Introduction to Program Testing

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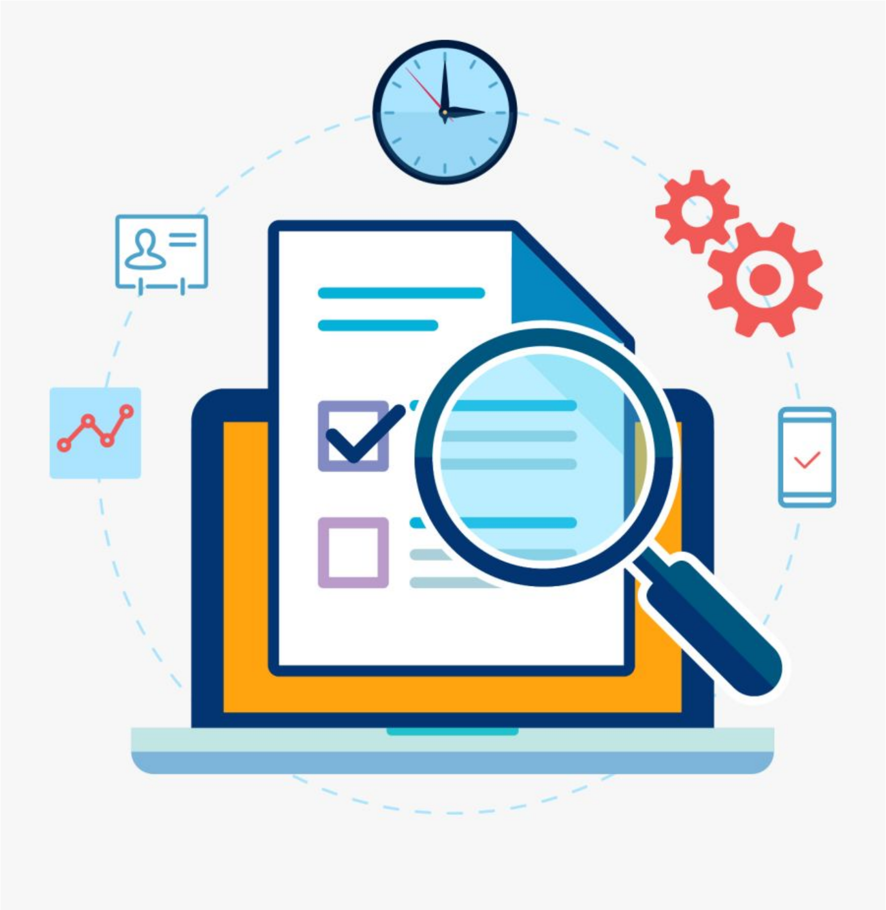
Program testing

- Programs contain bugs
  - industry average
    - 10-50 bugs per 1K LOC
- Program testing
  - Manual testing
    - Testers manually identify any unexpected behavior or bug
  - Automated testing
    - Use automated techniques to perform the testing



Program testing

Program behaviors during execution

Expected behaviors

Program testing

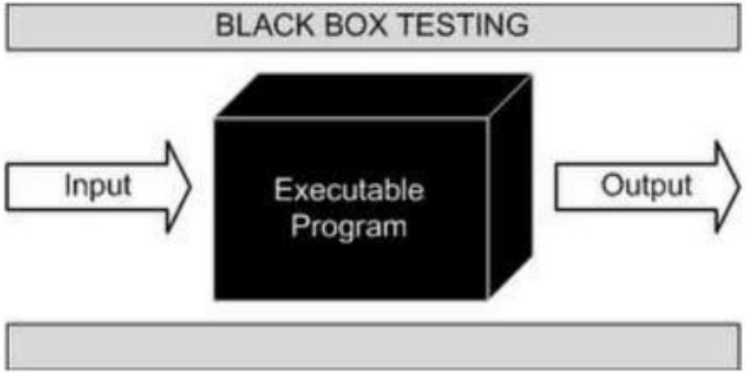
- Manual testing
  - predefined testing cases
    - Deep domain knowledge required
    - Specific for each individual program
  - Manual checking
    - if the execution matches the expected behavior
  - Limitations
    - Extremely inefficient
    - Poor coverage

