Software Security

Security Testing

especially

Fuzzing

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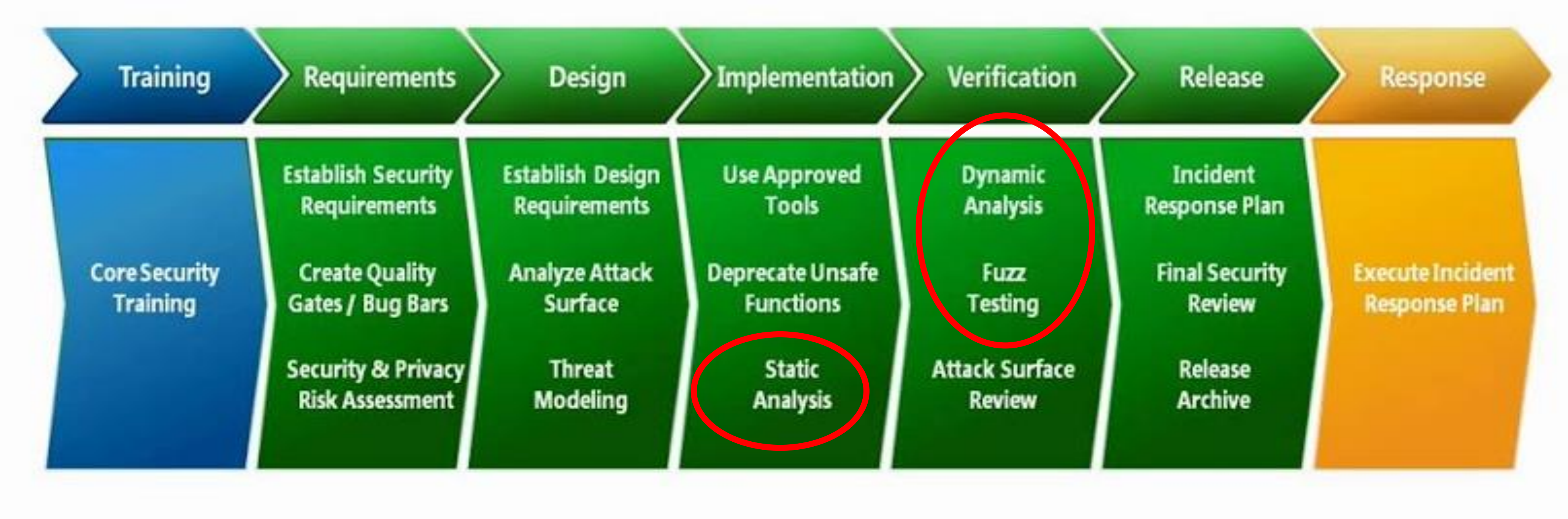
Security in the SDLC

Last week: static analysis/SAST with PREfast

This week: dynamic analysis/DAST esp. fuzzing



Focus of this lecture – and group assignment:
fuzzing aka fuzz testing of C/C++ code for memory corruption

The security testing paradox

- Security testing is ***harder*** than normal, functional testing
  - We have no idea what we are looking for!
    A bizarre input may trigger an obscure bug that is exploitable in some bizarre way, and finding that input with testing is hard
  - Normal users are good testers, as they will complain about functional problems, but they will not complain about many/any security flaws
- Security testing is ***easier*** than normal, functional testing
  - We *can* test for some classes of bugs in partly automated way using fuzzing
  - Fuzzing is the great success story in (software) security in the past decade

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/input format
  - For instance, any graphics library for image manipulation
  - Check on http://lcamtuf.coredump.cx if it has already been fuzzed with afl; if so, you will have to test old release
  - Check that the build process is not too complex given your C/C++ experience
- Try out fuzzing tools (afl++, zuff, HongFuzz, …) to look for security vulnerabilities (esp. memory corruption)
  - with/without instrumentation (ASan, MSan, UBSan, valgrind,…) for additional checks on memory safety
  - Optional variations: 1) investigate bugs; 2) check against known CVEs, 3) introduce bugs; 4) test older releases; 5) try different settings or seed inputs; 6) try other fuzzing tools; …

afl trophy list https://lcamtuf.coredump.cx/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

Fuzzing group project

1. Coming week: pick an application and hand in Brightspace assignment with application & its input format
   - If needed, next we can discuss suitability & feasibility
2. For the rest of Oct & Nov: spend > 4hrs per week to see how far you get & collect results in some report
   - Good to pick one day to work and/or sync on this with your groups
3. We will discuss & compare experiences at the end
   - And maybe along the way

For the fuzzing you can use your university Azure account, Google cloud - and you own computer, of course.

More important than using the ***maximal*** processing power is to use the ***same*** processing power for some experiments to compare tools & options.

Picking project

- Must be an open-source project written in C or C++
- Ideal project has
  - complex input format
  - simple build process
  - is not too mature, so it has not been thoroughly fuzzed before

- If the application has a GUI, fuzzer will have to by-pass the GUI
- Look for evidence of fuzzing in the code repository
- Steer clear of FFmpeg and ImageMagick

Overview

1. Testing basics

2. Abuse cases & negative tests

3. Fuzzing

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 to decide if response is 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 can measure how good a test suite:

- 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

Code coverage metrics can also be used to guide test case generation (as afl does)

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

Annotations as test oracle

- Annotations, eg `assert` statements or SAL annotations code, can be used as test oracle by doing runtime assertion checking
  - So annotations provide a test oracle for free! You can test by sending random data & checking if annotations are violated

- Information flow policies can also be used as test oracles
  - Eg SAL's `Tainted=SA_YES` annotations or nicer policy languages discussed later in this course

But: runtime checking for these require heavy instrumentation of the code, to trace the origin of data *inside* the running application, aka dynamic taint tracking

