neg p9 \end{array}$$

But how to tell the SAT solver this assignment doesn't work?

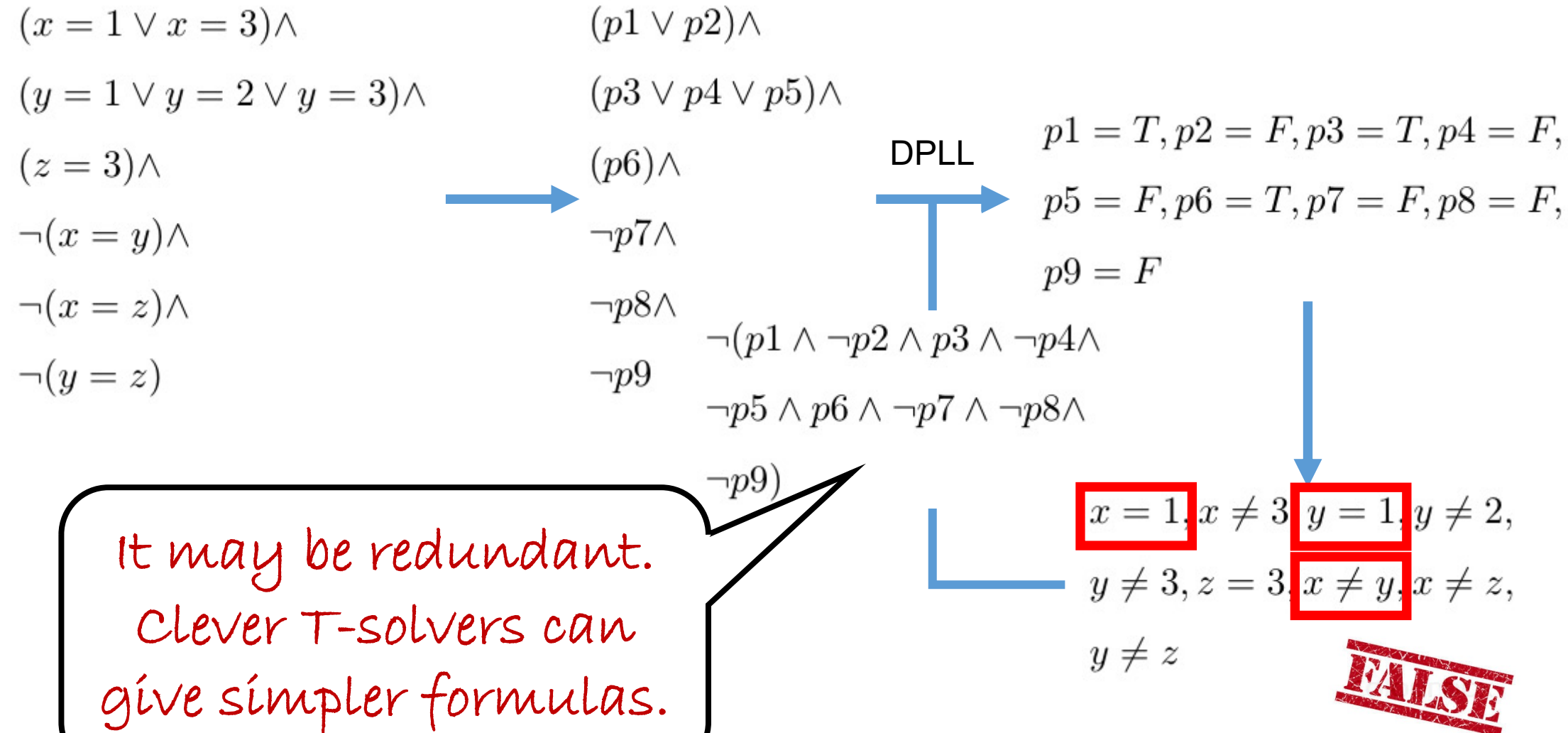
DPLL

$$\begin{array}{l} p1 = T, p2 = F, p3 = T, p4 = F, \\ p5 = F, p6 = T, p7 = F, p8 = F, \\ p9 = F \end{array}$$

