Systems and Software Verification Laboratory

The University of Manchester

Detection of Software Vulnerabilities: Dynamic Analysis

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Dynamic Analysis

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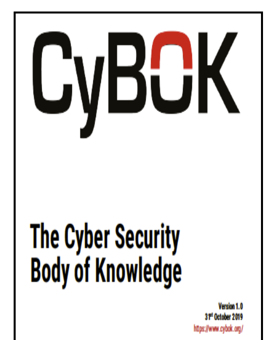
  - Office hours: 15-16 Tuesday, 14-15 Wednesday
- References:
  - *Software Security: Building Security In* (Chapter 6)
  - *Automated Whitebox Fuzz Testing* by Godefroid et al.
  - *The Cyber Security Body of Knowledge* by Rashid et al.
  - *Security Testing* by Erik Poll



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- Understand **dynamic detection techniques** to identify security vulnerabilities

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- A majority of **security defects** and vulnerabilities in software are **not directly related to functionality**

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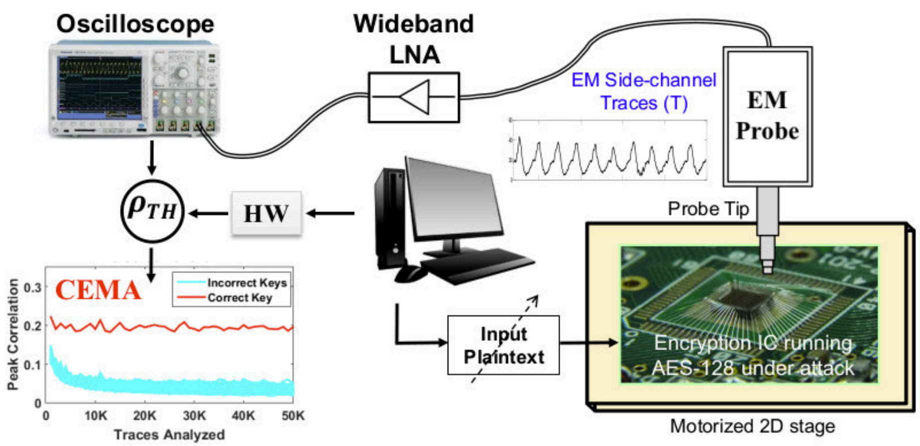
  - information obtained from the impl. rather than weaknesses in the code



STELLAR: A Generic EM Side-Channel Attack Protection through Ground-Up Root-cause Analysis, HOST2019.

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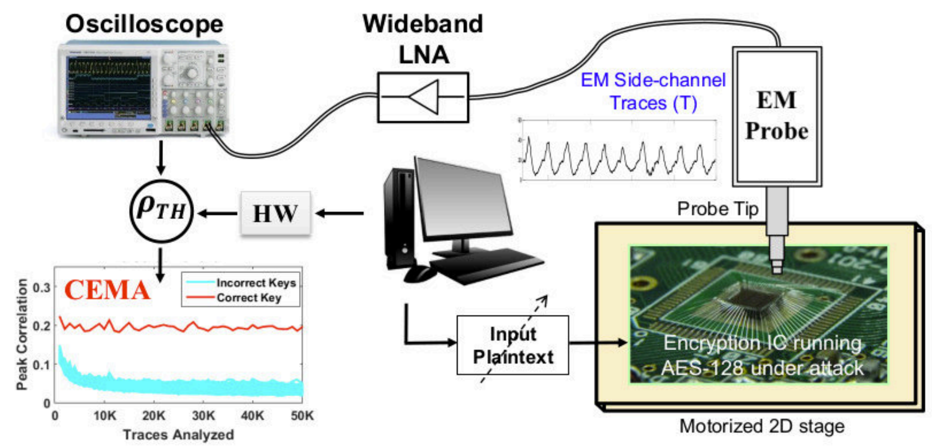

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timing information and power consumption can be exploited

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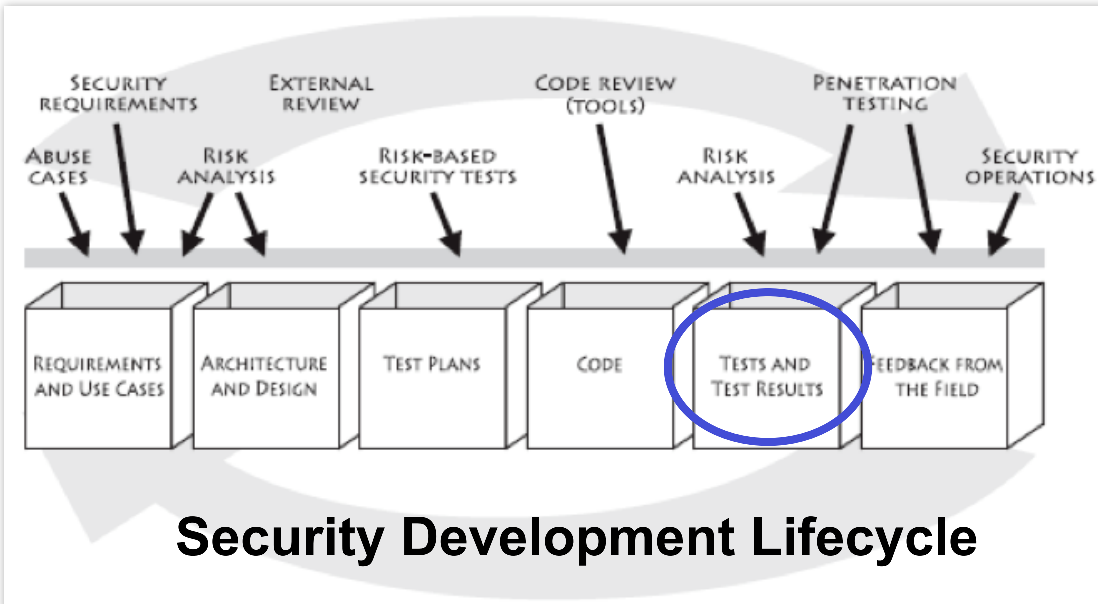