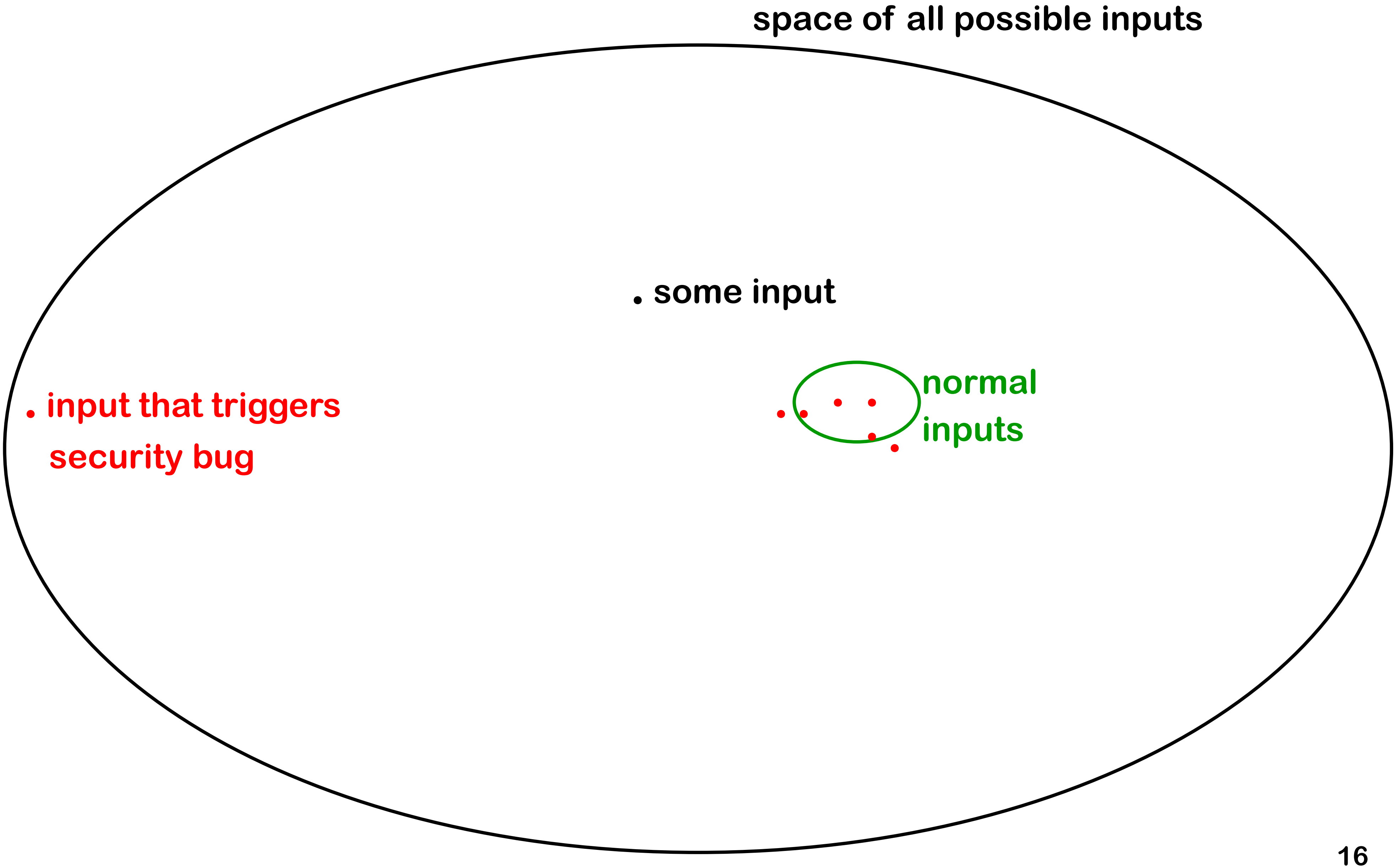
Security testing:
Abuse cases & Negative test cases

testing vs security testing

Difference in focus

- Normal (functional) testing focuses on correct, desired behaviour for sensible inputs (aka the happy flow), but will include some inputs for borderline conditions
- Security testing also – especially – looks for wrong, undesired behaviour for really strange inputs
- Similarly, normal use of a system is more likely to reveal functional problems than security problems

Security testing is HARD



Abuse cases → negative test cases

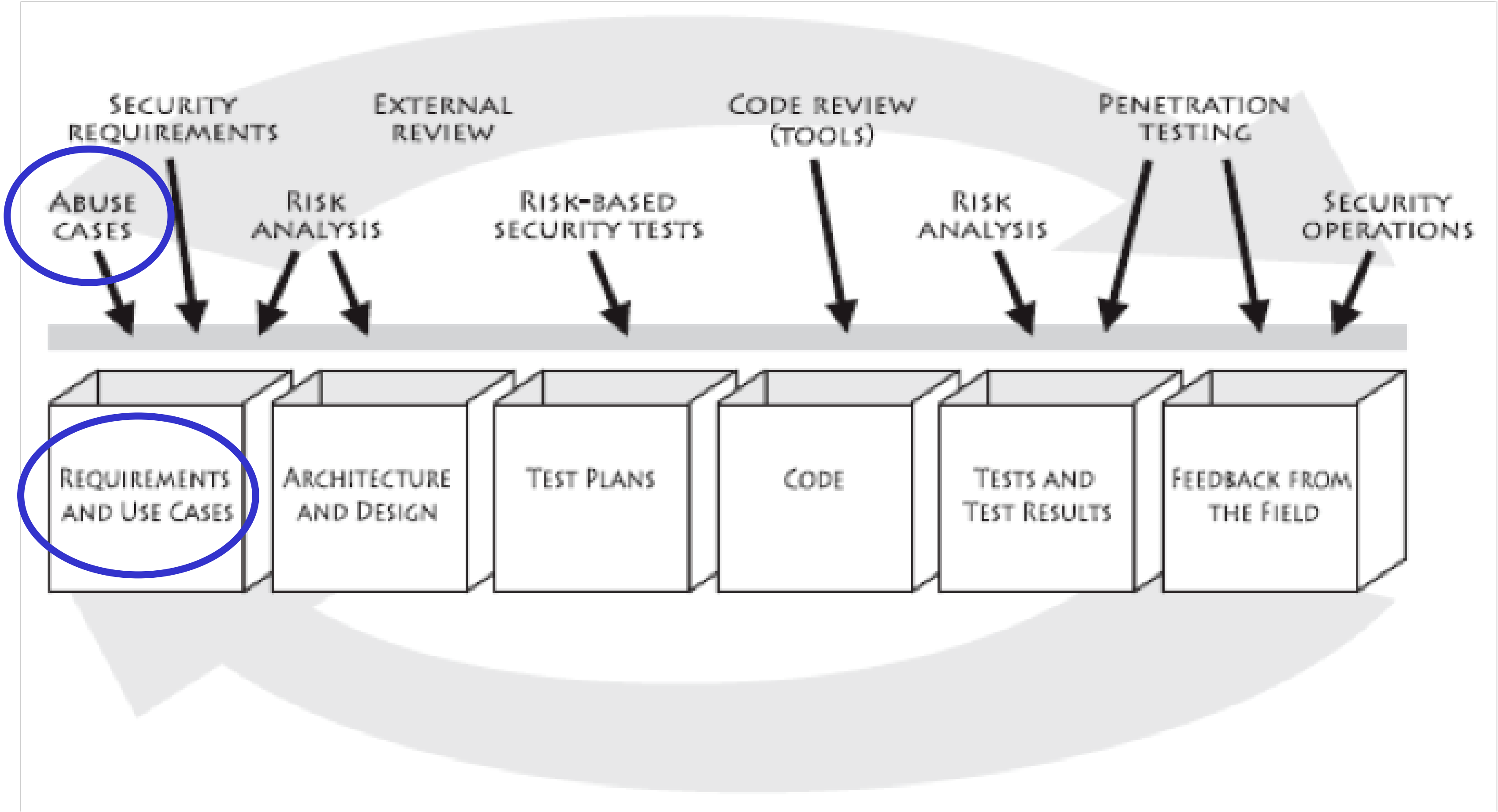
- Thinking about abuse cases is a useful way to come up with security tests
  - *what would an attacker try to do?*
  - *where could an implementation slip up?*

