Beyond Traditional Testing with Dynamic Analysis

17-313: Foundations of Software Engineering

https://cmu-313.github.io

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Fall 2025

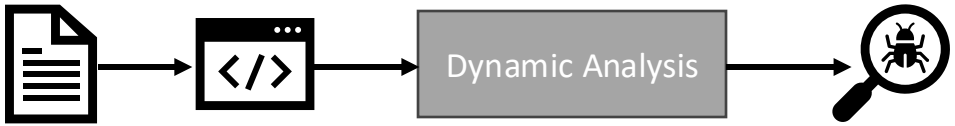
Administrivia

- Final Exam is scheduled for **Friday, Dec 12th** at **8:30 to 11:30am**

Learning Goals

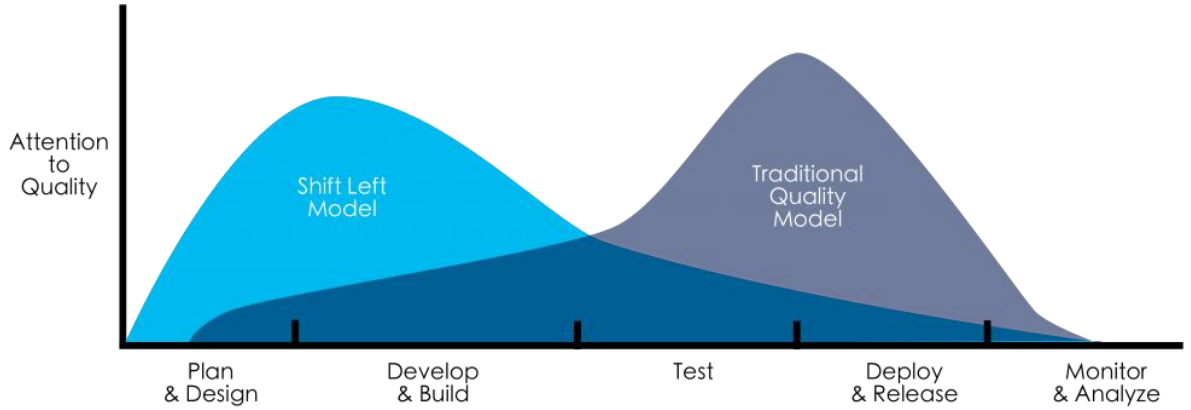
- Understand how dynamic analysis complements static analysis
- Recognize the strengths and limitations of dynamic techniques
- Use runtime oracles to make failures observable
- Explore techniques from fuzzing and property-based testing to mutation testing

Recap: Static vs. Dynamic Analysis



Recap: Shifting Left

- Key Idea: Find and prevent issues **as early as possible**
  - Many issues can't be found via static analysis



Let’s just write more tests?

What are the challenges and limitations of traditional, example-based testing?

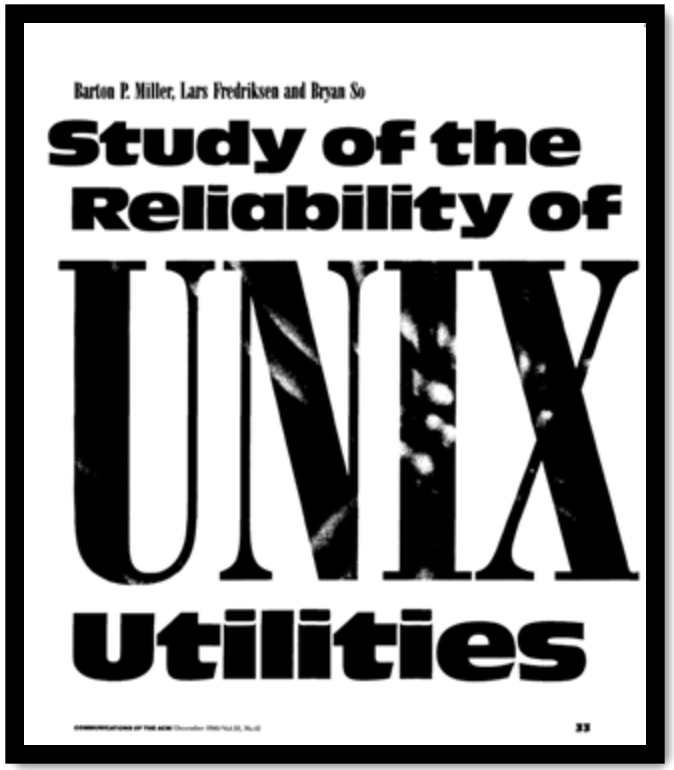
Today

- Fuzzing
- Oracles
- Mutation Testing
- Property-Based Testing

Today

- **Fuzzing**
- Oracles
- Mutation Testing
- Property-Based Testing

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.