Program testing

- Automated testing
  - Run tested programs automatically
  - Detect unexpected behaviors during execution
  - Produce the discovered bugs easily
  - Three categories
    - Black-box testing
    - Grey-box testing
    - White-box testing

Black-box testing

- View tested programs as Black Box
- Randomly fuzz an existing input
  - Keep mutating existing input to create test data
  - Hope to find test data that triggers bugs
  - ‘Dumb fuzzing’
  - Sometimes still effective



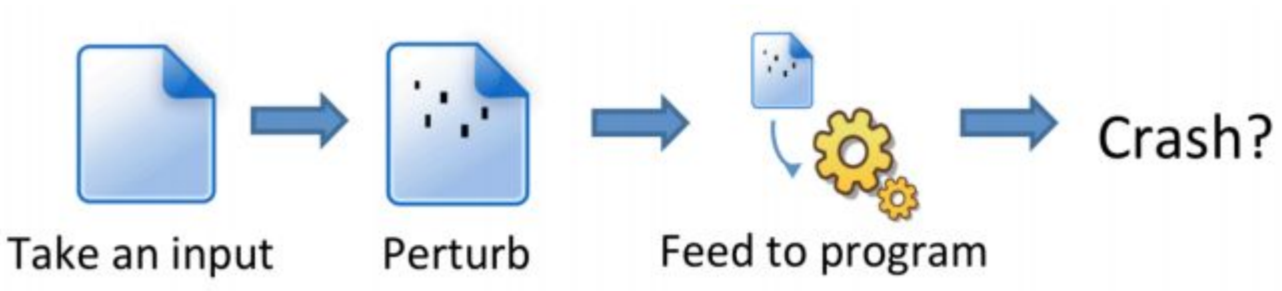
Black-box testing

- Can get stuck very easily

```
function( char *name, char *passwd, char *buf )
{
     if ( authenticate_user( name, passwd )) {
          if ( check_format( buf )) {
               update( buf ); // crash here
          }
     }
}
```

Black-box testing

- Mutation-based fuzzing
  - Idea: take a well-formed input as the initial input
  - Keep mutating the input (flipping random bits, etc)
  - Useful for passing some format checks



Black-box testing

- Mutation-based fuzzing Example: PDF fuzzing
    - Search for PDF files
    - Crawl and download the results
    - Use a mutation-based fuzzer to:
        - Grab a PDF file
        - Mutate the file
        - Send the file to a PDF viewer
        - Record any crashes

Mutation-based	Super easy to setup and automate +	Little to no protocol knowledge required +	Limited by initial corpus −	May fail for protocols with checksums, or other complexity −

Black-box testing

- Generation-based fuzzing
  - Generate test cases from certain well-documented formats (e.g., HTML spec)
  - Can generated well-formed inputs automatically
  - Take significant efforts to set up

```
<!--  A.  Local file header -->
 <Block name="LocalFileHeader">
  <String name="lfh_Signature" valueType="hex" value="504b0304" token="true" mut
  <Number name="lfh_Ver" size="16" endian="little" signed="false"/>
  ...
  [truncated for space]
  ...
  <Number name="lfh_CompSize" size="32" endian="little" signed="false">
    <Relation type="size" of="lfh_CompData"/>
  </Number>
  <Number name="lfh_DecompSize" size="32" endian="little" signed="false"/>
  <Number name="lfh_FileNameLen" size="16" endian="little" signed="false">
    <Relation type="size" of="lfh_FileName"/>
  </Number>
  <Number name="lfh_ExtraFldLen" size="16" endian="little" signed="false">
    <Relation type="size" of="lfh_FldName"/>
  </Number>
  <String name="lfh_FileName"/>
  <String name="lfh_FldName"/>
  <!--  B.  File data -->
  <Blob name="lfh_CompData"/>
 </Block>
```

