Beyond Traditional Testing with Dynamic Analysis

17-313: Foundations of Software Engineering

https://cmu-313.github.io

Michael Hilton and **Josh Sunshine**

Spring 2026

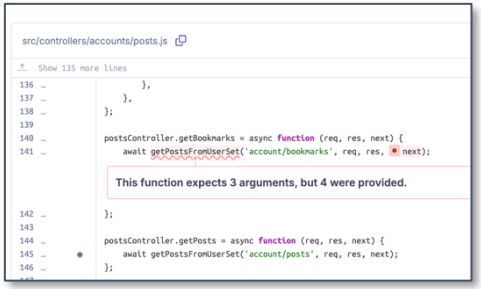
Course Announcements

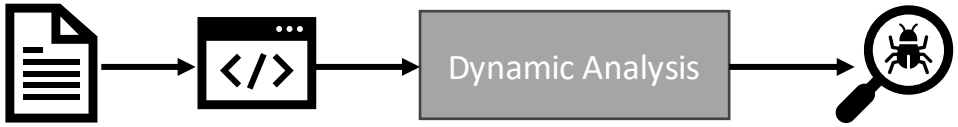
- Midterm review session
  - Monday, February 23 @ 7pm
  - GHC 4401 (Rashid)
- Midterm
  - Thursday, February 26
  - If you need a disability accommodation, please schedule with ODR immediately.
- Project 2C due ~~Thursday, February 26~~ Friday, February 27

