Program Verification

Agenda

Famous bugs

Common bugs

Testing (from lecture 6)

Reasoning about programs

Techniques for program verification

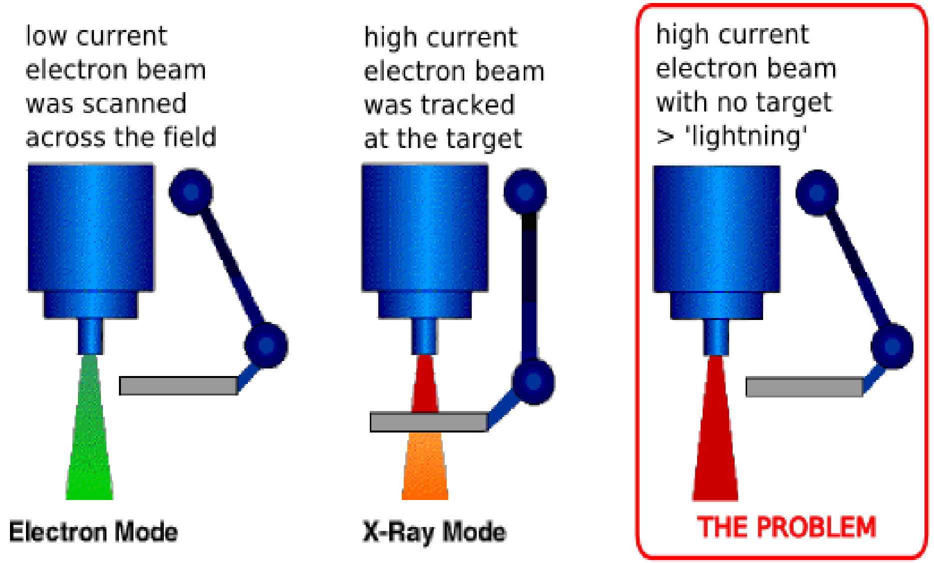
Famous Bugs

1100 Started Cosine Tape (Sine check)
1525 Started Mult+ Adder Test.
1545 Relay #70 Panel F (moth) in relay.
First actual case of bug being found.
[illegible] arctangent started.
1700 closed down.

The first bug: A moth in a relay (1945)
At the Smithsonian (currently not on display)

(in)Famous Bugs

- Safety-critical systems



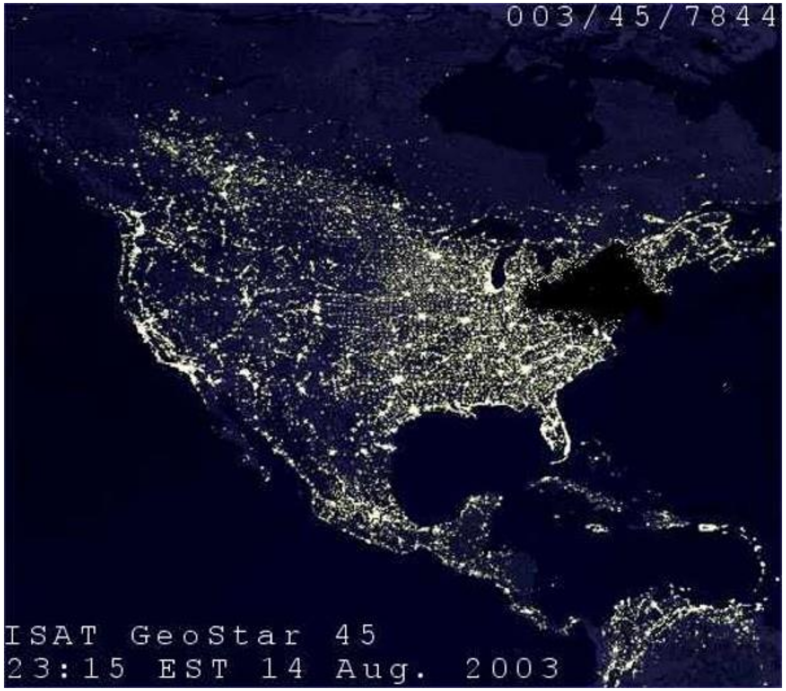
tray including the target, a flattening filter, the collimator jaws and an ion chamber was moved OUT for "electron" mode, and IN for "photon" mode.

