Week:
10 of 12

COMP 2120 / COMP 6120

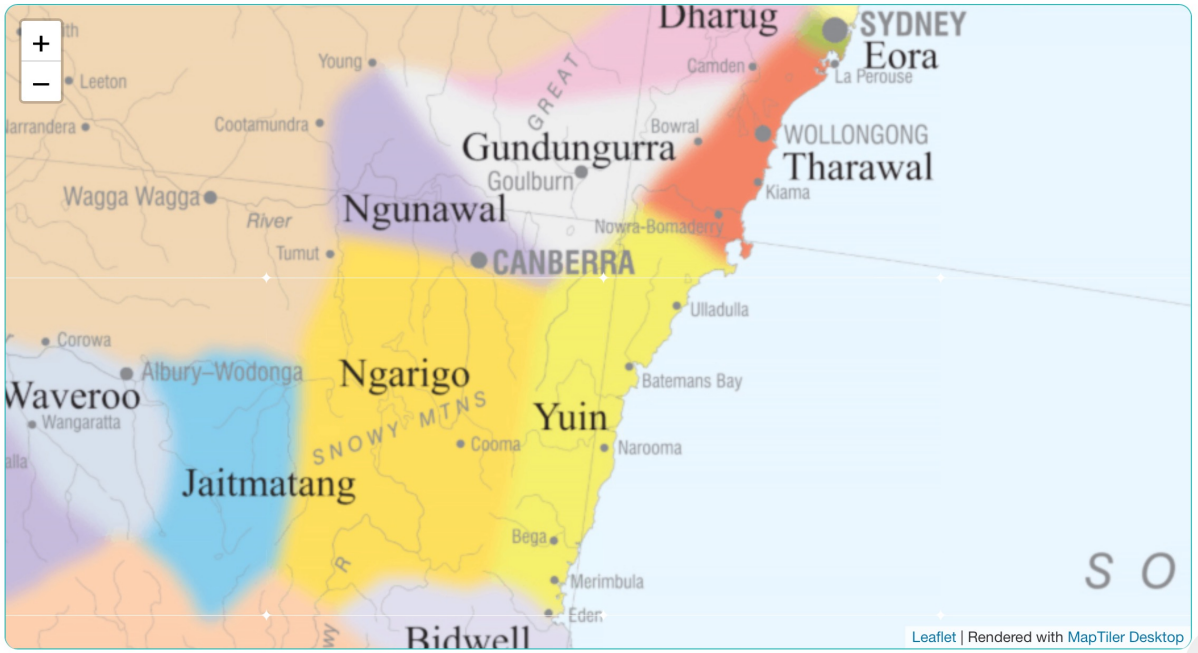
MORE TESTING, THEN STATIC ANALYSIS

A/Prof Alex Potanin and Dr Melina Vidoni

ANU Acknowledgment of Country

AIATSIS Explore Family history Collection Research Education What's new About Shop Search

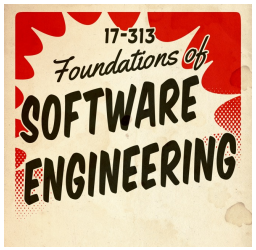
"We acknowledge and celebrate the First Australians on whose traditional lands we meet, and pay our respect to the elders past and present."



https://aiatsis.gov.au/explore/map-indigenous-australia

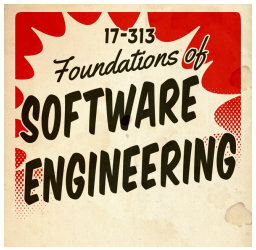
DYNAMIC ANALYSIS AND ADVANCED AUTOMATED TESTING

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



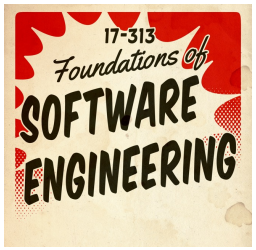

```
def p1(x):
    if x * x - 10 == 15:
        return True
    return False
```

Puzzle:
Find `x` such that `p2(x)` returns `True`



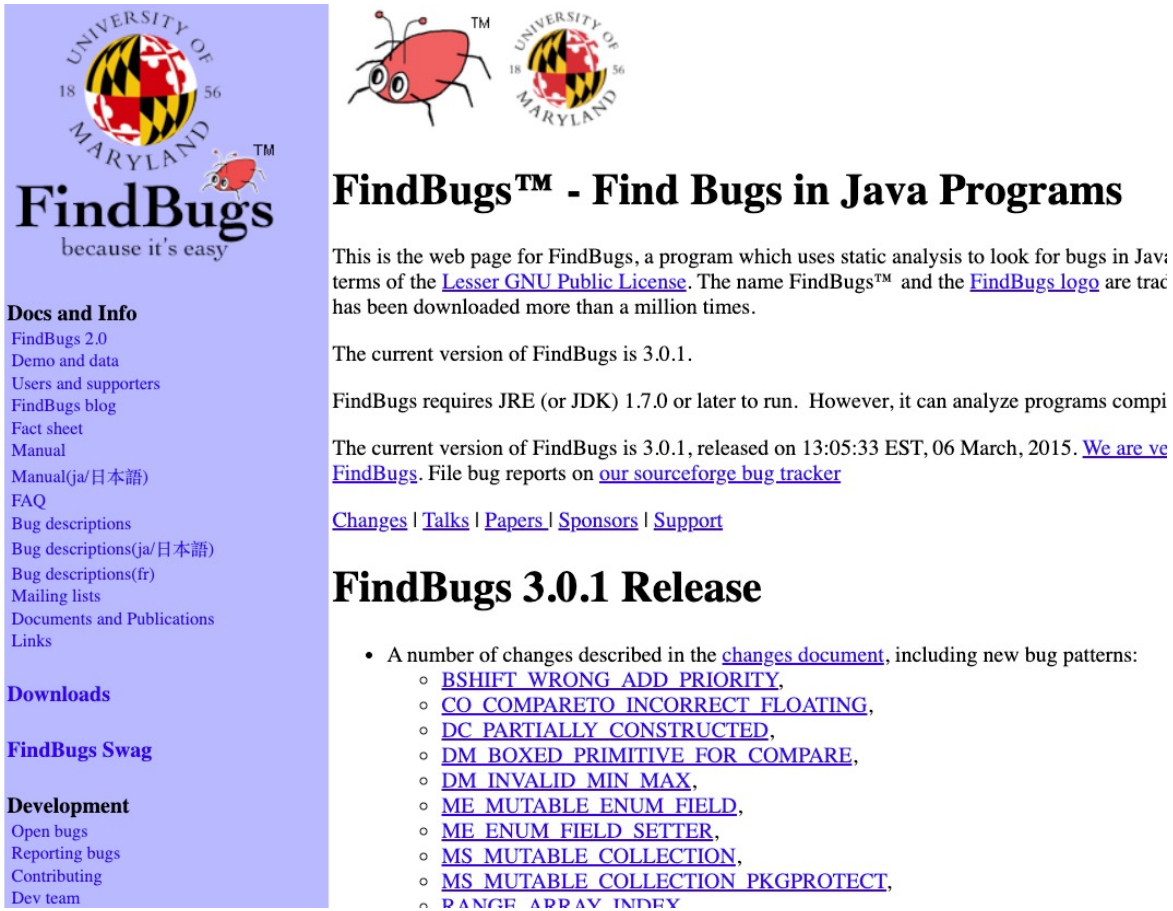

```
def p2(x):
  if x > 0 and x < 1000:
    if ((x - 32) * 5/9 == 100):
      return True
  return False
```

Puzzle:
Find `x` such that `p3(x)` returns `True`



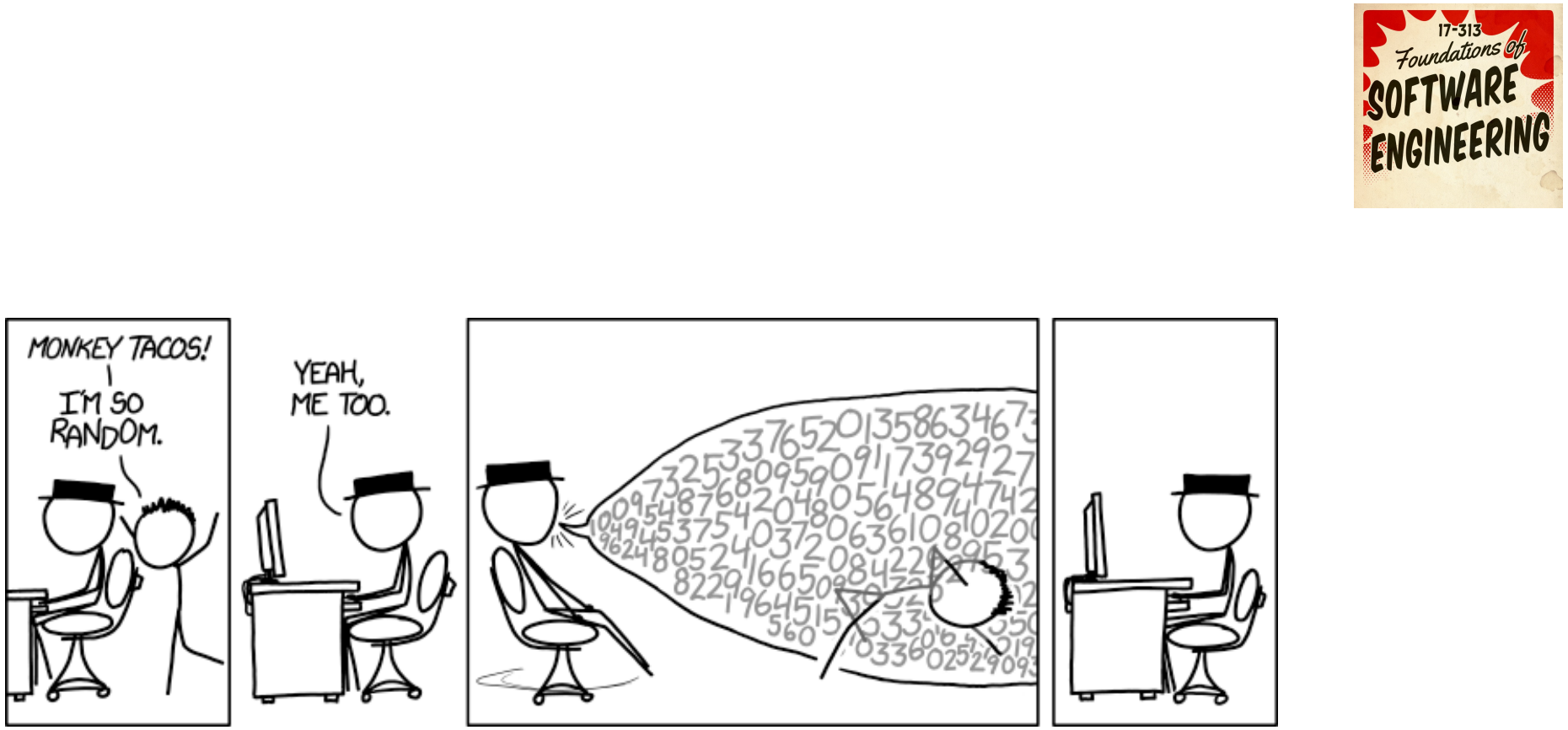

```
def p3(x):
  if x > 3 and x < 100:
    z = x - 2
    c = 0
    while z >= 2:
      if z ** (x - 1) % x == 1:
        c = c + 1
      z = z - 1
    if c == x - 3:
      return True
  return False
```

FindBugs (2006!)