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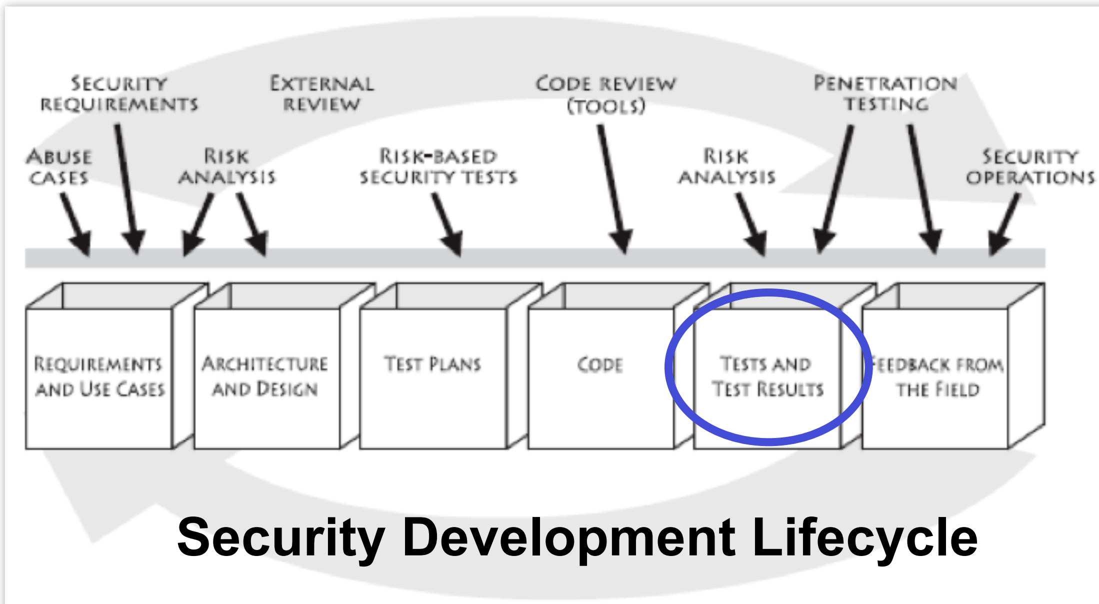

- **Testing for a negative** poses a much greater challenge than **verifying for a positive**

Testing for functionality vs testing for security

- **Traditional testing** checks **functionalities** for **sensible inputs** and **corner conditions**

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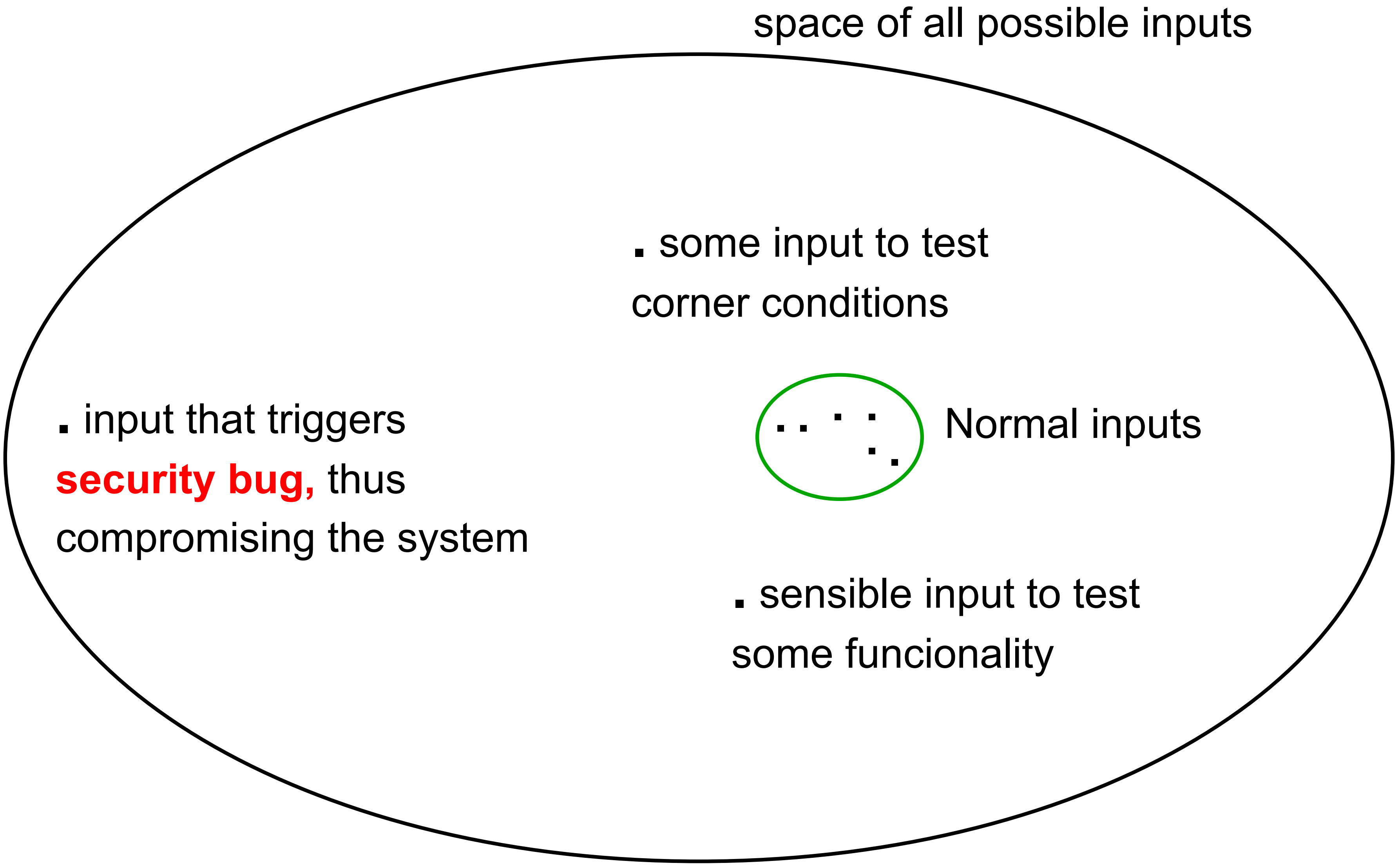
Testing for functionality vs testing for security

- **Traditional testing** checks **functionalities** for **sensible inputs** and **corner conditions**
- **Security testing** also requires looking for the wrong, unwanted behavior for **uncommon inputs**
- **Routine use** of a software system is more likely to reveal **functional problems** than **security problems**:
  - **users** will complain about **functional problems**, but **hackers** will not complain about **security problems**

Security testing is difficult



Definition of Test Suite and Oracle

- To test a software system, we need:

① **test suite:** a collection of input data

② **test oracle:** decides if a test succeeded or led to an error

- ➢ some way to decide if the software behaves as we want

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  - ➢ some way to decide if the software behaves as we want

- Both defining test suites and test oracles can be **a significant work**
  - A test oracle consists of a long list, which **for every individual test case, specifies what should happen**
  - A **simple test oracle**: just looking if the application does not crash

Statement Coverage

- **Statement coverage** involves the execution of all the executable statements at least once
  - (executed statements / total statements)*100

```c
#include "lib.h"
_Bool mul(int64_t a, int64_t b, int64_t *res) {
  // Trivial cases
  if((a == 0) || (b == 0)) {
    *res = 0;
    return 1;
  } else if(a == 1) {
    *res = b;
    return 1;
  } else if(b == 1) {
    *res = a;
    return 1;
  }
  *res = a * b; // there exists an overflow
  return 1;
}
```

