Verifying source code

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Main topics of the lecture

Program Verification Overview

- Verification Goals
- Analysis Properties
- Analysis Methods

Model Checking with SMT

- SMT Problem
- Technique
- Advantages
- Disadvantages

Practical Software Verification

- Challenges
- Tools

Example

```
k = ioread32();
i = 2;
j = k + 5;
while (i < 10) {
    i = i + 1;
    j = j + 3;
}
k = k / (i - j);
```

Division by zero?
For what *k*?

```
Verification FAILED.
  Divison by zero in example.c at line 14 column 11.
Error trace:
------------
#0 in function main():
  call ioread32() returned -19   at 6:13
  k := -19        at 6:13
  i := 2
  j := -14        at 8:15

  ...

  i := 10         at 10:15
  j := 10         at 11:15
  j := 10
  i := 10
```

Typical verification goals

- Improper resource management
  - Resource leaks: memory, files, sockets
- Illegal operations
  - Division by zero, overflow, index out-of-bounds, null pointer, **assertions**
- Dead code and data
  - Code and data not reached or used
- Incomplete code
  - Uninitialized variables, unspecified return values, missing cases in switch
- Other
  - Non-termination, uncaught exceptions, race conditions

+ security

dl.acm.org/citation.cfm?id=1390956

Analysis Properties

		Analysis	
		Correct	Faulty
Source code	Correct	Proven correct	False alarm
	Faulty	Missed bug	Found bug

Analysis properties

- Checking most of the run time properties is computationally complex or undecidable (see *Theory of Algorithms* course)
- Approximations: sacrifice precision to save analysis time
  - Flow sensitive < Path sensitive < Interprocedural
- Precision
  - False positive (false alarm): report an error that does not cause a real problem
  - False negative (missed bug): an actual problem does not get reported

		Analysis	
		Correct	Faulty
Source code	Correct	Proven correct	False alarm
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Flow sensitive

- Execution order of program statements is considered

- Example
  - Flow insensitive: x and y might point to same location
  - Flow sensitive: x and y might point to same location after line 6

```
1: int* x = malloc(...)
2: int* y = malloc(...)
3: *x = ...
4: *y = ...
5: f(*x, *y)
6: x = g()
7: y = g()
```

Path sensitive

- Distinguish between different execution paths
- Consider only feasible paths

- Example
  - Path insensitive: division by 0 possible at line 5
  - Path sensitive: division by 0 is not possible

```
1: f(int a, int b) {
2:     if (a == b) {
3:         return 0
4:     } else {
5:         return 1 / (a - b)
6:     }
7: }
```

Interprocedural

- Analyze method body at each call site
  - Otherwise it is called *intra*-procedural

- Example
  - Intraprocedural: create might return null pointer
  - Interprocedural: create never returns null, x can be dereferenced

```
int* create(int i) {
    int* p = malloc(...)
    if (p == NULL) exit(1)
    *p = i
    return p
}

void main() {
    int* x = create(5)
    print(*x)
}
```

