Fuzzing Class Interfaces for Generating and Running Tests with libFuzzer*

Barnabás Bágyi, Zoltán Porkoláb

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Overview

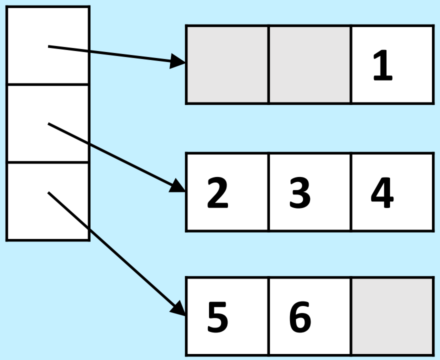
- Deficiencies of the testing ecosystem
- General fuzzing and libFuzzer introduction
- Design of an interface fuzzer
- Case studies

Let's follow the design and testing of a (container) class

The (simplified) container vision

Double ended queue

- similar to std::deque
- implemented with a vector of static sized arrays



The (simplified) container vision

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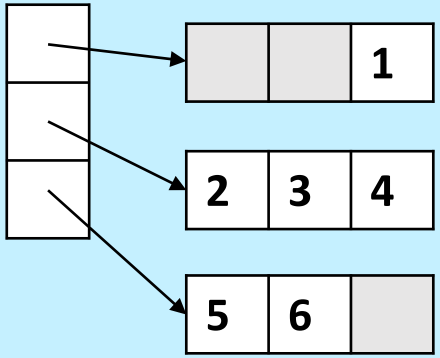


```
struct my_deque {
    void push_back(int);
    void pop_back();
    int back() const;

    void push_front(int);
    void pop_front();
    int front() const;

    std::size_t size() const;
private:
    // ...
};
```

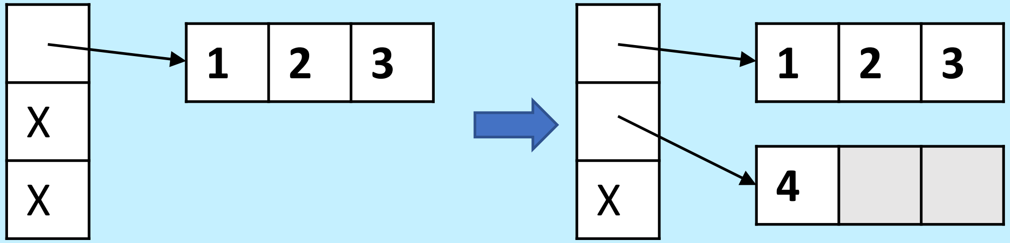
Example Unit Test Case

```
TEST(my_deque_test, push_pop)
{
    my_deque md;
    ASSERT_EQ(md.size(), 0);

    md.push_back(42);
    ASSERT_EQ(md.size(), 1);
    ASSERT_EQ(md.back(), 42);

    md.pop_back();
    ASSERT_EQ(md.size(), 0);
}
```

- Testing only a small part of the software - one unit
- Sequence of method calls and state assertions
- Did we do enough, if we only write this and a similar front test case?

Possible undetected bugs

- Creation of a new array



Possible undetected bugs

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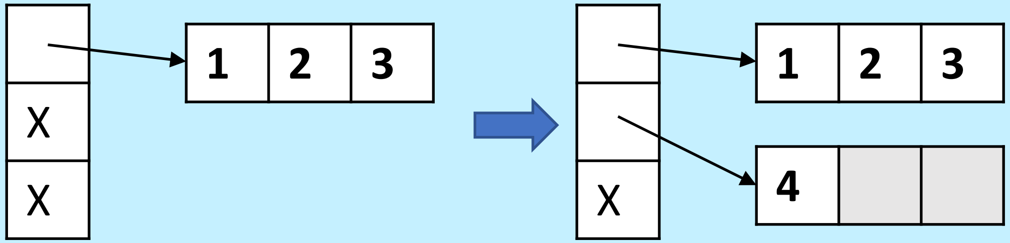
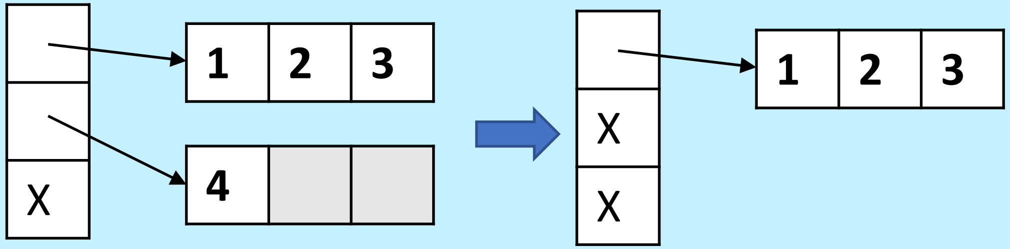


- Destruction of a new array



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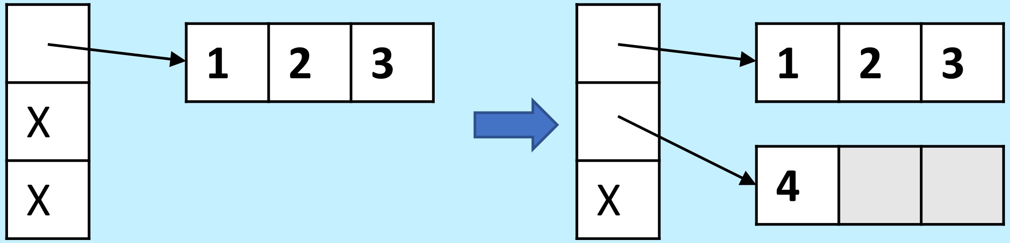

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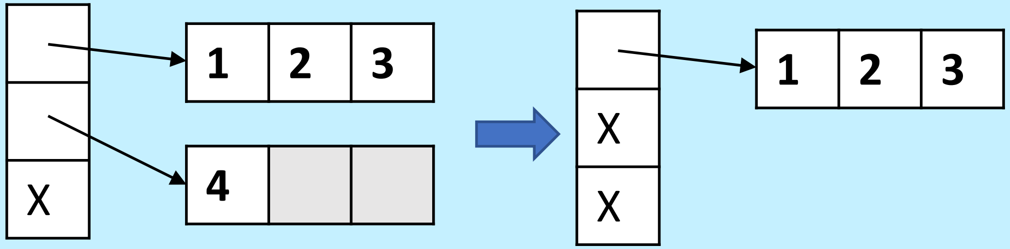
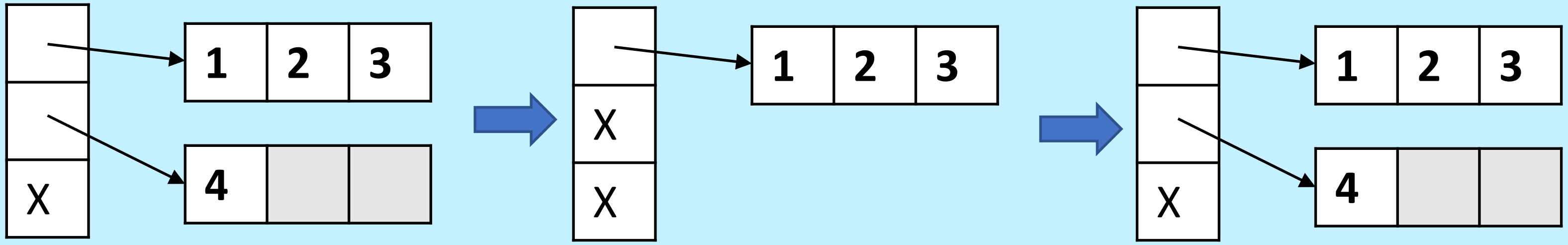


- Destruction of a new array, then a recreation of it

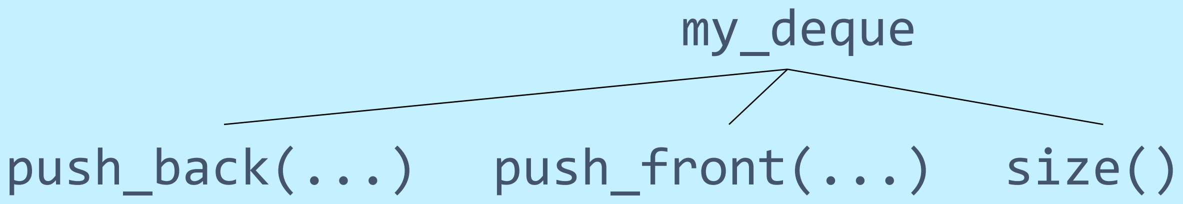


The last one contributes no additional LOC coverage

Too many states

```
my_deque
```

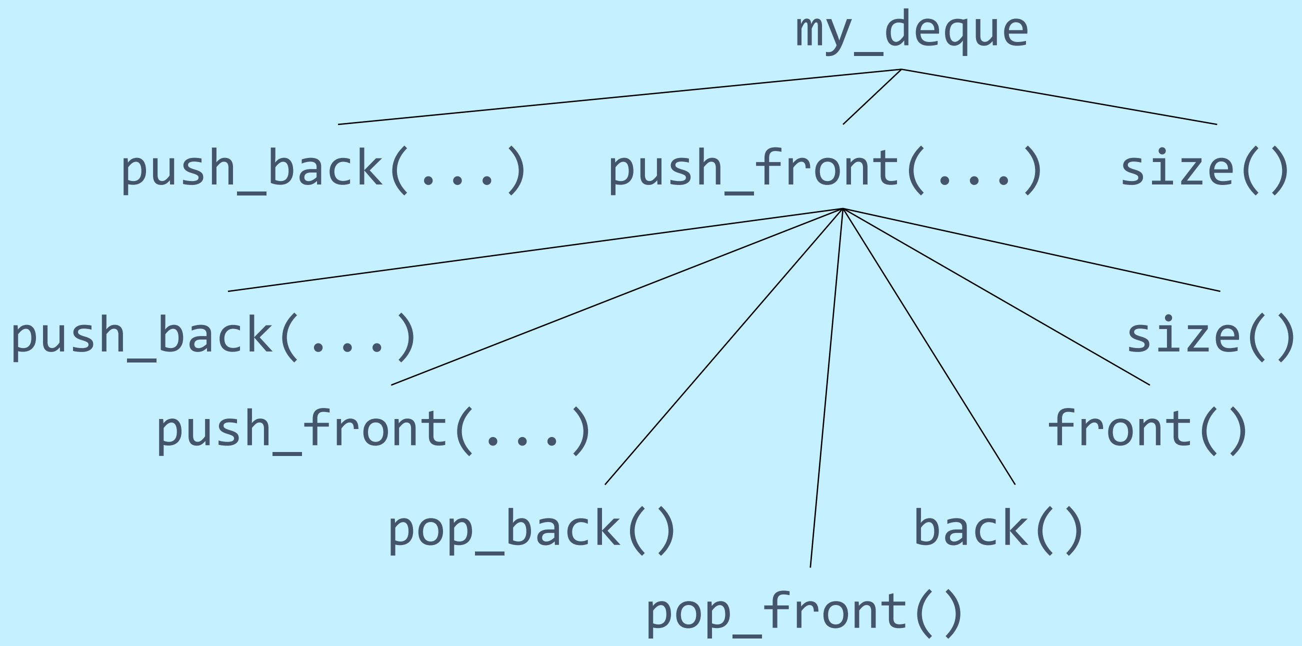
Too many states



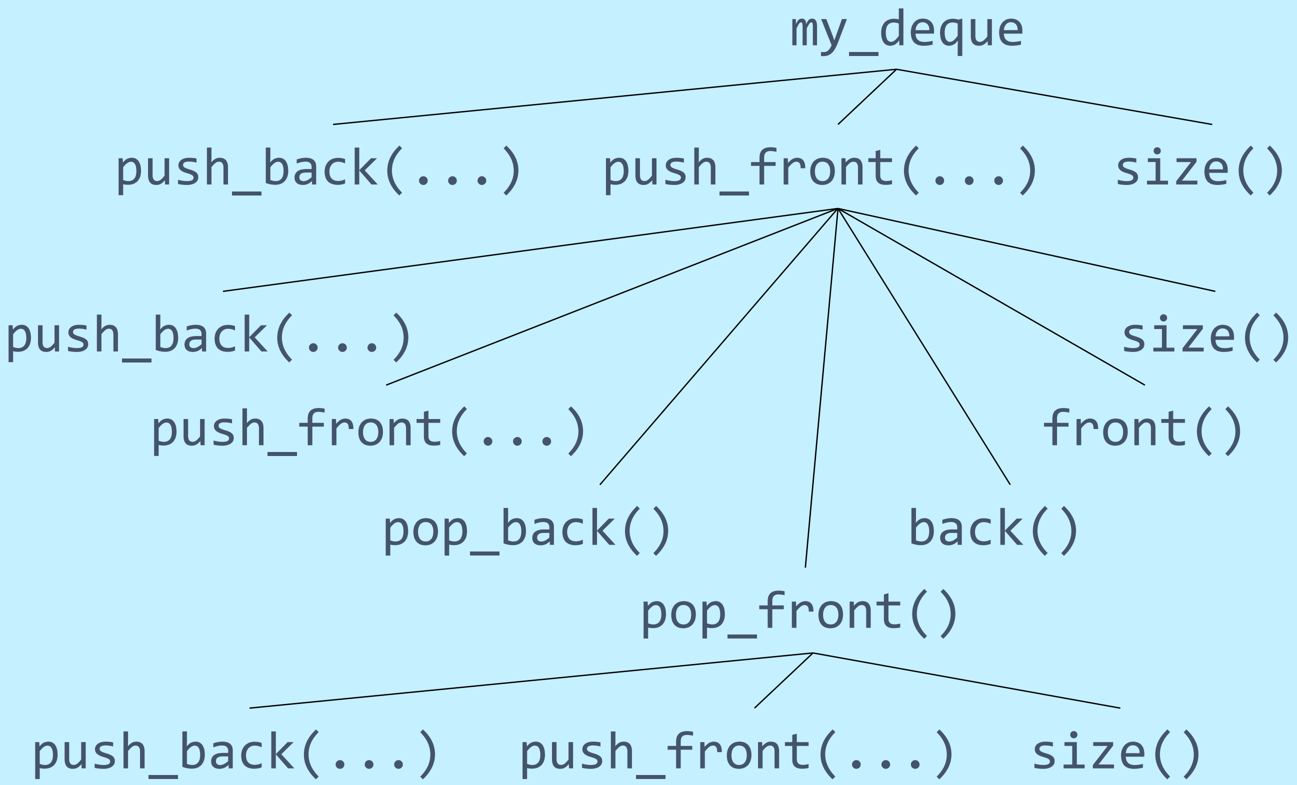
my_deque

push_back(...) push_front(...) size()

