Fuzz Testing

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Learning Goals

After today's lecture you should be able to

- ... explain and discuss why and how fuzz testing is used to find unexpected behaviour in software
- ... explain and discuss the different fuzz testing methods, including
  - blackbox
  - fuzzing using instrumentation
  - mutation-based and generation-based
  - whitebox
- ... apply fuzz testing via AFL++ on simple CLI programs

Easy to test?

Example 0

```
uint8_t tab[0x1ff + 1];

uint8_t target(int32_t value){
    if(value < 0) {
        return 0;
    }

    int32_t i = value * 0x1ff / 0xffff;
    if(i >= 0 && sizeof(tab) > i){
        return tab[i];
    }
    return 0;
}
```

Easy to test?

Example 0a

```
uint8_t target(int32_t value){
    if(value < 0) {
      ...
    }
    ...
    if(i >= 0 && sizeof(tab) > i){
        ...
    }
    ...
}
```

Easy to test?

Example 0

```
uint8_t tab[0x1ff + 1];

uint8_t target(int32_t value){
    if(value < 0) {
        return 0;
    }

    int32_t i = value * 0x1ff / 0xffff;
    if(i >= 0 && sizeof(tab) > i){
        return tab[i];
    }
    return 0;
}
```

- Integer overflow and optmisation removes check!

Original Example: `blog.pkh.me`

Why Fuzz Testing?

Why Fuzz Testing?

Secure, Secure, Secure(?)

Critical Systems: it goes without saying

- Military
- Healthcare
- Financial Systems
- Infrastructure

What about less critical systems?

- Computer/mobile applications
- IoT and embedded devices

Tests, tests, tests!

System test, unit test, user test and etc.

- expensive
- time consuming

We still have insecure systems and software. More tests?

Why Fuzz Testing?

B. Miller and Automated Test

- Barton Miller introduced the keyword "**fuzz**" in 1988
- An attempt to make automated test for UNIX command line utilities
- Doing so by generating random input and observing crashes

Fuzz testing works!

Miller et al. crashed up to 33% of utilities tested back in 1988. In 2020 the same method was applied on UNIX-bases systems and there was found upto 19% failure rates

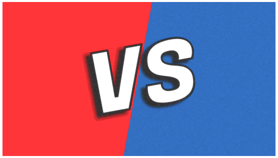
Why Fuzz Testing?

Fuzzing today - Red and Blue

Evolved since 1988

Fuzz testing have been widely adopted and applied. IT giants such as Google and Microsoft are using it as part of the CI/CD

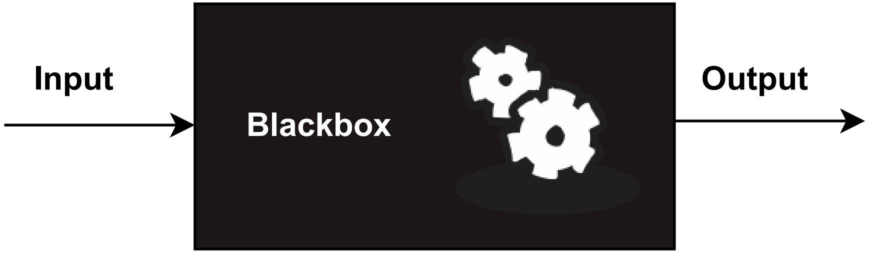
- Widely adopted in the red team community
- Recently increasing popularity tool for blue teamers



- Today, fuzz testing is better known as **fuzzing**

Blackbox Fuzzing

Blackbox Fuzzing
Input and Output



We, the fuzzer, can only observe input and output and is randomly guessing inputs!

- How long does random take?

Blackbox Fuzzing

Banality of Random

Example 1

```
int fuzzing_target(int input){
  int output = 0;

  if (input == 2023){
    abort();
  }

  return output;
}
```

- What is the flaw?

Blackbox Fuzzing

Banality of Random

Example 1

```
int fuzzing_target(int input){
  int output = 0;

  if (input == 2023){
    abort();
  }

  return output;
}
```

- What is the flaw?