- 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 eg. 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

   To see if there is a format string vulnerability

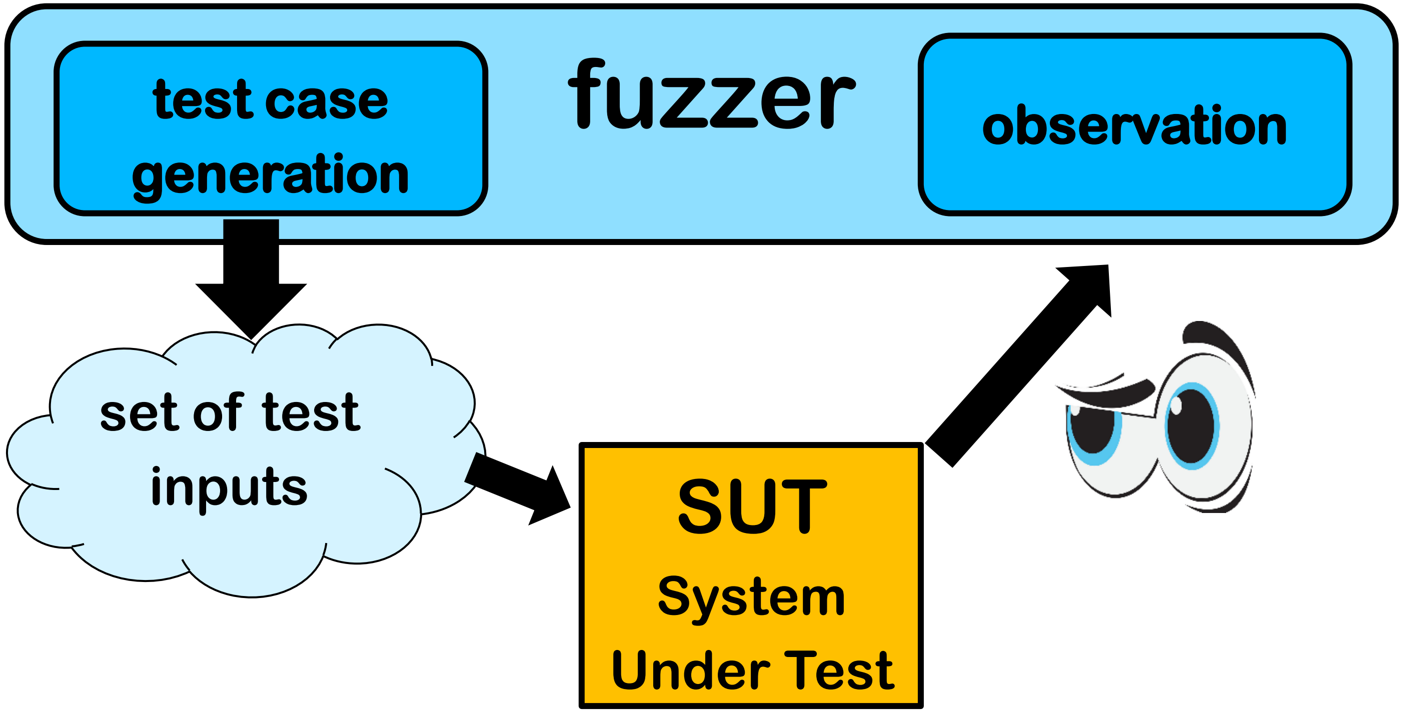
   On the command line, we cannot include a null terminator \0 *in* an input, but in other situations we may be able to

3. Other malicious inputs, depending on back-ends, technologies & APIs used: eg SQL, XML, JSN, Unicode character encodings,…

Fuzzing

(semi) *automatically* generate 'random' inputs and check if an application *crashes* or *misbehaves in observable way*

Great for certain classes of bugs, esp. memory corruption bugs



First tool to use this name: `fuzz` for UNIX

[Miller et al., An empirical study of the reliability of UNIX utilities, CACM 1990]

Fuzzing

1. Basic fuzzing with random/long inputs
2. 'Dumb' mutational fuzzing

   example: OCPP
3. Generational fuzzing aka grammar-based fuzzing

   example: GSM
4. Code-coverage guided evolutionary fuzzing with `afl`

   aka grey box fuzzing or 'smart' mutational fuzzing
5. Whitebox fuzzing with SAGE

   using symbolic execution

Beware: terminology for various forms of fuzzing is messy

The field of fuzzing has been exploding past 10 years!
See http://fuzzing-survey.org for an overview of fuzzing field

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 (aka compliance)

How to fuzz

Depending on input type

- very long inputs, very short inputs, or completely blank input
- min/max values of integers, 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, ...`
  - ....

Good validation and/or sanitisation would catch these problems.

