Adventures in Fuzzing Instruction Selection

Overview

- Hardening instruction selection using fuzzers
- Motivated by Global ISel
- Leveraging libFuzzer to find backend bugs
- Techniques applicable to other parts of LLVM

Fuzzing Recap

- Using random inputs to find bugs
- Input generation
- Mutations of representative inputs
- Guided evolutionary fuzzing (afl-fuzz, libFuzzer)

libFuzzer

```
extern "C" int LLVMFuzzerTestOneInput(
    const uint8_t *Data, size_t Size) {
  if (Size > 0 && Data[0] == 'H')
    if (Size > 1 && Data[1] == 'i')
      if (Size > 2 && Data[2] == '!')
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  return 0;
}
```

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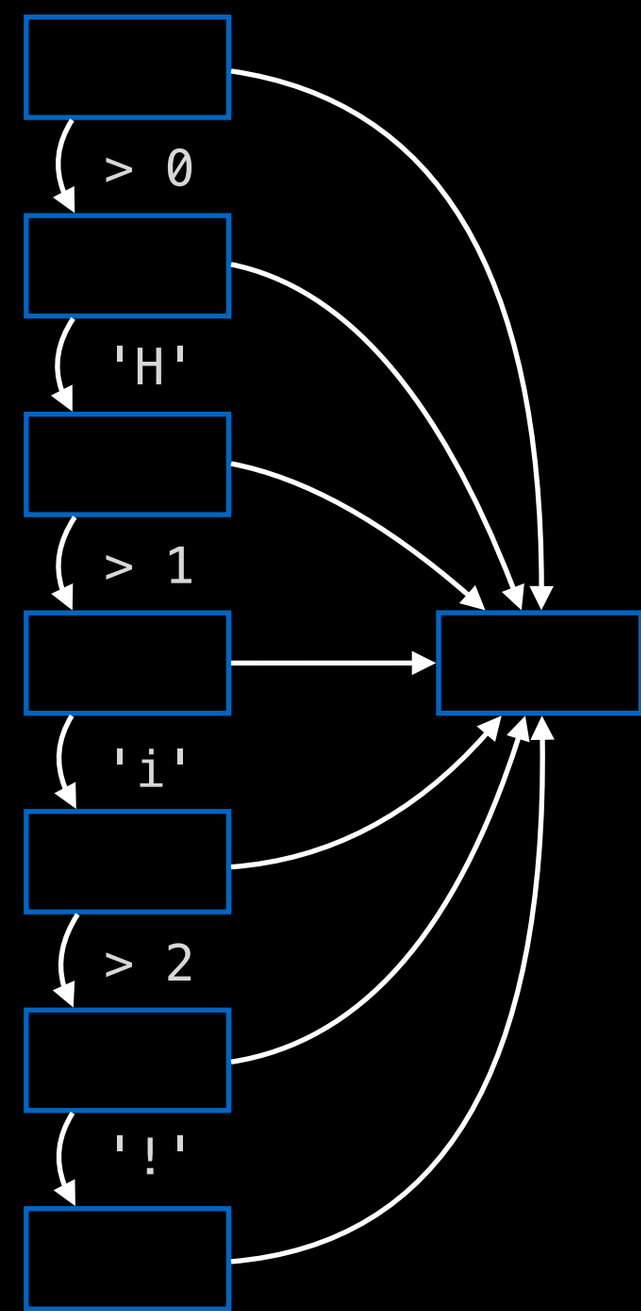
```



Corpus

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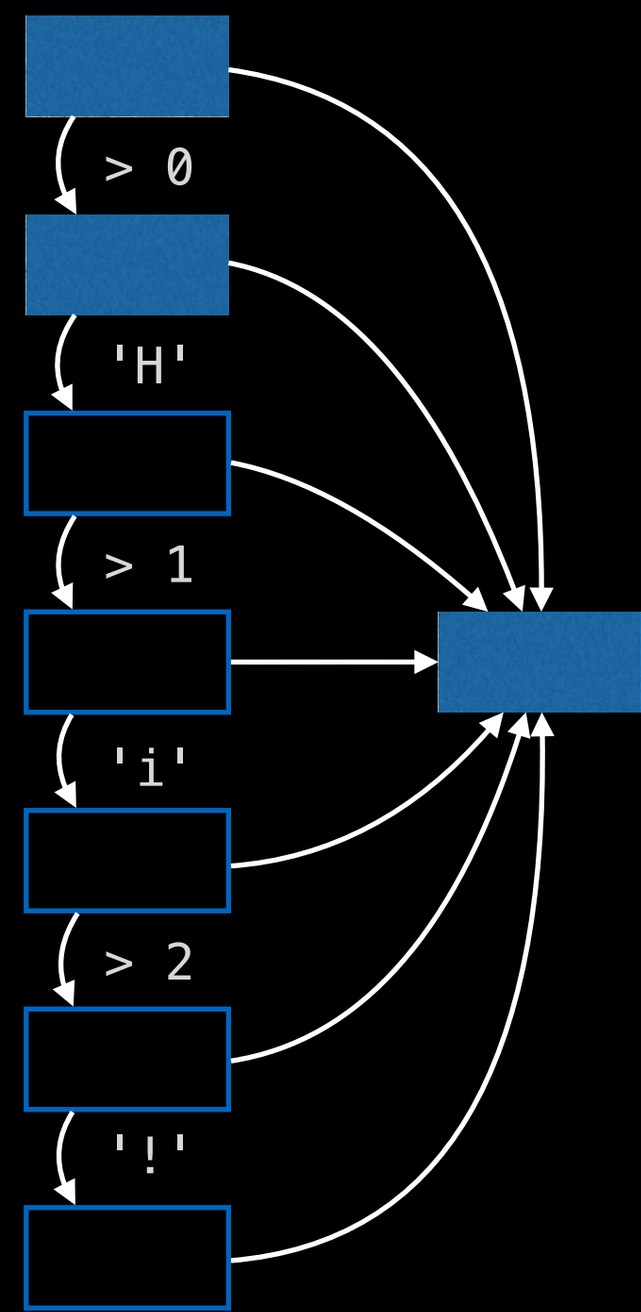
  return 0;
}
```