Analysis Methods

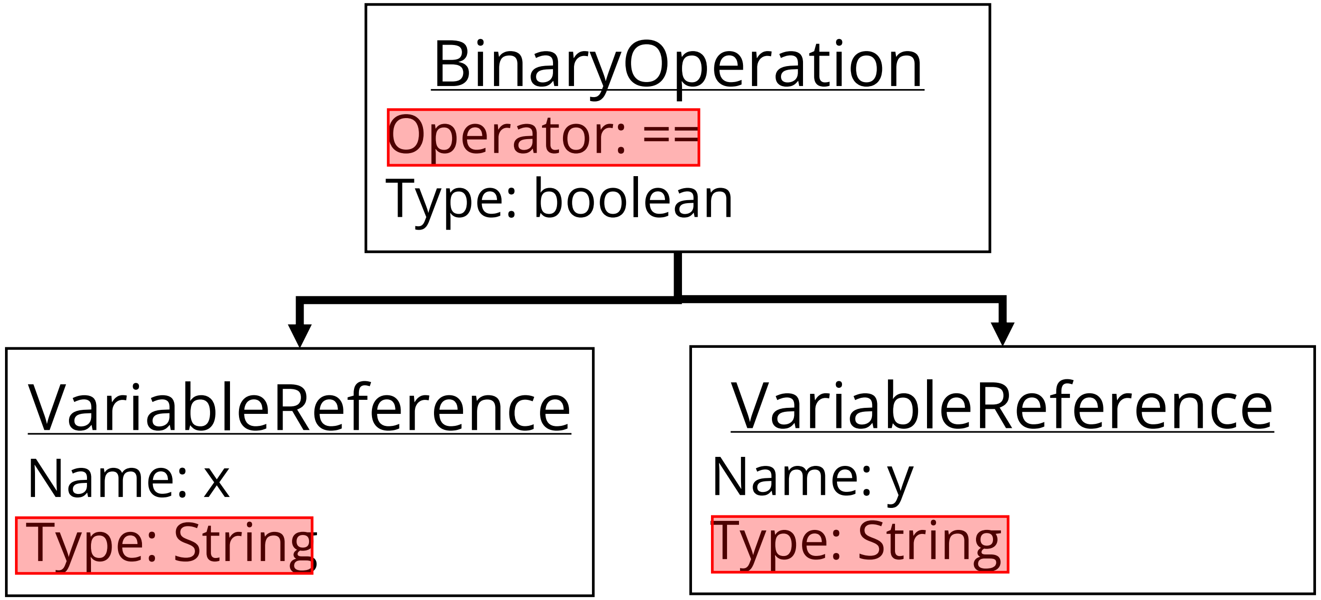
- Pattern-based
- Model checking
- Theorem proving

Pattern-based

- Syntactic pattern matching
  - Usually based on the AST (Abstract Syntax Tree)

```
f(String x, String y) {
    if (x == y) {
        …
    }
}
```

Use equals instead of == (Java)



Pattern-based (properties)

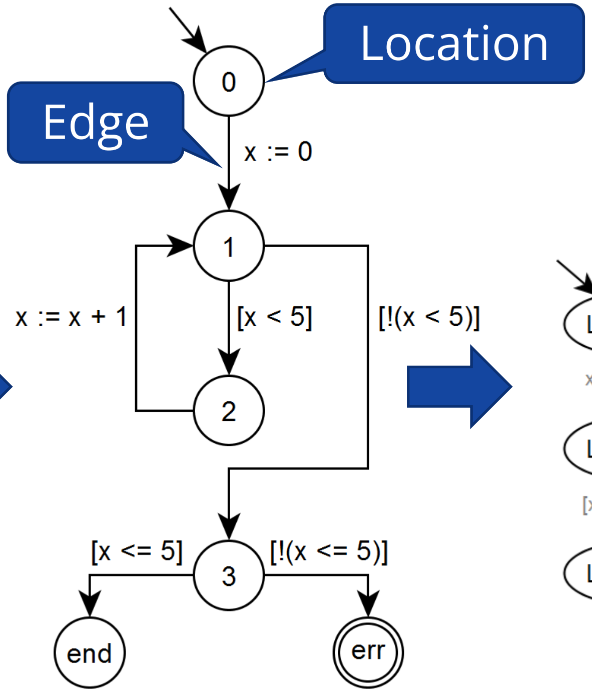
- Typically path and context insensitive
- Can analyze very large projects
- Fully automated
- Simple properties (patterns)
- Produce many false positives and false negatives