Therac-25 medical radiation device (1985)
At least 5 deaths attributed to a race condition in software

(in)Famous Bugs

- Mission-critical systems

Ariane-5 self-destruction (1995)
SW interface issue, backup failed
Cost: $400M payload

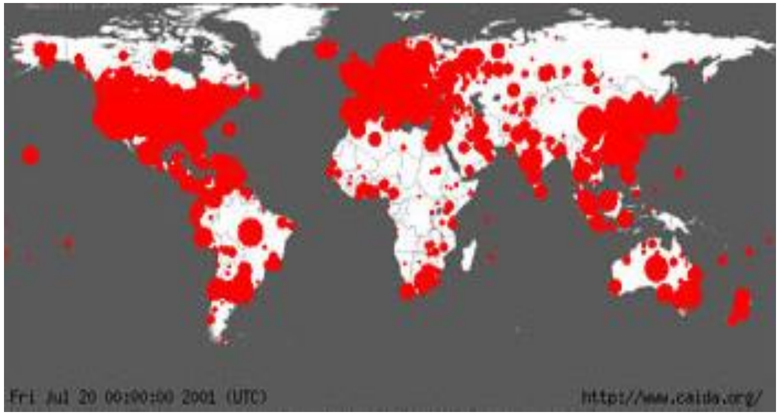


The Northeast Blackout (2003)
Race condition in power control software
Cost: $4B

(in)Famous Bugs

- Commodity hardware / software

Pentium bug (1994)
Float computation errors
Cost: $475M



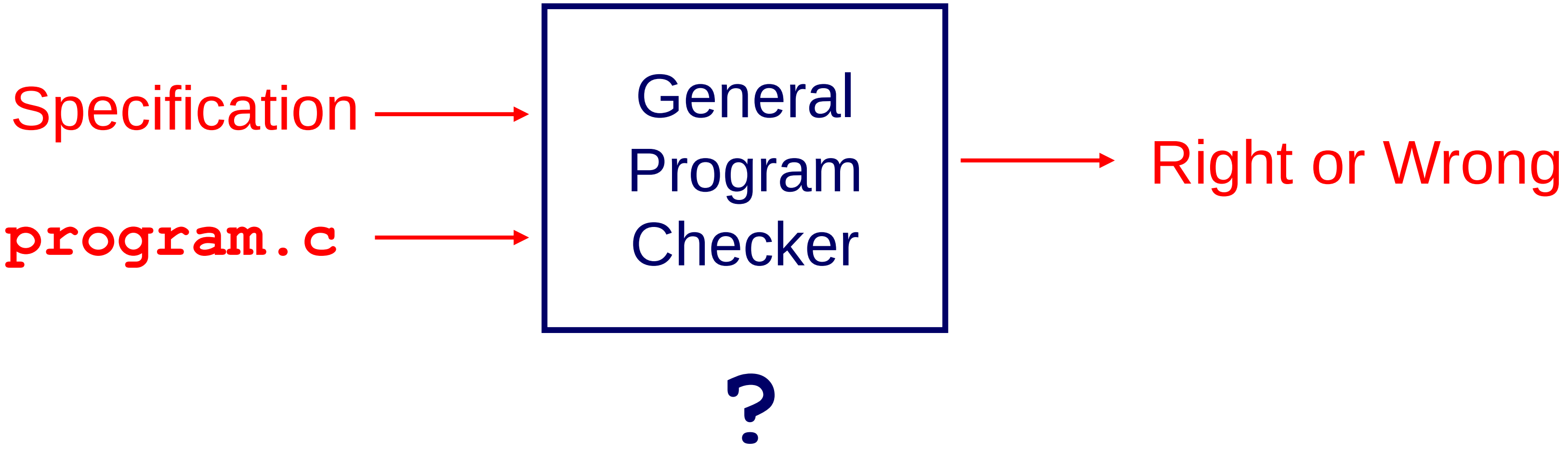
Code Red worm on MS IIS server (2001)
Buffer overflow exploited by worm
Infected 359k servers
Cost: >$2B

Common Bugs

- Runtime bugs
  - Null pointer dereference (access via a pointer that is Null)
  - Array buffer overflow (out of bound index)
    - Can lead to security vulnerabilities
  - Uninitialized variable
  - Division by 0
- Concurrency bugs
  - Race condition (flaw in accessing a shared resource)
  - Deadlock (no process can make progress)
- Functional correctness bugs
  - Input-output relationships
  - Interface properties
  - Data structure invariants
  - …

Program Verification

Ideally: Prove that any given program is correct



Specification

`program.c`

General Program Checker

Right or Wrong

?