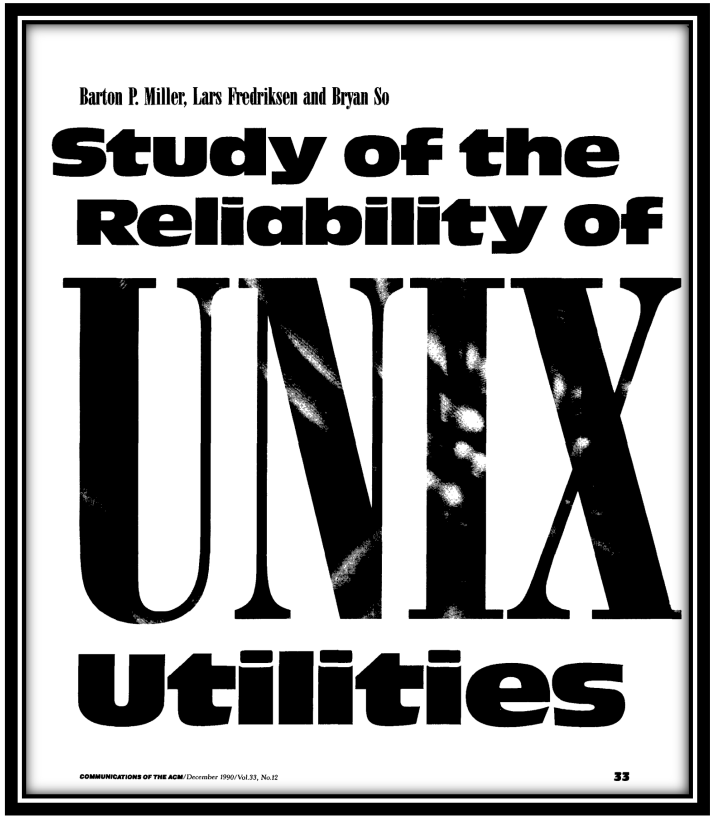


Security and Robustness

FUZZ TESTING



Original: https://xkcd.com/1210 CC-BY-NC 2.5



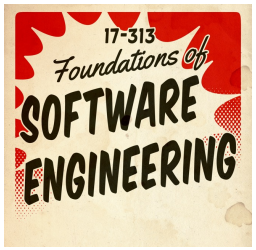
Barton P. Miller, Lars Fredriksen and Bryan So

Study of the Reliability of UNIX Utilities

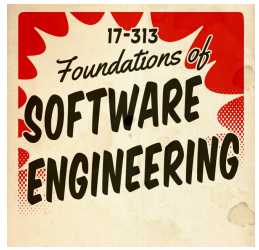
COMMUNICATIONS OF THE ACM/December 1990/Vol.33, No.12 33

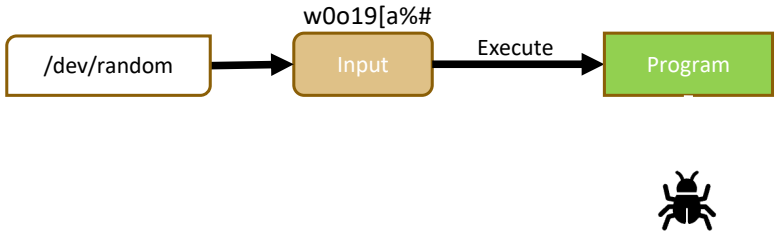
Communications of the ACM (1990)

> On a dark and stormy night one of the authors was logged on to his work-station 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.



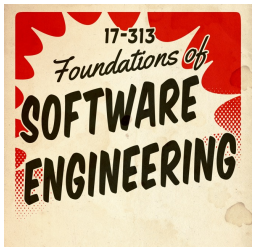
Fuzz Testing





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++



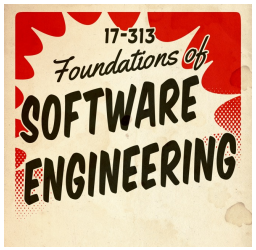
Causes: incorrect arg validation, incorrect type casting, executing untrusted code, etc.

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

Impact: security, reliability, performance, correctness

How to identify these bugs in languages like C/C++?

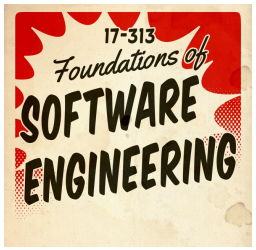
Automatic Oracles: Sanitizers



- 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];
}
```

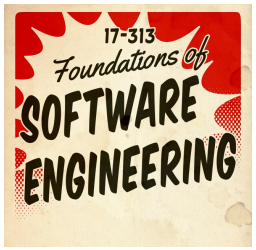
Is the access out of bounds?

```
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?

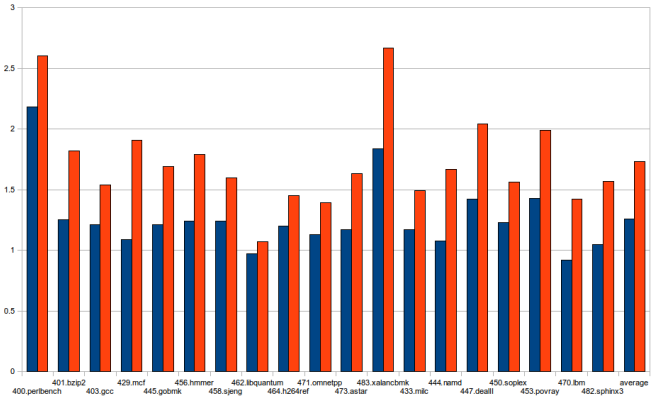
```
int get_element(int* a, int i) {
   if (a == NULL) abort();
   region = get_allocation(a);
   if (in_stack(region)) {
     if (popped(region)) abort();
     …
   }
   if (in_heap(region)) { ... }
   return a[i];
}
```

AddressSanitizer



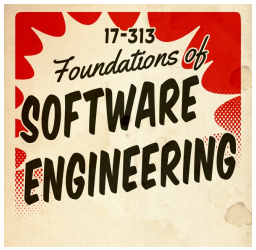
Asan is a memory error detector for C/C++. It finds:

- 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



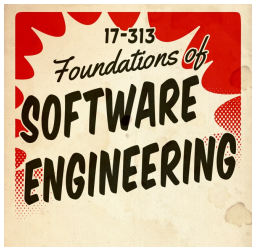
https://github.com/google/sanitizers/wiki/AddressSanitizer

Strengths and Limitations



- **Exercise**: Write down two strengths and two weaknesses of fuzzing. Bonus: Write down one or more assumptions that fuzzing depends on.

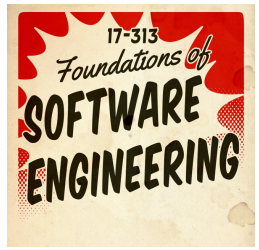
Strengths and Limitations

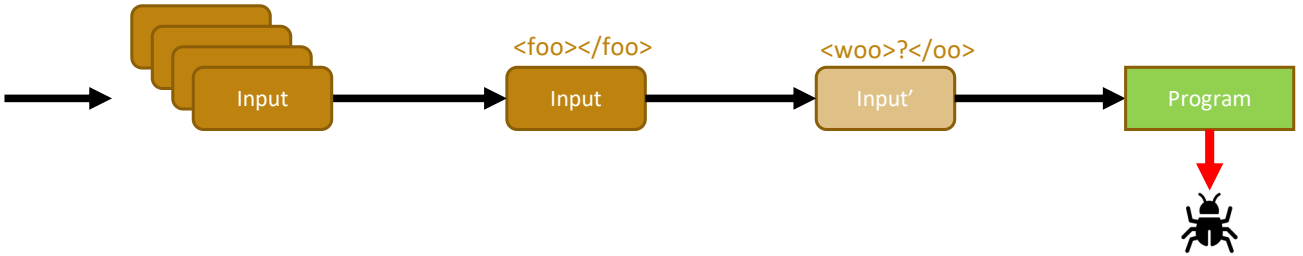


- Strengths:
  - Cheap to generate inputs
  - Easy to debug when a failure is identified

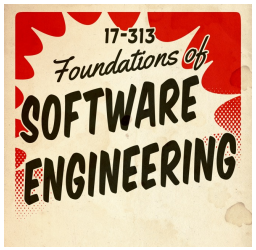
- Limitations:
  - Randomly generated inputs don’t make sense most of the time.
    - E.g. Imagine testing a browser and providing some ”input” HTML randomly: **dgsad5135o gsd;gj lsdkg3125j@!T%#(W+123sd asf j**
  - Unlikely to exercise interesting behavior in the web browser
  - Can take a long time 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, …
  - Other suggestions?
- Text input
  - Insert random symbols or keywords from a dictionary
  - Other suggestions?

American Fuzzy Lop (https://github.com/google/AFL)

2) The afl-fuzz approach

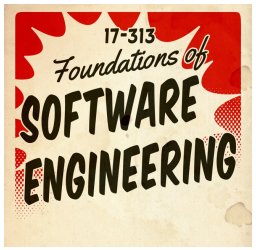
American Fuzzy Lop is a brute-force fuzzer coupled with an exceedingly simple but rock-solid instrumentation-guided genetic algorithm. It uses a modified form of edge coverage to effortlessly pick up subtle, local-scale changes to program control flow.

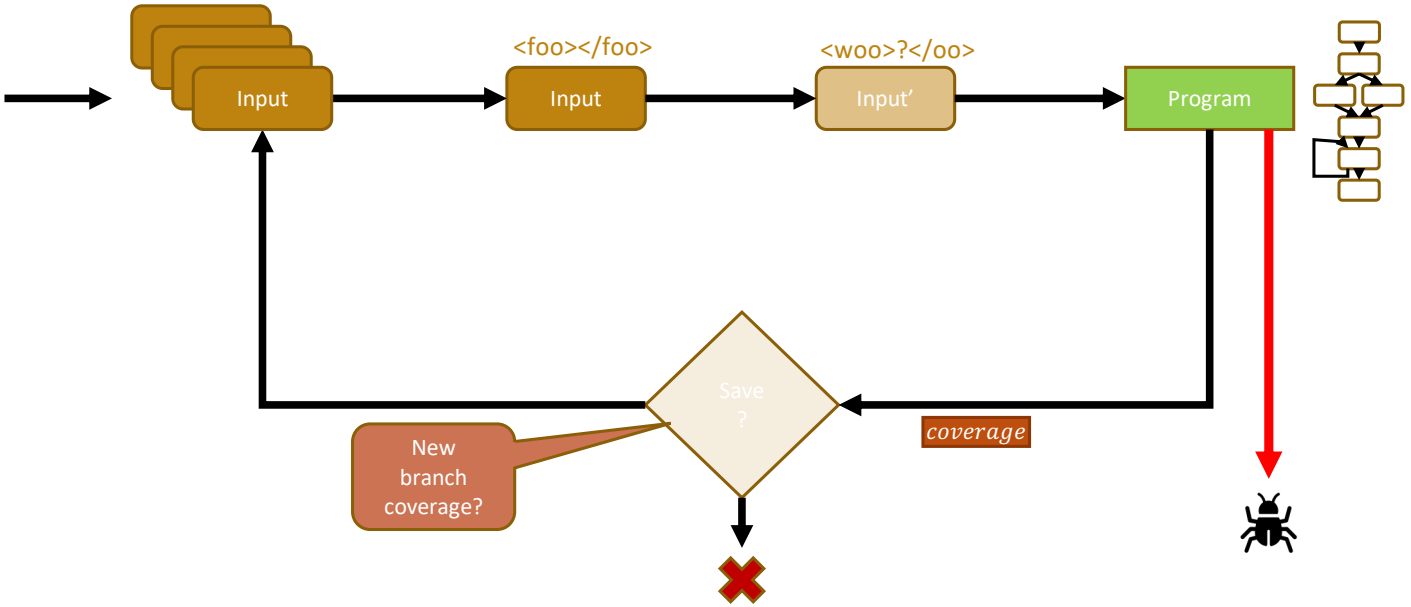
Simplifying a bit, the overall algorithm can be summed up as:

1. Load user-supplied initial test cases into the queue,
2. Take next input file from the queue,
3. Attempt to trim the test case to the smallest size that doesn't alter the measured behavior of the program,
4. Repeatedly mutate the file using a balanced and well-researched variety of traditional fuzzing strategies,
5. If any of the generated mutations resulted in a new state transition recorded by the instrumentation, add mutated output as a new entry in the queue.
6. Go to 2.

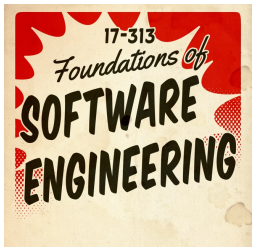
The discovered test cases are also periodically culled to eliminate ones that have been obsoleted by newer, higher-coverage finds; and undergo several other instrumentation-driven effort minimization steps.