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```

a=0,b=0
Coverage=18%

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a=1,b=3
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    return 1;
  } else if(b == 1) {
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    return 1;
  }
  *res = a * b; // there exists an overflow
  return 1;
}
```

a=2,b=1
Coverage=18%

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    *res = b;
    return 1;
  } else if(b == 1) {
    *res = a;
    return 1;
  }
  *res = a * b; // there exists an overflow
  return 1;
}
```

a=2,b=2
Coverage=31%

Statement Coverage

- **Statement coverage** involves the execution of all the executable statements at least once
  – (executed statements / total statements)*100

Test Case	Value of “a”	Value of “b”	Value of “res”	Statement Coverage
1	0	0	0	18%
2	1	3	b	18%
3	2	1	a	18%
4	2	2	a * b	31%

Decision Coverage

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  - (decision outcomes exercised / total decision outcomes) * 100

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```
void Demo(int a) {
  if (a > 5)
    a = a*3;
  printf("a: %i"\n);
}
```

a=4

(a>5) is false

Decision coverage = 50%

Decision Coverage

- **Decision coverage** reports the true or false outcomes of each Boolean expression (tough to achieve 100%)
  – (decision outcomes exercised / total decision outcomes) * 100

```
void Demo(int a) {
  if (a > 5)
    a = a*3;
  printf("a: %i"\n);
}
```

a=10
(a>5) is **true**
Decision coverage = 50%

Decision Coverage

- **Decision coverage** reports the true or false outcomes of each Boolean expression (tough to achieve 100%)
  - (decision outcomes exercised / total decision outcomes) * 100

```
void Demo(int a) {
  if (a > 5)
    a = a*3;
  printf("a: %i"\n);
}
```

Test Case	Value of "a"	Output	Decision Coverage
1	4	4	50%
2	10	30	50%

Branch Coverage

- **Branch coverage** tests every outcome from the code to ensure that every branch is executed at least once
  - (executed branches / total branches)*100

```c
void foo(int x) {
  if (x > 7)
    a = a*4;
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```

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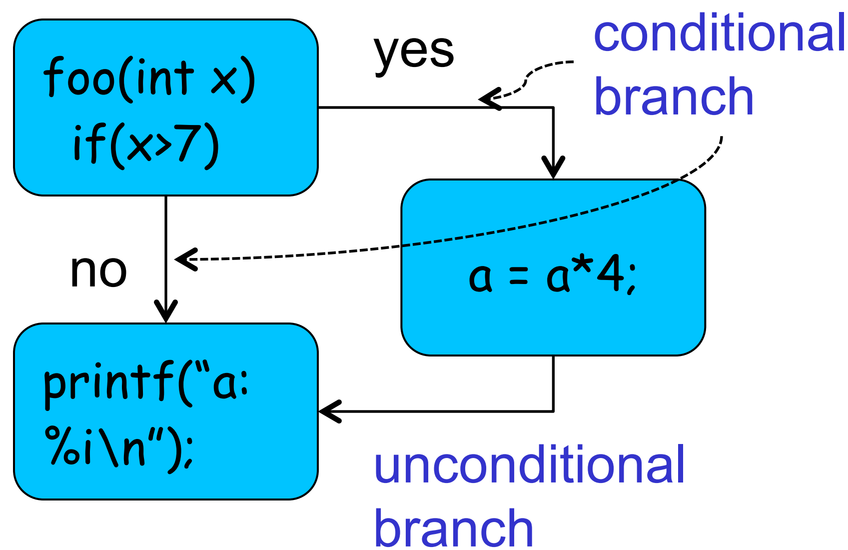

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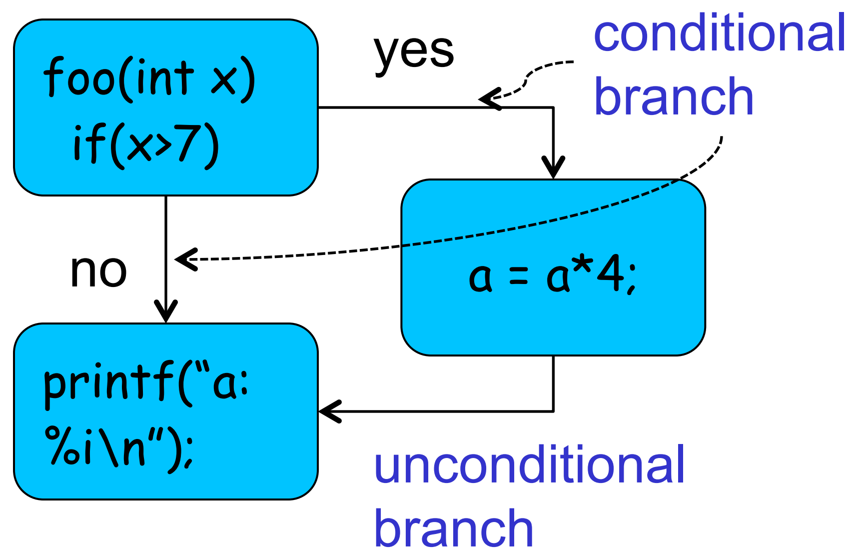

Test Case	Value of "a"	Output	Decision Coverage	Branch Coverage
1	4	4	50%	33%
2	10	40	50%	67%

Condition Coverage

- **Condition coverage** reveals how the variables in the conditional statement are evaluated (logical operands)
  - (executed operands / total operands)*100

```
int main() {
  unsigned int x, y, a, b;
  if((x < y) && (a>b))
    return 0;
  else
    return -1;
}
```

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  unsigned int x, y, a, b;
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x<y	a>b	(x < y) && (a>b)
0	0	0
0	1	0
1	0	0
1	1	1

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```

x<y	a>b	(x < y) && (a>b)
0	0	0
0	1	0
1	0	0
1	1	1

Input	Condition	Outcome	Coverage
x=3, x=4	x<y	TRUE	25%
a=3, b=4	a>b	FALSE	25%

Code coverage criteria

- Code coverage criteria to measure the **test suite quality**
  - **Statement, decision, branch and condition coverage**

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- Statement coverage does not imply branch coverage; e.g. for

```
void f (int a, int b) {
   if (a<100) {b--};
   a+=2;
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Statement coverage needs 1 test case; branch coverage needs 2

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- Code coverage criteria to measure the **test suite quality**
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void f (int a, int b) {
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```

Statement coverage needs 1 test case; branch coverage needs 2

- Other coverage criteria exists, e.g., **modified condition/ decision coverage** (MCDC), which is used to test **avionics embedded software**

Modified condition/decision coverage (MCDC)

- MC/DC coverage is similar to condition coverage, but we must **test every condition in a decision independently** to reach full coverage
- MC/DC requires all of the below during testing:
  - We invoke each entry and exit point
  - We test every possible outcome for each decision
  - Each condition in a decision takes every possible outcome
  - We show each condition in a decision to affect the outcome of the decision independently

Example of MCDC

- Consider the following fragment of C code:

