Slide credit for this deck: both William Griswold (UCSD) and Michael Hilton (CMU)

Testing

Program testing can be used to show the presence of bugs, but never to show their absence! -- Edsger Dijkstra

What makes a good test suite?

- You tell me.

Defining correct behavior

- Example-based: “For a given input, some assertions should be true”
- Properties: “Output should should satisfy some property for all inputs in some class"
- “It doesn’t crash”
- Invariance: “Changing the input in some way should maintain the same output”
- Regression: “It provides the same output as it used to”
- Differential: “Two systems implementing the same spec should provide the same output”
- Human oracle: “For a given user, they should be satisfied”

The Many Purposes of Testing

Not only are tests used to drive software design, but **we design our software for testing** (later in this lecture).

- ***Find*** **bugs**
  - Hard to prove of the *absence* of bugs (Dijkstra)
- ***Prevent*** **bugs** from sneaking in during enhancement **(Regression Testing)**
  - Loose synchronization among developers/teams can result in incorrect use or enhancement of existing code
- Give ***high confidence*** in the integrity of your product
- **Explore class/method design** (Test-First/Test-Driven Development and/or DbC)
- **Specification of expected behavior**

The **THREE BIG IDEAS** of Software Testing

Coverage: Seek to execute all possibilities.

(but does running a line mean you've "covered" it?)

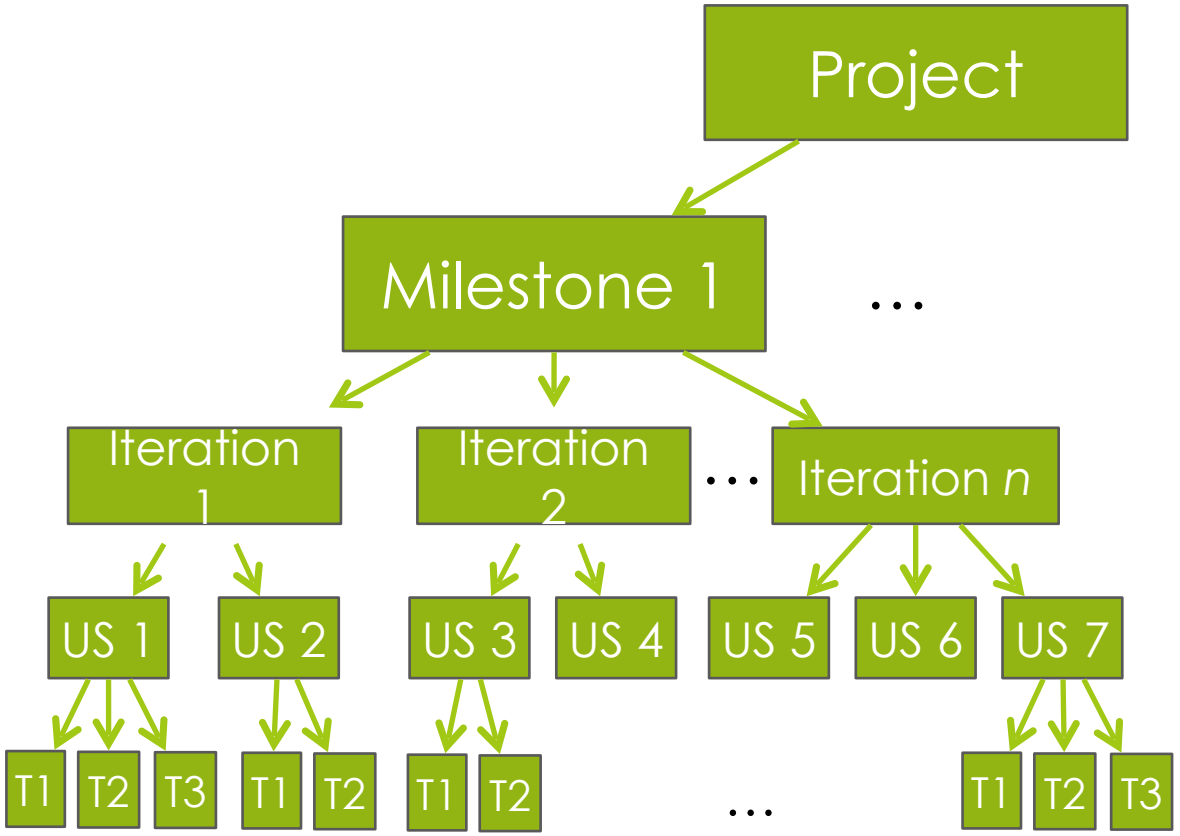
Test Equivalence Classes:

Tests should all cover *different* things.