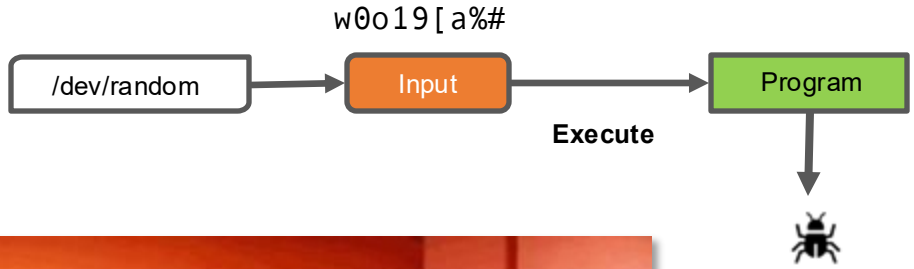
How can we identify these bugs?

Infinite Monkey Theorem

*"a **monkey** hitting keys **at random** on a typewriter **keyboard** for an **infinite amount of time** will almost surely type any given text, including the complete works of **William Shakespeare.** "*

https://en.wikipedia.org/wiki/Infinite_monkey_theorem

Fuzz Testing randomly generates inputs and checks for program crashes



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

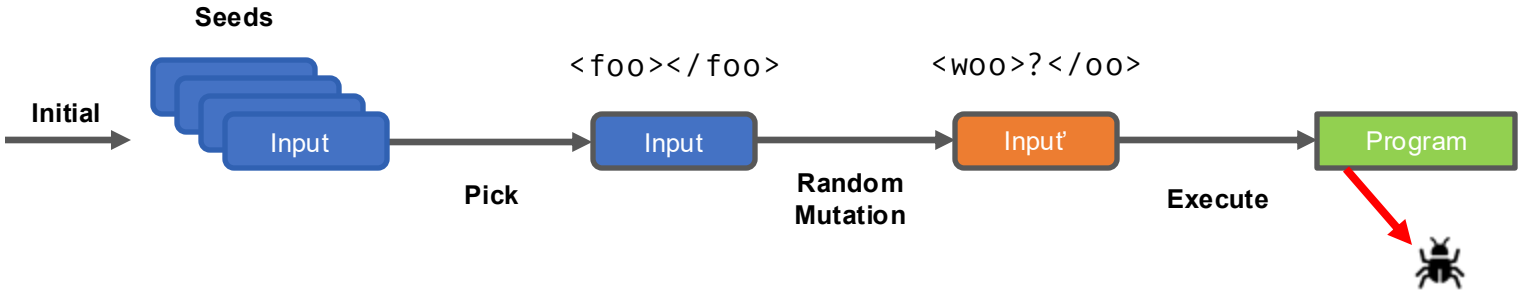
Common Fuzzer-Found Bugs in C/C++

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

Mutation-Based Fuzzing (e.g., Radamsa)



