Detection of Software Vulnerabilities: Static Analysis (Part I)

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Static Analysis

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• Textbook:
  - Model checking (Chapter 14)
  - Software model checking. ACM Comput. Surv., 2009
  - The Cyber Security Body of Knowledge, 2019
  - Software Engineering (Chapters 8, 13)
Motivating Example

- Functionality demanded increased significantly
  - Peer reviewing and testing
Motivating Example

• **Functionality** demanded *increased significantly*
  – Peer reviewing and testing

• Multi-core processors with scalable *shared memory / message passing*
  – Static and dynamic verification
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```c
void *threadA(void *arg) {
  lock(&mutex);
  x++;
  if (x == 1) lock(&lock);
  unlock(&mutex);
  lock(&mutex);
  x--;
  if (x == 0) unlock(&lock);
  unlock(&mutex);
}

void *threadB(void *arg) {
  lock(&mutex);
  y++;
  if (y == 1) lock(&lock);
  unlock(&mutex);
  lock(&mutex);
  y--;
  if (y == 0) unlock(&lock);
  unlock(&mutex);
}
```
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void *threadA(void *arg) {
    lock(&mutex);
    x++;
    if (x == 1) lock(&lock);
    unlock(&mutex); (CS1)
    lock(&mutex);
    x--;
    if (x == 0) unlock(&lock);
    unlock(&mutex);
}

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

void *threadB(void *arg) {
    lock(&mutex);
    y++;
    if (y == 1) lock(&lock); (CS2)
    unlock(&mutex);
    lock(&mutex);
    y--;
    if (y == 0) unlock(&lock);
    unlock(&mutex);
}
```
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    unlock(&mutex);  \(\text{(CS3)}\)
    lock(&mutex);
    x--;
    if (x == 0) unlock(&lock);
    unlock(&mutex);
}

void *threadB(void *arg) {
    lock(&mutex);
    y++;
    if (y == 1) lock(&lock);  \(\text{(CS2)}\)
    unlock(&mutex);
    lock(&mutex);
    y--;
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}
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Motivating Example

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void *threadA(void *arg) {
  lock(&mutex);
  x++;
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  lock(&mutex);  (CS3)
  x--;
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  unlock(&mutex);
}