```c
void foo(_Bool A, _Bool B, _Bool C) {
  if ( (A || B) && C ) {
    /* instructions */
  } else {
    /* instructions */
}
```

https://www.verifysoft.com/en_example_mcdc.html

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void foo(_Bool A, _Bool B, _Bool C) {
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}
```

- **Condition coverage:** A, B, and C should be evaluated at least one time “true” and one time “false”:
  - A = true / B = true / C = true
  - A = false / B = false / C = false

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void foo(_Bool A, _Bool B, _Bool C) {
  if ( (A || B) && C ) {
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  } else {
    /* instructions */
}
```

- **Decision coverage:** the condition ((A || B) && C) should also be evaluated at least one time to “true” and one time to “false”:
  - A = true / B = true / C = true
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- MC/DC: each Boolean variable should be evaluated one time to “true” and one time to “false”, and this with affecting the decision's outcome

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```

- MC/DC: For a decision with *n* atomic boolean conditions, we have to find at least *n+1* tests

A = false / B = false / C = true ---> decision evaluated to "false"
A = false / B = true / C = true ---> decision evaluated to "true"
A = false / B = true / C = false ---> decision evaluated to "false"
A = true / B = false / C = true ---> decision evaluated to "true"

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- There exist two essential and relatively independent aspects of **dynamic detection**:
  - How should one **monitor an execution** such that vulnerabilities are detected?
  - **How many and what program executions** (i.e., for what input values) should one monitor?

Monitoring

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- For vulnerabilities concerning **violations of a specified property of a single execution**
  - detection can be performed by **monitoring for violations of that specification**
- For other vulnerabilities, or when monitoring for violations of a specification is too expensive, **approximative monitors** can be defined
  - In cases where a dynamic analysis is approximative, it can also generate **false positives** or **false negatives**
    - even though it operates on a concrete execution trace

Monitoring

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- For **structured output generation vulnerabilities**, the main **challenge** is:
  - that the intended structure of the generated output is often implicit
    - there exists no explicit specification that can be monitored
- For example, a monitor can use a **fine-grained dynamic taint analysis** to track the flow of untrusted input strings
  - flag a violation when **untrusted input** has an impact on the parse tree of the generated output

Monitoring

- **Assertions**, **pre-conditions,** and **post-conditions** can be compiled into the code to provide a monitor for API vulnerabilities at testing time
  - even if the cost of these compiled-in run-time checks can be too high to use them in production code

Monitoring

- **Assertions**, **pre-conditions,** and **post-conditions** can be compiled into the code to provide a monitor for API vulnerabilities at testing time
  - even if the cost of these compiled-in run-time checks can be too high to use them in production code
- Monitoring for **race conditions is hard**, but some approaches for monitoring data races on shared memory cells exist
  - E.g., by monitoring whether all shared memory accesses follow a **consistent locking discipline**

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- This problem is an instance of the general problem in **software testing**
  - Systematically **select appropriate inputs** for a program under test
  - These techniques are often described by the umbrella term **fuzz testing** or **fuzzing**

Fuzzing

Fuzzing is a highly effective, mostly automated, security testing technique

- **Basic idea:** generate random inputs and check whether an application crashes
  - We are not testing functional correctness (compliance)
- **Original fuzzing:** generate long inputs and check whether the system crashes
  - What kind of bug would such a segfault signa*l?*
    - Buffer overflow
  - 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 only zero and negative values
  - depending on what you are fuzzing, include **unique 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, …**

Illustrative Example

- Is this circular buffer implementation correct?

```
#define BUFFER_MAX 10
static char buffer[BUFFER_MAX];
int first, next, buffer_size;
void initLog(int max) {
  buffer_size = max;
  first = next = 0;
}
int removeLogElem(void) {
  first++;
  return buffer[first-1];
}
void insertLogElem(int b) {
  if (next < buffer_size) {
    buffer[next] = b;
    next = (next+1)%buffer_size;
  }
}
```

Illustrative Example

- Does this test case expose some error?