That's still too many, so…

Bottom-Up Testing: When testing if something works, its parts should already be tested. ***We test just the current level***, reducing the explosion of combinations.

Bottom-Up Testing and the Hierarchical Structure of Agile Planning *and* Delivery



For example, Iteration testing assumes that the individual Stories/Features work, and tests how the Stories glue together.

- User, System Testing
  (perf, robustness, user experience)
  (i.e., End-to-End Scenarios + Personas)
- Acceptance Testing
  (customer demo, End-to-End Scenarios)
- Story Testing (features)
  (acceptance criteria)
- Unit Testing (methods)
  (black/gray/white box)

Each level of testing assumes all the lower levels of tests have passed. Only test for the "current-level" risk.

Black box vs. white box testing

- **Black box** testing: do not look inside the component being tested.
  - Pro: not biased by implementation details
  - Con: can't leverage opportunities
- **White box** testing: consider the implementation of the component being tested.
  - Pro: exploit possible weaknesses
  - Con: may miss "impossible" bugs
- **Gray box** testing: somewhere in the middle

Agile Testing: Hierarchical, Diverse (80/20)

- Write three kinds of tests, *bottom up*:
  1. Task level: Unit tests for critical units (black-box and/or white-box)
  2. Story/Iteration-level: BDD scenario tests (in unit or BDD tester)
     - Automating all could be expensive; some by hand
  3. Iteration/Milestone-level: End-to-end Scenario tests ("run" by hand - already done, from product design)
     - Additionally consider Personas, platforms/configurations, real people
- Diversification beyond the hierarchy:
  - Asserts from DbC
  - Logging for hard-to-test code (grey-box)

Include time for testing during Planning

Write tests for high-risk units

For each story, have a testing task

- Could have two: one for writing tests, one for passing

For a sprint, have a testing Story or "loose" Task

- This is a "Developer Story": As a developer, I want…
- End-to-End Scenarios, e.g.

For Milestone, have a testing Iteration or loose Story/ Task

- longer End-to-End Scenarios, e.g.

Testing early-stage software

- You want to test module A
- But A depends on module B.
- Module B isn't ready yet.
- What do?

Another situation

- Want to test code that depends on the current time
- Or the network
- Or the disk
- Now what?

Solution: mocking

- New class: MockCalendar

```
class MockCalendar extends Calendar {
  long millis;
  MockCalendar(long millis) {this.millis = millis;}
  static MockCalendar getInstance()
                  { return new MockCalendar(millis); }
  long getTimeInMillis() { return millis; }
  void setTimeInMillis(long ms) { millis = ms; }
  … // Lots of stubbed methods that we don't use
}
```

Pass MockCalendar instance into code to be tested.

Advanced Testing

Or: how to avoid writing tests manually (sometimes). Credit: CMU S3D (Michael Hilton)

Puzzle: Find `x` such `p1(x)` returns `True`

```
def p1(x):
  if x * x - 10 == 15:
    return True
  return False
```