Coverage-Guided Fuzzing (e.g. AFL)





Coverage-Guided Fuzzing with AFL

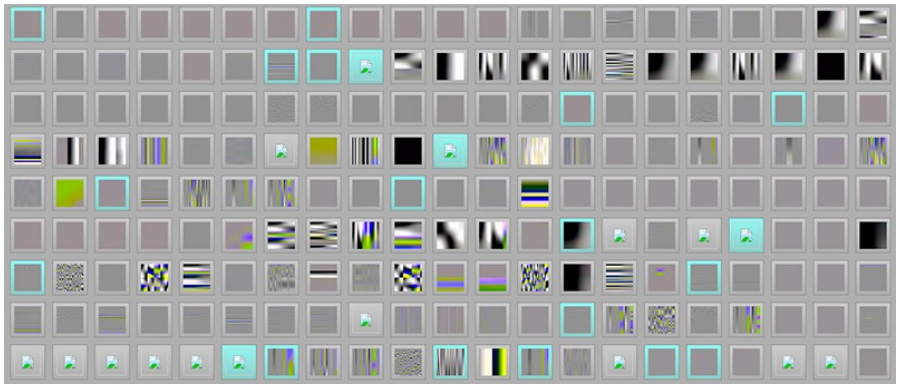


November 07, 2014

Pulling JPEGs out of thin air

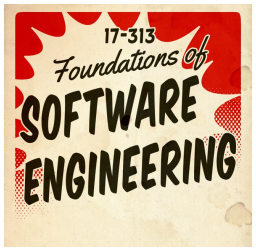
This is an interesting demonstration of the capabilities of afl; I was actually pretty surprised that it worked!

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



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

Coverage-Guided Fuzzing with AFL

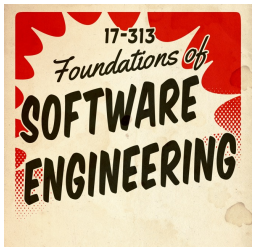


The bug-o-rama trophy case

IJG jpeg [1]	libjpeg-turbo [1] [2]	libpng [1]
libtiff [1] [2] [3] [4] [5]	mozjpeg [1]	PHP [1] [2] [3] [4] [5] [6] [7] [8]
Mozilla Firefox [1] [2] [3] [4]	Internet Explorer [1] [2] [3] [4]	Apple Safari [1]
Adobe Flash / PCRE [1] [2] [3] [4] [5] [6] [7]	sqlite [1] [2] [3] [4]...	OpenSSL [1] [2] [3] [4] [5] [6] [7]
LibreOffice [1] [2] [3] [4]	poppler [1] [2]...	freetype [1] [2]
GnuTLS [1]	GnuPG [1] [2] [3] [4]	OpenSSH [1] [2] [3] [4] [5]
PuTTY [1] [2]	ntpd [1] [2]	nginx [1] [2] [3]
bash (post-Shellshock) [1] [2]	tcpdump [1] [2] [3] [4] [5] [6] [7] [8] [9]	JavaScriptCore [1] [2] [3] [4]
pdfium [1] [2]	ffmpeg [1] [2] [3] [4] [5]	libmatroska [1]
libarchive [1] [2] [3] [4] [5] [6] ...	wireshark [1] [2] [3]	ImageMagick [1] [2] [3] [4] [5] [6] [7] [8] [9] ...
BIND [1] [2] [3] ···	QEMU [1] [2]	lcms [1]

http://lcamtuf.coredump.cx/afl/

ClusterFuzz @ Chromium

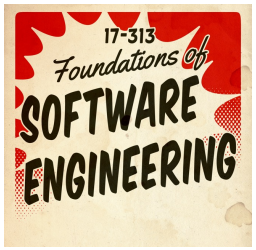


bugs chromium New issue All issues label:ClusterFuzz -status:Duplicate

1 - 100 of 25423 Next › List

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

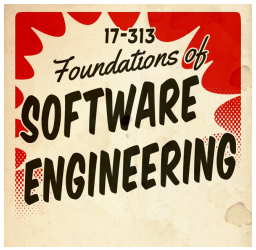
Can fuzzing be applied to unit testing?



- Where “inputs” are not just strings or binary files?
- Yes! Possible to randomly generate strongly typed values, data structures, API calls, etc.
- Recall: Property-Based Testing

```
@Property
public void testSameLength(List<Integer> input) {
    var output :List<Integer> = sort(input);
    // Check length
    assert output.size() == input.size() : "Length should match";
}
```

Generators



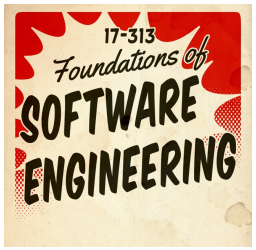
Random List<Integer>

Exercise: Write a generator for
Creating random HashMap<String, Integer>

```
List list = new ArrayList();
while (randomBoolean()) {     // randomly stop/go
  list.append(randomInt());   // random element
}
return list;
```

```
List list = new ArrayList();
int len = randomInt();          // pick a random length
for (int i = 0 to len) {
   list.append(randomInt());  // random element
}
return list;
```

Mutators



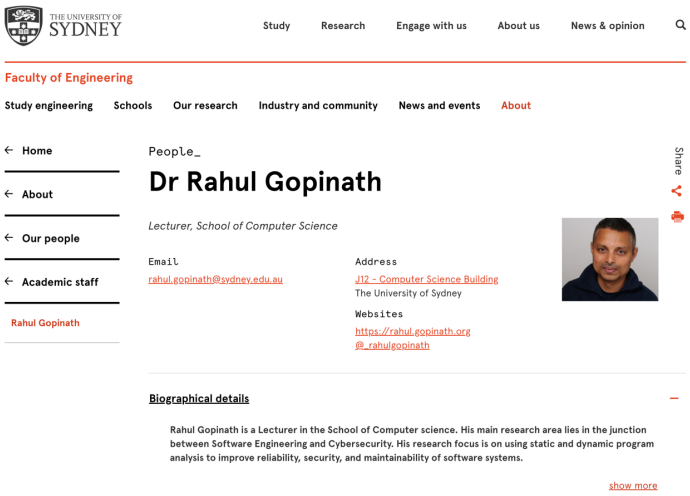
Mutator for `list`: List<Integer>

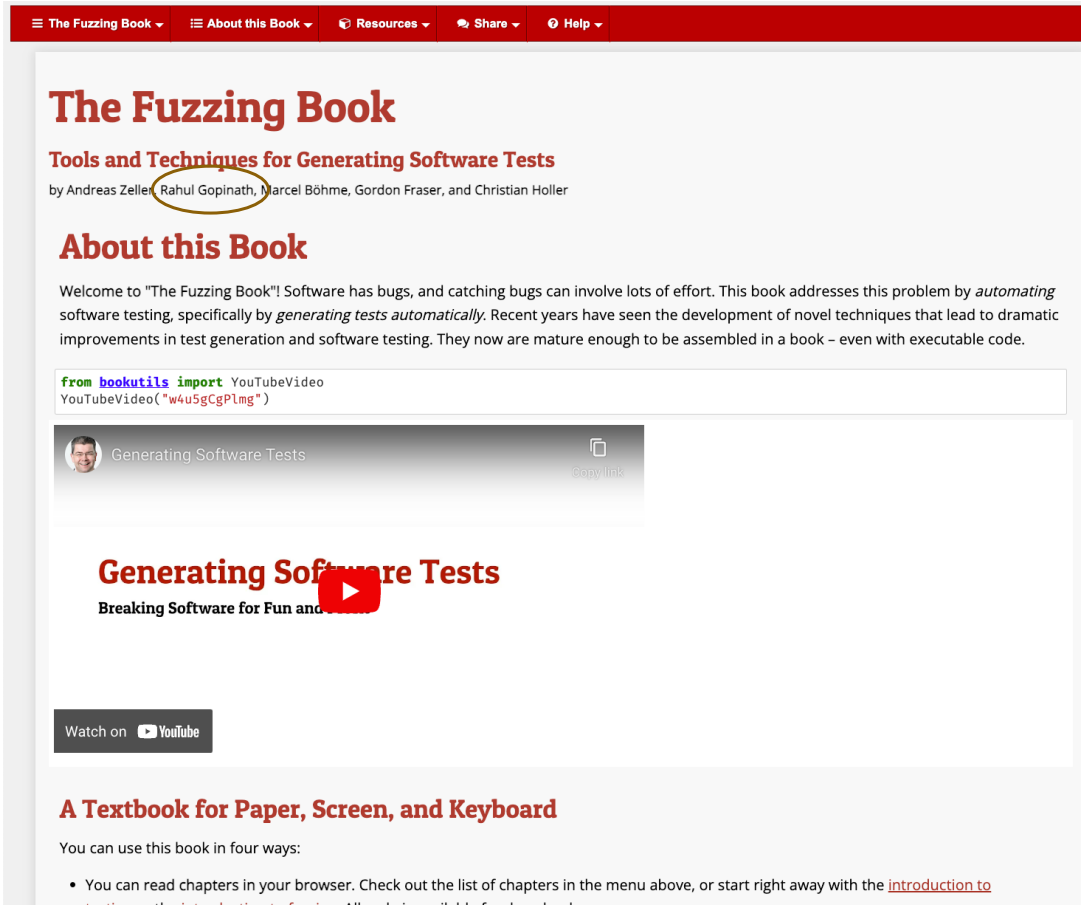
```
int k = randomInt(0, len(list));
int action = randomChoice(ADD, DELETE, UPDATE);
switch (action) {
  case UPDATE: list.set(k, randomInt()); // update element at k
  case ADD: list.addAt(k, randomInt());  // add random element at k
  case DELETE: list.removeAt(k);         // delete k-th element
}
```

Exercise: Write a mutator HashMap<String, Integer>

The Fuzzing Book

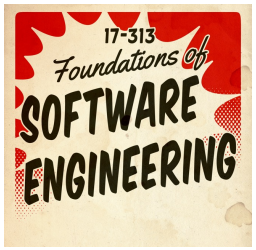
https://www.fuzzingbook.org/





TESTING PERFORMANCE

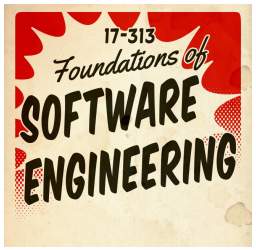
Performance Testing



- Goal: Identify *performance bugs*. What are these?
  - Unexpected bad performance on some subset of inputs
  - Performance degradation over time
  - Difference in performance across versions or platforms

- Not as easy as functional testing. What's the oracle?
  - Fast = good, slow = bad // but what's the threshold?
  - How to get reliable measurements?
  - How to debug where the issue lies?

Performance Regression Testing



- Measure execution time of critical components
- Log execution times and compare over time

Job 12e96643840000

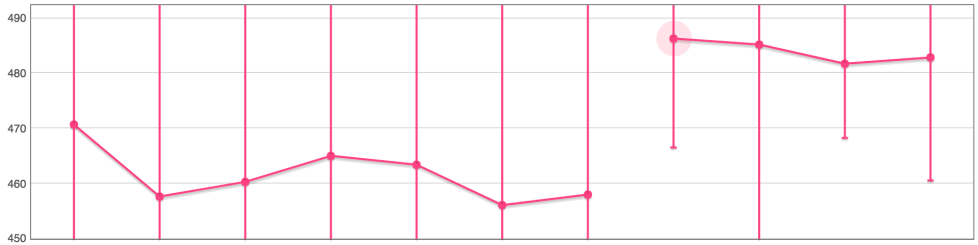
Issue 808613 · Analyze benchmark results · 2.0 hours · 2/14/2018, 9:48:34 AM

Differences found after commits

Re-record loading.desktop story set by ksakamoto@chromium.org

Job arguments

benchmark	loading.desktop
chart	cpuTimeToFirstMeaningfulPaint
configuration	chromium-rel-mac11-pro
statistic	avg
story	Pantip
target	telemetry_perf_tests
tir_label	warm
trace	Pantip



Re-record loading.desktop story set by ksakamoto@chromium.org

Build

builder	Mac Builder
isolate_hash	630b5fe7ae1b260e78db88233099249b5640517b

Test

task_id	3baea4beaa7f1710
bot_id	build197-b4
isolate_hash	146eb87de6d2594cc3a9ee9f3518f69fc3d0c2c3

Values

trace	Pantip_2018-02-14_11-40-07_93865.html
trace	Pantip_2018-02-14_11-40-42_21734.html

Source: https://chromium.googlesource.com/chromium/src/+/refs/heads/main/docs/speed/addressing_performance_regressions.md

Firefox

A Study of Performance Variations in the Mozilla Firefox Web Browser

Jan Larres[1] Alex Potanin[1] Yuichi Hirose[2]

[1] School of Engineering and Computer Science
Email: {larresjan,alex}@ecs.vuw.ac.nz

[2] School of Mathematics, Statistics and Operations Research
Email: hirose@msor.vuw.ac.nz
Victoria University of Wellington, New Zealand

aosabook.org/en/posa/talos.html

ANU Bills Blogs Home Mail

GNN Run

Talos

While hacking on the Talos harness in the summer of 2011 to add support for new platforms and tests, we encountered the results from Jan Larres's master's thesis, in which he investigated the large amounts of noise that appeared in the Talos tests. He analyzed various factors including hardware, the operating system, the file system, drivers, and Firefox that might influence the results of a Talos test. Building on that work, Stephen Lewchuk devoted his internship to trying to statistically reduce the noise we saw in those tests.