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 fuzz testing

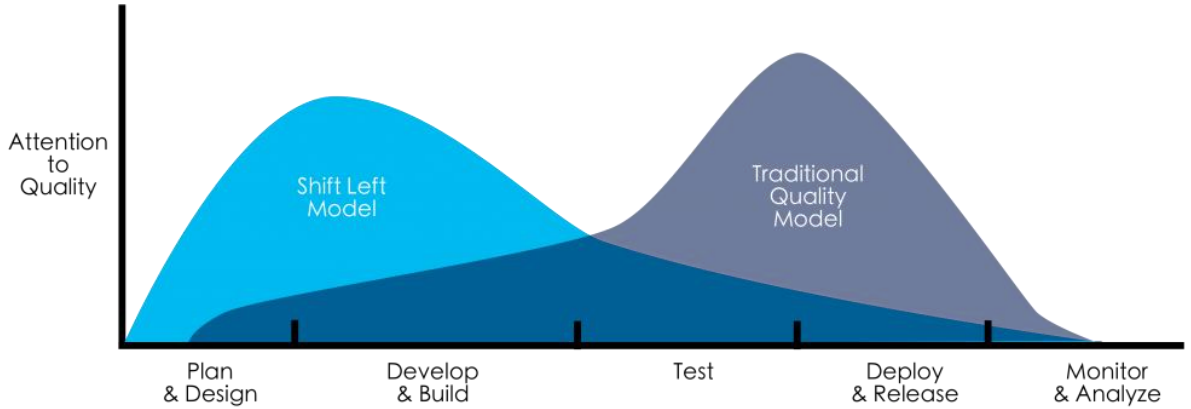
Recap: Static vs. Dynamic Analysis





Recap: Shifting Left

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

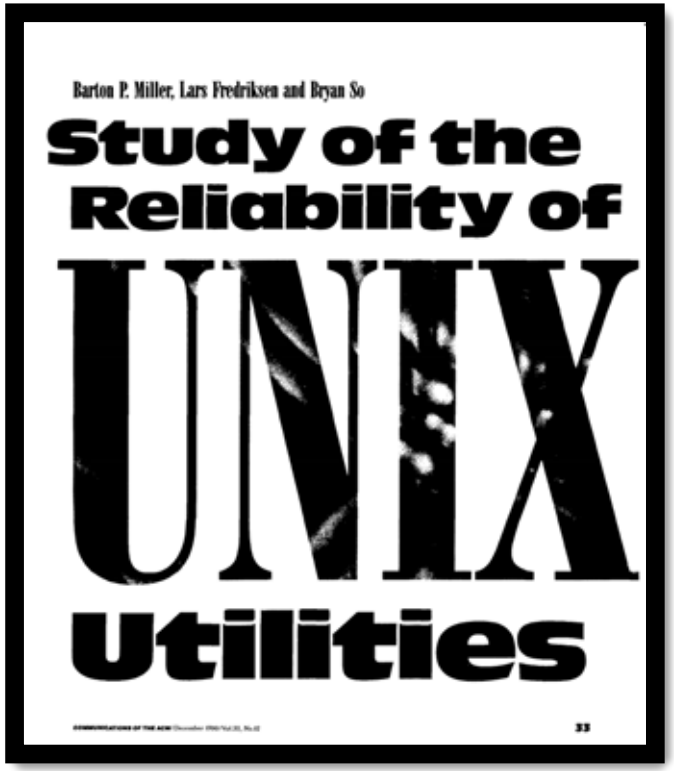


Let’s just write more tests?

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

Fuzz testing and input generation

Communications of the ACM (1990)


Barton P. Miller, Lars Fredriksen and Bryan So

Study of the Reliability of UNIX Utilities

> 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.

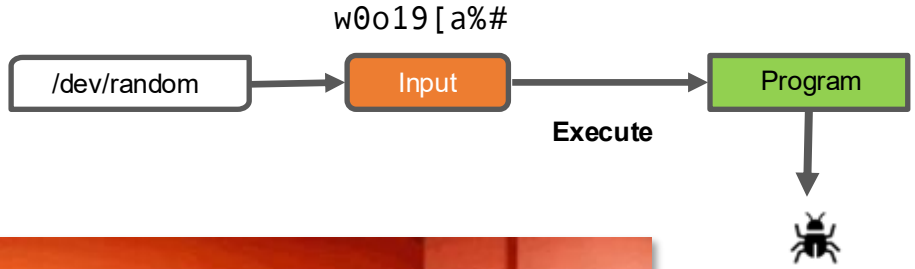
How can we identify these bugs?

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

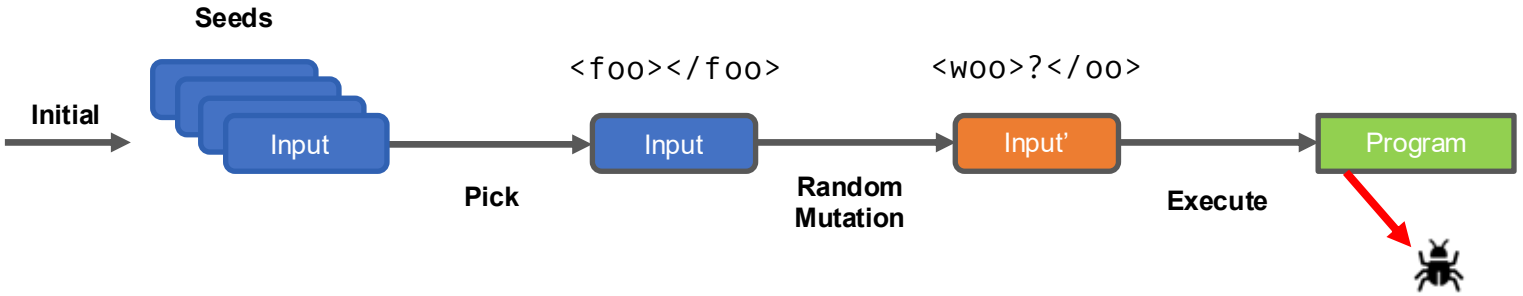
Common Fuzzer-Found Bugs in C/C++

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)