Puzzle: Find x such p2(x) returns True

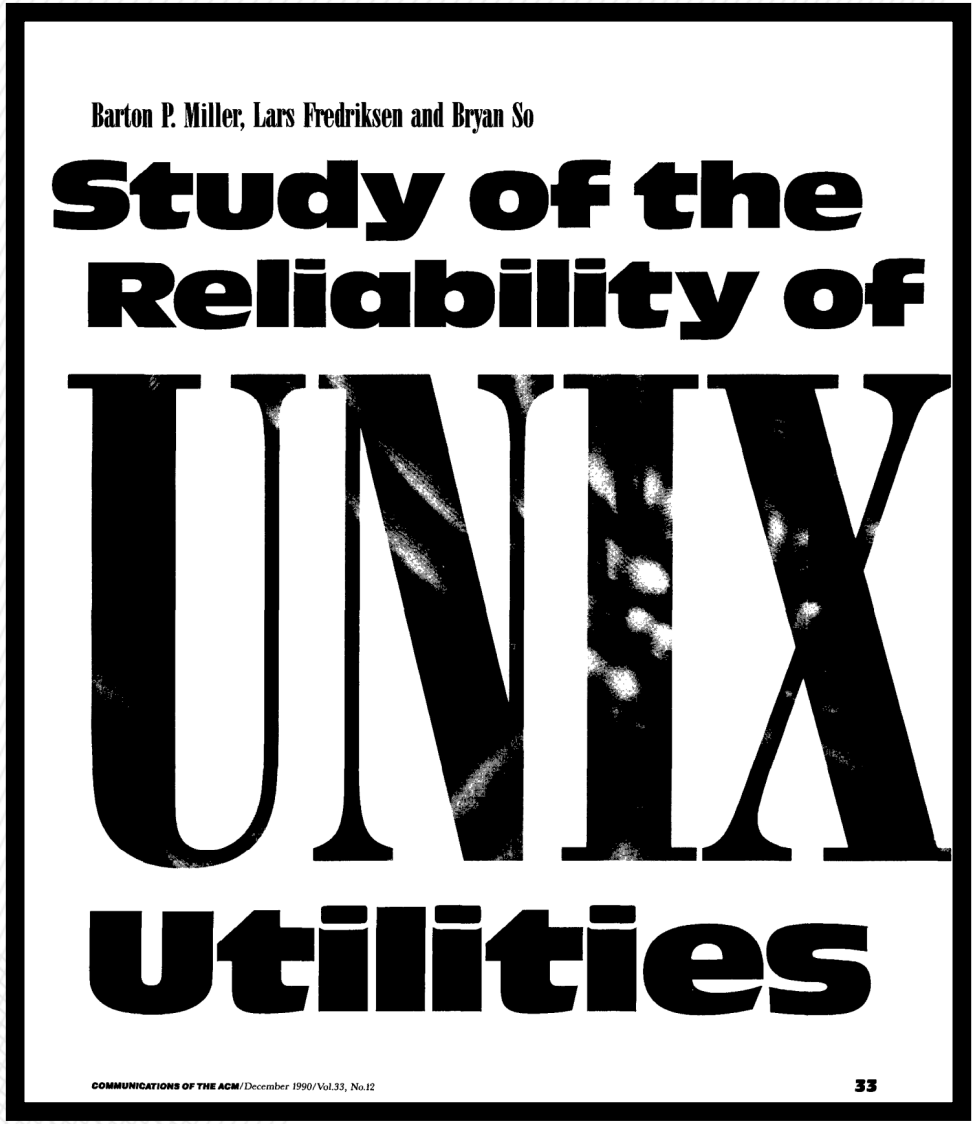
```
def p2(x):
  if x > 0 and x < 1000:
    if ((x - 32) * 5/9 == 100):
      return True
  return False
```

Puzzle: Find x such p3(x) returns True

```
def p3(x):
  if x > 3 and x < 100:
    z = x - 2
    c = 0
    while z >= 2:
      if z ** (x - 1) % x == 1:
        c = c + 1
      z = z - 1
    if c == x - 3:
      return True
  return False
```

Fuzz Testing

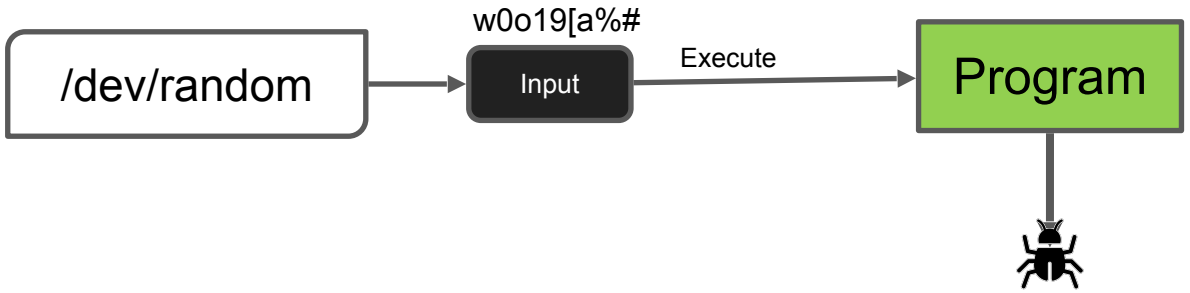
Security and Robustness



Communications of the ACM (1990)

“On a dark and stormy night one of the authors was logged on to his workstation on a dial-up line from home and the rain had affected the phone lines; there were frequent spurious characters on the line. The author had to race to see if he could type a sensible sequence of characters before the noise scrambled the command. This line noise was not surprising; but we were surprised that these spurious characters were causing programs to crash.”

Fuzz Testing



A 1990 study found crashes in:
adb, as, bc, cb, col, diction, emacs, eqn, ftp, indent, lex, look, m4, make, nroff, plot, prolog, ptx, refer!, spell, style, tsort, uniq, vgrind, vi

Common Fuzzer-Found Bugs in C/C++

Causes: incorrect arg validation, incorrect type casting, executing untrusted code, etc.

