Systems and Software
Verification Laboratory

Detection of Software Vulnerabilities: Static Analysis

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Motivating Example

- **Functionality** demanded **increased significantly**
  - Peer reviewing and testing

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void *threadA(void *arg) {
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  lock(&mutex);
  x--;
  if (x == 0) unlock(&lock);
  unlock(&mutex);
}
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void *threadB(void *arg) {
  lock(&mutex);
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  if (y == 1) lock(&lock);
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  lock(&mutex);
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void *threadB(void *arg) {
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  unlock(&mutex);
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Deadlock

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  unlock(&mutex);
  lock(&mutex);
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Intended learning outcomes

- Introduce **software verification** and **validation**

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    - The software should **conform to its specification**
- **Validation**: *"Are we building the right product"*
    - The software should do what the **user requires**
- Verification and validation must be applied at **each stage in the software process**
    - The **discovery of defects** in a system
    - The assessment of whether or not the system is **usable in an operational situation**

Static and Dynamic Verification

- **Software inspections** are concerned with the analysis of the static system representation to discover problems **(static verification)**
  - Supplement by **tool-based document** and **code analysis**
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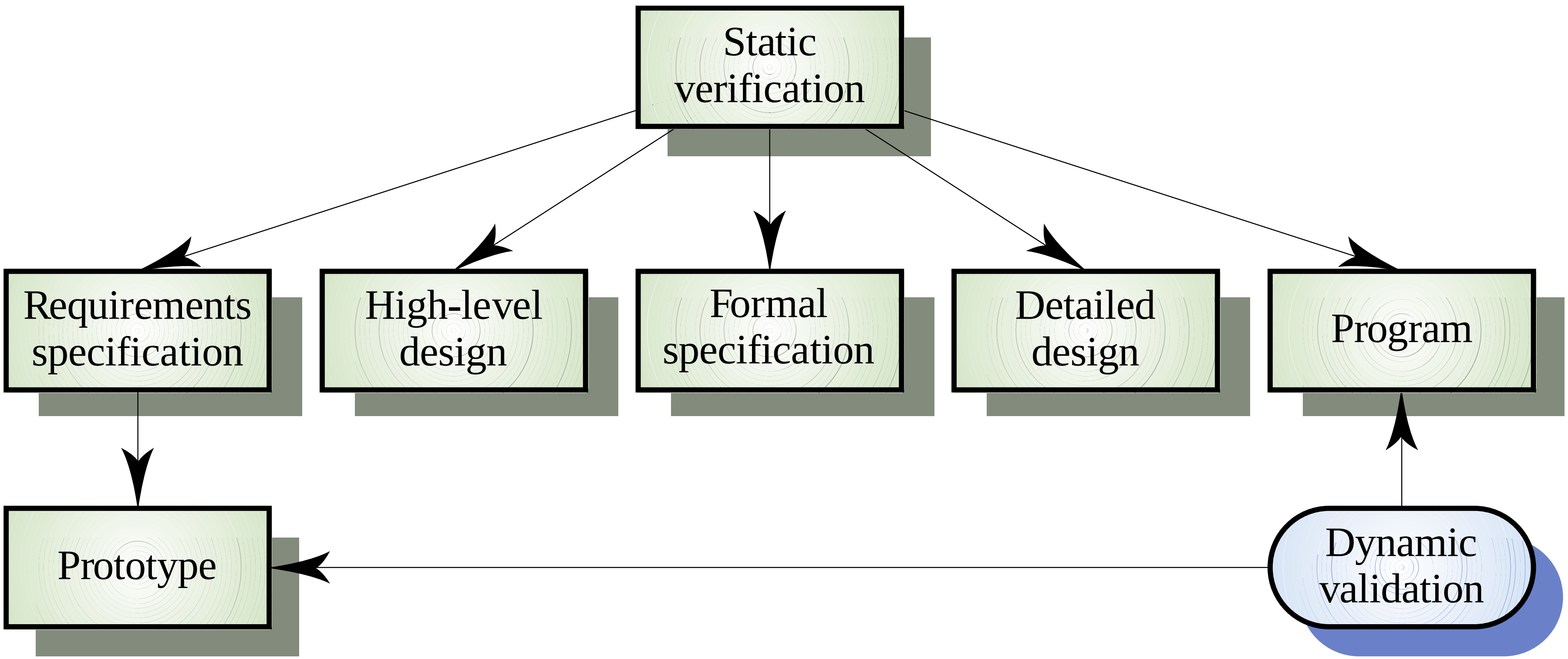
  - **Code analysis** can **prove the absence of errors** but might subject to **incorrect results**
- **Software testing** is concerned with exercising and observing product behaviour **(dynamic verification)**
  - The system is executed with **test data**
  - **Operational behaviour is observed**
  - Can reveal the presence of errors **NOT their absence**

Static and Dynamic Verification



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V & V planning

- **Careful planning** is required to get the most out of **dynamic and static verification**
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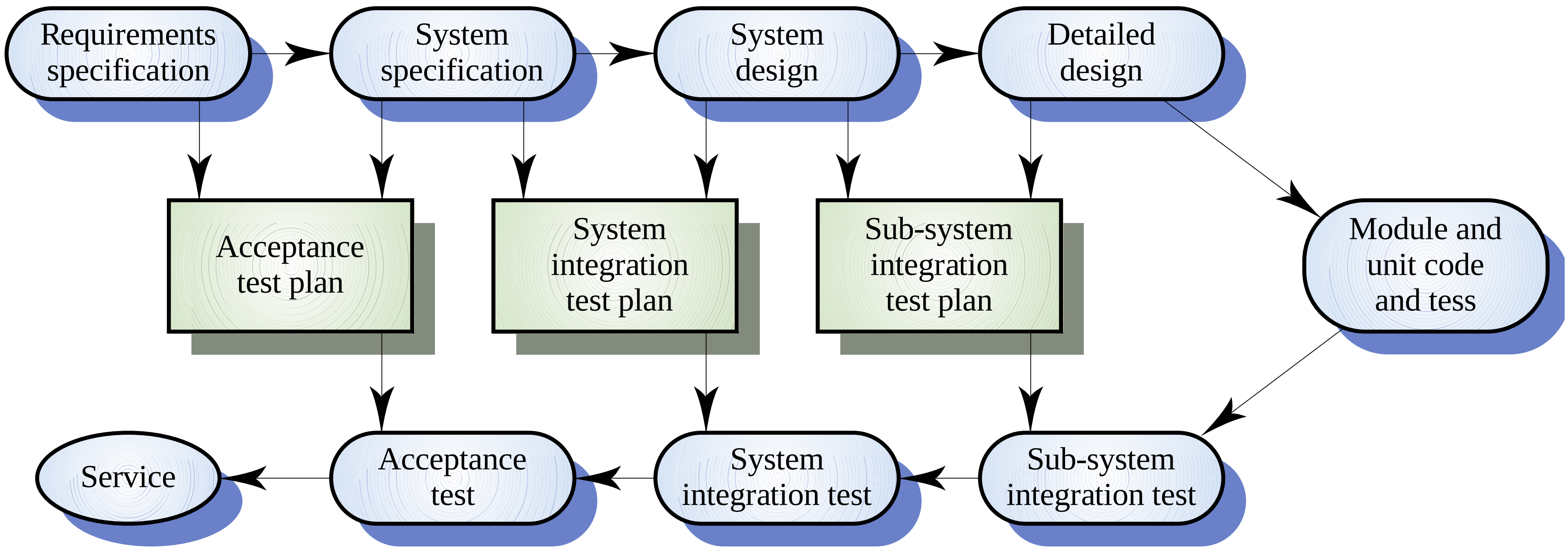
V & V planning depends **on system's purpose**, **user expectations** and **marketing environment**

The V-model of development



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- Explain **unbounded model checking of software**

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  - A detection technique is **sound** for a given category if it concludes that a given program has no vulnerabilities
    - An unsound detection technique may have ***false negatives***, i.e., actual vulnerabilities that the detection technique fails to find
  - A detection technique is **complete** for a given category, if any vulnerability it finds is an actual vulnerability
    - An incomplete detection technique may have ***false positives***, i.e., it may detect issues that do not turn out to be actual vulnerabilities

Detection of Vulnerabilities

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  - This can be done by static checking of the program code while making suitable abstractions of the executions
- Achieving **completeness** can be done by performing actual, **concrete executions** of a program that are witnesses to any vulnerability reported
  - The analysis technique has to come up with concrete inputs for the program that triggers a vulnerability
  - A typical dynamic approach is software testing: the tester writes test cases with concrete inputs and specific checks for the outputs

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Detection tools can use a **hybrid combination of static and dynamic analysis** techniques to achieve a good trade-off between **soundness and completeness**

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Dynamic verification should be used in conjunction with **static verification** to provide **full code coverage**

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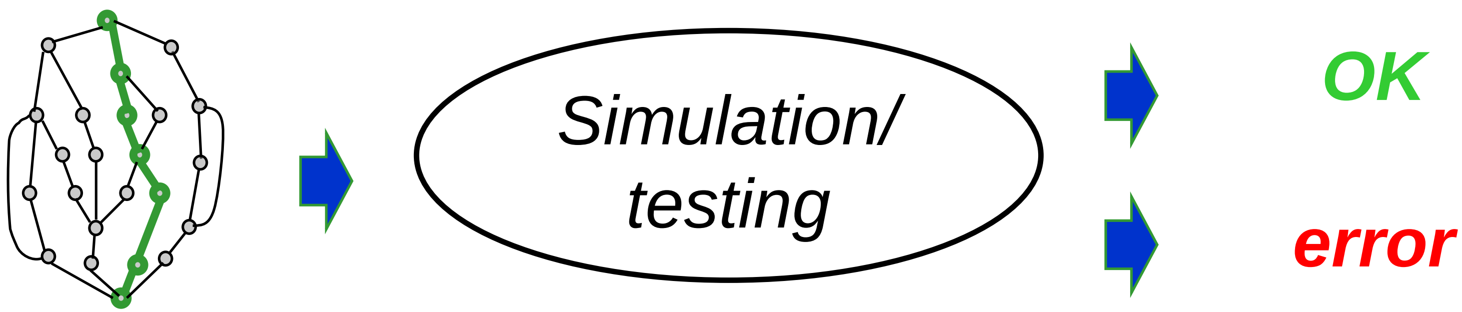
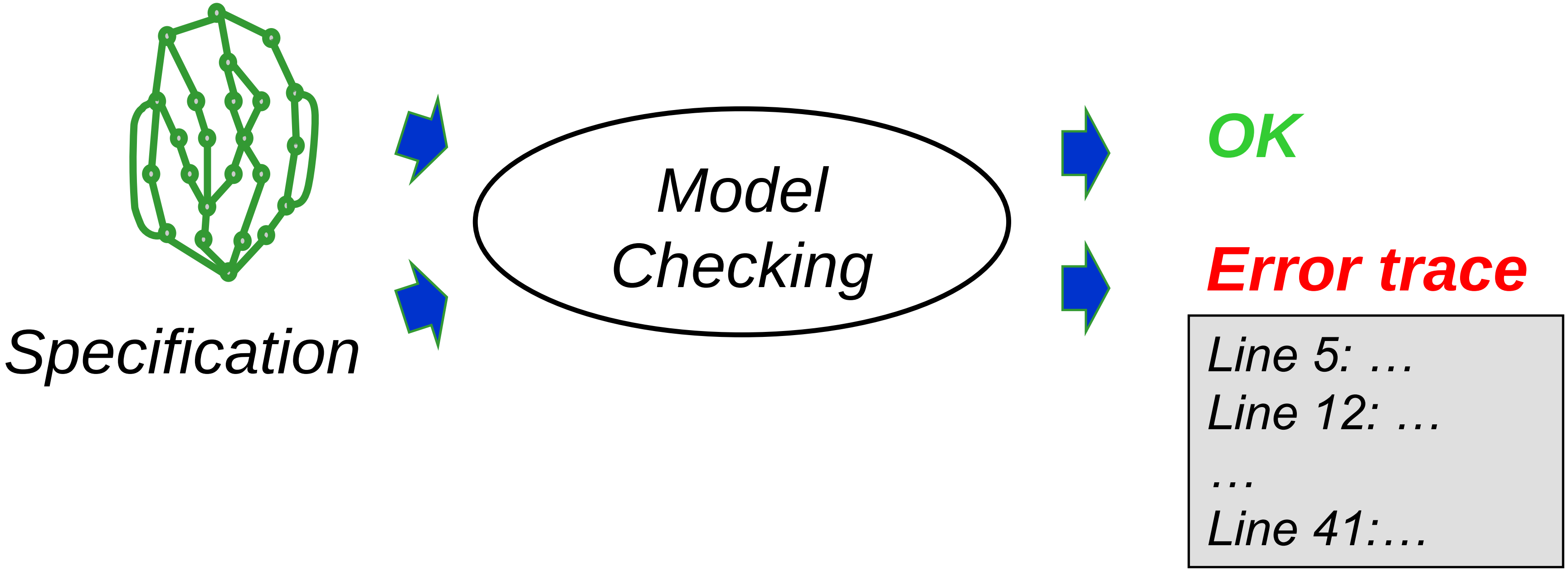
Static analysis vs Testing/Simulation