void *threadB(void *arg) {
  lock(&mutex);
  y++;
  if (y == 1) lock(&lock); (CS2)
  unlock(&mutex);
  lock(&mutex);
  y--;
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}
```

Deadlock
Intended learning outcomes

• Introduce software verification and validation
Intended learning outcomes

• Introduce **software verification** and **validation**
• Understand **soundness** and **completeness** concerning **detection techniques**
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Intended learning outcomes

• Introduce **software verification and validation**
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• Emphasize the difference among **static analysis**, **testing / simulation**, and **debugging**
• Explain **bounded model checking of software**
Intended learning outcomes

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• Explain **precise memory model for software verification**
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Verification vs Validation

• **Verification:** "Are we building the product right?"
  ▪ The software should **conform to its specification**
Verification vs Validation

- **Verification**: "Are we building the product right?"
  - The software should **conform to its specification**
- **Validation**: "Are we building the right product?"
  - The software should do what the **user requires**
Verification vs Validation

- **Verification**: "Are we building the product right?"
  - 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**
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
- Code analysis can prove the absence of errors but might subject to incorrect results
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
  - 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

Static verification
- Requirements specification
- High-level design
- Formal specification
- Detailed design
- Program

Dynamic validation

Prototype

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V & V planning

- Careful planning is required to get the most out of dynamic and static verification
  - Planning should start early in the development process
  - The plan should identify the balance between static and dynamic verification
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V & V planning

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  ▪ Planning should start **early in the development process**
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• V & V should establish confidence that the **software is fit for purpose**

V & V planning depends on system’s purpose, user expectations and marketing environment
The V-model of development

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Detection of Vulnerabilities

• Detect the presence of vulnerabilities in the code during the development, testing, and maintenance
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• Trade-off between soundness and completeness
Detection of Vulnerabilities

- Detect the presence of vulnerabilities in the code during the **development, testing, and maintenance**

- Trade-off between **soundness** and **completeness**
  - 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
Detection of Vulnerabilities

• Detect the presence of vulnerabilities in the code during the development, testing, and maintenance.

• Trade-off between soundness and completeness:
  - 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

- Achieving **soundness** requires reasoning about all **executions** of a program (usually an infinite number)
  - This can be done by static checking of the program code while making suitable abstractions of the executions
Detection of Vulnerabilities

• Achieving soundness requires reasoning about all executions of a program (usually an infinite number)
  ▪ 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
Detection of Vulnerabilities

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

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

Dynamic verification should be used in conjunction with static verification to provide full code coverage.
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• Explain unbounded model checking of software
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 $k$
Breadth-First Search (BFS)

\[
\text{BFS}(G,s)\\
01 \textbf{for} \ \text{each vertex } u \in V[G]-\{s\} \ // \ \text{anchor } (s)\\
02 \quad \text{colour}[u] \leftarrow \text{white} \ // \ u \ \text{colour}\\
03 \quad d[u] \leftarrow \infty \ // \ s \ \text{distance}\\
04 \quad \pi[u] \leftarrow \text{NIL} \ // \ u \ \text{predecessor}\\
05 \quad \text{colour}[s] \leftarrow \text{grey}\\
06 \quad d[s] \leftarrow 0\\
07 \quad \pi[s] \leftarrow \text{NIL}\\
08 \quad \text{enqueue}(Q,s)\\
09 \quad \textbf{while } Q \neq \emptyset \ \textbf{do}\\
10 \quad \quad u \leftarrow \text{dequeue}(Q)\\
11 \quad \quad \textbf{for} \ \text{each } v \in \text{Adj}[u] \ \textbf{do}\\
12 \quad \quad \quad \textbf{If } \ \text{colour}[v] = \text{white} \ \textbf{then}\\
13 \quad \quad \quad \quad \text{colour}[v] \leftarrow \text{grey}\\
14 \quad \quad \quad \quad d[v] \leftarrow d[u] + 1\\
15 \quad \quad \quad \quad \pi[v] \leftarrow u\\
16 \quad \quad \quad \quad \text{enqueue}(Q,v)\\
17 \quad \quad \text{colour}[u] \leftarrow \text{blue}\\
\]

- **Initialization of graph nodes**
- **Initializes the anchor node** (s)
- **Visit each adjacent node of** \( u \)
BFS Example

A graph representation of BFS (Breadth-First Search). The nodes are numbered and connected with edges to illustrate the search order.
BFS Example
BFS Example
BFS Example
BFS Example
BFS Example
BFS Example
BFS Example
Symbolic Execution

- Symbolic execution explores all paths individually
- Can only prove correctness if all paths are explored
Depth-first search (DFS)

DFS\((G)\)
1. for each vertex \(u \in V[G]\)
2. \hspace{1em} do color\([u]\) ← WHITE
3. \hspace{1em} \pi[u] ← NIL
4. \hspace{1em} time ← 0
5. for each vertex \(u \in V[G]\)
6. \hspace{1em} do if color\([u]\) = WHITE
7. \hspace{1em} then DFS-\text{VISIT}(u)

DFS-\text{VISIT}(u)
1. color\([u]\) ← GRAY  \hspace{1em} \triangleright \text{White vertex } u \text{ has just been discovered.}
2. time ← time + 1
3. d\([u]\) ← time
4. for each \(v \in \text{Adj}[u]\)  \hspace{1em} \triangleright \text{Explore edge } (u, v).
5. \hspace{1em} do if color\([v]\) = WHITE
6. \hspace{1em} then \pi[v] ← u
7. \hspace{1em} then DFS-\text{VISIT}(v)
8. color\([u]\) ← BLACK  \hspace{1em} \triangleright \text{Blacken } u; \text{ it is finished.}
9. f\([u]\) ← time ← time + 1

Paint all vertices white and initialize the fields \(\pi\) with NIL where \(\pi[u]\) represents the predecessor of \(u\).
DFS Example
DFS Example
DFS Example
DFS Example
DFS Example
DFS Example

Graph with vertices labeled 0, 1, 2, 3, 4, 5, 6, 7 and edges labeled with ratios.
DFS Example