Too many states



Too many states



my_deque

push_back(...) push_front(...) size()

push_back(...)

push_front(...)

pop_back()

pop_front()

back()

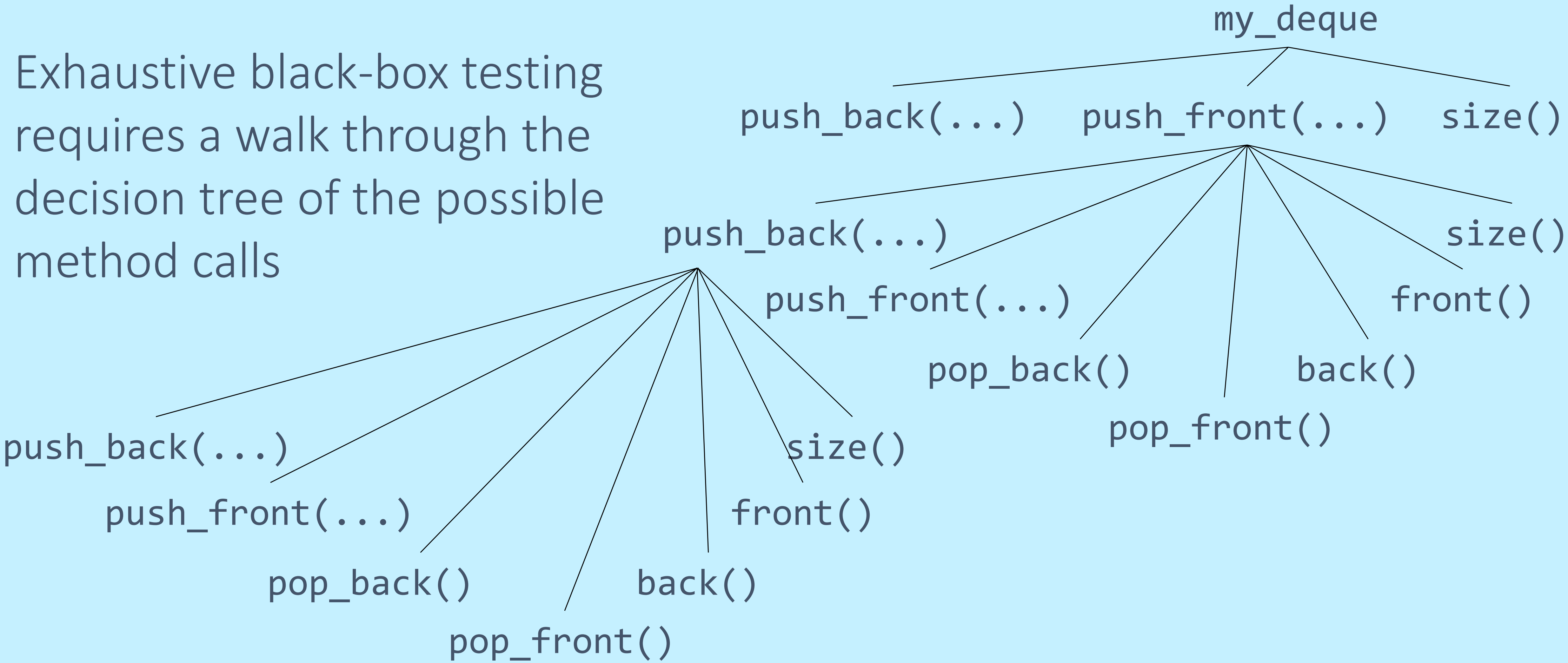
front()

size()

push_back(...) push_front(...) size()

Too many states

- Exhaustive black-box testing requires a walk through the decision tree of the possible method calls



my_deque

push_back(...) push_front(...) size()

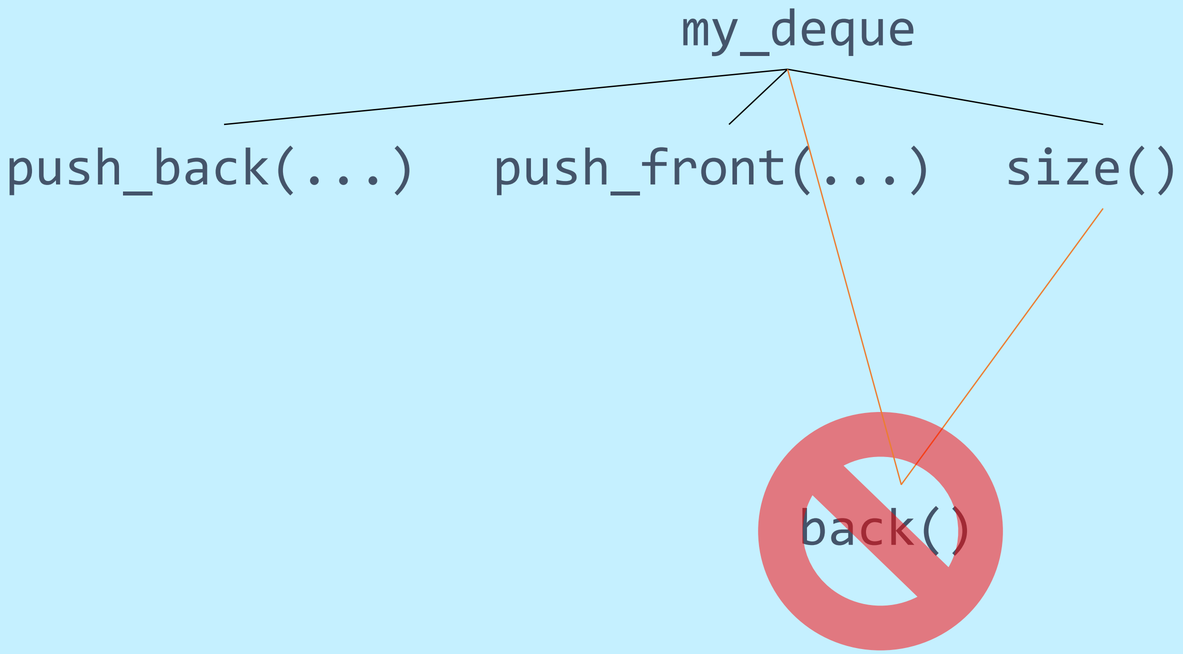
push_back(...)
push_front(...)
pop_back()
pop_front()
back()
front()
size()

push_back(...)
push_front(...)
pop_back()
pop_front()
back()
front()
size()

The sky is the limit!

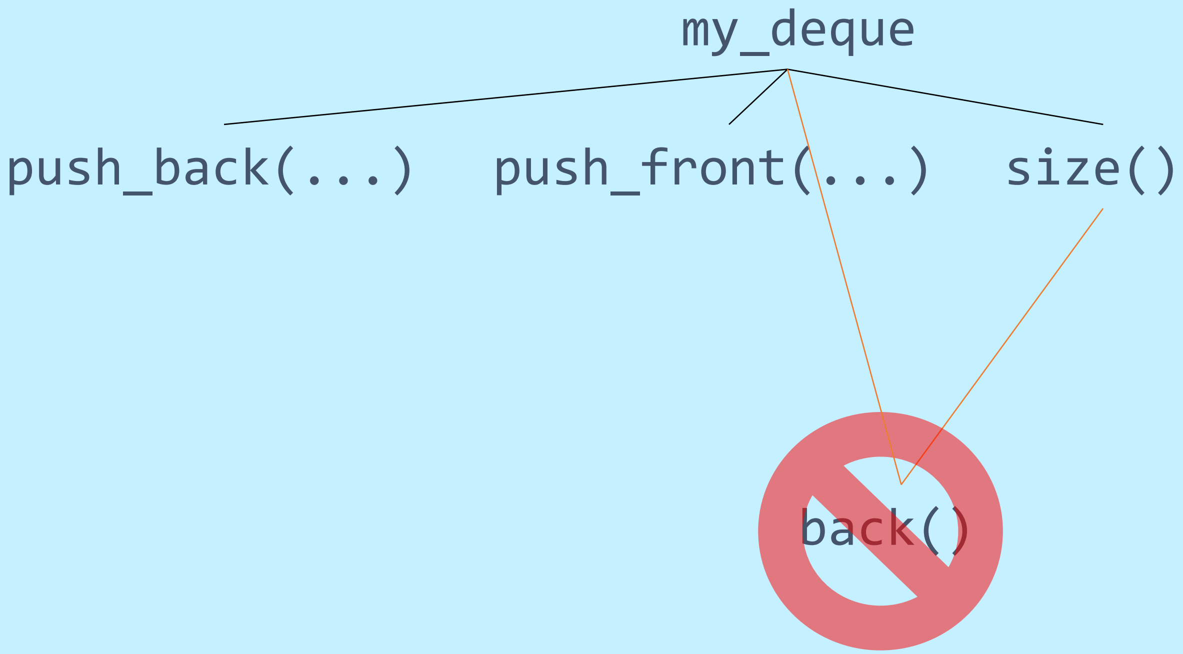
Too many states

- Exhaustive black-box testing requires a walk through the decision tree of the possible method calls
- Still need to pay attention to the preconditions



Too many states

- Exhaustive black-box testing requires a walk through the decision tree of the possible method calls
- Still need to pay attention to the preconditions
- Whitebox testing is limited by the imagination of the test developer



Too many states

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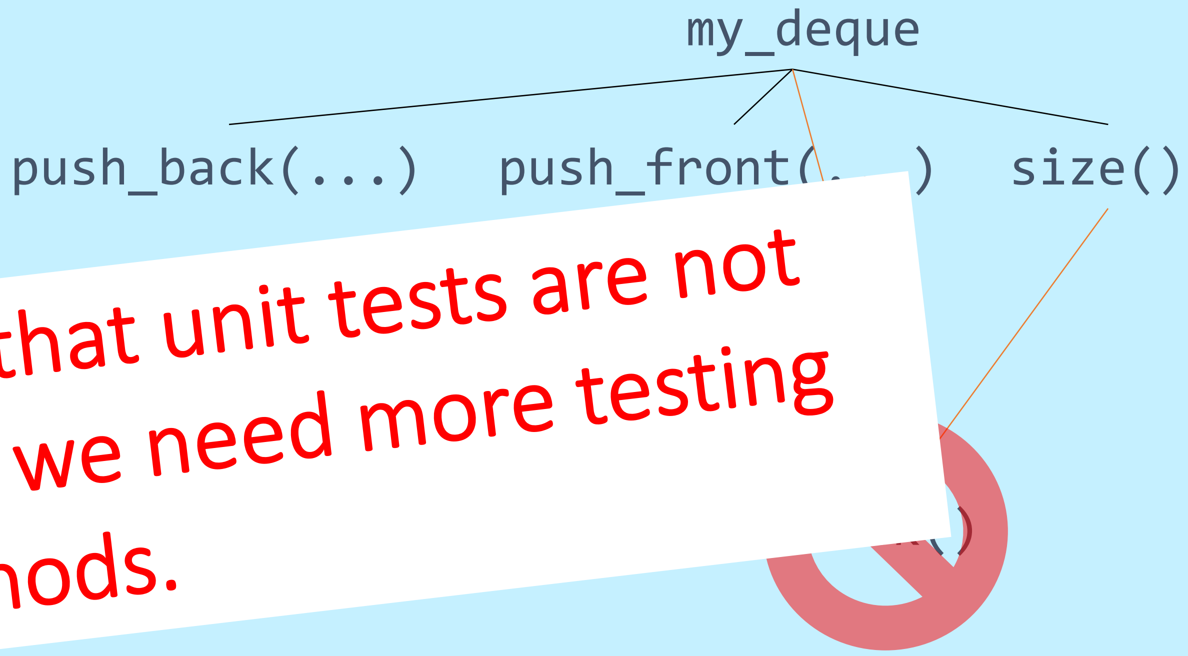

This is does not mean that unit tests are not worth doing. Only that we need more testing methods.