- **Checks only some of the system executions**
  - May **miss errors**
- A **successful execution** is an execution that **discovers one** or **more errors**

Static analysis vs Testing/Simulation



- **Exhaustively explores all executions**
- Report errors as **traces**
- May produce **incorrect results**

Avoiding state space explosion

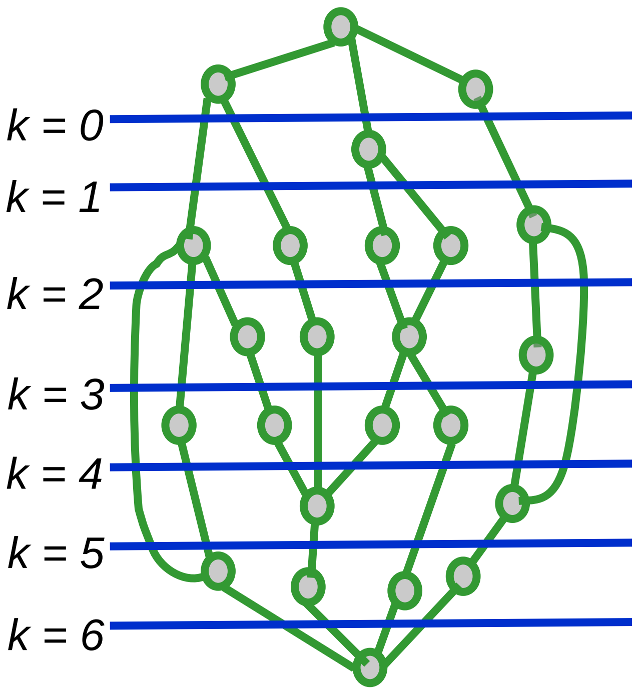
- Bounded Model Checking (BMC)
  - **Breadth-first search** (BFS) approach

- Symbolic Execution
  - **Depth-first search** (DFS) approach

Bounded Model Checking

A graph G = (V, E) consists of:

- V: a set of vertices or nodes
- $E \subseteq V \times V$: set of edges connecting the nodes



- Bounded model checkers explore the state space in depth
- Can only prove correctness if all states are reachable within the bound

Breadth-First Search (BFS)

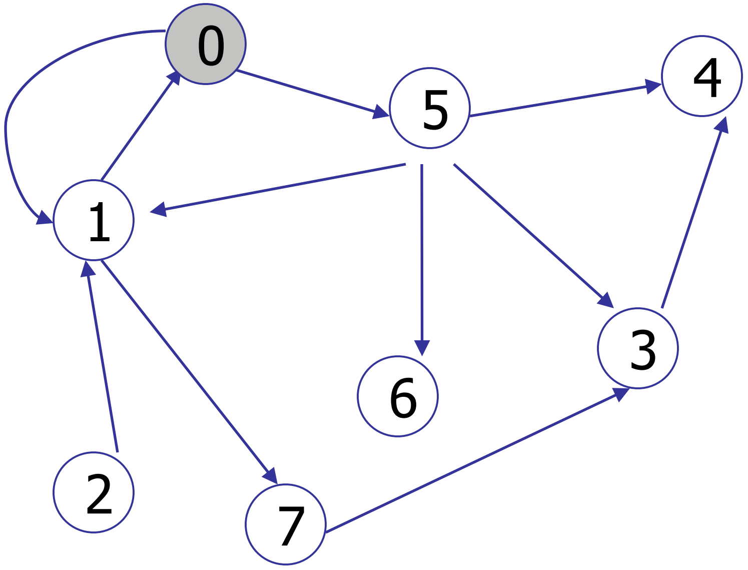
```
BFS(G,s)
for each vertex u ∈ V[G]-{s} // anchor (s)
    colour[u] ← white  // u colour
    d[u] ← ∞            // s distance
    π[u] ← NIL          // u predecessor
colour[s] ← grey
d[s] ← 0
π[s] ← NIL
enqueue(Q,s)
while Q ≠ ∅ do
    u ← dequeue(Q)
    for each v ∈ Adj[u] do
        If colour[v] = white then
            colour[v] ← grey
            d[v] ← d[u] + 1
            π[v] ← u
            enqueue(Q,v)
    colour[u] ← blue
```

Initialization of graph nodes

Initializes the anchor node (s)

Visit each adjacent node of *u*

BFS Example



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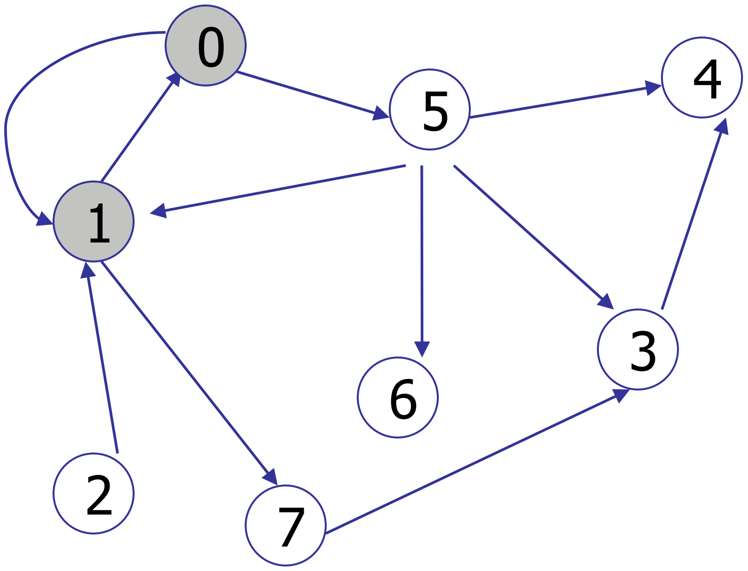

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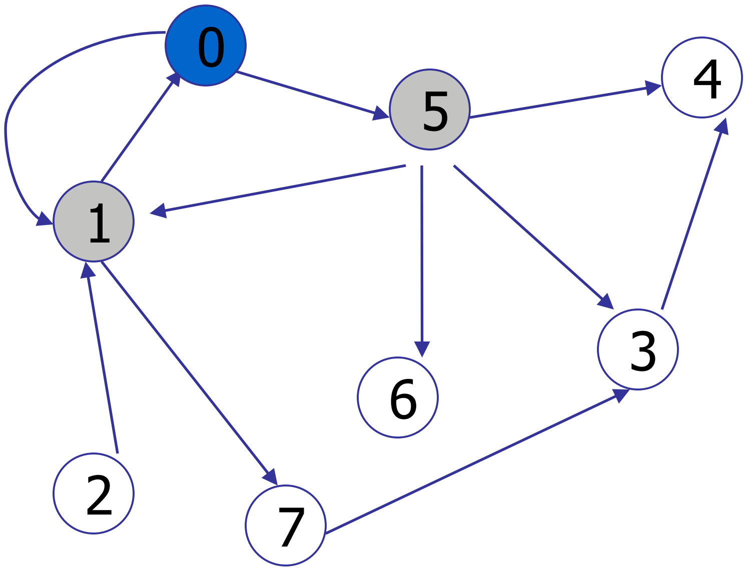

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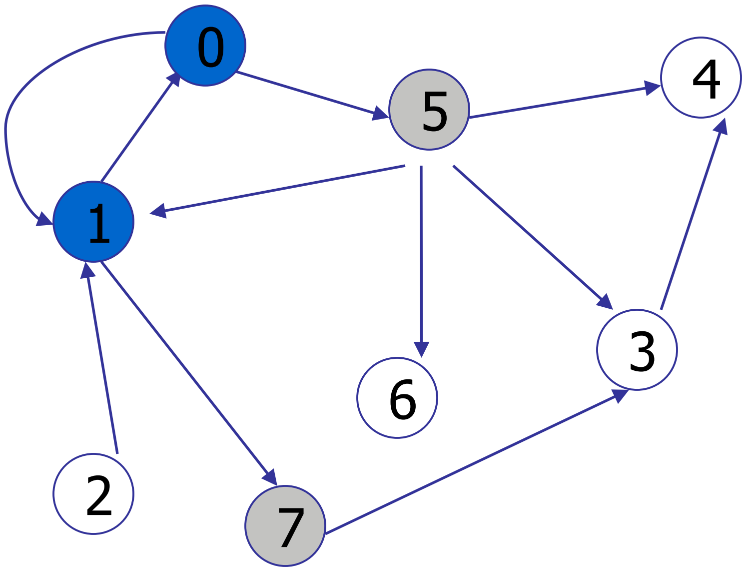

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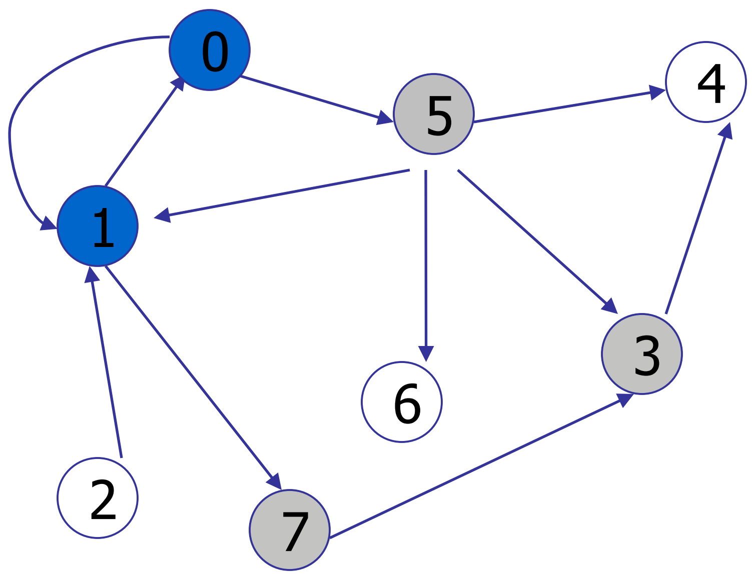

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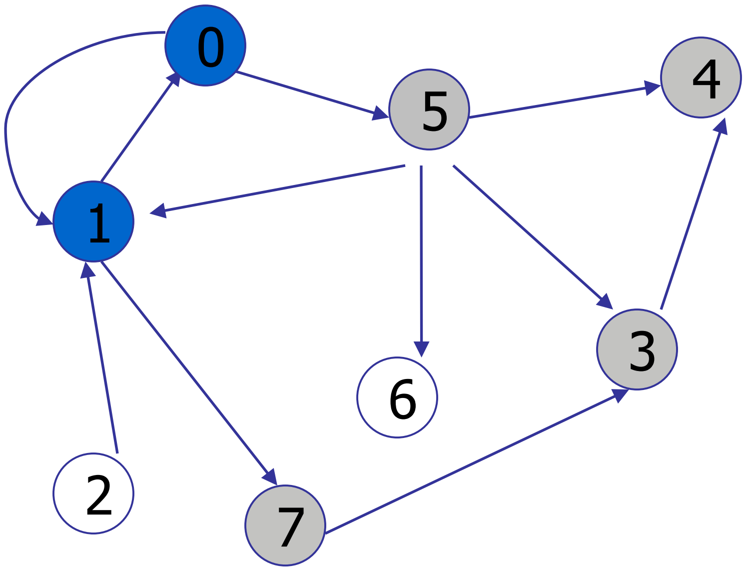

