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

Why now?

- Practicality: testing assignment is out today (because I want to reserve time later for project work)
- Writing tests can help hone specifications
- See literature on test-driven development
  - TDD may improve quality, but may cost time (studies conflict)

F. Shull, G. Melnik, B. Turhan, L. Layman, M. Diep and H. Erdogmus, "What Do We Know about Test-Driven Development?," in *IEEE Software*, vol. 27, no. 6, pp. 16-19, Nov.-Dec. 2010, doi: 10.1109/MS.2010.152.

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**

Key vocabulary

- **Unit testing** is a form of software testing by which **isolated source code** is tested to validate expected behavior. (Kolawa)
- **Integration testing** tests the behavior of large software components.

The **THREE BIG IDEAS** of Software Testing

Coverage: Seek to execute all possibilities.

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

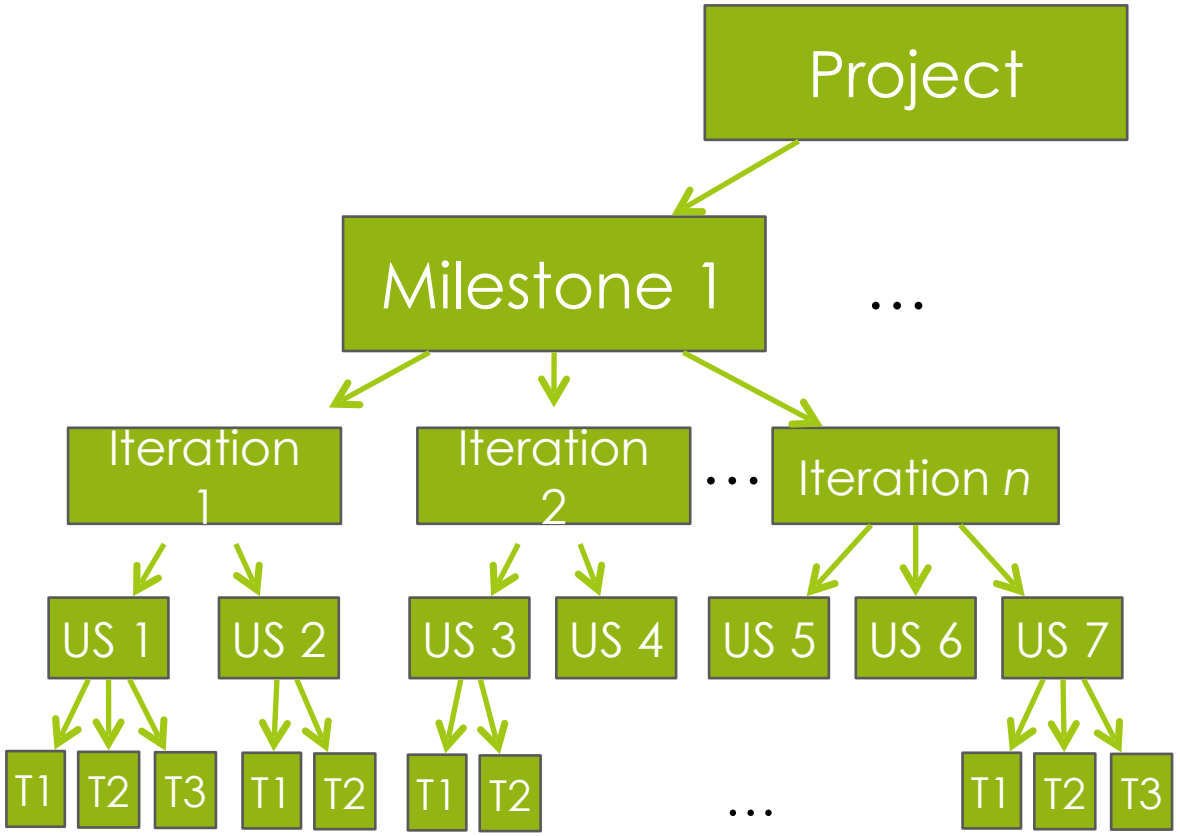
Test Equivalence Classes:

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
     - Automating all could be expensive; some by hand
  3. Iteration/Milestone-level: End-to-end Scenario tests
     - Additionally consider Personas, platforms/configurations, real people
- Diversification beyond the hierarchy:
  - Asserts from design by contract
  - 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