What we would need

- Automatic generation of test cases based on class interface

```cpp
struct my_deque {
    void push_back(int);
    void pop_back();
    int back() const;

    void push_front(int);
    void pop_front();
    int front() const;

    std::size_t size() const;
private:
    // ...
};
```

```cpp
my_deque md;
md.push_back(12);
md.push_back(35);
```

What we would need

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struct my_deque {
    void push_back(int);
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my_deque md;
md.push_back(12);
md.push_back(35);

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```
my_deque md;
md.push_back(12);
md.push_back(35);

my_deque md;
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md.pop_front();

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```

🚫

```
my_deque md;
md.pop_front();
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```

What we would need

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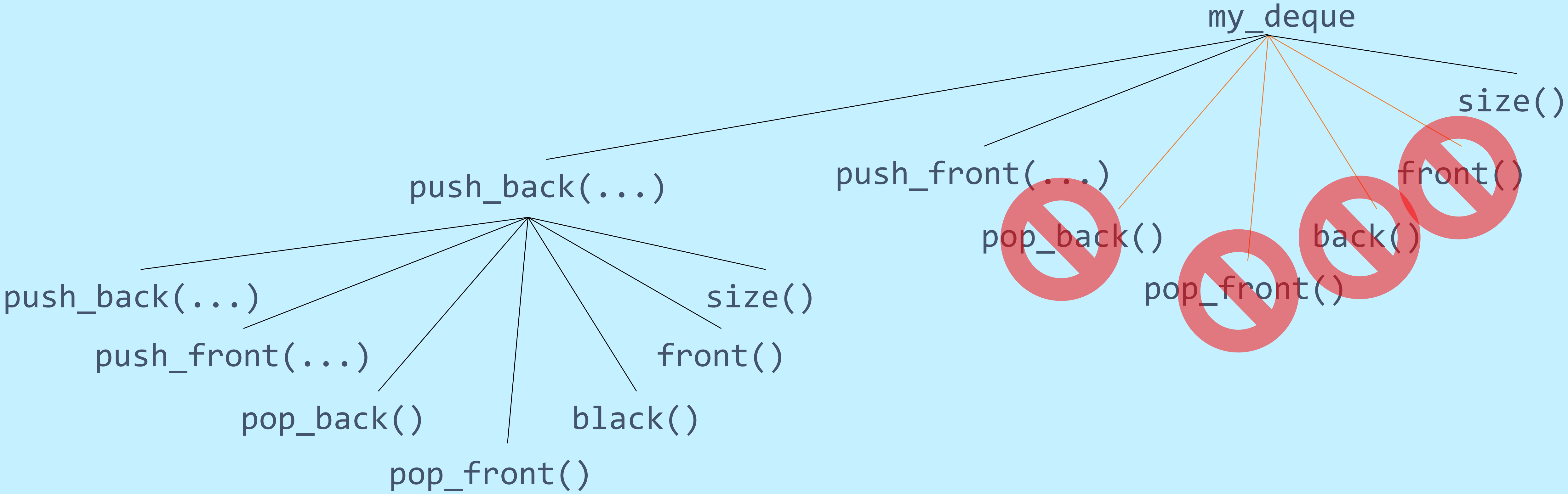
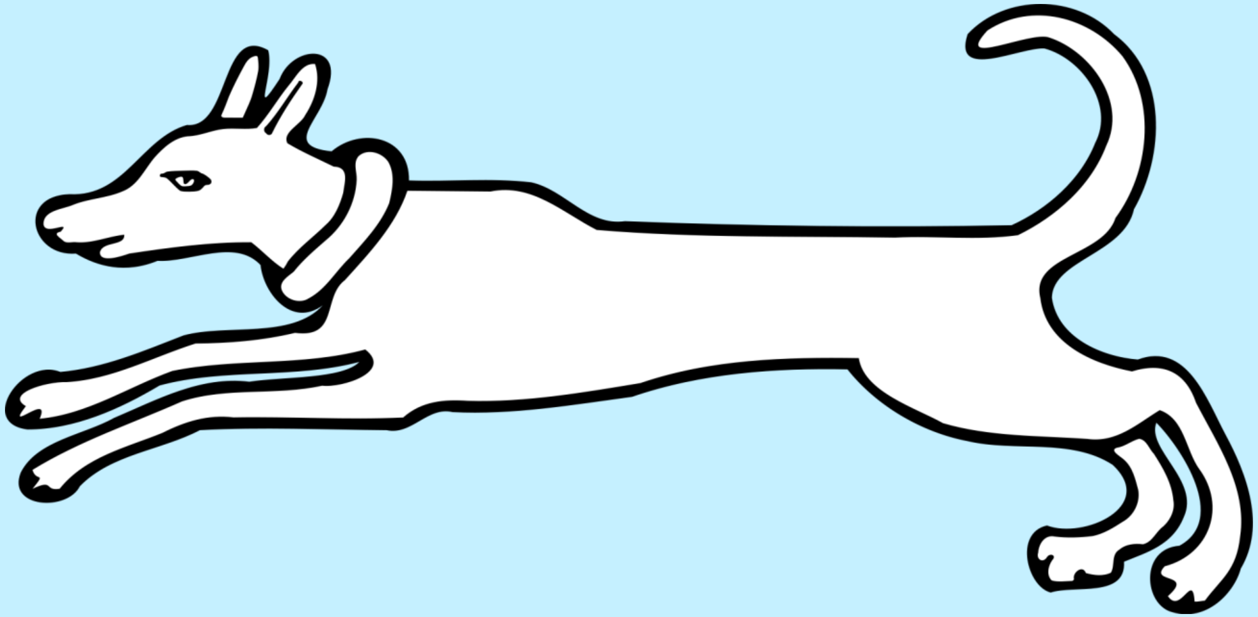


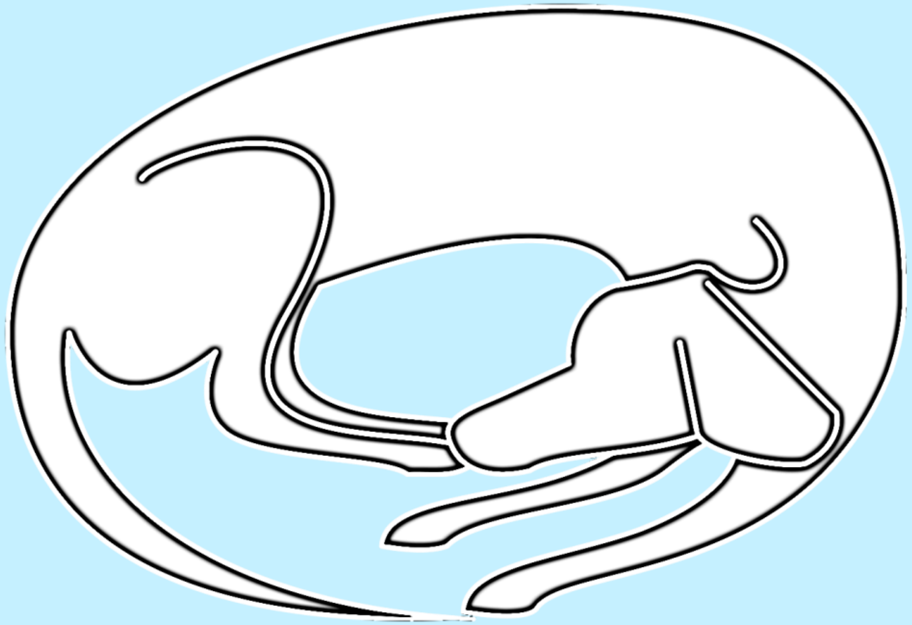
What we would need

- Automatic generation of test cases based on class interface
- Filtering out invalid method calls
- Running test cases on the fly



What we would need

- Automatic generation of test cases based on class interface
- Filtering out invalid method calls
- Running test cases on the fly
- Persisting test cases for later regression testing



What we would need

- Automatic generation of test cases based on class interface
- Filtering out invalid method calls
- Running test cases on the fly
- Persisting test cases for later regression testing
- Filtering out redundant test cases

```
MyDeque md;
MyDeque.size();
```

<

```
MyDeque md;
MyDeque.size();
MyDeque.size();
```

What we would need

- Automatic generation of test cases based on class interface
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- Maximize combined coverage
- Find more than just crashes

What we would need

- Automatic generation of test cases ✓
- Filtering out invalid method calls ?
- Running test cases on the fly ✓
- Persisting test cases for later regression testing ✓
- Filtering out redundant test cases ✓
- Maximize combined coverage ✓
- Find more than just crashes ?

Fuzzing fits most of the criteria

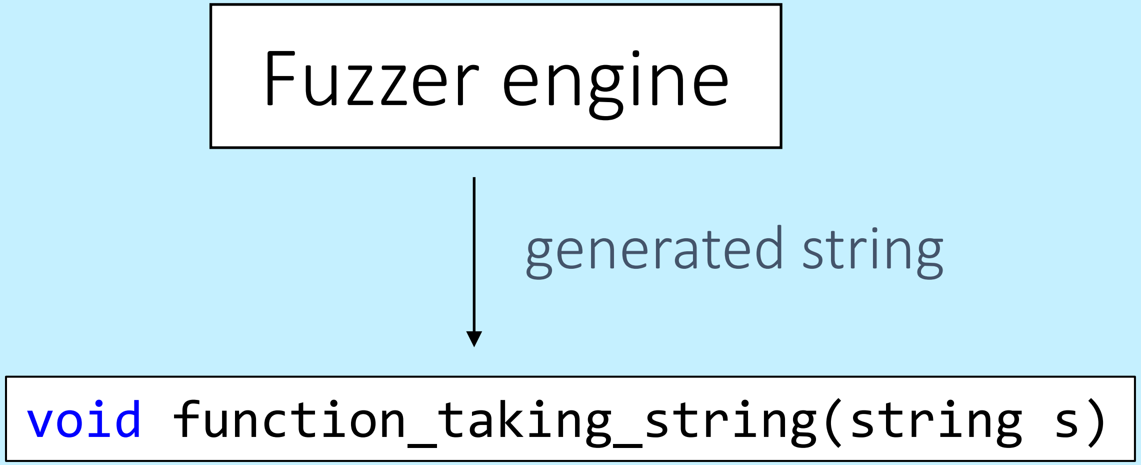
What is this "fuzzing"?

Additional info: "CppCon 2017: Kostya Serebryany \"Fuzz or lose...\""

Fuzzing in general

Fuzzer engine

Fuzzing in general

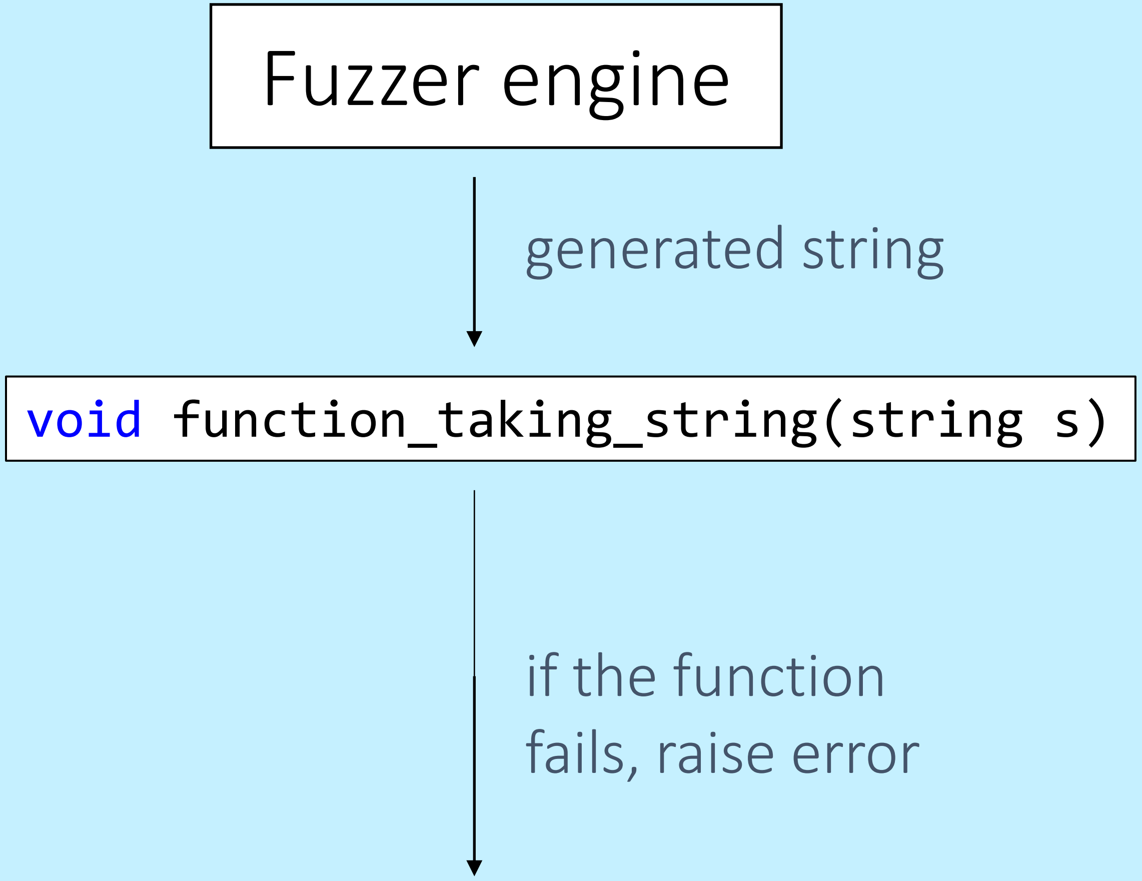


Fuzzer engine

generated string