Diagram showing a graph with nodes 0, 1, 2, 3, 4, 5, and 6 connected by directed edges labeled with fractions.
DFS Example
DFS Example
DFS Example

Diagram representing a depth-first search example.
V&V and debugging

• V & V and debugging are distinct processes
V&V and debugging

- V & V and debugging are distinct processes
- V & V is concerned with establishing the absence or existence of defects in a program, resp.
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• Debugging is concerned with two main tasks
  ▪ Locating and
  ▪ Repairing these errors
V&V and debugging

- V & V and debugging are distinct processes
- V & V is concerned with establishing the absence or existence of defects in a program, resp.
- Debugging is concerned with two main tasks
  - Locating and
  - Repairing these errors
- Debugging involves
  - Formulating a hypothesis about program behaviour
  - Test these hypotheses to find the system error
The debugging process

1. **Test results**
2. **Locate error**
3. **Design error repair**
4. **Repair error**
5. **Re-test program**

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Circuit Satisfiability

• A Boolean formula contains
  ▪ Variables whose values are 0 or 1
Circuit Satisfiability

- A Boolean formula contains
  - **Variables** whose values are 0 or 1
  - **Connectives**: \( \land \) (AND), \( \lor \) (OR), and \( \neg \) (NOT)

<table>
<thead>
<tr>
<th>( x )</th>
<th>( \neg x )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
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<table>
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Circuit Satisfiability

- A Boolean formula contains
  - **Variables** whose values are 0 or 1
  - **Connectives**: $\land$ (AND), $\lor$ (OR), and $\neg$ (NOT)

- 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

\[ SAT: <x_1 = 1, x_2 = 1, x_3 = 0> \]
Circuit-Satisfiability Problem

• Given a Boolean combinational circuit of AND, OR, and NOT gates, is it satisfiable?

CIRCUIT-SAT = {<C> : C is a satisfiable Boolean combinational circuit}
Circuit-Satisfiability Problem

• Given a **Boolean combinational circuit** of AND, OR, and NOT gates, is it **satisfiable**?

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\text{CIRCUIT-SAT} = \{ <C> : C \text{ is a satisfiable Boolean combinational circuit} \} 
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- **Size**: number of **Boolean combinational elements** plus the number of wires
  - if the circuit has **k inputs**, then we would have to check up to \(2^k\) possible assignments
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- **Size**: number of **Boolean combinational elements** plus the number of wires
  - If the circuit has **k inputs**, then we would have to check up to \(2^k\) possible assignments
- When the **size of C** is polynomial in **k**, checking each one takes \(\Omega(2^k)\)
  - Super-polynomial in the size of **k**
Formula Satisfiability (SAT)

• The SAT problem asks whether a given Boolean formula is satisfiable

\[ \text{SAT} = \{<\Phi> : \Phi \text{ is a satisfiable Boolean formula}\} \]
The SAT problem asks whether a given Boolean formula is satisfiable.

Example:

\[ \Phi = ((x_1 \rightarrow x_2) \lor \neg((\neg x_1 \leftrightarrow x_3) \lor x_4)) \land \neg x_2 \]

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**Formula Satisfiability (SAT)**

- The SAT problem asks whether a given Boolean formula is satisfiable.

SAT = \{ <\Phi> : \Phi \text{ is a satisfiable Boolean formula} \}

- Example:
  - $\Phi = ((x_1 \rightarrow x_2) \lor \lnot((\lnot x_1 \leftrightarrow x_3) \lor x_4)) \land \lnot x_2$
  - Assignment: $<x_1 = 0, x_2 = 0, x_3 = 1, x_4 = 1>$
Formula Satisfiability (SAT)

- The SAT problem asks whether a given Boolean formula is satisfiable

\[
\text{SAT} = \{ \langle \Phi \rangle : \Phi \text{ is a satisfiable Boolean formula} \}
\]

- **Example:**
  - \( \Phi = ((x_1 \to x_2) \lor \neg((\neg x_1 \leftrightarrow x_3) \lor x_4)) \land \neg x_2 \)
  - Assignment: \( \langle x_1 = 0, x_2 = 0, x_3 = 1, x_4 = 1 \rangle \)
  - \( \Phi = ((0 \to 0) \lor \neg((\neg 0 \leftrightarrow 1) \lor 1)) \land \neg 0 \)
Formula Satisfiability (SAT)

- The SAT problem asks whether a given Boolean formula is satisfiable

SAT = {<Φ> : Φ is a satisfiable Boolean formula}

- Example:
  - Φ = ((x₁ → x₂) ∨ ¬((¬x₁ ↔ x₃) ∨ x₄)) ∧ ¬x₂
  - Assignment: <x₁ = 0, x₂ = 0, x₃ = 1, x₄ = 1>
  - Φ = ((0 → 0) ∨ ¬((¬0 ↔ 1) ∨ 1)) ∧ ¬0
  - Φ = (1 ∨ ¬(1 ∨ 1)) ∧ 1
Formula Satisfiability (SAT)

- The SAT problem asks whether a given Boolean formula is satisfiable.

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**Example:**

- \( \Phi = ((x_1 \rightarrow x_2) \lor \neg((\neg x_1 \leftrightarrow x_3) \lor x_4)) \land \neg x_2 \)
- Assignment: \( <x_1 = 0, x_2 = 0, x_3 = 1, x_4 = 1> \)
- \( \Phi = ((0 \rightarrow 0) \lor \neg((\neg 0 \leftrightarrow 1) \lor 1)) \land \neg 0 \)
- \( \Phi = (1 \lor \neg(1 \lor 1)) \land 1 \)
- \( \Phi = (1 \lor 0) \land 1 \)
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  \[
  \Phi = ((0 \rightarrow 0) \lor \neg((\neg 0 \leftrightarrow 1) \lor 1)) \land \neg 0
  \]
  
  \[
  \Phi = (1 \lor \neg(1 \lor 1)) \land 1
  \]
  
  \[
  \Phi = (1 \lor \neg(1 \lor 1)) \land 1
  \]
  
  \[
  \Phi = 1
  \]
DPLL satisfiability solving

Given a Boolean formula $\varphi$ in clausal form (an AND of ORs)

$\{\{a, b\}, \{\neg a, b\}, \{a, \neg b\}, \{\neg a, \neg b\}\}$

determine whether a satisfying assignment of variables to truth values exists.
DPLL satisfiability solving

Given a Boolean formula $\phi$ in *clausal form* (an AND of ORs)

$$\{\{a, b\}, \{\neg a, b\}, \{a, \neg b\}, \{\neg a, \neg b\}\}$$

determine whether a *satisfying assignment* of variables to truth values exists.

Solvers based on Davis-Putnam-Logemann-Loveland algorithm:

1. If $\phi = \emptyset$ then SAT
2. If $\Box \in \phi$ then UNSAT
3. If $\phi = \phi' \cup \{x\}$ then DPLL($\phi'[x \mapsto \text{true}]$)
   If $\phi = \phi' \cup \{\neg x\}$ then DPLL($\phi'[x \mapsto \text{false}]$)
4. Pick arbitrary $x$ and return
   DPLL($\phi[x \mapsto \text{false}]$) $\lor$ DPLL($\phi[x \mapsto \text{true}]$)
**DPLL satisfiability solving**

Given a Boolean formula $\phi$ in *clausal form* (an AND of ORs)

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   If $\phi = \phi' \cup \{\neg x\}$ then DPLL($\phi'[x \mapsto \text{false}]$)
4. Pick arbitrary $x$ and return $\text{DPLL}(\phi[x \mapsto \text{false}]) \lor \text{DPLL}(\phi[x \mapsto \text{true}])$

+ NP-complete but many heuristics and optimizations

⇒ can handle problems with 100,000’s of variables
SAT solving as enabling technology
SAT Competition

[Graph showing CPU time vs. number of solved instances for various SAT solvers]
Bounded Model Checking (BMC)

**MC:** check if a property holds for all states

