Software Security

Security Testing

especially

Fuzzing

Erik Poll

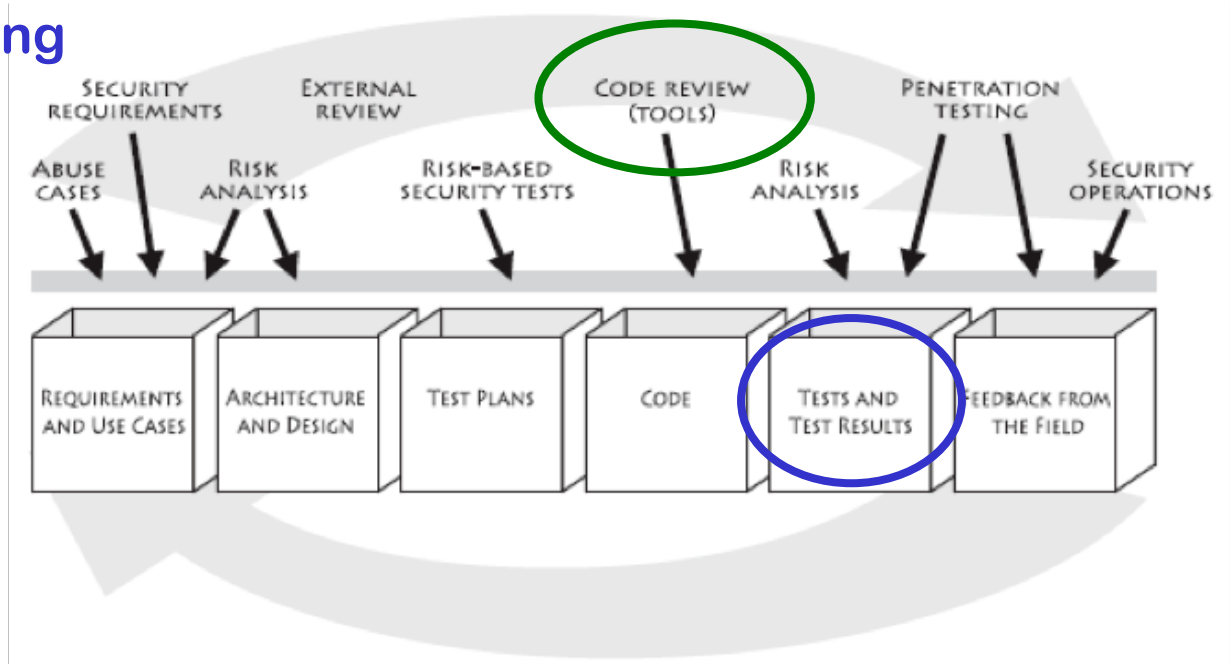
Radboud Universiteit Nijmegen

TU/e Master in Cyber Security

Security in the SDLC

Last week: static analysis aka code review tools

This week: security testing



Security testing can be used to find many kinds of security flaws, but focus of this lecture – and the group assignment – will be on use om testing C(++) code for memory corruption

Fuzzing group project

- Form a team with 4 students
- Choose an open-source C(++) application that can take input from the command line in some complex file format
  - For instance, any graphics library for image manipulation
  - Check if this application is mentioned on http://lcamtuf.coredump.cx/ - if so you may want to test old version
- Try out the fuzzing tools (Radamsa, zuff, and afl) with/without instrumentation with additional checks for memory safety code (valgrind, ASan)
- Optional variations: report any bugs found, check against known CVEs, test older vs newer release, try different settings or inputs for the tool, try another fuzzing tool, …

Overview

- Testing basics
- Abuse cases & negative tests
- Fuzzing
  - Dumb fuzzing
  - Mutational Fuzzing
    - example: OCPP
  - Generational aka grammar-based fuzzing
    - example: GSM
  - Whitebox fuzzing with SAGE
    - looking at symbolic execution of the code
  - Evolutionary fuzzing with `afl`
    - grey-box, observing execution of the (instrumented) code

Testing basics

SUT, test suite & test oracle

To test a SUT (System Under Test) we need two things

1. test suite, ie. collection of input data
2. a test oracle
   that decides if a test was passed ok or reveals an error
   - ie. some way to decide if the SUT behaves as we want

Both defining test suites and test oracles can be *a lot of work!*

- In the worst case, a test oracle is a long list which *for every individual test case, specifies exactly what should happen*
- A simple test oracle: just looking if application doesn't crash

Moral of the story: crashes are good ! (for testing)

Code coverage criteria

Code coverage criteria to measure how good a test suite is include

- statement coverage
- branch coverage

  Statement coverage does not imply branch coverage; eg for

```
void f (int x, y) { if (x>0) {y++};
                    y--; }
```

  Statement coverage needs 1 test case, branch coverage needs 2

- More complex coverage criteria exists, eg MCDC (Modified condition/decision coverage), commonly used in avionics