Unit: <empty>

Mutations: q

Corpus



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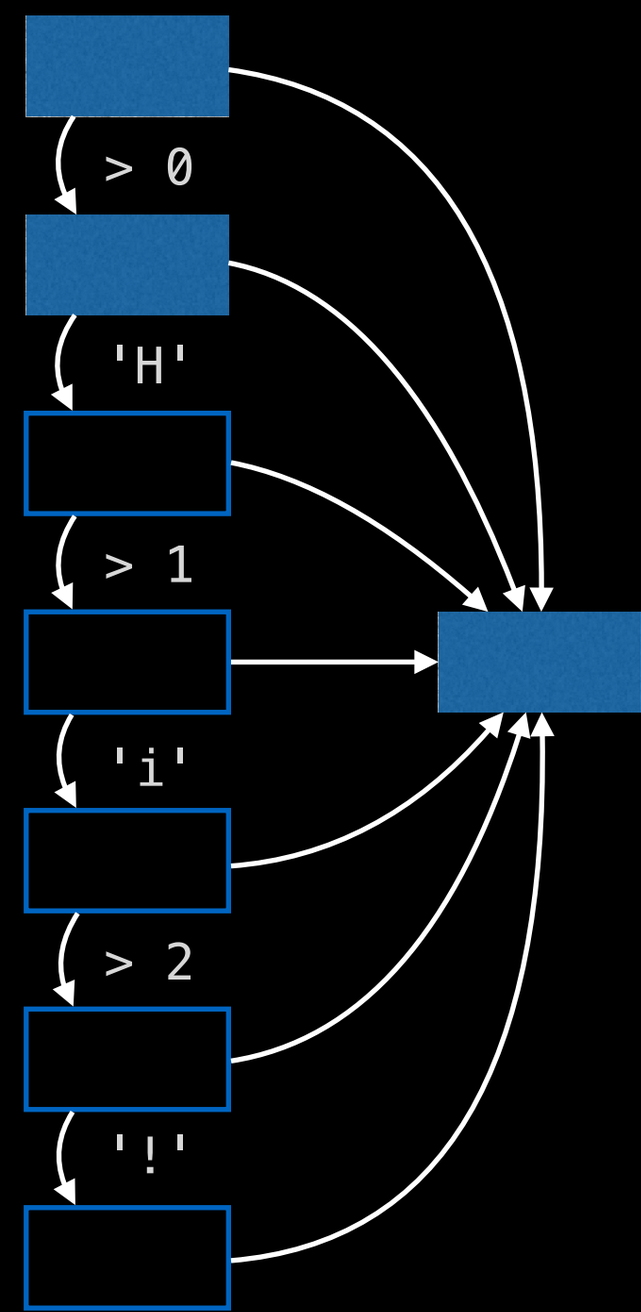
Mutations: q