In general: Undecidable

This lecture: For some (kinds of) properties, a Program Verifier can provide a proof (if right) or a counterexample (if wrong)

Program Testing (Lecture 6)

Pragmatically: Convince yourself that a **specific** program **probably** works

Specification

`program.c`

Specific Testing Strategy

Probably Right or Certainly Wrong

"Program testing can be quite effective for showing the presence of bugs, but is hopelessly inadequate for showing their absence."
– Edsger Dijkstra

Path Testing Example (Lecture 6)

Example pseudocode:

```
if (condition1)
    statement1;
else
    statement2;
…
if (condition2)
    statement3;
else
    statement4;
…
```

Path testing:

Should make sure all logical paths are executed

How many passes through code are required?

Four paths for four combinations of (condition1, condition 2): TT, TF, FT, FF

- Simple programs => maybe reasonable
- Complex program => combinatorial explosion!!!
    - Path test code fragments

Agenda

Famous bugs

Common bugs

Testing (from lecture 6)

Reasoning about programs

Techniques for program verification

Reasoning about Programs

```
1 int factorial(int x) {
2   int y = 1;
3   int z = 0;
4   while (z != x) {
5     z = z + 1;
6     y = y * z;
7   }
8   return y;
9 }
```

Example:
factorial program

Check:
If x >= 0, then y = fac(x)
(fac is the mathematical function)

- Try out the program, say for x=3
  - At line 4, before executing the loop: x=3, y=1, z=0
  - Since z != x, we will execute the while loop
  - At line 4, after 1st iteration of loop: x=3, z=1, y=1
  - At line 4, after 2nd iteration of loop: x=3, z=2, y=2
  - At line 4, after 3rd iteration of loop: x=3, z=3, y=6
  - Since z == x, exit loop, return 6: It works!

Reasoning about Programs

```
1 int factorial(int x) {
2   int y = 1;
3   int z = 0;
4   while (z != x) {
5     z = z + 1;
6     y = y * z;
7   }
8   return y;
9 }
```

Example:
factorial program

Check:
If x >= 0, then y = fac(x)

- Try out the program, say for x=4
  - At line 4, before executing the loop: x=4, y=1, z=0
  - Since z != x, we will execute the while loop
  - At line 4, after 1st iteration of loop: x=4, z=1, y=1
  - At line 4, after 2nd iteration of loop: x=4, z=2, y=2
  - At line 4, after 3rd iteration of loop: x=4, z=3, y=6
  - At line 4, after 4th iteration of loop: x=4, z=4, y=24
  - Since z == x, exit loop, return 24: It works!

Reasoning about Programs

```
1 int factorial(int x) {
2   int y = 1;
3   int z = 0;
4   while (z != x) {
5     z = z + 1;
6     y = y * z;
7   }
8   return y;
9 }
```

Example:
factorial program

Check:
If x >= 0, then y = fac(x)

- Try out the program, say for x=1000
  - At line 4, before executing the loop: x=1000, y=1, z=0
  - Since z != x, we will execute the while loop
  - At line 4, after 1st iteration of loop: x=1000, z=1, y=1
  - At line 4, after 2nd iteration of loop: x=1000, z=2, y=2
  - At line 4, after 3rd iteration of loop: x=1000, z=3, y=6
  - At line 4, after 4th iteration of loop: x=1

Want to keep going on???

Lets try some mathematics …

```
int factorial(int x) {
  int y = 1;
  int z = 0;
  while (z != x) {
    z = z + 1;
    y = y * z;
  }
  return y;
}
```

Example:
factorial program

Check:
If x >= 0, then y = fac(x)

- Annotate the program with “assertions” [Floyd 67]
  - Assertions (at program lines) are expressed as (logic) formulas
    - Here, we will use standard arithmetic
  - Meaning: Assertions hold before that line is executed
- For loops, we will use an assertion called a “loop invariant”
  - Invariant means that the assertion holds in each iteration of loop
  - We can prove this by using induction

Loop Invariant

```
1 int factorial(int x) {
2   int y = 1;
3   int z = 0;
4   while (z != x) {
5     z = z + 1;
6     y = y * z;
7   }
8   return y;
9 }
```