Possible perverse effect of coverage criteria

High coverage criteria may *dis*courage defensive programming, eg.

```
void m(File f){
  if <security_check_fails> {log (...);
                             throw (SecurityException);}
  try { <the main part of the method> }
  catch (SomeException) { log(...);
                          <some corrective action>;
                          throw (SecurityException); }
}
```

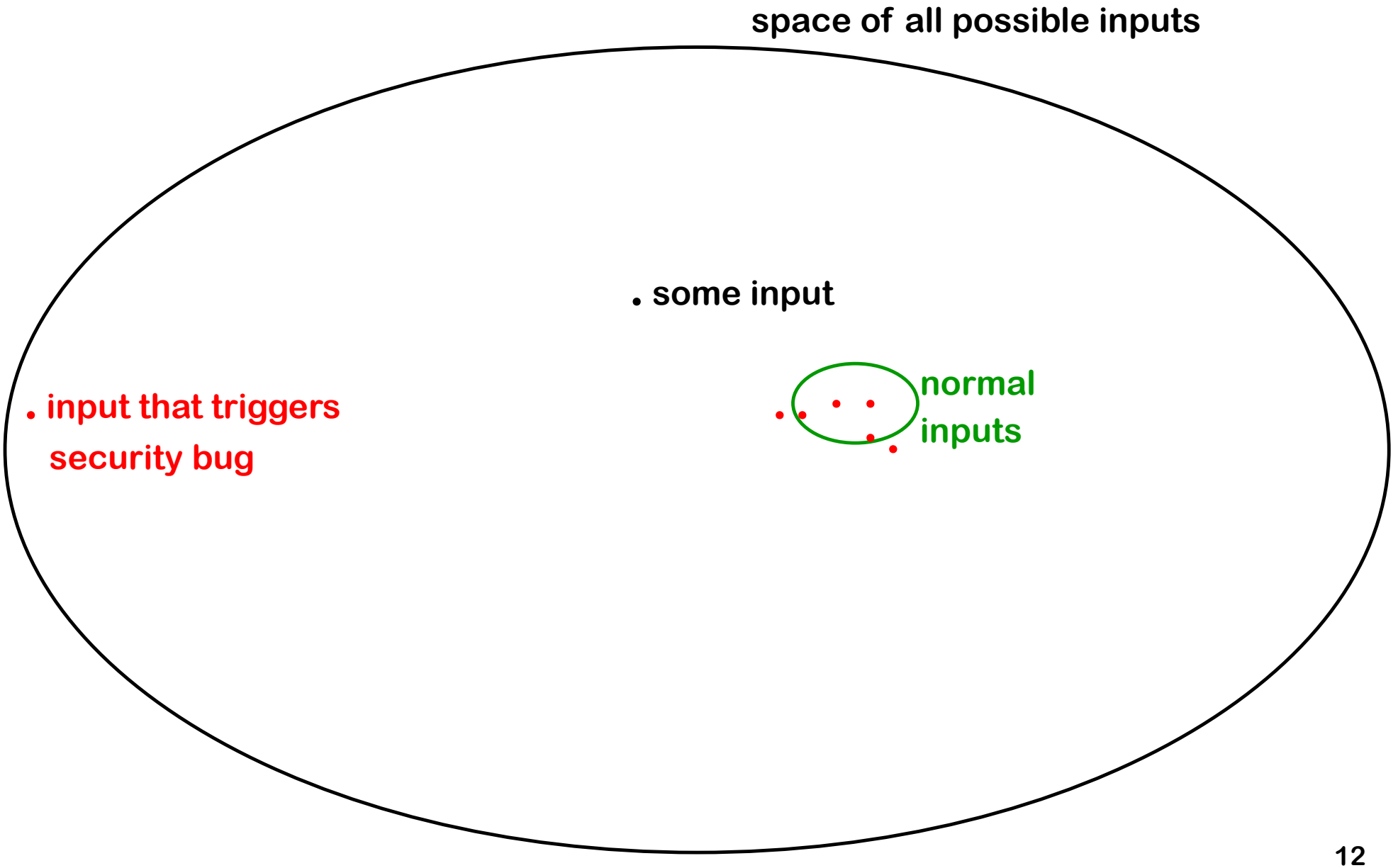
If the green defensive code, ie. the if & catch branch, is hard to trigger in tests, then programmers may be tempted (or forced) to remove this code to improve test coverage...