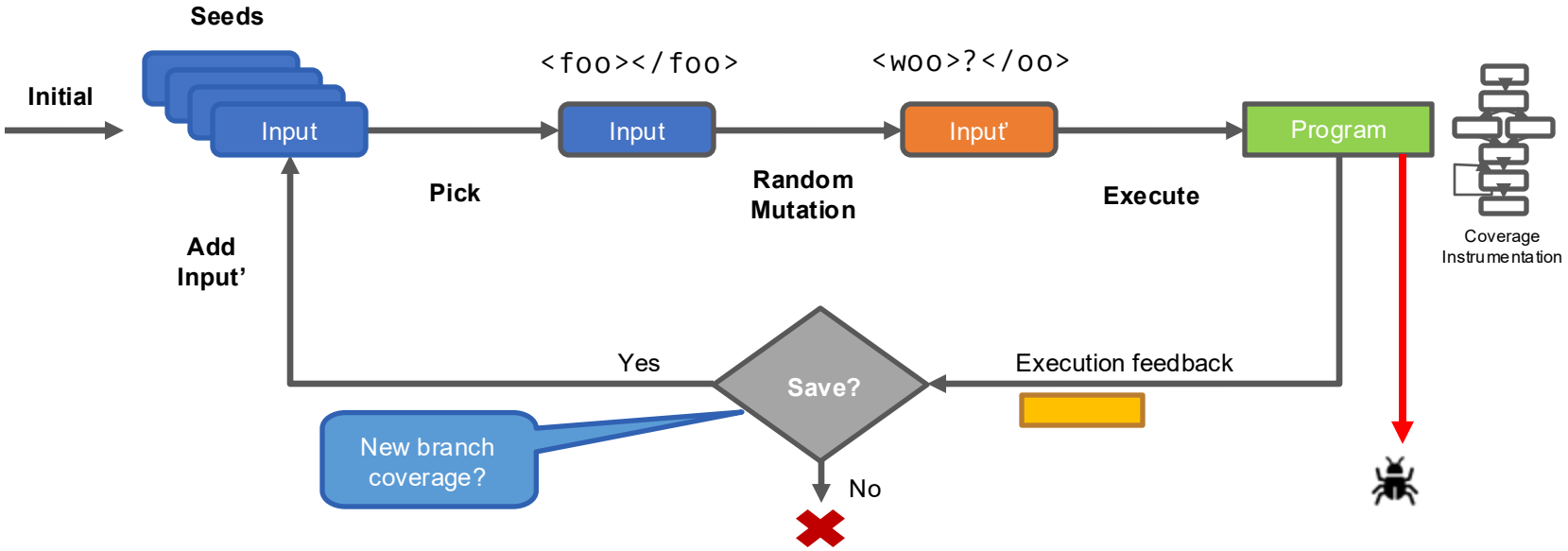
https://gitlab.com/akihe/radamsa

Mutation Heuristics

- **Binary Input**
  - bit flips, byte flips
  - modify, insert, 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 click types and targets
  - change text
  - click different buttons

```
<html><head><title>Hello</title></head><body>World<br/></body></html>
```

Coverage-Guided Fuzzing (e.g., AFL)



https://lcamtuf.coredump.cx/afl/

Finding Security Bugs = 💵

Meta

Meta Bug Bounty

If you believe you have found a security vulnerability on Meta (or another member of the Meta family of companies), we encourage you to let us know right away.