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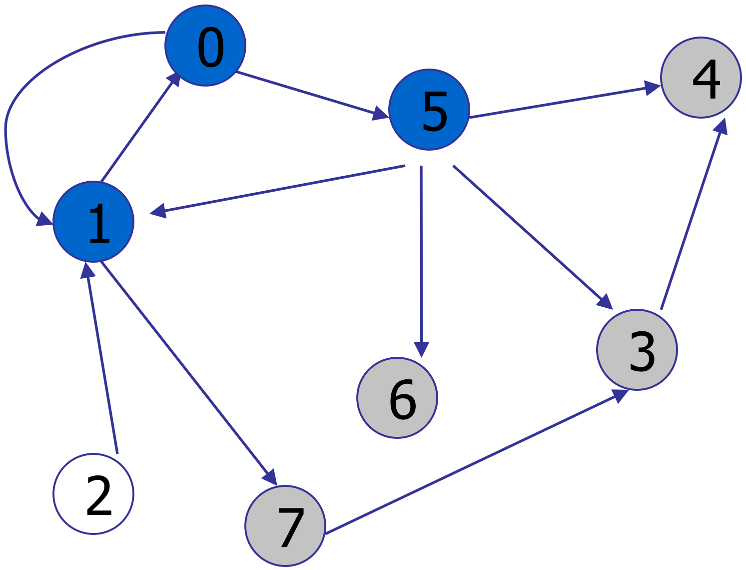

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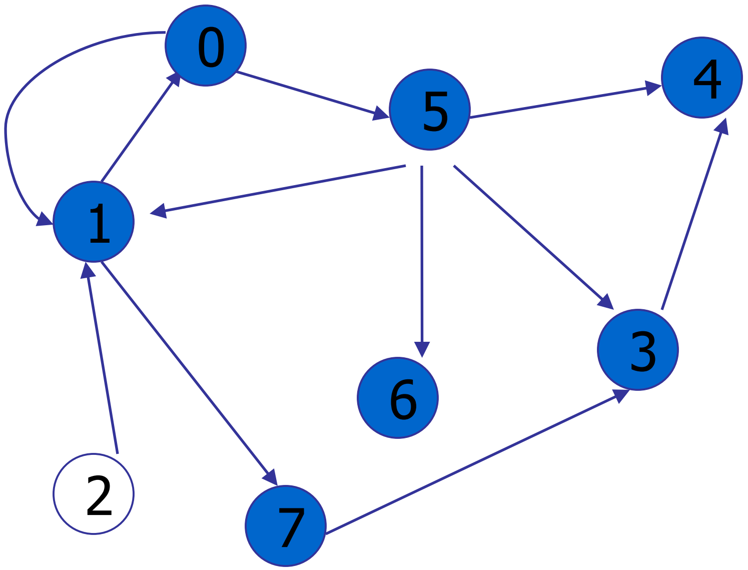
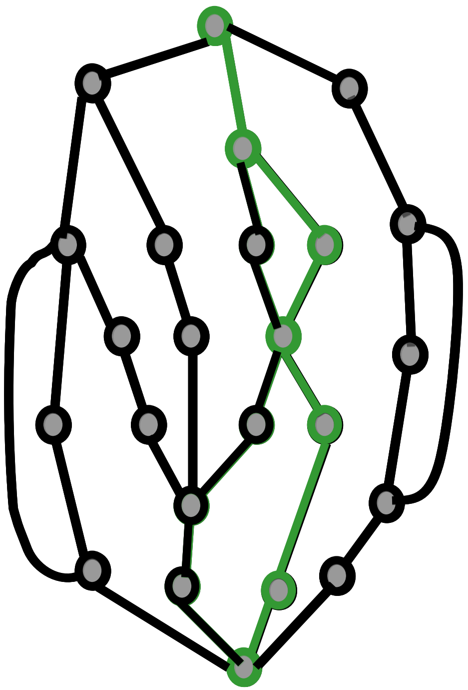


Symbolic Execution



- Symbolic execution explores all paths individually
- Can only prove correctness if all paths are explored

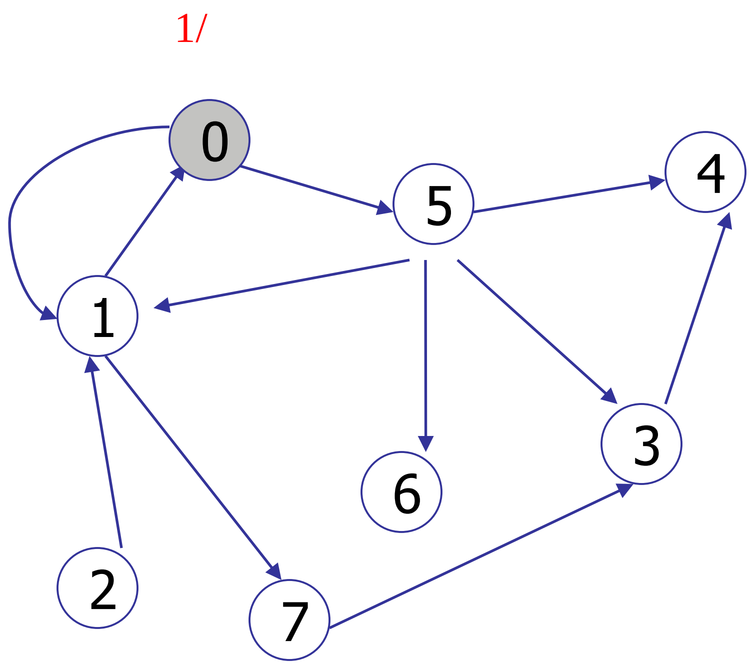
Depth-first search (DFS)

```
DFS(G)
for each vertex u ∈ V[G]
        do color[u] ← WHITE
           π[u] ← NIL
time ← 0
for each vertex u ∈ V[G]
        do if color[u] = WHITE
              then DFS-VISIT(u)
```

Paint all vertices white and initialize the fields π with NIL where π[u] represents the predecessor of u

```
DFS-VISIT(u)
color[u] ← GRAY                 ▷ White vertex u has just been discovered.
time ← time + 1
d[u] ← time
for each v ∈ Adj[u]             ▷ Explore edge (u, v).
        do if color[v] = WHITE
              then π[v] ← u
                   DFS-VISIT(v)
color[u] ← BLACK                ▷ Blacken u; it is finished.
f[u] ← time ← time + 1
```

DFS Example



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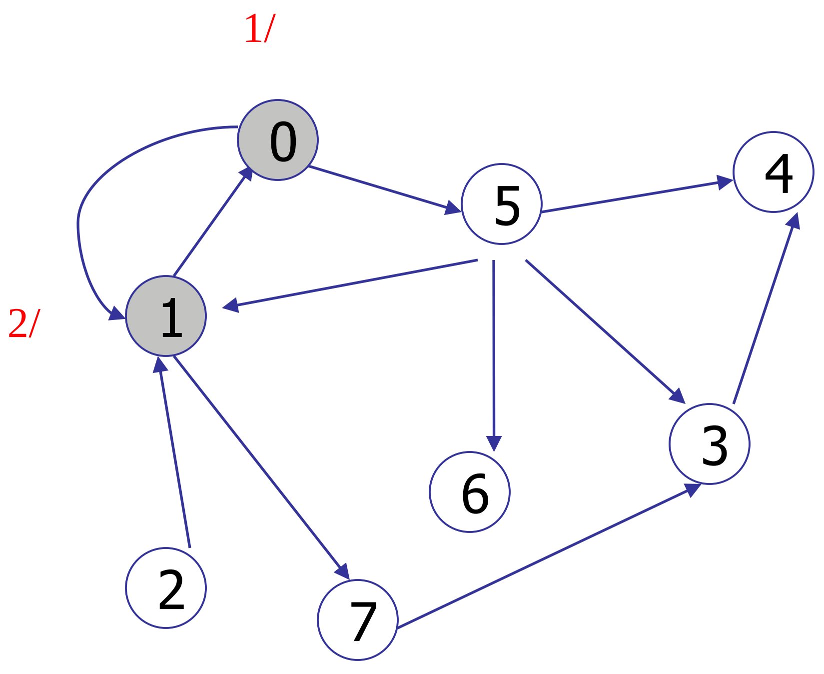

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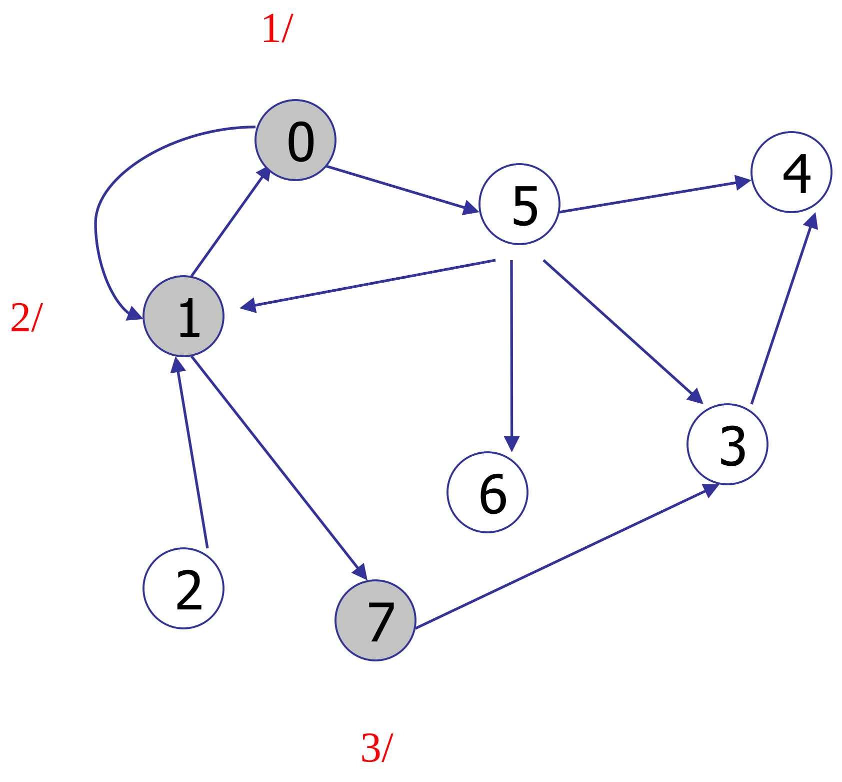

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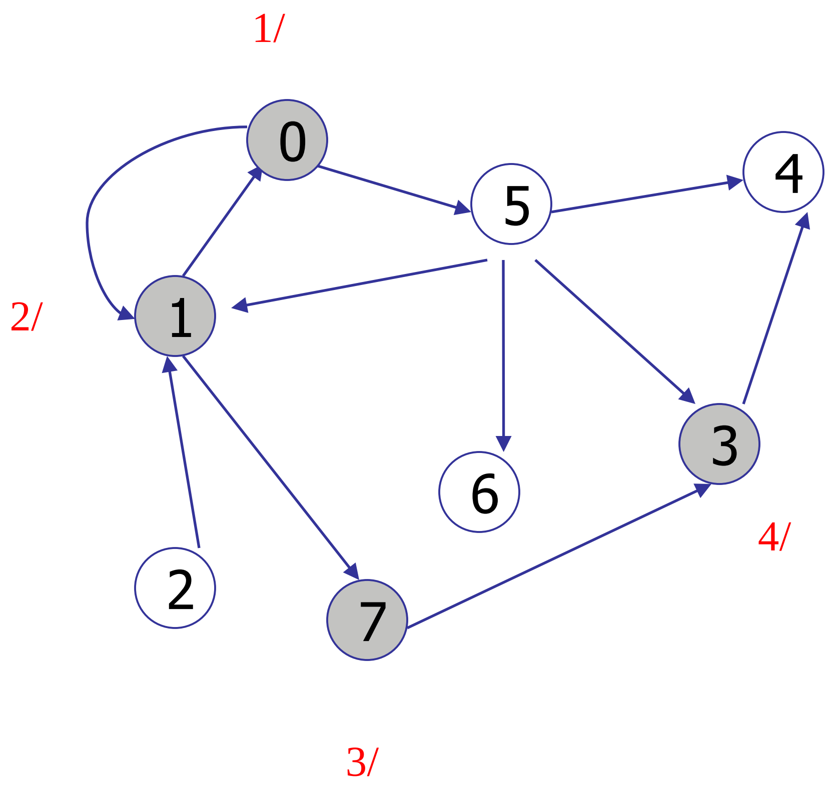