Abuse cases
&
Negative testing

Testing for functionality vs testing for security

- Normal testing will look at right, wanted behaviour for sensible inputs (aka the happy flow), and some inputs on borderline conditions
- Security testing also requires looking for the wrong, unwanted behaviour for really strange inputs
- Similarly, normal use of a system is more likely to reveal functional problems than security problems:
  - users will complain about functional problems, hackers won't complain about security problems

Security testing is HARD



Abuse cases & negative test cases

- Thinking about abuse cases is a useful way to come up with security tests
  - *what would an attacker try to do?*
  - *where could an implementation slip up?*

- This gives rise to negative test cases,

  i.e. test cases which are *supposed* to fail

iOS goto fail SSL bug

```
...
if ((err = SSLHashSHA1.update(&hashCtx, &clientRandom)) != 0)
    goto fail;
if ((err = SSLHashSHA1.update(&hashCtx, &serverRandom)) != 0)
    goto fail;
if ((err = SSLHashSHA1.update(&hashCtx, &signedParams)) != 0)
    goto fail;
    goto fail;
if ((err = SSLHashSHA1.final(&hashCtx, &hashOut)) != 0)
    goto fail;
err = sslRawVerify(...);
. . .
```

Negative test cases for flawed certificate chains

- David Wheeler's 'The Apple goto fail vulnerability: lessons learned' gives a good discussion of this bug & ways to prevent it, incl. the need for negative test cases

  http://www.dwheeler.com/essays/apple-goto-fail.html

- The FrankenCert test suite provides (broken) certificate chains to test for flaws in the program logic for handling certificate flaws.

  [Brubaker et al, Using Frankencerts for Automated Adversarial Testing of Certificate Validation in SSL/TLS Implementations, Oakland 2014]

- Code coverage requirements on the test suite would also have helped.

Fuzzing

Fuzzing

- Fuzzing aka fuzz testing is a highly effective, largely automated, security testing technique
- Basic idea: (semi) automatically generate random inputs and see if an application crashes
  - So we are NOT testing functional correctness (compliance)
- The original form of fuzzing: generate very long inputs and see if the system crashes with a segmentation fault.
  - *What kind of bug would such a segfault signal?*
    - A buffer overflow problem
  - *Why would inputs ideally be very long?*
    - To make it likely that buffer overruns cross segment boundaries, so that the OS triggers a fault

Simple fuzzing ideas

What inputs would you use for fuzzing?

- very long or completely blank strings
- min/max values of integers, or simply zero and negative values
- depending on what you are fuzzing, include special values, characters or keywords likely to trigger bugs, eg
  - nulls, newlines, or end-of-file characters
  - format string characters `%s %x %n`
  - semi-colons, slashes and backslashes, quotes
  - application specific keywords `halt, DROP TABLES, ...`
  - ....

Pros & cons of fuzzing

Pros

- Very little effort:
  - the test cases are automatically generated, and test oracle is simply looking for crashes
- Fuzzing of a C/C++ binary can quickly give a good picture of robustness of the code

Cons

- Will not find all bugs
- Crashes may be hard to analyse; but a crash is a clear *true positive* that something is wrong!
- For programs that take complex inputs, more work will be needed to get good code coverage, and hit interesting test cases. This has lead to lots of work on 'smarter' fuzzers.

Improved crash/error detection

Making systems crash on errors is useful for fuzzing!

So when fuzzing C(++) code, the memory safety checks listed in the SoK paper (discussed in week 2/3) can be deployed to make systems more likely to crash when memory corruption happens

- **Ideally checks both for spatial buffer overruns & for temporal malloc/free bugs, eg using tools like `valgrind`, `MemCheck`, and `AddressSanitizer`**

Types of fuzzers

1) Mutation-based: apply random mutations to set of valid inputs
   - Eg observe network traffic, than replay with some modifications
   - More likely to produce interesting invalid inputs than just random input
2) Generation-based aka grammar-based: generate semi-well-formed inputs from scratch, based on knowledge of file format or protocol
   - Tailor-made fuzzer fo specific input format, or generic fuzzer configured with a grammar
   - Downside: more work to construct the fuzzer
3) Evolutionary: observe how inputs are processed to learn which mutations are interesting
   - For example, afl, which uses a greybox approach
4) Whitebox approaches: analyse source code to construct inputs
   - For example, SAGE

Example mutational fuzzing

Example: Fuzzing OCPP [research internship Ivar Derksen]

- OCPP is a protocol for charge points to talk to a back-end server
- OCPP can use XML or JSN messages

Example message in JSN format

```
{ "location": NijmegenMercator215672,
  "retries": 5,
  "retryInterval": 30,
  "startTime": "2018-10-27T19:10:11",
  "stopTime":  "2018-10-27T22:10:11"  }
```

Example: Fuzzing OCPP

Simple classification of messages into

1. malformed JSN/XML
   (eg missing quote, bracket or comma)
2. well-formed JSN/XML, but not legal OCPP
   (eg using field names that are not in the OCPP specs)
3. well-formed OCPP

can be used for a simple test oracle:

- Malformed messages (type 1 & 2) should generate generic error response
- Well-formed messages (type 3) should not
- The application should never crash

Note: this does not require any understanding of the protocol semantics yet!
Figuring out correct responses to type 3 would.

Test results with fuzzing OCPP server

- Mutation fuzzer generated 26,400 variants from 22 example OCPP messages in JSN format
- Problems spotted by this simple test oracle:
  - 945 malformed JSN requests (type 1) resulted in malformed JSN response

    Server should never emit malformed JSN!
  - 75 malformed JSN requests (type 1) and 40 malformed OCPP requests (type 2) result in a valid OCPP response that is not an error message.