```
Init  . . .  error
```
Bounded Model Checking (BMC)

**MC:** check if a property holds for all states

**BMC:** check if a property holds for a subset of states
Bounded Model Checking (BMC)

MC:

M, S → IS THERE ANY ERROR?

no → ok

yes → fail
Bounded Model Checking (BMC)

**MC:**

- **M, S**

**IS THERE ANY ERROR?**

- **no** → ok
- **yes** → fail

**BMC:**

- **M, S**

**IS THERE ANY ERROR IN K STEPS?**

- **k+1** still tractable → ok
- **completeness threshold reached** → ok
- **k+1** intractable → fail

“never” happens in practice
Bounded Model Checking

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

\[ \neg \varphi_0 \lor \neg \varphi_1 \lor \neg \varphi_2 \lor \cdots \lor \neg \varphi_{k-1} \lor \neg \varphi_k \]

counterexample trace

transition system

property

bound
Bounded Model Checking

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

• transition system $M$ unrolled $k$ times
  – for programs: unroll loops, unfold arrays, ...

![Diagram of transition system with $\neg \varphi_0 \lor \neg \varphi_1 \lor \neg \varphi_2 \lor \ldots \lor \neg \varphi_{k-1} \lor \neg \varphi_k$ and corresponding labeled states $M_0, M_1, M_2, \ldots, M_{k-1}, M_k$.]

property

bound

counterexample trace

transition system
Bounded Model Checking

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

- transition system $M$ unrolled $k$ times
  - for programs: unroll loops, unfold arrays, ...
- translated into verification condition $\psi$ such that
  $\psi$ satisfiable iff $\varphi$ has counterexample of max. depth $k$
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- has been applied successfully to verify HW/SW systems
Satisfiability Modulo Theories (1)

SMT decides the **satisfiability** of first-order logic formulae using the combination of different **background theories** (building-in operators)
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• Checking $\Gamma \vDash_T \varphi$ can be reduced in the usual way to checking the T-satisfiability of $\Gamma \cup \{\neg \varphi\}$
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- let \( a \) be an array, \( b, c \) and \( d \) be signed bit-vectors of width 16, 32 and 32 respectively, and let \( g \) be an unary function.
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\( \downarrow \) \( \mathbf{b}' \) extends \( \mathbf{b} \) to the signed equivalent bit-vector of size 32

step 1: \( g(\text{select}(\text{store}(\mathbf{a}, \mathbf{c}, 12), \mathbf{b}' + 3)) \neq g(\mathbf{b}' - \mathbf{c} + 4) \land \mathbf{b}' = \mathbf{c} - 3 \land \mathbf{c} + 1 = \mathbf{d} - 4 \)
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**step 1:** \( g(\text{select}(\text{store}(a, c, 12), b' + 3)) \neq g(b' - c + 4) \land b' = c - 3 \land c + 1 = d - 4 \)

\( \downarrow \) replace \( b' \) by \( c - 3 \) in the inequality

**step 2:** \( g(\text{select}(\text{store}(a, c, 12), c' - 3 + 3)) \neq g(c' - 3 - c + 4) \land c' - 3 = c - 3 \land c + 1 = d - 4 \)
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using facts about bit-vector arithmetic

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applying the theory of arrays

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The function \( g \) implies that for all \( x \) and \( y \),
if \( x = y \), then \( g(x) = g(y) \) (congruence rule).

\[
\Downarrow
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step 5: SAT (\( c = 5 \), \( d = 10 \))
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- SMT solvers also apply:
  - standard algebraic reduction rules
    \[ r \land \text{false} \rightarrow \text{false} \]
  - contextual simplification
    \[ a = 7 \land p(a) \rightarrow a = 7 \land p(7) \]
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
  - Loop iterations
  - Context switches
- Unfolded program optimized to reduce blow-up
  - Constant propagation
  - Forward substitutions