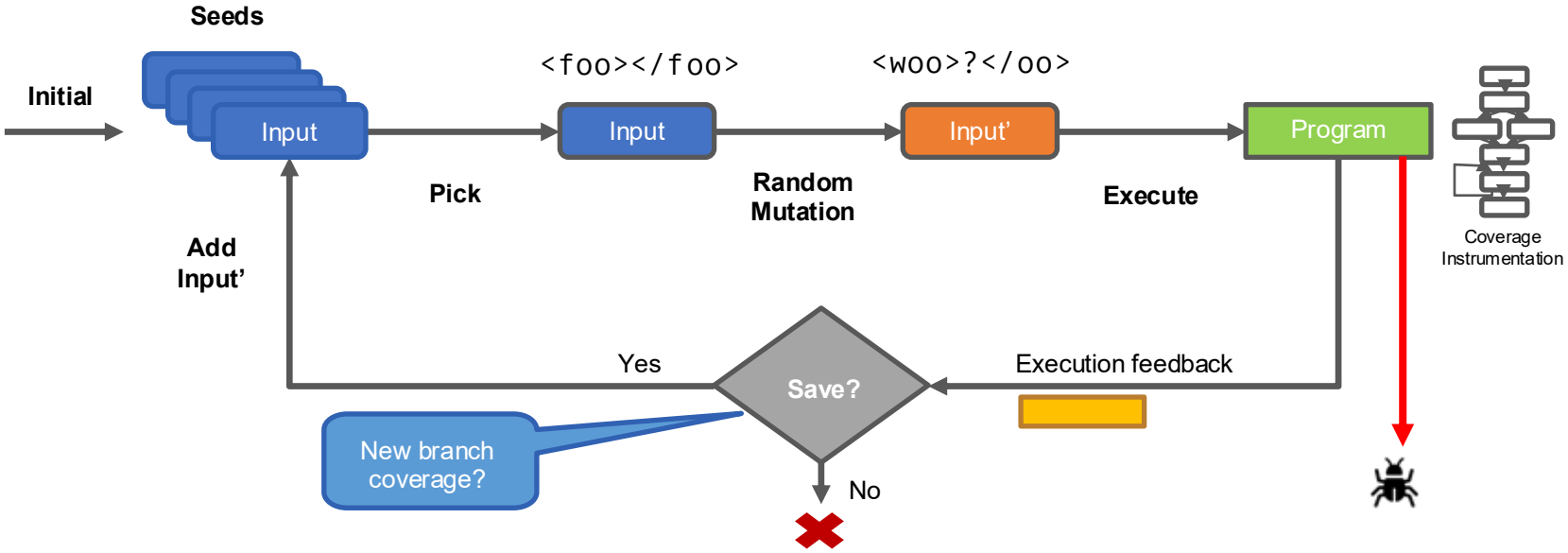
https://gitlab.com/akihe/radamsa

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

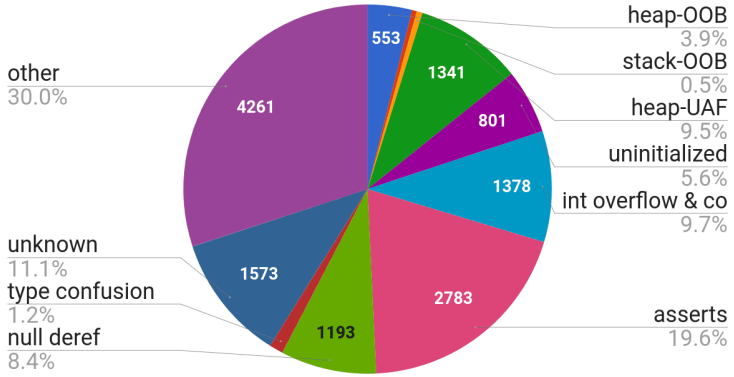
$300K*	$130K*	$30K*	$20K*	$10K*	$5K*	$500*
Mobile RCE WhatsApp Private Processing	Account Takeover	Quest Persistent full secure boot bypass	2FA Bypass	Contact point deanonymization	Page admin disclosure	Minimum bounty