    Server should not process malformed requests!
- One root cause of problems: the Google's `gson` library for parsing JSN by default uses lenient mode rather than strict mode
  - Why does `gson` even have a lenient mode, let alone by default?
- Fortunately, `gson` is written in Java, not C(++), so these flaws do not result in exploitable buffer overflows

Generational fuzzing
aka
Grammar-based fuzzing

CVEs as inspiration for fuzzing file formats

- **Microsoft Security Bulletin MS04-028**
  Buffer Overrun in JPEG Processing (GDI+) Could Allow Code Execution
  Impact of Vulnerability: Remote Code Execution
  Maximum Severity Rating: Critical
  Recommendation: Customers should apply the update immediately

  Root cause: a zero sized comment field, without content.

- **CVE-2007-0243**
  Sun Java JRE GIF Image Processing Buffer Overflow Vulnerability
  Critical: Highly critical Impact: System access Where: From remote

  Description: A vulnerability has been reported in Sun Java Runtime Environment (JRE). … The vulnerability is caused due to an error when processing GIF images and can be exploited to cause a heap-based buffer overflow via a specially crafted GIF image with an image width of 0. Successful exploitation allows execution of arbitrary code.

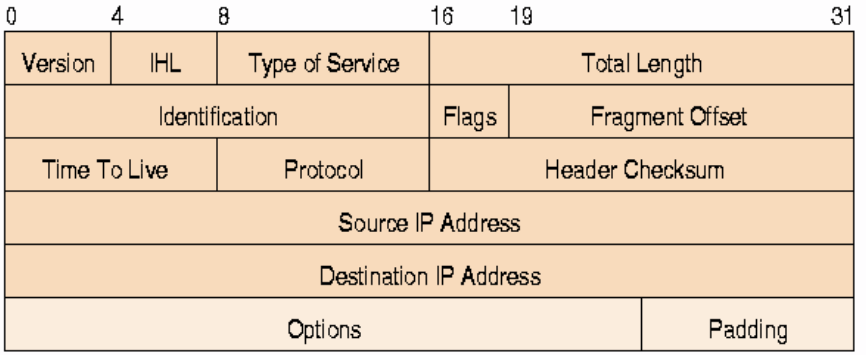
  Note: a buffer overflow in (native library of) a memory-safe language

Generation-based fuzzing

For a given file format or communication protocol, a generational fuzzer tries to generate files or data packets that are slightly malformed or hit corner cases in the spec.

Possible starting :

grammar defining legal inputs,
or a data format specification



Typical things to fuzz:

- many/all possible value for specific fields
  esp undefined values, or values Reserved for Future Use (RFU)
- incorrect lengths, lengths that are zero, or payloads that are too short/long

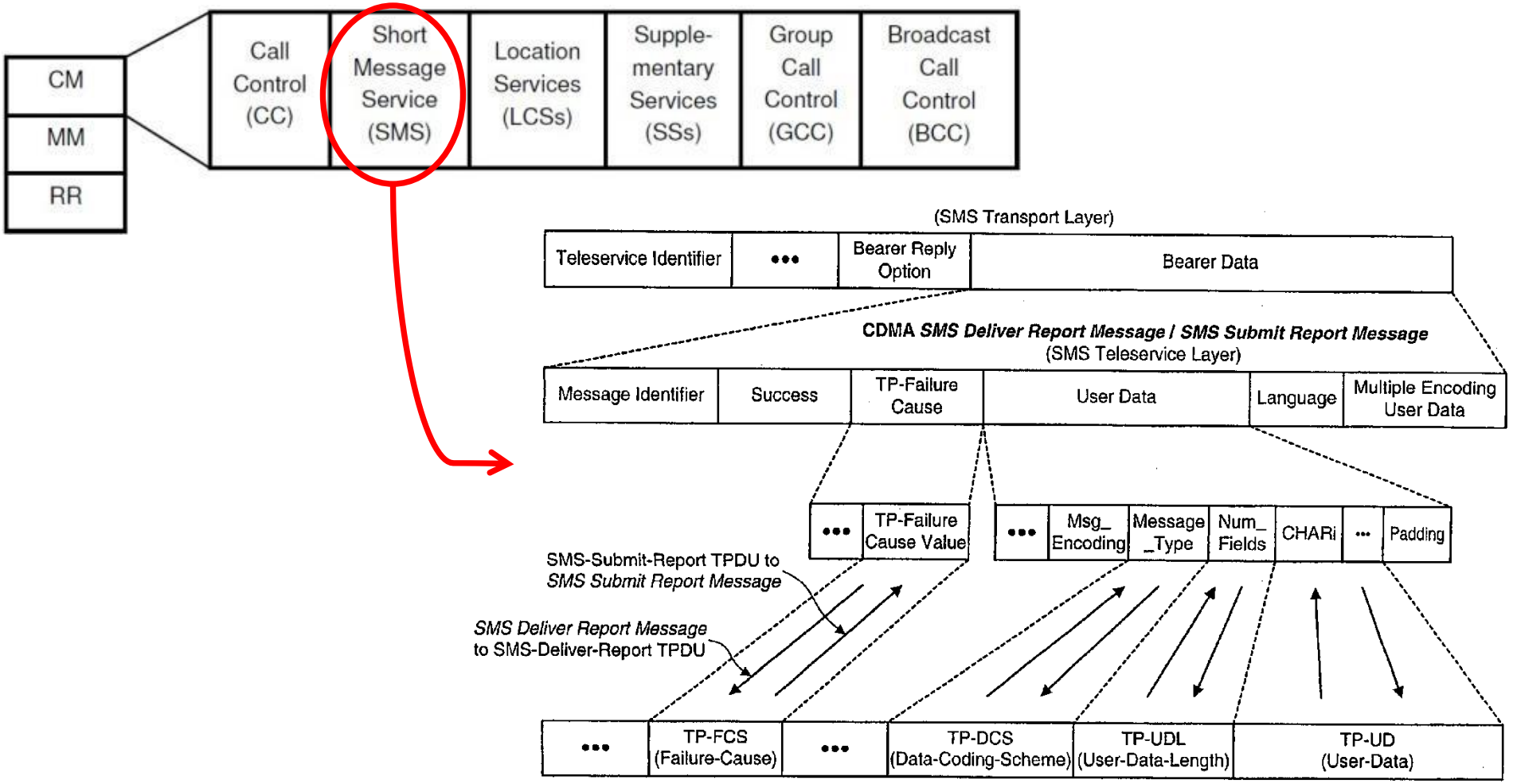
Tools for building such fuzzers:

SNOOZE, SPIKE, Peach, Sulley, antiparser, Netzob, ...

Example : generation based fuzzing of GSM

[MSc theses of Brinio Hond and Arturo Cedillo Torres]

GSM is a extremely rich & complicated protocol



SMS message fields

Field	size
Message Type Indicator	2 bit
Reject Duplicates	1 bit
Validity Period Format	2 bit
User Data Header Indicator	1 bit
Reply Path	1 bit
Message Reference	integer
Destination Address	2-12 byte
Protocol Identifier	1 byte
Data Coding Scheme (CDS)	1 byte
Validity Period	1 byte/7 bytes
User Data Length (UDL)	integer
User Data	depends on CDS and UDL

Example: GSM protocol fuzzing

Lots of stuff to fuzz!

We can use a USRP

with open source cell tower software (OpenBTS)

to fuzz any phone

Example: GSM protocol fuzzing

Fuzzing SMS layer of GSM reveals weird functionality in GSM standard and in phones

Example: GSM protocol fuzzing

Fuzzing SMS layer of GSM reveals weird functionality in GSM standard and in phones

- **eg possibility to receive faxes (!?)**

Only way to get rid if this icon; reboot the phone

Example: GSM protocol fuzzing

Malformed SMS text messages showing raw memory contents, rather than content of the text message

(a) Showing garbage

(b) Showing the name of a wallpaper and two games

Our results with GSM fuzzing

- Lots of success to DoS phones: phones crash, disconnect from the network, or stop accepting calls
  - eg requiring reboot or battery removal to restart, to accept calls again, or to remove weird icons
  - after reboot, the network might redeliver the SMS message, if no acknowledgement was sent before crashing, re-crashing phone

  But: not all these SMS messages could be sent over real network
- There is surprisingly little correlation between problems and phone brands & firmware versions
  - how many implementations of the GSM stack did Nokia have?
- *The scary part: what would happen if we fuzz base stations?*

[Fabian van den Broek, Brinio Hond and Arturo Cedillo Torres, Security Testing of GSM Implementations, Essos 2014]

[Mulliner et al., SMS of Death, USENIX 2011]

Security problem with more complex input formats

effective.

Power

لُلصّبُلُللصّبُررً ◌ّ ◌ّh ◌ّ ◌ّ

卐

Example dangerous SMS text message

- **This message can be sent over the network**
- **Different characters sets or characters encoding, are a constant source of problems. Many input formats rely on underlying notion of characters.**

Example: Fuzzing fonts

Google's Project Zero found many Windows kernel vulnerabilities by fuzzing fonts in the Windows kernel

Tracker ID	Memory access type at crash	Crashing function	CVE
1022	Invalid write of *n* bytes (memcpy)	`usp10!otlList::insertAt`	CVE-2017-0108
1023	Invalid read / write of 2 bytes	`usp10!AssignGlyphTypes`	CVE-2017-0084
1025	Invalid write of *n* bytes (memset)	`usp10!otlCacheManager::GlyphsSubstituted`	CVE-2017-0086
1026	Invalid write of *n* bytes (memcpy)	`usp10!MergeLigRecords`	CVE-2017-0087
1027	Invalid write of 2 bytes	`usp10!ttoGetTableData`	CVE-2017-0088
1028	Invalid write of 2 bytes	`usp10!UpdateGlyphFlags`	CVE-2017-0089
1029	Invalid write of *n* bytes	`usp10!BuildFSM` and nearby functions	CVE-2017-0090
1030	Invalid write of *n* bytes	`usp10!FillAlternatesList`	CVE-2017-0072

https://googleprojectzero.blogspot.com/2017/04/notes-on-windows-uniscribe-fuzzing.html

Even handling simple input languages can go wrong!