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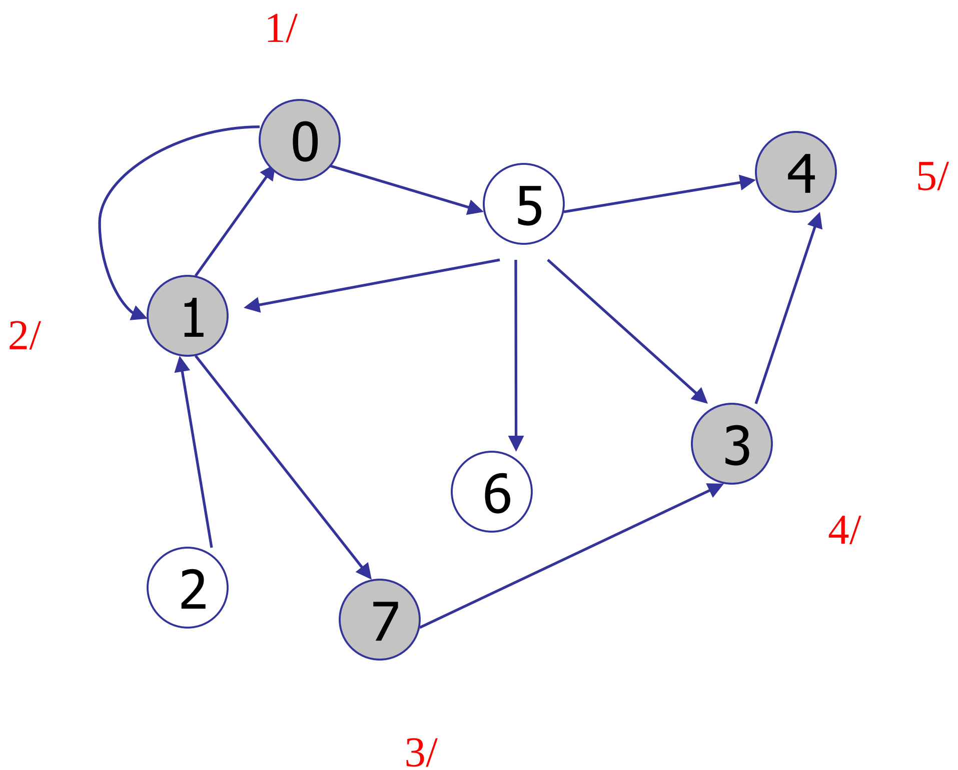

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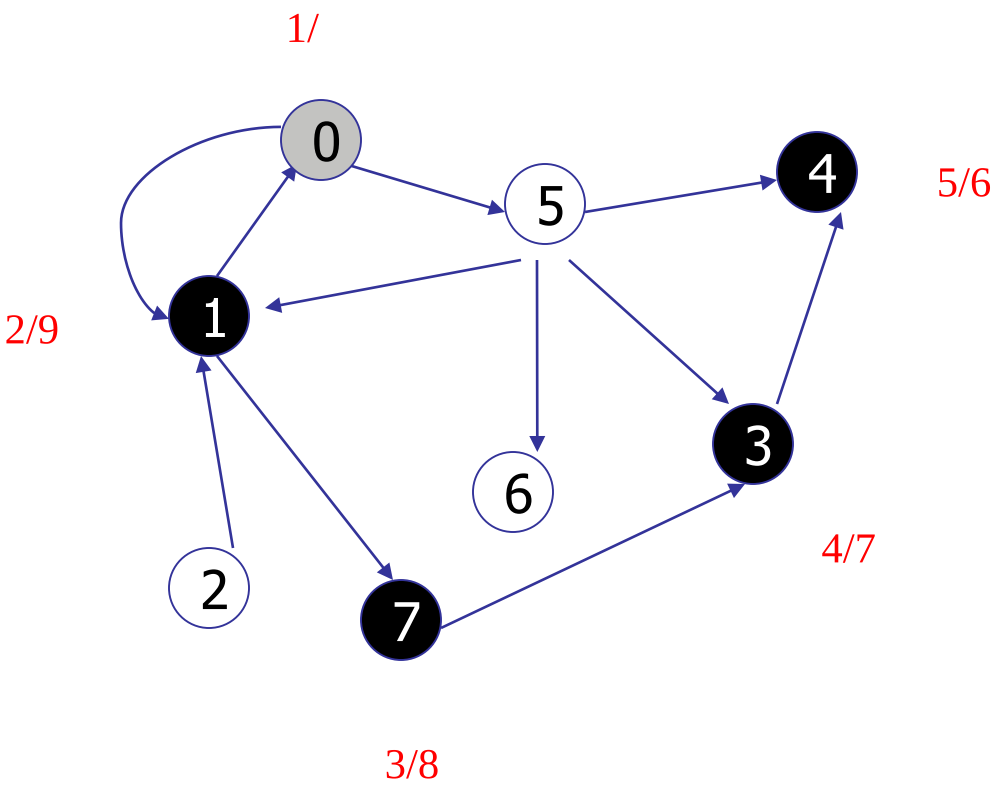

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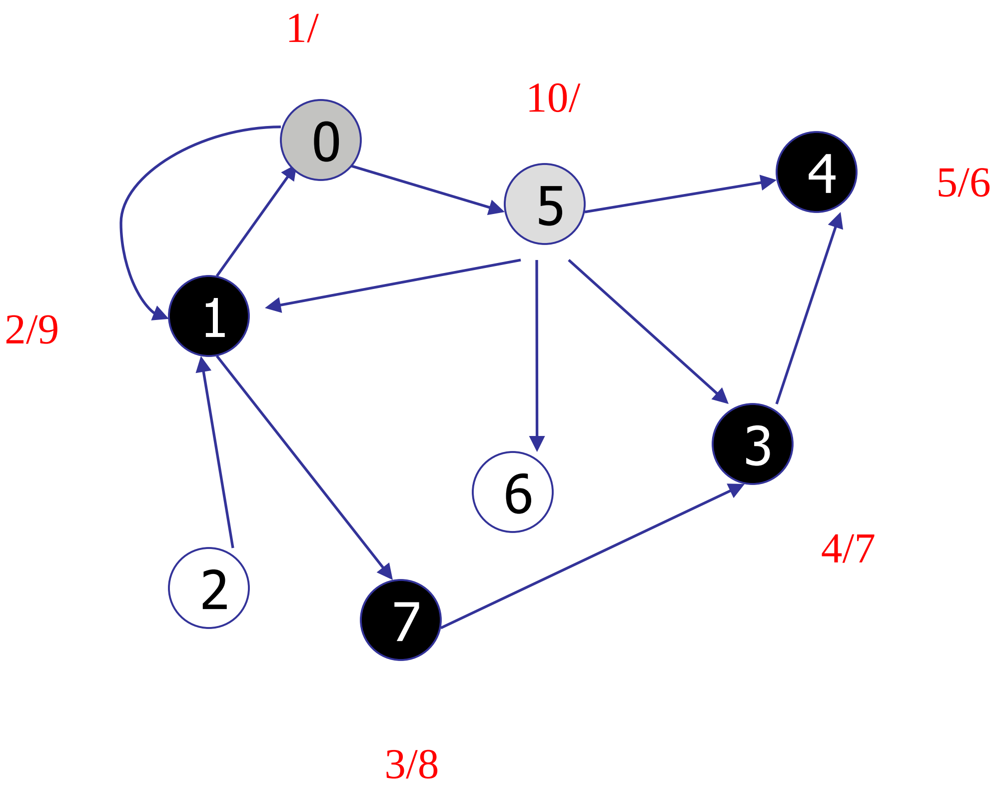

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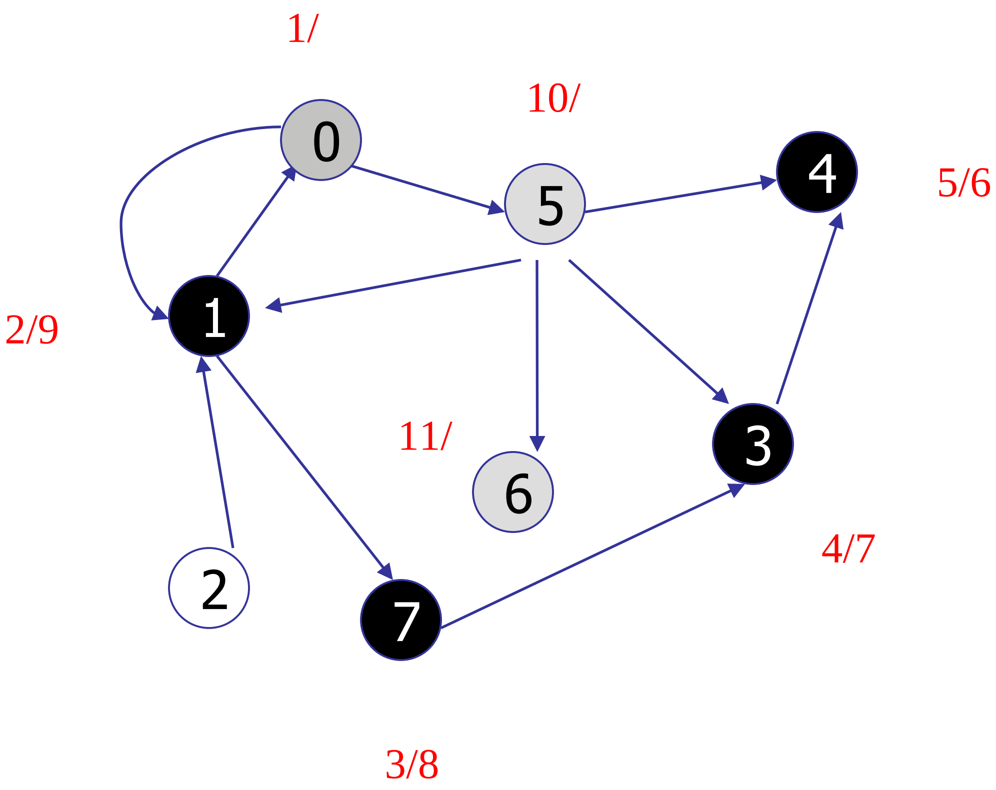