```
void function_taking_string(string s)
```

Fuzzing in general



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void function_taking_string(string s)
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if the function
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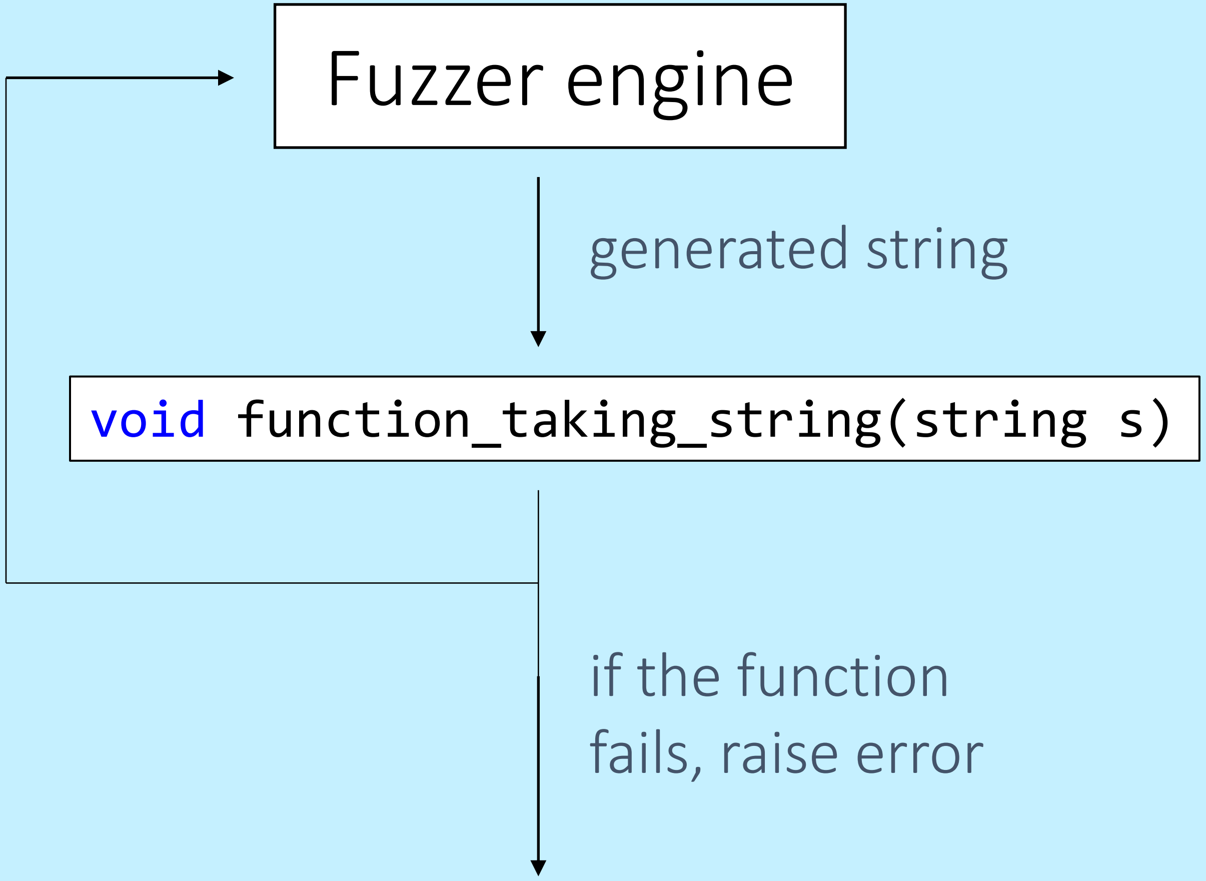
Fuzzing in general



Fuzzer engine

generated string

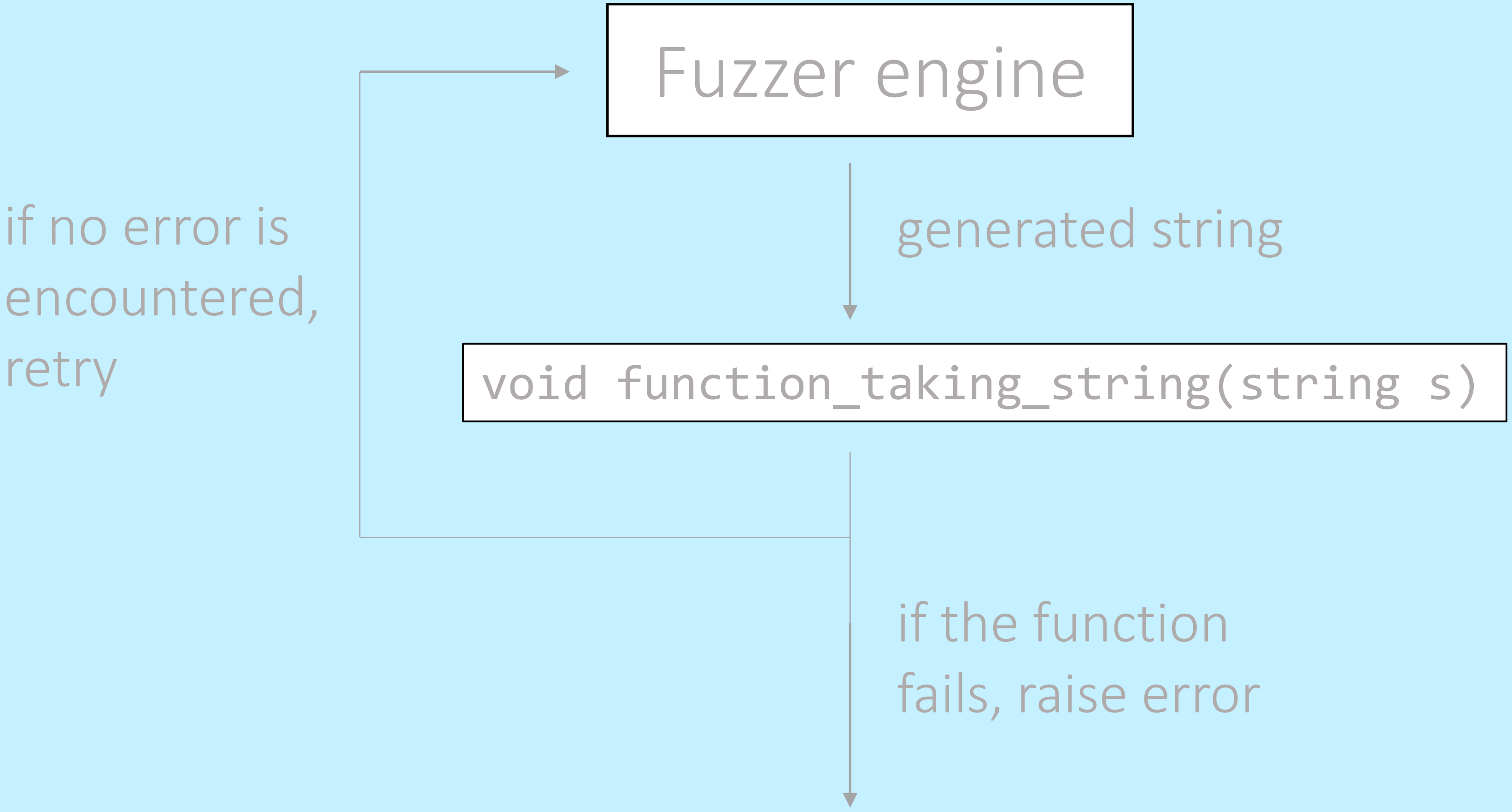
```
void function_taking_string(string s)
```

if no error is encountered, retry

if the function fails, raise error

Fuzzing methods have a proven track record, with thousands of crashes found

LLVM/Clang libFuzzer



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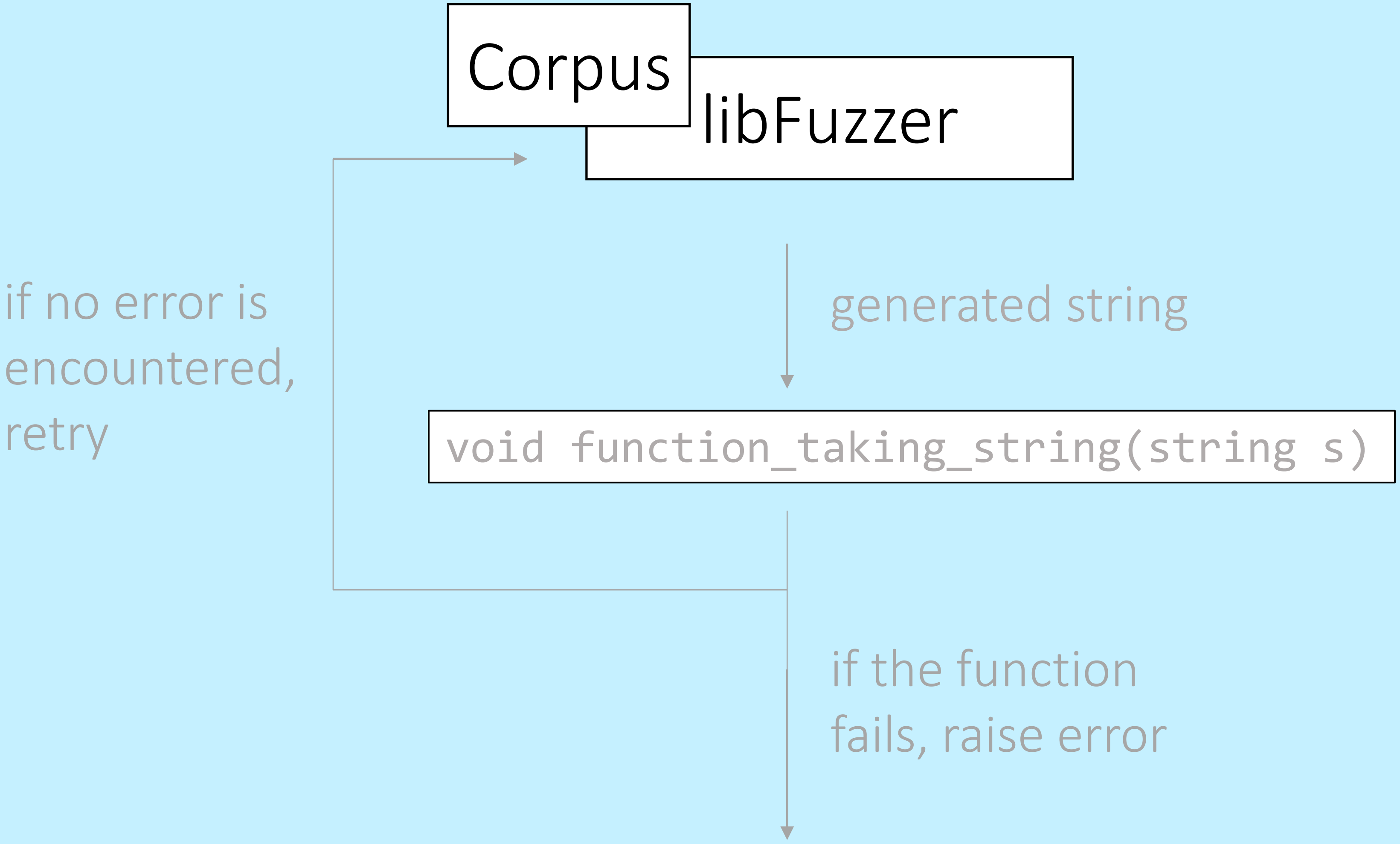
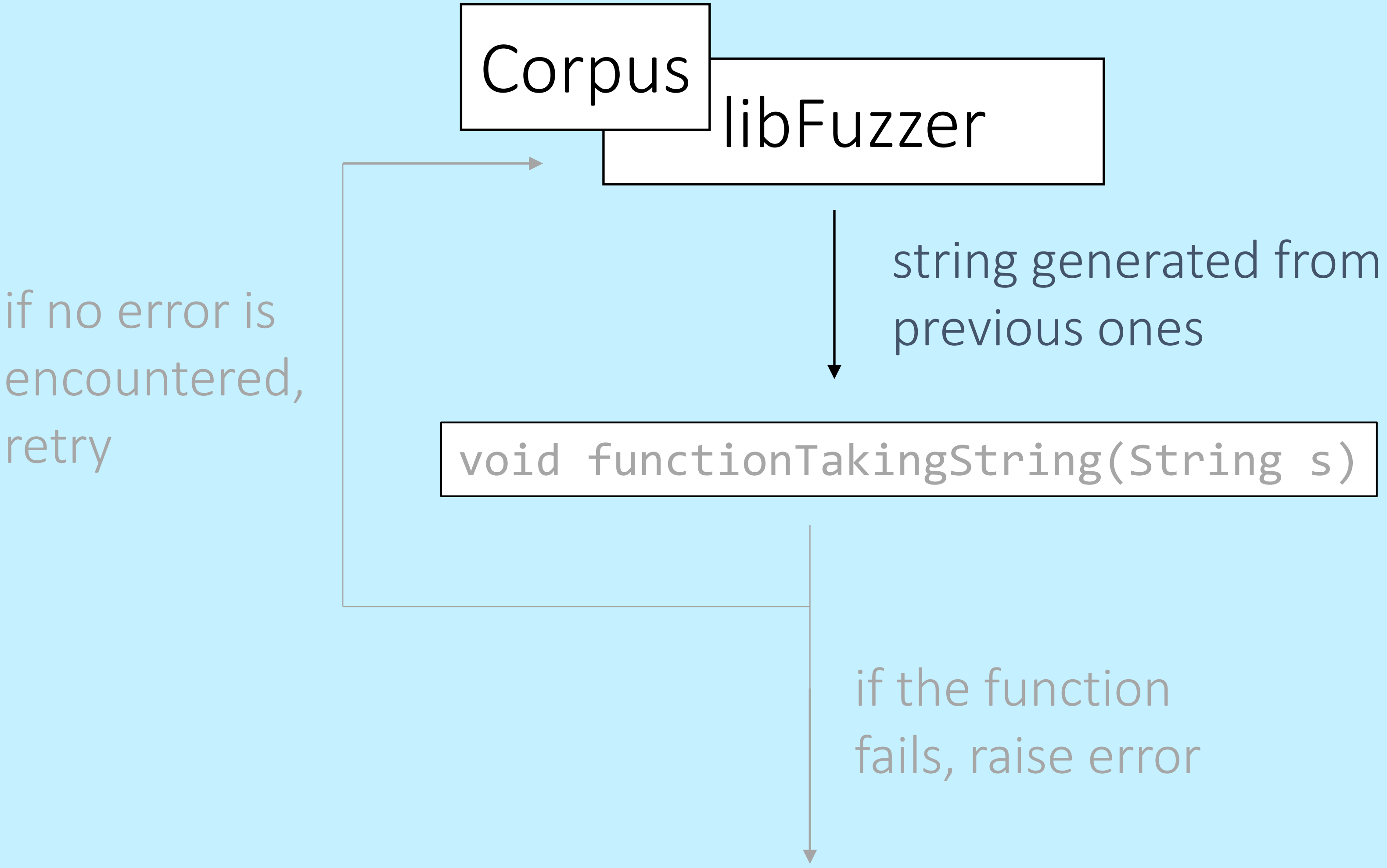

Corpus
libFuzzer
generated string
if no error is encountered, retry
if the function fails, raise error