Sending an extended length APDU can crash a contactless payment terminal.

APDU Response		
Body	Trailer	
Data Field	SW1	SW2

- **Found without even trying to fuzz, but by sending allowed (albeit non-standard) messages**

[Jordi van den Breekel, A security evaluation and proof-of-concept relay attack on Dutch EMV contactless transactions, MSc thesis, 2014]

Whitebox fuzzing with SAGE

Whitebox fuzzing using symbolic execution

- The central problem with fuzzing:
  how can we generate inputs that trigger interesting code executions?
  - Eg fuzzing the procedure below is unlikely to hit the error case

```
int foo(int x) {
    y = x+3;
    if (y==13) abort(); // error
}
```

- The idea behind whitebox fuzzing: if we know the code, then by analysing the code we can find interesting input values to try.
- SAGE (Scalable Automated Guided Execution) is a tool from Microsoft Research that uses symbolic execution of x86 binaries to generate test cases.

```
m(int x,y){
    x = x + y;
    y = y - x;
    if (2*y > 8) { ...
                 }
    else if (3*x < 10){ ...
                       }
    }
```

Can you provide values for `x` and `y` that will trigger execution of the two if-branches?

Symbolic execution

```
m(int x,y){
    x = x + y;
    y = y – x;
    if (2*y > 8) { ...
                 }
    else if (3*x < 10){ ...
    }                   }
```

Suppose `x` *= N and* `y` *= M.*

`x` *becomes N+M*

`y` *becomes M-(N+M) = -N*

if-branch taken if -2N > 8, i.e. N < -4

Aka the path condition

2nd if-branch taken if
N ≥ -4 & 3(M+N) < 10

We can use SMT solver (Yikes, Z3, …) aka constraint solver for this: given a set of constraints such a tool produces test data that meets them, or proves that they are not satisfiable.

This generates test data (i) *automatically* and (ii) *with good coverage*

- **These tools can also be used in static analyses as in PREfast, or more generally, for program verification**

Symbolic execution for test generation

- Symbolic execution can be used to automatically generate test cases with good coverage
- Basic idea of symbolic execution:
  instead of giving variables concrete values (say 42), variables are given symbolic values (say α), and program is executed with these symbolic values to see when certain program points are reached
- Downside of symbolic execution:
  - it is very expensive (in time & space)
  - things explode with loops
  - …

  SAGE mitigates this by using a *single* symbolic execution to generate many test inputs for *many* execution paths

SAGE example

Example program

```
void top(char input[4]) {
        int cnt = 0;
        if (input[0] == 'b') cnt++;
        if (input[1] == 'a') cnt++;
        if (input[2] == 'd') cnt++;
        if (input[3] == '!') cnt++;
        if (cnt >= 3) crash();
    }
```

What would be interesting test cases? How could you find them?

SAGE example

Example program

```
void top(char input[4]) {
    int cnt = 0;
    if (input[0] == 'b') cnt++;
    if (input[1] == 'a') cnt++;
    if (input[2] == 'd') cnt++;
    if (input[3] == '!') cnt++;
    if (cnt >= 3) crash();
}
```

path contraints:

$i_0 \neq$ 'b'

$i_1 \neq$ 'a'

$i_2 \neq$ 'd'