A integer value in C consist of four bytes, which can represent $2^{32} = 4,294,967,295$ different values. The probability of random guessing 2023 is then $1 : 4,294,967,295$

Blackbox Fuzzing

Banality of Random

Example 2

```
int fuzzing_target(int input_a, int input_b, int input_c){
  int output = 0;

  if (input_a == 2023){
    if (input_b == 2){
      if (input_c == 24){
        abort();
      }
    }
  }
  return output;
}
```

Well, the probability of random generating the correct sequence of integer values is $1 : 2^{96}$ – which is small

Blackbox Fuzzing

Still Random but Less

What is most likely to provoke an error?

- "A" or "AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA"
- "SejeReje" or "/>!S3JE0?r@Je#{';"
- "0" or 0x00
- ":-)" or "😃"

Random inputs can still be evaluated and prioritised - to improve accuracy

Blackbox Fuzzing
Pros and Cons

Pros:

- It works!
- Easy to implement – or reuse

Cons:

- Guarantee nothing
- Might never reach interesting code

Application of Blackbox

Blackbox fuzzing excels when the target is unknown:

- Pentesting and Red Teaming
- APIs, Embedded systems etc.
- For everybody :)

Test Cases

Test Cases
Example

Test Cases – inputs, seeds

Example 3

```c
int fuzzing_target(char* input){
  int output = 0;
  if (input[0] == 'F'){
    output++;
    if (input[1] == 'U'){
      output++;
      if (input[2] == 'Z'){
        output++;
        if (input[3] == 'Z'){
          output++;
          exciting_stuff(input);
        }
      }
    }
  }
  return output;
}
```

Test Cases
Mutation-based Fuzzing

Mutation of an initial test case:

FUZZing is great

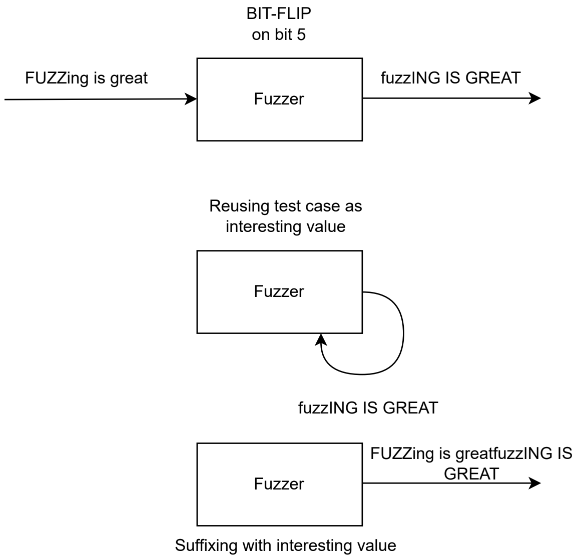
Is done by applying a mutation operations, such as:

- prefixing and suffixing interesting values
- Removing sub strings
- bit-flipping
- adding or subtracting

Resulting in:

fuzzING IS GREAT
FZinis gat
FUZZing is greatFUZZing is great
...

Test Cases
Mutation-based Fuzzing



Test Cases

Mutation-based Fuzzing

Using output as an indicator of interesting test cases

- xxxxxxx : 0
- Fxxxxxx : 1
- FUxxxxx : 2
- FUZxxxx : 3
- FUZZxxx : 4+y

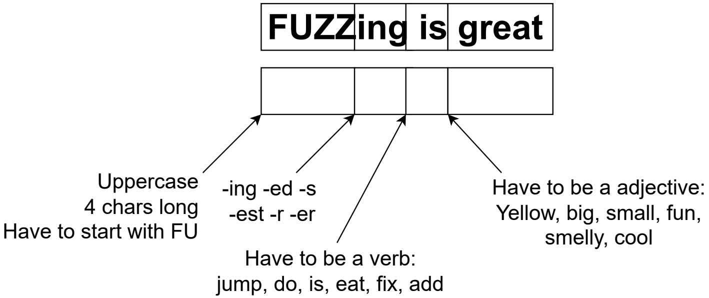
Example 3

```
int fuzzing_target(char* input){
  int output = 0;
  if (input[0] == 'F'){
    output++;
    if (input[1] == 'U'){
      output++;
      if (input[2] == 'Z'){
        output++;
        if (input[3] == 'Z'){
          output++;
          exciting_stuff(input);
        }
      }
    }
  }
  return output;
}
```