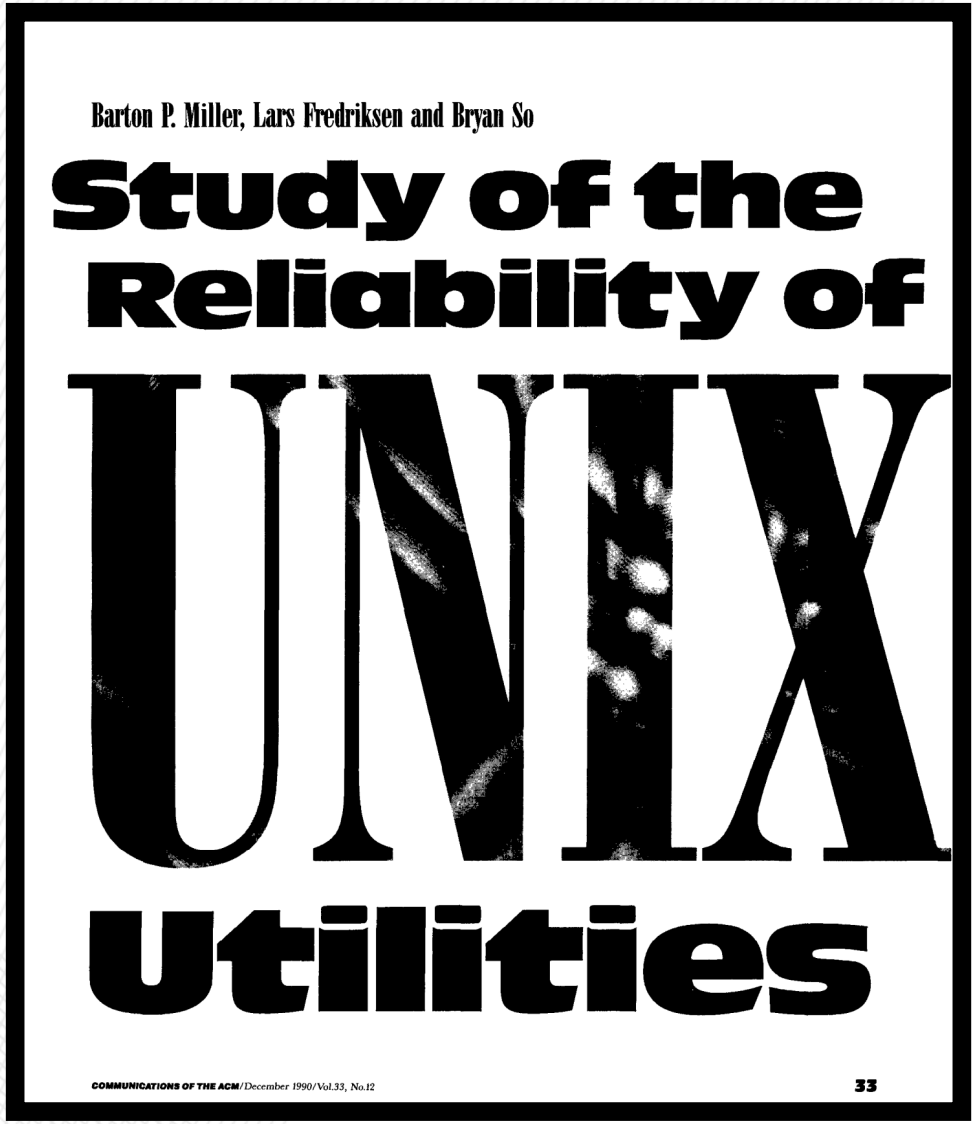
```
def p2(x):
  if x > 0 and x < 1000:
    if ((x - 32) * 5/9 == 100):
      return True
  return False
```