Example:
factorial program

Check:
If x >= 0, then y = fac(x)

- Loop invariant (assertion at line 4): y = fac(z)
- Try to *prove by induction* that the loop invariant holds
  - Base case: First time at line 4, z=0, y=1, fac(0)=1, y=fac(z) holds √
  - Induction hypothesis: Suppose y = fac(z) at line 4
  - Induction step: In next iteration of the loop (when z!=x)
    - z' = z+1 and y'= fac(z)*z+1 = fac(z') (z'/y' denote updated values)
    - Therefore, at line 4, y'=fac(z'), i.e., loop invariant holds again √

Proof of Correctness

```
1 int factorial(int x) {
2   int y = 1;
3   int z = 0;
4   while (z != x) {
5     z = z + 1;
6     y = y * z;
7   }
8   return y;
9 }
```

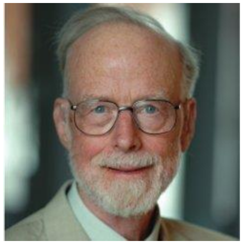
Example:
factorial program

Check:
If x >= 0, then y = fac(x)

- Loop invariant (assertion at line 4): y = fac(z) √
- What should we do now?
  - If loop condition is true, i.e., if (z!=x), execute loop again, y=fac(z)
  - If the loop condition is false, i.e., if (z==x), exit the loop
    - At line 8, we now know that y=fac(z) AND z==x, i.e., y=fac(x)
    - Thus, at return, y = fac(x)
- Proof of correctness of the factorial program is now done √

Program Verification

- Rich history in computer science
- *Assigning Meaning to Programs* [Floyd, 1967]
  - Program is annotated with assertions (formulas in logic)
  - Program is proved correct by reasoning about assertions
- *An Axiomatic Basis for Computer Programming* [Hoare, 1969]
  - Hoare Triple: {P} S {Q}
    - S: statement (or fragments) in program
    - P: precondition (formula in logic)
    - Q: postcondition (formula in logic)
  - Meaning: If S executes from a state where P is true, and if S terminates, then Q is true in the resulting state
  - This is called “partial correctness”
    - does not guarantee termination of S
  - For our example: {x >= 0} y = factorial(x) {y = fac(x)}



Program Verification

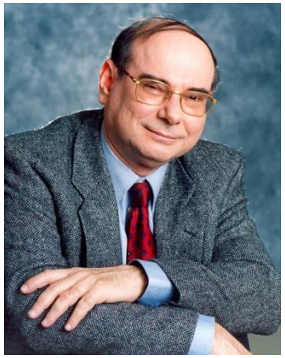
- Proof Systems
  - Perform reasoning using logic formulas and rules of inference
    - Soundness: If assertion A is proved, then A is true
    - Completeness: If assertion A is true, then A can be proved
- Hoare Logic [Hoare 69]
  - Inference rules for assignments, conditionals, loops, sequence
  - Given a program annotated with preconditions, postconditions, and loop invariants
    - Verification Condition (VC) can be generated automatically
    - If VC is “valid”, then program is correct
    - Validity of VC can be checked by a theorem-prover
- Question: Can these preconditions/postconditions/loop invariants be generated automatically?

Automatic Program Verification

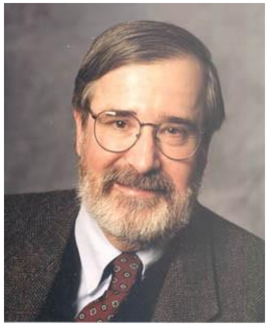
- Question: Can these preconditions/postconditions/loop invariants be generated automatically?
- Answer: Yes! (in many cases)
- Techniques for deriving the assertions automatically
  - Model checking: based on exploring “states” of programs
  - Abstract interpretation: based on static analysis using “abstractions” of programs
  - … many other techniques
- Still an active area of research (after more than 45 years)!