Test Cases
Generation-based Fuzzing

Generation-based Fuzzing - Aware of input structure

Some rules might apply to the input structure, these are used in generation-based fuzzing



- Generation of test cases that satisfy the rule set

Test Cases
Generation-based vs. Mutation-based

Generation-based

- Be aware of input structure
- Better accuracy
- Less Random
- Biased?

Mutation-based

- Only needs initial test case
- Reusable
- More random

Fuzzing harness

Fuzzing harness is the code which is needed in order to start fuzz testing, this can vary a lot depending on which methods and tools used

Exercise - 25 min

Time to make your first blackbox fuzz test with AFL++!

Take a look on the following exercises:

- `exercise/1/.`
- `exercise/1/a`
- `exercise/1/b`
- `exercise/1/c`
- `exercise/1/d`

The exercises can be found here: github.com/larsbpf/fuzzing-lecture

- Remember the changes you make in the Docker Container is not saved
- Rerunning the buildscript removes the existing container and makes a new with the current contents of the exercise folder

Greybox Fuzzing

Greybox Fuzzing

Grey is the New Black

Box, Box, Box

The three boxes indicate how much the tester knows about the target.
The tester has access to...

- Black: only input and output
- White: source code (everything)
- Grey: something in between?

Greybox Fuzzing

Grey is the New Black

Box, Box, Box

The three boxes indicate how much the tester knows about the target. The tester has access to...

- Black: only input and output
- White: source code (everything)
- Grey: something in between? – it's a bit fuzzy

50 shades of Greybox

Greybox is very loosely defined which also result in a very broad interpretation of the term

Not-Quite-Greybox Fuzzing

American Fuzzy Lop

American Fuzzy Lop better known as AFL

AFL is not self-proclaimed greybox, but is sometimes referred to as one. It have been forked 500+ times and parent most community acknowledge fuzzers

- Low effort
- Highly optimised

Directed & Coverage-based

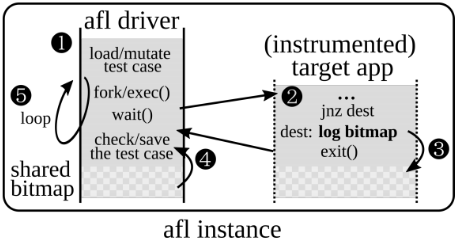
Directed fuzzers are trying to discover some specific block in a program, where as coverage-based try to discover as much as possible

Not-Quite-Greybox Fuzzing

American Fuzzy Lop - Instrumentation and Mutation

Repeating

(1) Reading and mutating inputs
(2) Launching the target application
(3) Executing and recording runtime coverage
(4) Bookkeeping results



Instrumentation by compiler

AFL uses a custom compiler in order to insert logging calls in the targeted application

American Fuzzing Lop
Pros & Cons

Pros:

- Highly optimised
- Easy-to-use (using mutation-based)
- Offers blackbox fuzz testing and fuzz testing with instrumentation
- Random

Cons:

- Hard to master
- Need to instrument source code in order to work optimal
- Limited to C and C++
- Random

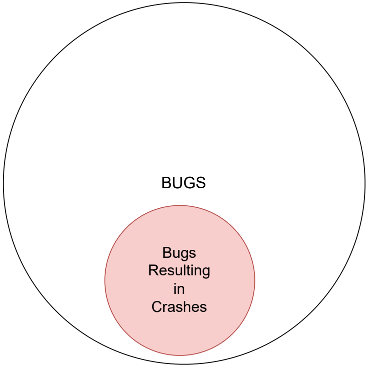
Assertion and Exposing

Searching For More

Assertion-Based Fuzzing

To Crash or not to Crash?