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

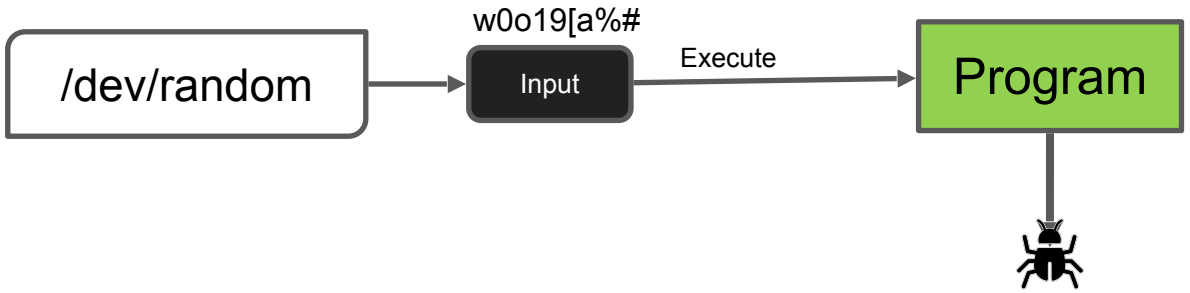
Security and Robustness



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];
}
```

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];
}
```

AddressSanitizer

Compile with `clang –fsanitize=address`

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

AddressSanitizer

Compile with `clang –fsanitize=address`

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];
}
```

