

An Introduction to Satisfiability Modulo Theories

Philipp Rümmer

University of Regensburg
Uppsala University

February 11, 2025

Outline

- From theory ...
 - From DPLL to DPLL(T)
 - Slides courtesy of Alberto Griggio
- ... to practice
 - SMT-LIB and some common theories
 - <https://microsoft.github.io/z3guide/>
 - <https://cvc5.github.io/app/>
 - <https://eldarica.org/princess/>

Typical Applications of SMT

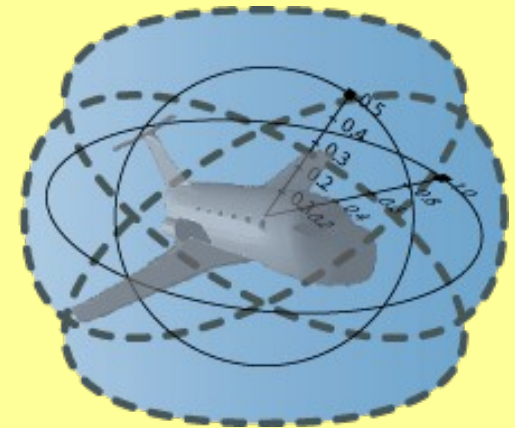
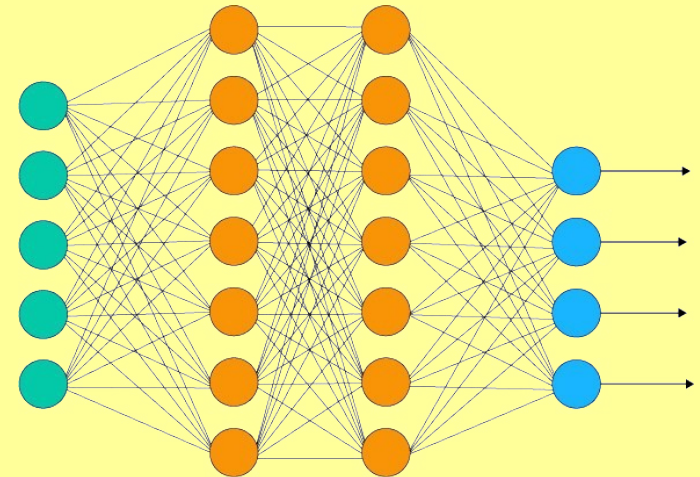
- Deductive program verification
 - Correctness of contracts, invariants
- Testing, symbolic execution
 - Path feasibility
- Bounded model checking
 - Reachability of errors within k steps
- Model checking
 - Computation of finite-state abstraction of programs

Broader Applications

$$(x > 3.0 \vee y < 2.0) \wedge \\ (x = y \vee x \neq y - 1.0) \wedge \\ y < 1.0$$



```
i = 0;  
x = j;  
while (i < 50) {  
    i++;  
    x++;  
}  
if (j == 0)  
    assert (x >= 50);
```



SAT and SMT

Def.: SAT Solver

Input: **Propositional** formula C
in n variables

Output: **C sat** + satisfying assignment (model)
C unsat [+ Proof]

Def.: SAT Modulo Theories Solver

Input: **First-order** formula C
in n variables and **theories** T_1, \dots, T_m

Output: **C sat** + satisfying assignment (model)
C unsat [+ Proof]

SAT and SMT

Def.: SAT Solver

Input: **Propositional** formula C
in n variables

Output: **C sat** + satisfying assignment (model)
 C unsat [+ Proof]

Also called a
solution

Def.: SAT Modulo Theories Solver

Input: **First-order** formula C
in n variables and **theories** T_1, \dots, T_m

Output: **C sat** + satisfying assignment (model)
 C unsat [+ Proof]

Theories

Definition (theory)

A (first-order) theory T is specified by a signature Σ_T of operations (sorts, functions, predicates), and a class \mathcal{S}_T of intended interpretations of the symbols in Σ_T .

- A theory is like a library:
 - Data-types
 - Operations on those data-types
- Various examples later

We know how to ...

Solve **Boolean formulas** efficiently:

- DPLL, CDCL
- Implemented in SAT solvers

Solve **theory constraints** efficiently:

- Linear arithmetic: LP, ILP, MIP
- Finite domains: CP, local search
- *etc.*

We know how to ... ???

Solve **Boolean formulas** efficiently:

- DPLL, CDCL
- Implemented in SAT solvers



Solve **theory constraints** efficiently:

- Linear arithmetic: LP, ILP, MIP
- Finite domains: CP, local search
- *etc.*

Example!