'Classic' fuzz testing methods only search for memory related bugs. Bugs that results in crashes.



- What is an example of a bug that does not result in a crash?

Searching For More
Assertion-Based Fuzzing

- What kind of behaviour does we expect?

Example 4

```c
struct UserProfile {
    unsigned int id;
    char firstname[32];
    char lastname[32];
    int balance;
}
struct User* withdraw(struct UserProfile* user){
    /* Code handling the withdrawal process */
    return user;
}
```

Assertions - Make sure ... or die!

An assertion is used to check and expression and if it evaluates false then crash otherwise continue

Searching For More

Assertion-Based Fuzzing

Example 4a

```
struct User* withdraw(struct UserProfile* user){
    /* Code handling the withdraw process */

    assert(new_balance < prev_balance);
    assert(user->balance >= 0);
    assert(user->id == id);
    /* etc. */

    return user;
}
```

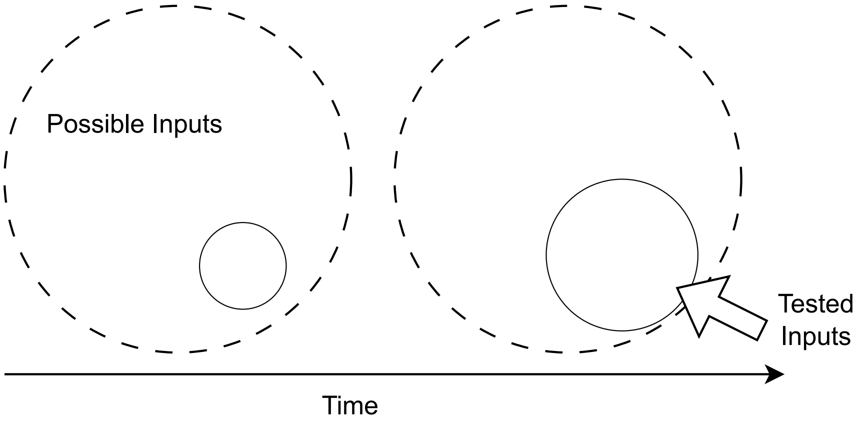
Assertion-based Fuzz Testing

Assertions make it possible to fuzz test logic, and makes fuzz testing to a much stronger tool

Ignore the Irrelevant

Faster is More

- How big can an input be?
- How many different inputs exists?
- How long does random take?



Ignore the Irrelevant

Removing IO and Sleeps

Example 5

```
int main(){
  char* input[64];
  int sleep_time;

  printf("Welcome to the sleeping machine\n");
  printf("How long you want to sleep?\n:");
  scanf("%d",sleep_time);

  sleep(sleep_time);

  printf("Oooh, no. A program that needs to be fuzzed!\n"
         "Give an input:");
  scanf("%63s", input);

  fuzzing_target(input);

  return 0;
}
```

Ignore the Irrelevant

Removing IO and Sleeps

Example 5a

```
int main(){
  char* input[64];
  int sleep_time;

  printf("Welcome to the sleeping machine\n");
  printf("How long you want to sleep?\n:");
  scanf("%d",sleep_time);

  // sleep(sleep_time);

  printf("Oooh, no. A program that needs to be fuzzed!\n"
         "Give an input:");
  scanf("%63s", input);

  fuzzing_target(input);

  return 0;
}
```

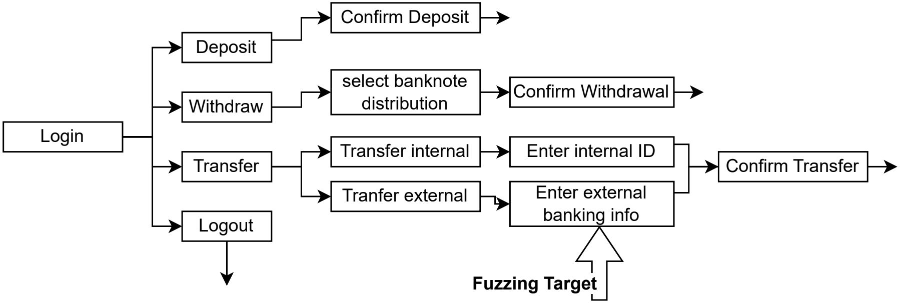
Ignore the Irrelevant
Removing IO and Sleeps