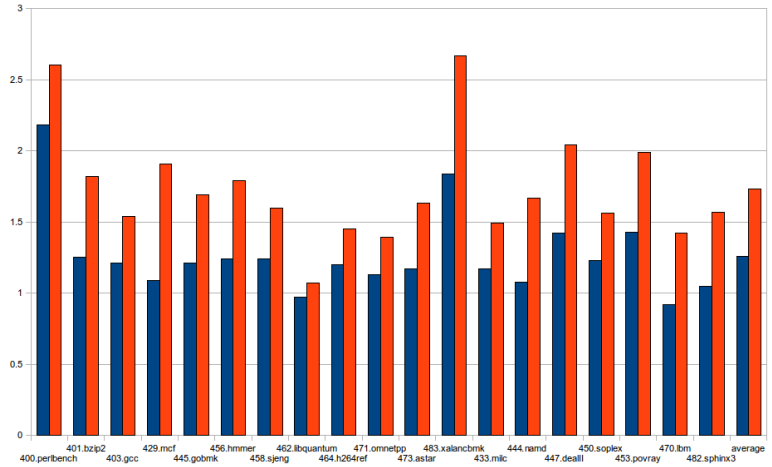
AddressSanitizer

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

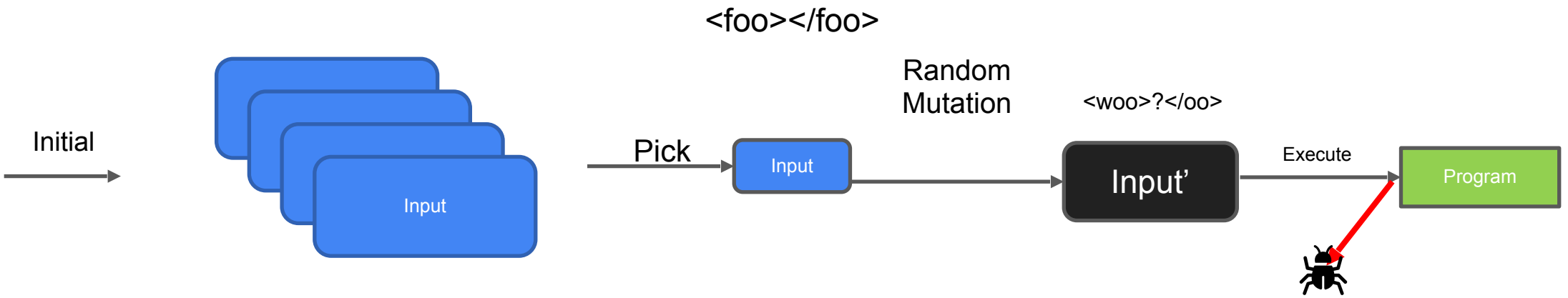
Limitations:

- 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.

Sanitizers...

A. Can be relied on to find most bugs that pertain to undefined behavior.
B. Only work when test cases execute dangerous codepaths.
C. Impose only trivial runtime overhead, so they can be used in production.
D. Intervene at run time to avoid bad behavior.