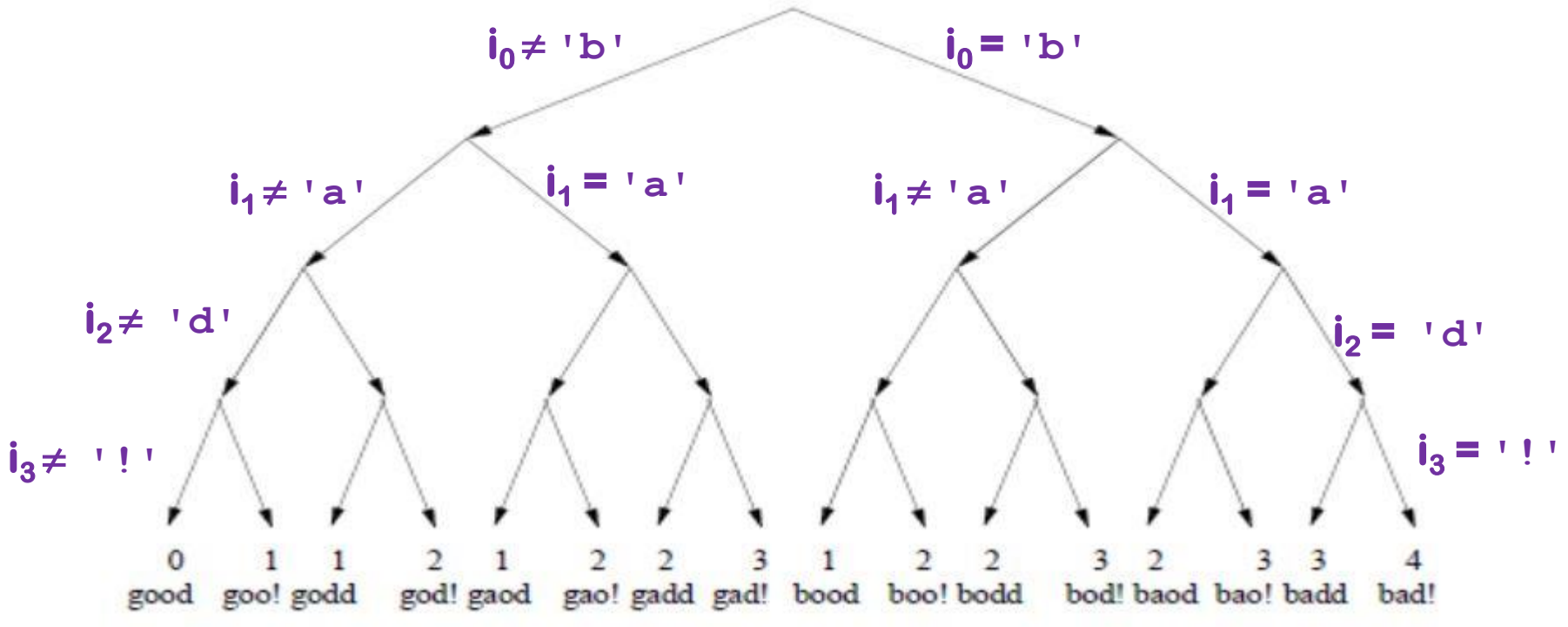
$i_3 \neq$ '!'

SAGE executes the code for some concrete `input`, say `'good'`

It then collects *path constraints* for an arbitrary symbolic input of the form $i_0 i_1 i_2 i_3$

Search space for interesting inputs

Based on this one execution, combining all these constraints now yields 16 test cases



Note: the initial execution with the input 'good' was not very interesting, but these others are

SAGE success

- SAGE proved successful at uncovering security bugs, eg

  Microsoft Security Bulletin MS07-017 aka CVE-2007-0038: Critical

  Vulnerabilities in GDI Could Allow Remote Code Execution

  Stack-based buffer overflow in the animated cursor code in Microsoft Windows 2000 SP4 through Vista allows remote attackers to execute arbitrary code or cause a denial of service (persistent reboot) via a large length value in the second (or later) `anih` block of a RIFF .ANI, cur, or .ico file, which results in memory corruption when processing cursors, animated cursors, and icons

  Security vulnerablity in parsing ANI/cur/ico-formats. SAGE generated (semi)well-formed input triggering the bug without knowing these formats

- First experiments with SAGE also found bugs in handling a compressed file format, media file formats, and generated 43 test cases to crash Office 2007

Evolutionary Fuzzing with `afl`

`(American Fuzzy Lop)`

Evolutionary Fuzzing with `afl`

- Downside of generation-based fuzzing:
  - lots of work work to write code to do the fuzzing, even if you use tools to generate this code based on some grammar
- Downside of mutation-based fuzzer:
  - chance that random changes in inputs hits interesting cases is small
- `afl` (American Fuzzy Lop) takes an *evolutionary* approach to learn interesting mutations based on measuring *code coverage*
  - basic idea: if a mutation of the input triggers a new execution path through the code, then it is an interesting mutation & it is kept; if not, the mutation is discarded.
  - by trying random mutations of the input and observering their effect on code coverage, `afl` can learn what interesting inputs are

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

- Supports programs written in C/C++/Objective C and variants for Python/Go/Rust/OCaml
- Code instrumented to observe execution paths:
  - if source code is available, by using modified compiler
  - if source code is not available, by running code in an emulator
- Code coverage represented as a 64KB bitmap, where control flow jumps are mapped to changes in this bitmap
  - different executions could result in same bitmap, but chance is small
- Mutation strategies include: bit flips, incrementing/decrementing integers, using pre-defined interesting integer values (eg. 0, -1, MAX_INT,....), deleting/combining/zeroing input blocks, ...
- The fuzzer forks the SUT to speed up the fuzzing
- Big win: no need to specify the input format!