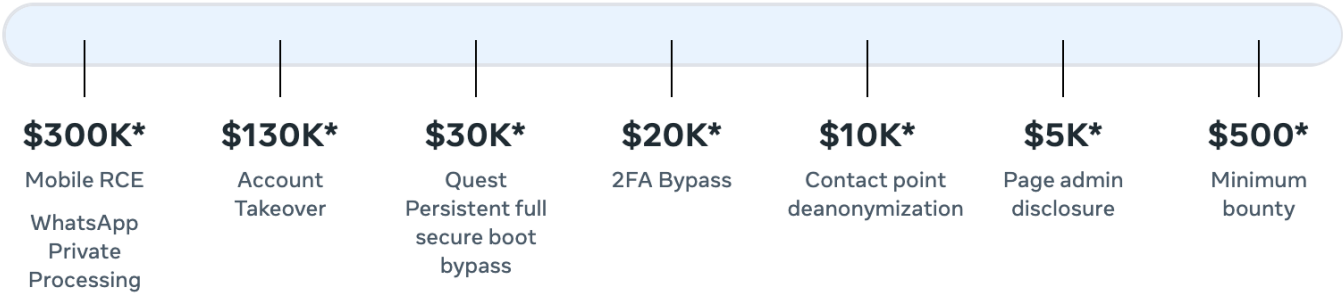
Submit a report

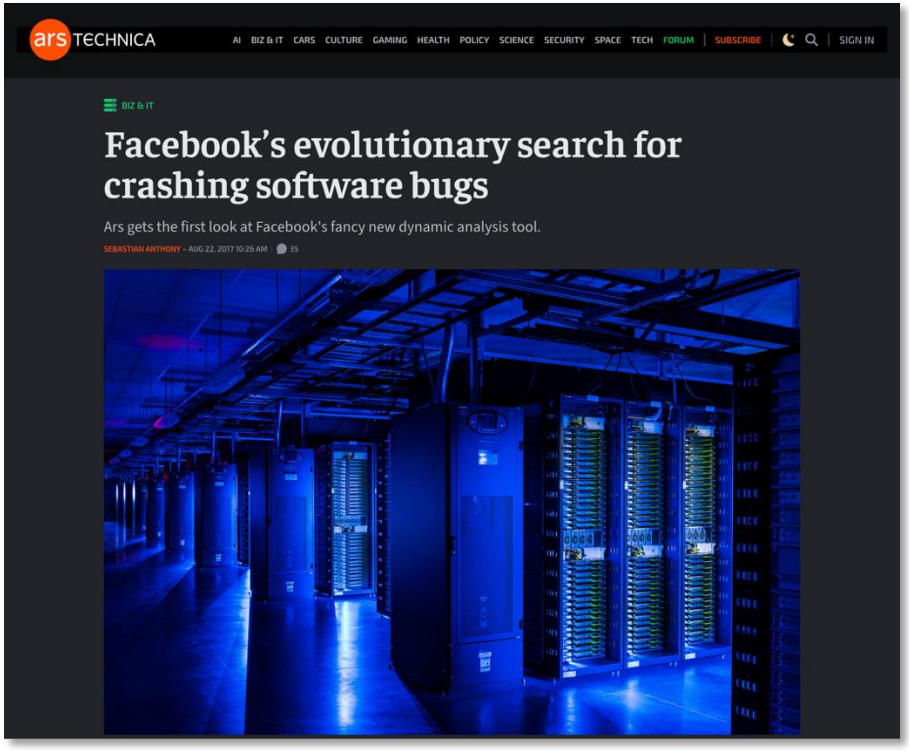
Total rewards for 2025

$4,353,212

Total rewards to date

$25,497,082




ars TECHNICA
AI BIZ & IT CARS CULTURE GAMING HEALTH POLICY SCIENCE SECURITY SPACE TECH FORUM SUBSCRIBE SIGN IN
BIZ & IT
Facebook's evolutionary search for crashing software bugs
Ars gets the first look at Facebook's fancy new dynamic analysis tool.
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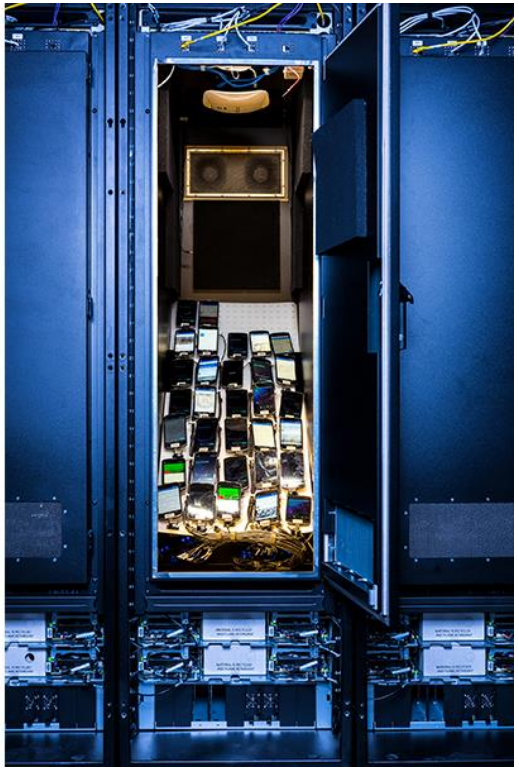
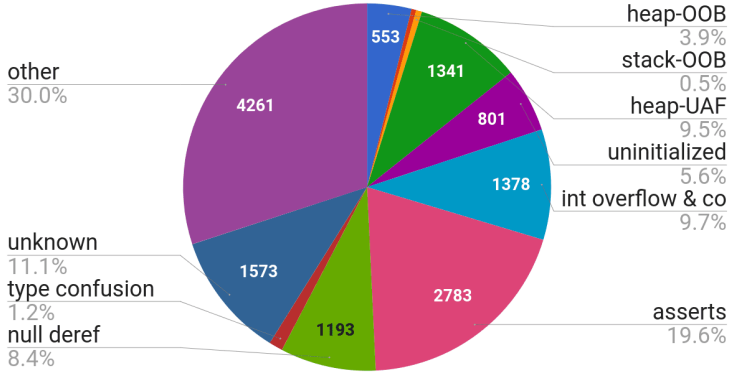
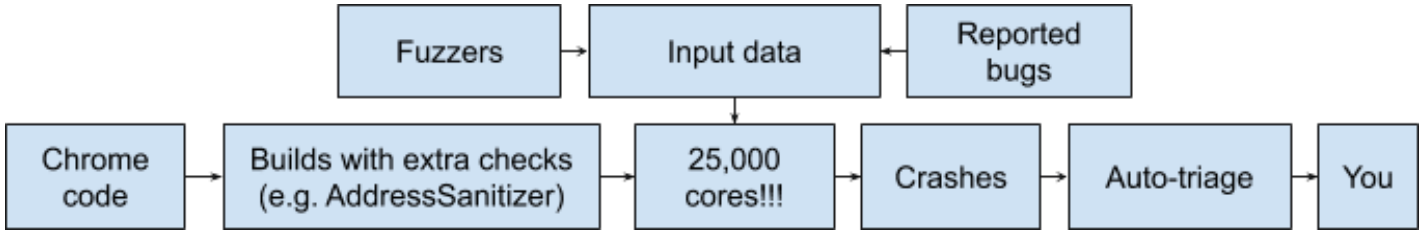