- **How can we solve this formula?**

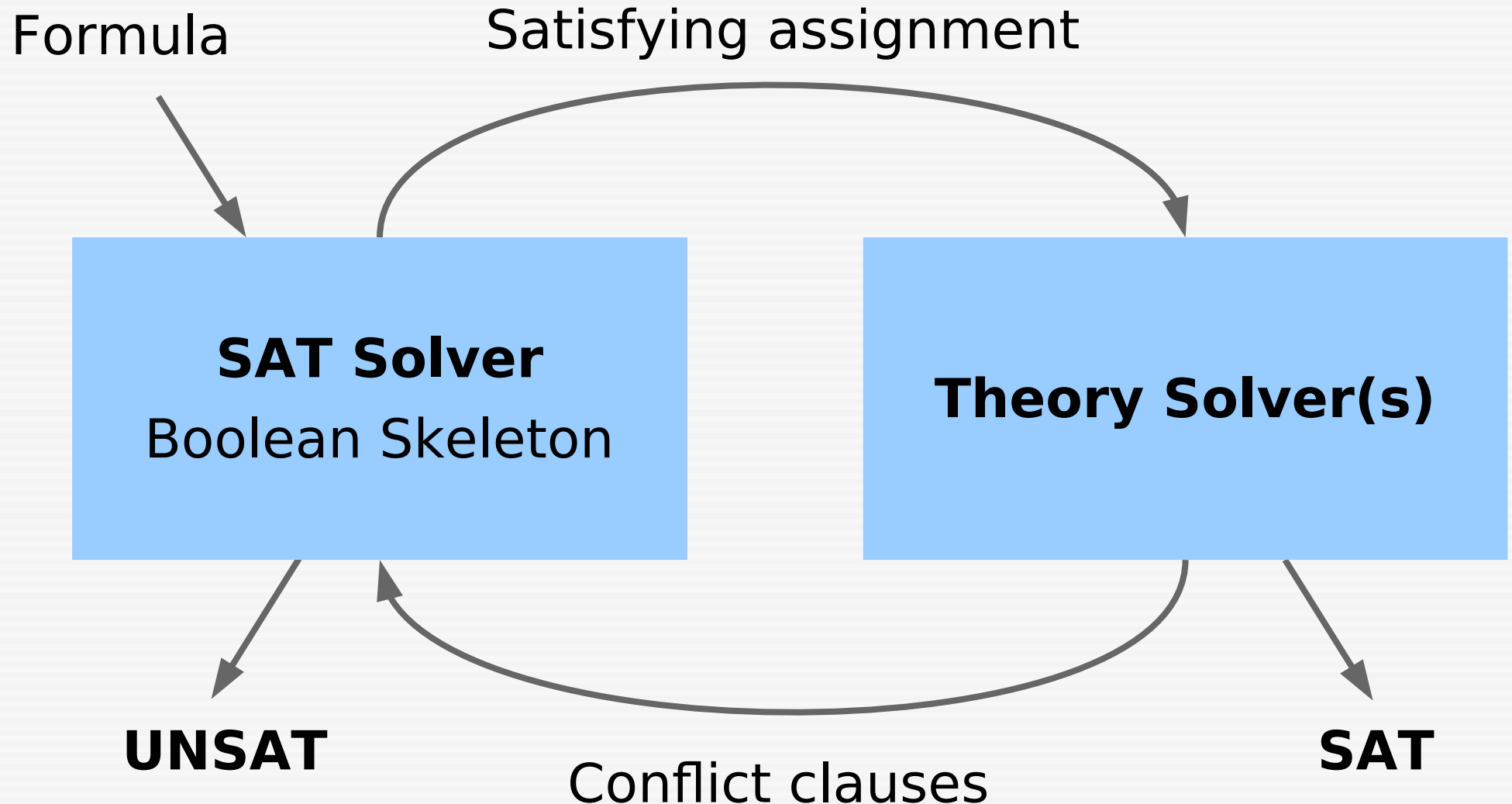
Eager SMT

- Wide range of data-types can directly be encoded in propositional logic:
 - Bit-vectors/machine arithmetic
 - Equality logic
 - Integer arithmetic (*how?*)
- Approach pioneered by UCLID (2004)
- Today mostly used for bit-vectors

Lazy, Offline SMT

- Construct a **Boolean** skeleton of a formula, and solve it using SAT
- **UNSAT** → Finished!
- **SAT** → Check consistency of assigned theory literals
→ Produce a **model** or **refine skeleton**

Lazy, Offline SMT



Lazy, **Online** SMT

- Tightly interleave/integrate **Boolean** and **theory** reasoning
 - SAT solver informs theory solvers each time a literal is asserted
→ **incremental** theory solving
 - Theory solver informs SAT solver when there is a **conflict**
 - + *Some further refinements*
- Formalised in the **DPLL(T)** algorithm
[Nieuwenhuis, Oliveras, Tinelli, 2006]

The DPLL(T) Loop

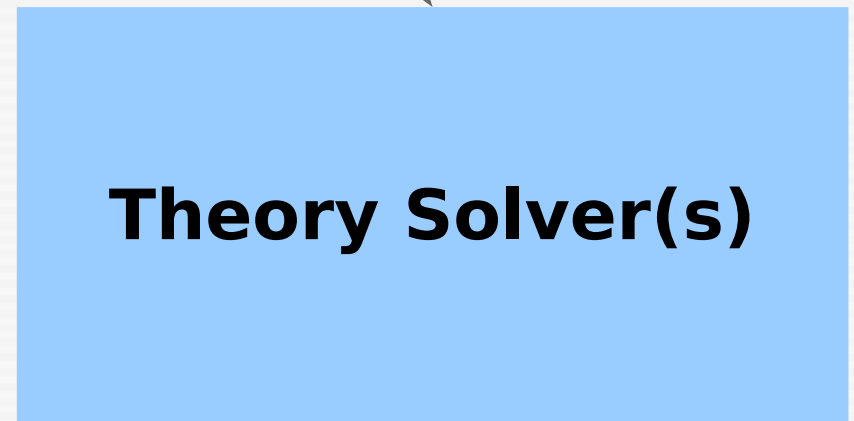
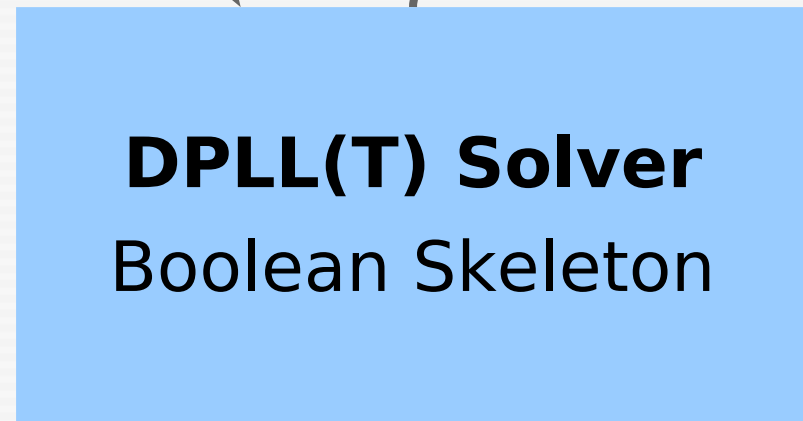
Inform about literals

Assert literals (decision/propagation)

Check conjunction of asserted literals

Backtrack

Formula



SAT/UNSAT

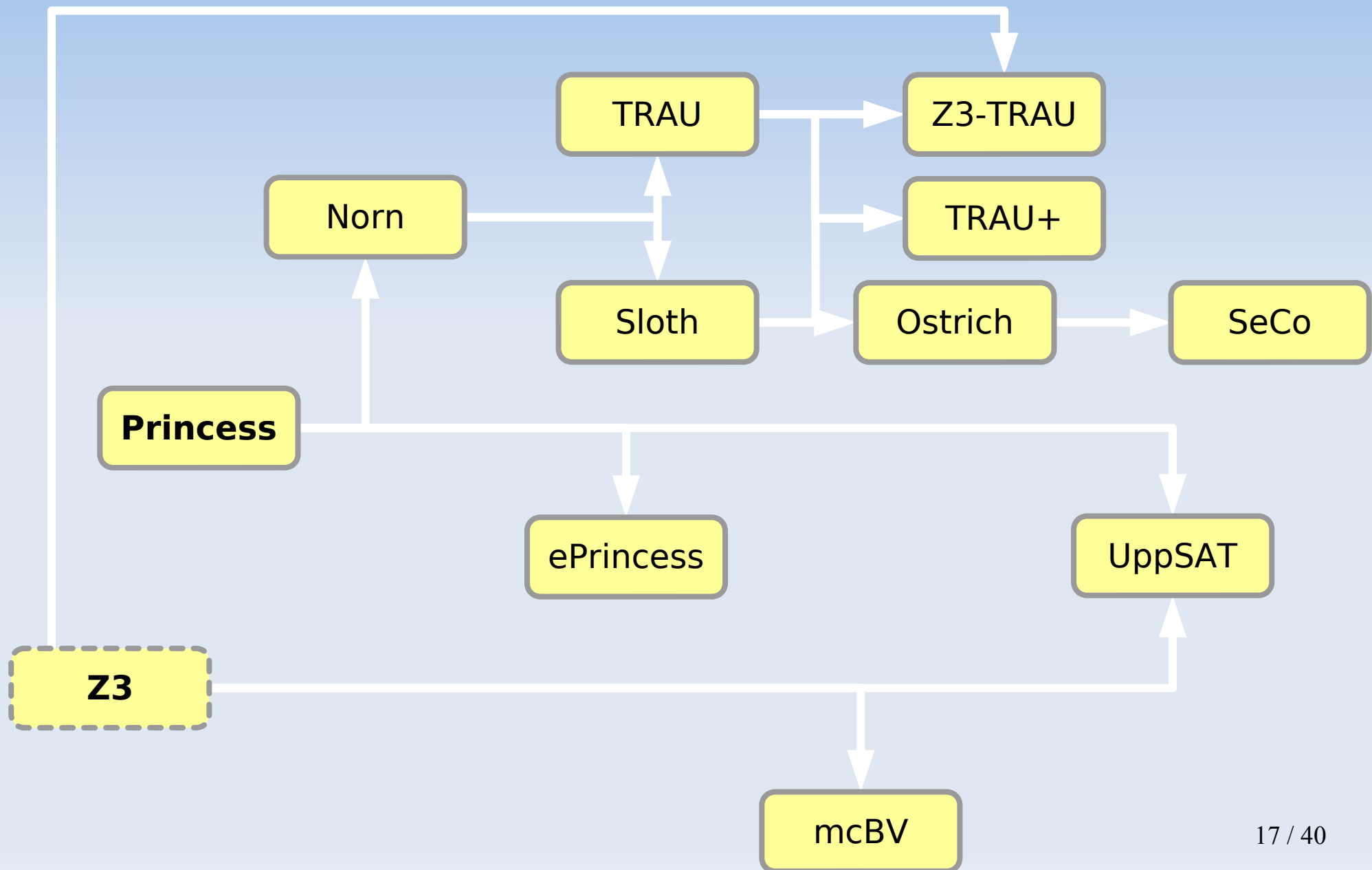
Conflict sets
Implied literals

On to the other slide set ...

