Software Security

Security Testing

especially

Fuzzing

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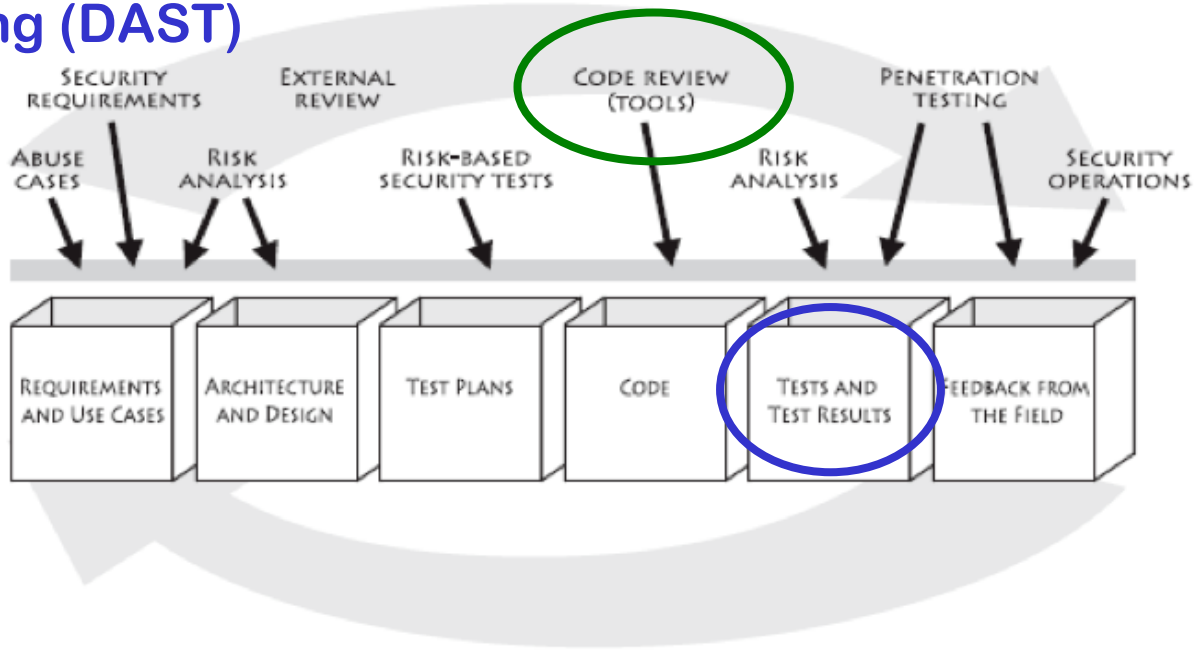
Security in the SDLC

Last week: static analysis aka code review tools (SAST)

This week: security testing (DAST)



Security testing can be used to find many kinds of security flaws.

Focus of this lecture – and group assignment – is on 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 for additional checks on memory safety (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. 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
  - *How many of you are taking Jan Tretmans Testing Techniques course?*