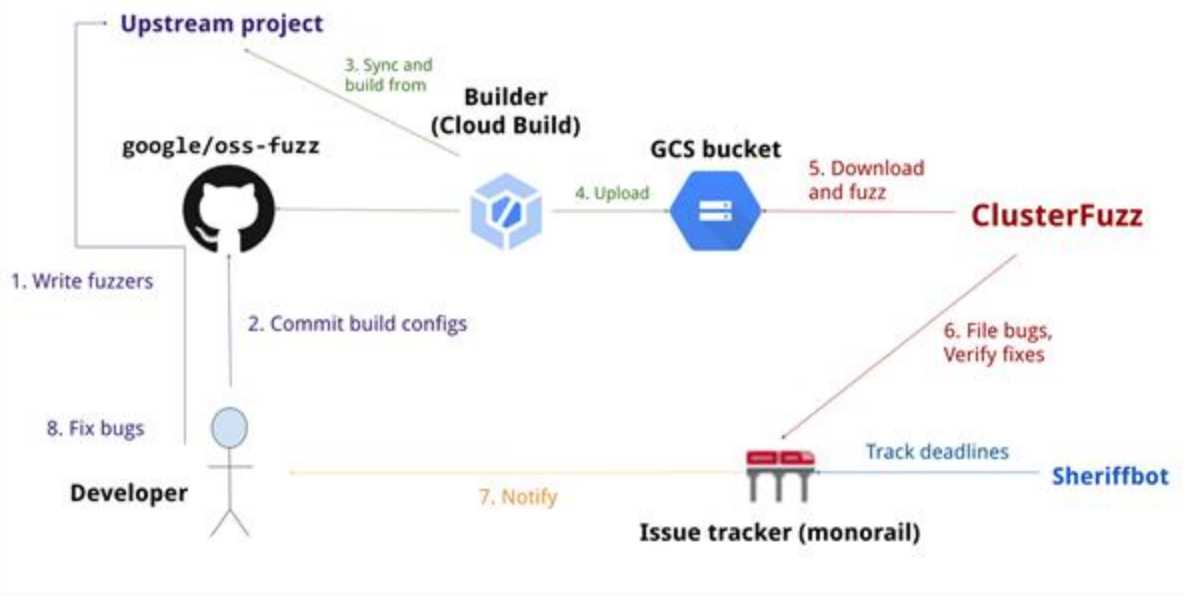
Fuzzing in Practice

- Google uses **ClusterFuzz** to fuzz all of their products
  - supports multiple fuzzing strategies
- *"As of February 2023, ClusterFuzz has found ~27,000 bugs in Google (e.g., Chrome)."*