Model checking

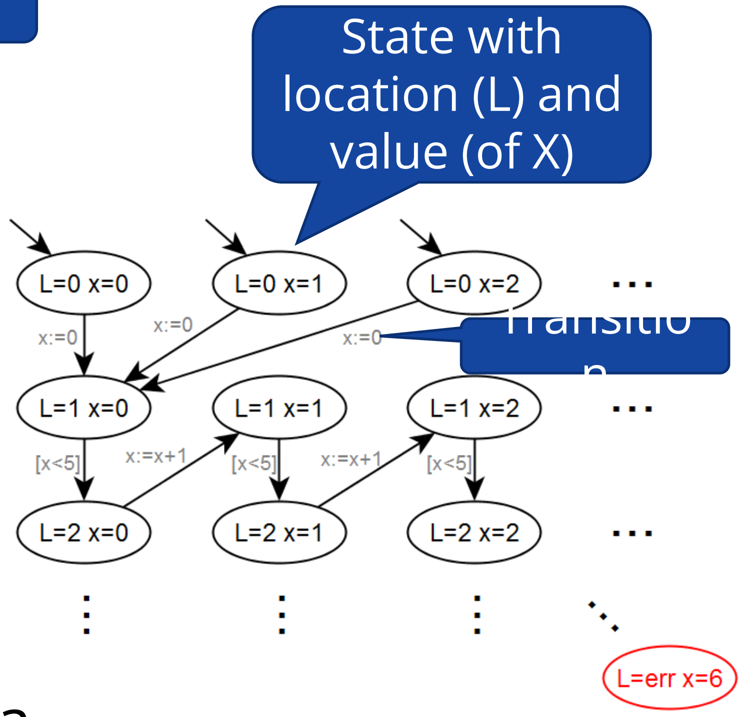
- Describe program and property in a formal language
- Enumerate all states and transitions

```
   x : int
0: x = 0
1: while (x < 5) {
2:     x = x + 1
   }
3: assert (x <= 5)
```

Program



Control Flow Automata (formal representation)



States and transitions

Model checking (properties)

- Flow and path sensitive
- Can be context sensitive and interprocedural
- Usually automated, but might require user annotations
- Fully formal: no false alarms, no missed bugs (w.r.t. property)
- Limited scalability
  - Symbolic techniques, bounded model checking, abstraction

Theorem proving

- Describe the program and property with logical formulas
- Apply inference rules to prove that the program satisfies the property

```
int abs(int x) {
    if (x < 0) {
        r = -x
    } else {
        r = x
    }
    return r
}
```

r >= 0 ?

$$(x < 0) \land (r = -x) \lor (x \geq 0) \land (r = x) \Rightarrow r \geq 0$$

Theorem proving (properties)

- Fully formal: no false alarms, no missed bugs (w.r.t. property)
- Manual user assistance is usually required
- Formal methods expertise required

Analysis methods: Summary

- General experience, but exceptions are possible
- Combined methods are possible

Method	Flow sensitive	Path sensitive	Context sensitive	Interprocedural	Arbitrary property	Automated	No false alarms	No missed bugs	Large codebase
Pattern matching	X	X	X	X	X	✓	X	X	✓
Model checking	✓	✓	(✓)	(✓)	✓	(✓)	✓	✓	(X)
Theorem proving	✓	✓	(✓)	(✓)	✓	(X)	✓	✓	X

Satisfiability Modulo Theories

Z3

CVC5

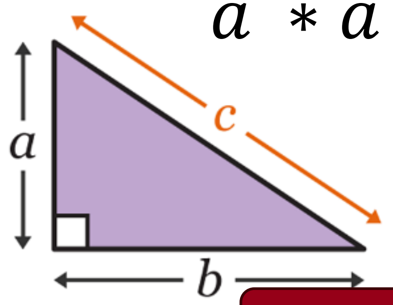
MathSAT 5

An SMT Solver for Formal Verification & More

SMT – Satisfiability Modulo Theories

- **Satisfiability**
  - *Given a logical formula, how to assign **values** to **symbols** to make it true?*

$$a * a + b * b = c * c$$



SAT

a	b	c
0	0	0
3	4	5
…	…	…

$$a < b \text{ and } b > a$$

UNSAT

- **Modulo Theories**
  - *What is the **semantics** of **operations**?*
  - *Overflow (UB)? Wraparound? Infinite integers?*

$$a = 127 + 1$$

Model Checking with SMT

```
k = ioread32();
i = 2;
j = k + 5;
i = i + 1;
j = j + 3;
k = k/(i - j);
```

input

Precise, can create test case

Complex, specialized SW needed

```
k⁰ = ioread32();
i⁰ = 2;
j⁰ = k⁰ + 5;
i¹ = i⁰ + 1;
j¹ = j⁰ + 3;
assert(i¹–j¹!=0);
k¹ = k⁰/(i¹ – j¹);
```

Static-Single-Assignment Form

```
Input: free variable
i0 = 2
j0 = k0 + 5
i1 = i0 + 1
j1 = j0 + 3
i1-j1 == 0 (negated!)
k1 = k0 / (i1 – j1)
```