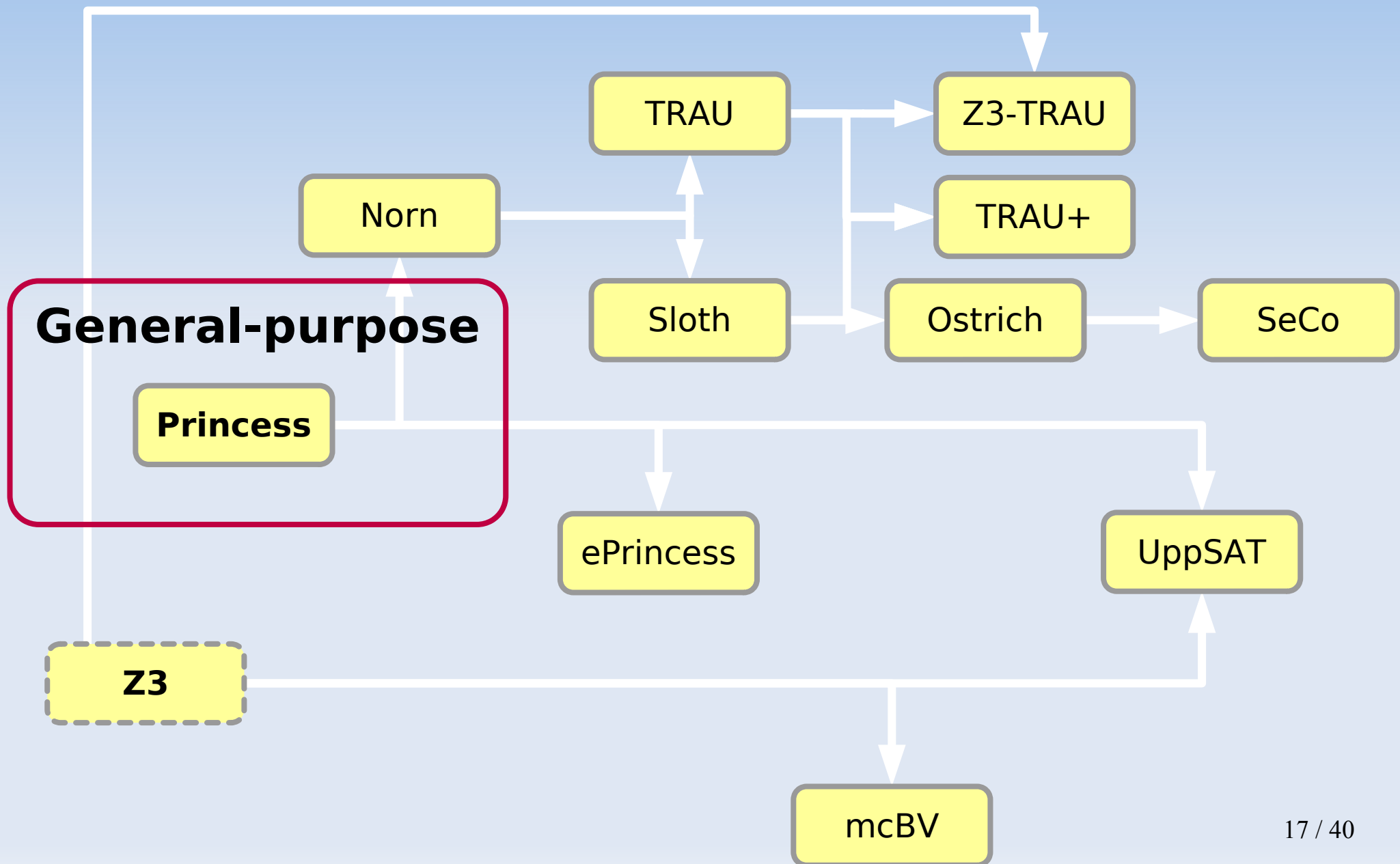
Some SMT solvers

- Z3
- cvc5
- MathSAT
- Yices
- OpenSMT
- Bitwuzla
- SMTInterpol

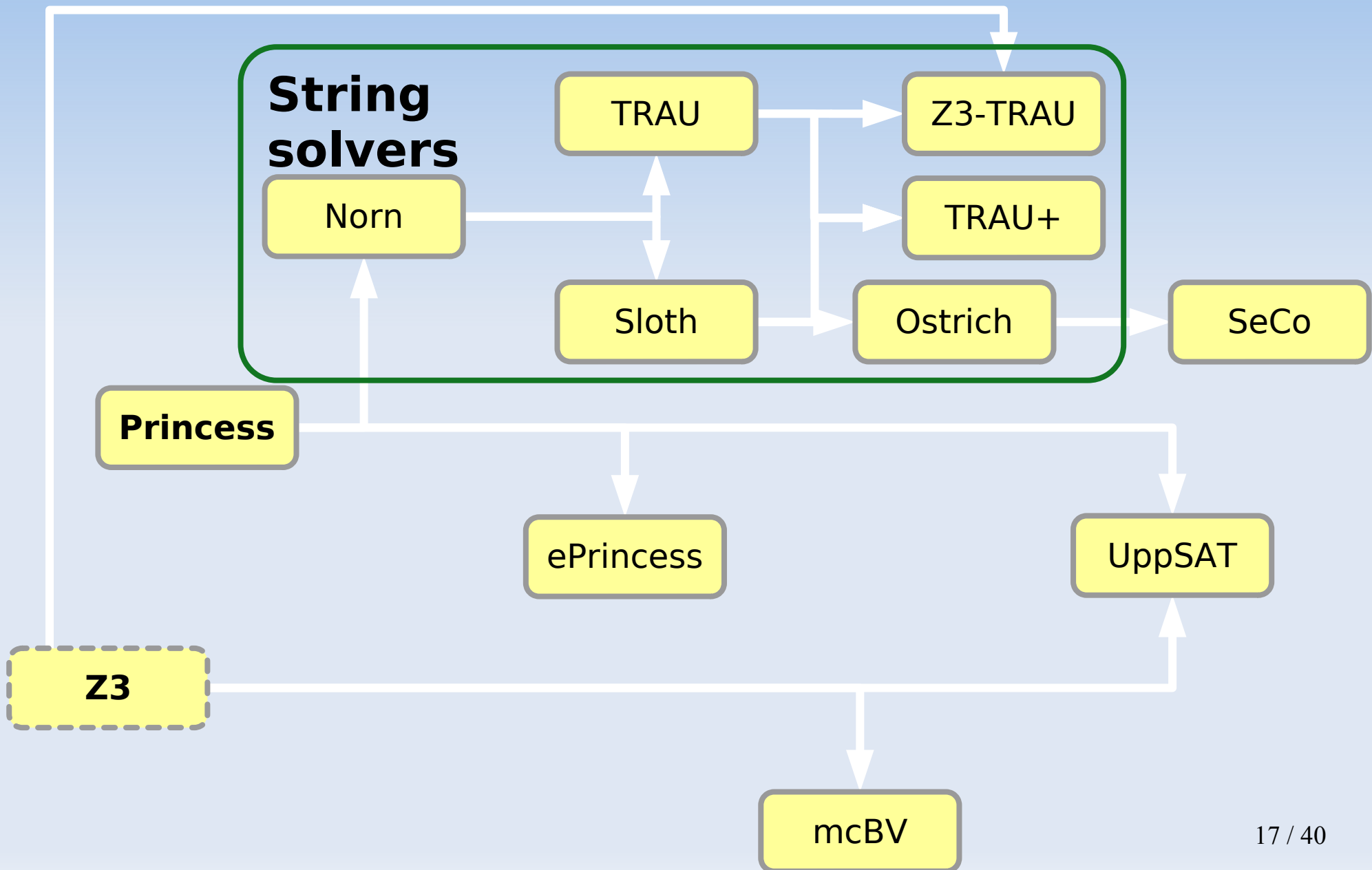
SMT in Uppsala / Regensburg



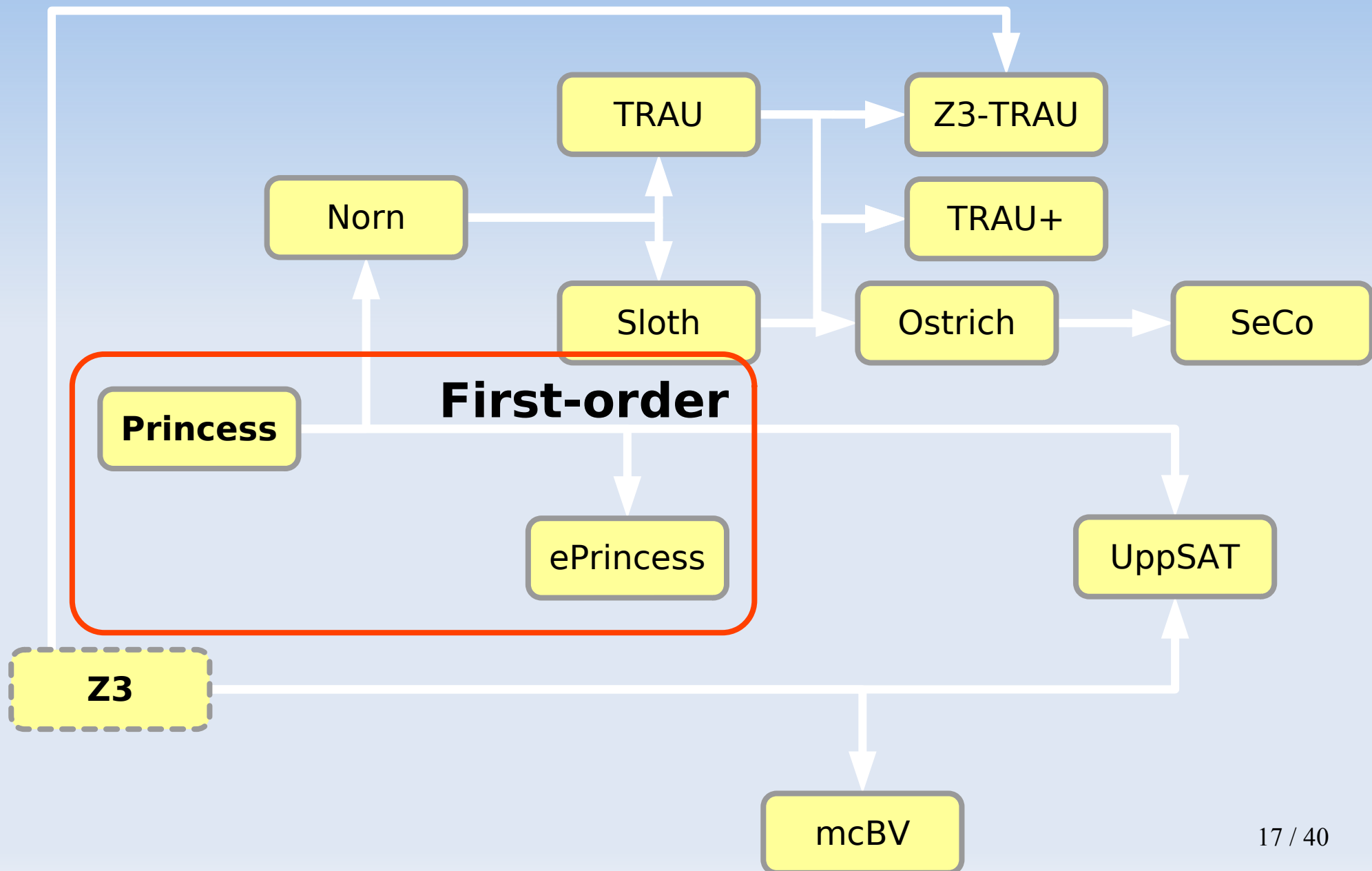
SMT in Uppsala / Regensburg



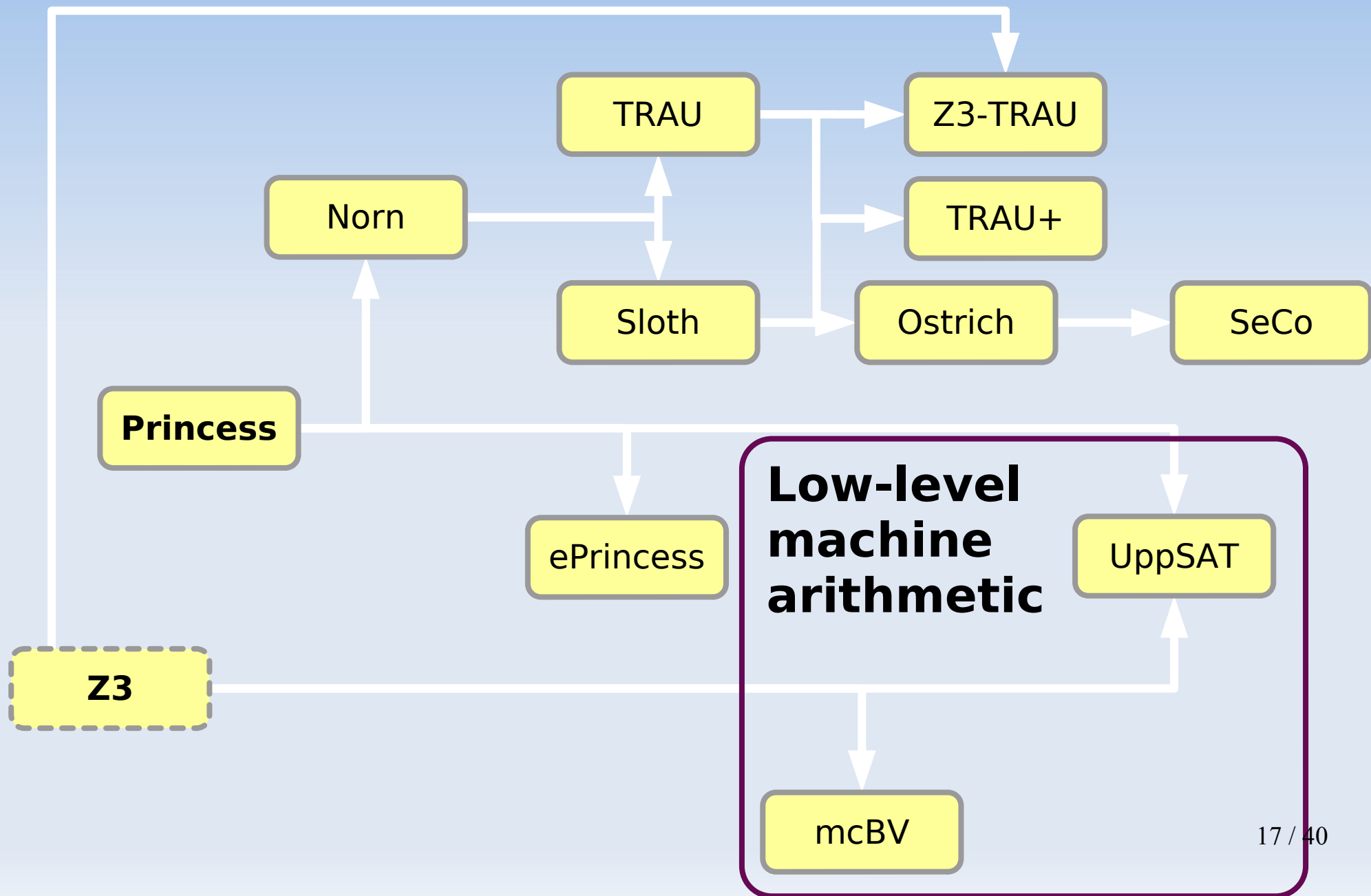
SMT in Uppsala / Regensburg



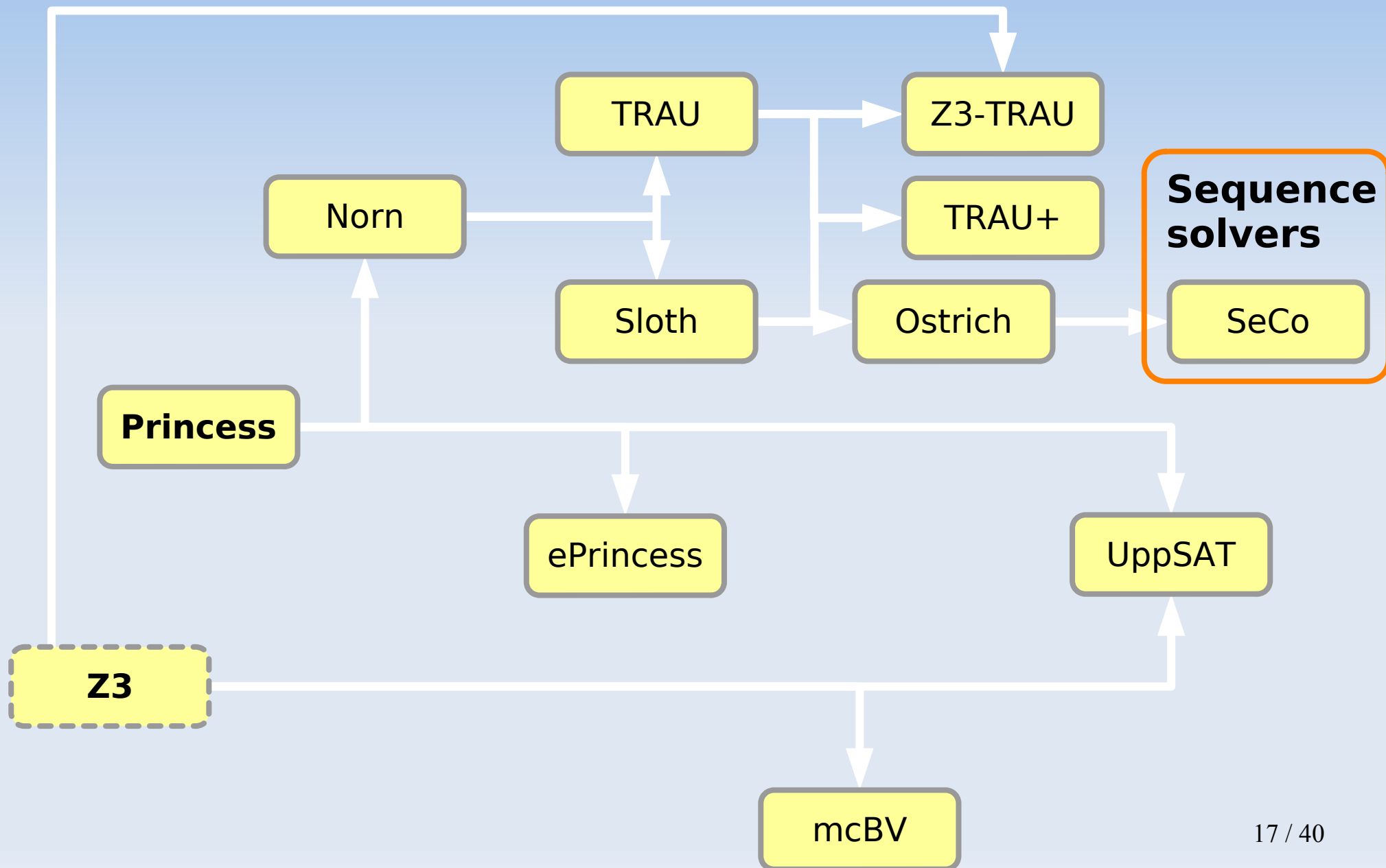
SMT in Uppsala / Regensburg



SMT in Uppsala / Regensburg



SMT in Uppsala / Regensburg



The SMT-LIB Standard

Version 2.6

Clark Barrett

Pascal Fontaine

Cesare Tinelli

Release: 2017-07-18

SMT-LIB

- Standardised interface for SMT solvers, supported by most tools
- Rich set of features, many theories