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); }
}
```

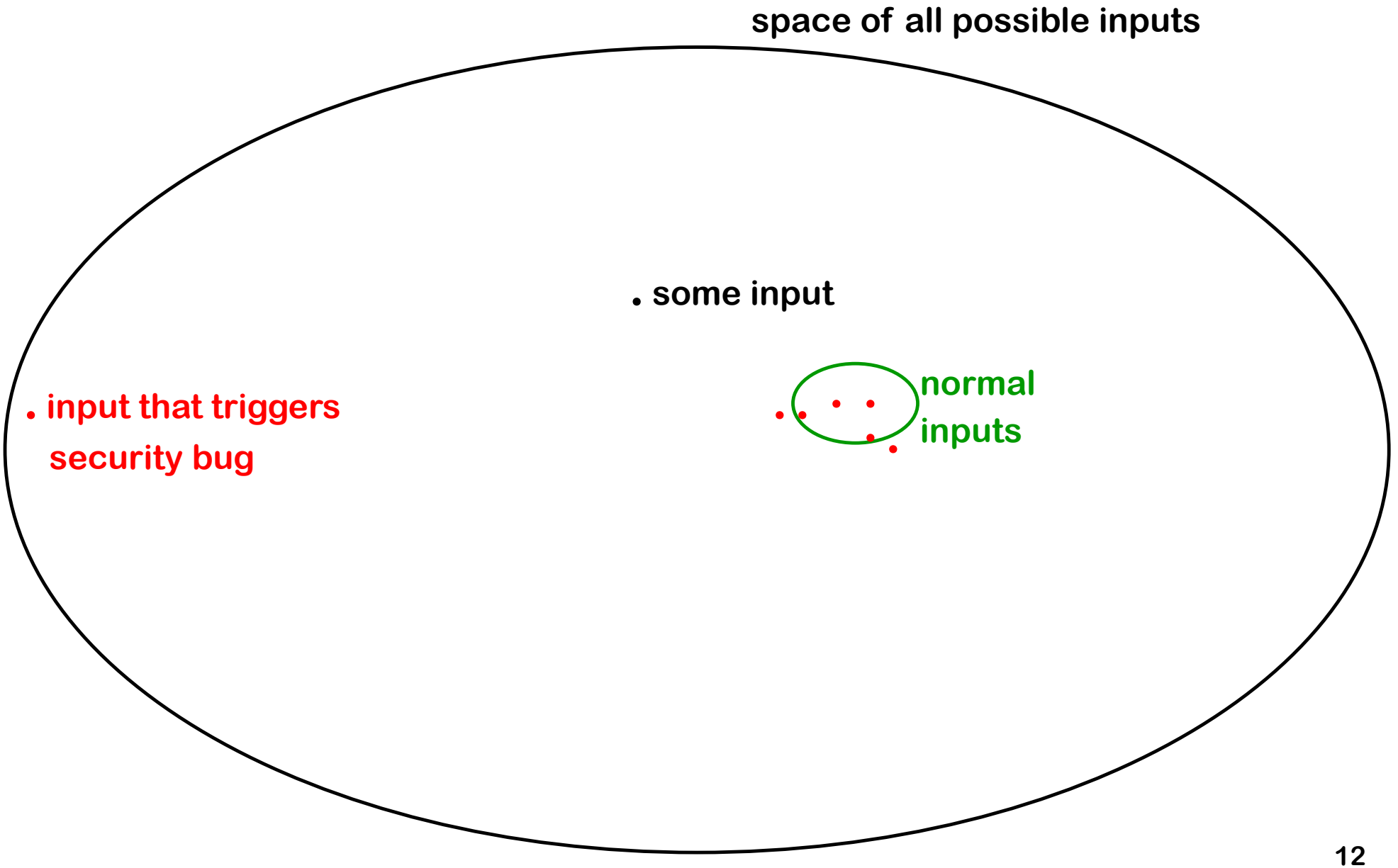
If the green defensive code, ie. the if- & catch-branches, is hard to trigger in test, programmers may be tempted (or forced?) to remove this code to improve test coverage...

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

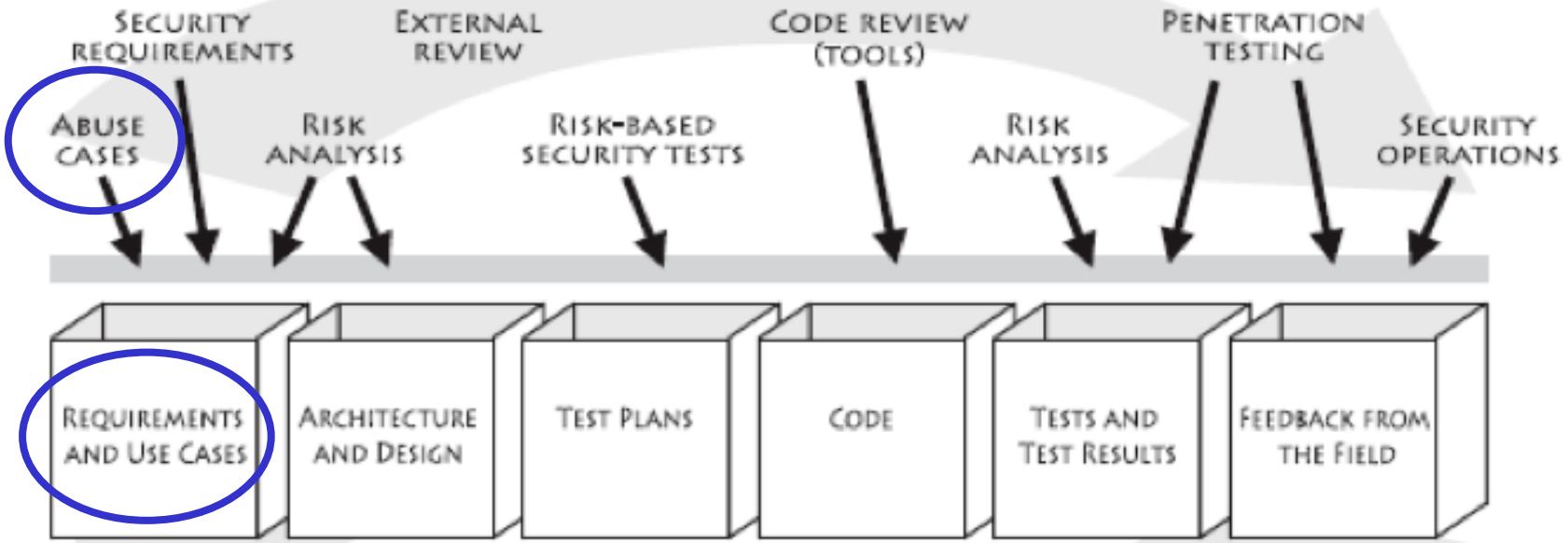
- Thinking about abuse cases is a useful way to come up with security tests
  - *what would an attacker try to do?*
  - *where could an implementation slip up?*

- This gives rise to negative test cases,

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

  as opposed to positive test cases, which are meant to succeed

Abuse cases – early in the SDCL



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 checking certificates.

  [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

The idea

Suppose some C(++) binary asks from some input