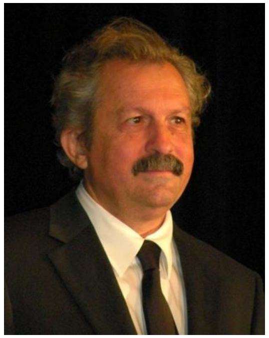
Model Checking

- Temporal logic
  - Used for specifying correctness properties
  - [Pnueli, 1977]



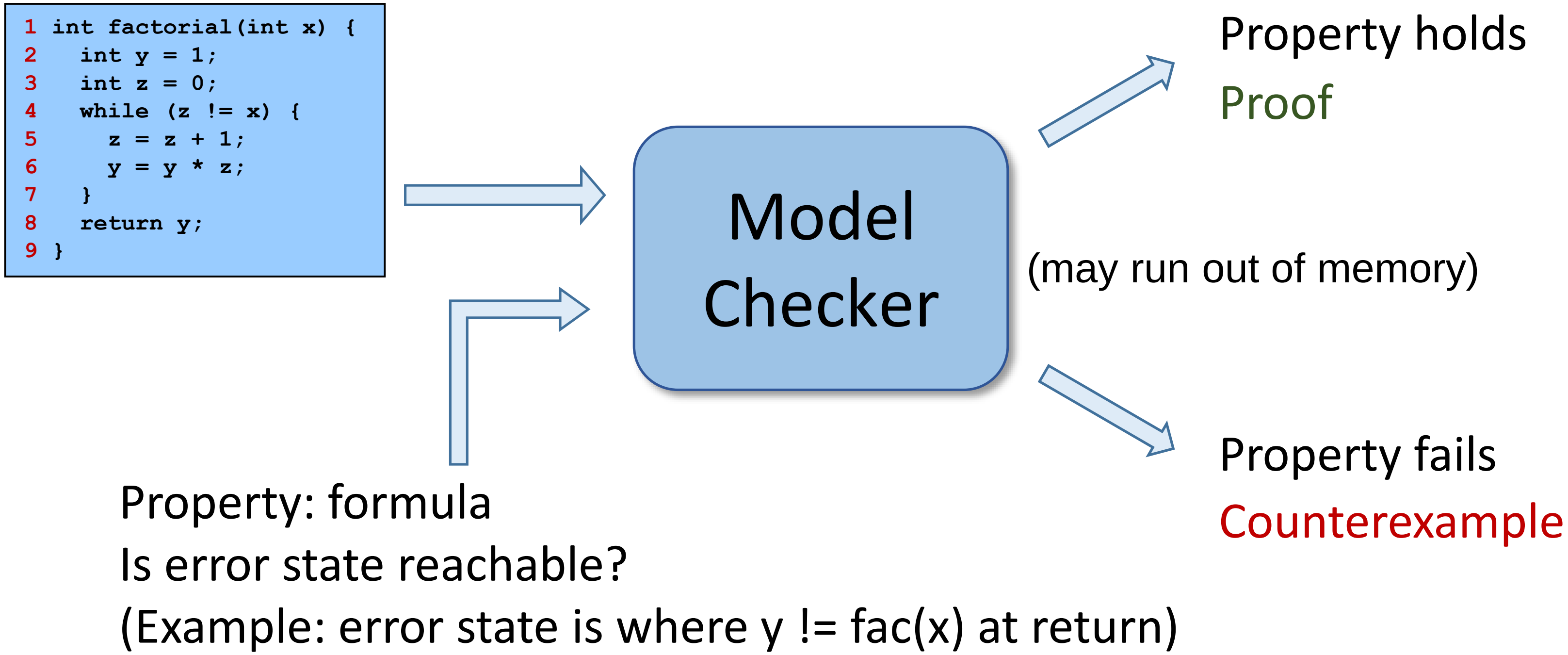
- Model checking
  - Verifying temporal logic properties by state space exploration
  - [Clarke & Emerson, 1981] and [Queille & Sifakis, 1981]





Model Checker

- Model checker performs automatic state space exploration
  - If all reachable states are visited and error state is not reached, then property is proved correct
  - Otherwise, it provides a counterexample (trace to error state)



```
int factorial(int x) {
  int y = 1;
  int z = 0;
  while (z != x) {
    z = z + 1;
    y = y * z;
  }
  return y;
}
```

Model Checker

Property holds

Proof

(may run out of memory)

Property fails

Counterexample

Property: formula

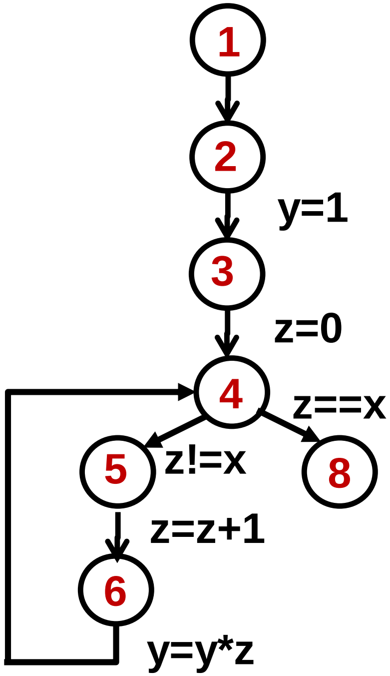
Is error state reachable?

