Dynamic Analysis and Advanced Automated Testing

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Learning Goals

- 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

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

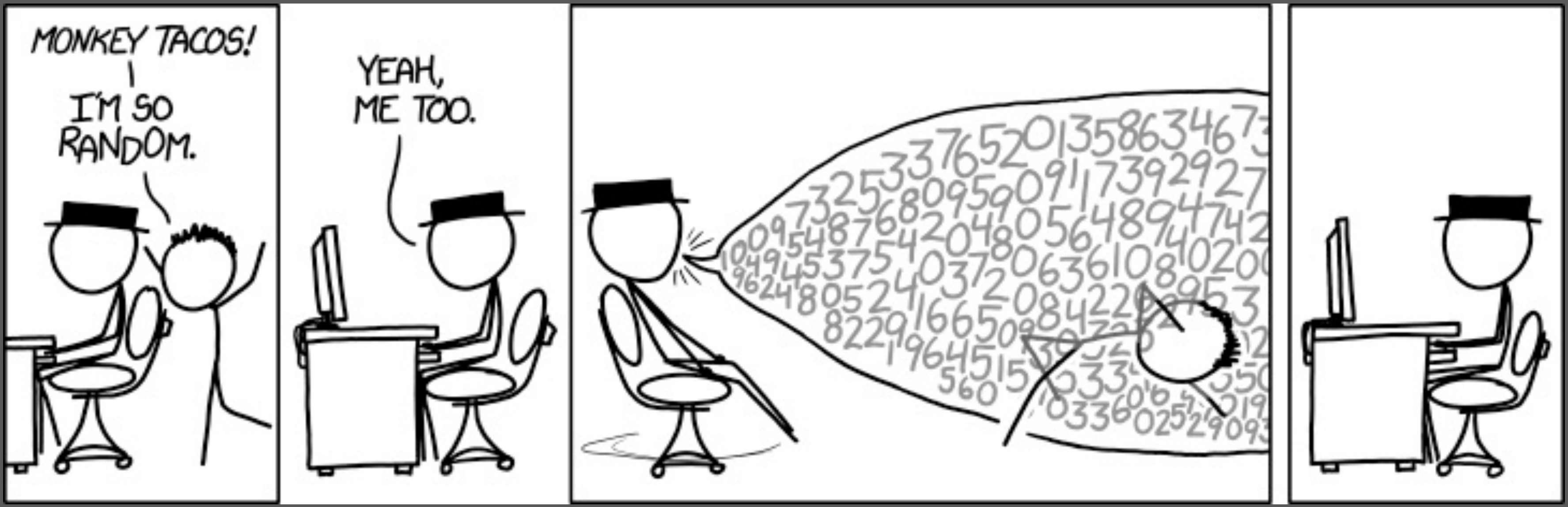
```
def p1(x):
  if x * x – 10 == 15:
    return True
  return False
```

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`

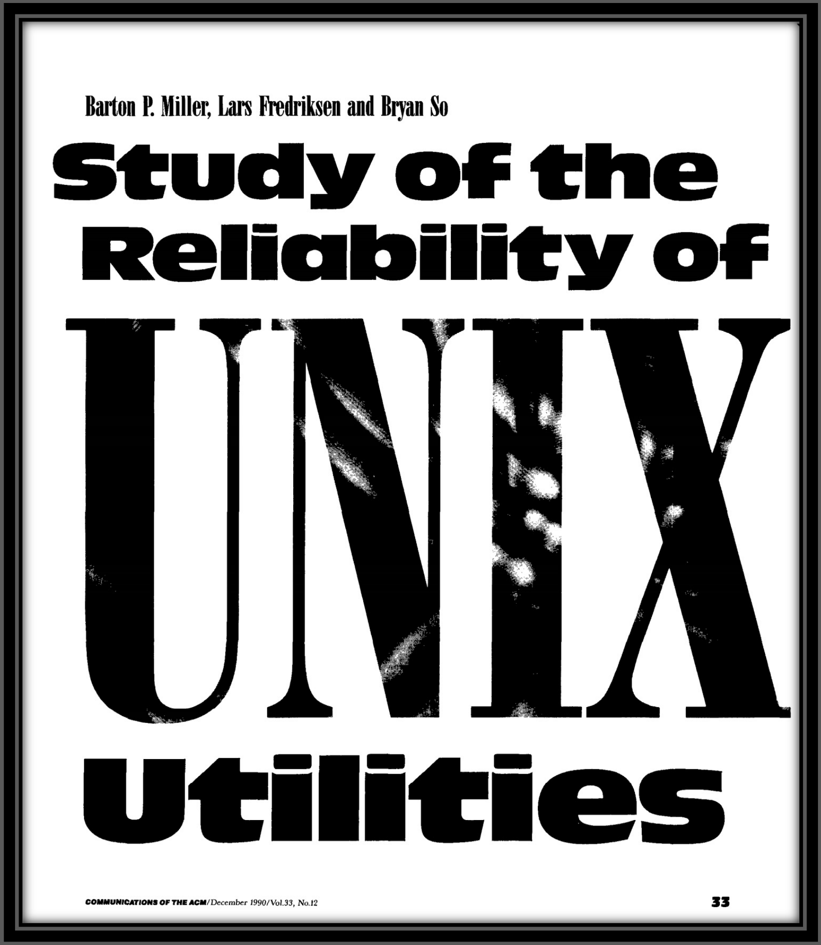
```
def p3(x):
  if x > 3 and x < 100:
    z = x - 2
    c = 0
    while z >= 2:
      if z ** (x - 1) % x == 1:
        c = c + 1
      z = z - 1
    if c == x - 3:
      return True
  return False
```



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

Security and Robustness

FUZZ TESTING

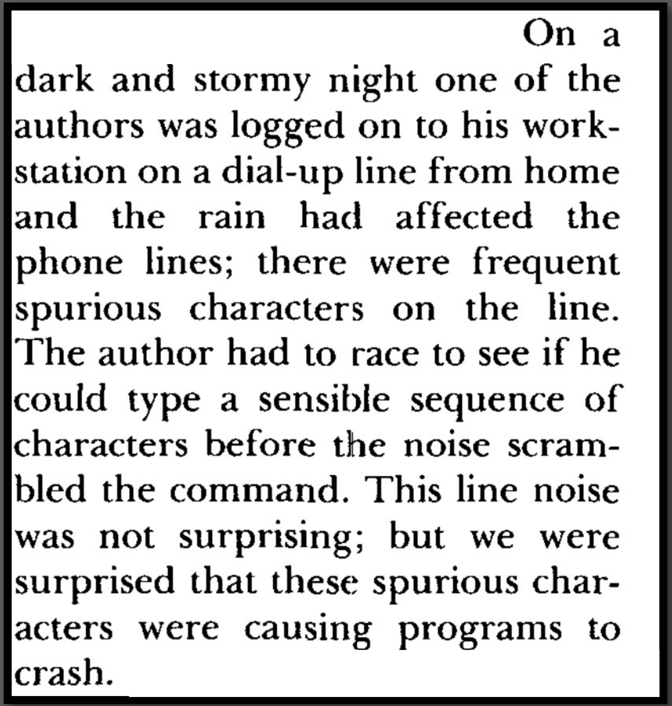


Barton P. Miller, Lars Fredriksen and Bryan So

Study of the Reliability of UNIX Utilities

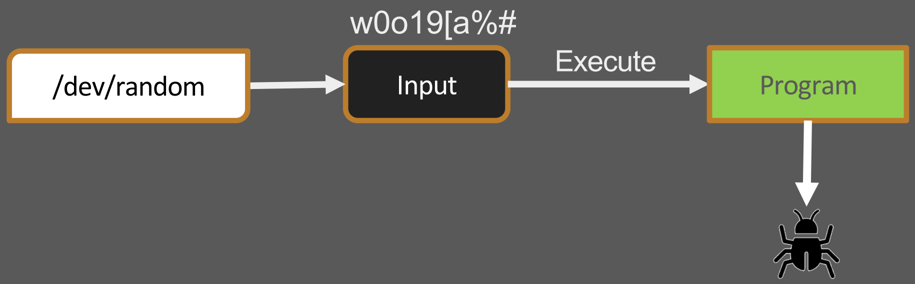
COMMUNICATIONS OF THE ACM/December 1990/Vol.33, No.12 33