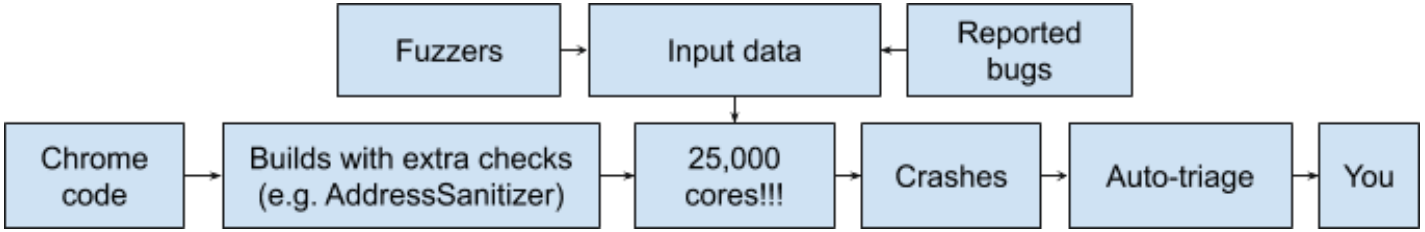
Fuzzing in Practice

- After the OpenSSL Heartbleed vulnerability discovered in 2016, Google launched **OSS-Fuzz**
- Free service for open-source projects
  - “The project must have a significant user base and/or be critical to the global IT infrastructure.”
- OSS-Fuzz privately alerts developers to vulnerabilities

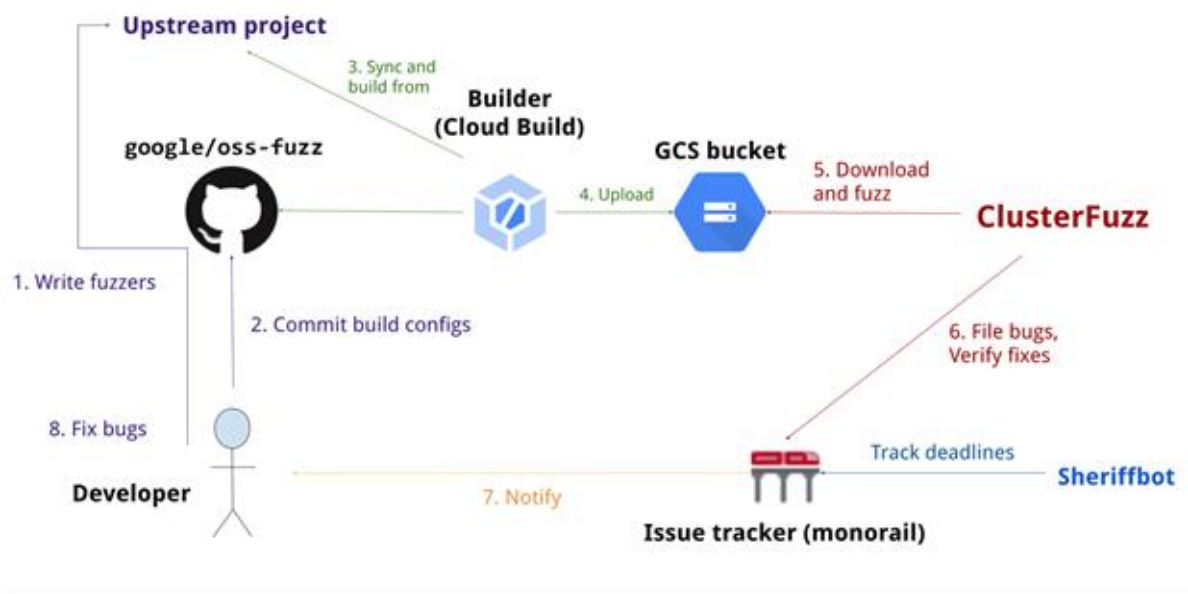
Fuzzing in Practice

- Google uses **ClusterFuzz** to fuzz all of their products
  - supports multiple fuzzing strategies
- *As of February 2026, ClusterFuzz has found 30,000+ bugs in Google code (e.g., Chromium)*