```
Please enter your username
>
```

What would you try?

1. ridiculous long input, say a few MB

   If there is a buffer overflow, a long input is likely to trigger a SEG FAULT

2. %x%x%x%x%x%x%x%x%x%x

   To see if there is a format string vulnerability

3. Other malicious inputs, depending on back-ends, technologies or APIs used : eg SQL, XML, …

   Out of scope for the project assignment

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.

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
  - For programs that take complex inputs, more work will be needed to get good code coverage, and hit interesting test cases. This has led to lots of work on 'smarter' fuzzers.
- Crashes may be hard to analyse; but a crash is a clear *true positive* that something is wrong!
  - unlike a complaint from a static analysis tool like PREfast

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 crash in the event of memory corruptions more likely

- eg using tools like
  - `valgrind`
  - `MemCheck`
  - `AddressSanitizer (Asan)`
- Ideally for both spatial bugs (buffer overruns)

  & temporal bugs (malloc/free bugs)

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 aka model-based: generate semi-well-formed inputs from scratch, based on knowledge of file format or protocol
   - with tailor-made fuzzer for a specific input format, or a generic fuzzer configured with a grammar
   - *Downside?*

     more work to construct this fuzzer or grammar
3) Evolutionary: observe execution to try 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 JSON messages

Example message in JSON 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