```
void testCircularBuffer(void) {
  int senData[] = {1, -128, 98, 88, 59, 1,
-128, 90, 0, -37};
  int i;
  initLog(5);
  for(i=0; i<10; i++)
    insertLogElem(senData[i]);
  for(i=5; i<10; i++)
    assert(senData[i], removeLogElem());
}
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}
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  if (next < buffer_size) {
    buffer[next] = b;
    next = (next+1)%buffer_size;
  }
}
```

The buffer array is of type char and size BUFFER_MAX

Increment first without checking the array bound: buffer overflow

Assign an integer to a char variable: typecast overflow

Pros & cons of fuzzing

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

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

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Black-box fuzzing

The generation of values depends on the program input/output behaviour, and not on its internal structure

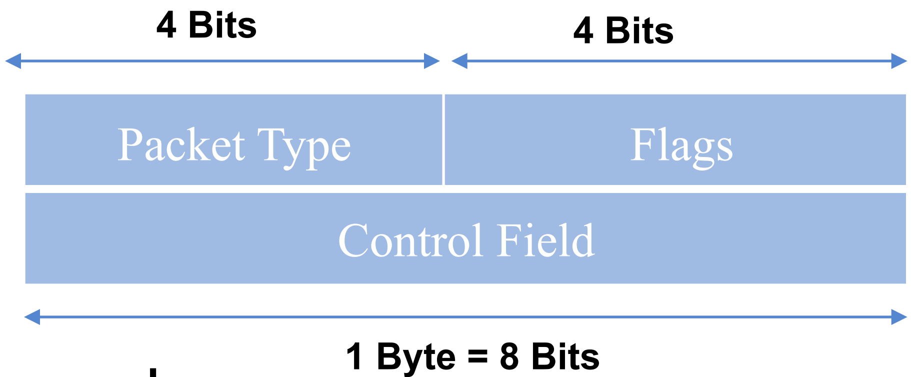
① **Random testing:** input values are randomly sampled from the appropriate value domain

② **Grammar-based fuzzing:** a model of the expected format of input values is taken into account during the generation of input values

③ **Mutation-based fuzzing:** the fuzzer is provided with typical input values; it generates new input values by performing small mutations on the provided input

Grammar-based fuzzing

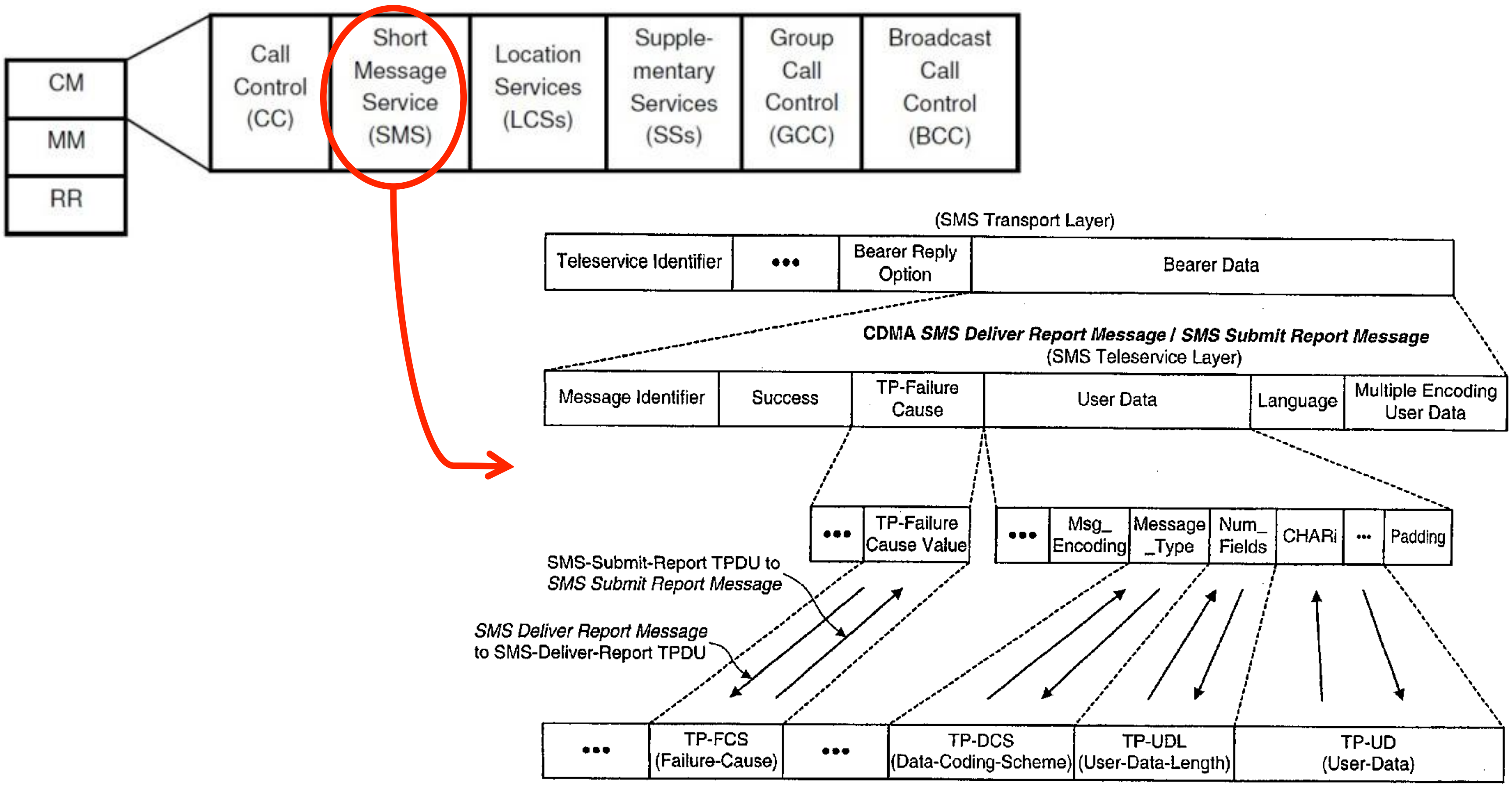
- For communication protocols, a **grammar-based fuzzer** generate files or data packets, which are:
  - Slightly malformed
  - Hit corner cases in the spec
  - **Grammar** defining legal input or **a data format specification**



- Typical things that can be fuzzed:
  - many/all possible value for specific fields (undefined values)
  - 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: Grammar-based Fuzzing of GSM

GSM is an extremely rich and complicated protocol



Fabian van den Broek, Brinio Hond, Arturo Cedillo Torres: Security Testing of GSM Implementations. ESSoS 2014: 179-195

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

- We can use a **Universal Software Radio Peripheral** (USRP)
  - Most USRPs connect to a host computer through a high-speed link
    - the host-based software uses to control the USRP hardware and transmit/ receive data
  - With open-source cell tower software (OpenBTS) to fuzz any phone

Example: GSM protocol fuzzing

- Fuzzing SMS layer of GSM reveals unexpected behaviour in GSM standard and phones

Example: GSM protocol fuzzing

- Fuzzing SMS layer of GSM reveals unexpected behaviour in GSM standard and phones

you have a fax!

possibility to receive faxes?

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

Example: GSM protocol fuzzing

- Malformed SMS text messages
  - show **raw memory** instead of the **text message**

(a) Showing garbage

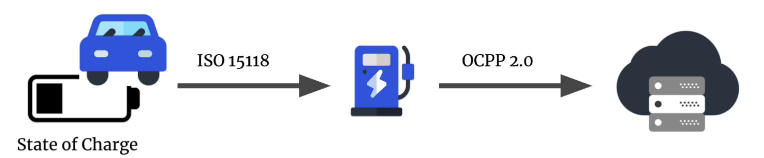
(b) Showing the name of a wallpaper and two games

Mutation-based fuzzing: Fuzzing OCPP

- The **Open Charge Point Protocol** (OCPP) is an application protocol
  - communication between Electric vehicle (EV) charging stations and a central management system
- OCPP can use XML or JSN messages

Example message in JSN format