OSS-Fuzz: Free Fuzzing for Open-Source Software



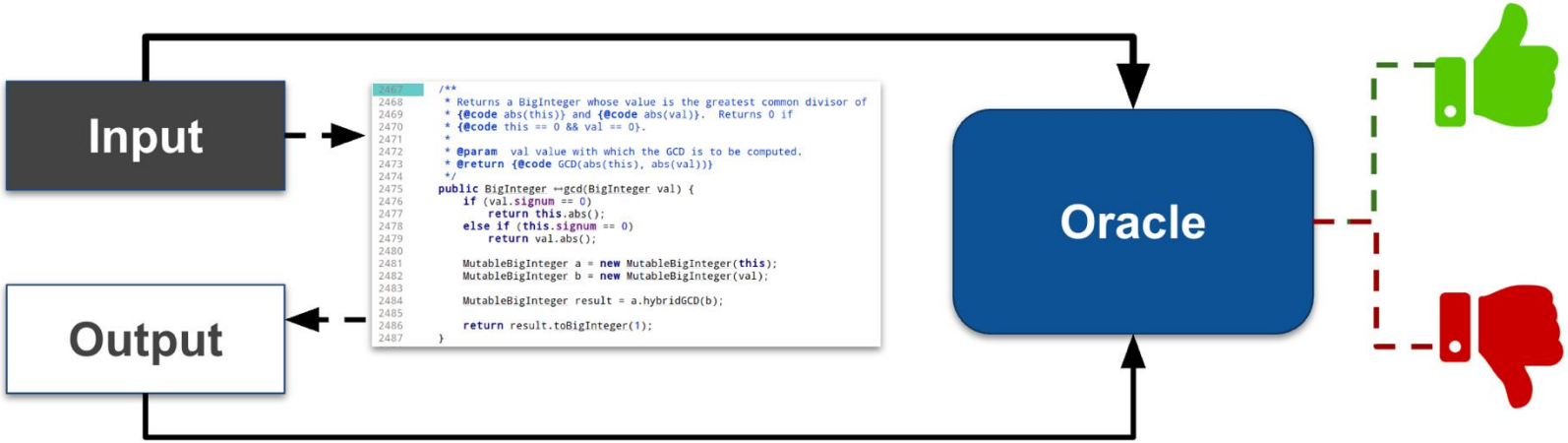
"As of August 2023, OSS-Fuzz has helped identify and fix over 10,000 vulnerabilities and 36,000 bugs across 1,000 projects." (e.g., nodejs, django, openvpn, openssl)

Today

- Fuzzing
- **Oracles**
- Mutation Testing
- Property-Based Testing

Testing is Only as Good as your Oracle

- An oracle decides if behavior is correct for a given input
  - **strong oracles** catch bugs that **weak oracles** miss
  - designing strong oracles is difficult and often the bottleneck



Oracle: Assertions in Example-Based Tests

- **This is the most common type of oracle in traditional tests**
- These assertions are often hardcoded to a specific test input
  - tedious to write for complex outputs (e.g., documents, actions)
  - can be very brittle (e.g., formatting changes lead to test failures)
  - non-determinism and environment coupling lead to flaky tests

```
it('should redirect to login if user is not logged in', async () => {
    const { response, body } = await request.get(`${nconf.get('url')}/me/bookmarks`);
    assert.equal(response.statusCode, 200);
    assert(body.includes('Login to your account'), body.slice(0, 500));
});
```

Oracle: The Program Shouldn’t Crash!

- **This is the oracle used by most fuzzing approaches**
- This oracle is a **generic property** that is not tied to any test inputs
  - that allows us to automatically generate and test any input
  - but the oracle is weak (i.e., not crashing does not imply correct)
- We can make the oracle slightly stronger by using **sanitizers**
  - detects illegal program states that might not cause an immediate crash
  - instruments the program at compile time (e.g., `-fsanitize=address`)
  - finds more safety issues but slows down execution / fuzzing
  - doesn’t reveal logic bugs