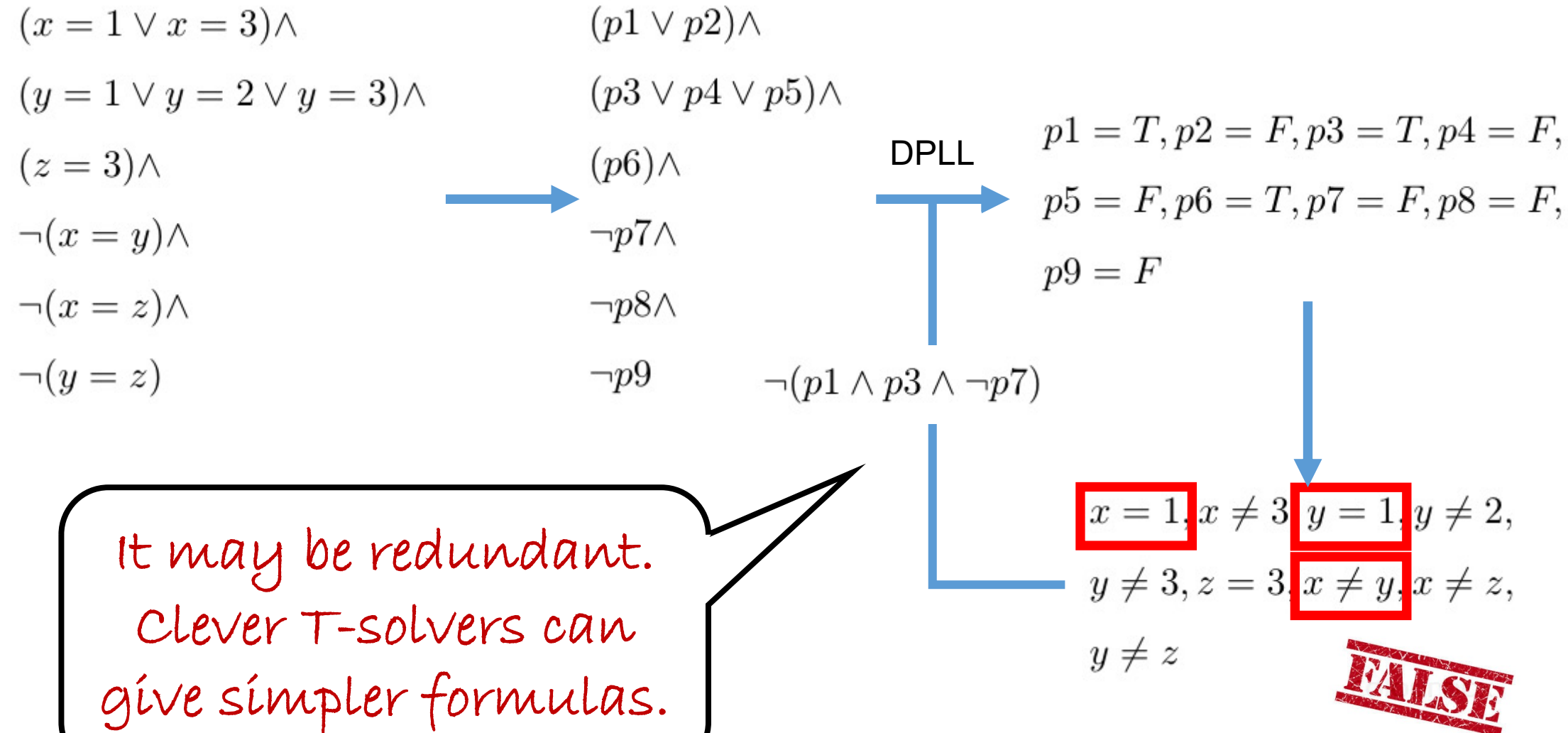
$$\begin{array}{l} x = 1, x \neq 3, y = 1, y \neq 2, \\ y \neq 3, z = 3, x \neq y, x \neq z, \\ y \neq z \end{array}$$