Based on their work and interest, we began forming a plan to eliminate or reduce the noise in the Talos tests. We brought together harness hackers to work on the harness itself, web developers to update Graph Server, and statisticians to determine the optimal way to run each test to produce predictable results with minimal noise.

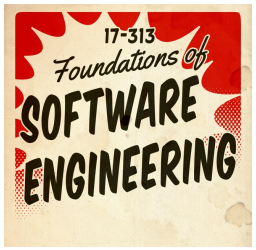
cannot easily be attributed to either genuine changes Automated tests help with this balance by alert-

modification since its inception i.. changed hands.

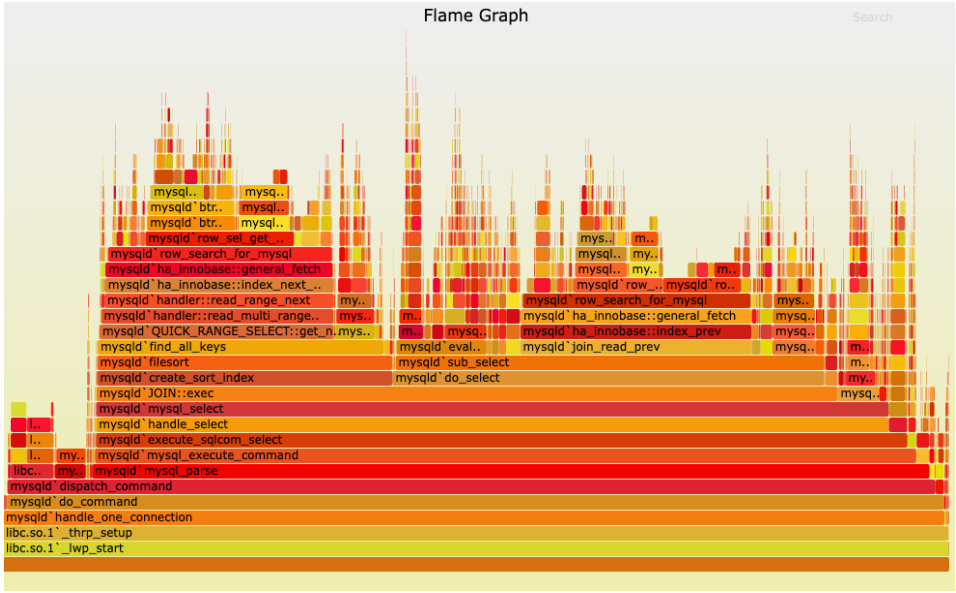
In the summer of 2011, we finally began to look askance at the noise and the variation in the Talos numbers, and we began to wonder how we could make some small modification to the system to start improving it. We had no idea we were about to open Pandora's Box.

In this chapter, we will detail what we found as we peeled back layer after layer of this software, what problems we uncovered, and what steps we took to address them in hopes that you might learn from both our mistakes and our successes.

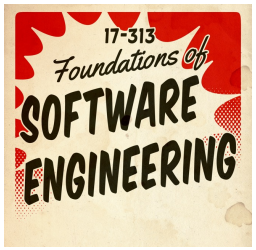
Profiling

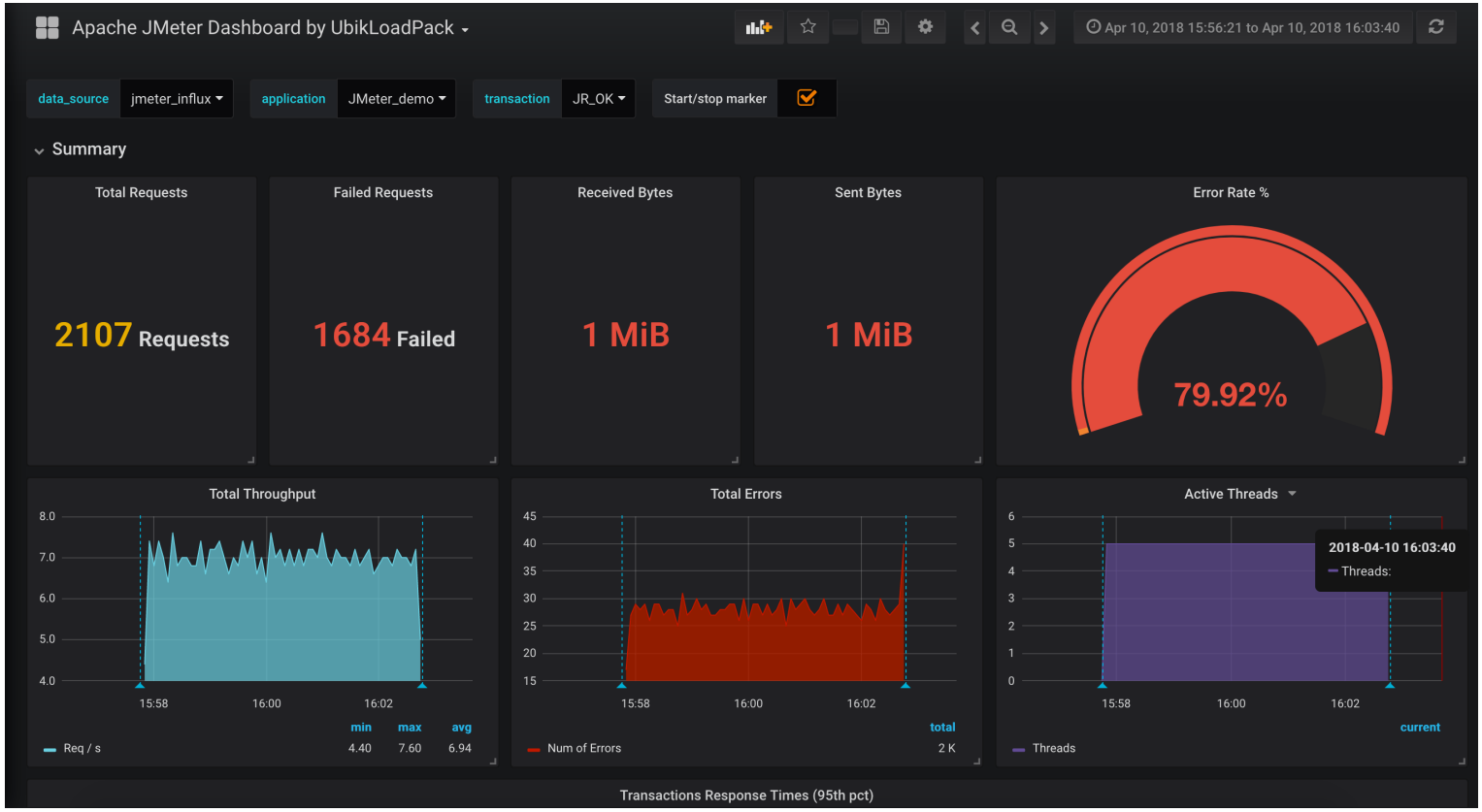


- Finding bottlenecks in execution time and memory
- Flame graphs are a popular visualization of resource consumption by call stack.



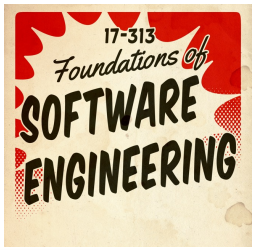
Domain-Specific Perf Testing (e.g. JMeter)



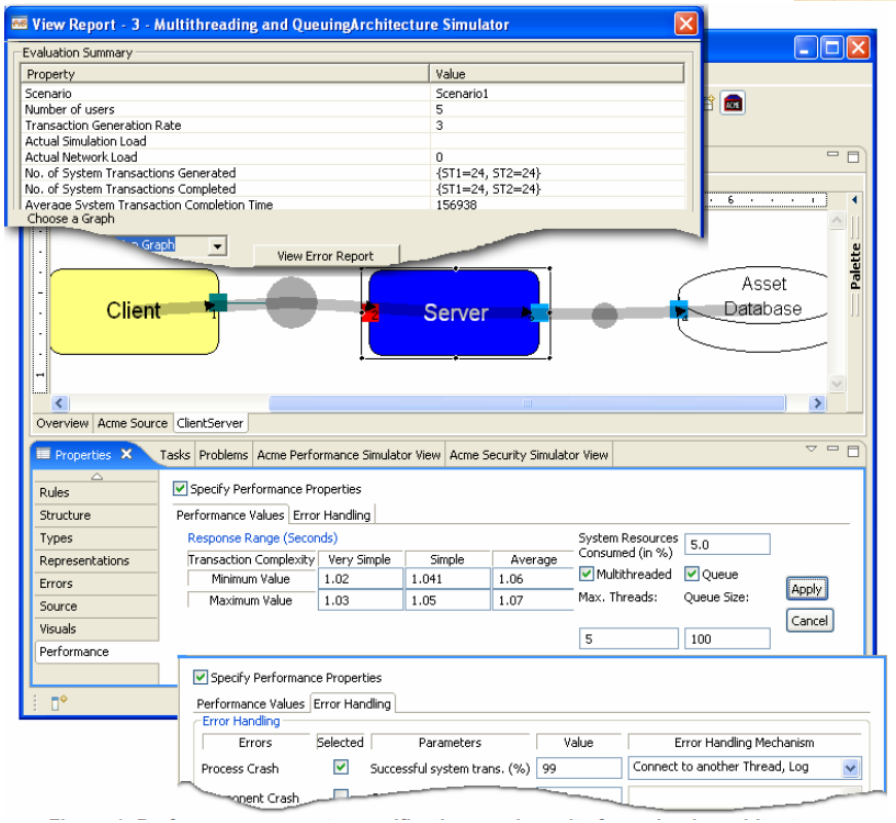


http://jmeter.apache.org

Performance-driven Design



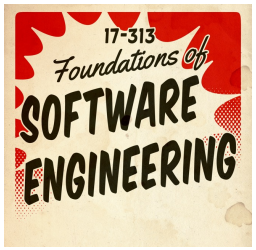
- Modeling and simulation
  - e.g. queuing theory
- Specify load distributions and derive or test configurations



Stress testing

- Robustness testing technique: test beyond the limits of normal operation.
- Can apply at any level of system granularity.
- Stress tests commonly put a greater emphasis on robustness, availability, and error handling under a heavy load, than on what would be considered “correct” behavior under normal circumstances.

Soak testing

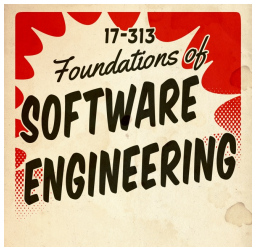


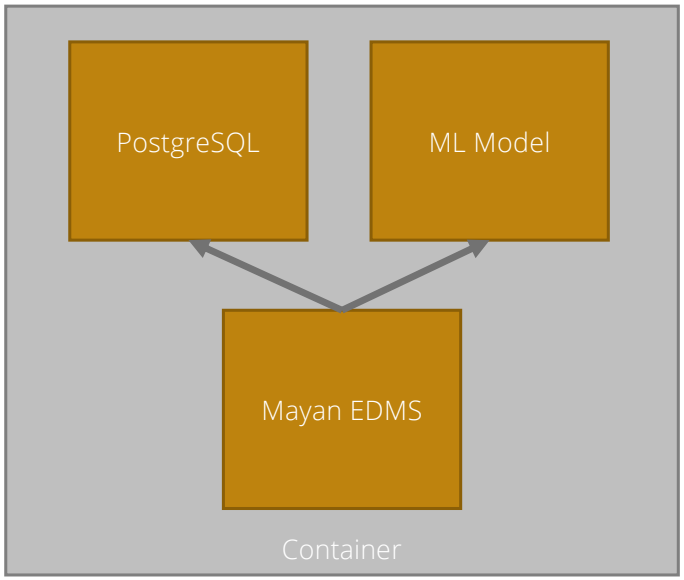
- **Problem:** A system may behave exactly as expected under artificially limited execution conditions.
  - E.g., Memory leaks may take longer to lead to failure (also motivates static/dynamic analysis, but we'll talk about that later).
- **Soak testing:** testing a system with a significant load over a significant period of time (*positive*).
- Used to check reaction of a subject under test under a possible simulated environment for a given duration and for a given threshold.

Slides credit Christopher Meiklejohn

CHAOS ENGINEERING

Monolithic Application





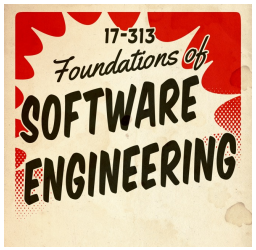
What kind of failures can happen here?