(Example: error state is where y != fac(x) at return)

Model Checking (simplified)

- Consider viewing a program *like* a DFA (not quite, …)
  - “State” in a program
    - Line number
    - Value of each program variable (not shown below)
  - “Transition” in a program
    - Statement in program (updates state)
- Example: factorial program

```
1 int factorial(int x) {
2   int y = 1;
3   int z = 0;
4   while (z != x) {
5     z = z + 1;
6     y = y * z;
7   }
8   return y;
9 }
```



Model Checking (simplified)

- Example: factorial program

```
1 int factorial(int x) {
2   int y = 1;
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4   while (z != x) {
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9 }
```
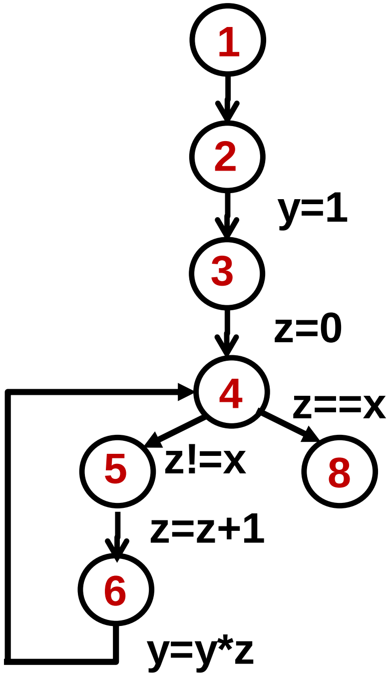
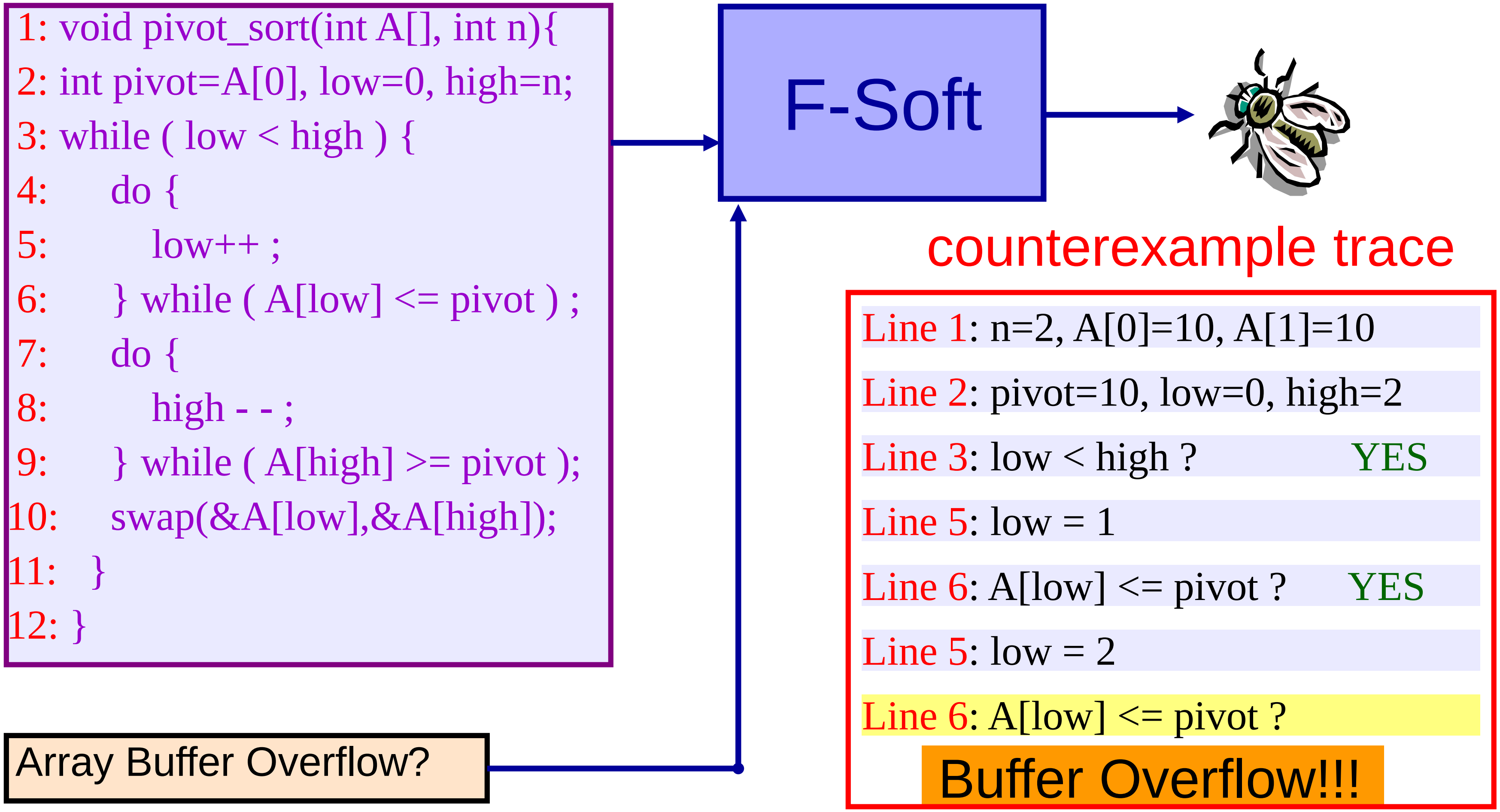