E. Remove sensitive data, such as passwords, from outputs.

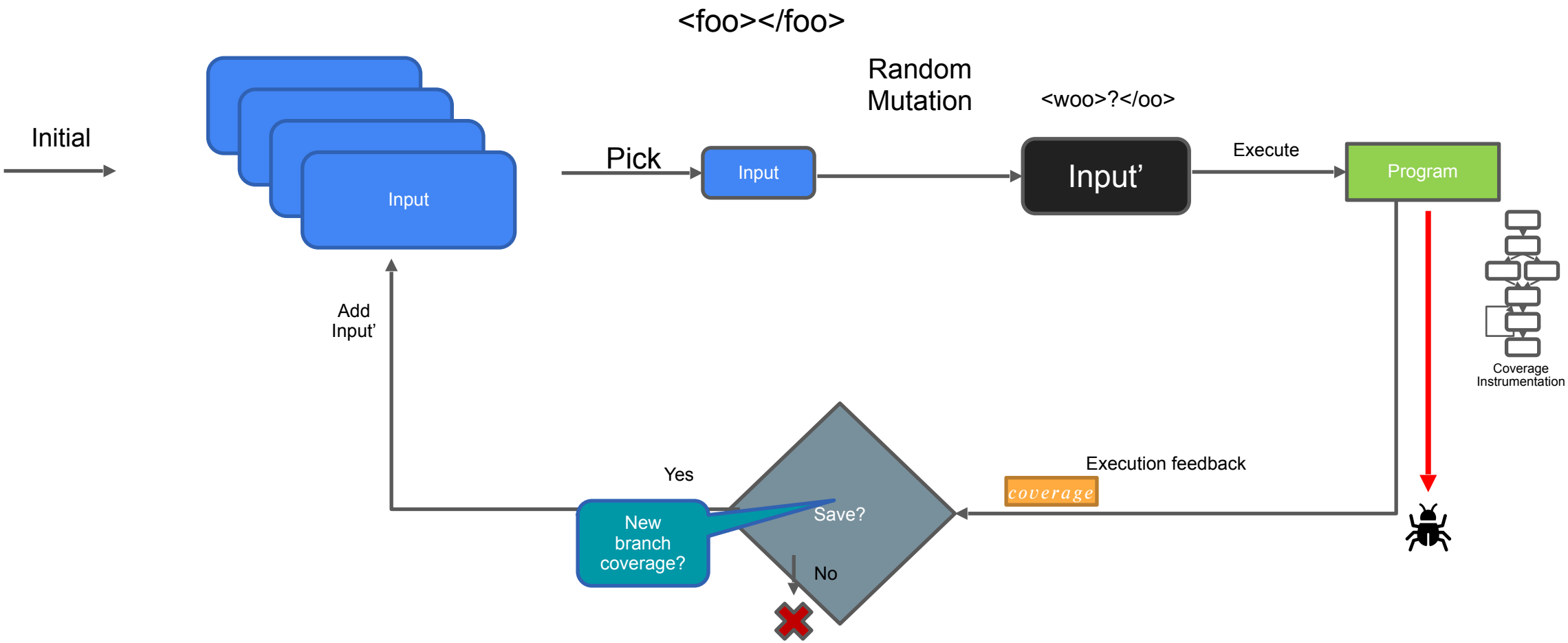
Mutation-Based Fuzzing (e.g. Radamsa)



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)



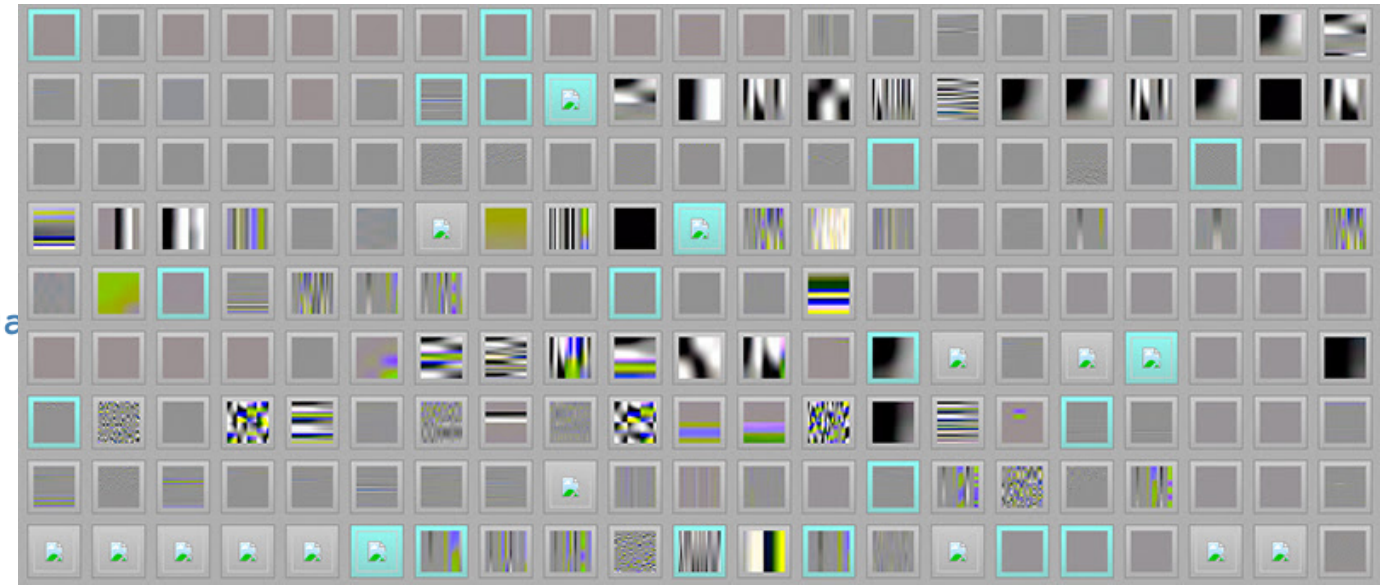
Coverage-Guided Fuzzing with AFL

November 07, 2014

Pulling JPEGs out of thin air

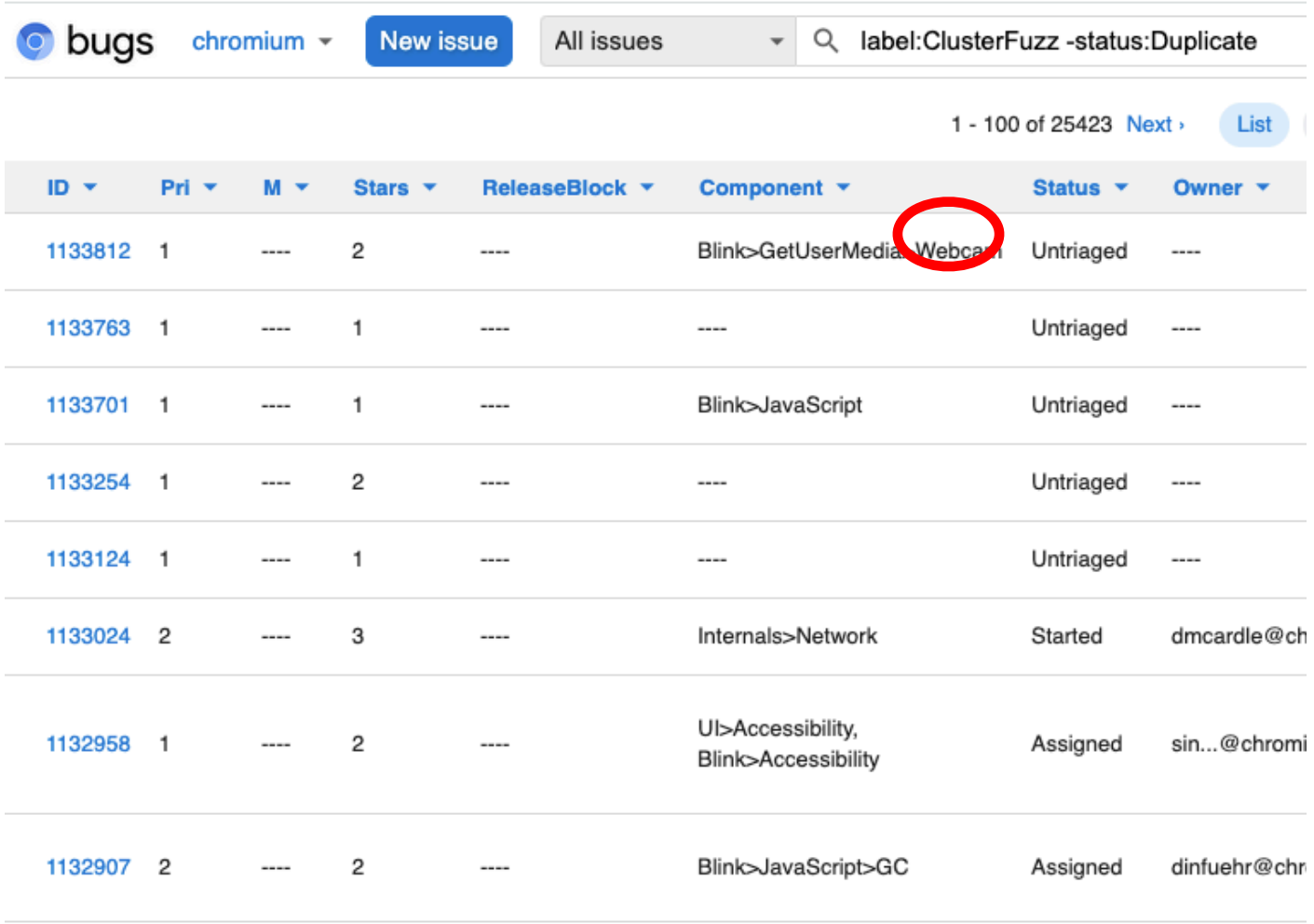
This is an interesting demonstration of the capabilities of afl; I was actually pretty surprised that it worked!