More on this in later lecture on secure input handling.

Pros & cons of fuzzing

Pros

- Very little effort: test cases are automatically generated, and test oracle is trivial
  - Fuzzing of a C/C++ binary quickly gives a good indication of robustness of the code

Cons

- Only finds ‘shallow’ bugs and not ‘deeper’ bugs
  - If a program takes complex inputs or the program is stateful, ‘smarter’ fuzzing is needed to trigger bugs.
- 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, all memory safety checks discussed in previous weeks can be deployed to make crashing in the event of memory corruptions more likely

Tools for this include

- `ASan - AddressSanitizer`
- `MSan – MemorySanitizer`
- `UBSan – UndefinedBehaviorSanitizer`
- `valgrind`
  - `MemCheck`

Ideally checks for both spatial bugs (e.g. buffer overruns)

& temporal bugs (e.g. malloc/free bugs)

Improvements to just trying random and/or long inputs

1) Mutation-based: apply random mutations to 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 description of file format or protocol
   - Either tailor-made fuzzer for a specific input format, eg. FrankenCert, or a generic fuzzer configured with a grammar
   - *Downside?*

     More work to construct this fuzzer or grammar

3) Evolutionary/greybox: observe execution to try to learn which mutations are interesting

   Eg. afl

4) Whitebox approaches: analyse source code to construct inputs

   Eg. SAGE

Example mutational fuzzing

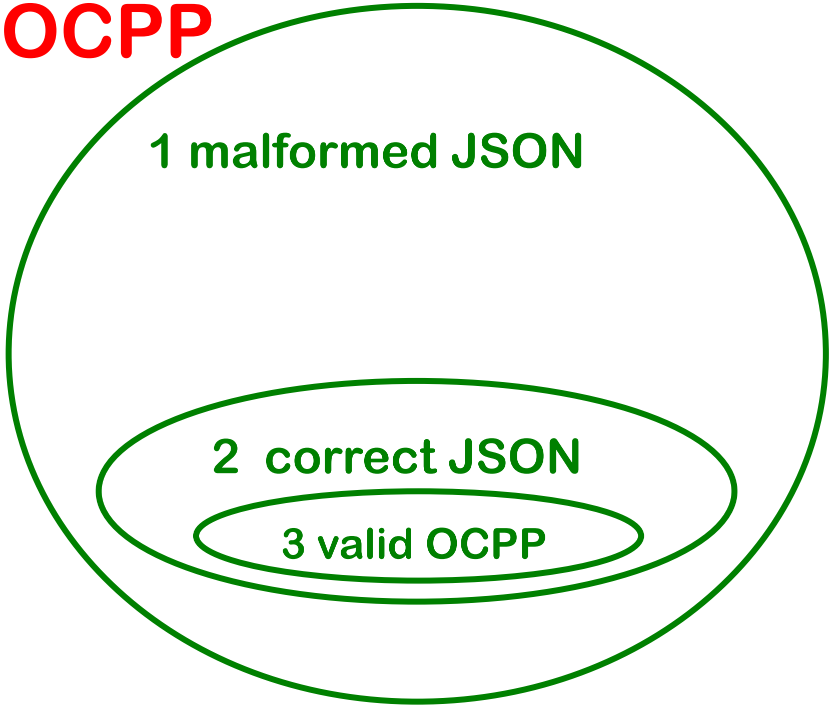
Example: Fuzzing OCPP [research internship Ivar Derksen]

- 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



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:

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

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

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]

Is this good or bad?

- Good for getting interoperable implementations up & running ☺
- Bad for security, as it leads to implementations with 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

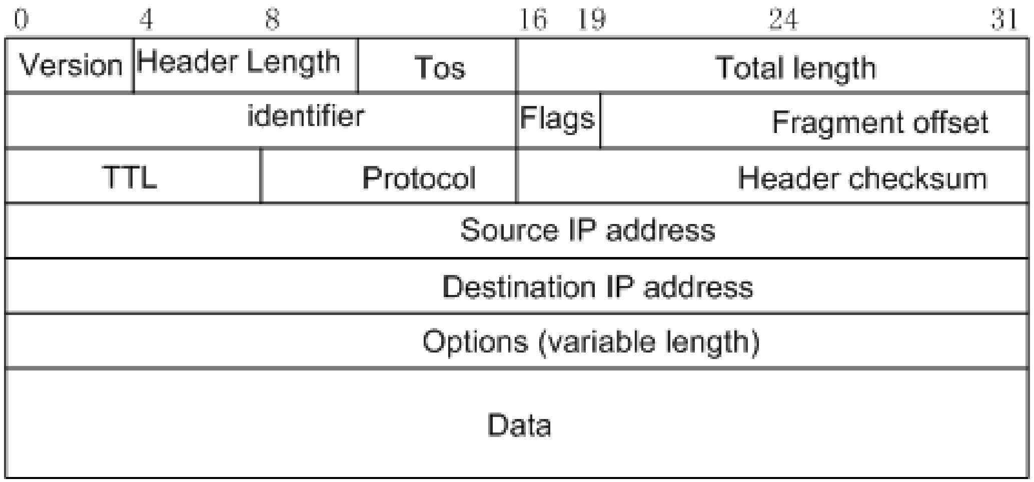
  Description: A vulnerability has been reported in Sun Java Runtime Environment (JRE). … The vulnerability is caused due to an error when processing GIF images and can be exploited to cause a heap-based buffer overflow via a specially crafted GIF image with an image width of 0. Successful exploitation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

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

Generation/grammar/model-based fuzzing

Generate inputs that are malformed or hit corner cases,
based on knowledge of input format/protocol

Eg using
regular expression
context free grammar, or
some other description



Typical things to fuzz:

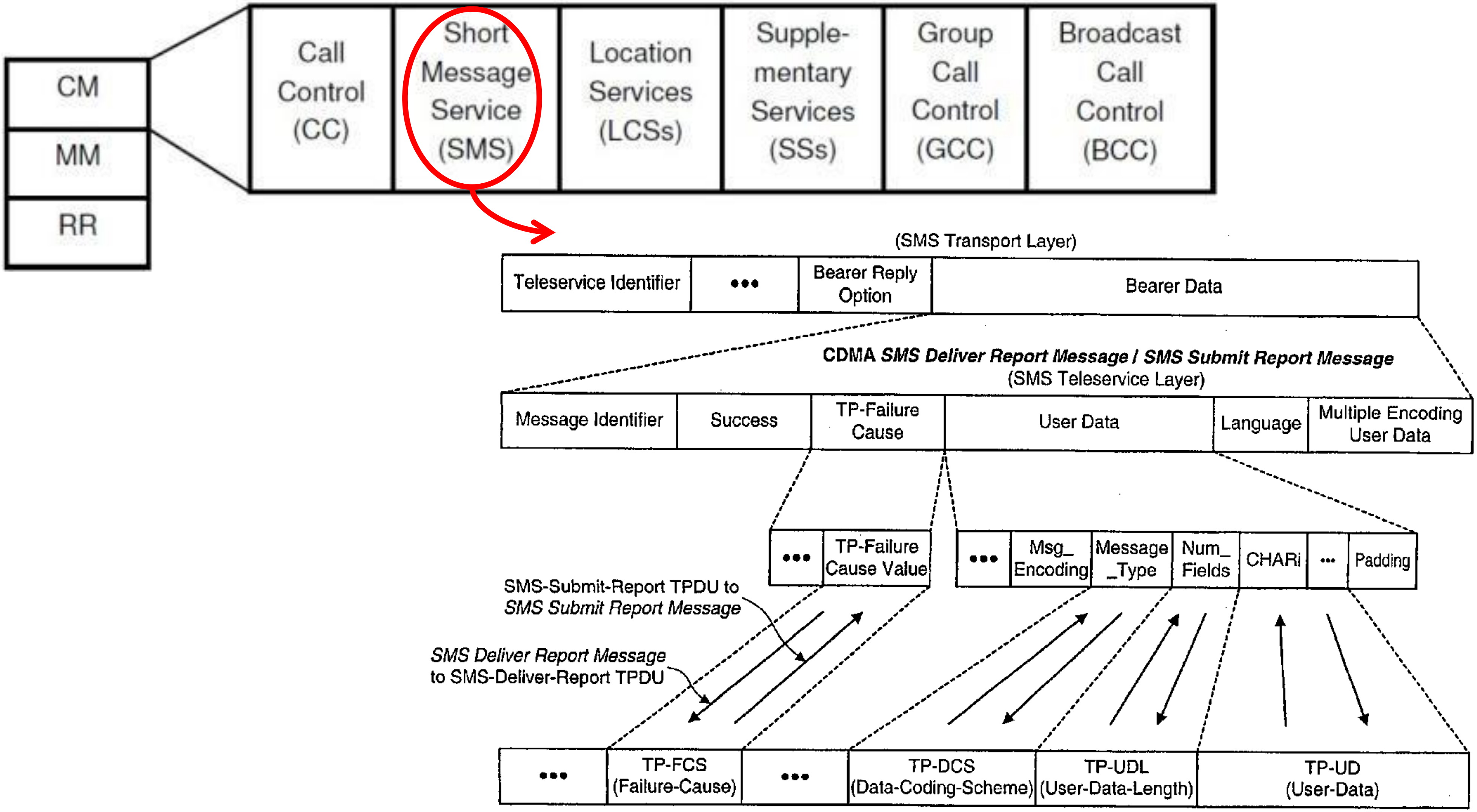
- **many/all possible value for specific fields**
  esp undefined values, or values Reserved for Future Use (RFU)
- **incorrect lengths, lengths that are zero, or payloads that are too short/long**

Fuzzing tools: SNOOZE, SPIKE, Peach, Sulley, antiparser, Netzob, ...

Example: generation based fuzzing of GSM

[Master 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

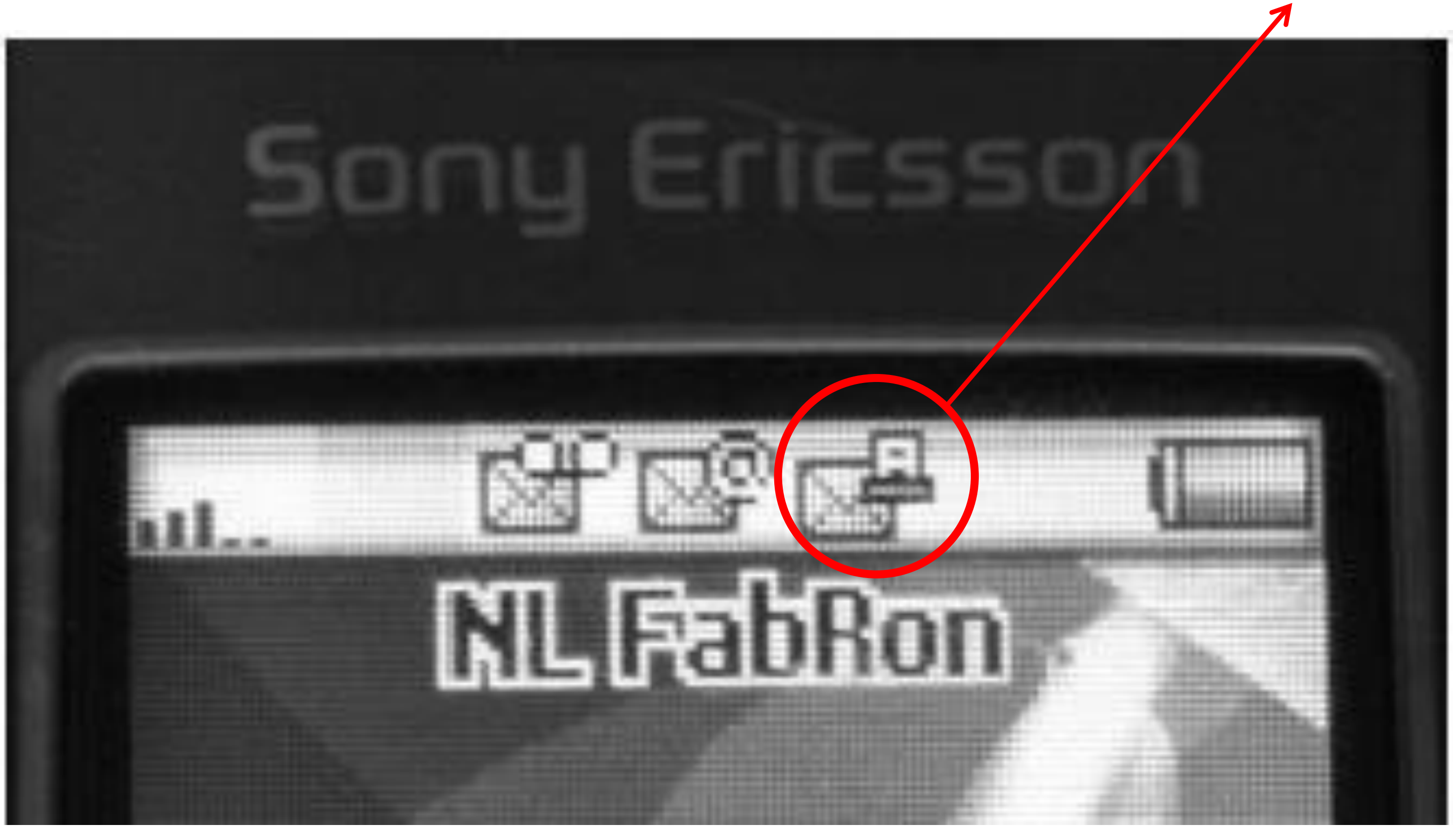
Fuzzing SMS layer of GSM reveals weird functionality in GSM standard and in phones