Black-box testing

- Generation-based fuzzing V.S Mutation-based fuzzing

Mutation-based	Super easy to setup and automate	Little to no protocol knowledge required	Limited by initial corpus	May fail for protocols with checksums, or other complexity
Generation-based	Writing generator is labor intensive for complex protocols	have to have spec of protocol (frequently not a problem for common ones http, snmp, etc...)	Completeness	Can deal with complex checksums and dependencies

Grey-box testing

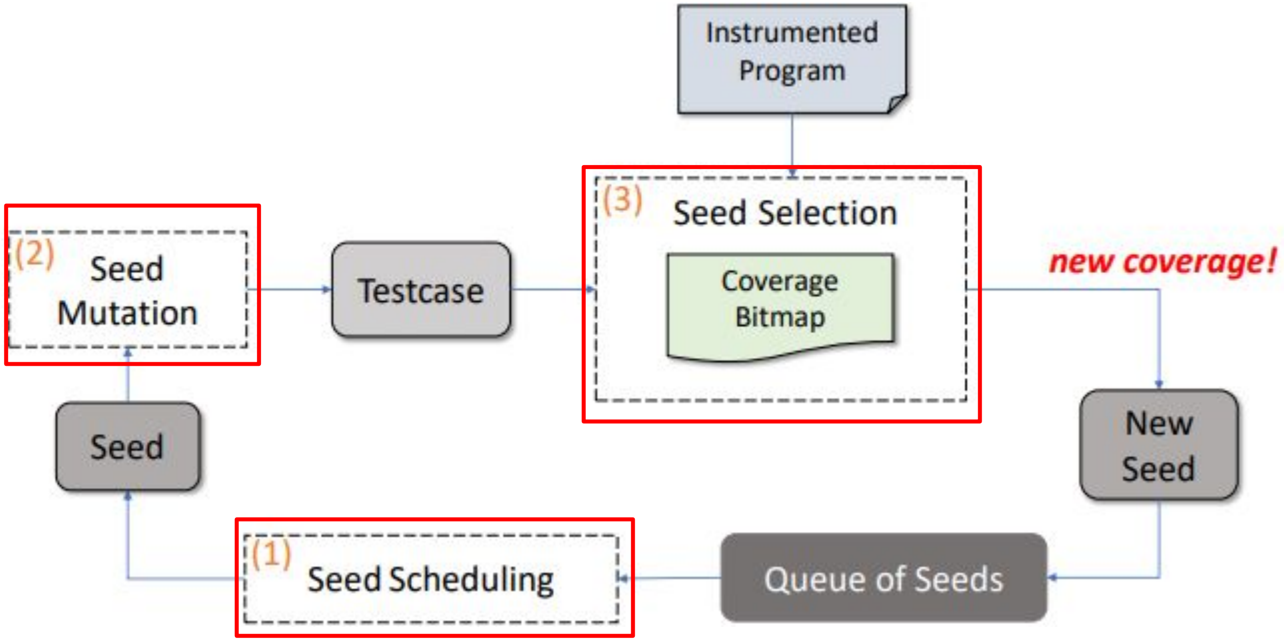
- Some knowledge is acquired during testing
- Generate inputs based on the response of the tested program
- Generated inputs can be preserved only when:
    - Considered as ‘interesting’ by fuzzer
        - How to define?
        - Inputs that can identify something new
    - Can contribute significantly
        - How to define?
- Other inputs will be discarded

Grey-box testing

- Coverage-guided fuzzing
  - ‘Interesting’ standard: new code coverage
    - Statement coverage
    - Branch coverage
    - Path coverage
    - And more
  - Try to maximize code coverage during testing
  - Hopefully bugs can be executed and discovered
  - Limitations?