FALSE

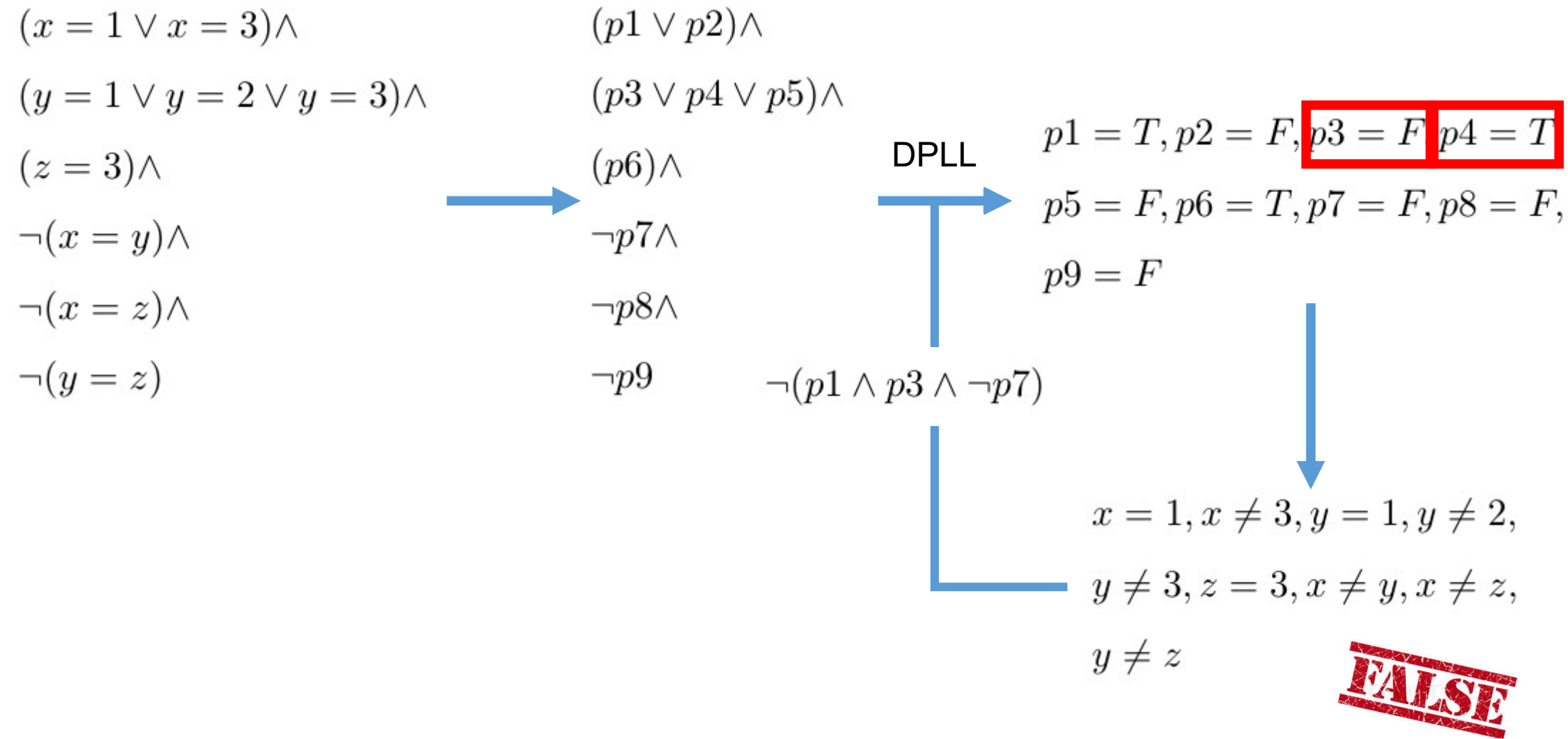
Lazy SMT Techniques



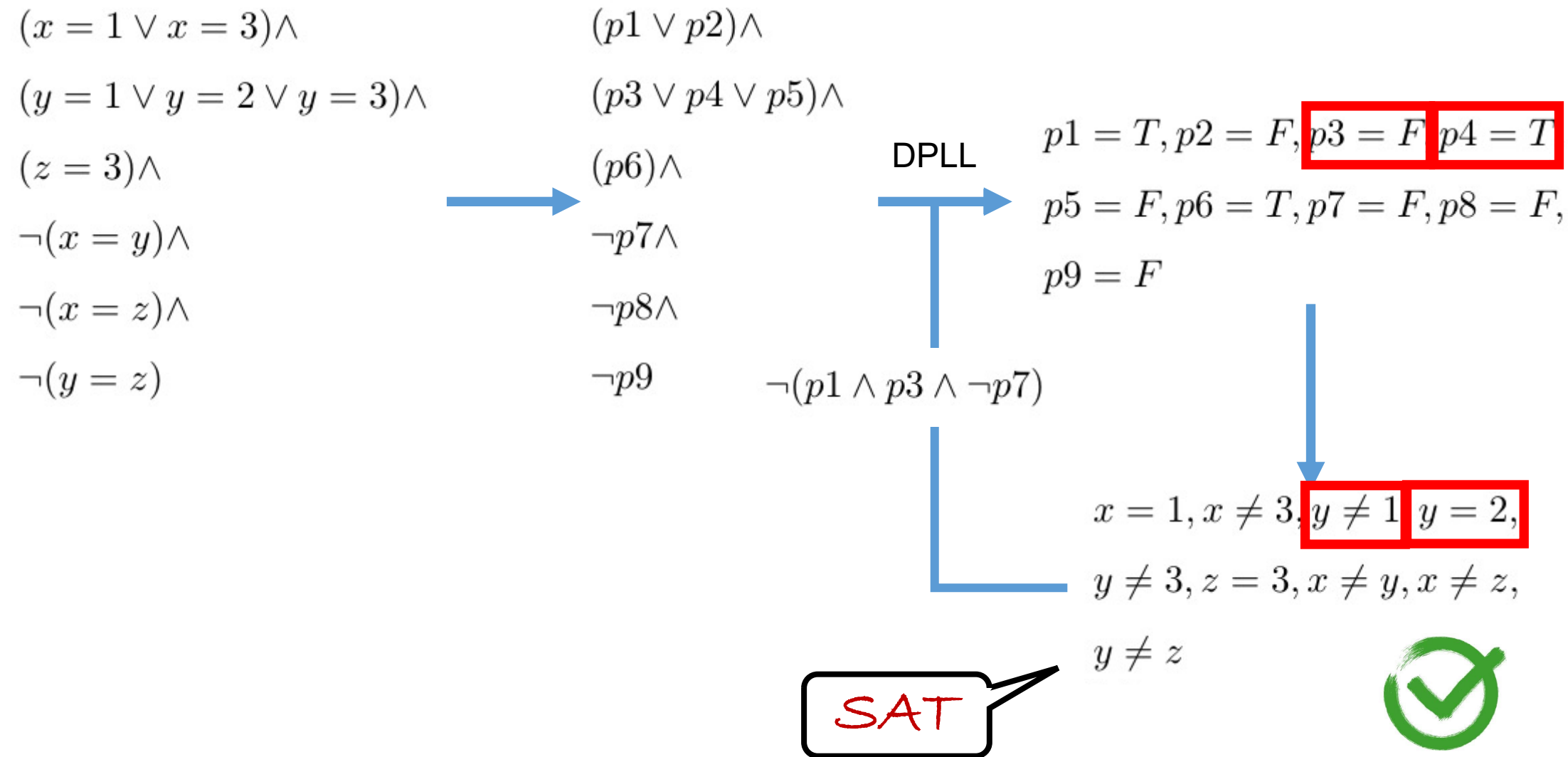
Lazy SMT Techniques



Lazy SMT Techniques

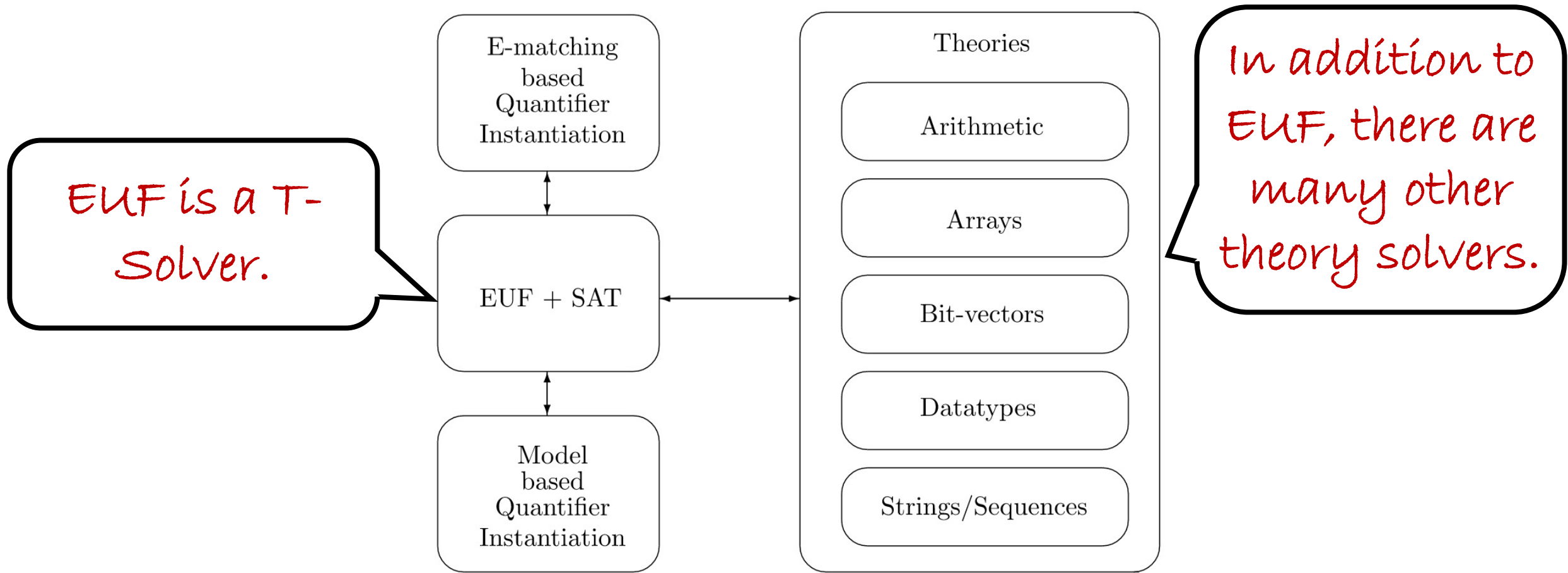


Lazy SMT Techniques



Lazy SMT Techniques

The main advantage of the lazy approach is its **flexibility**, since it can easily combine any SAT solver with any T-solver.



Architecture of Z3's SMT Core solver

Theory Solver

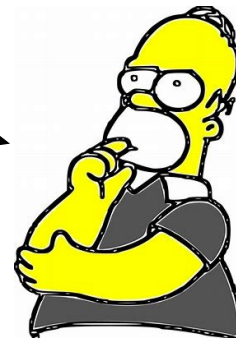
What does T-Solver looks Like?

EUUF

The logic of **equality and uninterpreted function**, EUF, is a basic ingredient for (first-order) predicate logic.

$$a = b, b = c, d = e, b = s, d = t$$

How to check if it is
satisfiable?