```
void function_taking_string(string s)
```

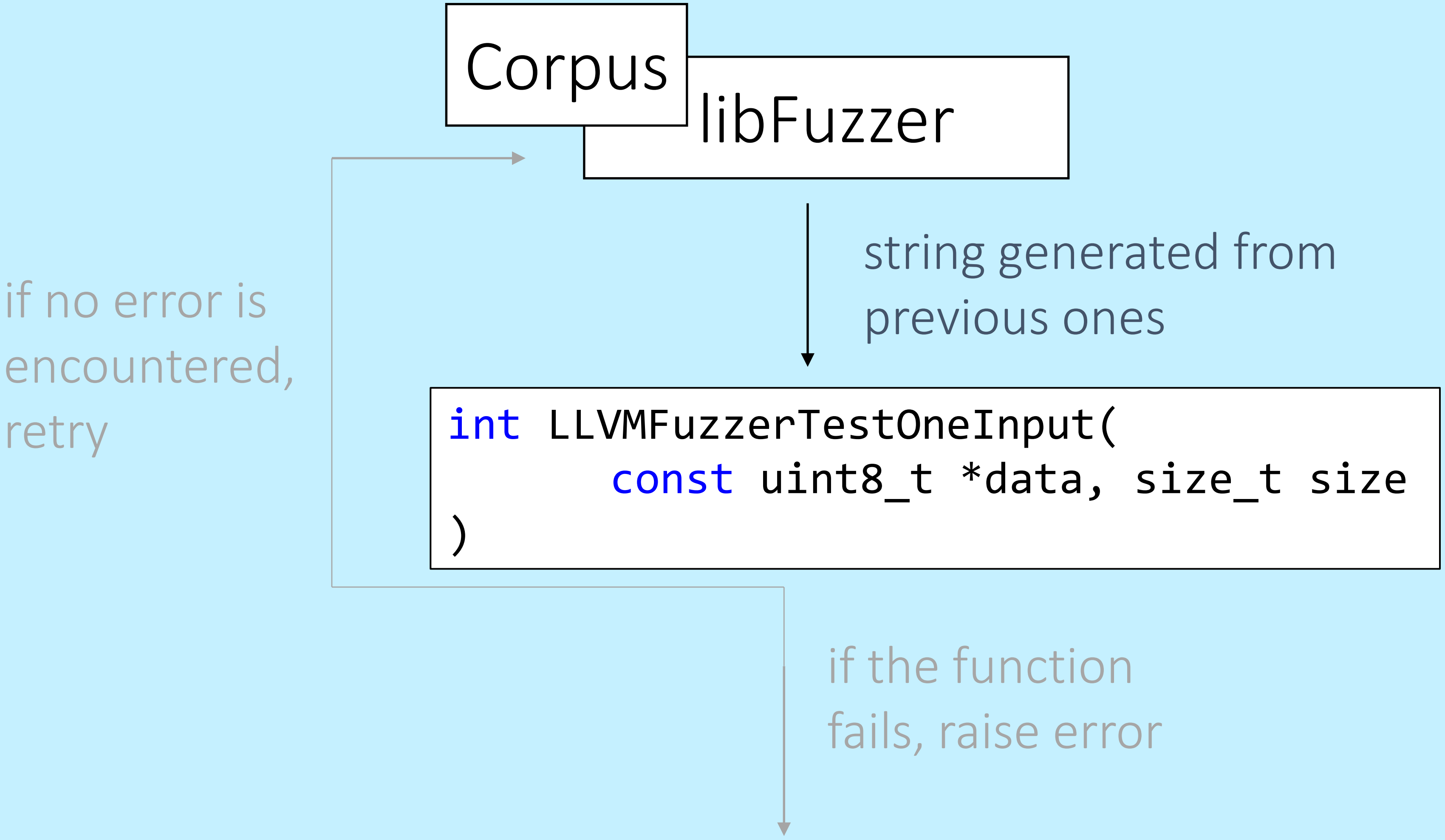
- maintains a set of interesting string arguments

LLVM/Clang libFuzzer


Corpus
libFuzzer
string generated from previous ones
void functionTakingString(String s)
if no error is encountered, retry
if the function fails, raise error

- maintains a set of string arguments which achieves maximum coverage
- uses coverage to guide the string generation

LLVM/Clang libFuzzer



Corpus

libFuzzer

string generated from previous ones

```
int LLVMFuzzerTestOneInput(
        const uint8_t *data, size_t size
)
```

if no error is encountered, retry

if the function fails, raise error

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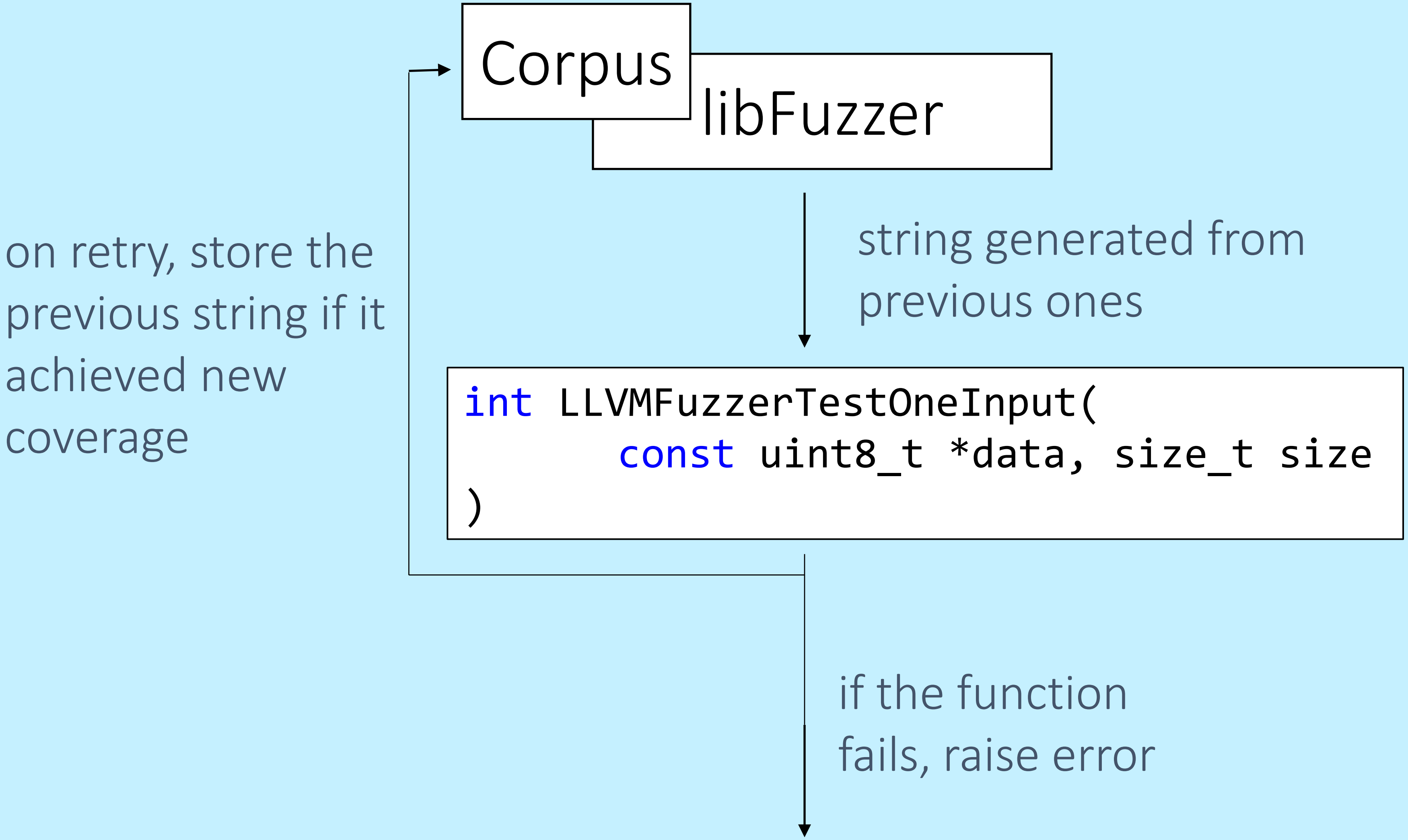
LLVM/Clang libFuzzer



Corpus

libFuzzer

string generated from previous ones

```
int LLVMFuzzerTestOneInput(
        const uint8_t *data, size_t size
)
```

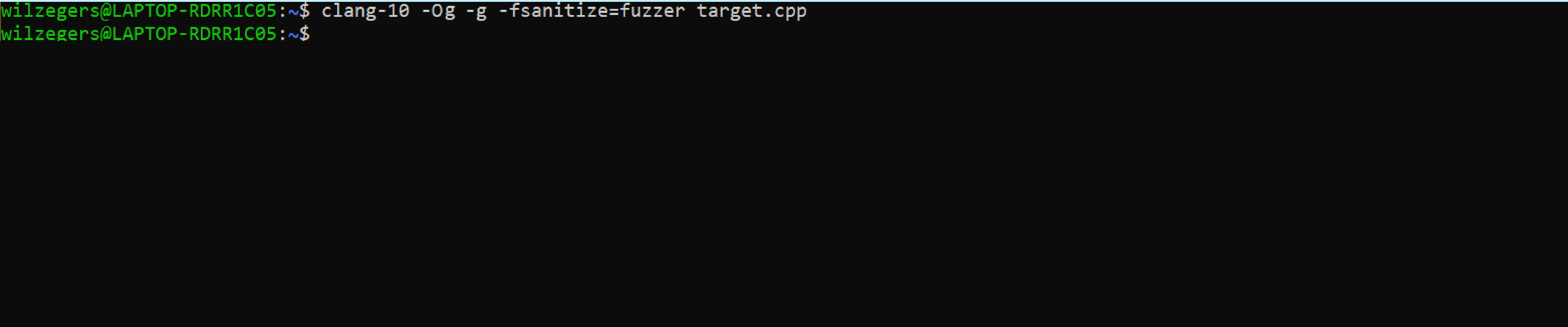
on retry, store the previous string if it achieved new coverage

if the function fails, raise error

- maintains a set of string arguments which achieves maximum coverage
- uses coverage to guide the string generation

Fuzzing example

```
extern "C" int LLVMFuzzerTestOneInput(const uint8_t *data, size_t size) {
    if (size > 1 && data[0] == '1' && data[1] == '2') {
        if (data[2] == '3') {
            static_cast<char*>(0)[4] = '4';
        }
    }
}
```