Communications of the ACM (1990)



“ On a dark and stormy night one of the authors was logged on to his 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



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];
}
```

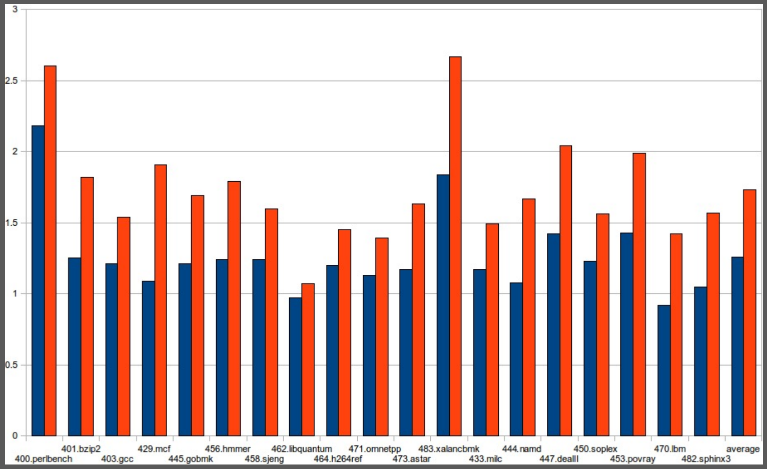
AddressSanitizer

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

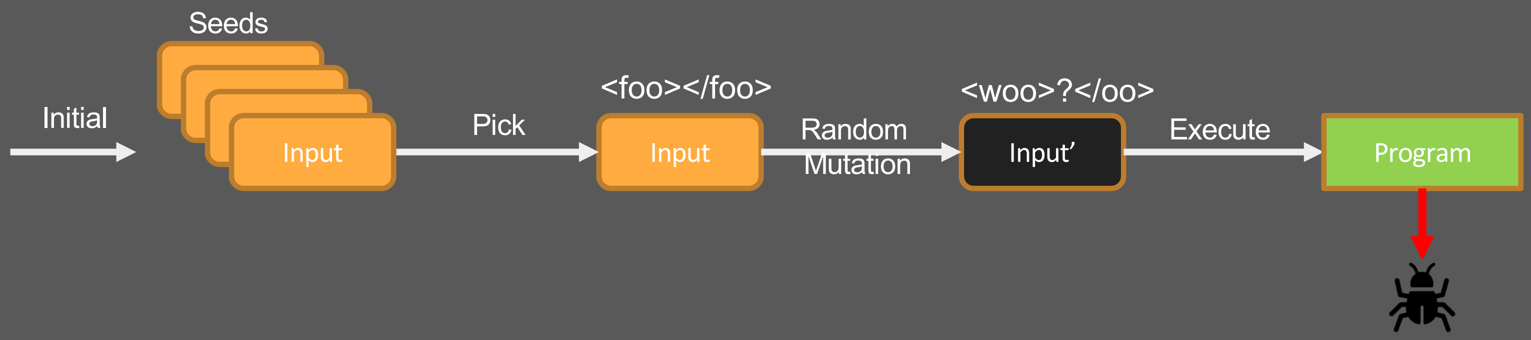
Slowdown about 2x on SPEC CPU 2006



Strengths and Limitations