```c
int main() {
    int a[2], i, x;
    if (x==0)
        a[i]=0;
    else
        a[i+2]=1;
    assert(a[i+1]==1);
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\[
g_1 = x_1 == 0
a_1 = a_0 \text{ WITH } [i_0:=0]
\]
\[
a_2 = a_0
a_3 = a_2 \text{ WITH } [2+i_0:=1]
\]
\[
a_4 = g_1 ? a_1 : a_3
\]
\[
t_1 = a_4 [1+i_0] == 1
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- Extraction of constraints C and properties P
  - Specific to selected SMT solver, uses theories

- Satisfiability check of $C \land \neg P$

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Encoding of Numeric Types

- SMT solvers typically provide different encodings for numbers:
  - abstract domains ($\mathbb{Z}$, $\mathbb{R}$)
  - fixed-width bit vectors (unsigned int, ...)
    - “internalized bit-blasting”
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\[(a > 0) \land (b > 0) \Rightarrow (a + b > 0)\]
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$$(a > 0) \land (b > 0) \Rightarrow (a + b > 0)$$

valid in abstract domains such as $\mathbb{Z}$ or $\mathbb{R}$

doesn’t hold for bitvectors, due to possible overflows
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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

- type casts and implicit conversions
  - arithmetic conversions implemented using word-level functions (part of the bitvector theory: Extract, SignExt, …)
    - different conversions for every pair of types
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  - conversion to / from bool via if-then-else operator
    \[
    t = \text{ite}(v \neq k, \text{true}, \text{false}) \quad \text{//conversion to bool}
    \]
    \[
    v = \text{ite}(t, 1, 0) \quad \text{//conversion from bool}
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  - standard requires modulo-arithmetic for unsigned integer
    \[ \text{unsigned\_overflow} \Leftrightarrow (r - (r \mod 2^w)) < 2^w \]
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- arithmetic over- / underflow
  - standard requires modulo-arithmetic for unsigned integer
    $$\text{unsigned}_\text{overflow} \iff (r - (r \mod 2^w)) < 2^w$$
  - define error literals to detect over- / underflow for other types
    $$\text{res}_\text{op} \iff \neg \text{overflow}(x, y) \land \neg \text{underflow}(x, y)$$
    - similar to conversions
Floating-Point Numbers

- Over-approximate floating-point by fixed-point numbers
  - encode the integral (i) and fractional (f) parts
Floating-Point Numbers

- Over-approximate floating-point by fixed-point numbers
  - encode the integral (i) and fractional (f) parts
- **Binary encoding**: get a new bit-vector $b = i \oplus f$ with the same bitwidth before and after the radix point of $a$.