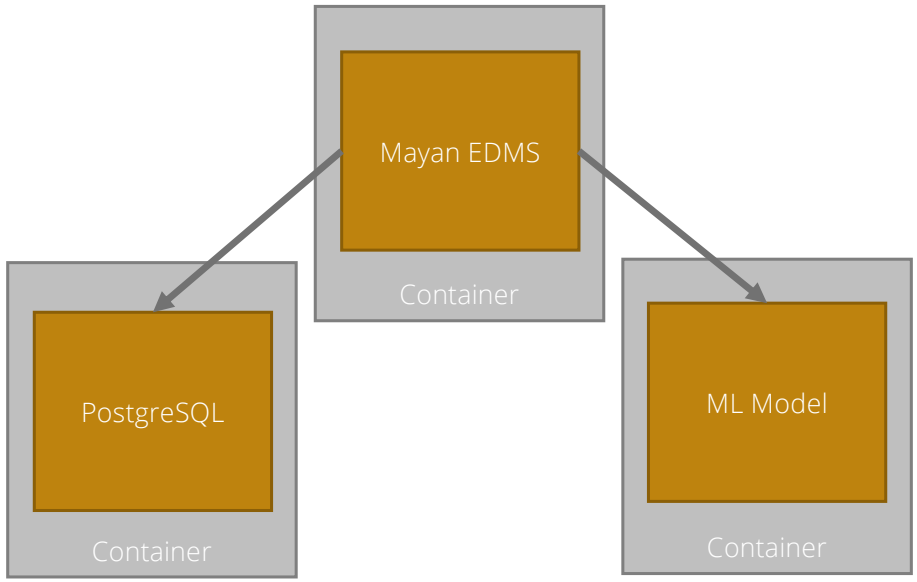
How likely is that error to happen?

How do I fix it?

Microservice

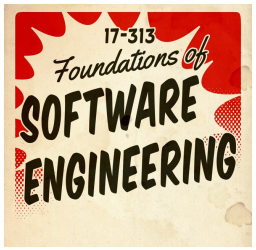
Microservice Application





Remember, these calls are messages sent on an **unreliable network.**

Failures in Microservice Architectures



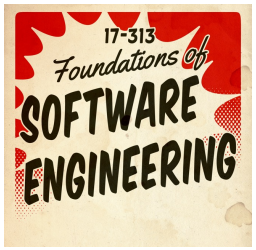
1. Network may **be partitioned**
2. Server instance **may be down**
3. Communication between services may **be delayed**
4. Server **could be overloaded** and responses delayed
5. Server **could run out of** memory or CPU

All of these issues **can be indistinguishable** from one another!

Making the calls across the network to multiple machines makes the probability that the system is operating under failure **much higher.**

These are the problems of **latency** and **partial failure.**

Where Do We Start?

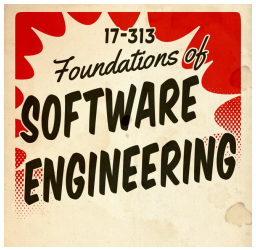


How do we even **begin to test these scenarios?**

Is there any **software** that can be used to test these types of failures?

Let's look at a **few ways** companies do this.

Game Days



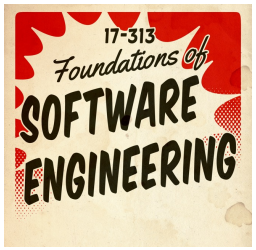
Purposely **injecting failures** into critical systems in order to:

- Identify **flaws** and “latent defects”
- Identify **subtle dependencies** (which may or may not lead to a flaw/defect)
- Prepare a **response** for a disastrous event

Comes from “resilience engineering” typical in high-risk industries

Practiced by Amazon, Google, Microsoft, Etsy, Facebook, Flickr, etc.

Game Days



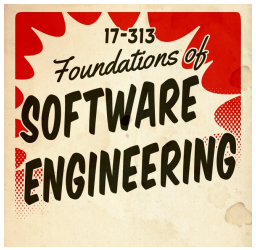
Our applications are built on and with **“unreliable”** components

Failure is inevitable (fraction of percent; at Google scale, ~multiple times)

Goals:

- **Preemptively trigger** the failure, observe, and fix the error
- Script testing of **previous failures** and ensure system remains resilient
- Build the necessary relationships between teams **before** disaster strikes

Example: Amazon GameDay



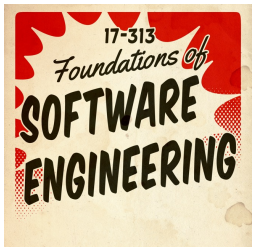
Full data center destruction (Amazon EC2 region)

- No advanced notice of **which** data center will be taken offline
- No notice o be taken offline
- Only advan ameDay **will be happening**
- **Real failures in the production environment**

Not all failures can be actually performed and must be **simulated!**

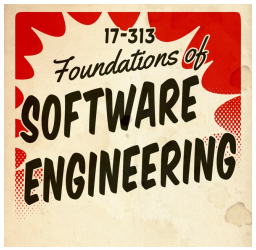
Discovered **latent defect** where the monitoring infrastructure responsible for detecting errors and paging employees **was located in the zone of the failure!**

Cornerstones of Resilence



1. Anticipation: know what to expect
2. Monitoring: know what to look for
3. Response: know what to do
4. Learning: know what just happened
   (e.g, postmortems)

Some Example Google Issues



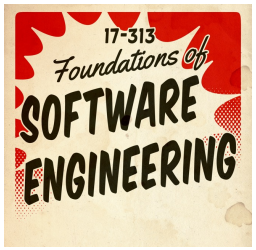
Terminate network in Sao Paulo for testing:

- Hidden dependency takes down links in Mexico which would have remained undiscovered without testing

Turn off data center to find that machines won't come back:

- Ran out of DHCP leases (for IP address allocation) when a large number of machines come back online unexpectedly.

Netflix: Cloud Computing

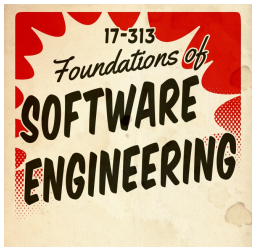


Significant deployment in Amazon Web Services in order to remain **elastic** in times of high and low load (first public, 100% w/o content delivery.)

Pushes code into production and modifies runtime configuration hundreds of times a day

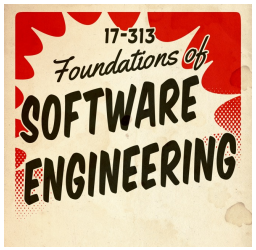
Key metric: **availability**

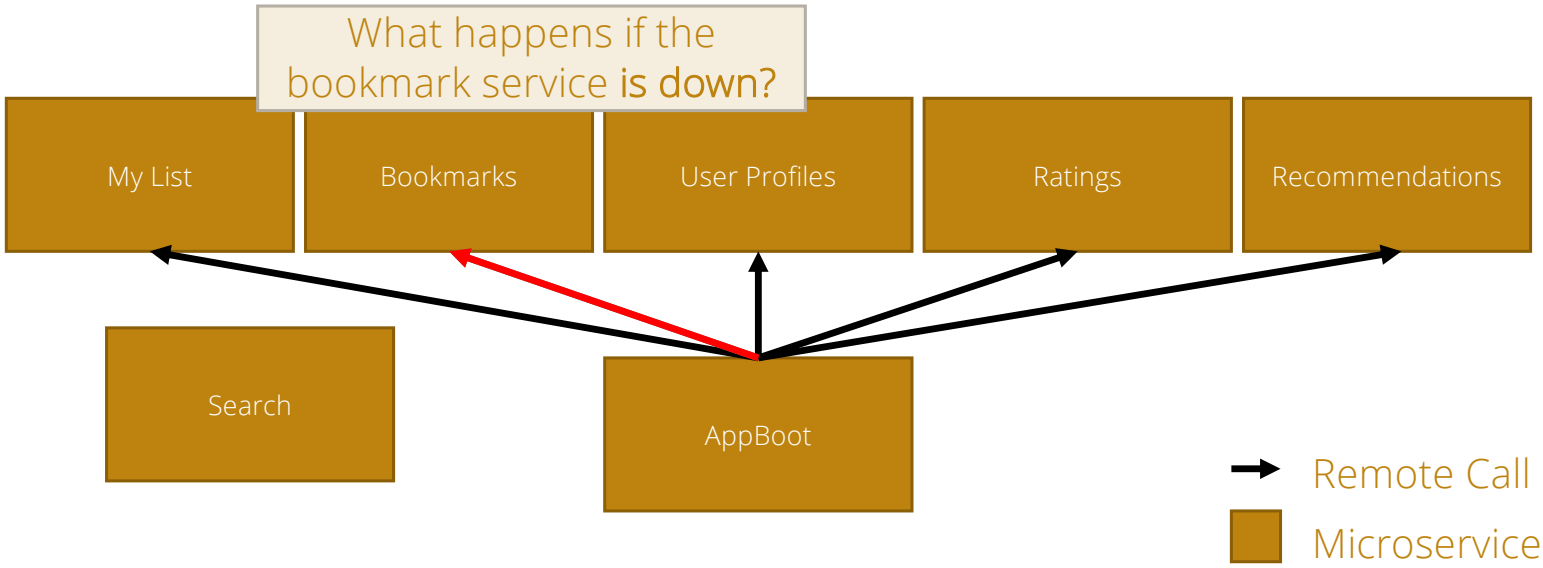
Chaos monkey/Simian army



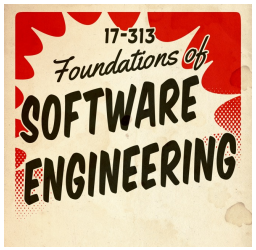
- A Netflix infrastructure testing system.
- "Malicious" programs randomly trample on components, network, datacenters, AWS instances…
  - Chaos monkey was the first – disables production instances at random.
  - Other monkeys include Latency Monkey, Doctor Monkey, Conformity Monkey, etc… Fuzz testing at the infrastructure level.
  - Force failure of components to make sure that the system architecture is resilient to unplanned/random outages.
- Netflix has open-sourced their chaos monkey code.

Netflix UI: AppBoot





Graceful Degradation: Anticipating Failure



Allow the system to degrade in a way it's still usable

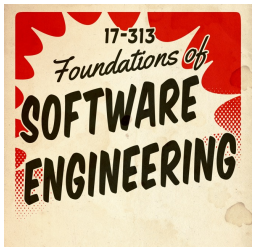
Fallbacks:

- Cache miss due to failure of cache;
- Go to the bookmarks service and use value at possible latency penalty

Personalized content, use a reasonable default instead:

- What happens if **recommendations** are unavailable?
- What happens if **bookmarks are unavailable?**

Principles of Chaos Engineering



1. Build a **hypothesis** around steady state behavior

2. Vary **real-world events**
   experimental events, crashes, etc.

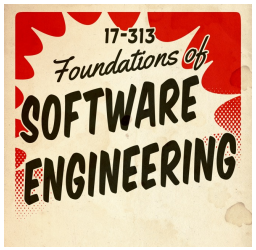
Does everything seem to be working properly?

Are users complaining?

3. Run **experiments** in production
   control group vs. experimental group
   draw conclusions, invalidate hypothesis

4. **Automate experiments** to run continuously

Steady State Behavior



Back to **quality attributes: availability!**

SPS is the primary indicator of the system's overall health.