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

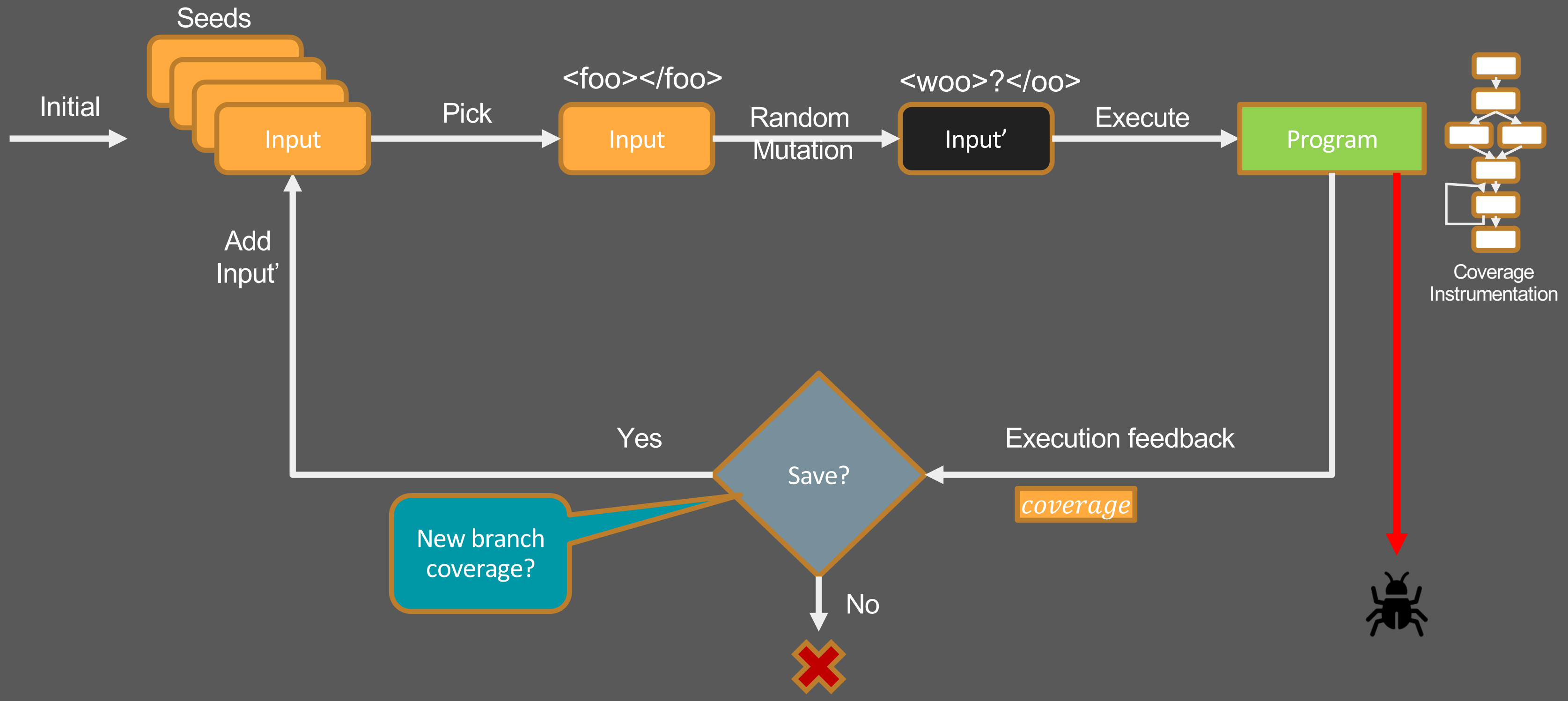
Mutation-Based Fuzzing (e.g. Radamsa)



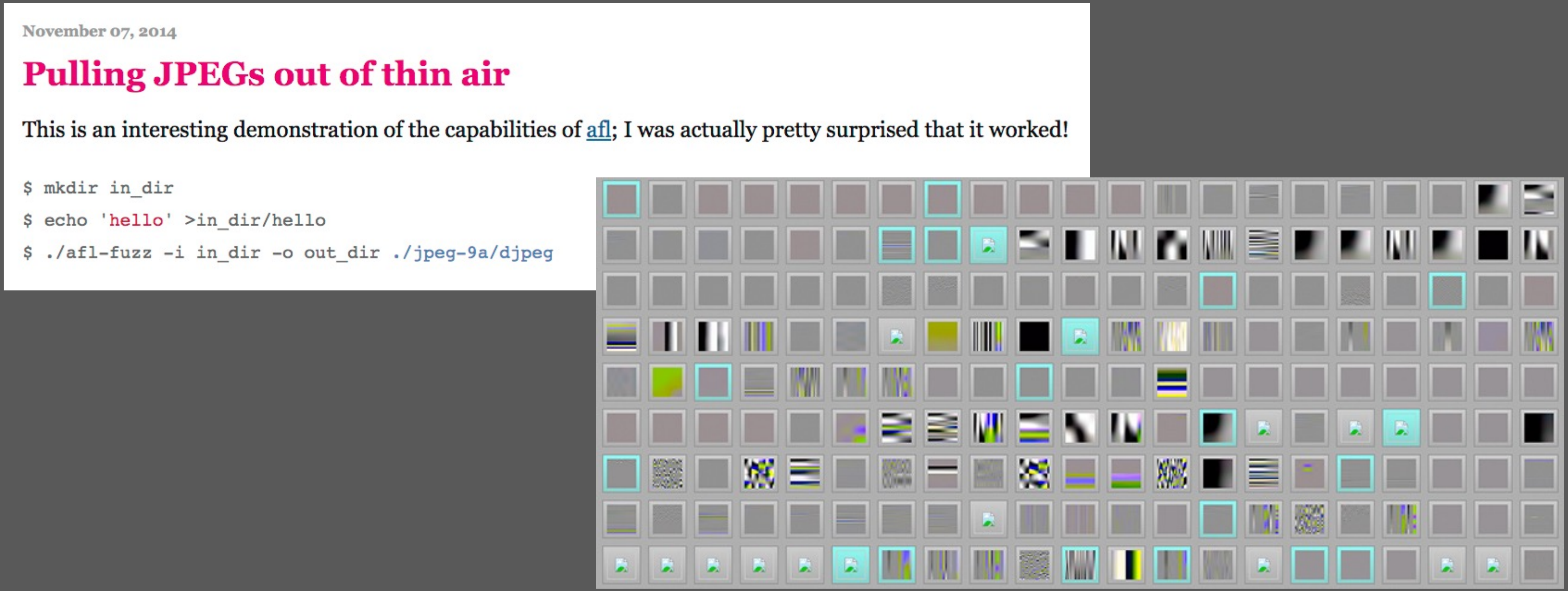
Mutation Heuristics

- 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?

Coverage-Guided Fuzzing (e.g. AFL)



Coverage-Guided Fuzzing with AFL



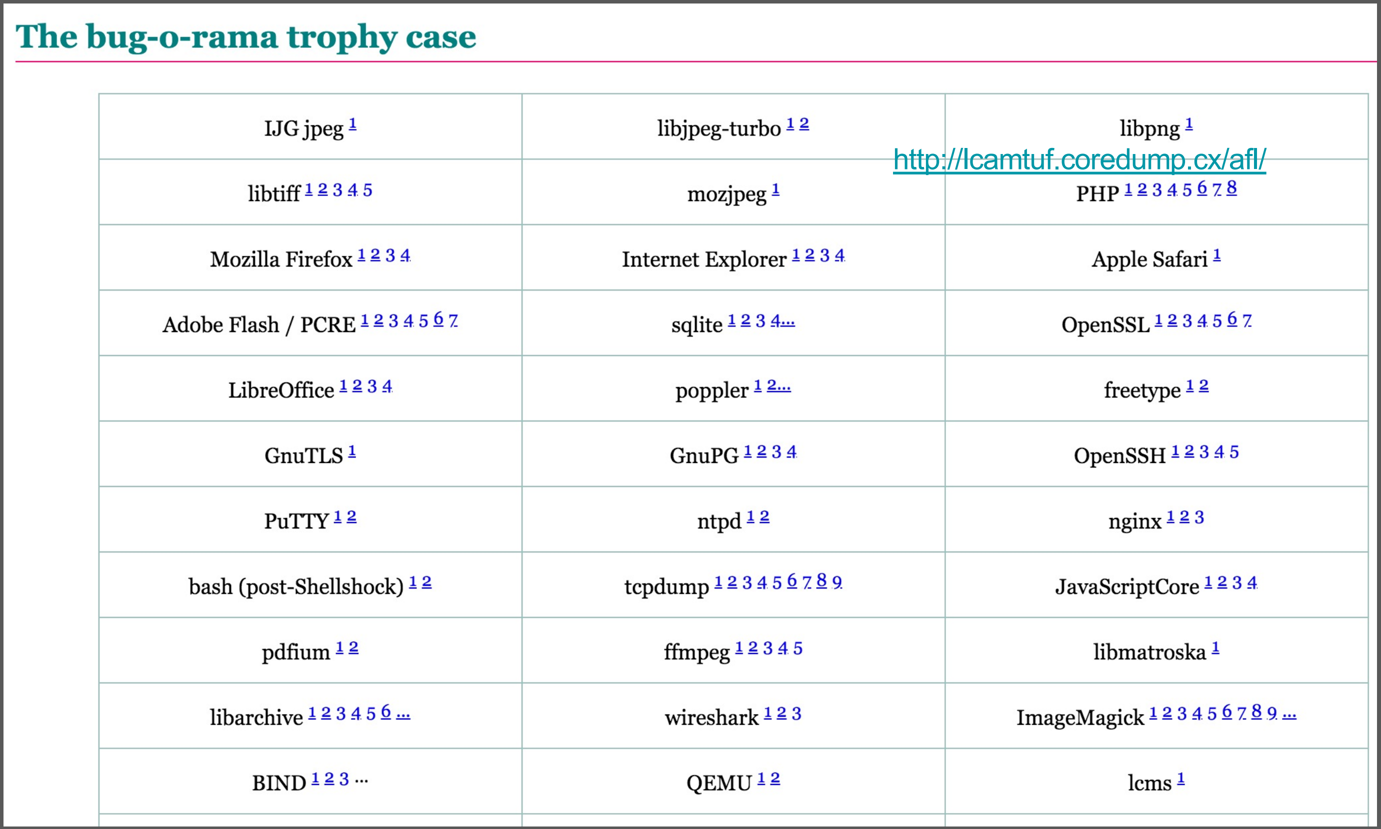
November 07, 2014

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
```