SMT

SAT:	unsafe
UNSAT:	safe

Practical Software Verification

Challenges

- Language standards: rarely formal!
  - **Undefined behavior**: *anything* can happen – we cannot verify!
    - *Example in C:* data races, signed overflow (before C23)
      If anything can happen, why not assume the program is unsafe?
  - **Unspecified behavior**: *several things* can happen – who decides?
    - *Example in C:* when you call `f(g(), h())`, which of *`g()`* and *`h()`* is executed first?
      CLANG and GCC disagree! Which to choose?
- Floating points, arrays, structs, linked lists, trees, ...
  - Hard to transform into SMT
  - Floating points: differing standards (e.g.: C floats and Java floats differ!)

Pattern-based

- FindBugs (SpotBugs)
  - spotbugs.github.io
  - Java
  - 400+ bug patterns in different categories

- Error Prone (by Google)
  - errorprone.info
  - Java
  - 300+ bug patterns in different categories

Smart pattern-based (using additional techniques)

- Sonar{lint/cloud/qube}
  - sonarsource.com
  - 20+ languages, including Java, C#, C, C++
  - Code quality management platform
- PMD
  - pmd.github.io
  - Java, JavaScript, PLSQL
- Coverity
  - synopsys.com
  - Many languages, including Java, C, C++, C#, Python, JS

Model checker

- CPAchecker
  - Configurable software-verification platform
  - Input: C program + specification
    - Assertion, error label, deadlock, null dereference, ...
  - Highly configurable
    - Different kinds of abstractions
    - Various algorithms and strategies
- Theta
  - Generic, configurable and modular verification framework
  - Gazer: LLVM-based frontend for C programs
  - Abstraction-based algorithms for state reachability

github.com/FTSRG/theta
cpachecker.sosy-lab.org

Model checker

- SLAM
  - Part of Static Driver Verifier Research Platform (SDVRP)
  - Structure
    - Driver C code: analyzed components
    - Platform model: describe environment
    - Analysis: adherence to API usage rules
  - Applies abstraction and symbolic model checking

microsoft.com/en-us/research/project/slam

Theorem prover

- PVS
  - Specification language
  - Pre-defined theories
  - Integrated type checker, theorem prover and symbolic model checker
  - Utilities, e.g., code generator, random tester

SRI International

```
sum: THEORY
  BEGIN

   n: VAR nat
   f, g: VAR [nat -> nat]

   sum(f, n): RECURSIVE nat =
  (IF n = 0
      THEN 0
      ELSE f(n-1) + sum(f, n - 1)
   ENDIF)
  MEASURE n
```

```
sum_plus: LEMMA
   sum((lambda n: f(n) + g(n)), n)
  = sum(f, n) + sum(g, n)

 square(n): nat = n*n

 sum_of_squares: LEMMA
   6 * sum(square, n+1) = n * (n + 1) * (2*n + 1)

 cube(n): nat = n*n*n

 sum_of_cubes: LEMMA
   4 * sum(cube, n+1) = n*n*(n+1)*(n+1)

END sum
```

pvs.csl.sri.com

Using static verification in practice

- J. Carmack. In-Depth: Static Code Analysis
  - “**it is irresponsible to not use it**”
  - “there was an epic multi-programmer, multi-day bug hunt that wound up being traced to something that `/analyze` had flagged, but I hadn't fixed yet.”

- A few Billion Lines of code Later using static Analysis to find Bugs in the Real World
  - Turning a prototype into commercial tool
  - “False positives do matter. In our experience, more than 30% easily cause problems. People ignore the tool. True bugs get lost in the false.”

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Using verification in practice

- [Lessons from Building Static Analysis Tools at Google]
  - "Static analysis authors should focus on developer feedback"
  - "Crowdsourcing analysis development"
- [Facebook: Moving Fast with Software Verification]
  - Developers should see analysis results as part of their normal workflow, no context switch should be required
- [Amazon: Code Level Model-Checking in the Software Development Workflow]
  - Experience report on applying model checking at AWS
  - "AWS developers are increasingly writing their own formal specifications"