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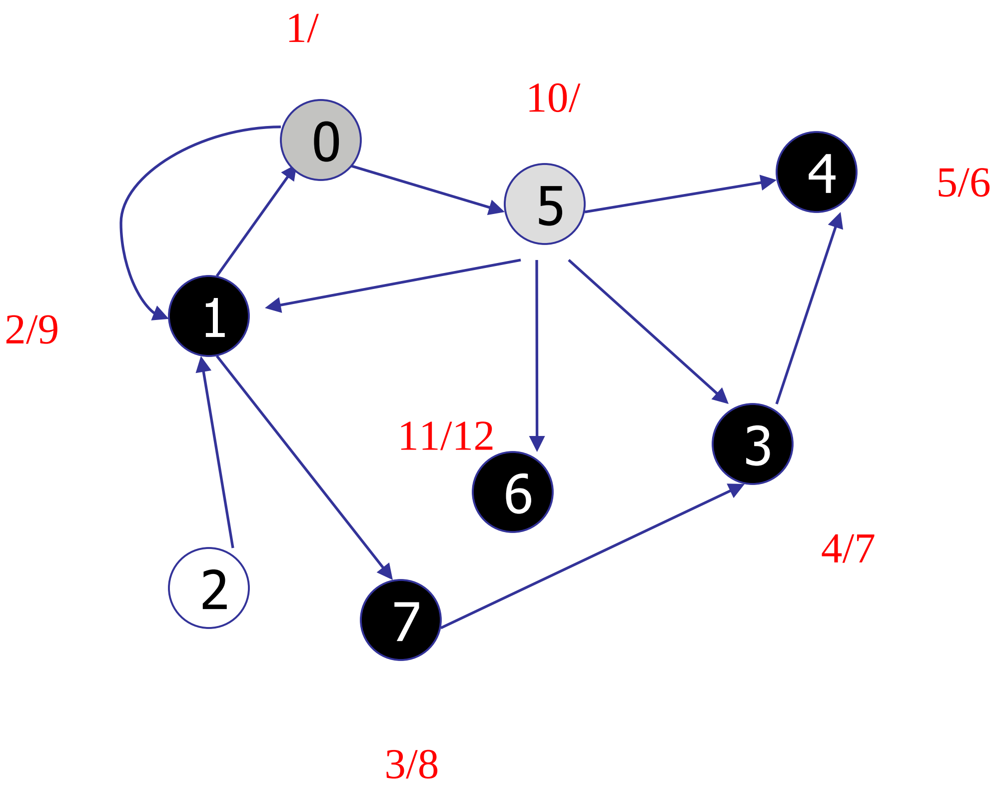

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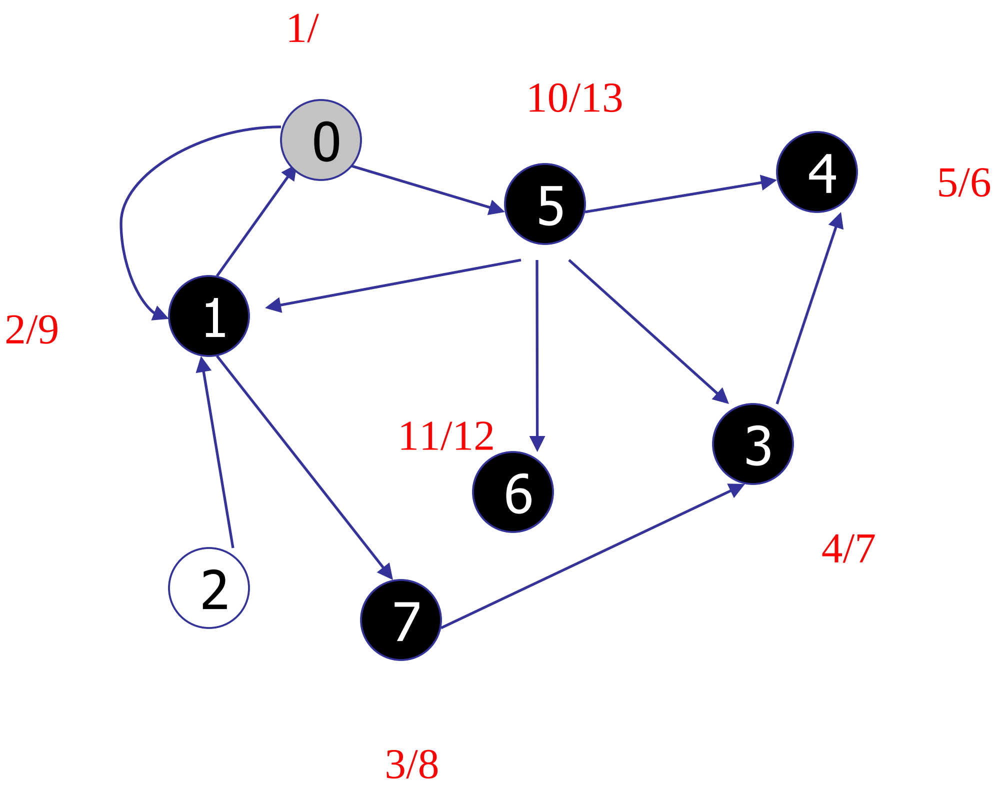

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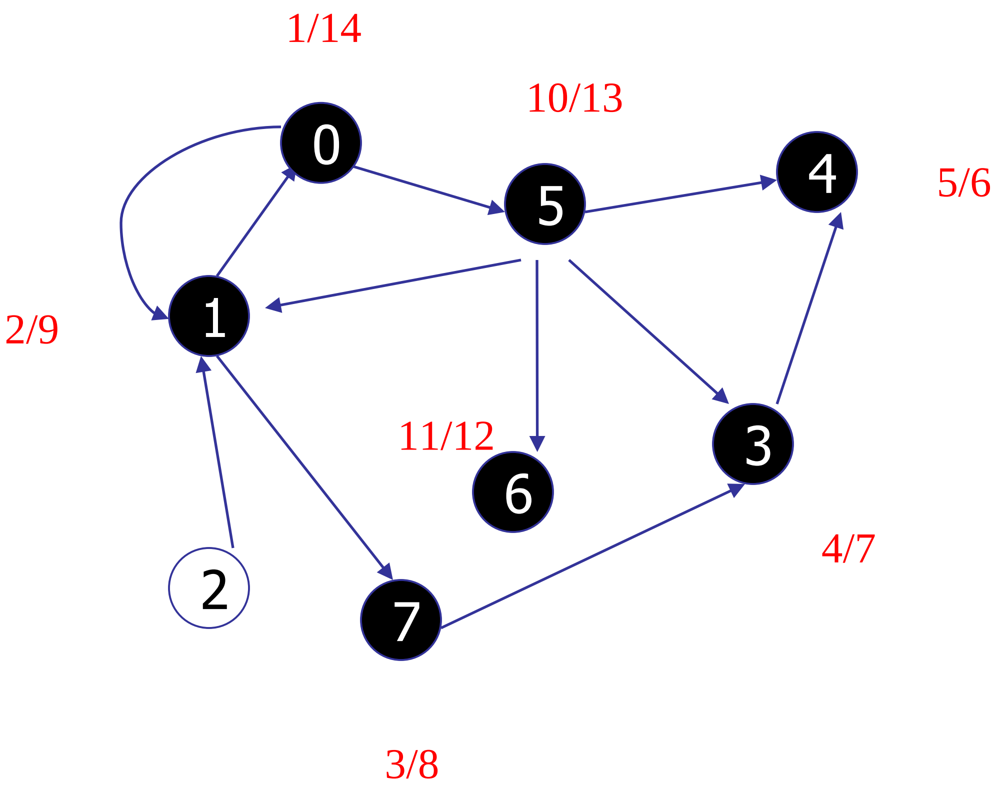

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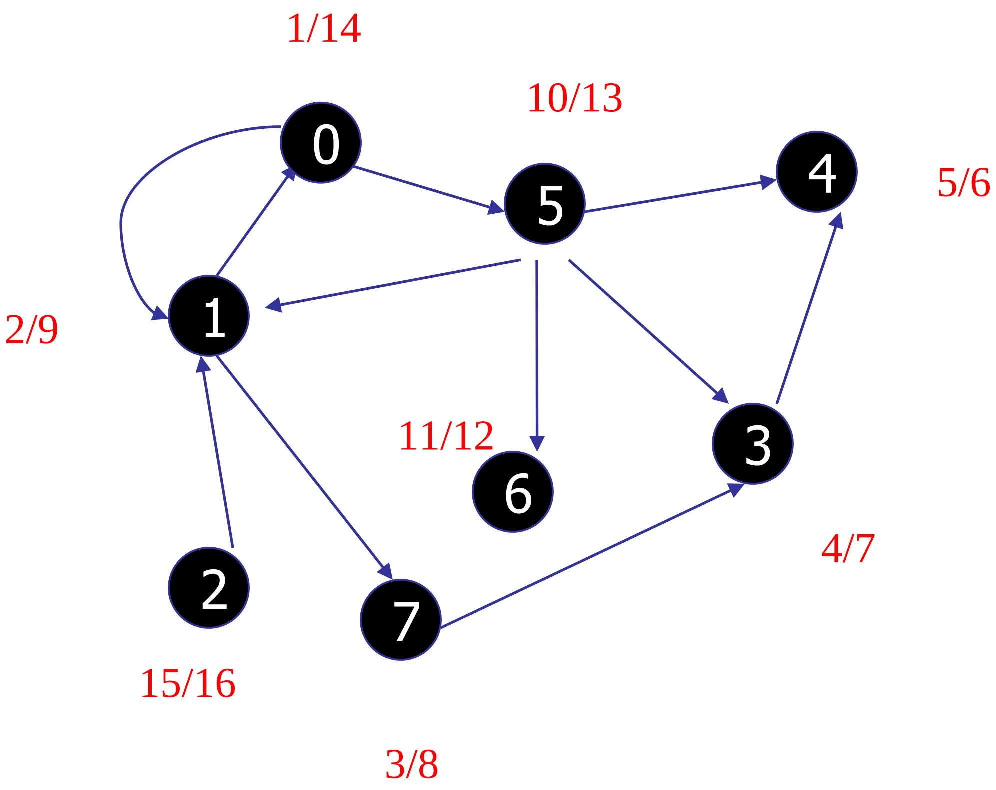

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- **Debugging** is concerned with two main tasks
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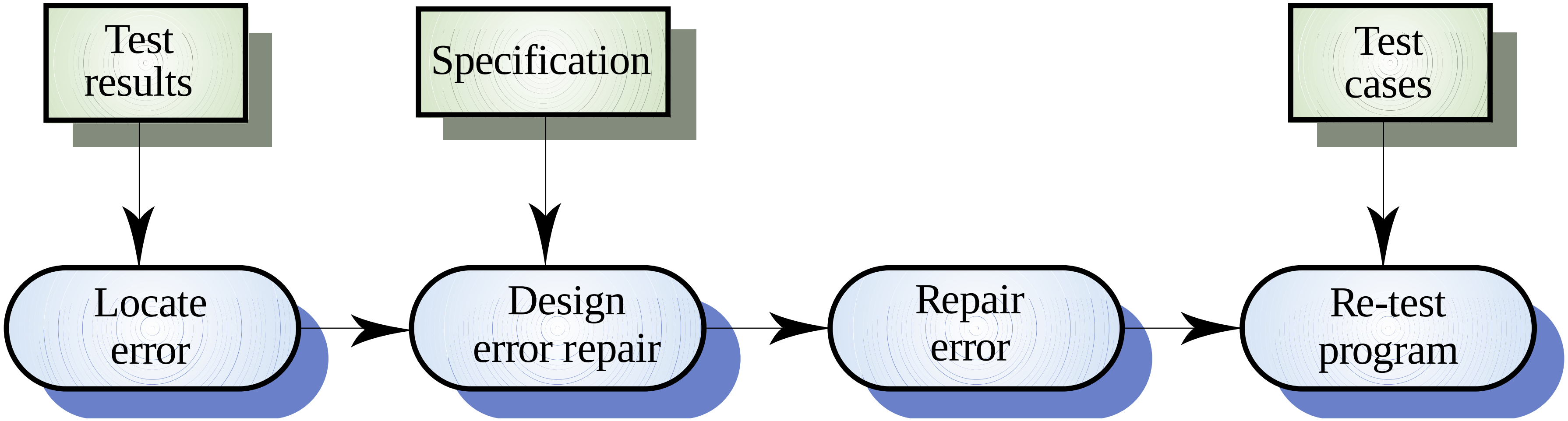
- Debugging involves
  - Formulating a hypothesis about program behaviour
  - Test these hypotheses to find the system error

The debugging process



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- A Boolean formula contains
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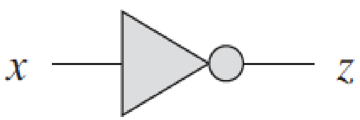
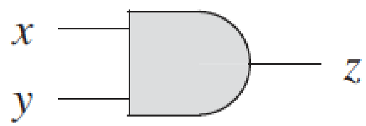
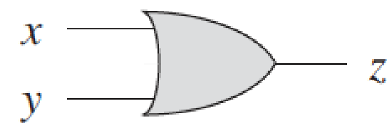


x	$\neg x$
0	1
1	0



x	y	$x \wedge y$
0	0	0
0	1	0
1	0	0
1	1	1



x	y	$x \vee y$
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0	1	1
1	0	1
1	1	1