Coverage-Guided Fuzzing with AFL

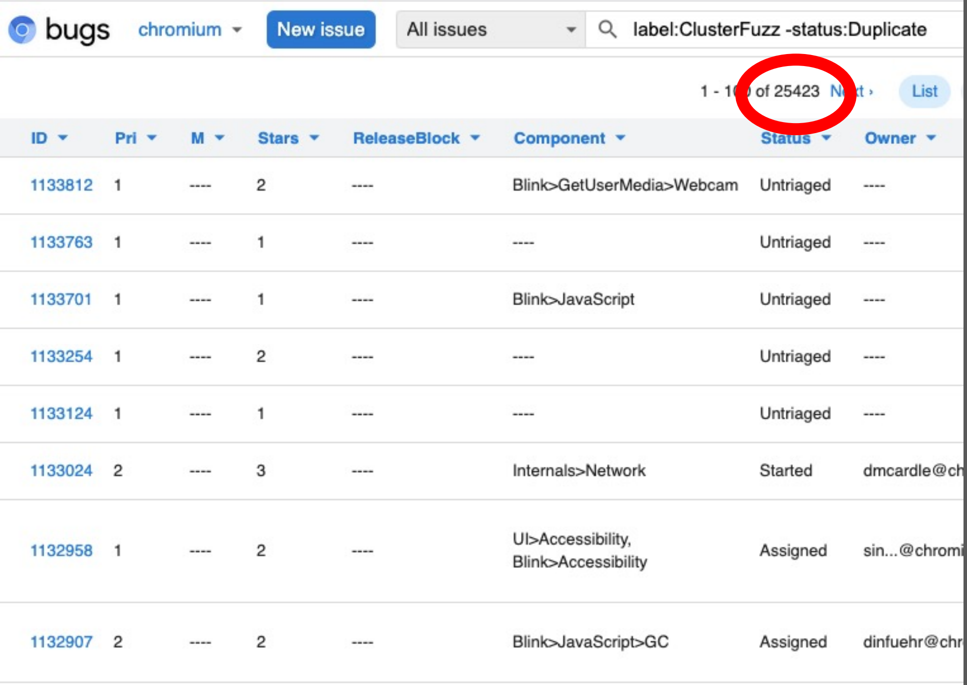


The bug-o-rama trophy case

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



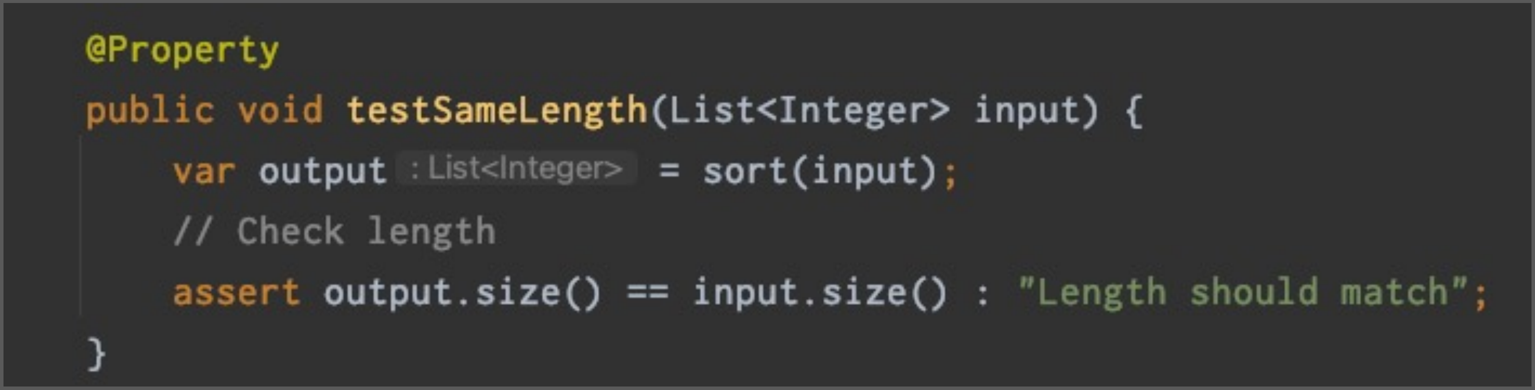
label:ClusterFuzz -status:Duplicate

1 - 100 of 25423 Next ›

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

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

- Random `List<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

Exercise: Write a mutator
HashMap<String, Integer>

- 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
    }
    ```

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TESTING PERFORMANCE

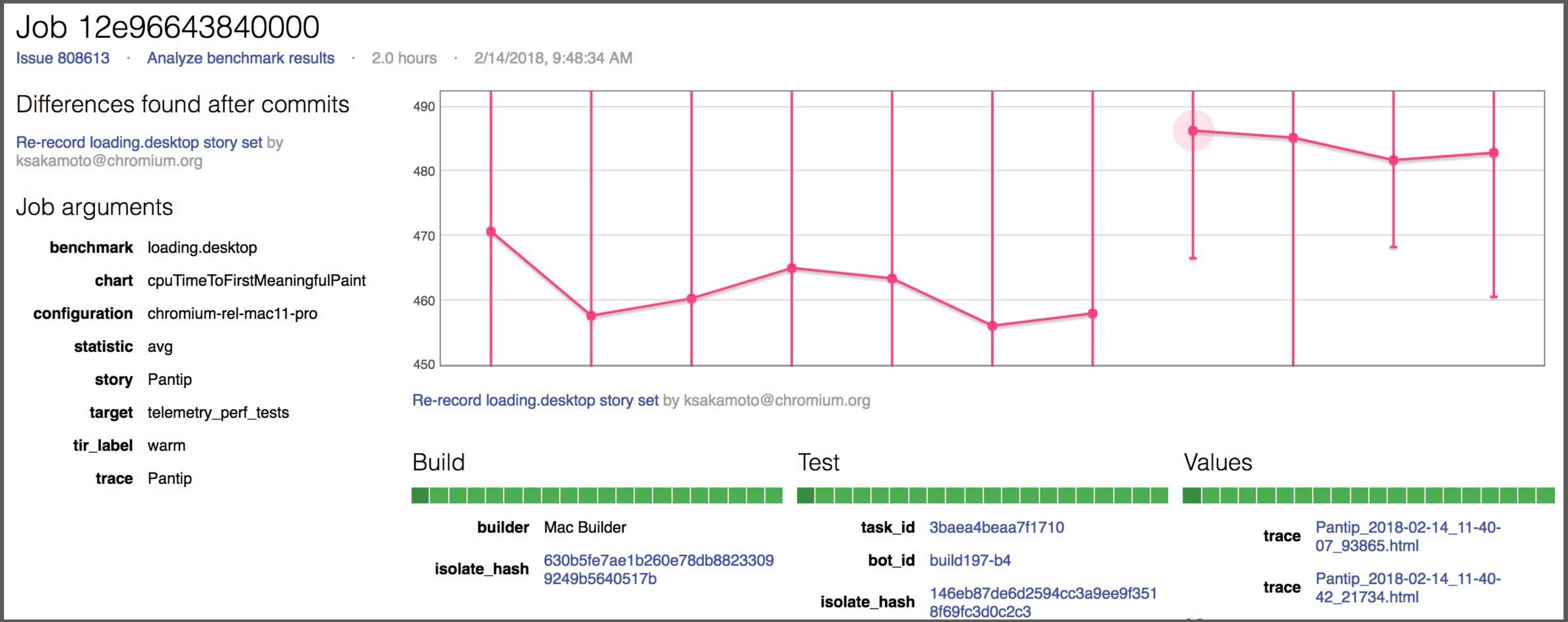
Performance Testing

- 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 630b5fe7ae1b260e78db8823309 9249b5640517b