$$i = \begin{cases} 
  \text{Extract}(b, n_b + m_a - 1, n_b) & : \ m_a \leq m_b \\
  \text{SignExt(Extract}(b, \ t_b - 1, n_b), m_a - m_b) & : \ \text{otherwise}
\end{cases}$$

$$f = \begin{cases} 
  \text{Extract}(b, n_b - 1, n_b - n_b) & : \ n_a \leq n_b \\
  \text{Extract}(b, n_b, 0) \oplus \text{SignExt}(b, n_a - n_b) & : \ \text{otherwise}
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  \text{Extract}(b, n_b, 0) \oplus \text{SignExt}(b, n_a - n_b) & : \quad \text{otherwise}
\end{cases}
\]

• **Rational encoding:** convert \( a \) to a rational number

\[
a = \begin{cases} 
  \left( i \cdot p + \left( \frac{f \cdot p}{2^n} + 1 \right) \right) & : \quad f \neq 0 \\
  p & : \quad \text{otherwise}
\end{cases}
\]

\[\quad \text{where} \quad p = \text{number of decimal places}\]
Floating-point SMT Encoding

• The SMT floating-point theory is an addition to the SMT standard, proposed in 2010 and formalises:
  ▪ Floating-point arithmetic
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  ▪ 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
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• Missing from the standard:
  ▪ Floating-point exceptions
  ▪ Signaling NaNs
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• Two solvers currently support the standard:
  ▪ Z3: implements all operators
  ▪ MathSAT: implements all but two operators
    o \textit{fp.rem}: remainder: x - y \times n, where n in Z is nearest to \( x/y \)
    o \textit{fp.fma}: fused multiplication and addition; \((x \times y) + z\)
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    o $fp\textunderscore fma$: fused multiplication and addition; $(x \times y) + z$

• Both solvers offer non-standard functions:
  ▪ $fp\_as\_ieeebv$: converts floating-point to bitvectors
  ▪ $fp\_from\_ieeebv$: 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

```c
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

```plaintext
(assert (= (ite |main::c|
            (fp #b0 #b01111111111 #x000000000000000)
            (fp #b0 #b00000000000 #x000000000000000))
  |main::b|))
```
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```plaintext
(assert (= (ite |main::c| (fp #b0 #b01111111111 #x0000000000000000) (fp #b0 #b000000000000 #x0000000000000000)) |main::b|))
```

*If true, assign 1f to b*
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(assert (= (ite |main::c|
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|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 #b0000000000000 #x0000000000000000))
            |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 operators evaluate to false if one of their arguments is NaN."
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    ```c
    (assert (= (not (fp.eq |main::b| (fp #b0 #b0000000000000 #x0000000000000000)))
             |main::c|))
    ```

    true when the floating is not 0.0

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"(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 operators evaluate to false if one of their arguments is NaN."
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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 #b000000000000 #x0000000000000000)))
         |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 operators evaluate to false if one of their arguments is NaN."
Floating-point Encoding: Illustrative Example

```c
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 nondeterministic 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))))
Floating-point Encoding: Illustrative Example

; declaration of x and y
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(assert (= |main::x| |main::y|))

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

Floating-point Encoding: Illustrative Example

; declaration of x and y
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                          (=> |execution_statet::\guard_exec|
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(assert (= |nondet_symex::nondet0| |main::x|))

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

; assert x == y
(assert (let ((a!1 (not (=> true
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                      (=> |execution_statet::\guard_exec|
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             (or a!1))))
Floating-point Encoding: Illustrative Example

; declaration of x and y
(declare-fun \texttt{main::x} () (_ FloatingPoint 8 24))
(declare-fun \texttt{main::y} () (_ FloatingPoint 8 24))

; symbol created to represent a nondeterministic number
(declare-fun \texttt{nondet_symex::nondet0} () (_ FloatingPoint 8 24))

; Global guard, used for checking properties
(declare-fun \texttt{execution_statet::\textbackslash\textbackslash guard_exec} () Bool)

; assign the nondeterministic symbol to x
(assert (= \texttt{nondet_symex::nondet0} \texttt{main::x})

; assign x to y
(assert (= \texttt{main::x} \texttt{main::y}))

; assert x == y
(assert (let ((a!1 (not (=> true
                        (= \texttt{execution_statet::\textbackslash\textbackslash guard_exec}
                            (fp.eq \texttt{main::x} \texttt{main::y})))))
            (or a!1)))))
Floating-point Encoding: Illustrative Example

- Z3 produces:

```plaintext
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:

```prolog
sat
  ( (\(\text{main}::\text{x}\)) (\_ \text{NaN} 8 24))
  ( (\(\text{main}::\text{y}\)) (\_ \text{NaN} 8 24))
  ( (\(\text{nondet\_symex}::\text{nondet0}\)) (\_ \text{NaN} 8 24))
  ( (\(\text{execution\_statet}::\\\text{guard\_exec}\)) true) )
```
Floating-point Encoding:
Illustrative Example

Counterexample:

State 1 file main3.c line 3 function main thread 0
main

---------------------------------------------
main3::main::1::x=-NaN (1111111110000000000000000000000001)

State 2 file main3.c line 4 function main thread 0
main

---------------------------------------------
main3::main::2::y=-NaN (1111111110000000000000000000000001)

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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```c
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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        a[i+1]=1;
    assert(*(p+2)==1);
}
```

C:=

\[
\begin{align*}
p_1 & := \text{store}(p_0, 0, \&a[0]) \\
\land p_2 & := \text{store}(p_1, 1, 0) \\
\land g_2 & := (x_2 == 0) \\
\land a_1 & := \text{store}(a_0, i_0, 0) \\
\land a_2 & := a_0 \\
\land a_3 & := \text{store}(a_2, 1+ i_0, 1) \\
\land a_4 & := \text{ite}(g_1, a_1, a_3) \\
\land p_3 & := \text{store}(p_2, 1, \text{select}(p_2, 1)+2)
\end{align*}
\]
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```c
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);
}
```

\[
\begin{align*}
\text{C} := & \quad p_1 := \text{store}(p_0, 0, \&a[0]) \\
& \quad \land p_2 := \text{store}(p_1, 1, 0) \\
& \quad \land g_2 := (x_2 == 0) \\
& \quad \land a_1 := \text{store}(a_0, i_0, 0) \\
& \quad \land a_2 := a_0 \\
& \quad \land a_3 := \text{store}(a_2, 1 + i_0, 1) \\
& \quad \land a_4 := \text{ite}(g_1, a_1, a_3) \\
& \quad \land p_3 := \text{store}(p_2, 1, \text{select}(p_2, 1)+2)
\end{align*}
\]

Store object at position 0
Encoding of Pointers

- arrays and records / tuples typically handled directly by SMT-solver
- pointers modelled as tuples
  - \( p.o \triangleq \) representation of underlying object
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```c
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);
}
```

\[
\begin{align*}
p_1 & := \text{store}(p_0, 0, &a[0]) \\
p_2 & := \text{store}(p_1, 1, 0) \\
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a_1 & := \text{store}(a_0, i_0, 0) \\
a_2 & := a_0 \\
a_3 & := \text{store}(a_2, 1 + i_0, 1) \\
a_4 & := \text{ite}(g_1, a_1, a_3) \\
p_3 & := \text{store}(p_2, 1, \text{select}(p_2, 1)+2)
\end{align*}
\]

\text{Store object at position 0}
\text{Store index at position 1}
Encoding of Pointers

- arrays and records / tuples typically handled directly by SMT-solver
- pointers modelled as tuples
  - $p.o \triangleq$ representation of underlying object
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```c
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);
}
```
Encoding of Pointers

- arrays and records / tuples typically handled directly by SMT-solver
- pointers modelled as tuples
  - \( p.o \triangleq \) representation of underlying object
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```c
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);
}
```

\[
P := \neg \text{satisfiable (a[2] unconstrained)} \Rightarrow \text{assert fails}
\]
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
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 $d_\circ$ consists of
  - $m \triangleq$ memory array
  - $s \triangleq$ size in bytes of $m$
  - $\rho \triangleq$ unique identifier
  - $\nu \triangleq$ 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
  - $m \triangleq$ memory array
  - $s \triangleq$ size in bytes of $m$
  - $\rho \triangleq$ unique identifier
  - $\nu \triangleq$ indicate whether the object is still alive
  - $l \triangleq$ 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
  
  $$l_{is\_dynamic\_object} \iff \left( \forall_{j=1}^{k} d_o \cdot \rho = j \right) \land (0 \leq i < n)$$
Encoding of Memory Allocation

• to check for invalid objects, we
  – set \( \nu \) to \textit{true} if the function \texttt{malloc} can allocate memory (\( d_o \) is alive)
  – set \( \nu \) to \textit{false} if the function \texttt{free} is called (\( d_o \) is not longer alive)

\[ l_{\text{valid\_object}} \iff (l_{\text{is\_dynamic\_object}} \Rightarrow d_o \cdot \nu) \]
Encoding of Memory Allocation

• to check for invalid objects, we
  – set \( \nu \) to \textit{true} if the function \texttt{malloc} can allocate memory (\( d_o \) is alive)
  – set \( \nu \) to \textit{false} if the function \texttt{free} is called (\( d_o \) is not longer alive)

\[
\text{l}_{\text{valid\_object}} \iff (\text{l}_{\text{is\_dynamic\_object}} \Rightarrow d_o \cdot \nu)
\]

• to detect forgotten memory, at the end of the (unrolled) program we check
  – whether the \( d_o \) has been deallocated by the function \texttt{free}

\[
\text{l}_{\text{deallocated\_object}} \iff (\text{l}_{\text{is\_dynamic\_object}} \Rightarrow \neg d_o \cdot \nu)
\]
Example of Memory Allocation