```
{ "location": NijmegenMercator2156
  "retries": 5,
  "retryInterval": 30,
  "startTime": "2018-10-27T19:10:11",
  "stopTime":  "2018-10-27T22:10:11"  }
```



Mutation-based fuzzing: Fuzzing OCPP

- Simple classification of messages into
  ① **malformed JSN/XML:** missing quote, bracket or comma
  ② **well-formed JSN/XML, but not legal OCPP:** use 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 a 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 need

Evolutionary Fuzzing with American Fuzzy Lop

- **Grammar-based fuzzer:**
  - Significant work to write code to fuzz, even if we use tools to generate this code based on some grammar
- **Mutation-based fuzzer:**
  - chance that random changes in inputs hits unusual cases is small

- **AFL** (American Fuzzy Lop) takes an evolutionary approach to learn mutations based on measuring code coverage
  - basic idea: if a mutation of the input triggers a new path through the code, then it is an interesting mutation; otherwise, the mutation is discarded
  - produce random mutations of the input and observe their effect on code coverage, **AFL** can learn what interesting inputs are

American Fuzzy Lop

- Support 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, then use **modified compiler**; otherwise, **run 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 lead to the same bitmap, but the chance is small
- Mutation strategies: bit flips, incrementing/decrementing integers, using pre-defined integer values (e.g., 0, -1, MAX_INT,....), deleting/combining/zeroing input blocks, …

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

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

Intended learning outcomes

- Understand **dynamic detection techniques** to identify security vulnerabilities
- Generate **executions of the program** along paths that will lead to the **discovery of new vulnerabilities**
- Explain **black-box fuzzing: grammar-based** and **mutation-based fuzzing**
- Explain **white-box fuzzing: dynamic symbolic execution**

White-box fuzzing

The internal structure of the program is analysed to assist in the generation of appropriate input values

- The main systematic white-box fuzzing technique is **dynamic symbolic execution**
  - Executes a program with concrete input values and builds at the same time a path condition
    - An expression that specifies the constraints on those input values that have to be fulfilled to take this specific execution path
  - Solve input values that do not satisfy the path condition of the current execution
    - the fuzzer can make sure that these input values will drive the program to a different execution path, thus improving coverage

White-box Fuzzing

- Combine fuzz testing with **dynamic test generation**
  - **Run the code** with some initial input
  - **Collect constraints on input** with symbolic execution
  - **Generate new constraints**
  - **Solve constraints** with constraint solver
  - **Synthesize new inputs**
  - Leverages **Directed Automated Random Testing** (**DART**) ([Godefroid-Klarlund-Sen-05,…])
  - See also previous talk on **EXE** [Cadar-Engler-05, Cadar-Ganesh-Pawlowski-Engler-Dill-06, Dunbar-Cadar-Pawlowski-Engler-08,…]

Dynamic Test Generation

```
input =
  “good”
```

```
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();
}
```

Dynamic Test Generation

```
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();
}
```

input = "good"

I_0 != 'b'

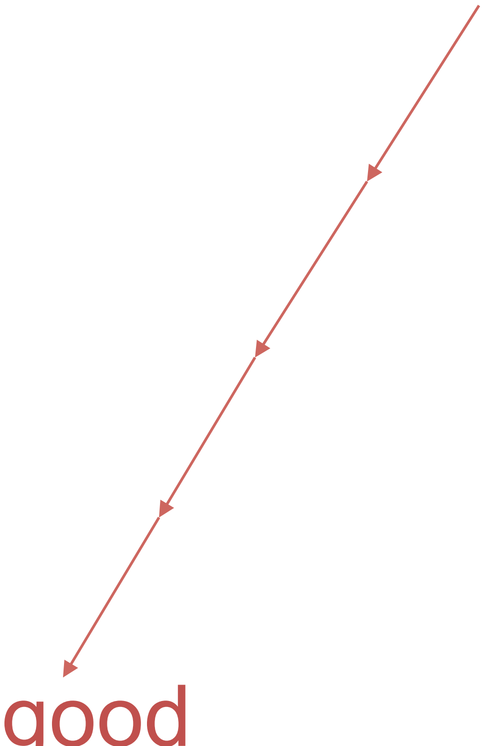
I_1 != 'a'

I_2 != 'd'

I_3 != '!'

Collect constraints from trace
Create new constraints
Solve new constraints → new input.

Depth-First Search




```
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();
}
```

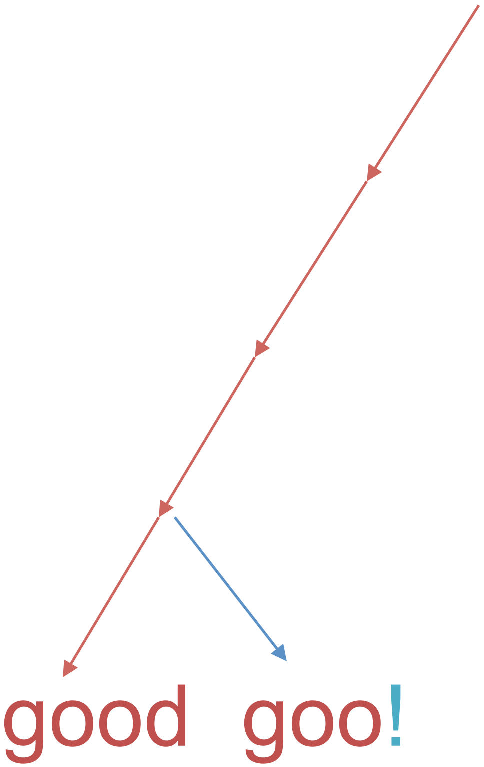
I_0 != 'b'

I_1 != 'a'

I_2 != 'd'

I_3 != '!'

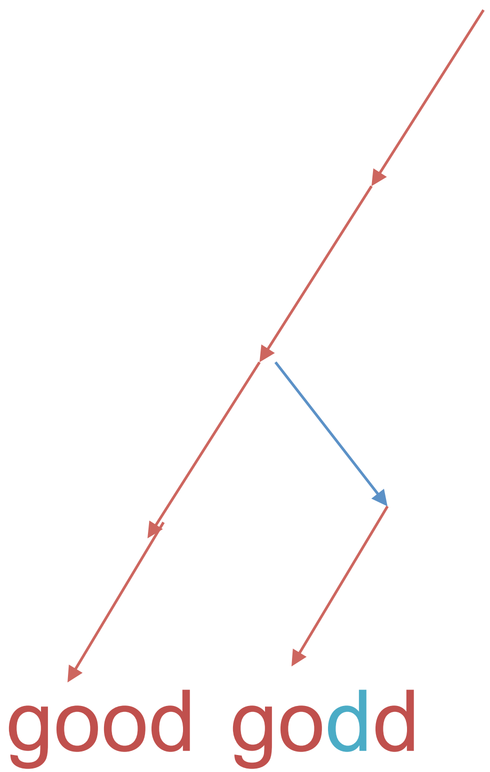
Depth-First Search




```
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();
}
```

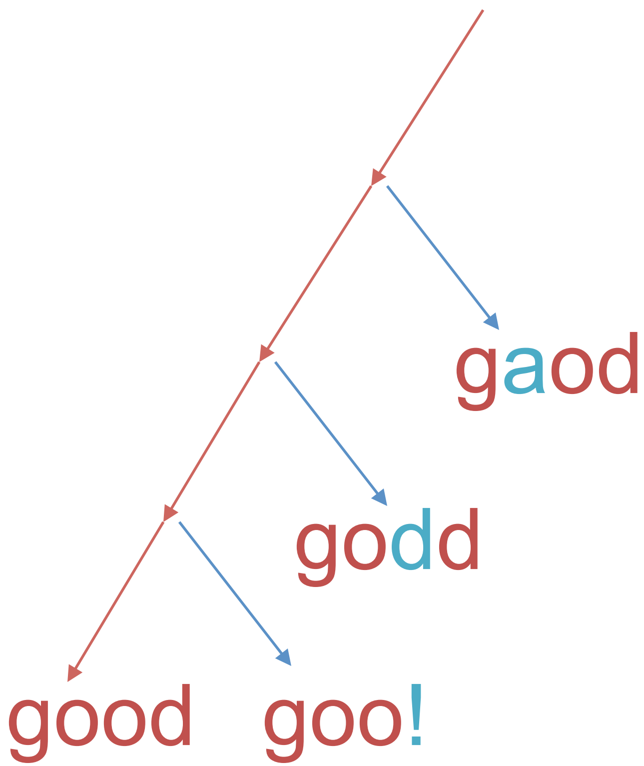
I_0 != 'b'
I_1 != 'a'
I_2 != 'd'
I_3 == '!'

Depth-First Search