Test

task_id 3baea4beaa7f1710

bot_id build197-b4

isolate_hash 146eb87de6d2594cc3a9ee9f351 8f69fc3d0c2c3

Values

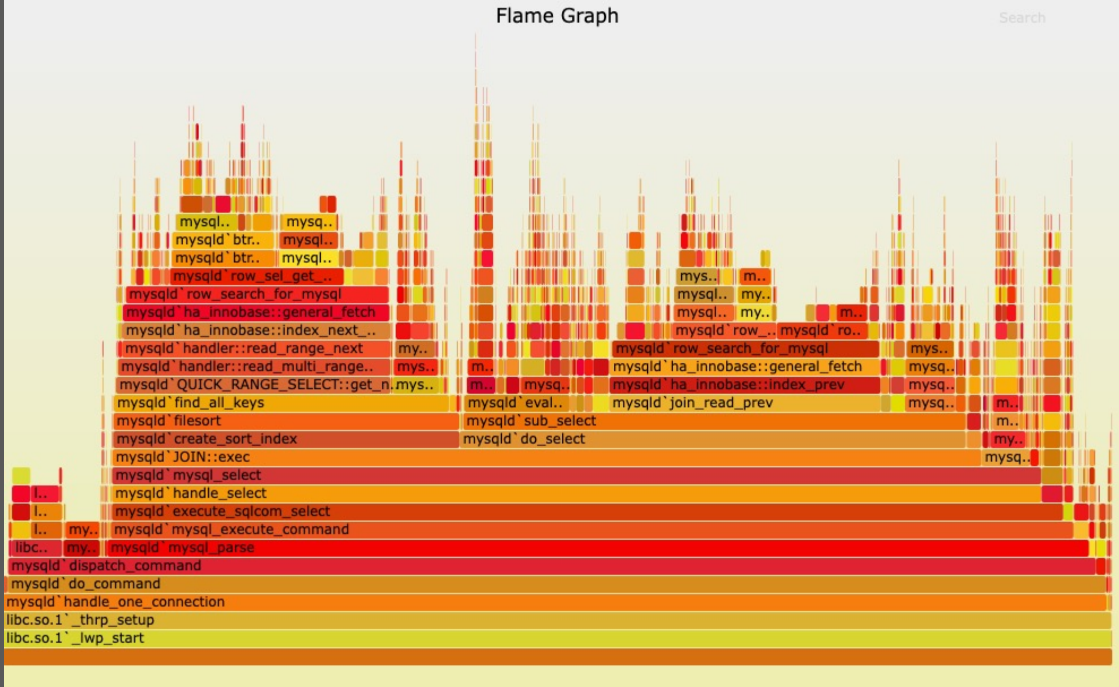
trace Pantip_2018-02-14_11-40-07_93865.html

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

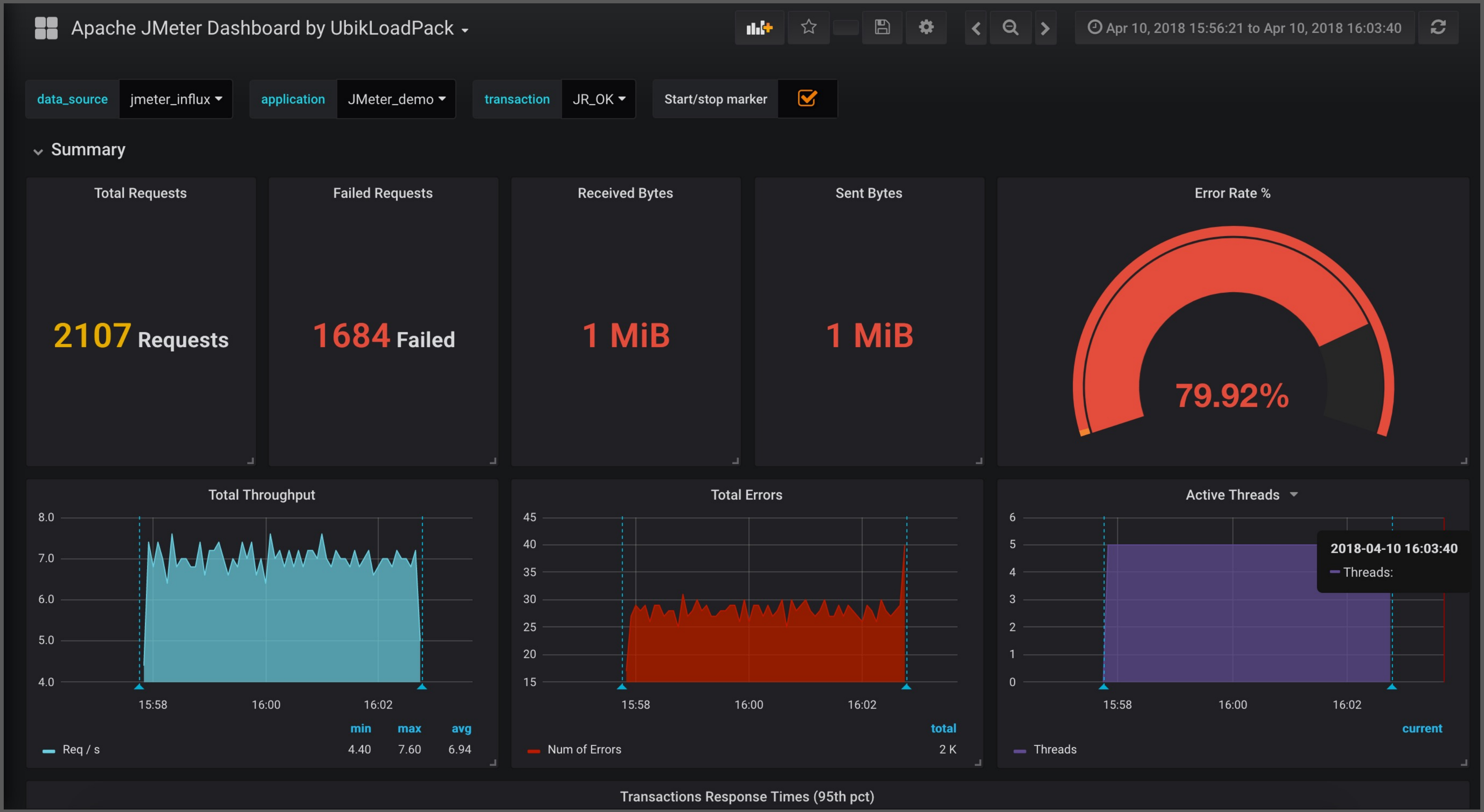
Source: https://chromium.googlesource.com/chromium/src/+/refs/heads/main/docs/speed/addressing_performance_regressions.md