Example 5b

```
int main(){
  char* input[64];
  scanf("%63s", input);
  fuzzing_target(input);

  return 0;
}
```

Ignore the Irrelevant
Exposing Functions



Example 6

```
int main(){
  char* input[1024];/* Initialising input buffer */
  fgets(input, sizeof(input), stdin);/* Reading from terminal */
  check_ex_banking_info(input);/* Calling fuzzing target */
  return 0;
}
```

Exercise - 25 min

AFL++ a coverage-based with the help of instrumentation

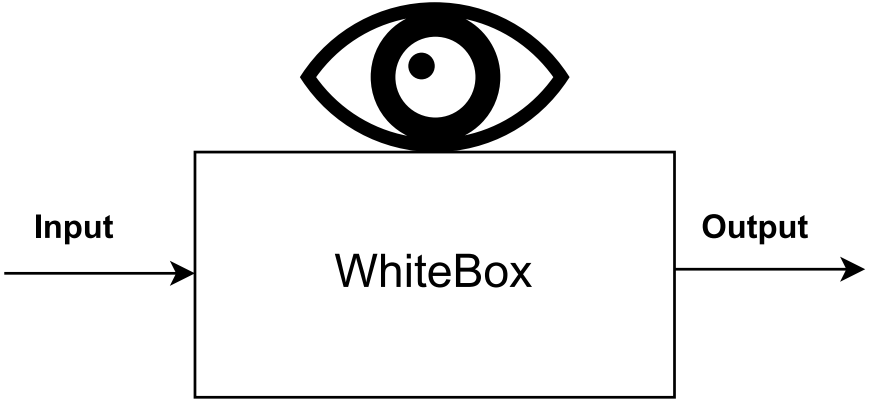
Take a look on the following exercises:

- `exercise/2/.`
- `exercise/2/a`
- `exercise/2/c`
- `exercise/4/a`

Whitebox Fuzzing

Whitebox Fuzzing

Fuzzing and Beyond



We know and are aware of everything including the source code and specification

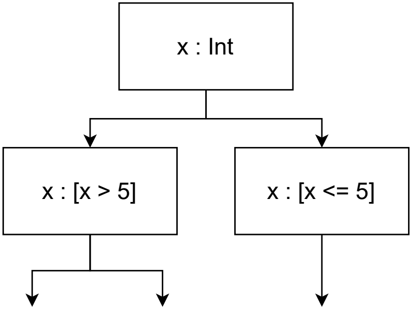
Whitebox Fuzzing

Fuzzing and Beyond

Symbolic Execution

is when the program is executed with symbols instead of actual values. One of the main results of symbolic execution is a execution tree containing constraints that must be true to execute a given path

```
int x;
...
if(x > 5){
    ...
} else {
    ...
}
```



Whitebox Fuzzing

Fuzzing and Beyond

The Curse of Knowledge

Analyses such as symbolic executions is complex and often suffers from complexity problems. Here is the main problems of symbolic execution:

- Path explosion - the number of paths rise exponential with control structures
- Determining if a formula can be satisfied - SAT or harder

Ignorance is Bliss

Whitebox fuzzers uses symbolic execution to find interesting paths with combination of the *traditional* fuzz technique of using random inputs, to achieve greater depth on less time

Whitebox Fuzzing

Fuzzing and Beyond

Pros:

- Very precise
- Can cover much larger code bases
- Able to find logic related errors

Cons:

- Time and memory consuming
- For experts!

To be Continued...

Whitebox fuzzing is still evolving, since it combines two non obvious ideas: static/dynamic analyses of a application and testing with random generation of inputs.