OSS-Fuzz: Free Fuzzing for Open-Source Software



As of May 2025, OSS-Fuzz has helped identify and fix over 13,000 vulnerabilities and 50,000 bugs across 1,000 projects. (e.g., nodejs, django, openvpn, openssl)

Fuzz-testing in the AI era

Rediscovering an old technique for new challenges

/thoughtworks

Engineering Stack

Testing Security Blog

By **Richard Gall**

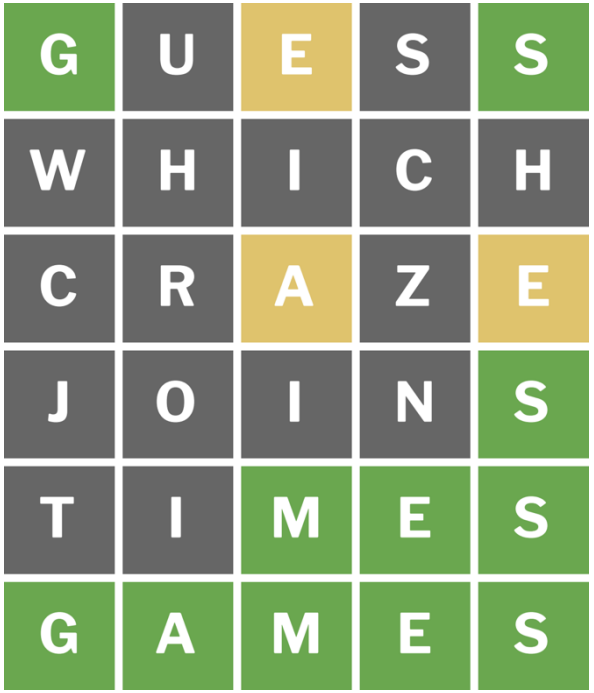
Published: July 07, 2025

Fuzz testing is a software testing technique that's been around for some time. But, despite being nearly forty years old, the technique hasn't been widely adopted by software development teams. While it's commonly used in specialist fields like penetration testing, it's often viewed as somewhat marginal by the industry mainstream.

What are the limitations of random input generation?

Activity: Wordle Input Generator

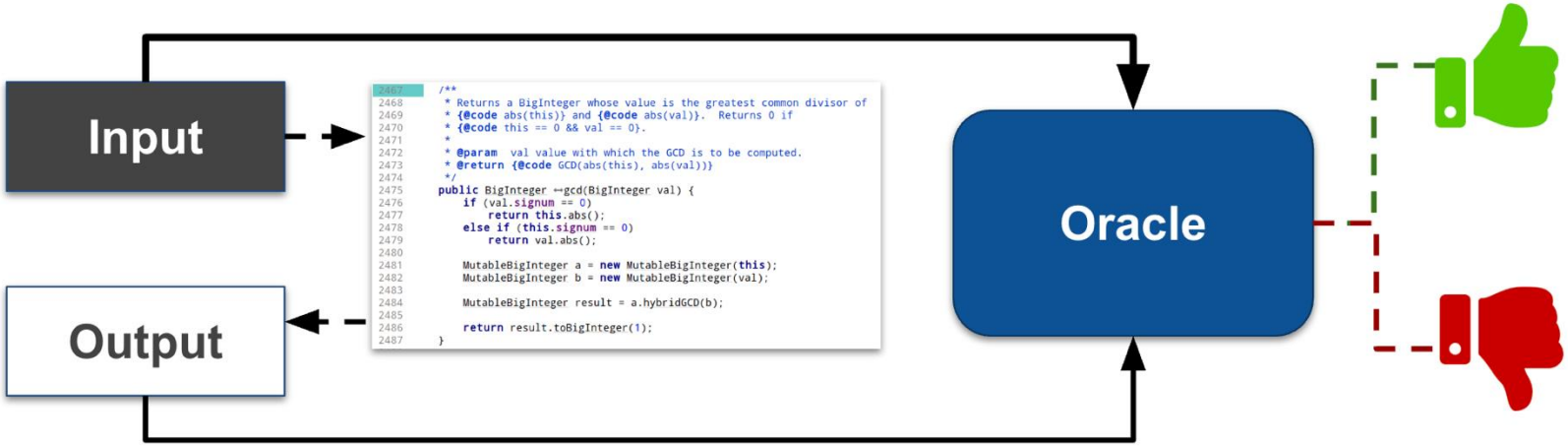
1. How can you generate random inputs for `match_guess`?
2. What inputs are more likely to find bugs in `match_guess`?
3. Describe a strategy for generating these “likely bug” inputs.