Oracle: Assertions in Source Code

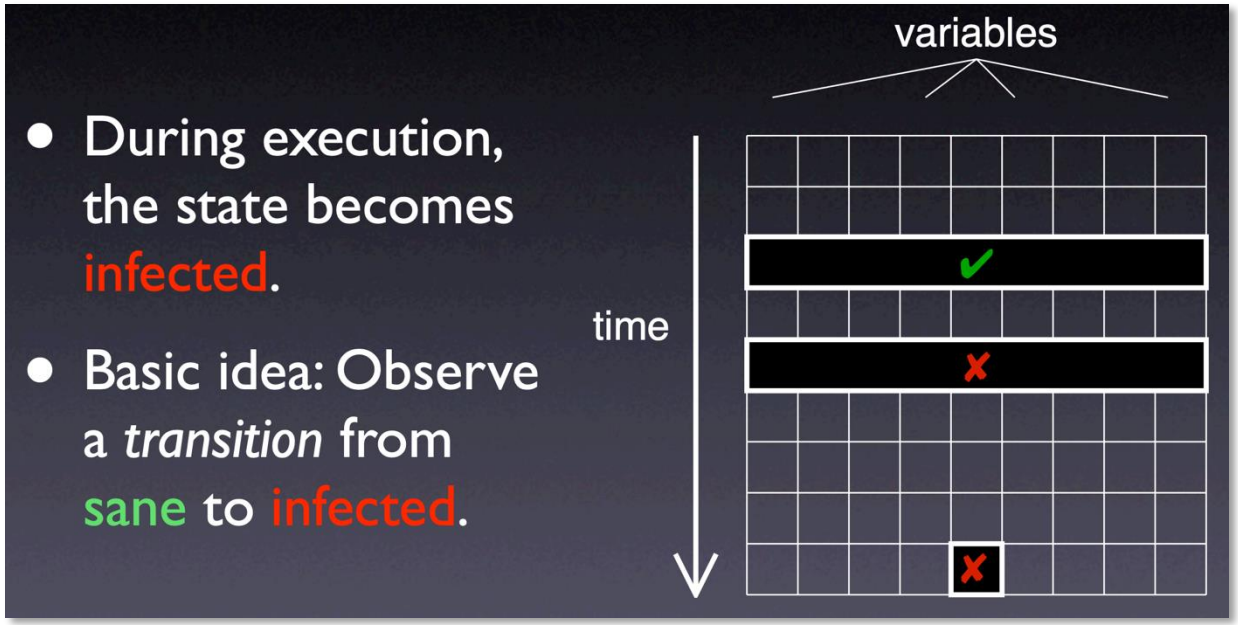
- Assertions are **executable specifications**
  - document intended behavior (pre/postconditions, invariants)
- This oracle is generic and **not tied to any test inputs**
  - if we add assertions, we can use fuzzing to find some logic bugs!

```
function toUSD(amountCents: number): string {
  assert(Number.isInteger(amountCents), 'amount must be integer cents');
  assert(amountCents >= 0, 'amount must be non-negative');
  const dollars = (amountCents / 100).toFixed(2);
  return `$${dollars}`;
}
```


https://blog.regehr.org/archives/1091
https://nullprogram.com/blog/2022/06/26

Assertions catch infections earlier

- Finds more bugs (e.g., during fuzzing) and helps to localize them



What's wrong with this code?

```
async function checkout(cart, payment) {
  assert(payment.cardNumber.length === 16);

  await chargeCard(payment);

  const resp = await fetch(ShippingAPI, {
    method: "POST”,
    body: JSON.stringify(cart),
  });
  assert(resp.status === 200);

  return "ok";
}
```

Assertions should always be true unless you have a bug in your code

- Assertions state invariants: conditions that must always hold if the program is correct (e.g., impossible states, internal consistency).
  - **Never rely on asserts for control flow or user-visible behavior**
  - Make sure that your assertions **don’t contain side effects**
- Use exceptions and returns for errors that can reasonably happen and should be handled (e.g., invalid inputs, failed API calls).

Assertions in the Wild: Apache Cassandra

- Used to enforce an **invariant** that must hold throughout sorting

```
218         *
219         * @param a the array in which a range is to be sorted
220         * @param lo the index of the first element in the range to be sorted
221         * @param hi the index after the last element in the range to be sorted
222         * @param start the index of the first element in the range that is
223         *        not already known to be sorted (@code lo <= start <= hi}
224         * @param c comparator to used for the sort
225         */
226        @SuppressWarnings("fallthrough")
227        private static void binarySort(long[] a, int lo, int hi, int start,
228                                       LongComparator c) {
229            if (DEBUG) assert lo <= start && start <= hi;
230            if (start == lo)
231                start++;
232            for ( ; start < hi; start++) {
233                long pivot = a[start];
234                // Set left (and right) to the index where a[start] (pivot) belongs
235                int left = lo;
236                int right = start;
237                if (DEBUG) assert left <= right;
```