```c
#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)
}
```

Assume that the malloc call succeeds
Example of Memory Allocation

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#include <stdlib.h>

void main() {
    char *p = malloc(5);  // ρ = 1
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    p = q;
    free(p)
    p = malloc(5);       // ρ = 3
    free(p)
}
```

memory leak: pointer reassignment makes d_{01,\nu} to become an orphan.
#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)
}

\[ P := \neg d_{o1}.v \land \neg d_{o2}.v \land \neg d_{o3}.v \]

\[ C := \begin{cases} 
    d_{o1}.\rho=1 \land d_{o1}.s=5 \land d_{o1}.v=true \land p=d_{o1} \\
    \land d_{o2}.\rho=2 \land d_{o2}.s=5 \land d_{o2}.v=true \land q=d_{o2} \\
    \land p=d_{o2} \land d_{o2}.v=false \\
    \land d_{o3}.\rho=3 \land d_{o3}.s=5 \land d_{o3}.v=true \land p=d_{o3} \\
    \land d_{o3}.v=false
\end{cases} \]
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    p = malloc(5); // ρ = 3
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}
```

\[ P := \left( \neg d_{o1}.u \wedge \neg d_{o2}.u \wedge \neg d_{o3}.u \right) \]

\[ C := \left\{ \begin{array}{l}
    d_{o1}.\rho=1 \wedge d_{o1}.s=5 \wedge d_{o1}.u=true \wedge p=d_{o1} \\
    \wedge d_{o2}.\rho=2 \wedge d_{o2}.s=5 \wedge d_{o2}.u=true \wedge q=d_{o2} \\
    \wedge p=d_{o2} \wedge d_{o2}.u=false \\
    \wedge d_{o3}.\rho=3 \wedge d_{o3}.s=5 \wedge d_{o3}.u=true \wedge p=d_{o3} \\
    \wedge d_{o3}.u=false
\end{array} \right. \]
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
Align-guaranteed memory mode

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  ▪ 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
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
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

```c
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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- SAT: immediate access to bit-level representation
ESBMC’s memory model

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*quux;  // pointer and object types do not match
```

- SMT: sorts must be repeatedly unwrapped
Byte-level data extraction in SMT

• access to underlying data bytes is complicated
  – requires manipulation of arrays / tuples
Byte-level data extraction in SMT

• access to underlying data bytes is complicated
  – requires manipulation of arrays / tuples

• problem is magnified by nondeterministic offsets

```c
uint16_t *fuzz;
if (nondet_bool()) {
  fuzz = &qux.bar[0];
} else {
  fuzz = &qux.baz;
}
```

– chooses accessed field nondeterministically
– requires a `byte_extract` expression
– handles the `tuple` that encoded the `struct`
Byte-level data extraction in SMT

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  – chooses accessed field nondeterministically
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• supporting **all legal behaviors** at SMT layer **difficult**
  – extract (unaligned) 16bit integer from `*fuzz`
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  – extract (unaligned) 16bit integer from `*fuzz`

• experiments showed significantly increased **memory consumption**
“Aligned” Memory Model

• framework cannot easily be changed to SMT-level byte representation (a la LLBMC)
“Aligned” Memory Model

• framework cannot easily be changed to SMT-level byte representation (a la LLBMC)
• push unwrapping of SMT data structures to dereference
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- enforce C alignment rules
  - static analysis of pointer alignment eliminates need to encode unaligned data accesses
    → reduces number of behaviors that must be modeled
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“Aligned” Memory Model

- framework cannot easily be changed to SMT-level byte representation (a la LLBMC)
- push unwrapping of SMT data structures to dereference
- **enforce C alignment rules**
  - static analysis of pointer alignment eliminates need to encode unaligned data accesses
    → reduces number of behaviors that must be modeled
  - add alignment assertions (if static analysis not conclusive)
  - extracting 16-bit integer from *fuzz* if guard is true:
    - 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