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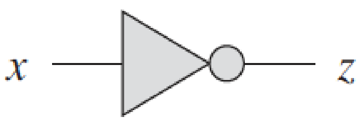

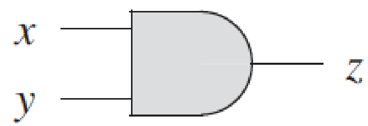

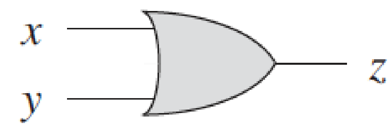

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x	y	$x \wedge y$
0	0	0
0	1	0
1	0	0
1	1	1

x	y	$x \vee y$
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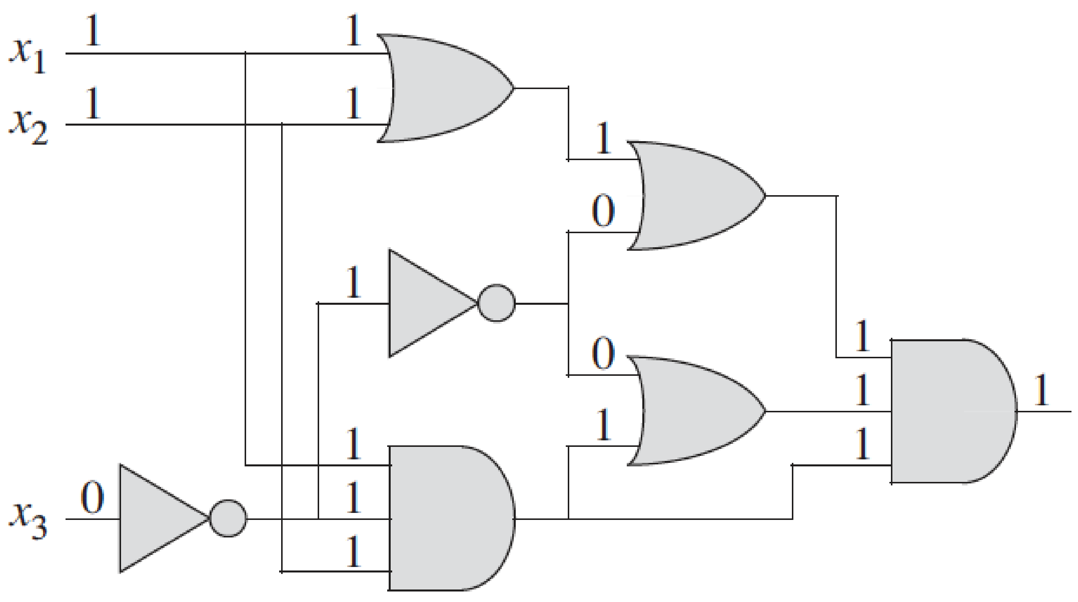
- A Boolean formula is **SAT** if there exists some assignment to its variables that **evaluates it to 1**

Circuit Satisfiability

- A **Boolean combinational circuit** consists of one or more **Boolean combinational elements** interconnected by **wires**



SAT: <x_1 = 1, x_2 = 1, x_3 = 0>

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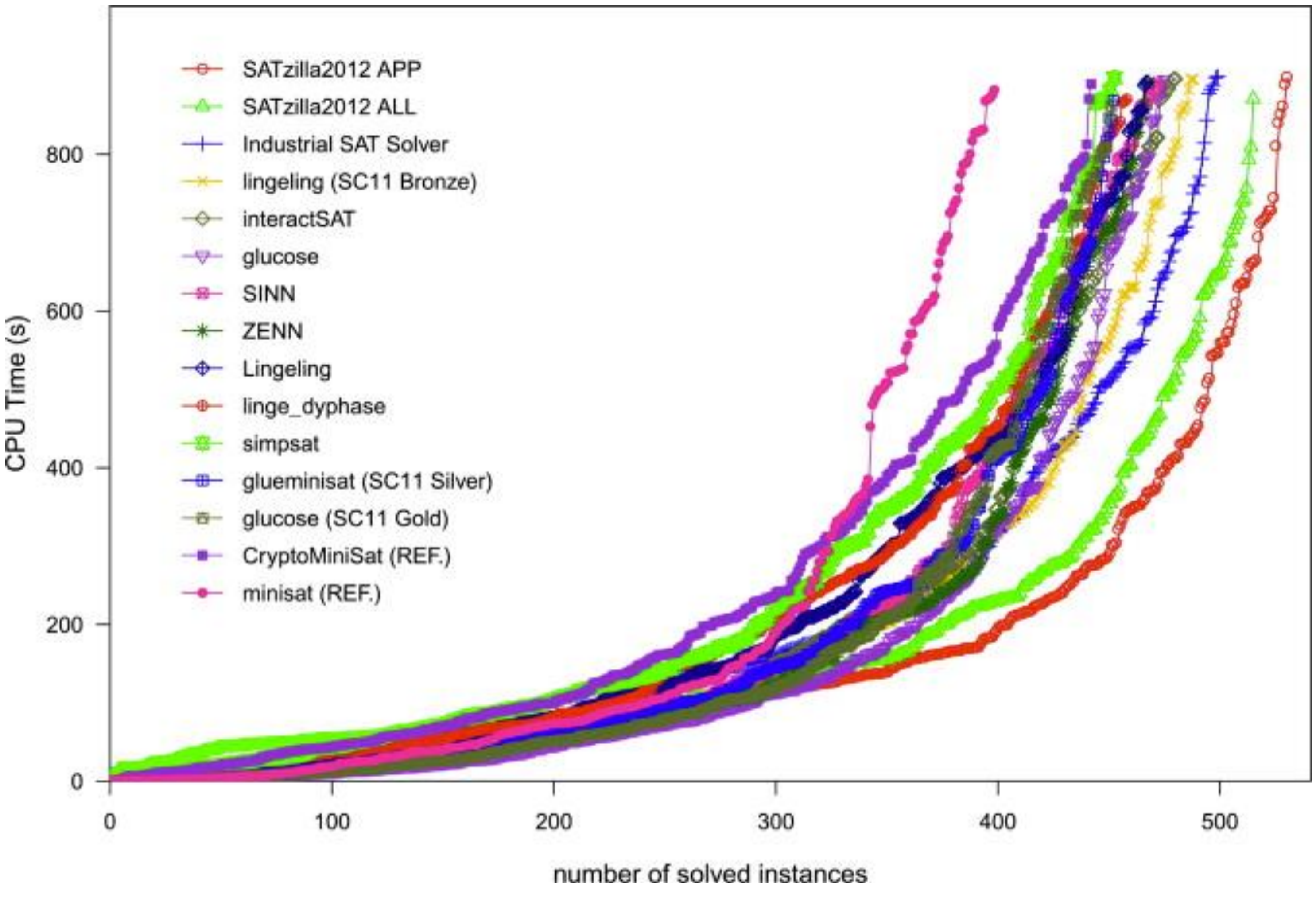
SAT Competition



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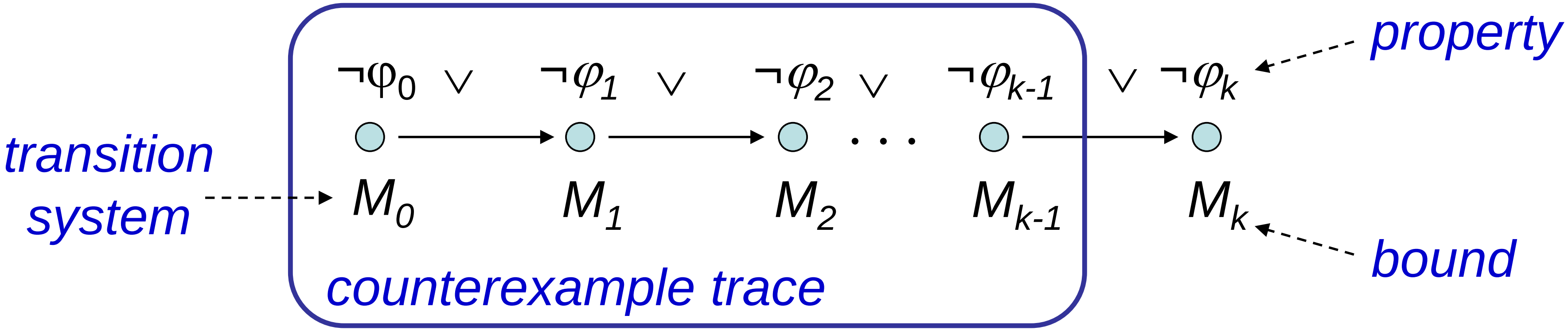
Basic Idea: check negation of given property up to given depth



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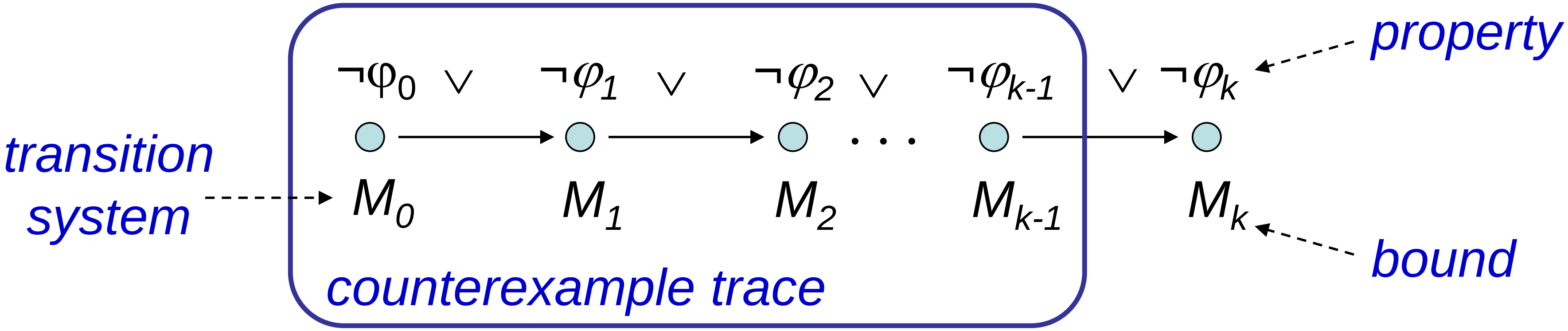

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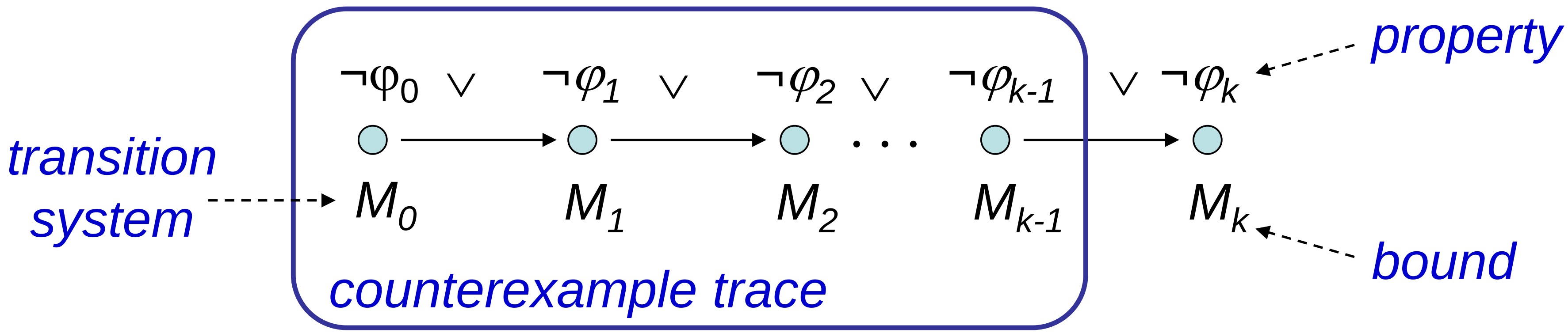