Effects: buffer-overflows, memory leak, division-by-zero, use-after-free, assertion violation, etc. (“crash”)

Impact: security, reliability, performance, correctness

But: bugs don't always result in crashes.

```
int *x = malloc(sizeof(int));
free(x);
printf("%d", *x);
```

How do you make programs “crash” when a bug is encountered?

Automatic Oracles: Sanitizers

- Address Sanitizer (ASAN) ***
- LeakSanitizer (comes with ASAN)
- Thread Sanitizer (TSAN)
- Undefined-behavior Sanitizer (UBSAN)

https://github.com/google/sanitizers

AddressSanitizer

Compile with `clang –fsanitize=address`

```
int get_element(int* a, int i) {
   return a[i];
}
```

Is it null?

```
int get_element(int* a, int i) {
   if (a == NULL) abort();
   return a[i];
}
```

Is the access out of bounds?

```
int get_element(int* a, int i) {
   if (a == NULL) abort();
   region = get_allocation(a);
   if (in_heap(region)) {
     low, high = get_bounds(region);
     if ((a + i) < low || (a +i) > high) {
       abort();
     }
   }
   return a[i];
}
```

Is this a reference to a stack-allocated variable after return?

```
int get_element(int* a, int i) {
   if (a == NULL) abort();
   region = get_allocation(a);
   if (in_stack(region)) {
     if (popped(region)) abort();
     …
   }
   if (in_heap(region)) { ... }
   return a[i];
}
```