- Comes with a large library of benchmarks; annual competition SMT-COMP
- <http://www.smtlib.org>

SMT-LIB Version 2.7

- **Released February 5 2025!**
- Some new features:
 - Polymorphic sorts and functions
 - Higher-order logic syntax, lambdas

Example 1

$$2y - z > 2 \vee p$$

$$3x - z > 6 \vee \neg p$$

$$2z - 4y > 5 \vee p$$

$$y - z \not> 6 \vee \neg p$$

In SMT-LIB

```
(set-logic QF_LIA)

(declare-const p Bool)
(declare-const x Int)
(declare-const y Int)
(declare-const z Int)

(assert (or (> (- (* 2 y) z) 2) p))
(assert (or (> (- (* 3 x) z) 6) (not p)))
(assert (or (> (- (* 2 z) (* 4 y)) 5) p))
(assert (or (not (> (- y z) 6)) (not p)))

(check-sat)
(get-model)
```

Permalink:

https://eldarica.org/princess/?ex=perma%2F1644243468_187318180

Important SMT-LIB commands

- `(set-logic QF_BV)`
`(set-option ...)`
- `(declare-const b (_ BitVec 8))`
`(declare-fun f ((x (_ BitVec 2))) Bool)`
- `(assert (= b #b10100011))`
- `(check-sat)`
- `(get-value (b)), (get-model)`
- `(get-unsat-core)`
- `(push 1), (pop 1)`
- `(reset), (exit)`

Important SMT-LIB commands

- `(set-logic QF_BV)`
`(set-option ...)`
- `(declare-const b (_ BitVec 8))`
`(declare-fun f ((x (_ BitVec 2))) Bool)`
- `(assert (= b #b10100011))`
- `(check-sat)`
- `(get-value (b)), (get-model)`
- `(get-unsat-core)`
- `(push 1), (pop 1)`
- `(reset), (exit)`

Z3, and many
solvers don't
care ...