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)



Apache JMeter Dashboard by UbikLoadPack

Apr 10, 2018 15:56:21 to Apr 10, 2018 16:03:40

data_source: jmeter_influx
application: JMeter_demo
transaction: JR_OK
Start/stop marker ☑

Summary

Total Requests: 2107 Requests

Failed Requests: 1684 Failed

Received Bytes: 1 MiB

Sent Bytes: 1 MiB

Error Rate %: 79.92%

Total Throughput

	min	max	avg
Req / s	4.40	7.60	6.94

Total Errors

	total
Num of Errors	2 K

Active Threads

2018-04-10 16:03:40
Threads:

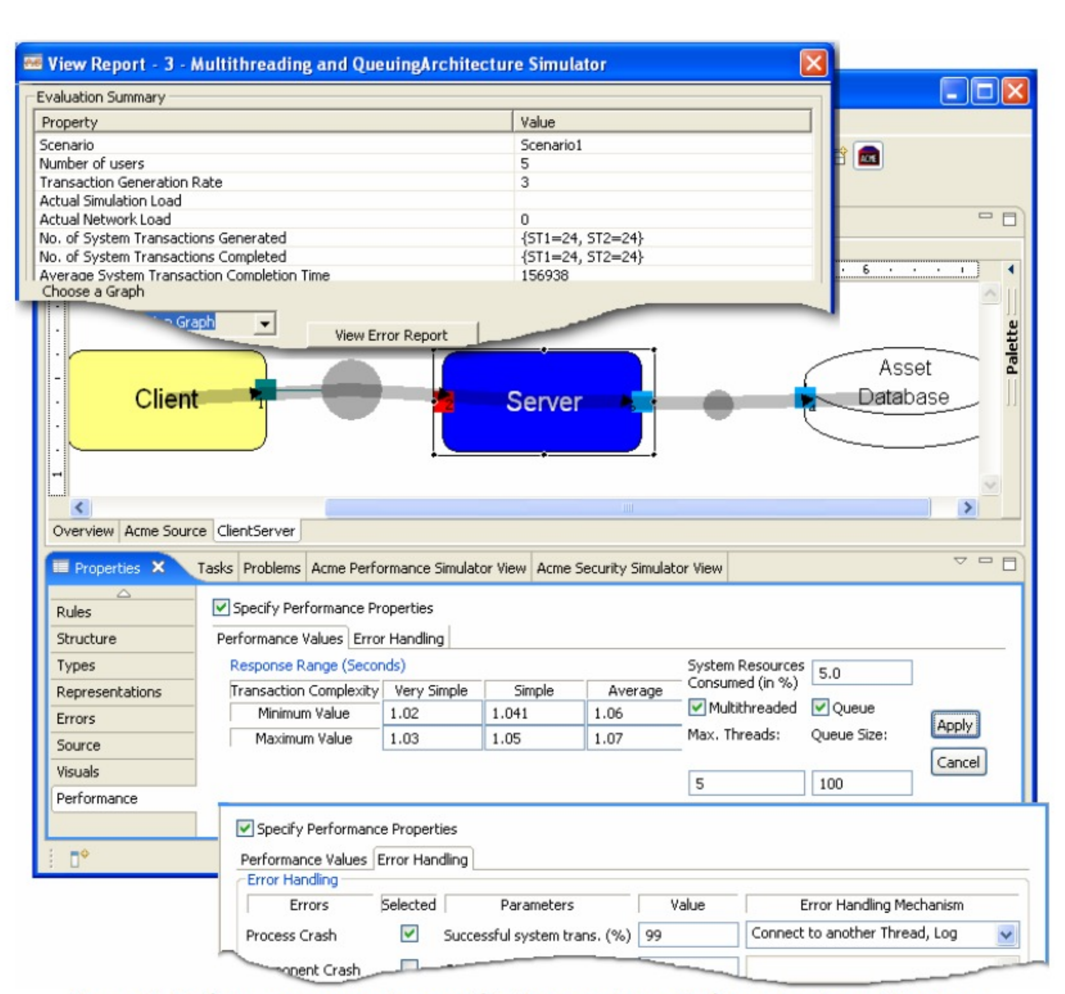
	current
Threads	

Transactions Response Times (95th pct)

http://jmeter.apache.org

Performance-driven Design

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



View Report - 3 - Multithreading and QueuingArchitecture Simulator

Evaluation Summary

Property	Value
Scenario	Scenario1
Number of users	5
Transaction Generation Rate	3
Actual Simulation Load	
Actual Network Load	0
No. of System Transactions Generated	{ST1=24, ST2=24}
No. of System Transactions Completed	{ST1=24, ST2=24}
Average System Transaction Completion Time	156938

☑ Specify Performance Properties

Performance Values | Error Handling

Response Range (Seconds)

Transaction Complexity	Very Simple	Simple	Average
Minimum Value	1.02	1.041	1.06
Maximum Value	1.03	1.05	1.07

System Resources Consumed (in %) 5.0

☑ Multithreaded ☑ Queue

Max. Threads: 5

Queue Size: 100

☑ Specify Performance Properties

Performance Values | Error Handling

Error Handling

Errors	Selected	Parameters	Value	Error Handling Mechanism
Process Crash	☑	Successful system trans. (%)	99	Connect to another Thread, Log
...onent Crash	□			

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.

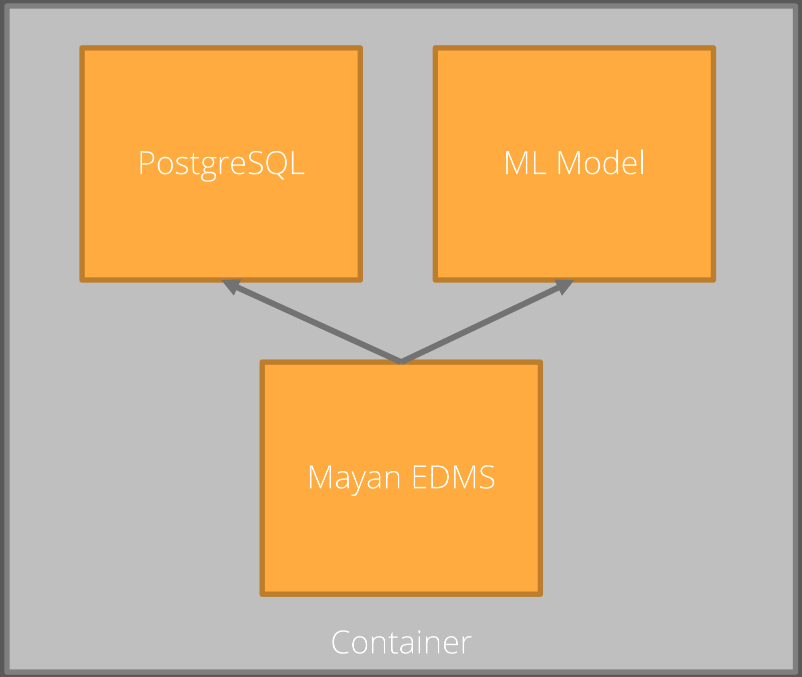
Soak testing

- 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?