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     …
   }
   if (in_heap(region)) { ... }
   return a[i];
}
```

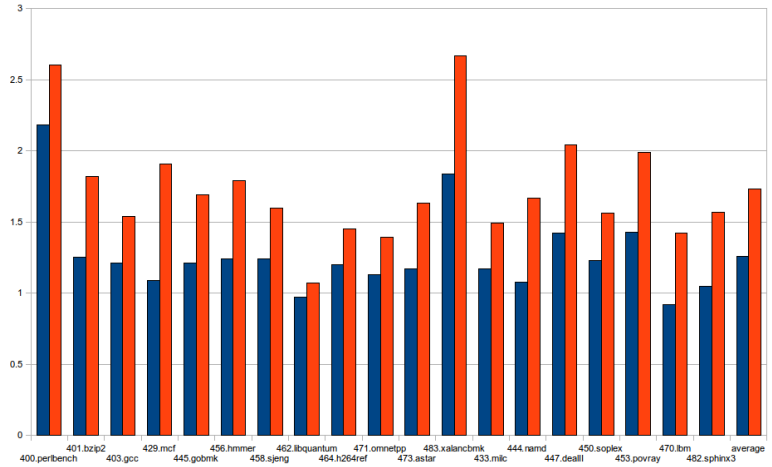
AddressSanitizer

https://github.com/google/sanitizers/wiki/AddressSanitizer

Asan is a memory error detector for C/C++. It finds:

- Use after free (dangling pointer dereference)
- Heap buffer overflow
- Stack buffer overflow
- Global buffer overflow
- Use after return
- Use after scope
- Initialization order bugs
- Memory leaks

Slowdown about 2x on SPEC CPU 2006



Strengths and Limitations

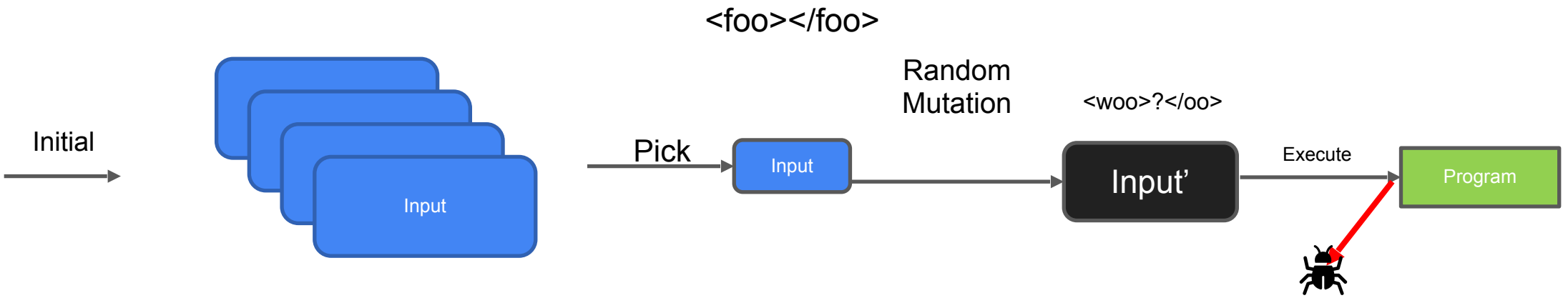
Strengths:

- Cheap to generate inputs
- Easy to debug when a failure is identified

Limitations:

- Randomly generated inputs don’t make sense most of the time.
  - E.g. Imagine testing a browser and providing some ”input” HTML randomly: **dgsad5135o gsd;gj lsdkg3125j@! T%#(W+123sd asf j**
- Unlikely to exercise interesting behavior in the web browser
- Can take a long time to find bugs. Not sure when to stop.