```
$ 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)

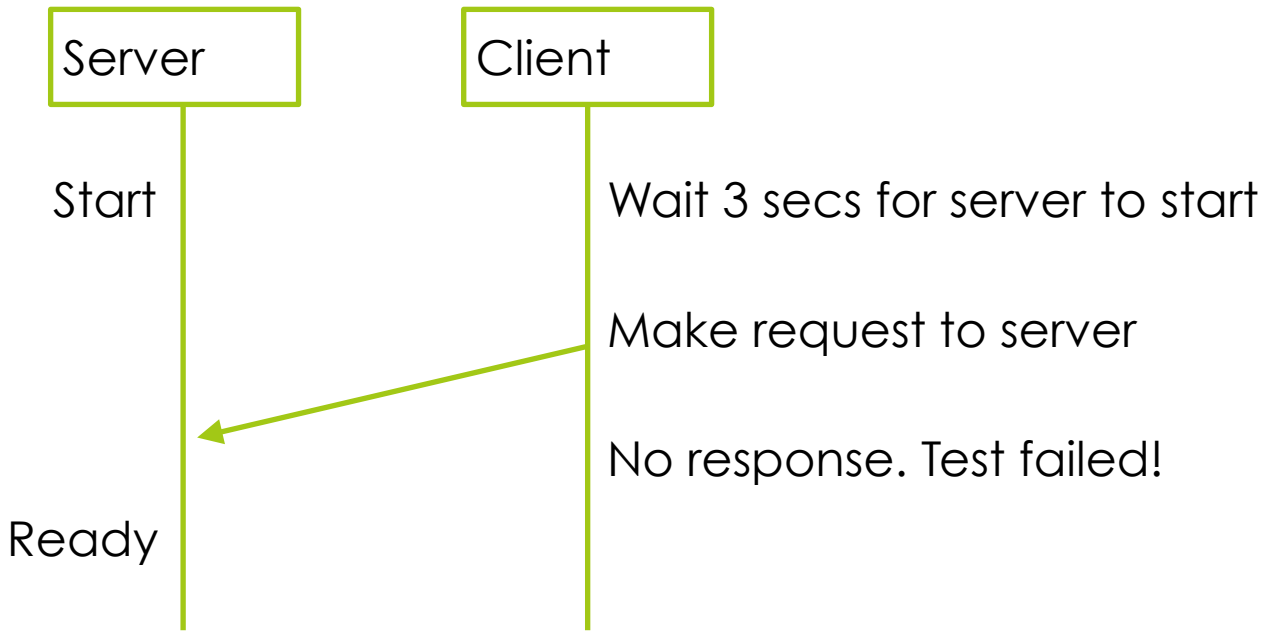
Testing user interfaces

- 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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