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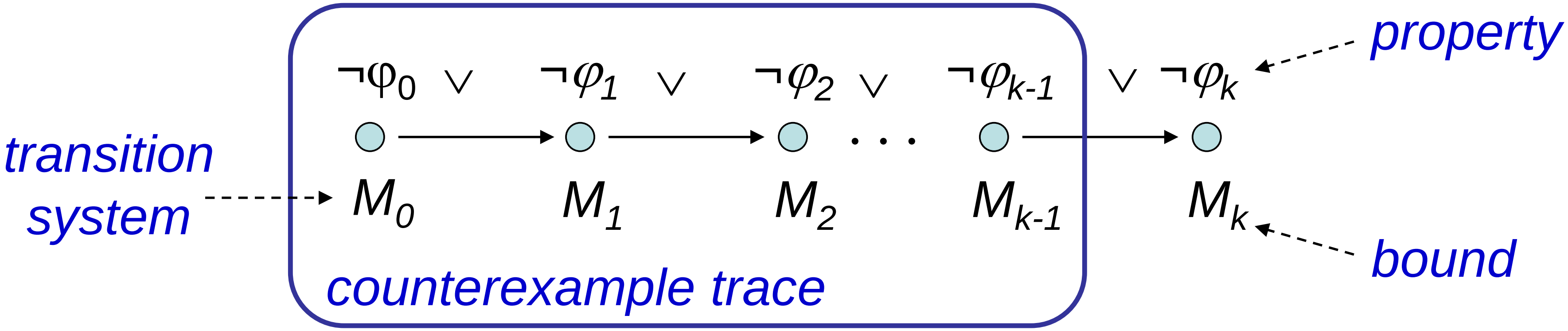

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- Checking $\Gamma \models_T \varphi$ can be reduced in the usual way to checking the T-satisfiability of $\Gamma \cup \{\neg\varphi\}$

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⇩ using facts about bit-vector arithmetic

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- SMT solvers also apply:
  - standard algebraic reduction rules $\boxed{r \wedge false \mapsto false}$
  - contextual simplification $\boxed{a = 7 \wedge p(a) \mapsto a = 7 \wedge p(7)}$

BMC of Software

- program modelled as state transition system
  - state: program counter and program variables
  - derived from control-flow graph
  - checked safety properties give extra nodes
- program unfolded up to given bounds
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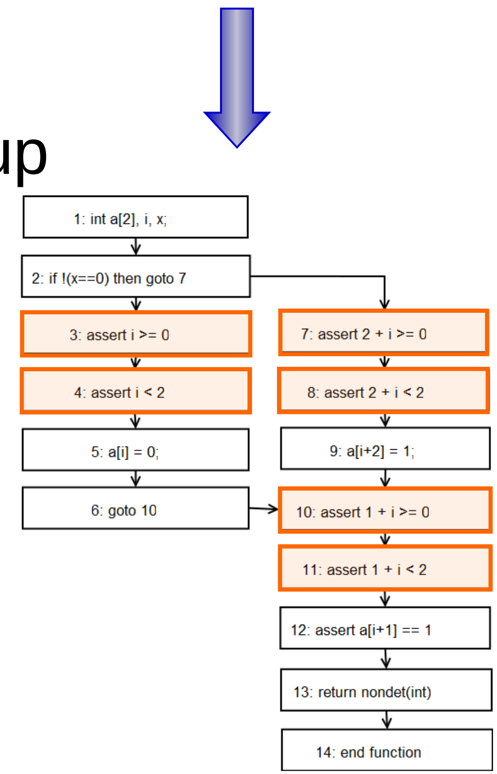

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\begin{aligned}
g_1 &= x_1 == 0 \\
a_1 &= a_0 \text{ WITH } [i_0:=0] \\
a_2 &= a_0 \\
a_3 &= a_2 \text{ WITH } [2+i_0:=1] \\
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t_1 &= a_4[1+i_0] == 1
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$$C := \left[\begin{array}{l} g_1 := (x_1 = 0) \\ \wedge\, a_1 := store(a_0, i_0, 0) \\ \wedge\, a_2 := a_0 \\ \wedge\, a_3 := store(a_2, 2+i_0, 1) \\ \wedge\, a_4 := ite(g_1, a_1, a_3) \end{array}\right]$$

$$P := \left[\begin{array}{l} i_0 \geq 0 \wedge i_0 < 2 \\ \wedge\, 2+i_0 \geq 0 \wedge 2+i_0 < 2 \\ \wedge\, 1+i_0 \geq 0 \wedge 1+i_0 < 2 \\ \wedge\, select(a_4, i_0+1) = 1 \end{array}\right]$$

Encoding of Numeric Types

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  - majority of VCs solved faster if numeric types are modelled by abstract domains but possible loss of precision
  - ESBMC supports both types of encoding and also combines them to improve scalability and precision

Encoding Numeric Types as Bitvectors

Bitvector encodings need to handle

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  - define error literals to detect over- / underflow for other types

    $$\text{res\_op} \Leftrightarrow \neg\, \text{overflow}(x, y) \wedge \neg\, \text{underflow}(x, y)$$
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- **Rational encoding:** convert a to a rational number

$$a = \begin{cases} \dfrac{\left(i * p + \left(\dfrac{f * p}{2^n} + 1 \right) \right)}{p} & : \quad f \neq 0 \\ i \quad : \quad \mathit{otherwise} \end{cases}$$

// p = number of decimal places

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  - Positive and negative infinities and zeroes
  - NaNs
  - Comparison operators

Floating-point SMT Encoding

- The SMT floating-point theory is an addition to the SMT standard, proposed in 2010 and formalises:
  - Floating-point arithmetic
  - Positive and negative infinities and zeroes
  - NaNs
  - Comparison operators
  - Five rounding modes: round nearest with ties choosing the even value, round nearest with ties choosing away from zero, round towards zero, round towards positive infinity and round towards negative infinity

Floating-point SMT Encoding

- Missing from the standard:
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  - Signaling NaNs

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  - Z3: implements all operators
  - MathSAT: implements all but two operators
    - *fp.rem:* remainder: x - y * n, where n in Z is nearest to x/y
    - *fp.fma:* fused multiplication and addition; (x * y) + z

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    - *fp.rem:* remainder: x - y * n, where n in Z is nearest to x/y
    - *fp.fma:* fused multiplication and addition; (x * y) + z
- Both solvers offer non-standard functions:
  - *fp_as_ieeebv:* converts floating-point to bitvectors
  - *fp_from_ieeeb*v: converts bitvectors to floating-point

How to encode Floating-point programs?

- Most operations performed at program-level to encode FP numbers have a **one-to-one conversion to SMT**
- Special cases being casts to boolean types and the fp.eq operator
  - Usually, cast operations are encoded using **extend/extract operation**
  - Extending floating-point numbers is non-trivial because of the format

```
int main()
{
  _Bool c;

  double b = 0.0f;
  b = c;
  assert(b != 0.0f);

  c = b;
  assert(c != 0);
}
```

Cast to/from booleans

- Simpler solutions:
  - Casting **booleans** to **floating-point numbers** can be done using an ite operator

```
(assert (= (ite |main::c|
              (fp #b0 #b01111111111 #x0000000000000)
              (fp #b0 #b00000000000 #x0000000000000))
   |main::b|))
```

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If true, assign 1f to b

```
(assert (= (ite |main::c|
        (fp #b0 #b01111111111 #x0000000000000)
        (fp #b0 #b00000000000 #x0000000000000))
   |main::b|))
```

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(assert (= (ite |main::c|
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           (fp #b0 #b00000000000 #x0000000000000))
    |main::b|))
```

Otherwise, assign 0f to b

Cast to/from booleans

- Simpler solutions:
  - Casting **floating-point numbers** to **booleans** can be done using an equality and one not:

```
(assert (= (not (fp.eq |main::b|
          (fp #b0 #b00000000000 #x0000000000000)))
   |main::c|))
```

```
:note
"(fp.eq x y) evaluates to true if x evaluates to -zero and y
to +zero, or vice versa. fp.eq and all the other comparison op-
erators evaluate to false if one of their arguments is NaN."
```

Cast to/from booleans

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true when the floating is not 0.0

```
(assert (= (not (fp.eq |main::b|
        (fp #b0 #b00000000000 #x0000000000000)))
   |main::c|))
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otherwise, the result is false

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erators evaluate to false if one of their arguments is NaN."
```

Floating-point Encoding: Illustrative Example

```
int main()
{
    float x;
    float y = x;
    assert(x==y);
    return 0;
}
```

Floating-point Encoding: Illustrative Example

```
; declaration of x and y
(declare-fun |main::x| () (_ FloatingPoint 8 24))
(declare-fun |main::y| () (_ FloatingPoint 8 24))

; symbol created to represent a nondeteministic number
(declare-fun |nondet_symex::nondet0| () (_ FloatingPoint 8 24))

; Global guard, used for checking properties
(declare-fun |execution_statet::\\guard_exec| () Bool)

; assign the nondeterministic symbol to x
(assert (= |nondet_symex::nondet0| |main::x|))

; assign x to y
(assert (= |main::x| |main::y|))

; assert x == y
(assert (let ((a!1 (not (=> true
                    (=> |execution_statet::\\guard_exec|
                        (fp.eq |main::x| |main::y|))))))
  (or a!1)))
```

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Variable declarations

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(assert (let ((a!1 (not (=> true
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  (or a!1)))
```

Nondeterministic symbol declaration (optional)

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(declare-fun |main::y| () (_ FloatingPoint 8 24))

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(assert (let ((a!1 (not (=> true
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```

Guard used to check satisfiability

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  (or a!1)))
```

Assignment of nondeterministic *value to x*

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(declare-fun |main::x| () (_ FloatingPoint 8 24))
(declare-fun |main::y| () (_ FloatingPoint 8 24))

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; assign the nondeterministic symbol to x
(assert (= |nondet_symex::nondet0| |main::x|))

; assign x to y
(assert (= |main::x| |main::y|))
```

Assignment *x to y*

```
; assert x == y
(assert (let ((a!1 (not (=> true
                    (=> |execution_statet::\\guard_exec|
                        (fp.eq |main::x| |main::y|))))))
  (or a!1)))
```

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(assert (let ((a!1 (not (=> true
                    (=> |execution_statet::\\guard_exec|
                        (fp.eq |main::x| |main::y|))))))
  (or a!1)))
```

Check if the comparison *satisfies the guard*

Floating-point Encoding: Illustrative Example

- Z3 produces:

```
sat
(model
  (define-fun |main::x| () (_ FloatingPoint 8 24)
    (_ NaN 8 24))
  (define-fun |main::y| () (_ FloatingPoint 8 24)
    (_ NaN 8 24))
  (define-fun |nondet_symex::nondet0| () (_ FloatingPoint 8 24)
    (_ NaN 8 24))
  (define-fun |execution_statet::\\\\guard_exec| () Bool
    true)
)
```

Floating-point Encoding: Illustrative Example

- MathSAT produces:

```
sat
( (|main::x| (_ NaN 8 24))
  (|main::y| (_ NaN 8 24))
  (|nondet_symex::nondet0| (_ NaN 8 24))
  (|execution_statet::\\guard_exec| true) )
```

Floating-point Encoding: Illustrative Example

```
Counterexample:

State 1 file main3.c line 3 function main thread 0
main
----------------------------------------------------
  main3::main::1::x=-NaN (11111111100000000000000000000001)

State 2 file main3.c line 4 function main thread 0
main
----------------------------------------------------
  main3::main::2::y=-NaN (11111111100000000000000000000001)

State 3 file main3.c line 5 function main thread 0
main
----------------------------------------------------
Violated property:
  file main3.c line 5 function main
  assertion
  (_Bool)(x == y)