- **Number of program states**
  - 9 (lines)*(states of x)*(states of y)*(states of z): $9 * 2^{32} * 2^{32} * 2^{32}$
  - States are not represented explicitly, but *symbolically* as formulas
    - e.g. (z<y) represents all program states where z is less than y
- **Many other enhancements are used …**

F-Soft Model Checker

Automatic tool for finding bugs in large C/C++ programs (NEC)



```
1: void pivot_sort(int A[], int n){
2: int pivot=A[0], low=0, high=n;
3: while ( low < high ) {
4:      do {
5:          low++ ;
6:      } while ( A[low] <= pivot ) ;
7:      do {
8:          high - - ;
9:      } while ( A[high] >= pivot );
10:     swap(&A[low],&A[high]);
11:   }
12: }
```

Array Buffer Overflow?

counterexample trace

Line 1: n=2, A[0]=10, A[1]=10

Line 2: pivot=10, low=0, high=2

Line 3: low < high ? YES

Line 5: low = 1

Line 6: A[low] <= pivot ? YES

Line 5: low = 2

Line 6: A[low] <= pivot ?

Buffer Overflow!!!

Summary

- Program verification
  - Provide *proofs of correctness* for classes of properties & programs
  - Testing *cannot* provide proofs of correctness (unless exhaustive)

- Proof systems based on logic
  - Users annotate the program with assertions
  - Theorem-provers perform search for proofs (with user guidance)
- Automatic verification techniques
  - Program assertions are derived automatically
  - But, scalability is an issue
    - Explosion in sets of reachable states
    - Worse for concurrent multi-threaded programs
      - Need to explore all possible interleavings of different threads
- *COS 597B in Fall '15: Automatic Reasoning about Software*

Course Summary

We have covered:

Programming in the large

- The C programming language
- Testing
- Building
- Debugging
- Program & programming style
- Data structures
- Modularity
- Performance

Course Summary

We have covered (cont.):

Under the hood

- Number systems
- Language levels tour
    - Assembly language
    - Machine language
    - Assemblers and linkers
- Service levels tour
    - Exceptions and processes
    - Storage management
    - Dynamic memory management
    - Process management
    - I/O management
    - Signals

The Rest of the Course

Assignment 7

- Due on Dean’s Date (5/12) at 5PM
- Cannot submit late (University regulations)
- Cannot use late pass

Office hours and exam prep sessions

- Will be announced on Piazza

Final exam

- When: Tuesday 5/19, 1:30 PM
- Where: Friend Center 101
- Closed book, closed notes, no electronic devices

Thank you!