```
wilzegers@LAPTOP-RDRR1C05:~$ clang-10 -Og -g -fsanitize=fuzzer target.cpp
wilzegers@LAPTOP-RDRR1C05:~$
```

Fuzzing example

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            static_cast<char*>(0)[4] = '4';
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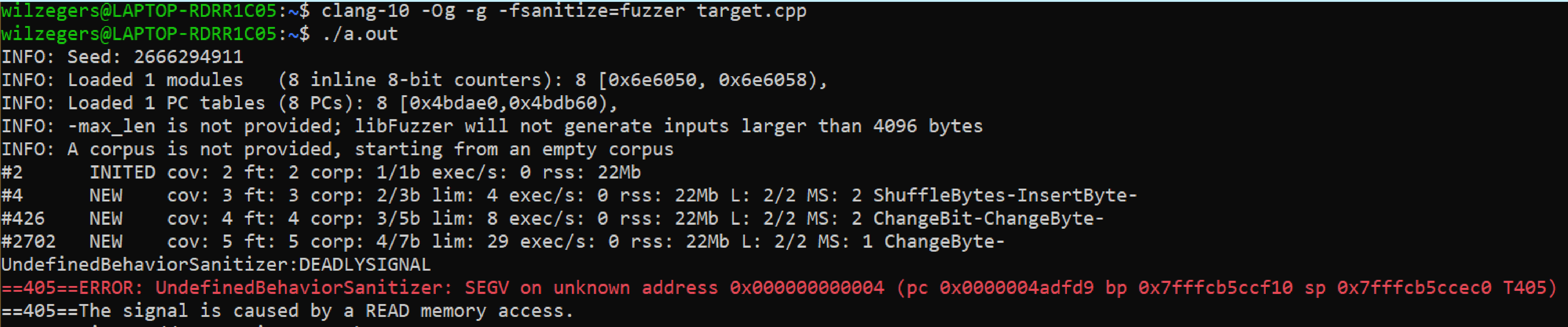
    }
}
```



```
wilzegers@LAPTOP-RDRR1C05:~$ clang-10 -Og -g -fsanitize=fuzzer target.cpp
wilzegers@LAPTOP-RDRR1C05:~$ ./a.out
INFO: Seed: 2666294911
INFO: Loaded 1 modules   (8 inline 8-bit counters): 8 [0x6e6050, 0x6e6058),
INFO: Loaded 1 PC tables (8 PCs): 8 [0x4bdae0,0x4bdb60),
INFO: -max_len is not provided; libFuzzer will not generate inputs larger than 4096 bytes
INFO: A corpus is not provided, starting from an empty corpus
#2      INITED cov: 2 ft: 2 corp: 1/1b exec/s: 0 rss: 22Mb
#4      NEW    cov: 3 ft: 3 corp: 2/3b lim: 4 exec/s: 0 rss: 22Mb L: 2/2 MS: 2 ShuffleBytes-InsertByte-
#426    NEW    cov: 4 ft: 4 corp: 3/5b lim: 8 exec/s: 0 rss: 22Mb L: 2/2 MS: 2 ChangeBit-ChangeByte-
#2702   NEW    cov: 5 ft: 5 corp: 4/7b lim: 29 exec/s: 0 rss: 22Mb L: 2/2 MS: 1 ChangeByte-
UndefinedBehaviorSanitizer:DEADLYSIGNAL
==405==ERROR: UndefinedBehaviorSanitizer: SEGV on unknown address 0x000000000004 (pc 0x0000004adfd9 bp 0x7fffcb5ccf10 sp 0x7fffcb5ccec0 T405)
==405==The signal is caused by a READ memory access.
```

Clang Sanitizers

Sanitizers are compiler build-in error detectors with relatively small runtime cost. Clang has

- AddressSanitizer - use-after-free, double-free, ...
- MemorySanitizer - uninitialized reads
- UndefinedBehaviourSanitizer - overflows, divide by zero, ...
- ThreadSanitizer - data races

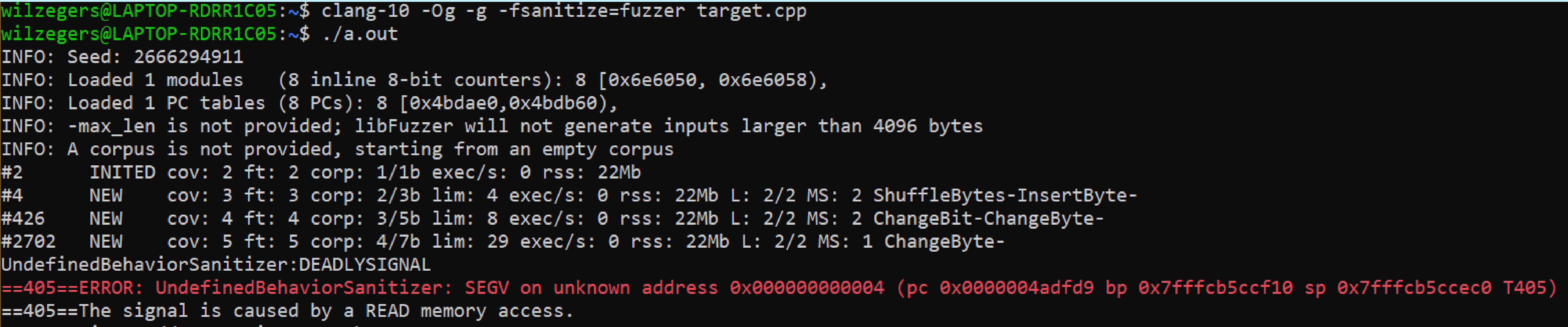
Turning them on:

```
$ clang -g -fsanitize=fuzzer,memory target.cpp
```

Additional info: "CppCon 2014: Kostya Serebryany \"Sanitize your C++ code\""

Fuzzing example - UBSanitizer

```
extern "C" int LLVMFuzzerTestOneInput(const uint8_t *data, size_t size) {
    if (size > 1 && data[0] == '1' && data[1] == '2') {
        if (data[2] == '3') {
            static_cast<char*>(0)[4] = '4';
        }
    }
}
```



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==405==The signal is caused by a READ memory access.
```
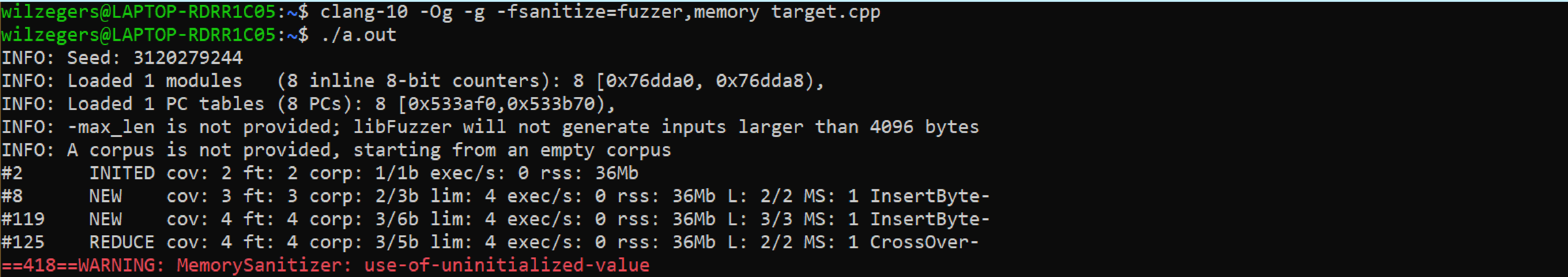

Fuzzing example - MemorySanitizer

```
extern "C" int LLVMFuzzerTestOneInput(const uint8_t *data, size_t size) {
    if (size > 1 && data[0] == '1' && data[1] == '2') {
        if (data[2] == '3') {
            static_cast<char*>(0)[4] = '4';
        }
    }
}
```



```
wilzegers@LAPTOP-RDRR1C05:~$ clang-10 -Og -g -fsanitize=fuzzer,memory target.cpp
wilzegers@LAPTOP-RDRR1C05:~$ ./a.out
INFO: Seed: 3120279244
INFO: Loaded 1 modules   (8 inline 8-bit counters): 8 [0x76dda0, 0x76dda8),
INFO: Loaded 1 PC tables (8 PCs): 8 [0x533af0,0x533b70),
INFO: -max_len is not provided; libFuzzer will not generate inputs larger than 4096 bytes
INFO: A corpus is not provided, starting from an empty corpus
#2      INITED cov: 2 ft: 2 corp: 1/1b exec/s: 0 rss: 36Mb
#8      NEW    cov: 3 ft: 3 corp: 2/3b lim: 4 exec/s: 0 rss: 36Mb L: 2/2 MS: 1 InsertByte-
#119    NEW    cov: 4 ft: 4 corp: 3/6b lim: 4 exec/s: 0 rss: 36Mb L: 3/3 MS: 1 InsertByte-
#125    REDUCE cov: 4 ft: 4 corp: 3/5b lim: 4 exec/s: 0 rss: 36Mb L: 2/2 MS: 1 CrossOver-
==418==WARNING: MemorySanitizer: use-of-uninitialized-value
```

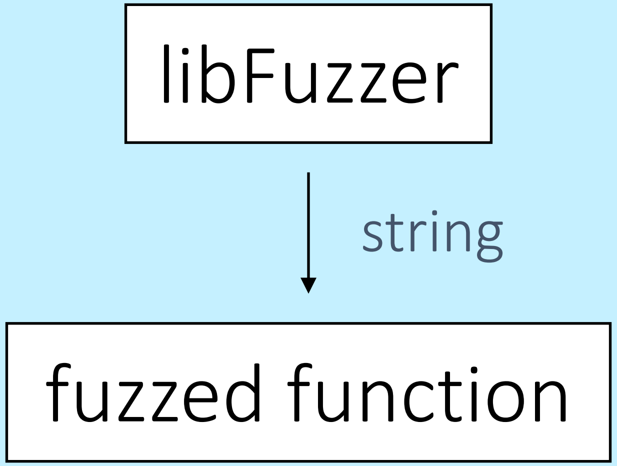
What we would need

- Automatic generation of test cases ✓
- Filtering out invalid method calls ?
- Running test cases on the fly ✓
- Persisting test cases for later regression testing ✓
- Filtering out redundant test cases ✓
- Maximize combined coverage ✓
- Find more than just crashes ?

Fuzzing fits most of the criteria

How does fuzzing help us?
We won't be testing just
string interfaces...

Transforming libFuzzer to an Interface Fuzzer



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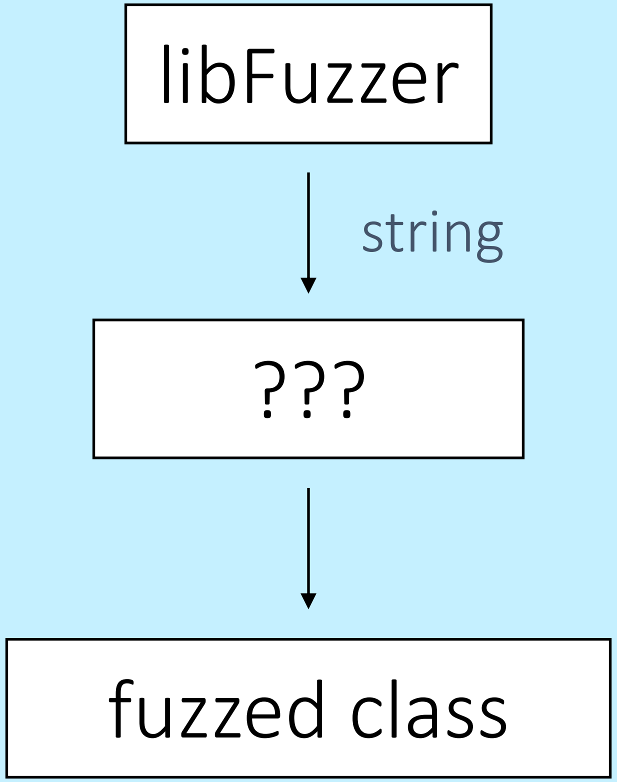
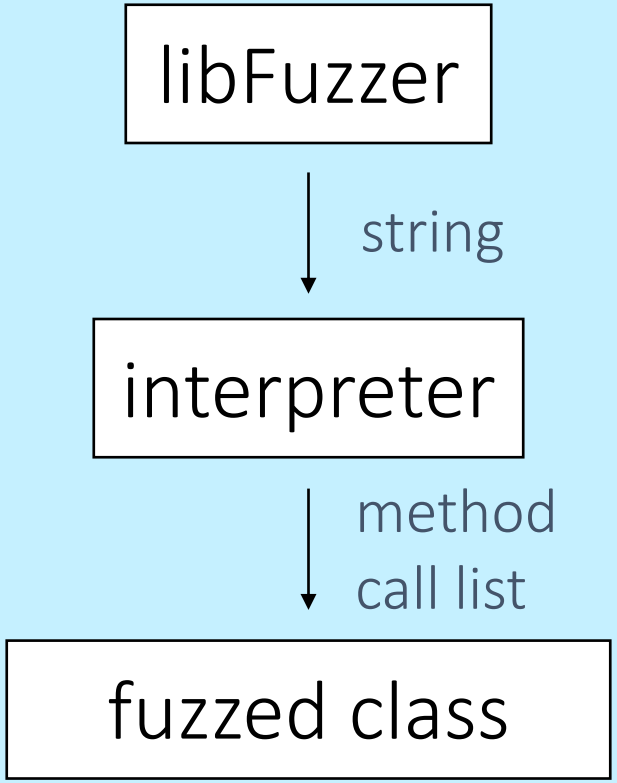
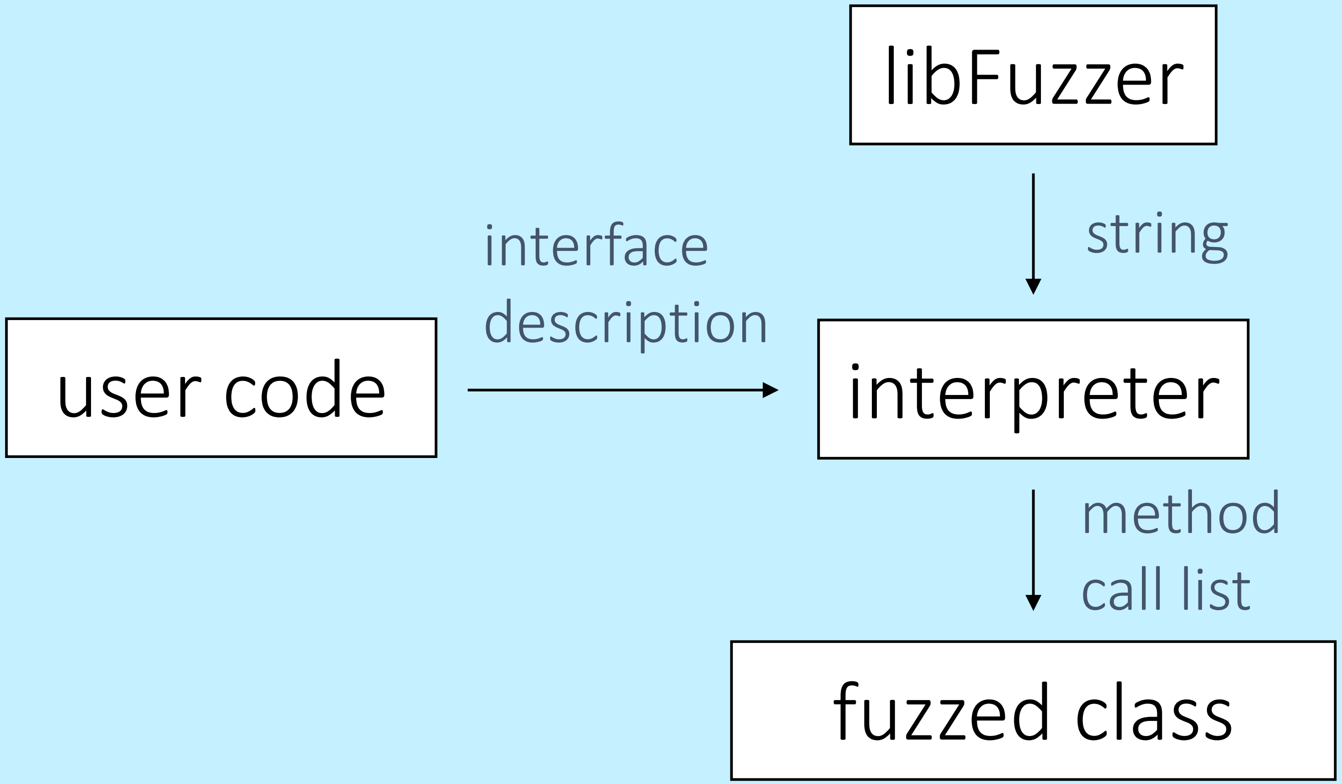


Transforming libFuzzer to an Interface Fuzzer



Transforming libFuzzer to an Interface Fuzzer



Interface Description

List of the methods