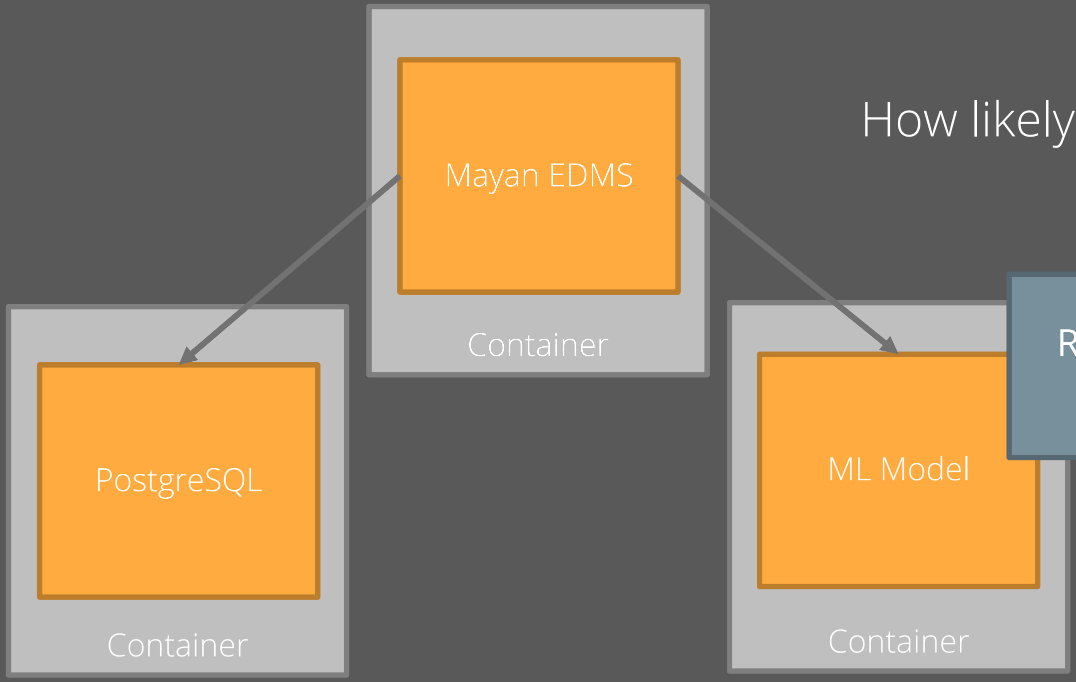
How likely is that error to happen?

How do I fix it?

→ Process Call

🟧 Microservice

Microservice Application



What kind of failures can happen here?

How likely is that error to happen?

How do I fix it?

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

→ Process Call

🟧 Microservice

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
- r will be taken offline
- t a GameDay **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

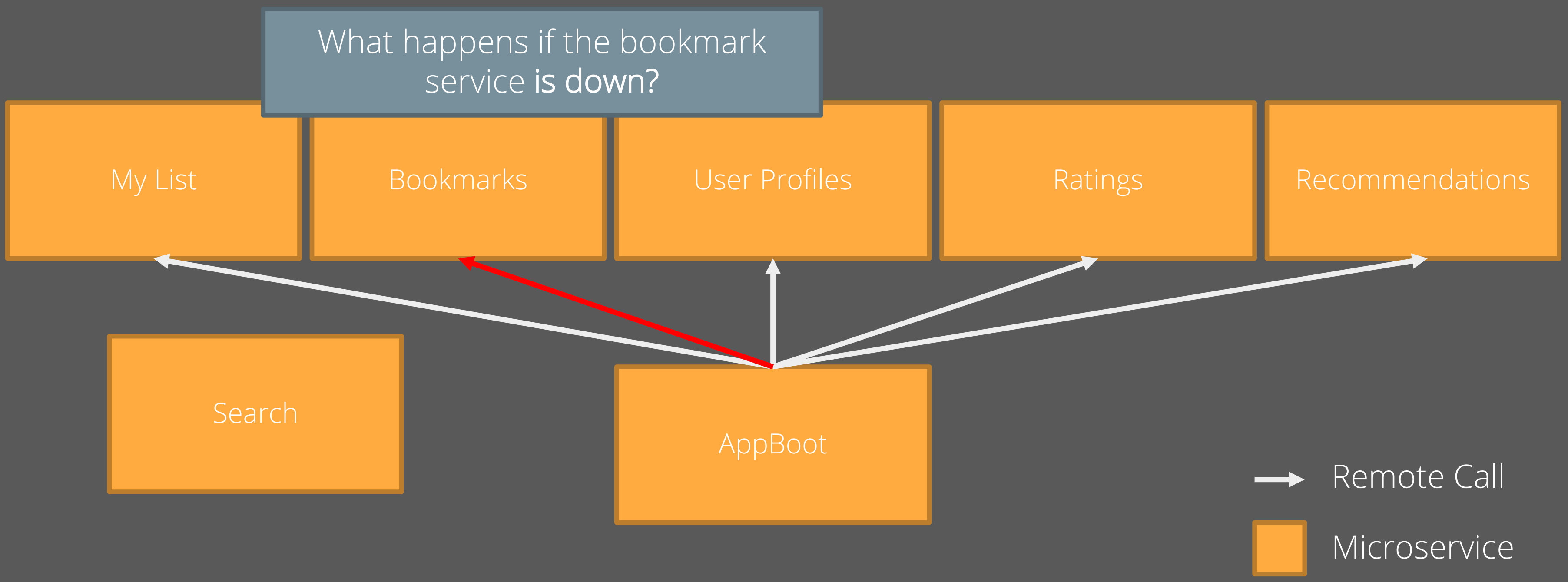
Key metric: availability

amazon web services
CHAOS MONKEY

Chaos monkey/Simian army

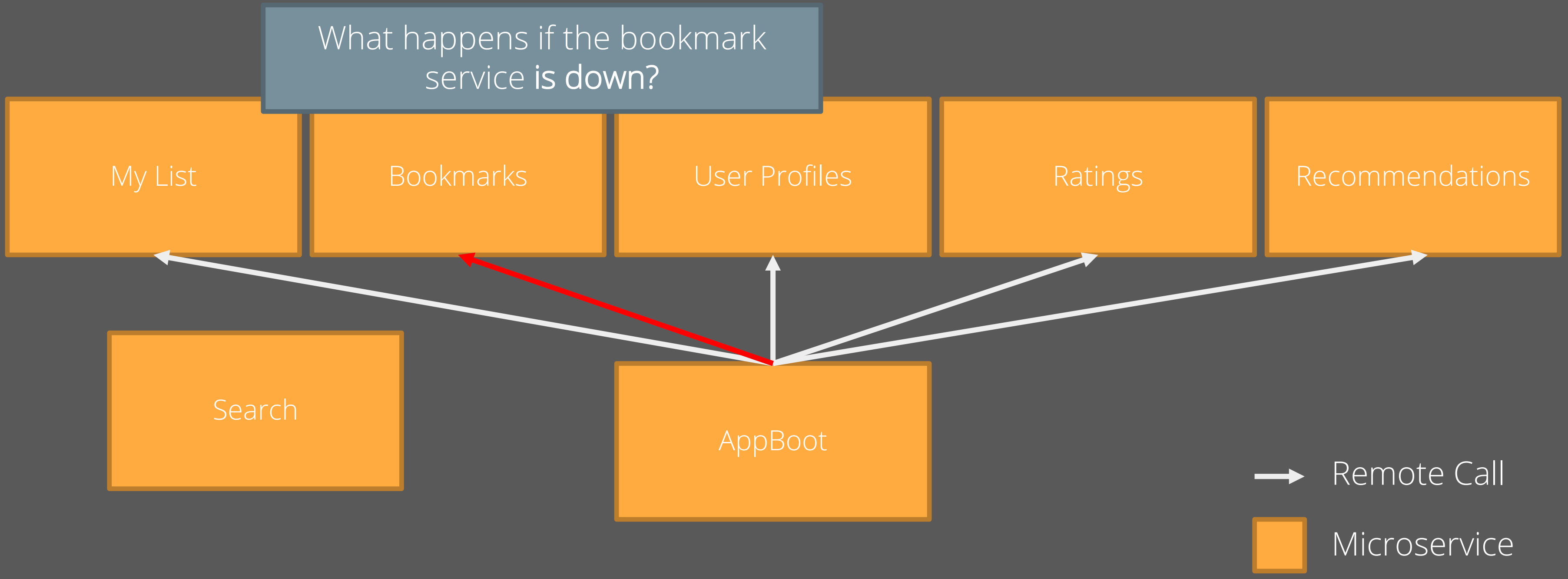
- A Netflix infrastructure testing system.
- “Malicious” programs randomly trample on components, network, datacenters, AWS instances...
  - Chaos monkey was the first – disables production instances at random.
  - Other monkeys include Latency Monkey, Doctor Monkey, Conformity Monkey, etc... Fuzz testing 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