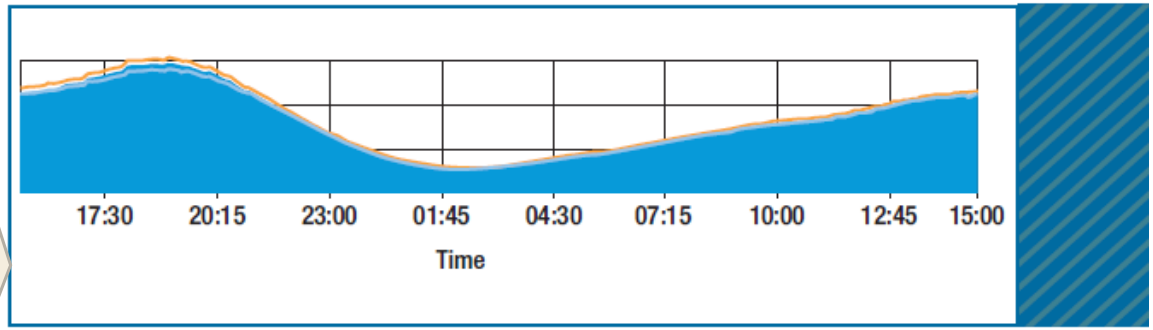
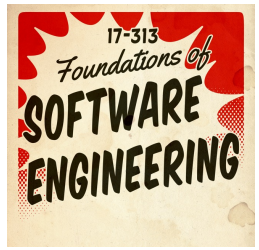


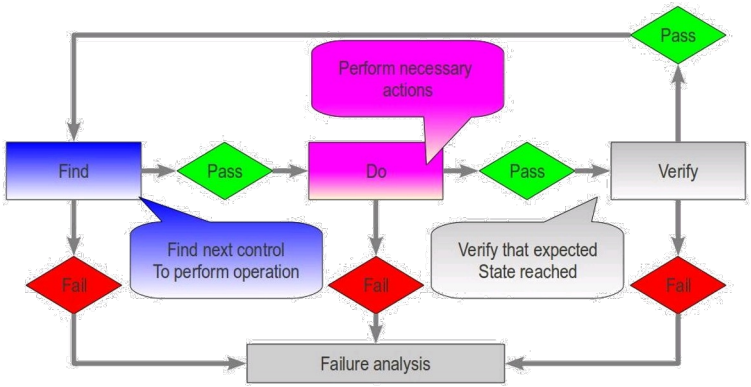
FIGURE 2. A graph of SPS ([stream] starts per second) over a 24-hour period. This metric varies slowly and predictably throughout a day. The orange line shows the trend for the prior week. The *y*-axis isn't labeled because the data is proprietary.

Mini Break in Monday Lecture

TESTING USABILITY

Automating GUI/Web Testing





- This is hard
- Capture and Replay Strategy
  - mouse actions
  - system events
- Test Scripts: (click on button labeled "Start" expect value X in field Y)
- Lots of tools and frameworks
  - e.g. Selenium for browsers
- (Avoid load on GUI testing by separating model from GUI)
- Beyond functional correctness?

Manual Testing

- Live System?
- Extra Testing System?
- Check output / assertions?
- Effort, Costs?
- Reproducible?
- Higher Quality Feedback to Developers

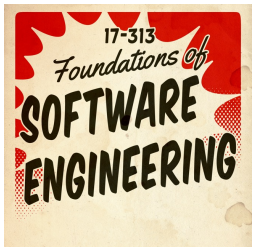
GENERIC TEST CASE: USER SENDS MMS WITH PICTURE ATTACHED.

Step ID	User Action	System Response
1	Go to Main Menu	Main Menu appears
2	Go to Messages Menu	Message Menu appears
3	Select "Create new Message"	Message Editor screen opens
4	Add Recipient	Recipient is added
5	Select "Insert Picture"	Insert Picture Menu opens
6	Select Picture	Picture is Selected
7	Select "Send Message"	Message is correctly sent

Usability: A/B testing

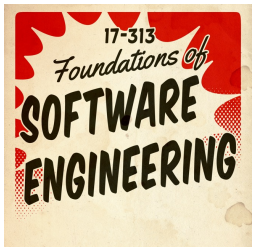
- Controlled randomized experiment with two variants, A and B, which are the control and treatment.
- One group of users given A (current system); another random group presented with B; outcomes compared.
- Often used in web or GUI-based applications, especially to test advertising or GUI element placement or design decisions.

Example

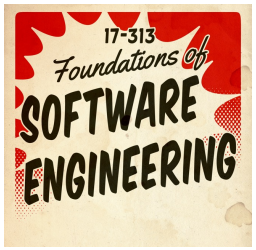


- A company sends an advertising email to its customer database, varying the photograph used in the ad...

Example: group A (99% of users)



Example: group B (1%)



A/B Testing

- Requires good metrics and statistical tools to identify significant differences.
- E.g. clicks, purchases, video plays
- Must control for confounding factors

What smells?


```java
class Foo {
    int a; int b;

    public boolean equals(Object other) {
        Foo foo = (Foo) other;
        if (foo != null)
          if (foo.a != this.a)
            return false;
          if (foo.b == this.b)
            return true;
          else return false;
    }

    public int a() {
        return this.a();
    }

    public int b() {
        return this.b();
    }
}
```

What smells?


```c
int dtls1_process_heartbeat(SSL *s)
    {
    unsigned char *p = &s->s3->rrec.data[0], *pl;
    unsigned short hbtype;
    unsigned int payload;
    unsigned int padding = 16; /* Use minimum padding */

    /* Read type and payload length first */
    hbtype = *p++;
    n2s(p, payload);
    pl = p;

    if (s->msg_callback)
        s->msg_callback(0, s->version, TLS1_RT_HEARTBEAT,
            &s->s3->rrec.data[0], s->s3->rrec.length,
            s, s->msg_callback_arg);

    if (hbtype == TLS1_HB_REQUEST)
        {
        unsigned char *buffer, *bp;
        int r;

        /* Allocate memory for the response, size is 1 byte
         * message type, plus 2 bytes payload length, plus
         * payload, plus padding
         */
        buffer = OPENSSL_malloc(1 + 2 + payload + padding);
        bp = buffer;

        /* Enter response type, length and copy payload */
        *bp++ = TLS1_HB_RESPONSE;
        s2n(payload, bp);
        memcpy(bp, pl, payload);
        bp += payload;
        /* Random padding */
        RAND_pseudo_bytes(bp, padding);

        r = dtls1_write_bytes(s, TLS1_RT_HEARTBEAT, buffer, 3 + payload + padding);
```

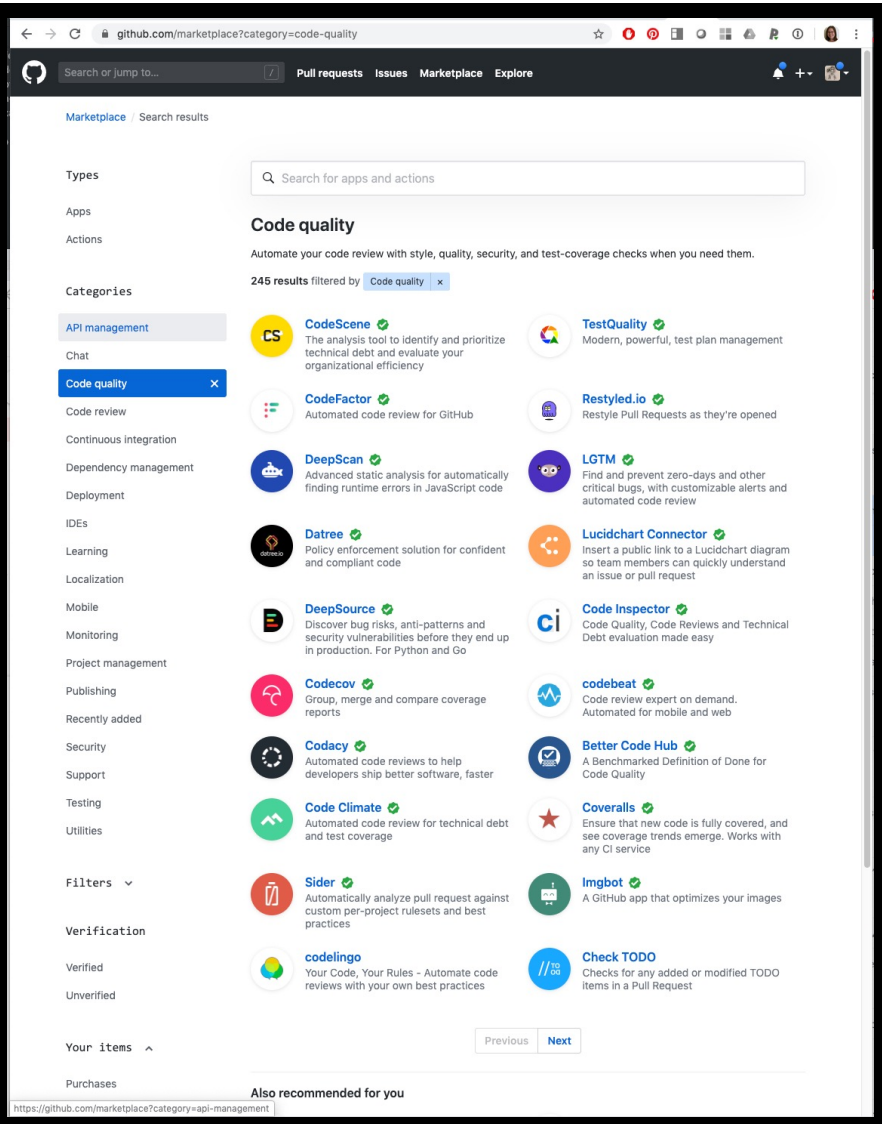
Static Analysis

- Try to discover issues by analyzing source code. No need to run.
- Defects of interest may be on uncommon or difficult-to-force execution paths for testing.
- **What we really want to do is check the entire possible state space of the program for particular properties.**

Defects Static Analysis can Catch

- **Defects that result from inconsistently following simple design rules.**
  - **Security:** Buffer overruns, improperly validated input.
  - **Memory safety:** Null dereference, uninitialized data.
  - **Resource leaks:** Memory, OS resources.
  - **API Protocols:** Device drivers; real time libraries; GUI frameworks.
  - **Exceptions:** Arithmetic/library/user-defined
  - **Encapsulation:** Accessing internal data, calling private functions.
  - **Data races:** Two threads access the same data without synchronization

Key: check compliance to simple, mechanical design rules



https://github.com/marketplace?category=code-quality


```
package com.google.devtools.staticanalysis;

public class Test {
```

▾ Lint — Missing a Javadoc comment.
Java
1:02 AM, Aug 21
Please fix — Not useful

```
  public boolean foo() {
    return getString() == "foo".toString();
```

//depot/google3/java/com/google/devtools/staticanalysis/Test.java

```
package com.google.devtools.staticanalysis;

public class Test {
  public boolean foo() {
    return getString() == "foo".toString();
  }

  public String getString() {
    return new String("foo");
  }
}
```

```
package com.google.devtools.staticanalysis;

import java.util.Objects;

public class Test {
  public boolean foo() {
    return Objects.equals(getString(), "foo".toString());
  }

  public String getString() {
    return new String("foo");
  }
}
```

Apply Cancel

How do they work?


```java
class Foo {
    int a; int b;

    public boolean equals(Obje
        Foo foo = (Foo) other;
        if (foo != null)
          if (foo.a != this.a)
            return false;
          if (foo.b == this.b)
            return true;
          else return false;
    }

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```

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```

Two fundamental concepts

- **Abstraction.**
  - Elide details of a specific implementation.
  - Capture semantically relevant details; ignore
- **Programs as data.**
  - Programs are just trees/graphs!
  - …and we know lots of ways to analyze trees/graphs, right?

Defining Static Analysis

- **Systematic** examination of an **abstraction** of program **state space**.
  - Does not execute code! (like code review)
- **Abstraction:** A representation of a program that is simpler to analyze.
  - Results in fewer states to explore; makes d
- Check if a **particular property** holds over the entire state space:
  - Liveness: “something good eventually happens.”
  - Safety: “this bad thing can’t ever happen.”
  - Compliance with mechanical design rules.

The Bad News: Rice's Theorem

Every static analysis is necessarily incomplete or unsound or undecidable (or multiple of these)

"Any nontrivial property about the language recognized by a Turing machine is undecidable.“

Henry Gordon Rice, 1953

SIMPLE SYNTACTIC AND STRUCTURAL ANALYSES

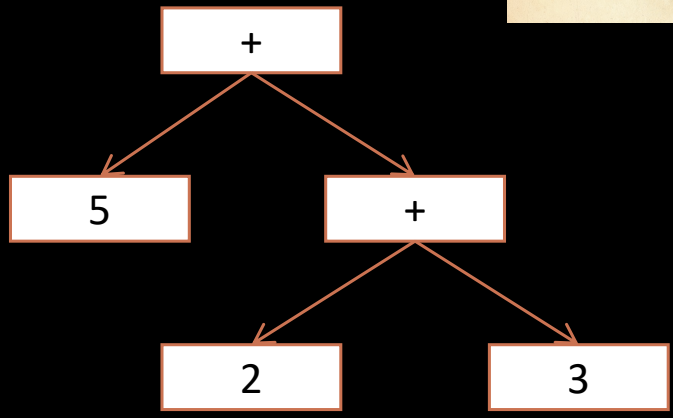
Type Analysis