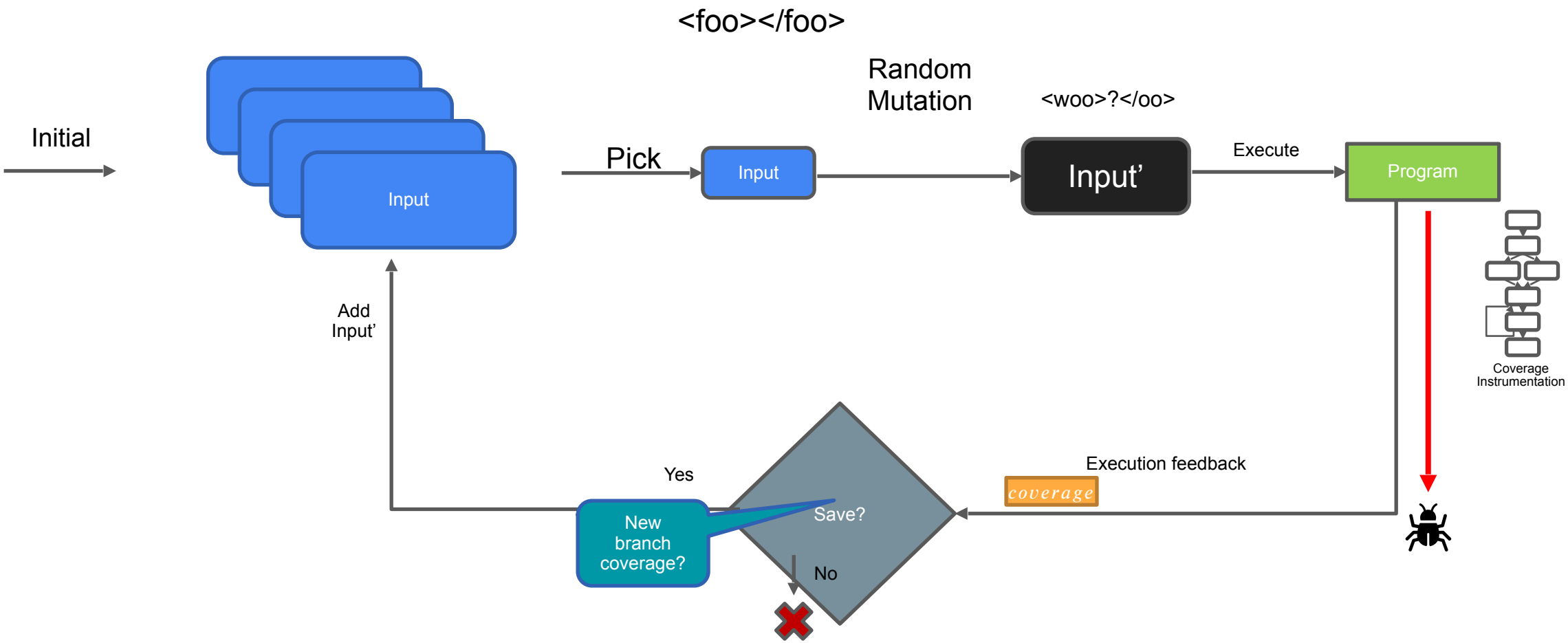
Mutation-Based Fuzzing (e.g. Radamsa)



Mutation Heuristics

- Binary input
  - Bit flips, byte flips
  - Change random bytes
  - Insert random byte chunks
  - Delete random byte chunks
  - Set randomly chosen byte chunks to *interesting* values e.g. INT_MAX, INT_MIN, 0, 1, -1, …
- Text input
  - Insert random symbols relevant to format (e.g. “<“ and “>” for xml)
  - Insert keywords from a dictionary (e.g. “<project>” for Maven POM.xml)
- GUI input
  - Change targets of clicks
  - Change type of clicks
  - Select different buttons
  - Change text to be entered in forms
  - … Much harder to design

Coverage-Guided Fuzzing (e.g. AFL)



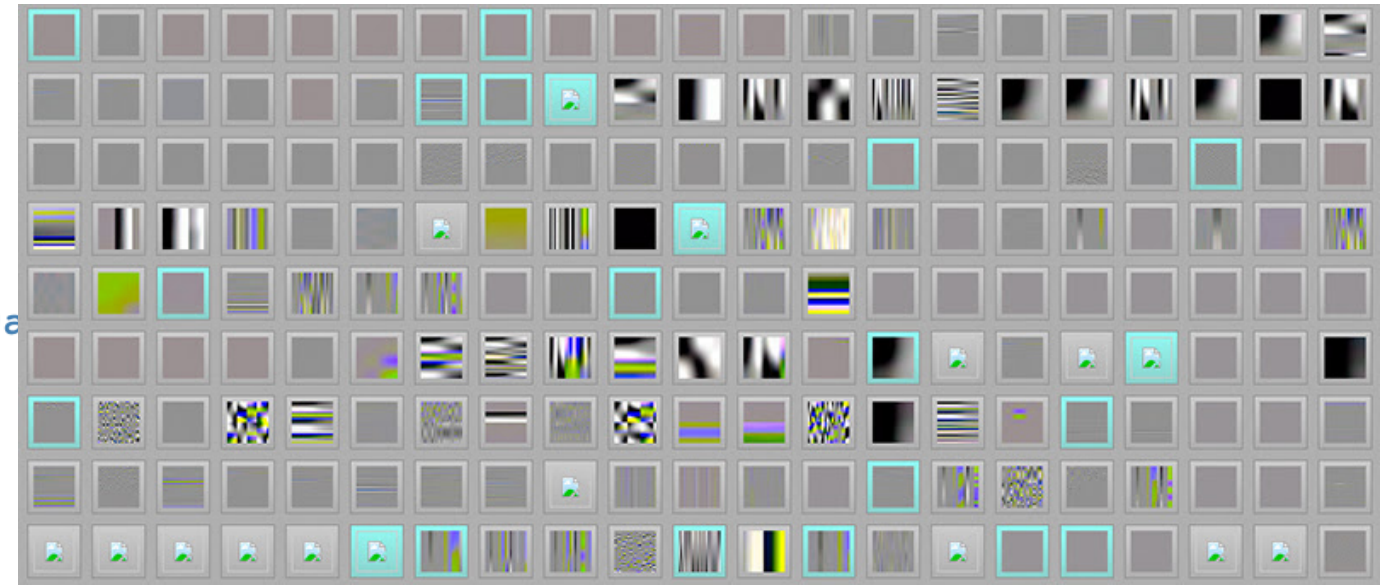
Coverage-Guided Fuzzing with AFL

November 07, 2014

Pulling JPEGs out of thin air

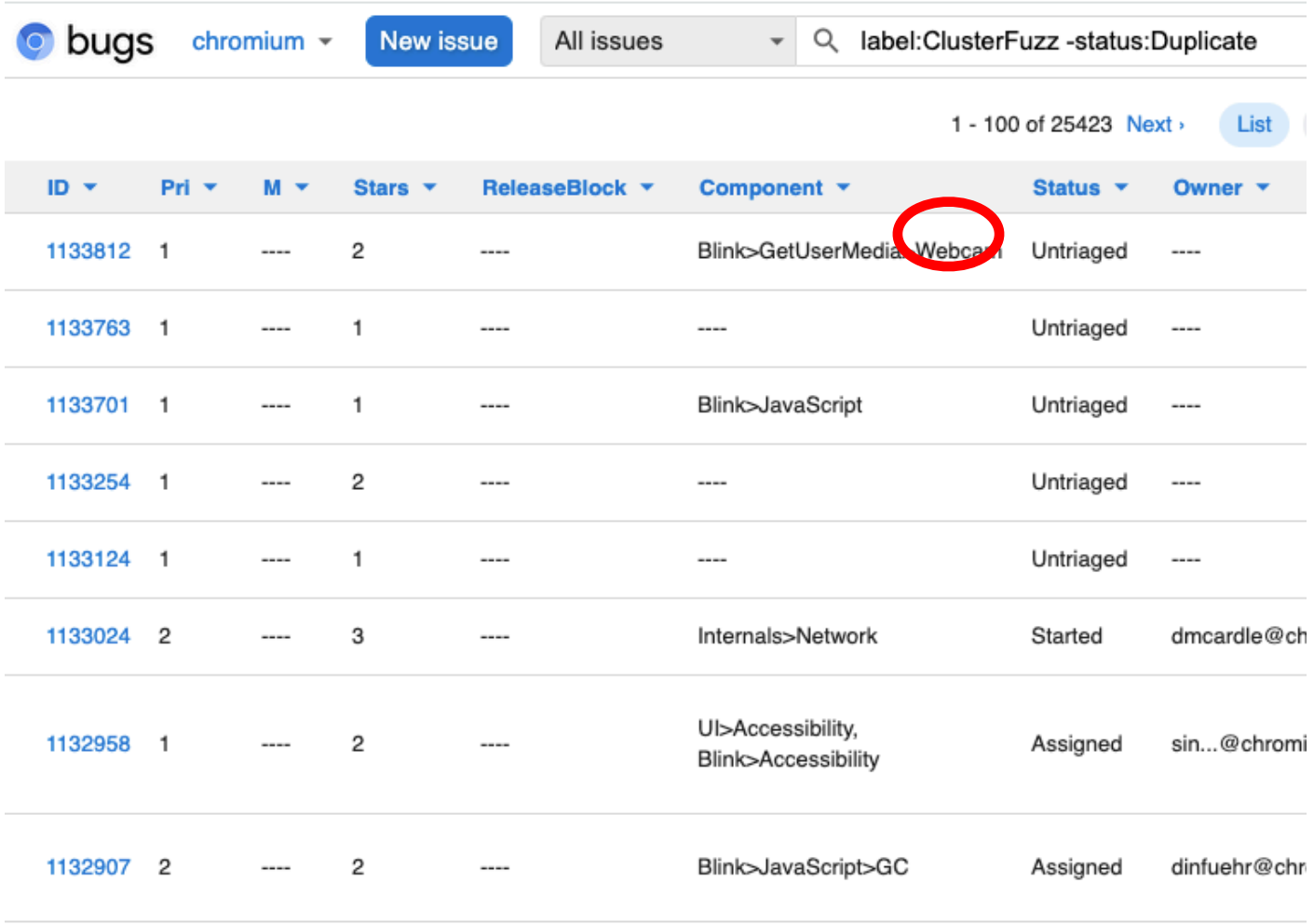
This is an interesting demonstration of the capabilities of afl; I was actually pretty surprised that it worked!