What happens if the bookmark service is down?

Netflix UI: AppBoot



What happens if the bookmark service is down?

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.

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

4. **Automate experiments** to run continuously

Does everything seem to be **working properly?**

Are users **complaining?**

Steady State Behavior

Back to quality attributes: availability!

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

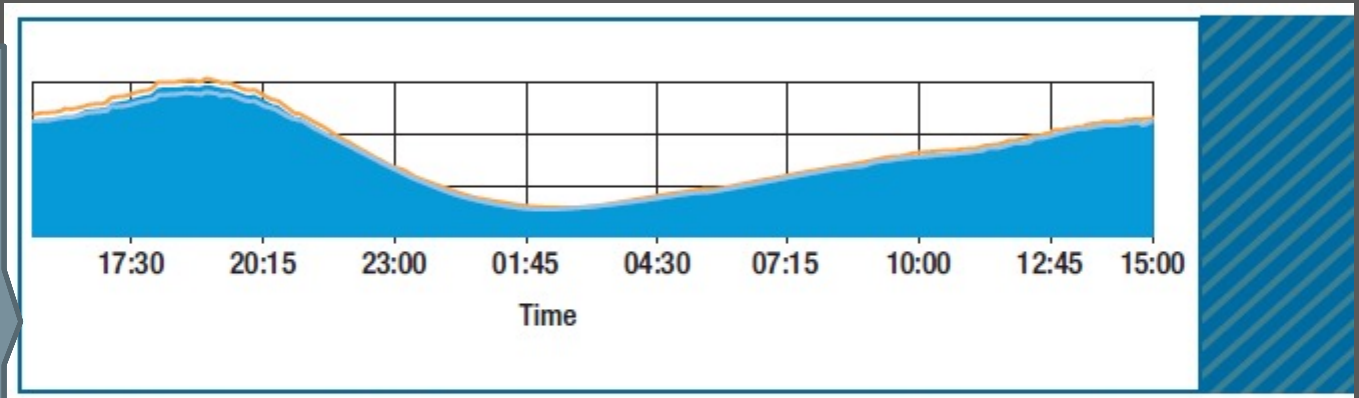
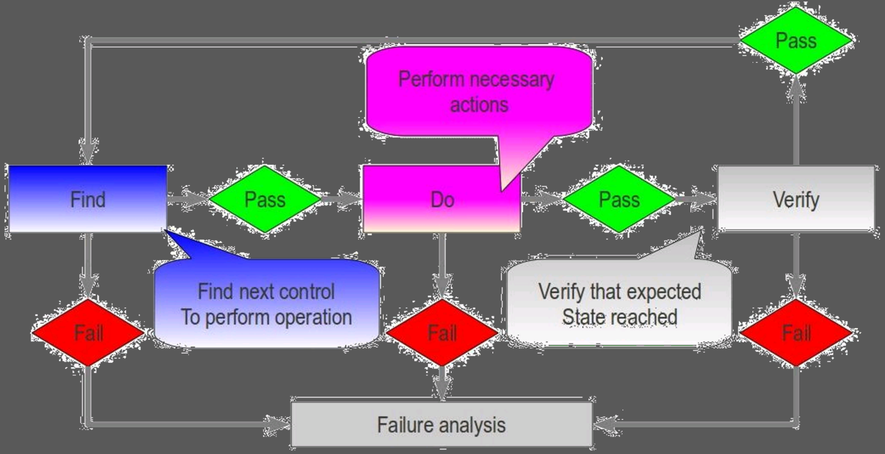


FIGURE 2. A graph of SPS ([stream] starts per second) over a 24-hour period. This metric varies slowly and predictably throughout a day. The orange line shows the trend for the prior week. The *y*-axis isn’t labeled because the data is proprietary.

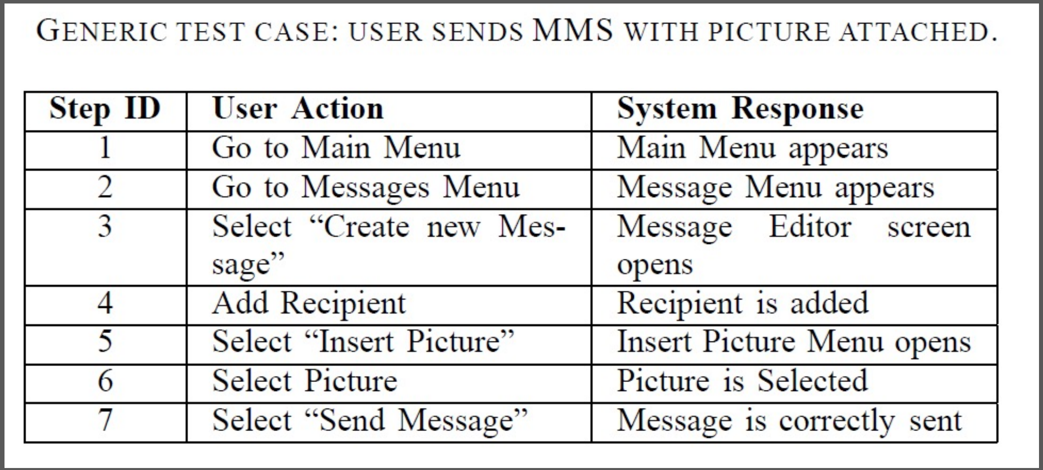
TESTING USABILITY

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?


Pass
Perform necessary actions
Find
Pass
Do
Pass
Verify
Find next control To perform operation
Verify that expected State reached
Fail
Fail
Fail
Failure analysis

Manual Testing?



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

- Live System?
- Extra Testing System?
- Check output / assertions?
- Effort, Costs?
- Reproducible?

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)

Act now!

Sale ends soon!

Example: group B (1%)

Act now! Sale ends soon!

A/B Testing

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

Next Week

- Static Analysis: Finding issues in code without even running it