EUF

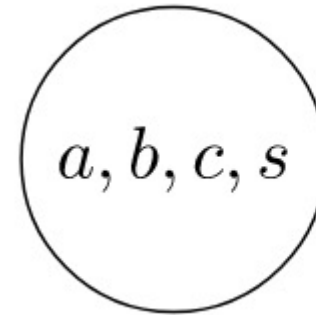
While formulas are not empty:

 remove $a=b$;

 merge(a, b);

$$a = b, b = c, d = e$$

$$b = s, d = t$$



EUF

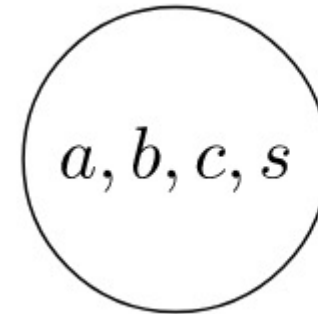
```
While formulas are not empty:  
    remove a=b;  
    merge(a, b);  
If find(a) = find(b) for some a≠b  
    return false;  
else  
    return true;
```

$$a = b, b = c, d = e$$

$$b = s, d = t$$



SAT



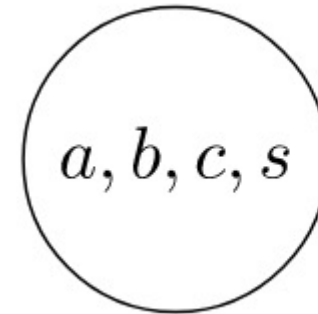
EUF

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If find(a) = find(b) for some a≠b  
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else  
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```