Example: GSM protocol fuzzing

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

- eg possibility to receive faxes (!?)

you have a fax!

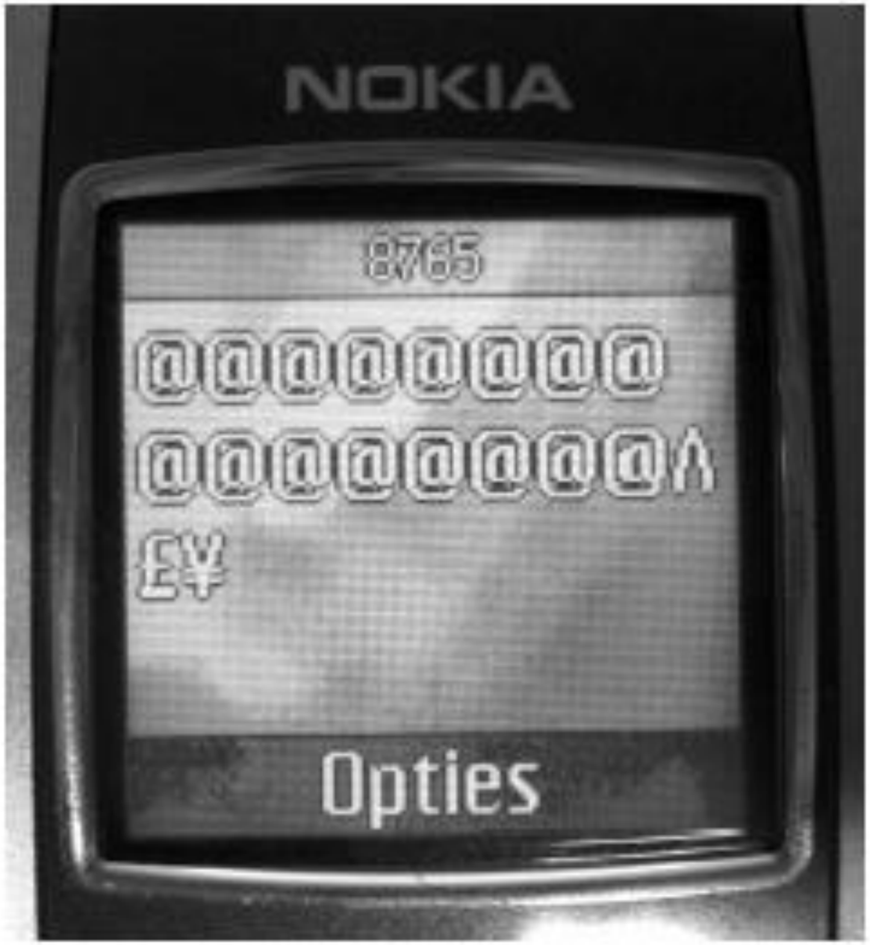


Only way to get rid if this icon; reboot the phone

Example: GSM protocol fuzzing

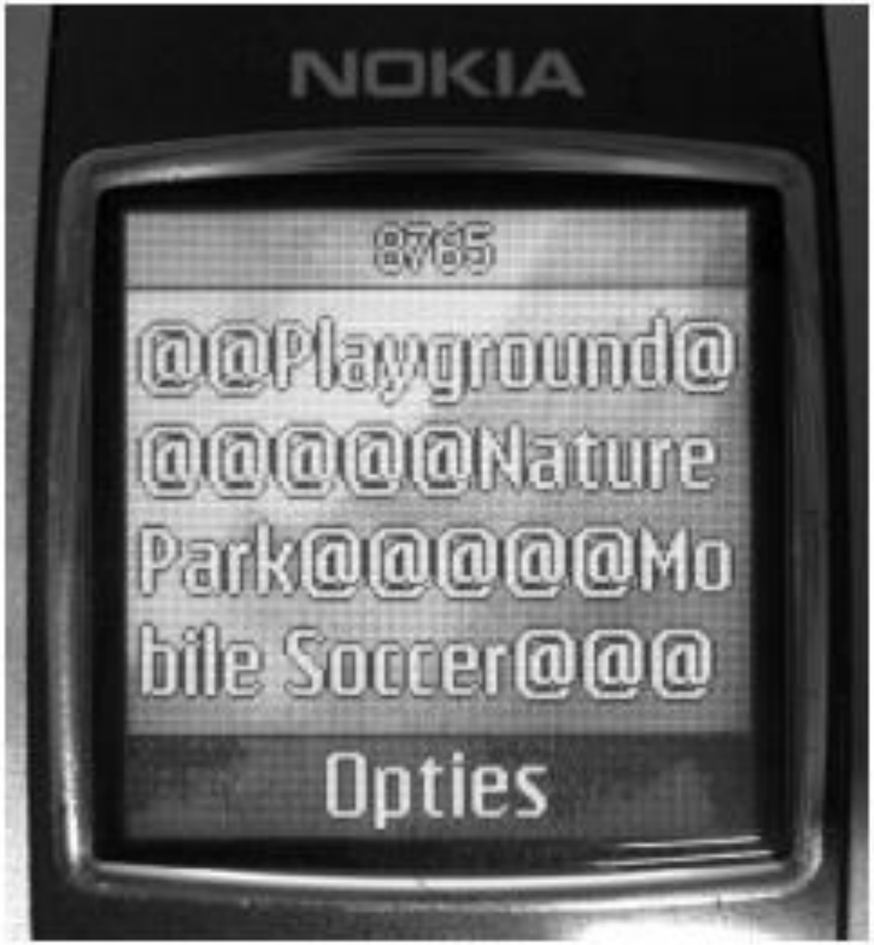
Malformed SMS text messages showing raw memory contents, rather than content of the text message