Oracles

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

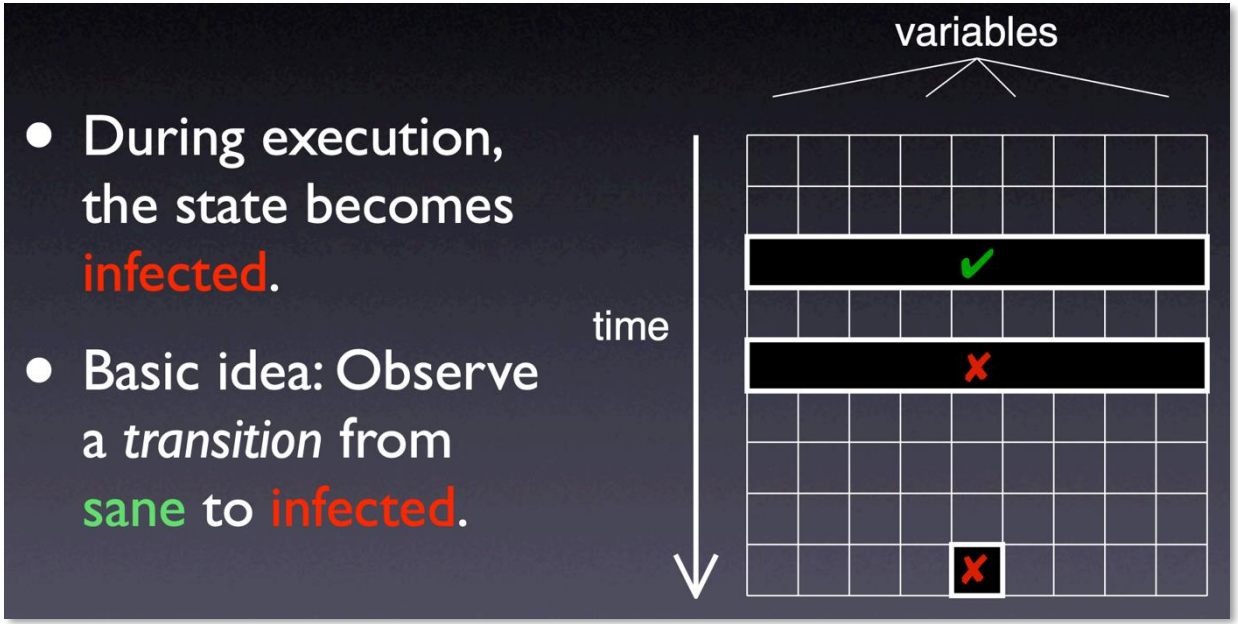
- Assertions are **executable specifications**
  - document intended behavior (pre/postconditions, invariants)
- This oracle is generic and **not tied to any test inputs**
  - if we add assertions, we can use fuzzing to find some logic bugs!

```
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



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 audio packet is the correct size after processing

```
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: Wordle Oracle

1. What precondition assertions could you add to `mark_guess`?
2. What postcondition assertions could you add?