Grey-box testing

- Example: coverage-guided fuzzing



Grey-box testing

- Coverage-guided fuzzing
  - Seed scheduling
    - Pick the next seed for testing from a set of seed inputs
  - Seed mutation
    - More test cases can be generated based on scheduled seeds through mutation
  - Seed selection
    - Define the ‘interesting’ standard: metrics
    - Preserve only the interesting inputs for next round

Grey-box testing

- Coverage-guided fuzzing
  - Statement coverage
    - Measure how many lines of code have been executed
  - Branch coverage
    - Measure how many branches (conditional jumps) have been executed
  - Path coverage
    - Measure how many paths have been executed

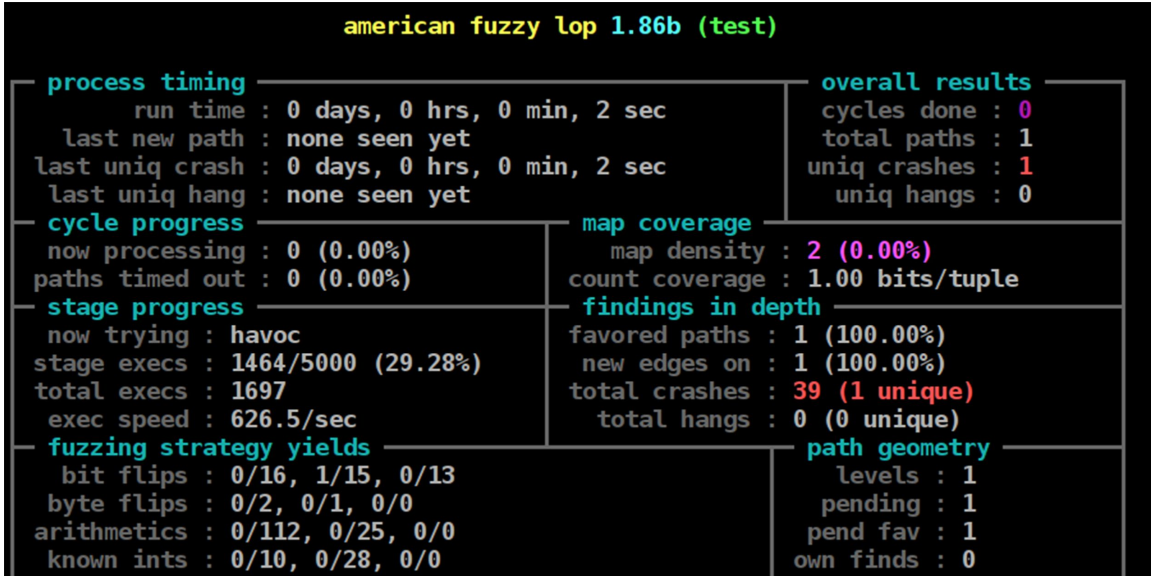
Grey-box testing

- Exercise
  - Are these inputs ‘interesting’ under the three coverage metrics?
    - Input 1: a = 1, b = 1
    - Input 2: a = 3, b = 1
    - Input 3: a =3, b = 3
    - Input 4: a = 1, b = 3

```
if( a > 2 )
    a = 2;
if( b > 2 )
    b = 2;
```

Grey-box testing

- De facto fuzzing tool: American Fuzzy Lop
  - https://lcamtuf.coredump.cx/afl/
  - Monitor execution during testing



Grey-box testing

- Limitation

```
x = int(input())
if x > 10:
    if x < 100:
        print "You win!"
    else:
        print "You lose!"
else:
    print "You lose!"
```

Let's fuzz it!

1 ⇒ "You lose!"

593 ⇒ "You lose!"

183 ⇒ "You lose!"

4 ⇒ "You lose!"

498 ⇒ "You lose!"

48 ⇒ "You win!"

```
x = int(input())
if x > 10:
    if x^2 == 152399025:
        print "You win!"
    else:
        print "You lose!"
else:
    print "You lose!"
```

Let's fuzz it!

1 ⇒ "You lose!"

593 ⇒ "You lose!"

183 ⇒ "You lose!"

4 ⇒ "You lose!"

498 ⇒ "You lose!"

42 ⇒ "You lose!"

3 ⇒ "You lose!"

....

57 ⇒ "You lose!"