$$a = b, b = c, d = e$$

$$b = s, d = t, a \neq d$$

SAT

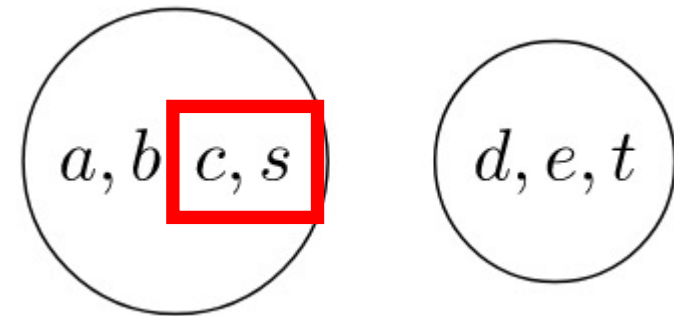


EUF

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While formulas are not empty:  
    remove a=b;  
    merge(a, b);  
If find(a) = find(b) for some a≠b  
    return false;  
else  
    return true;
```

$a = b, b = c, d = e$
 $b = s, d = t, c \neq s$

UNSAT



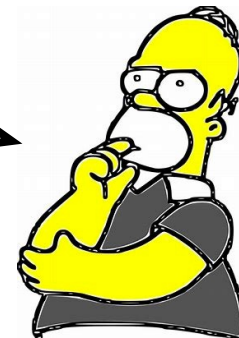
EUF

$$a = b, b = c, d = e$$

$$b = s, d = t$$

$$f(a, g(d)) \neq f(b, g(e))$$

What if there are
uninterpreted functions?



EUf

THEOREM

Congruence rule:

$$x_1 = y_1, \dots, x_n = y_n \Rightarrow f(x_1, \dots, x_n) = f(y_1, \dots, y_n)$$

$$a = b, b = c, d = e$$

$$b = s, d = t$$

$$f(a, g(d)) \neq f(b, g(e))$$

We can construct the
graph with
congruence rule.



EUF

1) introduce constants that can be used as shorthands for sub-terms.

$$a = b, b = c, d = e$$

$$b = s, d = t$$

$$f(a, g(d)) \neq f(b, g(e))$$



$$a = b, b = c, d = e$$

$$b = s, d = t, v3 \neq v4$$

$$v1 := g(e), v2 := g(d)$$

$$v3 := f(a, v2), v4 := f(b, v1)$$

EUF

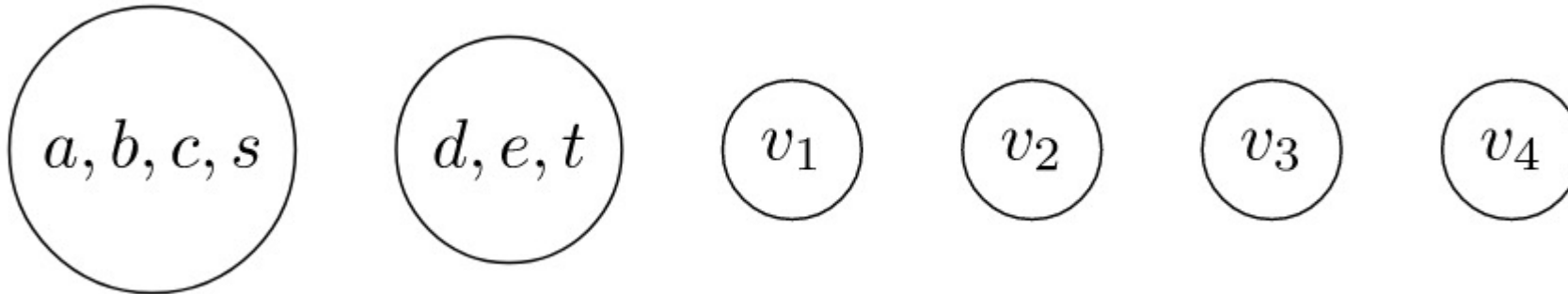
2) Working bottom-up, the congruence rule dictates how to merge groups

$$a = b, b = c, d = e$$

$$b = s, d = t, v3 \neq v4$$

$$v1 := g(e), v2 := g(d)$$

$$v3 := f(a, v2), v4 := f(b, v1)$$



EUF

2) Working bottom-up, the congruence rule dictates how to merge groups

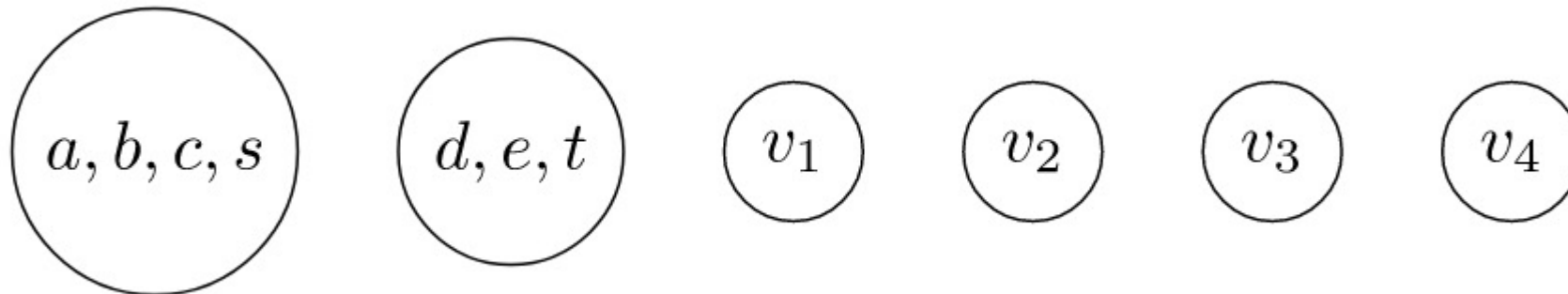
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$$v3 := f(a, v2), v4 := f(b, v1)$$

$$e = d \Rightarrow g(e) = g(d)$$



EUF

2) Working bottom-up, the congruence rule dictates how to merge groups

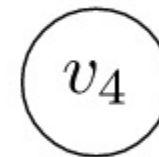
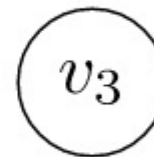
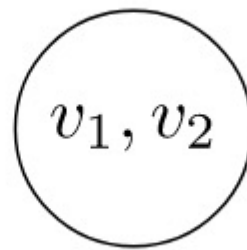
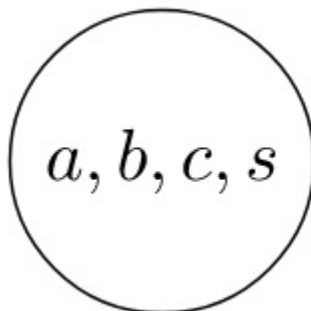