```
$ mkdir in_dir
$ echo 'hello' >in_dir/hello
$ ./afl-fuzz -i in_dir -o out_dir ./jpeg-9a
```



https://lcamtuf.blogspot.com/2014/11/pulling-jpegs-out-of-thin-air.html

ClusterFuzz @ Chromium



ID	Pri	M	Stars	ReleaseBlock	Component	Status	Owner
1133812	1	----	2	----	Blink>GetUserMedia>Webcam	Untriaged	----
1133763	1	----	1	----	----	Untriaged	----
1133701	1	----	1	----	Blink>JavaScript	Untriaged	----
1133254	1	----	2	----	----	Untriaged	----
1133124	1	----	1	----	----	Untriaged	----
1133024	2	----	3	----	Internals>Network	Started	dmcardle@ch
1132958	1	----	2	----	UI>Accessibility, Blink>Accessibility	Assigned	sin...@chromi
1132907	2	----	2	----	Blink>JavaScript>GC	Assigned	dinfuehr@chr

Property-based testing

- Manually writing tests:
  - - work
  - - requires creativity
  - - biased toward your expectations of where bugs are
  - + precise (test relevant use cases)
  - + can test basically anything

Can we generate lots of tests?

First, write down a property that a function should have, and a range:

```
@given(s.integers(min_value=-(10 ** 6), max_value=10 ** 6))
def test_factorize_multiplication_property(n):
    """The product of the integers returned by factorize(n) needs to be n."""
    factors = factorize(n)
    product = 1
    for factor in factors:
        product *= factor
    assert product == n, f"factorize({n}) returned {factors}"
```

Then, run Hypothesis, which searches the space…

```
================================= test session starts ==================================
platform linux -- Python 3.8.4, pytest-6.0.1, py-1.9.0, pluggy-0.13.1
rootdir: /home/moose/GitHub/MartinThoma/algorithms/medium/property-based-testing
plugins: hypothesis-5.23.8
collected 9 items

test_factorize_parametrize.py ........                                          [ 88%]
test_factorize_property.py F                                                    [100%]