Important SMT-LIB commands

- `(set-logic QF_BV)`
`(set-option ...)`
- `(declare-const b (_ BitVec 8))`
`(declare-fun f ((x (_ BitVec 2))) Bool)`
- `(assert (= b #b10100011))`
- `(check-sat)`
- `(get-value (b)), (get-model)`
- `(get-unsat-core)`
- `(push 1), (pop 1)`
- `(reset), (exit)`

Z3, and many solvers don't care ...

In CP or MIP, this would be called
assume or
constraint

General SMT-LIB constructors

- `(and ...) , (or ...) , (not ...) , (\Rightarrow ...)`
- `(= b c)`
- `(ite (= b c) #b101 #b011)`
- `(let ((a #b001) (b #b010)) (= a b))`
- `(exists ((x (_ BitVec 2))) (= #b101 x))`
`(forall ...)`
- `(! (= b c) :named X)`

Example 2

Example 2

- Every 32bit number x that is a power of 2 has the property that

$$x \ \& \ (x - 1) == 0$$

(and vice versa)

Quantifying Satisfaction?

- SAT/SMT solvers check **satisfiability**:

$$\phi[x, y, z] \text{ is sat} \iff \exists x, y, z. \phi[x, y, z] \text{ is sat}$$

- How to prove a universal property?

$$\forall x, y, z. \phi[x, y, z] \text{ is valid?}$$

Quantifying Satisfaction?

- SAT/SMT solvers check **satisfiability**:

$$\phi[x, y, z] \text{ is sat} \iff \exists x, y, z. \phi[x, y, z] \text{ is sat}$$

- How to prove a universal property?

$$\forall x, y, z. \phi[x, y, z] \text{ is valid?}$$

$$\forall x, y, z. \phi[x, y, z] \text{ is valid}$$

$$\iff \neg \forall x, y, z. \phi[x, y, z] \text{ is unsat}$$

$$\iff \exists x, y, z. \neg \phi[x, y, z] \text{ is unsat}$$

$$\iff \neg \phi[x, y, z] \text{ is unsat}$$

In SMT-LIB

```
(set-logic QF_BV)

(declare-const e (_ BitVec 32))
(declare-const x (_ BitVec 32))

(assert (= x (bvshl #x00000001 e)))
(assert (not (= (bvand x (bvsb x #x00000001)) #x00000000)))

(check-sat)
```

Permalink

https://eldarica.org/princess/?ex=perma%2F1644322914_843217432

41/57

Main SMT-LIB Bit-vector ops.

http://smtlib.cs.uiowa.edu/logics-all.shtml#QF_BV

- `(_ BitVec 8)`
- `#b1010, #xff2a, (_ bv42 32)`
- `(= (concat #b1010 #b0011) #b10100011)`
- `(= ((_ extract 1 3) #b10100011) #b010)`
- **Unary:** `bvnot, bvneg`
- **Binary:** `bvand, bvor, bvadd, bvsub, bvmul, bvudiv, bvurem, bvshl, bvlsr`
- `(bvult #b0100 #b0110)`
- *And many more derived operators ...*

Example 3: Programs

```
int x, y;
```

```
x = x * x;
```

```
y = x + 1;
```

```
assert(y > 0);
```

Example 3: Programs

```
int x, y;
```

```
x = x * x;
```

```
y = x + 1;
```

```
assert(y > 0);
```

Z3-specific

```
(set-option :pp.bv-literals false)
```

```
(declare-const x0 (_ BitVec 32))
```

```
(declare-const y0 (_ BitVec 32))
```

```
(declare-const x1 (_ BitVec 32))
```

```
(declare-const y1 (_ BitVec 32))
```

```
(assert (= x1 (bvmul x0 x0)))
```

```
(assert (= y1 (bvadd x1 (_ bv1 32))))
```

```
(assert (not (bvsgt y1 (_ bv0 32))))
```

```
(check-sat)
```

```
(get-model)
```

Signed
comparison

Example 3: Programs

```
int x, y;
```

```
x = x * x;
```

```
y = x + 1;
```

```
assert(y > 0);
```

Z3-specific

```
(set-option :pp.bv-literals false)
```

```
(declare-const x0 (_ BitVec 32))
```

```
(declare-const y0 (_ BitVec 32))
```

```
(declare-const x1 (_ BitVec 32))
```

```
(declare-const y1 (_ BitVec 32))
```

```
(assert (= x1 (bvmul x0 x0)))
```

```
(assert (= y1 (bvadd x1 (_ bv1 32))))
```

```
(assert (not (bvsgt y1 (_ bv0 32))))
```

```
(check-sat)
```

```
(get-model)
```

Signed
comparison

Permalink:

<https://eldarica.org/princess/?ex=perma%2F16442436>

Modelling of Program Variables

- An SMT-LIB constant represents a **single** value
 - Just like mathematical variables
- Program variables can be reassigned ... how to model computations?
- Main idea: every assignment creates a new “version” of a variable
 - x_0/y_0 vs. x_1/y_1 in example

Modelling of Program Variables

- An SMT-LIB constant represents a **single** value
 - Just like mathematical variables
- Program variables can be reassigned ... how to model computations?
- Main idea: every assignment creates a new “version” of a variable
 - x_0/y_0 vs. x_1/y_1 in example

In compilers, this is called “Single Static Assignment” form (SSA)

Example 4: Conditionals

```
int x, y;
```

```
if (x > 0)
```

```
    y = x;
```

```
else
```

```
    y = -x;
```

```
assert(y >= 0);
```

Example 4: Conditionals

```
int x, y;  
  
if (x > 0)  
    y = x;  
else  
    y = -x;  
  
assert(y >= 0);
```

```
(set-option :pp.bv-literals false)  
  
(declare-const x0 (_ BitVec 32))  
(declare-const y0 (_ BitVec 32))  
(declare-const y1a (_ BitVec 32))  
(declare-const y1b (_ BitVec 32))  
(declare-const y2 (_ BitVec 32))  
(declare-const b Bool)  
  
(assert (= b (bvsgt x0 (_ bv0 32))))  
(assert (=> b (= y1a x0)))  
(assert (=> (not b) (= y1b (bvneg x0))))  
(assert (= y2 (ite b y1a y1b)))  
  
(assert (not (bvsge y2 (_ bv0 32))))  
  
(check-sat)  
(get-model)
```