```
void top(char input[4])
{
    int cnt = 0;
    if (input[0] ==  'b' ) cnt++; I0 != 'b'
    if (input[1] ==  'a' ) cnt++; I1 != 'a'
    if (input[2] ==  'd' ) cnt++; I2 == 'd'
    if (input[3] ==  '!' ) cnt++; I3 != '!'
    if (cnt >= 3) crash();
}
```

Depth-First Search




```
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();
}
```

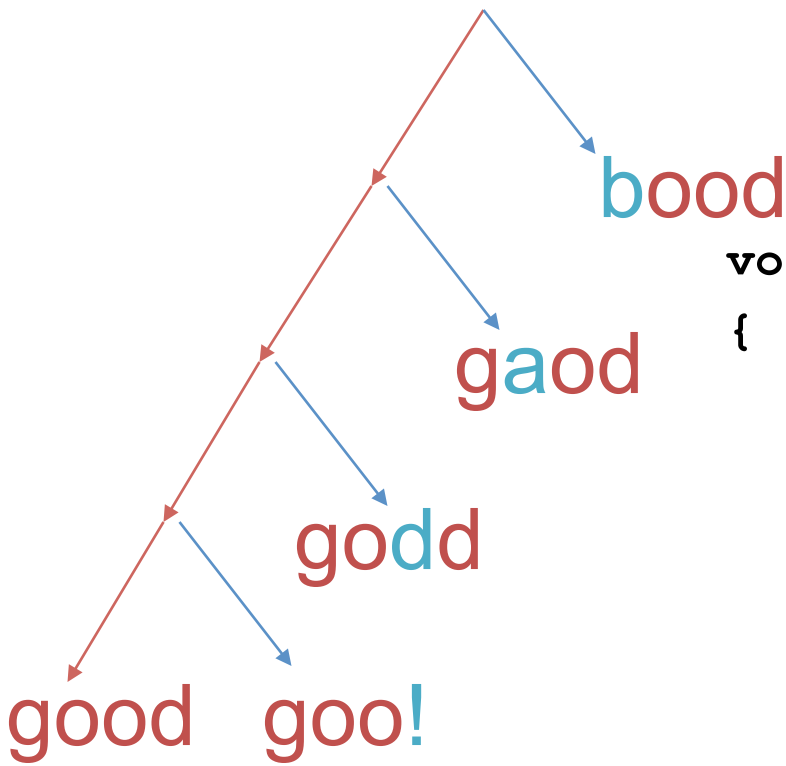
$I_0 \mathrel{!=} \text{'b'}$

$I_1 == \text{'a'}$

$I_2 \mathrel{!=} \text{'d'}$

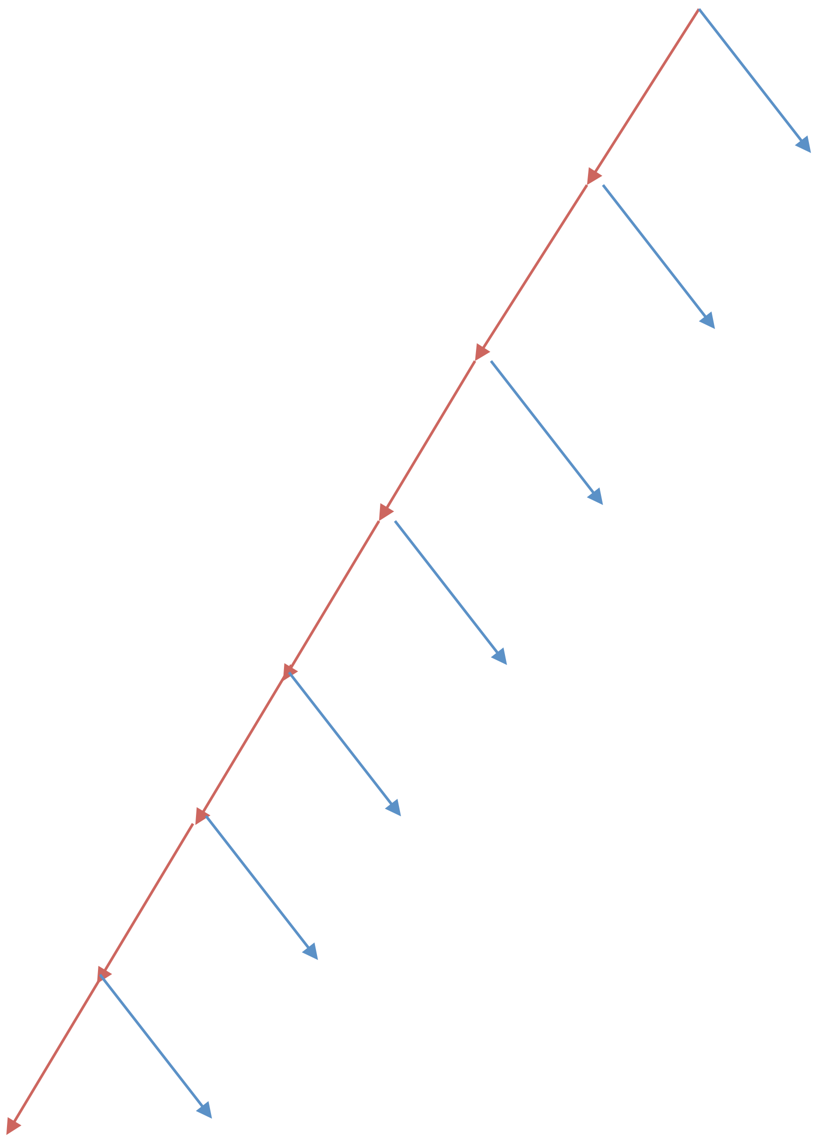
$I_3 \mathrel{!=} \text{'!'}$

Depth-First Search