afl's instrumentation of compiled code

Code is injected at every branch point in the code

```
cur_location = <COMPILE_TIME_RANDOM_FOR_THIS_CODE_BLOCK>;

shared_mem[cur_location ^ prev_location]++;

prev_location = cur_location >> 1;
```

where `shared_mem` is a 64 KB memory region

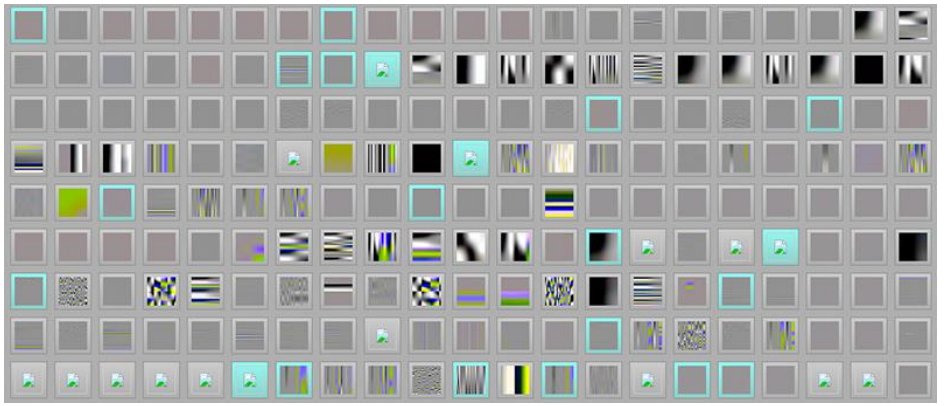
Intuition: for every jump from `src` to `dest` in the code a different byte in `shared_mem` is changed.

This byte is determined by the compile time randoms inserted at source and destination.

Cool example: learning the JPG file format

- Fuzzing a program that expects a JPG as input, starting with 'hello world' as initial test input, afl can learn to produce legal JPG files
  - along the way producing/discovering error messages such as
    - `Not a JPEG file: starts with 0x68 0x65`
    - `Not a JPEG file: starts with 0xff 0x65`
    - `Premature end of JPEG file`
    - `Invalid JPEG file structure: two SOI markers`
    - `Quantization table 0x0e was not defined`

and then JPGs like



[Source http://lcamtuf.blogspot.nl/2014/11/pulling-jpegs-out-of-thin-air.html]

Vulnerabilities found with `afl`

IJG jpeg [1]
libtiff [1] [2] [3] [4] [5]
Mozilla Firefox [1] [2] [3] [4]
Adobe Flash / PCRE [1] [2] [3] [4]
LibreOffice [1] [2] [3] [4]
GnuTLS [1]
PuTTY [1] [2]
bash (post-Shellshock) [1] [2]
pdfium [1] [2]
BIND [1] [2] [3] ...
Oracle BerkeleyDB [1] [2]
FLAC audio library [1] [2]
strings (+ related tools) [1] [2] [3] [4] [5] [6] [7]
Info-Zip unzip [1] [2]
NetBSD bpf [1]
clang / llvm [1] [2] [3] [4] [5] [6] [7] [8] ...
mutt [1]
pdksh [1] [2]
redis / lua-cmsgpack [1]
perl [1] [2] [3] [4] [5] [6] [7...]
SleuthKit [1]
exifprobe [1]
Xerces-C [1] [2] [3]

libjpeg-turbo [1] [2]
mozjpeg [1]
Internet Explorer [1] [2] [3] [4]
sqlite [1] [2] [3] [4...]
poppler [1]
GnuPG [1] [2] [3] [4]
ntpd [1] [2]
tcpdump [1] [2] [3] [4] [5] [6] [7] [8] [9]
ffmpeg [1] [2] [3] [4] [5]
QEMU [1] [2]
Android / libstagefright [1] [2]
libsndfile [1] [2] [3] [4]
file [1] [2] [3] [4]
libtasn1 [1] [2] ...
man & mandoc [1] [2] [3] [4] [5] ...
nasm [1] [2]
procmail [1]
Qt [1] [2...]
taglib [1] [2] [3]
libxmp
fwknop [reported by author]
jhead [?]
metacam [1]

libpng [1]
PHP [1] [2] [3] [4] [5]
Apple Safari [1]
OpenSSL [1] [2] [3] [4] [5] [6] [7]
freetype [1] [2]
OpenSSH [1] [2] [3]
nginx [1] [2] [3]
JavaScriptCore [1] [2] [3] [4]
libmatroska [1]
lcms [1]
iOS / ImageIO [1]
less / lesspipe [1] [2] [3]
dpkg [1] [2]
OpenBSD pfctl [1]
IDA Pro [reported by authors]
ctags [1]
fontconfig [1]
wavpack [1]
privoxy [1] [2] [3]
radare2 [1] [2]
X.Org [1] [2]
capnproto [1]
djvulibre [1]

Moral of the story

- If you ever produce code that handles some non-trivial input format, run a tool like `afl` to look for bugs

Conclusions

- Fuzzing is great technique to find (a certain kind of) security flaws!
- If you ever write or deploy C(++) code, you should fuzz it.
- The bottleneck: how to do smart fuzzing without too much effort

  Successful approaches include

  - White-box fuzzing based on symbolic execution with SAGE
  - Evolutionary mutation-based fuzzing with `afl`
- A newer generation of tools not only tries to find security flaws, but also to then build exploits for them, eg. `angr`

To read (see links on the course page)

- David Wheeler, The Apple goto fail vulnerability: lessons learned
- Patrice Godefroid et al., SAGE: whitebox fuzzing for security testing, ACM Queue