Example 4: Conditionals

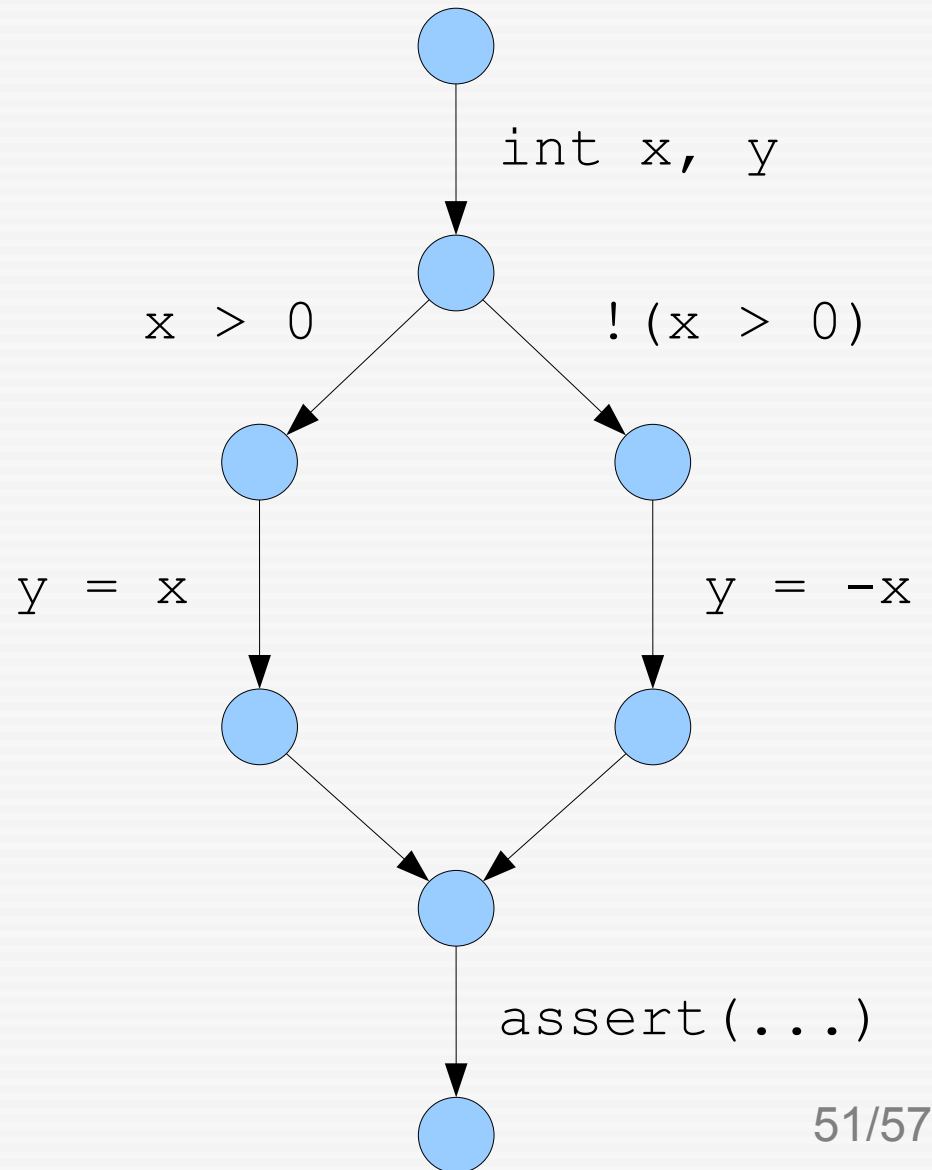
```
int x, y;  
  
if (x > 0)  
    y = x;  
else  
    y = -x;  
  
assert(y >= 0);
```

```
(set-option :pp.bv-literals false)  
  
(declare-const x0    (_ BitVec 32))  
(declare-const y0    (_ BitVec 32))  
(declare-const y1a   (_ BitVec 32))  
(declare-const y1b   (_ BitVec 32))  
(declare-const y2    (_ BitVec 32))  
(declare-const b     Bool)  
  
(assert (= b (bvsgt x0 (_ bv0 32))))  
(assert (=> b      (= y1a x0)))  
(assert (=> (not b) (= y1b (bvneg x0))))  
(assert (= y2 (ite b y1a y1b)))  
  
(assert (not (bvsge y2 (_ bv0 32))))  
  
(check-sat)  
(get-model)
```

Permalink:

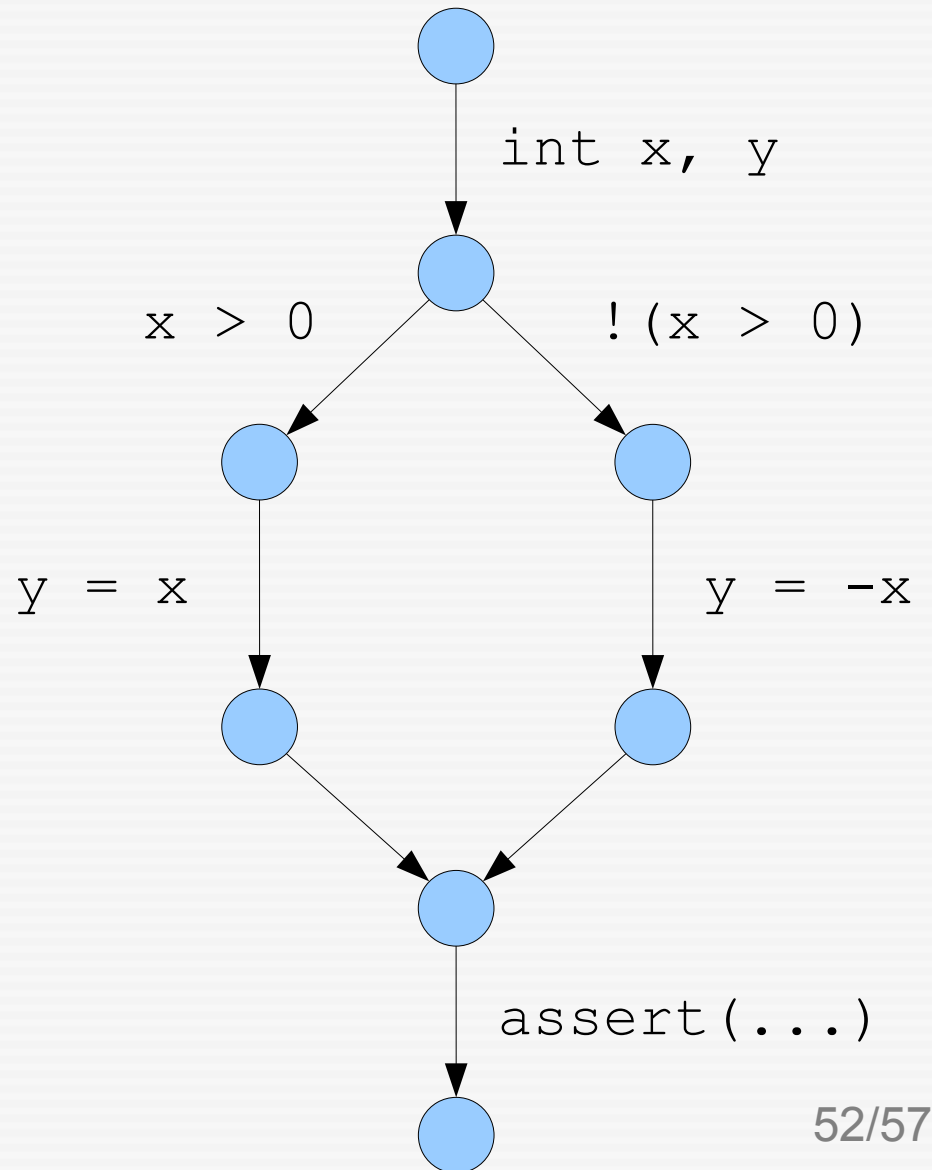
https://eldarica.org/princess/?ex=perma%2F1644243661_2074758304