```
void top(char input[4])
{
    int cnt = 0;
    if (input[0] == ‘b’ ) cnt++; I0 == ‘b’
    if (input[1] == ‘a’ ) cnt++; I1 != ‘a’
    if (input[2] == ‘d’ ) cnt++; I2 != ‘d’
    if (input[3] == ‘!’ ) cnt++; I3 != ‘!’
    if (cnt >= 3) crash();
}
```

Key Idea: One Trace, Many Tests

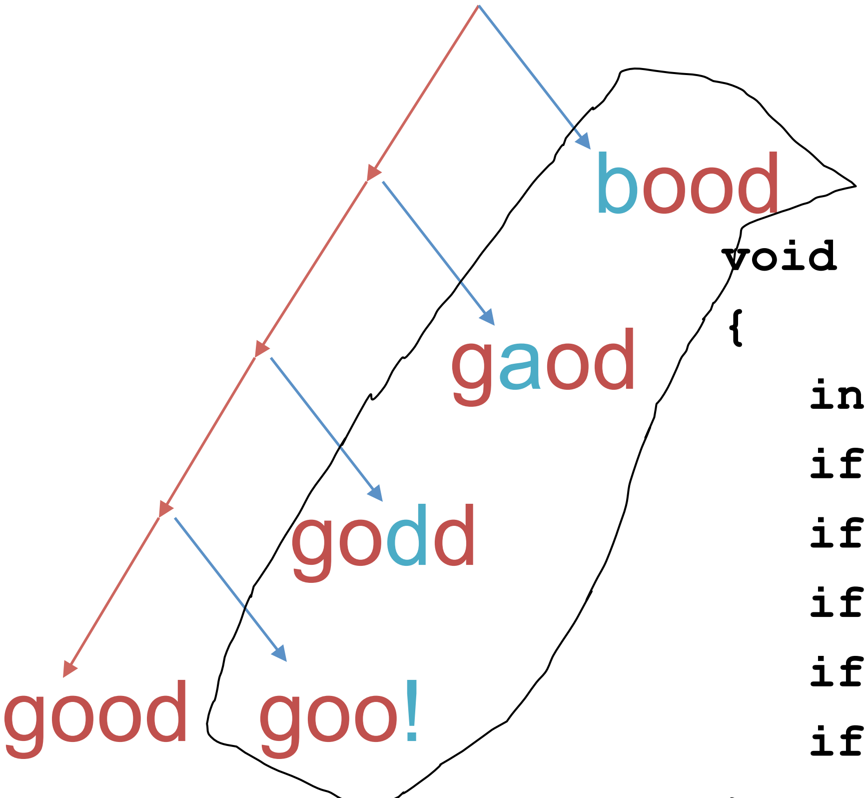


Office 2007 application:
Time to **gather constraints**: 25m30s
Tainted branches/trace: ~1000

Time per branch to
solve,
generate new test,
check for crashes: ~1s

Therefore, solve+check **all** branches for each trace!

Generational Search

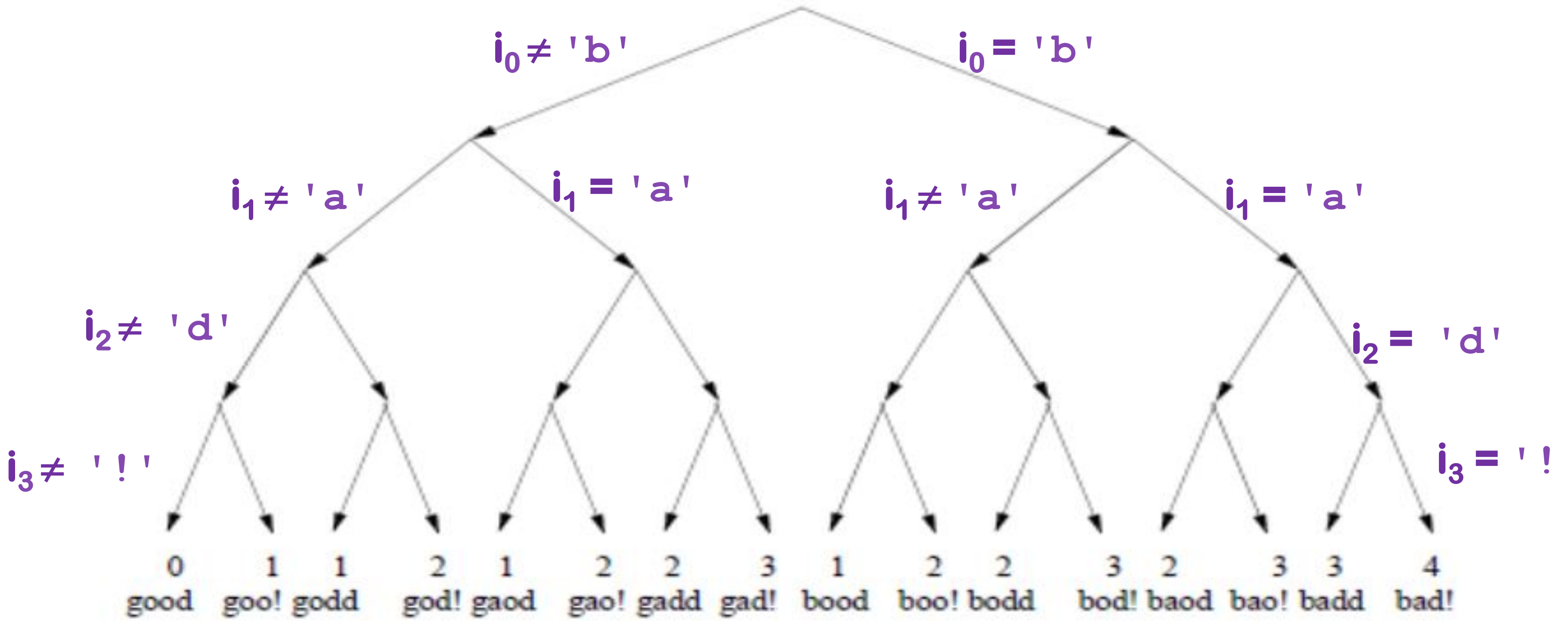



```
void top(char input[4])
{
    int cnt = 0;
    if (input[0] ==  'b' ) cnt++;
    if (input[1] ==  'a' ) cnt++;
    if (input[2] ==  'd' ) cnt++;
    if (input[3] ==  '!' ) cnt++;
    if (cnt >= 3) crash();
}
```

I_0 == 'b'
I_1 == 'a'
I_2 == 'd'
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

Summary

- Cost/precision tradeoffs
  - Blackbox is lightweight, easy and fast, but weak coverage
  - Whitebox is smarter, but complex and slower
  - Recent "**semi-whitebox**" approaches
    - Less smart but more lightweight: **Flayer** (taint-flow analysis, may generate false alarms), **Bunny-the-fuzzer** (taint-flow, source-based, heuristics to fuzz based on input usage), **autodafe**, etc.

- Which is more effective at finding bugs? It depends…
  - Many apps are buggy; any form of fuzzing finds bugs!
  - Once low-hanging bugs are gone, fuzzing must become smarter: use whitebox and/or user-provided guidance (grammars, etc.)

- Bottom line: in practice, **use both**!