```
public void foo() {
    int a = computeSomething();

    if (a == "5")
        doMoreStuff();
}
```

Abstraction: abstract syntax tree

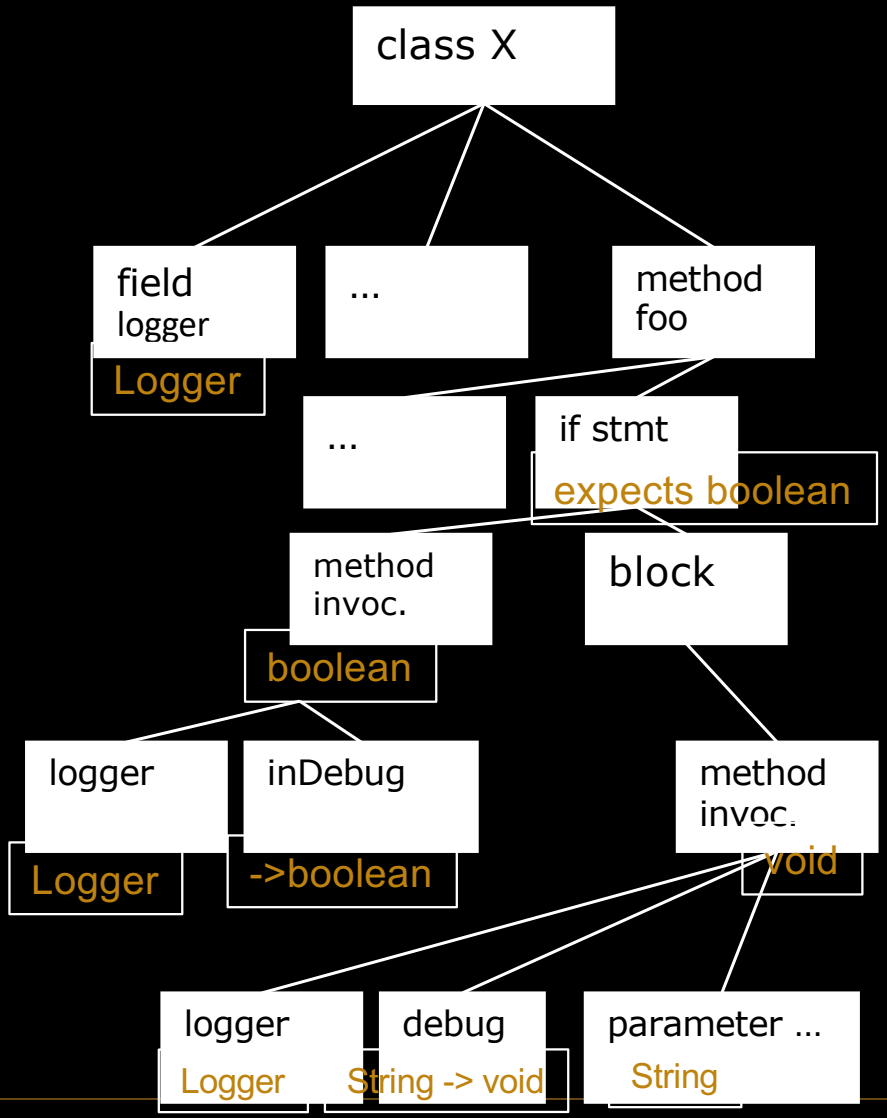
- Tree representation of the syntactic structure of source code.
  - Parsers convert concrete syntax into abstract syntax, and deal with resulting ambiguities.
- Records only the semantically relevant information.
  - Abstract: doesn't represent every detail (like parentheses); these can be inferred from the structure.
- (How to build one? Take compilers!)



Example: 5 + (2 + 3)

Type checking

```
class X {
  Logger logger;
  public void foo() {
    …
    if (logger.inDebug()) {
      logger.debug(“We have ” +
conn + “connections.”);
    }
  }
}
class Logger {
   boolean inDebug() {…}
   void debug(String msg) {…}
}
```



Syntactic Analysis

Find every occurrence of this pattern:

```
public foo() {
  …
   logger.debug(“We have ” + conn + “connections.”);
}
```

```
public foo() {
  …
  if (logger.inDebug()) {
    logger.debug(“We have ” + conn + “connections.”);
  }
}
```

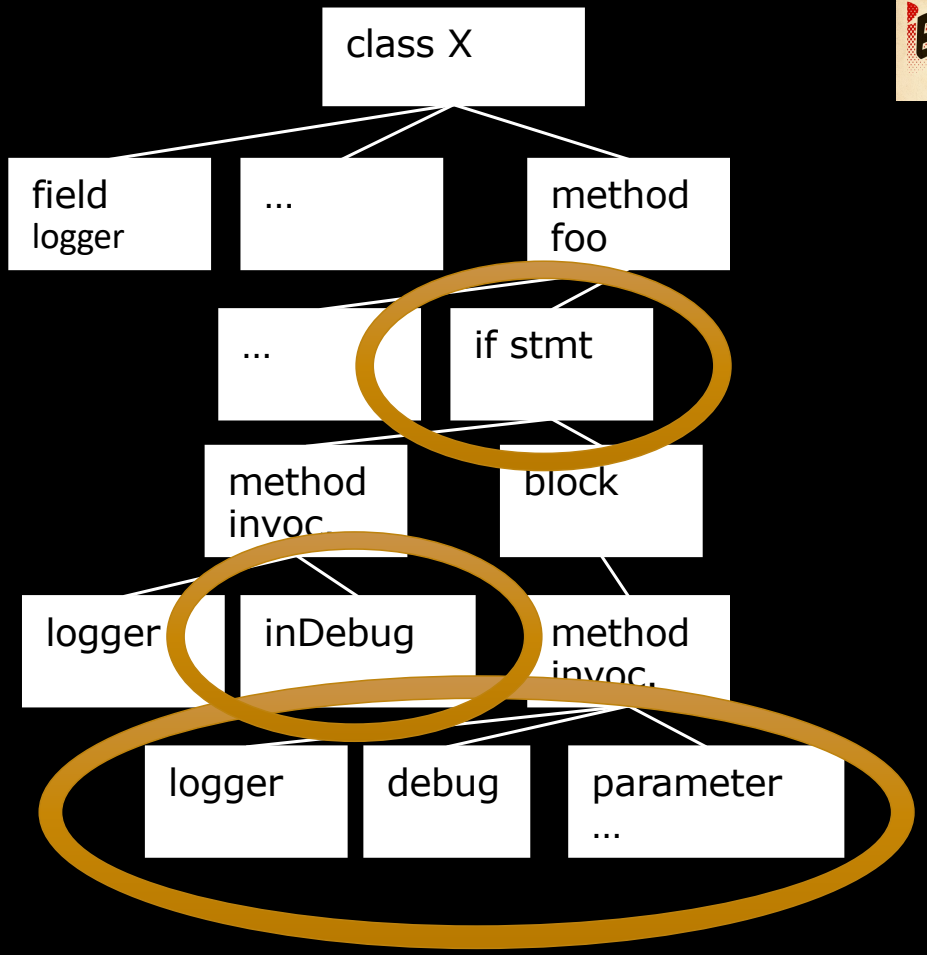
grep "if \(logger\.inDebug" . -r

Abstract syntax tree walker

- Check that we don't create strings outside of a `Logger.inDebug` check
- Abstraction:
  - Look only for calls to `Logger.debug()`
  - Make sure they're all surrounded by if (`Logger.inDebug()`)
- Systematic: Checks all the code
- Known as an Abstract Syntax Tree (AST) walker
  - Treats the code as a structured tree
  - Ignores control flow, variable values, and the heap
  - Code style checkers work the same way

Structural Analysis


```
class X {
  Logger logger;
  public void foo() {
    …
    if (logger.inDebug()) {
      logger.debug(“We have ” +
conn + “connections.”);
    }
  }
}
class Logger {
   boolean inDebug() {…}
   void debug(String msg) {…}
}
```



Structural analysis for possible NPEs?


```
1  if (foo != null)
2      foo.a();
3  foo.b();
```

Which of these should be flagged for NPE?

Surely safe? Surely bad? Suspicious?

// Limitations of structural analysis

A

```
1  if (foo != null)
2      foo.a();
3  foo.b();
```

B

```
1  if (foo == null)
2      foo = new Foo();
3  foo.b();
```

C

```
1  if (foo != null)
2      foo.a();
3  else
4      foo = new Foo();
5
6  foo.b();
```

D

```
1  if (foo != null)
2      foo.a();
3  else
4      foo.b();
```

CONTROL-FLOW AND DATA-FLOW ANALYSIS

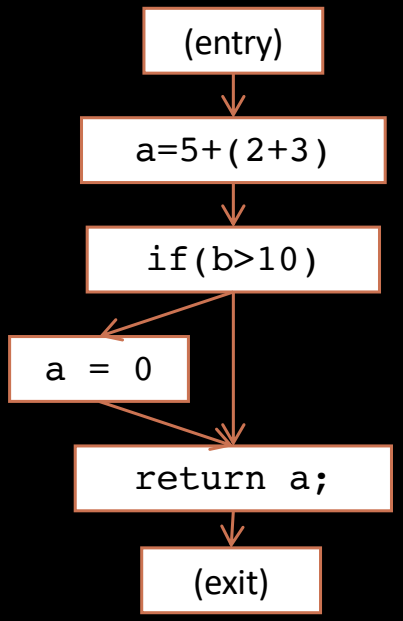
Control/Dataflow analysis

- **Reason** about all possible executions, via paths through a *control flow graph*.
  - Track information relevant to a property of interest at every *program point*.
- Define an **abstract domain** that captures only the values/states relevant to the property of interest.
- **Track** the abstract state, rather than all possible concrete values, for all possible executions (paths!) through the graph.

Control flow graphs

- A tree/graph-based representation of the flow of control through the program.
  - Captures all possible execution paths.
- Each node is a basic block: no jumps in or out.
- Edges represent control flow options between nodes.
- *Intra-procedural*: within one function.
  - cf. inter-procedural

```
1.  a = 5 + (2 + 3)
2.  if (b > 10) {
3.    a = 0;
4.  }
5.  return a;
```



How can CFG be used to identify this issue?


```
public int foo() {
    doStuff();

    return 3;

    doMoreStuff();
    return 4;
}
```

NPE analysis revisited

A

```
1  if (foo != null)
2      foo.a();
3  foo.b();
```

B

```
1  if (foo == null)
2      foo = new Foo();
3  foo.b();
```

C

```
1  if (foo != null)
2      foo.a();
3  else
4      foo = new Foo();
5
6  foo.b();
```

D

```
1  if (foo != null)
2      foo.a();
3  else
4      foo.b();
```

Abstract Domain for NPE Analysis

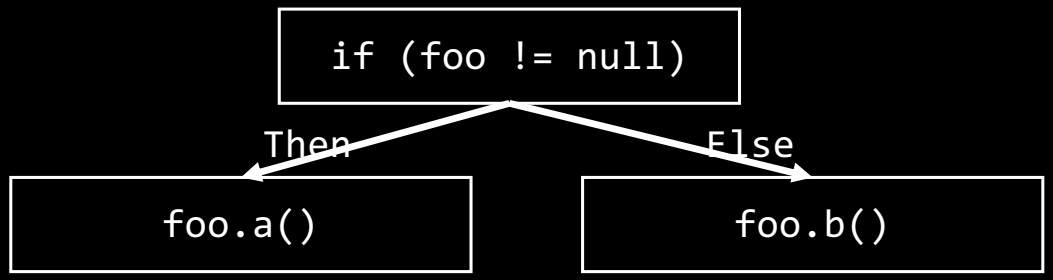
- Map of `Var -> {Null, NotNull, Unknown}`
- For example:

```
foo -> Null
bar -> NonNull
baz -> Unknown
```

- Mapping tracked at every program point (before/after each CFG node). Updated across nodes and edges.
- // let's say `foo -> Null` and `bar->Null`

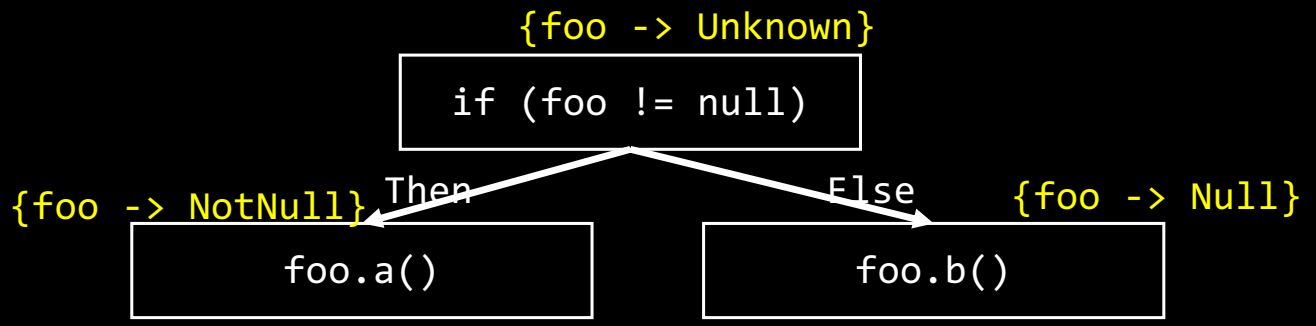
```
foo = new Foo();
// at this point, we have foo -> NotNull and bar -> Null
```

Data-Flow Analysis Examples



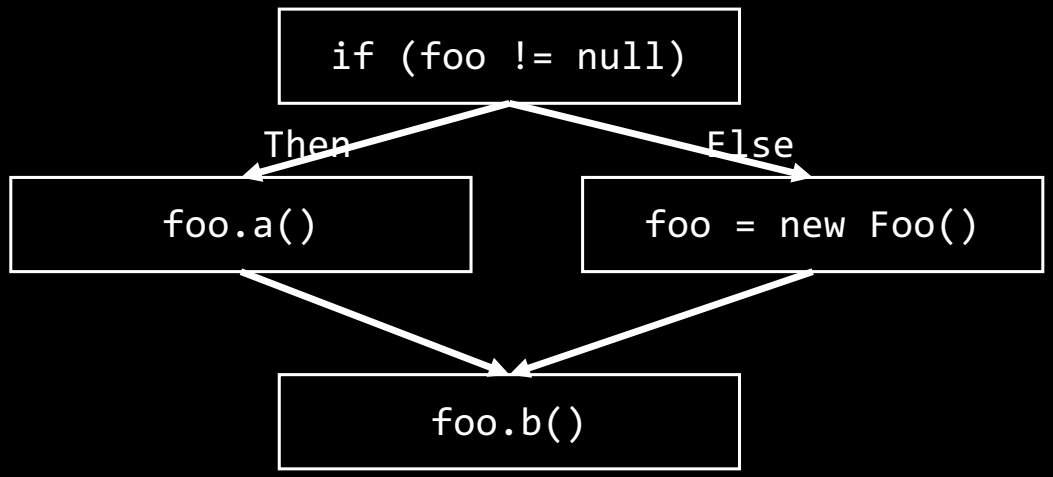

```
1  if (foo != null)
2      foo.a();
3  else
4      foo.b();
```

Data-Flow Analysis Examples



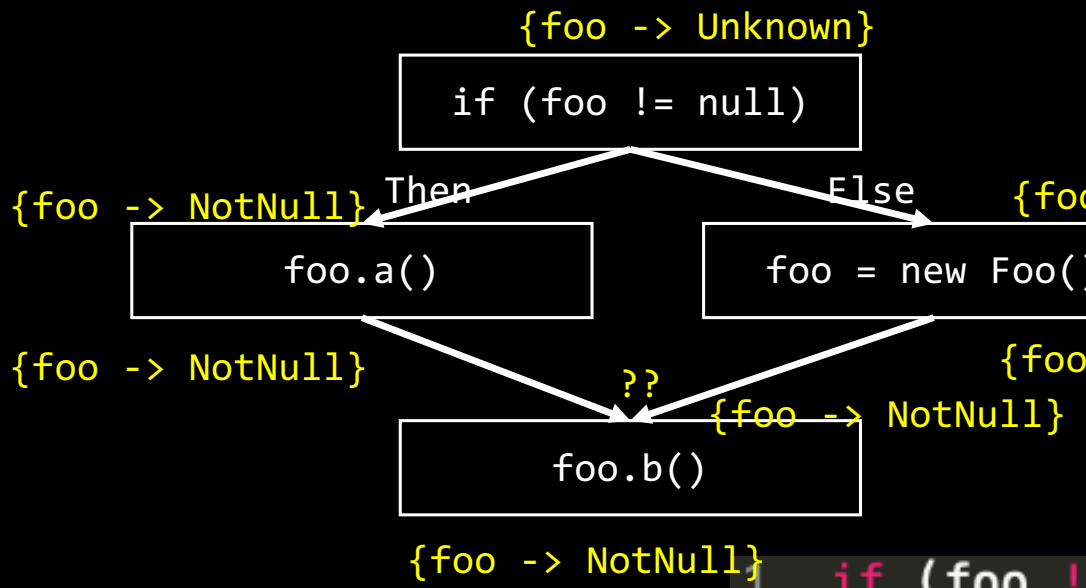

```
1  if (foo != null)
2      foo.a();
3  else
4      foo.b();
```

Data-Flow Analysis Examples




```
1  if (foo != null)
2      foo.a();
3  else
4      foo = new Foo();
5
6  foo.b();
```

Data-Flow Analysis Examples



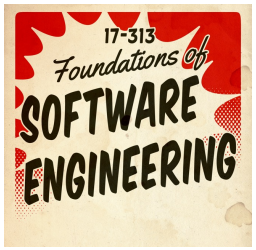

```
1  if (foo != null)
2      foo.a();
3  else
4      foo = new Foo();
5
6  foo.b();
```

Data-Flow Analysis Examples

Exercise: Work this out for yourself. Is foo.b() safe?

```
1  if (foo == null)
2      foo = new Foo();
3  foo.b();
```

Data-Flow Analysis Examples




```
if (foo == null)
```

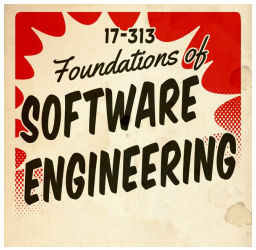
Then Else

```
foo = new Foo()
```

```
foo.b()
```

```
1  if (foo == null)
2      foo = new Foo();
3  foo.b();
```

Data-Flow Analysis Examples



{foo -> Unknown}

```
if (foo == null)
```

Then

{foo -> Null}

```
foo = new Foo()
```

{foo -> NotNull}

Else

{foo -> NotNull}

{foo -> NotNull}

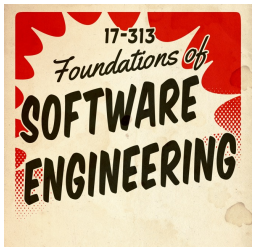
{foo -> NotNull}

```
foo.b()
```

{foo -> NotNull}

```
1  if (foo == null)
2      foo = new Foo();
3  foo.b();
```

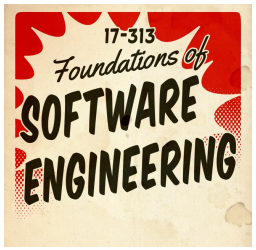
Interpreting abstract states

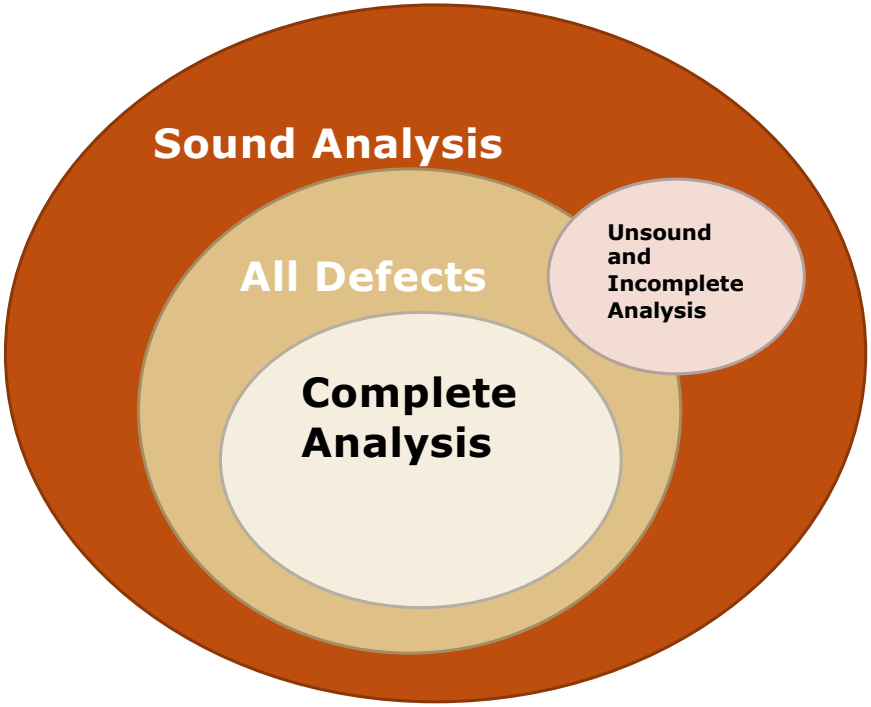


- "Null" means "must be NULL at this point, regardless of path taken"
- "NotNull" is similar
- "Unknown" means "may be NULL or not null depending on the path taken"

- Unknown must be dealt with due to Rice's theorem
  - Can make analysis smarter (at the cost of more algorithmic complexity) to reduce Unknowns, but can't get rid of them completely

- Whether to raise a flag on UNKNOWN access depends on usability/soundness.
  - False positives if warning on UNKNOWN
  - False negatives if no warning on UNKNOWN





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Formalisation and implementation of an algorithm for bytecode verification of @NonNull types

Chris Male, David J. Pearce, Alex Potanin, Constantine Dymnikov

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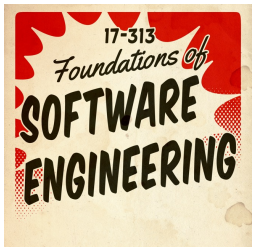
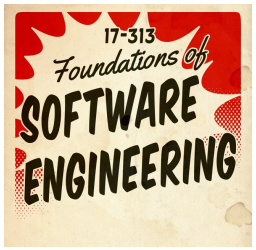
Examples of Data-Flow Anlayses



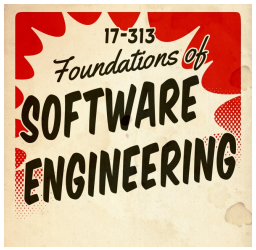
- Null Analysis
  - Var -> {Null, NotNull, UNKNOWN}
- Zero Analysis
  - Var -> {Zero, NonZero, UNKNOWN}
- Sign Analysis
  - Var -> {-, +, 0, UNKNOWN}
- Range Analysis
  - Var -> {[0, 1], [1, 2], [0, 2], [2, 3], [0, 3], …, UNKNOWN}
- Constant Propagation
  - Var -> {1, 2, 3, …, UNKNOWN}
- File Analysis
  - File -> {Open, Close, UNKNOWN}
- Tons more!!!

Data-Flow Analysis: Challenges



- Loops
  - Fixed-point algorithms guarantee termination at the cost of losing information ("Unknown")
- Functions
  - Analyze them separately or analyze whole program at once
  - "Context-sensitive" analyses specialize on call sites (think: duplicate function body for every call site via inlining)
- Recursion
  - Makes context-sensitive analyses explode (cf. loops)
- Object-oriented programming
- Heap memory
  - Need to abstract mapping keys not just values
- Exceptions

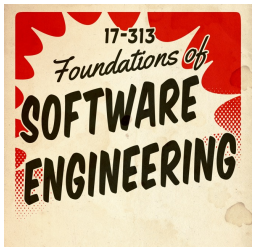
Static Analysis vs. Testing



- Which one to use when?
- Points in favor of Static Analysis
  - Don’t need to set up run environment, etc.
  - Can analyze functions/modules independently and in parallel
  - Don’t need to think of (or try to generate) program inputs

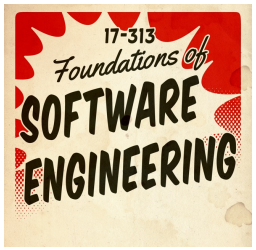
- Points in favor of Testing / Dynamic Analysis
  - Not deterred by complex program features
  - Can easily handle external libraries, platform-specific config, etc.
  - Ideally no false positives
  - Easier to debug when a failure is identified

Key Points



- Describe random test-input generation strategies such as fuzz testing
- Write generators and mutators for fuzzing different types of values
- Characterize challenges of performance testing and suggest strategies
- Reason about failures in microservice applications
- Describe chaos engineering and how it can be applied to test resiliency of cloud-based applications
- Describe A/B testing for usability

Key Points



- Give a one sentence definition of static analysis. Explain what types of bugs static analysis targets.
- Give an example of syntactic or structural static analysis.
- Construct basic control flow graphs for small examples by hand.
- Give a high-level description of dataflow analysis and cite some example analyses.
- Explain at a high level why static analyses cannot be sound, complete, and terminating; assess tradeoffs in analysis design.
- Characterize and choose between tools that perform static analyses.
- Contrast static analysis tools with software testing and dynamic analysis tools as a means of catching bugs.