```
Autotest::Builder<my_deque>
    .CONST_FUN(size)
    .CONST_FUN(back)
    .CONST_FUN(front)
    .FUN(pop_back)
    .FUN(pop_front)
    .FUN(push_back)
    .FUN(push_front)
```

Interface Description

List of the methods, their preconditions

```
auto not_empty = [](const auto& self) {
    return self.size() > 0;
};

Autotest::Builder<my_deque>
    .CONST_FUN(size)
    .CONST_FUN(back).If(not_empty)
    .CONST_FUN(front).If(not_empty)
    .FUN(pop_back).If(not_empty)
    .FUN(pop_front).If(not_empty)
    .FUN(push_back)
    .FUN(push_front)
```

Interface Description

List of the methods, their preconditions and "argument placeholders"

```
auto not_empty = [](const auto& self) {
    return self.size() > 0;
};

Autotest::Builder<my_deque>
    .CONST_FUN(size)
    .CONST_FUN(back).If(not_empty)
    .CONST_FUN(front).If(not_empty)
    .FUN(pop_back).If(not_empty)
    .FUN(pop_front).If(not_empty)
    .FUN(push_back, integral<int>)
    .FUN(push_front, integral<int>)
```

Interface Description

List of the methods, their preconditions and "argument placeholders"

```
auto not_empty = [](const auto& self) {
    return self.size() > 0;
};

Autotest::Builder<my_deque>
    .CONST_FUN(size)
    .CONST_FUN(back).If(not_empty)
    .CONST_FUN(front).If(not_empty)
    .FUN(pop_back).If(not_empty)
    .FUN(pop_front).If(not_empty)
    .FUN(push_back, integral<int>)
    .FUN(push_front, integral<int>)
```

0	`std::size_t size() const`
1	`int back() const`
2	`int front() const`
3	`void pop_back()`
4	`void pop_front()`
5	`void push_back(int)`
6	`void push_front(int)`

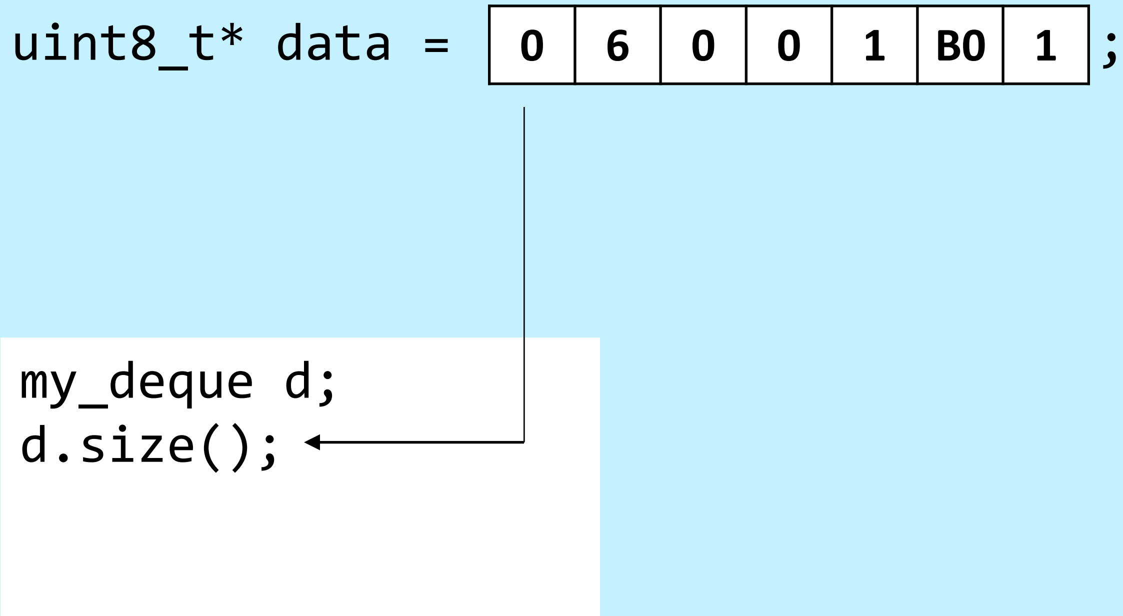
Interpreting the Generated Strings

```
uint8_t* data = | 0 | 6 | 0 | 0 | 1 | B0 | 1 | ;
```

Process:

- Choose nth method with a satisfied precondition

Interpreting the Generated Strings



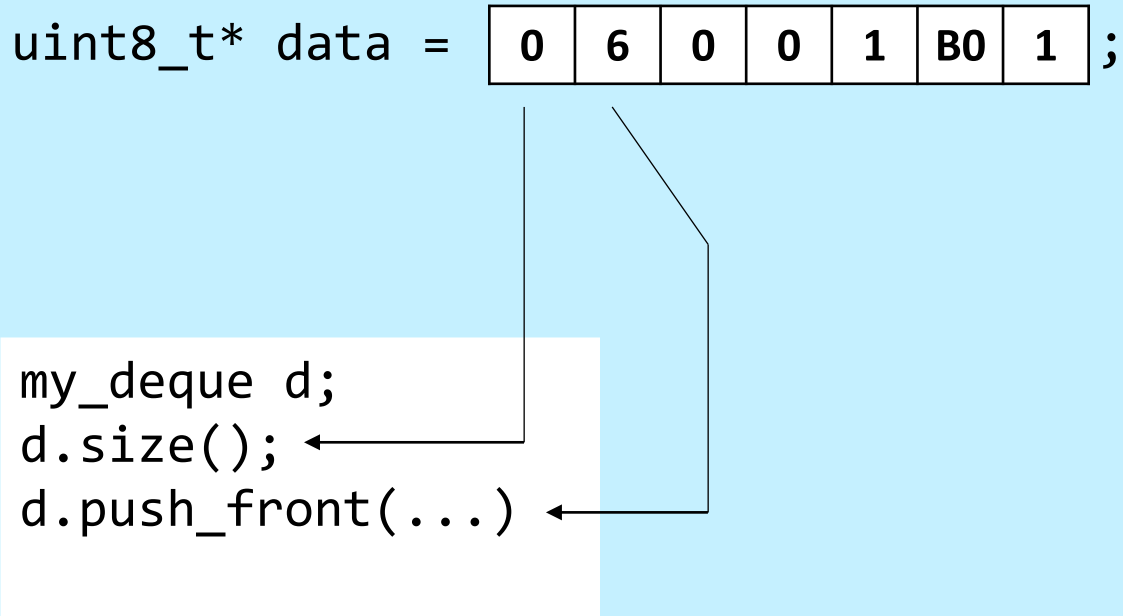
```
uint8_t* data = | 0 | 6 | 0 | 0 | 1 | B0 | 1 | ;
```

```
my_deque d;
d.size();
```

Process:

- Choose nth method with a satisfied precondition

Interpreting the Generated Strings



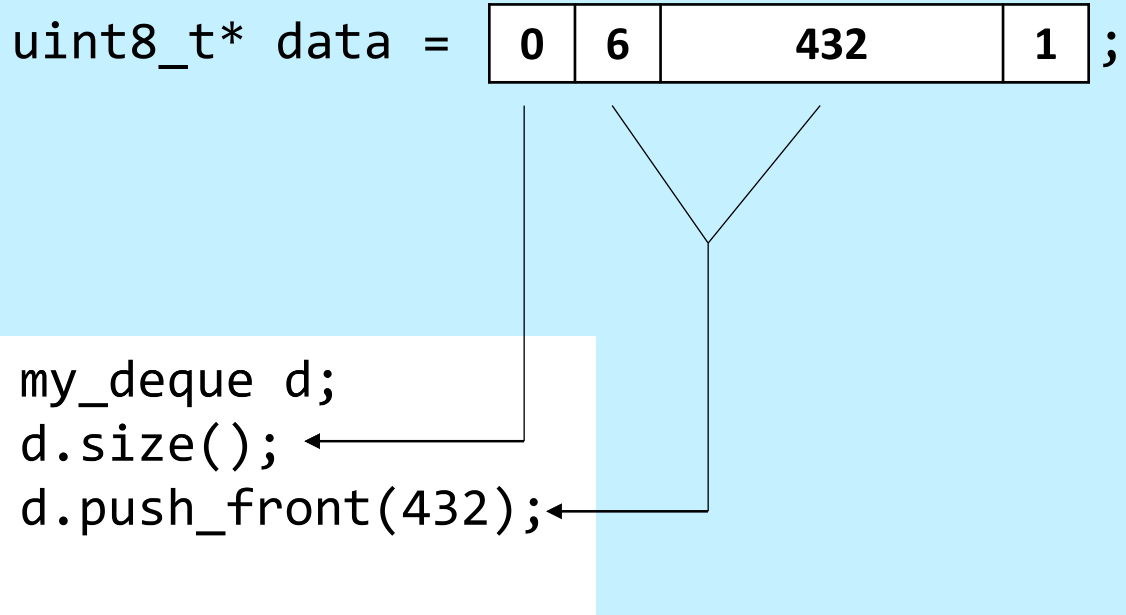
```
uint8_t* data = | 0 | 6 | 0 | 0 | 1 | B0 | 1 | ;
```

```
my_deque d;
d.size();
d.push_front(...)
```

Process:

- Choose n^th method with a satisfied precondition

Interpreting the Generated Strings



uint8_t* data =

0	6	432	1

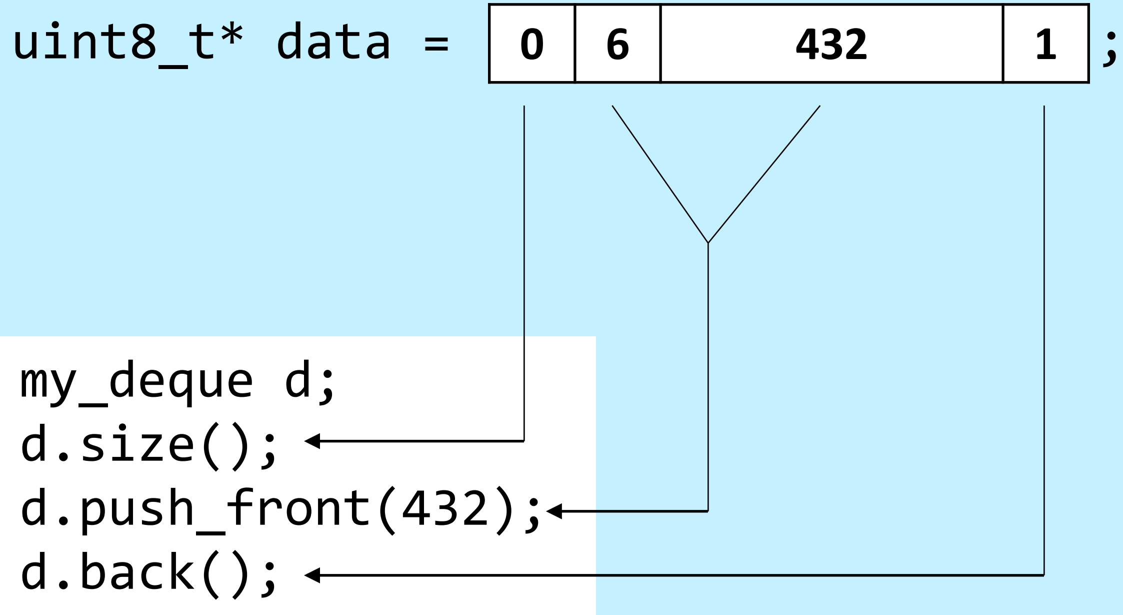
;