======================================= FAILURES =======================================
_____________________________ test_factorize_multiplication_property _____________________________

    @given(s.integers(min_value=-(10 ** 6), max_value=10 ** 6))
>   def test_factorize_multiplication_property(n):

test_factorize_property.py:10:
_ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _

n = 5

    @given(s.integers(min_value=-(10 ** 6), max_value=10 ** 6))
    def test_factorize_multiplication_property(n):
        """The product of the integers returned by factorize(n) needs to be n."""
        factors = factorize(n)
        product = 1
        for factor in factors:
            product *= factor
>       assert product == n, f"factorize({n}) returned {factors}"
E       AssertionError: factorize(5) returned []
E       assert 1 == 5

test_factorize_property.py:16: AssertionError
---------------------------------- Hypothesis ----------------------------------
Falsifying example: test_factorize_multiplication_property(
    n=5,
)
=============================== short test summary info ================================
FAILED test_factorize_property.py::test_factorize_multiplication_property - AssertionEr...
============================== 1 failed, 8 passed in 0.12s ==============================
```

Oops! factorize(5) returned an empty list of factors!

Generating tests

- Mutate existing "interesting" inputs
  - e.g. apply transformations to images
- Can you relate input transformations to output transformations?
  - Rotate input -> expect rotated output

Slide credit: adapted from Jonathan Bell (CC BY-SA)

Regression Testing

- Goal: know if something changed
- Try snapshot tests
- First time: record output
  - Later: compare output to saved output
- Useful with GUIs, API testing

Slide credit: adapted from Jonathan Bell (CC BY-SA)

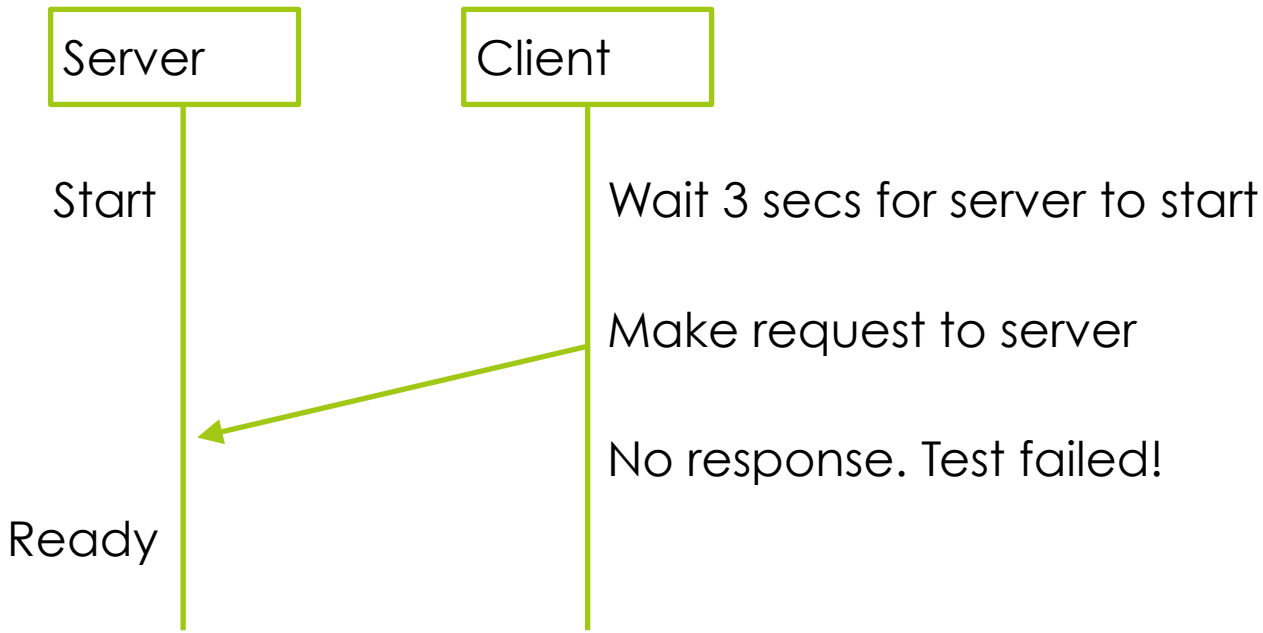
Testing user interfaces

- Need humans!
- Could try A/B tests to see if a real change impacts users

Slide credit: adapted from Jonathan Bell (CC BY-SA)

Avoiding Flaky Tests

- Ensure a consistent starting configuration
- Ensure consistent cleanup
- Test order dependencies
- Control asynchronous startup



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