Assertions in the Wild: SQLite & LLVM

- Used to enforce a **precondition** and find bugs at call sites

```c
/*
** Insert a new entry into the cache.  If the cache is full, expel
** the least recently used entry.  Return SQLITE_OK on success or a
** result code otherwise.
**
** Cache entries are stored in age order, oldest first.
*/
static int jsonCacheInsert(
  sqlite3_context *ctx,   /* The SQL statement context holding the cache */
  JsonParse *pParse       /* The parse object to be added to the cache */
){
  JsonCache *p;

  assert( pParse->zJson!=0 );
  assert( pParse->bJsonIsRCStr );
  assert( pParse->delta==0 );
  p = sqlite3_get_auxdata(ctx, JSON_CACHE_ID);
  if( p==0 ){
    sqlite3 *db = sqlite3_context_db_handle(ctx);
```

lldb / include / lldb / Interpreter / OptionValueUInt64.h

Code | Blame | 99 lines · 3.08 KB

```
69          m_current_value = value;
70          return true;
71        }
72        return false;
73      }
74
75      bool SetDefaultValue(uint64_t value) {
76        assert(value >= m_min_value && value <= m_max_value &&
77               "disallowed default value");
78        m_default_value = value;
79        return true;
80      }
```

Assertions in the Wild: Firefox

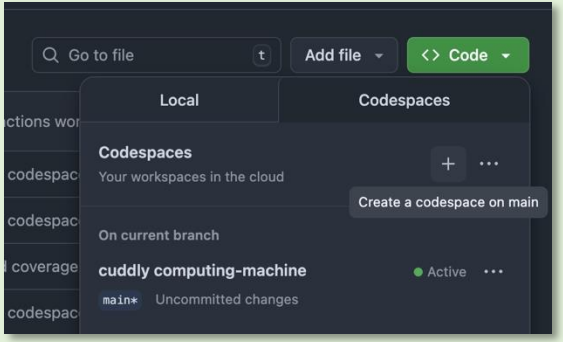
- Used to enforce a **postcondition** that makes sure

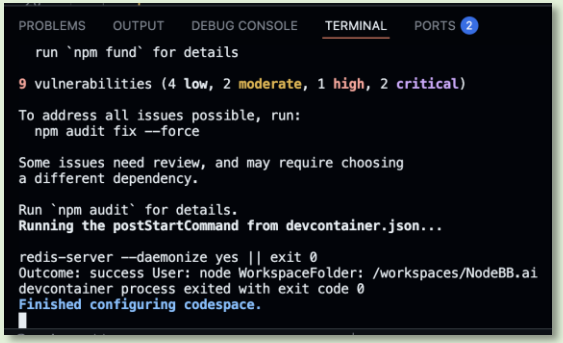
```
namespace mozilla {
void AudioInputProcessing::Process(AudioProcessingTrack* aTrack,

  // Postconditions of the audio-processing logic.
  MOZ_ASSERT(static_cast<uint32_t>(mSegment.GetDuration()) +
                 mPacketizerInput->FramesAvailable() ==
             mPacketizerInput->mPacketSize);
  MOZ_ASSERT(mSegment.GetDuration() >= 1);
  MOZ_ASSERT(mSegment.GetDuration() <= mPacketizerInput->mPacketSize);
}
```

Activity: Setup

- Everyone should participate on their laptop
- Open **CMU-313/PierogI/O** in **Codespaces**
  - https://github.com/CMU-313/PierogIO
- Create a **branch** for this activity
  - `git checkout -b andrew-id/tests`
  - `git push -u origin andrew-id/tests`
- Add your branch name to the spreadsheet
  - http://bit.ly/3WqXBBe





Activity: Write tests to find the bugs

- Find bugs in the implementation by writing test cases
  - “npm run test” to run the tests (or hit the run test button in the IDE)
- Fix any bugs that you find!
  - every bug should have a corresponding regression test
  - **only start fixing the bug once you have written the test**
- Push the changes to your branch to GitHub
  - `git push -u origin andrew-id/tests`
- When you have written at least one test, fixed a bug, and pushed your changes to GitHub, **update the spreadsheet**