Alternative method: path-wise exploration



Alternative method: path-wise exploration

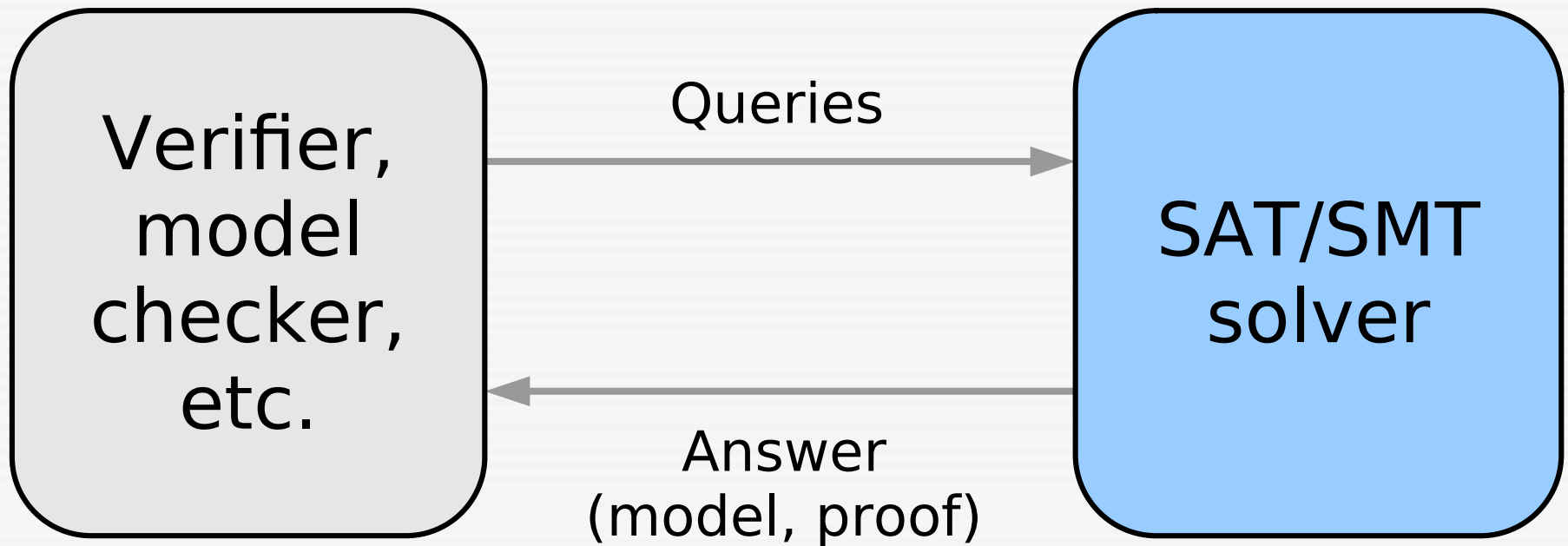
- Each query smaller, but possibly exponentially many paths
- Learning similar to CDCL can be used to avoid analysing all paths



The assertion stack

- Holds both assertions and declarations, but no options
- Important for incremental use of solver
- `(push n)` → add n new frames to the stack
- `(pop n)` → pop n frames from the stack

Typical Architecture



Example 5: Functions

- Every monotonic function

$$f : \{0, 1\} \rightarrow \{0, 1\}$$

is idempotent:

$$f \circ f = f$$

In SMT-LIB

```
(declare-fun f (Int) Int)

(assert (forall ((x Int))
  (=> (and (<= 0 x) (< x 2))
    (and (<= 0 (f x)) (< (f x) 2)))))

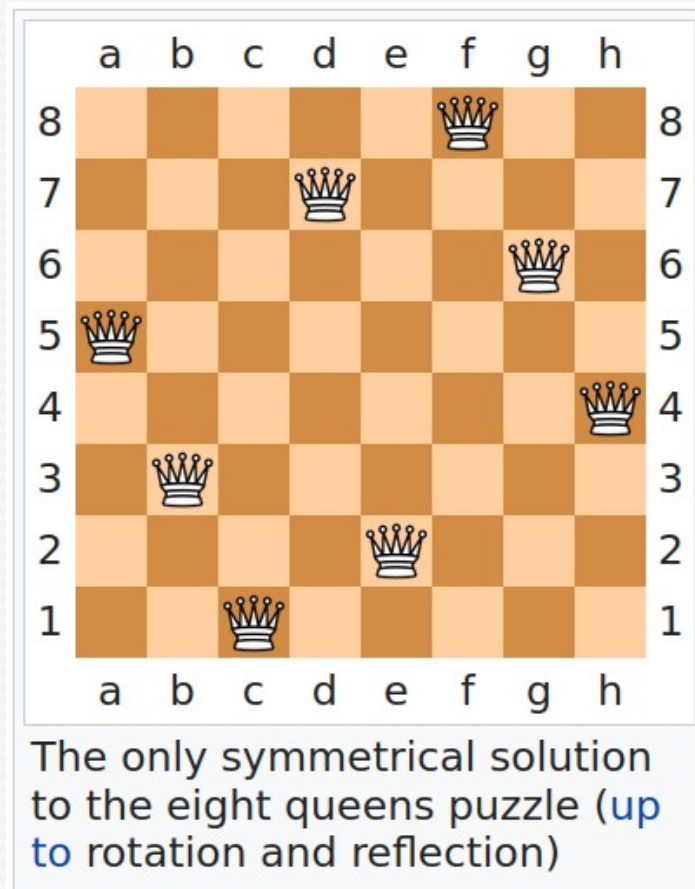
(assert (<= (f 0) (f 1)))

(assert (not (forall ((x Int))
  (=> (and (<= 0 x) (< x 2))
    (= (f (f x)) (f x)))))

(check-sat)
```

Example 6

- N -queens problem using SMT



[Wikipedia]

In SMT-LIB

```
(define-fun N () Int 4)
```

```
(declare-const q0 Int)
(declare-const q1 Int)
(declare-const q2 Int)
(declare-const q3 Int)
```

```
(assert (and (>= q0 0) (< q0 N)))
(assert (and (>= q1 0) (< q1 N)))
(assert (and (>= q2 0) (< q2 N)))
(assert (and (>= q3 0) (< q3 N)))
```

```
(assert (distinct q0 q1 q2 q3))
(assert (distinct (+ q0 0) (+ q1 1) (+ q2 2) (+ q3 3)))
(assert (distinct (- q0 0) (- q1 1) (- q2 2) (- q3 3)))
```

```
(check-sat)
```

Permalink:

https://eldarica.org/princess/?ex=perma%2F1668764522_925741057

Conclusions

- Most important idea in this lecture:
Lazy encoding of formulas to SAT
- SMT solvers are ...
 - Usually optimised for verification:
Good at proving unsat
 - Able to handle infinite domains:
Arithmetic, arrays, strings, etc.
 - Side-effect: restricted set of operators:
Capture *decidable* domains
 - Good at propositional reasoning

Conclusions

Compare to
relaxations

- Most important idea in this lecture:
Lazy encoding of formulas to SAT
- SMT solvers are ...
 - Usually optimised for verification:
Good at proving unsat
 - Able to handle infinite domains:
Arithmetic, arrays, strings, etc.
 - Side-effect: restricted set of operators:
Capture *decidable* domains
 - Good at propositional reasoning

Outlook

- Various further topics:
 - More theories: ADTs, floats, strings, etc.
 - Handling of quantifiers
 - MaxSAT/MaxSMT
 - Optimising SMT
- Python API of SMT solvers:
 - Jupyter notebook: <https://shorturl.at/bWaPb>
- More lecture slides:
 - <http://ssa-school-2016.it.uu.se/>
 - <https://sat-smt-ar-school.gitlab.io/www/2022/>