(a) Showing garbage



```
8765
@@@@@@@@
@@@@@@@@Λ
£¥
```

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



```
8765
@@Playground@
@@@@@Nature
Park@@@@@Mo
bile Soccer@@@
```

Our results with GSM fuzzing

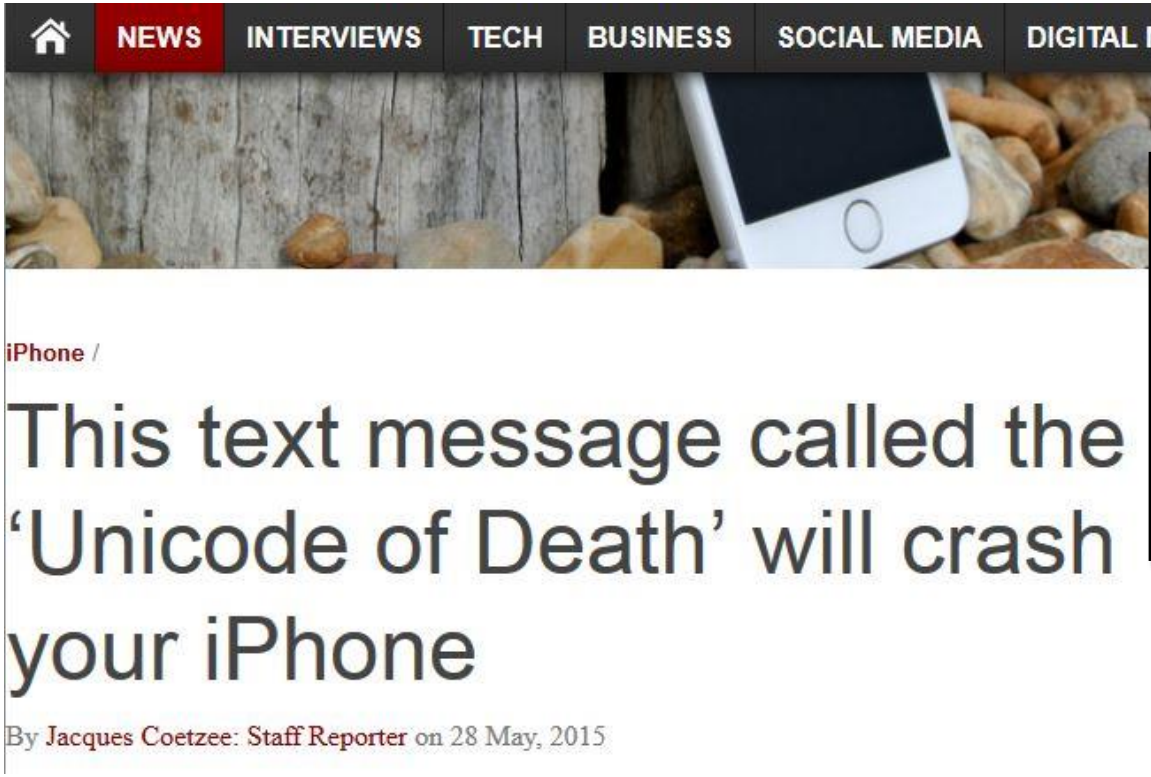
- Lots of success to DoS phones:
  phone crashes, disconnects from network, stops accepting calls,…
  - eg requiring reboot or battery removal to restart, to accept calls again, or to remove weird icons
  - after reboot, the network might redeliver the SMS message, if no acknowledgement was sent before 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]

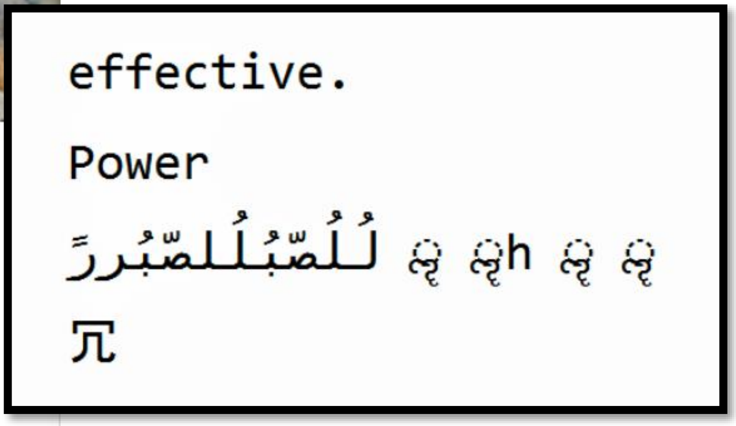
Security problem with more complex input formats



iPhone /

This text message called the ‘Unicode of Death’ will crash your iPhone

By Jacques Coetzee: Staff Reporter on 28 May, 2015



effective.