White-box testing

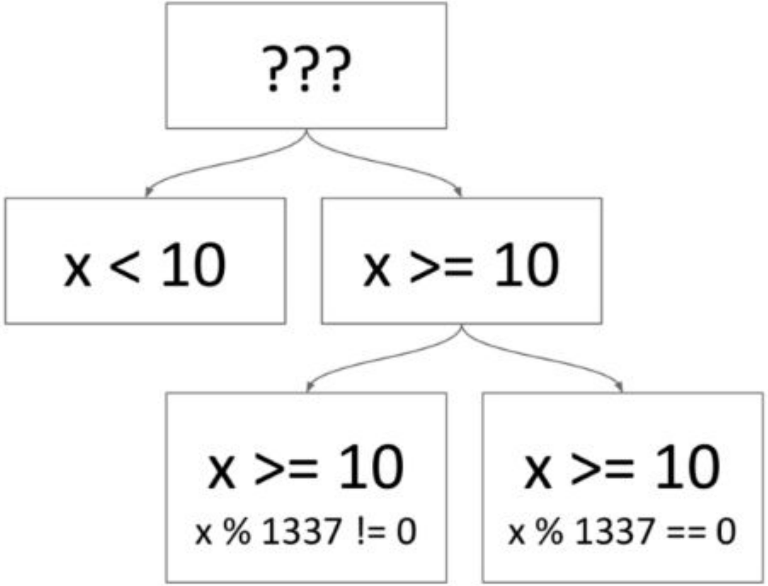
- Full knowledge about tested programs is collected during testing
- Also known as
  - Dynamic symbolic execution
  - or Concolic execution
- Key idea:
  - Evaluate the tested program on *symbolic* input values
    - Symbolic input: input that can take any value
  - Collect path constraints during testing
  - Use an automated theorem prover to generate concrete inputs

```
if( a > 2 )
    a = 2;
if( b > 2 )
    b = 2;
```

Path constraint:
a > 2 && b > 2
Solved input:
a = 3, b = 3

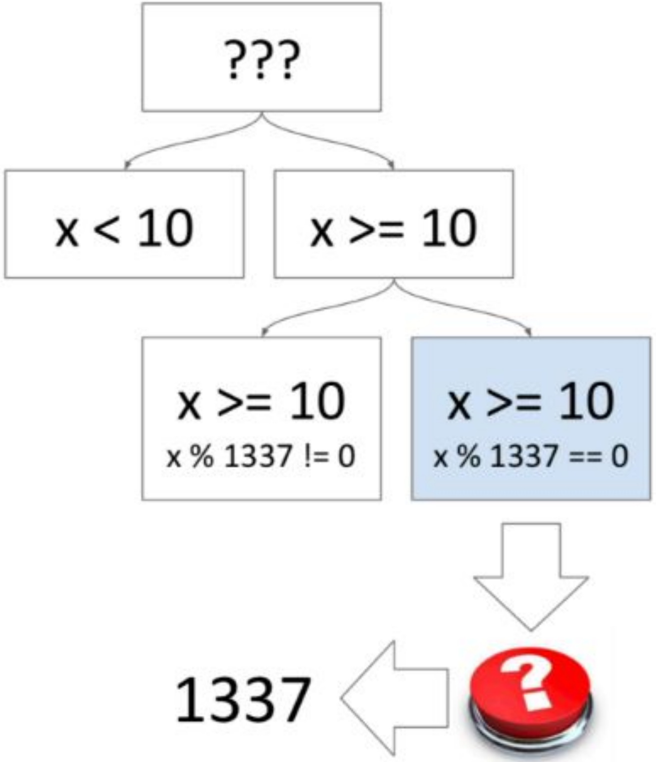
White-box testing

```
x = input()
if x >= 10:
  if x % 1337 == 0:
      print "You win!"
  else:
      print "You lose!"
else:
    print "You lose!"
```



White-box testing

```
x = input()
if x >= 10:
    if x % 1337 == 0:
        print "You win!"
    else:
        print "You lose!"
else:
    print "You lose!"
```