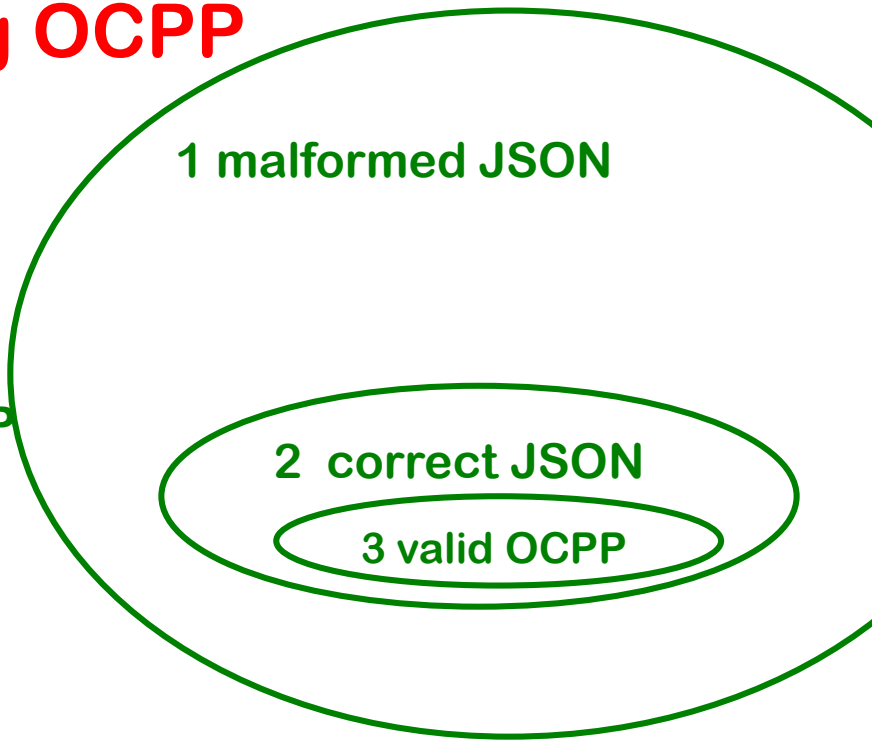
1. malformed JSON/XML

   (eg missing quote, bracket or comma)

2. well-formed JSON/XML, but not legal OCPP

   (eg with field names not in 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 JSON format
- Problems spotted by this simple test oracle:
  - 945 malformed JSON requests (type 1) resulted in malformed JSON response

    Server should never emit malformed JSN!
  - 75 malformed JSON 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 JSON 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

Postel's Law aka Robustness Principle

"Be conservative in what you send,

be liberal in what you accept"

Named after Jon Postel, who wrote early version of TCP spec.

Is this A) good or B) bad?

- Good for getting interoperable implementations up & running ☺
- Bad for security, as lots of these implementations will have non-standard behavior, deviating from the official specs, in corner cases, which may lead to WEIRD BEHAVIOUR and BUGS ☹ ☹

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.

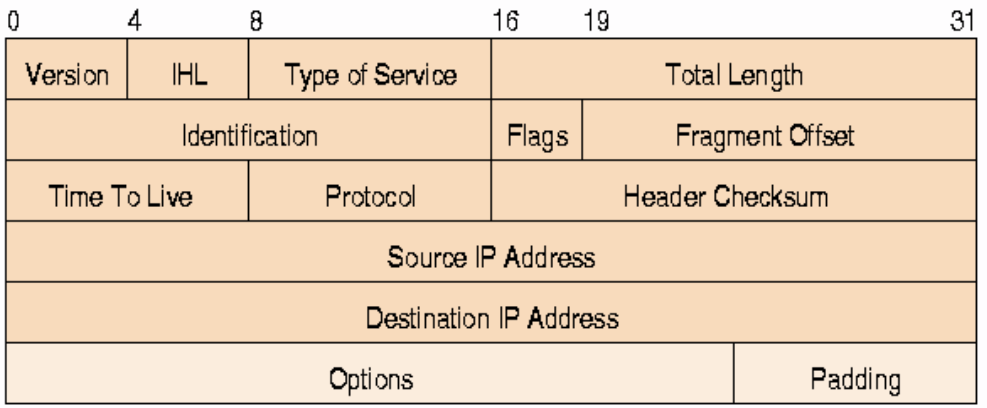
  Note: a buffer overflow in (native library of) a memory-safe language

Generation- aka model-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

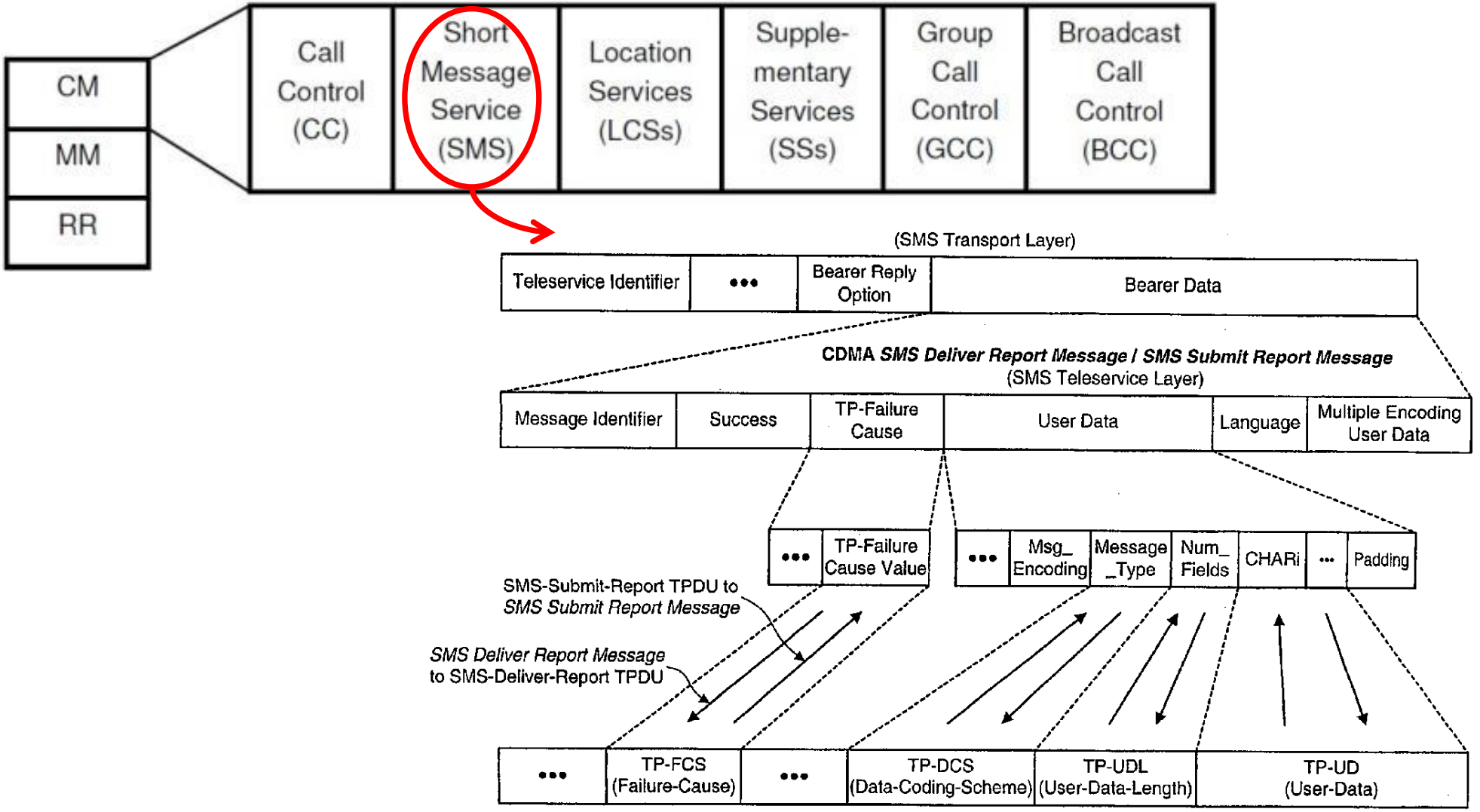
Tools for building such fuzzers:

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

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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 accidentally, without even trying to fuzz,
when sending legal (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]