Power

لُلُصّبُلُلصّبُررً ॣ ॣh ॣ ॣ

冗

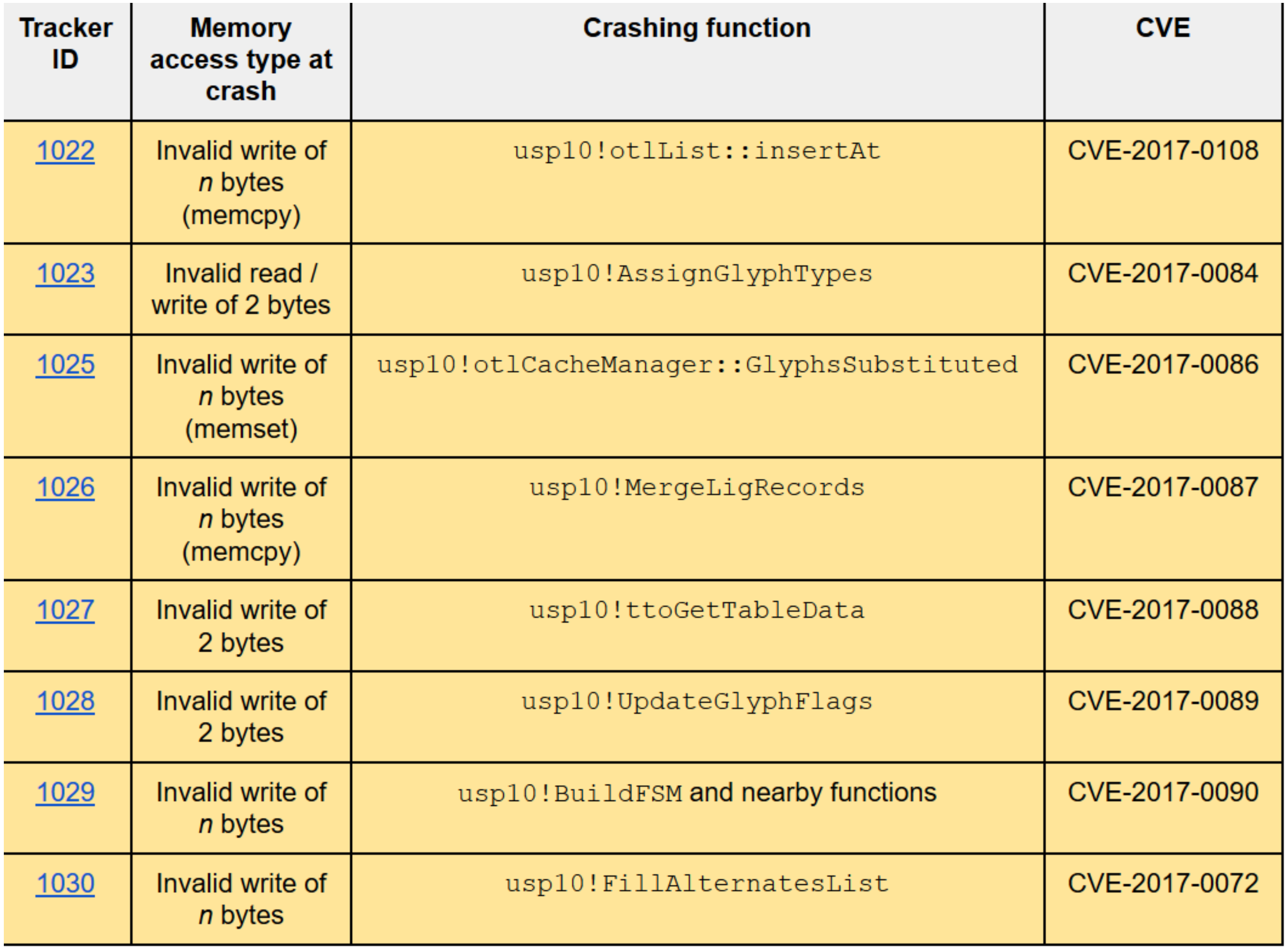
Example dangerous SMS text message

- This message *can* be sent over the network

- Different characters sets & 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

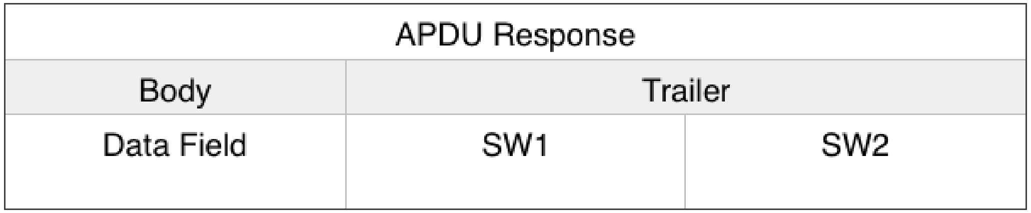


Tracker ID	Memory access type at crash	Crashing function	CVE
1022	Invalid write of *n* bytes (memcpy)	`usp10!otlList::insertAt`	CVE-2017-0108
1023	Invalid read / write of 2 bytes	`usp10!AssignGlyphTypes`	CVE-2017-0084
1025	Invalid write of *n* bytes (memset)	`usp10!otlCacheManager::GlyphsSubstituted`	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.



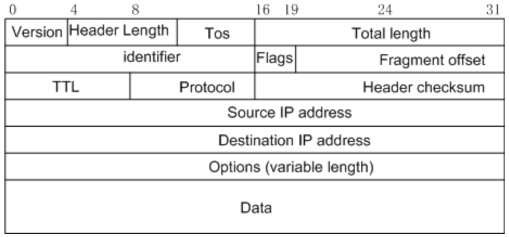
APDU Response		
Body	Trailer	
Data Field	SW1	SW2

Found accidentally, without even trying to fuzz, when sending legal (albeit non-standard) messages

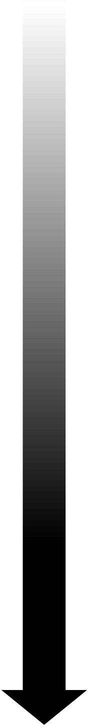
[Jordi van den Breekel, A security evaluation and proof-of-concept relay attack on Dutch EMV contactless transactions, MSc thesis, 2014]

So far

1. **Totally dumb fuzzing** - generate random (long) inputs
2. **Mutation-based** - apply random mutations to valid inputs
   - Eg OCPP
   - Tools: Radamsa, zzuf, …
3. **Generation-based** aka **grammar-based**
   - Eg GSM
   - Pro: can reach 'deeper' bugs than 1 & 2 ☺
   - Con: but lots of work to construct fuzzer or grammar ☹
   - Tools: SNOOZE, SPIKE, Peach, Sulley, antiparser, Netzob, …



0	4	8	16	19	24	31
Version	Header Length	Tos	Total length			
identifier			Flags	Fragment offset		
TTL		Protocol	Header checksum			
Source IP address						
Destination IP address						
Options (variable length)						
Data						



Less shallow