White-box testing

- Limitations
  - Low inefficiency
    - Throughput comparison
      - Fuzzing: thousands per second
      - Symbolic execution: 1 per multiple minutes
  - Path explosion
    - Too many paths to explore: exponential
  - Unsolvable path constraints
    - Time-consuming
    - May never get an answer

White-box testing

```
x = input()

def recurse(x, depth):
  if depth == 2000
    return 0
  else {
    r = 0;
    if x[depth] == “B”:
      r = 1
    return r + recurse(x
[depth], depth)

if recurse(x, 0) == 1:
  print “You win!”
```

Fuzzing Wins

```
x = int(input())
if x >= 10:
    if x^2 == 152399025:
        print "You win!"
    else:
        print "You lose!"
else:
    print "You lose!"
```

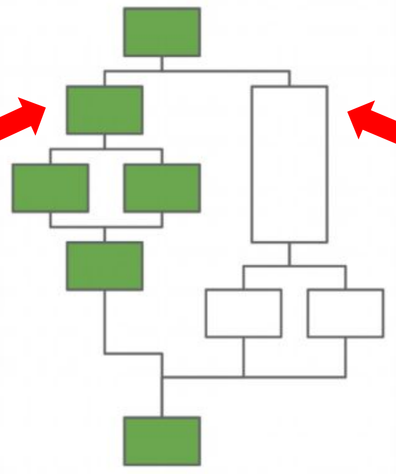
Symbolic Execution Wins

Fuzzing + Symbolic execution?

- Hybrid fuzzing
  - Key idea:
    - Let fuzzer take major responsibility
      - Take advantage of its high throughput
    - Let symbolic executor solve hard problems
      - Utilize its capability of solving specific conditional checks

Fuzzing + Symbolic execution?

Condition: if (a > 5)

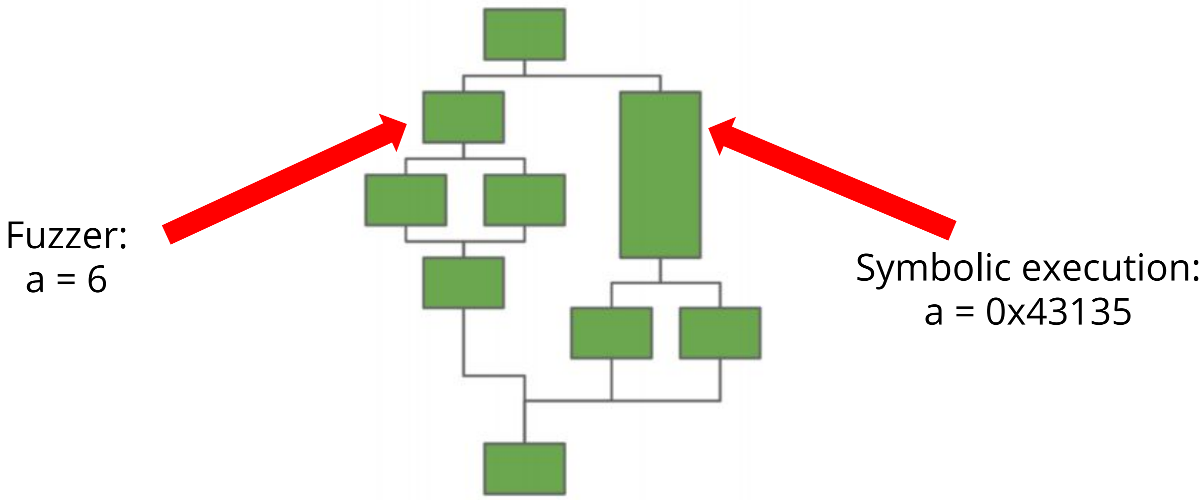


Control Flow Graph

Condition: if (a = 0x43135)

Unreachable by fuzzing

Fuzzing + Symbolic execution?



Control Flow Graph

Summary

- Program testing
  - Manual testing
  - Automated testing
- Black-box testing
  - Mutation-based
  - Generation-based
- Grey-box testing
  - Coverage-based
- White-box testing
  - Symbolic execution
- Hybrid approach

Thank you!

Question?