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EUF

2) Working bottom-up, the congruence rule dictates how to merge groups

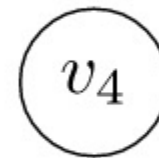
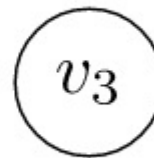
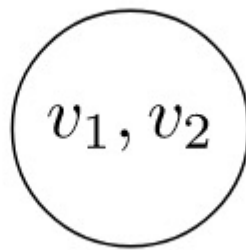
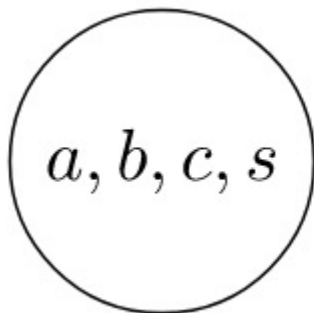
$$a = b, b = c, d = e$$

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$$v3 := f(a, v2), v4 := f(b, v1)$$

$$a = b, v2 = v1 \Rightarrow$$
$$f(a, v2) = f(b, v1)$$



EUF

2) Working bottom-up, the congruence rule dictates how to merge groups

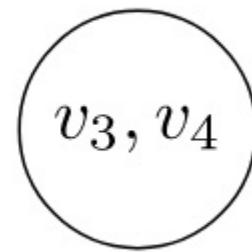
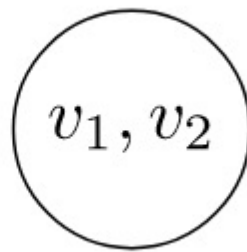
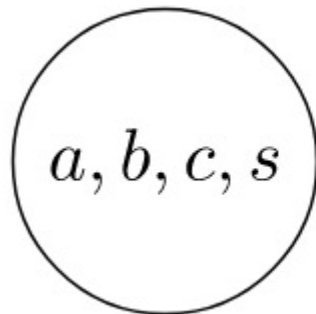
$$\begin{aligned} a = b, v2 = v1 &\Rightarrow \\ f(a, v2) = f(b, v1) \end{aligned}$$

$$a = b, b = c, d = e$$

$$b = s, d = t, v3 \neq v4$$

$$v1 := g(e), v2 := g(d)$$

$$v3 := f(a, v2), v4 := f(b, v1)$$



EUF

3) Check satisfiability like before

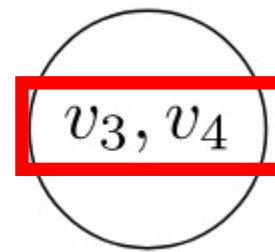
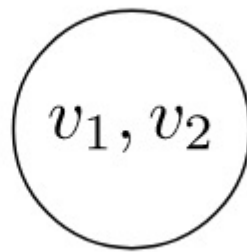
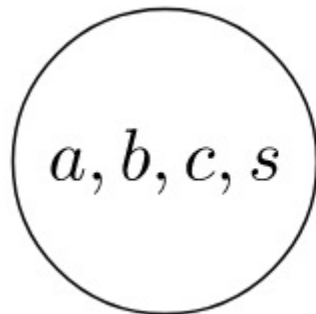
$$a = b, b = c, d = e$$

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$$v1 := g(e), v2 := g(d)$$

$$v3 := f(a, v2), v4 := f(b, v1)$$

UNSAT



Z3

$(x = 1 \vee x = 3) \wedge$

$(y = 1 \vee y = 2 \vee y = 3) \wedge$

$(z = 3) \wedge$

$(x \neq y) \wedge$

$(x \neq z) \wedge$

$(y \neq z)$

individuals

Predicate logic
formulas

Solve it and
return sat

```
context ctx;  
expr x = ctx.int_const("x");  
expr y = ctx.int_const("y");  
expr z = ctx.int_const("z");
```

```
solver s(ctx);  
s.add(x==1 || x==3);  
s.add(y==1 || y==2 || y==3);  
s.add(z==3);  
s.add(x != y);  
s.add(x != z);  
s.add(y != z);
```

```
if(s.check() == sat) cout << "sat";  
else cout << "unsat";
```

Thanks & Questions