VERIFICATION FAILED
```

Intended learning outcomes

- Introduce **software verification** and **validation**
- Understand **soundness** and **completeness** concerning **detection techniques**
- Emphasize the difference among **static analysis**, **testing / simulation**, and **debugging**
- Explain **bounded model checking of software**
- Explain **precise memory model for software verification**

Encoding of Pointers

- arrays and records / tuples typically handled directly by SMT-solver
- pointers modelled as tuples
  - p.o $\triangleq$ representation of underlying object
  - p.i $\triangleq$ index (if pointer used as array base)

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```
int main() {
  int a[2], i, x, *p;
  p=a;
  if (x==0)
    a[i]=0;
  else
    a[i+1]=1;
  assert(*(p+2)==1);
}
```

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```

$\Longrightarrow$

$$C := \left(\begin{array}{l} p_1 := \mathrm{store}(p_0, 0, \&a[0]) \\ \wedge\ p_2 := \mathrm{store}(p_1, 1, 0) \\ \wedge\ g_2 := (x_2 == 0) \\ \wedge\ a_1 := \mathrm{store}(a_0, i_0, 0) \\ \wedge\ a_2 := a_0 \\ \wedge\ a_3 := \mathrm{store}(a_2, 1 + i_0, 1) \\ \wedge\ a_4 := \mathrm{ite}(g_1, a_1, a_3) \\ \wedge\ p_3 := \mathrm{store}(p_2, 1, \mathrm{select}(p_2\,, 1) + 2) \end{array} \right)$$

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Store object at position 0

```
int main() {
  int a[2], i, x, *p;
  p=a;
  if (x==0)
    a[i]=0;
  else
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```

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  p=a;
  if (x==0)
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  else
    a[i+1]=1;
  assert(*(p+2)==1);
}
```

$$
C := \left(\begin{array}{l}
p_1 := \text{store}(p_0, 0, \&a[0]) \\
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\end{array}\right)
$$

Store index at position 1

Encoding of Pointers

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- pointers modelled as tuples
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```
int main() {
  int a[2], i, x, *p;
  p=a;
  if (x==0)
    a[i]=0;
  else
    a[i+1]=1;
  assert(*(p+2)==1);
}
```

C

$$
\left(\begin{array}{l}
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\wedge\ p_3 := store(p_2, 1, select(p_2 , 1)+2)
\end{array}\right)
$$

Store object at position 0

Store index at position 1

Update index

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int main() {
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  p=a;
  if (x==0)
    a[i]=0;
  else
    a[i+1]=1;
  assert(*(p+2)==1);
}
```

$$P := \left(\begin{array}{l} i_0 \geq 0 \wedge i_0 < 2 \\ \wedge\ 1+ i_0 \geq 0 \wedge 1+ \quad\quad 2 \\ \wedge\ \mathrm{select}(p_3, 0) == \&a[0] \\ \wedge\ \mathrm{select}(\mathrm{select}(p_3, 0), \\ \quad\quad\quad\quad \mathrm{select}(p_3, 1)) == 1 \end{array} \right)$$

negation satisfiable
*(*a[2] *unconstrained)*
$\Rightarrow$ assert fails

Encoding of Memory Allocation

- model memory just as an array of bytes (array theories)
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- each dynamic object d_o consists of
  - $m \triangleq$ memory array
  - $s \triangleq$ size in bytes of m
  - $\rho \triangleq$ unique identifier
  - $\upsilon \triangleq$ indicate whether the object is still alive
  - $l \triangleq$ the location in the execution where m is allocated

Encoding of Memory Allocation

- model memory just as an array of bytes (array theories)
  - read and write operations to the memory array on the logic level
- each dynamic object d_o consists of
  - m ≜ memory array
  - s ≜ size in bytes of m
  - ρ ≜ unique identifier
  - υ ≜ indicate whether the object is still alive
  - l ≜ the location in the execution where m is allocated
- to detect invalid reads/writes, we check whether
  - d_o is a dynamic object
  - i is within the bounds of the memory array

$$l_{is\_dynamic\_object} \Leftrightarrow \left(\bigvee_{j=1}^{k} d_o.\rho = j \right) \wedge (0 \leq i < n)$$

Encoding of Memory Allocation

- to check for invalid objects, we
  - set υ to *true* when the function `malloc` is called (d_o is alive)
  - set υ to *false* when the function `free` is called (d_o is not longer alive)

$$l_{valid\_object} \Leftrightarrow (l_{is\_dynamic\_object} \Rightarrow d_o.\upsilon)$$

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$$l_{valid\_object} \Leftrightarrow (l_{is\_dynamic\_object} \Rightarrow d_o.\upsilon)$$

- to detect forgotten memory, at the end of the (unrolled) program we check
  - whether the d_o has been deallocated by the function free

$$l_{deallocated\_object} \Leftrightarrow (l_{is\_dynamic\_object} \Rightarrow \neg d_o.\upsilon)$$

Example of Memory Allocation

```
#include <std
void main() {
  char *p = m
  char *q = malloc(5);    // ρ = 2
  p=q;
  free(p)
  p = malloc(5);          // ρ = 3
  free(p)
}
```

memory leak: pointer reassignment makes $d_{o1}.\upsilon$ to become an orphan

Example of Memory Allocation

```
#include <stdlib.h>
void main() {
  char *p = malloc(5);  // ρ = 1
  char *q = malloc(5);  // ρ = 2
  p=q;
  free(p)
  p = malloc(5);             // ρ = 3
  free(p)
}
```

$$P := \left(\neg d_{o1}.\upsilon \wedge \neg d_{o2}.\upsilon \ \neg d_{o3}.\upsilon \right)$$

$$C := \left(\begin{array}{l} d_{o1}.\rho=1 \wedge d_{o1}.s=5 \wedge d_{o1}.\upsilon=\mathit{true} \wedge p=d_{o1} \\ \wedge\ d_{o2}.\rho=2 \wedge d_{o2}.s=5 \wedge d_{o2}.\upsilon=\mathit{true} \wedge q=d_{o2} \\ \wedge\ p=d_{o2} \wedge d_{o2}.\upsilon=\mathit{false} \\ \wedge\ d_{o3}.\rho=3 \wedge d_{o3}.s=5 \wedge d_{o3}.\upsilon=\mathit{true} \wedge p=d_{o3} \\ \wedge\ d_{o3}.\upsilon=\mathit{false} \end{array} \right)$$

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Align-guaranteed memory mode

- Alignment rules require that any pointer variable must be aligned to at least the alignment of the pointer type
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  - To guard against executions where an unaligned pointer is dereferenced

Align-guaranteed memory mode

- Alignment rules require that any pointer variable must be aligned to at least the alignment of the pointer type
  - E.g., an integer pointer’s value must be aligned to at least 4 bytes, for 32-bit integers
- Encode **property assertions** when dereferences occur during symbolic execution
  - To guard against executions where an unaligned pointer is dereferenced
  - This is not as strong as the C standard requirement, that a pointer variable may never hold an unaligned value
    - But it provides a guarantee that any pointer dereference will either be correctly aligned or result in a verification failure

ESBMC’s memory model

- statically tracks possible pointer variable targets (objects)
  - dereferencing a pointer leads to the construction of **guarded references** to each **potential target**

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- C is very **liberal** about **permitted dereferences**

```
struct foo {
  uint16_t bar[2];
  uint8_t baz;
};
```

```
struct foo qux;
char *quux = &qux;
quux++;
*quux;
```

pointer and object types do not match

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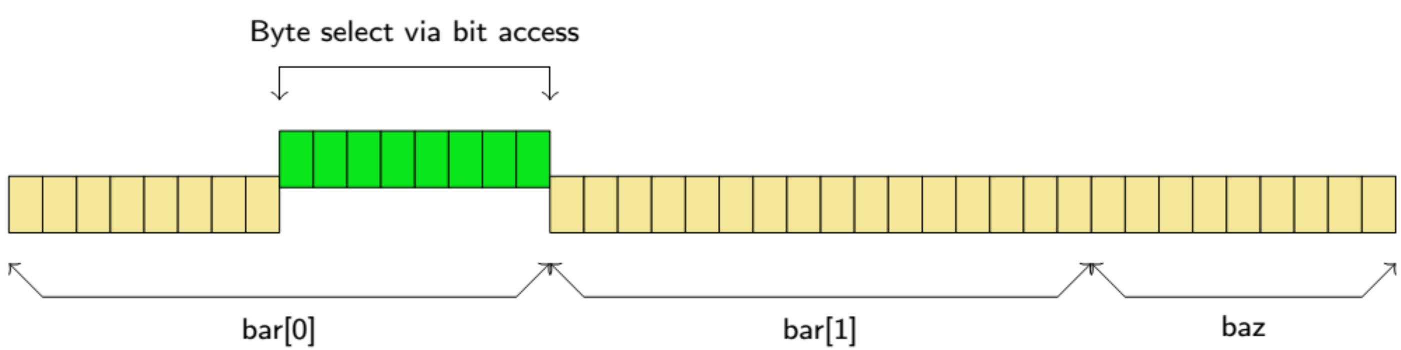
pointer and object types do not match

- **SAT: immediate access** to bit-level representation



ESBMC's memory model

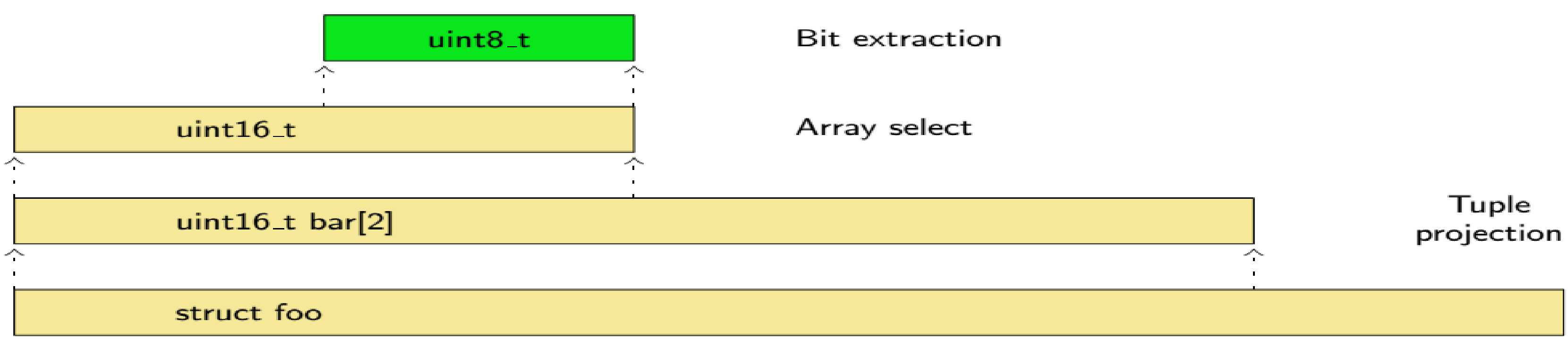
- statically tracks possible pointer variable targets (objects)
  - dereferencing a pointer leads to the construction of **guarded references** to each **potential target**
- C is very **liberal** about **permitted dereferences**

```
struct foo {
  uint16_t bar[2];
  uint8_t baz;
};
```

```
struct foo qux;
char *quux = &qux;
quux++;
*quux;
```

pointer and object types do not match

- **SMT:** sorts must be **repeatedly unwrapped**



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if (nondet_bool()) {
    fuzz = &qux.bar[0];
  } else {
    fuzz = &qux.baz;
  }
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  - chooses accessed field nondeterministically
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  - extract (unaligned) 16bit integer from *fuzz
- experiments showed significantly increased **memory consumption**

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– extracting 16-bit integer from `*fuzz`:

  - offset = 0: project `bar[0]` out of foo
  - offset = 1: **“unaligned memory access” failure**
  - offset = 2: project `bar[1]` out of foo
  - offset = 3: **“unaligned memory access” failure**
  - offset = 4: “access to object out of bounds” failure

Summary

- Described the difference between **soundness** and **completeness** concerning **detection techniques**
  - **False positive** and **false negative**
- Pointed out the difference between **static analysis** and **testing / simulation**
  - **hybrid combination** of static and dynamic analysis techniques to achieve a good trade-off between **soundness** and **completeness**
- Explained **bounded model checking of software**
  - they have been applied successfully to verify **single-threaded software using a precise memory model**