```
my_deque d;
d.size();
d.push_front(432);
```

Process:

- Choose nth method with a satisfied precondition
- Read arguments from the generated data

Interpreting the Generated Strings



```
uint8_t* data = 
```

0	6	432	1

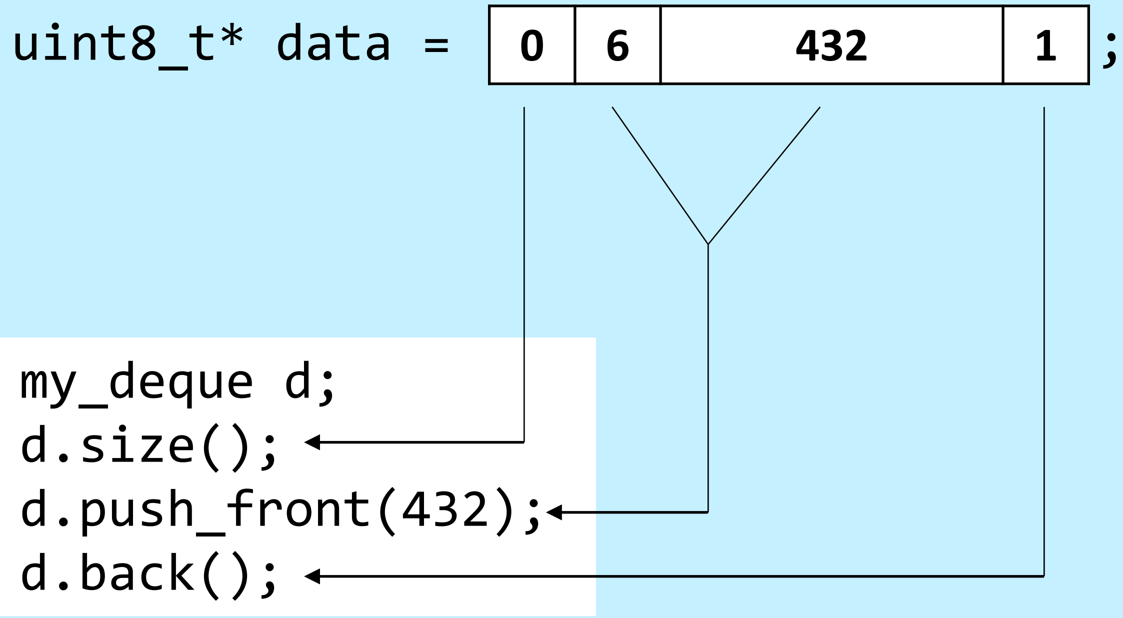
```
;
```

```
my_deque d;
d.size();
d.push_front(432);
d.back();
```

Process:

- Choose nth method with a satisfied precondition
- Read arguments from the generated data

Interpreting the Generated Strings



```
my_deque d;
d.size();
d.push_front(432);
d.back();
```

Process:

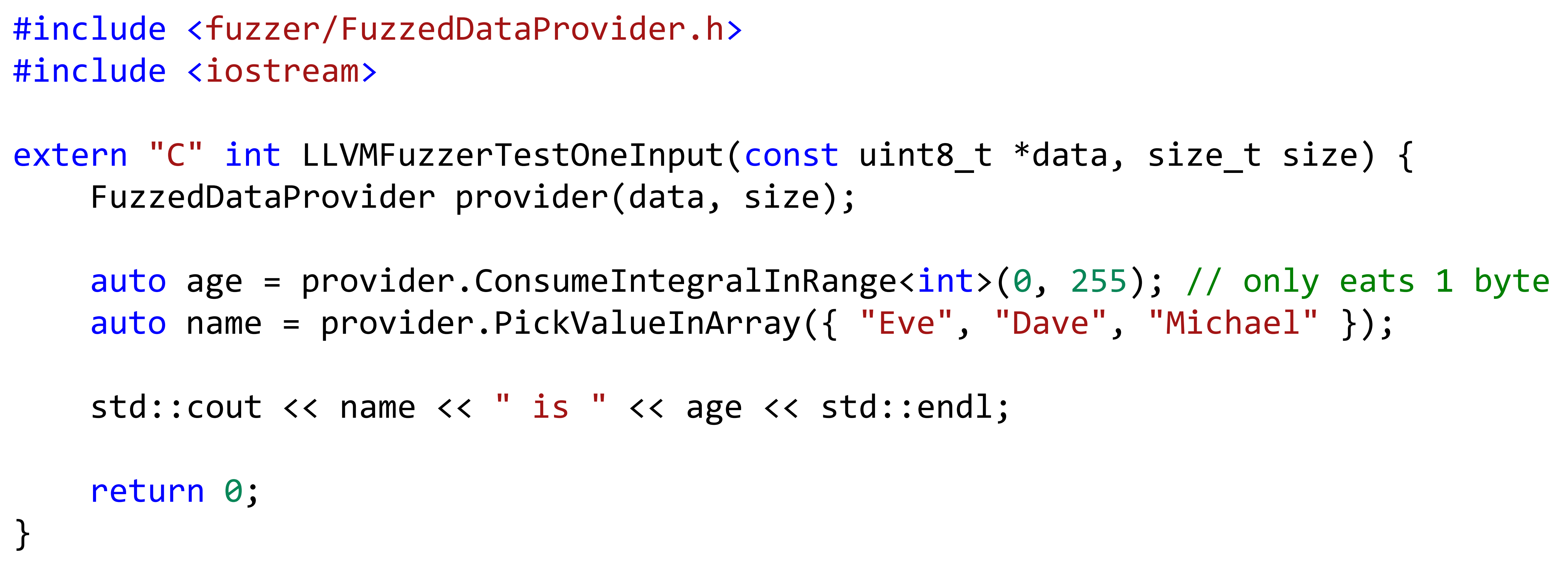
- Choose n^{th} method with a satisfied precondition
- Read arguments from the generated data

Edge cases:

- Integer too big
- Not enough bytes available

libFuzzer utilities to the rescue!

libFuzzers FuzzedDataProvider



```cpp
#include <fuzzer/FuzzedDataProvider.h>
#include <iostream>

extern "C" int LLVMFuzzerTestOneInput(const uint8_t *data, size_t size) {
    FuzzedDataProvider provider(data, size);

    auto age = provider.ConsumeIntegralInRange<int>(0, 255); // only eats 1 byte
    auto name = provider.PickValueInArray({ "Eve", "Dave", "Michael" });

    std::cout << name << " is " << age << std::endl;

    return 0;
}
```

The argument placeholders are implemented as T(FuzzedDataProvider&) functions

Crashes are not Enough

Currently the tool is generating test cases like the following

```
MyDeque md;

md.push_back(123)m;
md.push_back(-76);
md.push_back(0);
md.pop_back();
```

```
MyDeque md;

md.push_front(456);
md.front();
md.back();
```

```
MyDeque md;

md.push_back(1);
md.push_front(2);
md.push_back(3);
md.push_front(4);
md.pop_back();
md.pop_front();
md.push_back(5);
md.push_front(6);
```

What if we have bugs which are not revealed by crashes?

Invariants

An invariant is a condition that is always true as long as the object is in a valid state (e.g. in the deque the front position must be <= the back)

```
TEST(my_deque_test, push_pop)
{
    my_deque md;
    ASSERT_EQ(md.size(), 0);

    md.push_back(42);
    ASSERT_EQ(md.size(), 1);
    ASSERT_EQ(md.back(), 42);

    md.pop_back();
    ASSERT_EQ(md.size(), 0);
}
```

Invariants

An invariant is a condition that is always true as long as the object is in a valid state (e.g. in the deque the front position must be <= the back)

```
TEST(my_deque_test, push_pop)
{
    my_deque md;
    ASSERT_EQ(md.size(), 0);

    md.push_back(42);
    ASSERT_EQ(md.size(), 1);
    ASSERT_EQ(md.back(), 42);

    md.pop_back();
    ASSERT_EQ(md.size(), 0);
}
```

```
MyDeque md;

checkInvariant(md);
md.push_front(456);
checkInvariant(md);
md.front();
checkInvariant(md);
md.back();
checkInvariant(md);
```

Invariants

An invariant is a condition that is always true as long as the object is in a valid state (e.g. in the deque the front position must be <= the back)

```
TEST(my_deque_test, push_pop)
{
    my_deque md;
    ASSERT_EQ(md.size(), 0);

                back(), 42);

    md.pop_back();
    ASSERT_EQ(md.size(), 0);
}
```

```
 MyDeque d;

     Invariant(d);
 d.front();
 checkInvariant(d);
 d.back();
 checkInvariant(d);
```

Of course, this is not as strong of a check as manual assertions in unit tests.

Let's put it to the test

Case Study 1: Simplified Deque

- Single-ended "deque": A single ended queue implemented with a vector of static arrays. Shares problems with a real deque.
  - 100% code coverage reached reliably within seconds

```
template<class T>
struct block_array {

    template<class... Args>
    void emplace_back(Args&&... args);
    void pop_back();
    T& back();
    const T& back() const;

   std::size_t size() const;
private:
    // ...
};
```

Case Study 1: Simplified Deque

```
#include "autotest/autotest.hpp"
#include "block-array.hpp"

extern "C" int LLVMFuzzerTestOneInput(const uint8_t *data, size_t size) {
    auto not_empty = [](const auto& self) {
        return self.size() > 0;
    };
    AutoTest::Builder<block_array<int>>{ data, size }
        .AUTOTEST_FUN(emplace_back, AutoTest::Args::integral<int>)
        .AUTOTEST_FUN(pop_back).If(not_empty)
        .AUTOTEST_FUN(back).If(not_empty)
        .AUTOTEST_CONST_FUN(back).If(not_empty)
        .AUTOTEST_CONST_FUN(size)
    .execute();
    return 0;
}
```

Case Study 2: Robin-hood Hash Map

- A Robin-hood hash map implementation: A state-of-the-art hash map implementation, according to some measurements one of the fastest currently available (header only, +2200 lines).
  - fluctuating 88%-93% code coverage reached within a minute
  - after fine-tuning fuzzing parameters, 93% code-coverage reached reliably within a minute
  - the remaining 7% did not seem reachable in the test

hash-map library source: https://github.com/martinus/robin-hood-hashing

Case Study 2: Robin-hood Hash Map

```
extern "C" int LLVMFuzzerTestOneInput(const uint8_t *data, size_t size) {
    using hash_map = robin_hood::unordered_flat_map<
        std::string, std::string
    >;
    auto to_res = Autotest::Args::integralRange(1, 10000);
    auto key = Autotest::Args::randomString(20);
    auto key_val = [](auto& state) {
        return robin_hood::pair<std::string, std::string>(
            Autotest::Args::randomString(20)(state),
            Autotest::Args::randomString(20)(state)
        );
    };

    // ...

}
```

hash-map library source: https://github.com/martinus/robin-hood-hashing

Case Study 2: Robin-hood Hash Map

```
extern "C" int LLVMFuzzerTestOneInput(const uint8_t *data, size_t size) {

    // ...

    Autotest::Builder<hash_map>{ data, size }
        .AUTOTEST_FUN(insert, key_val)
        .AUTOTEST_FUN(emplace, key, key)
        .AUTOTEST_CONST_FUN(count, key)
        .AUTOTEST_CONST_FUN(contains, key)
        .AUTOTEST_FUN(erase, key)
        .AUTOTEST_FUN(reserve, to_res)
        .AUTOTEST_FUN(rehash, to_res)
        .AUTOTEST_CONST_FUN(find, key)
    .execute();
    return 0;
}
```

hash-map library source: https://github.com/martinus/robin-hood-hashing

Summary

- Problem: no tools for mass-testing classes
- Solution: adapt existing fuzzing technology
  - create interface description
  - interpret fuzz string as method list
  - exclude invalid states based on precondition
  - execute interpreted test case
  - smooth interoperation with sanitizers
- First results seem promising
- prototype available at https://gitlab.com/wilzegers/autotest/

Future work

- What about non-containers?
- Make the prototype less prototype-y
- Answering any questions you may have

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- What about non-containers?
- Make the prototype less prototype-y
- Answering any questions you may have

Thank you for your attention

Feel free to contact me (Barnabás Bágyi) at bagyibarna@gmail.com