Corpus

q



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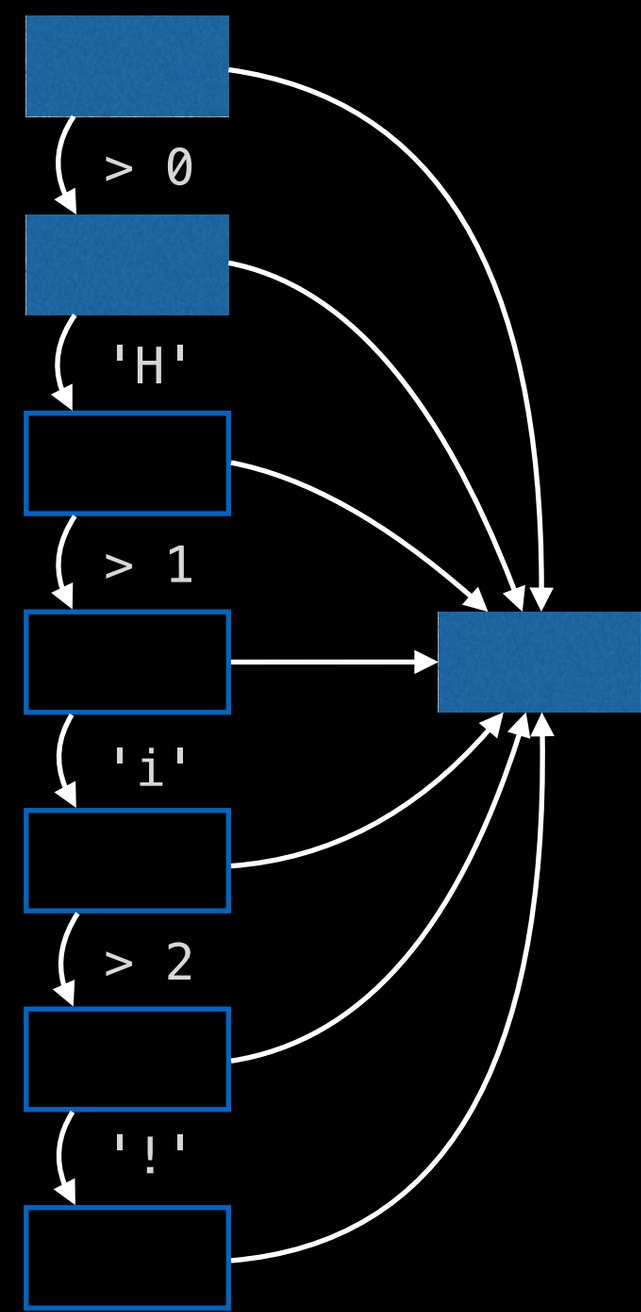
}
```

Unit: <empty>

Mutations: q X 7 y

Corpus

q



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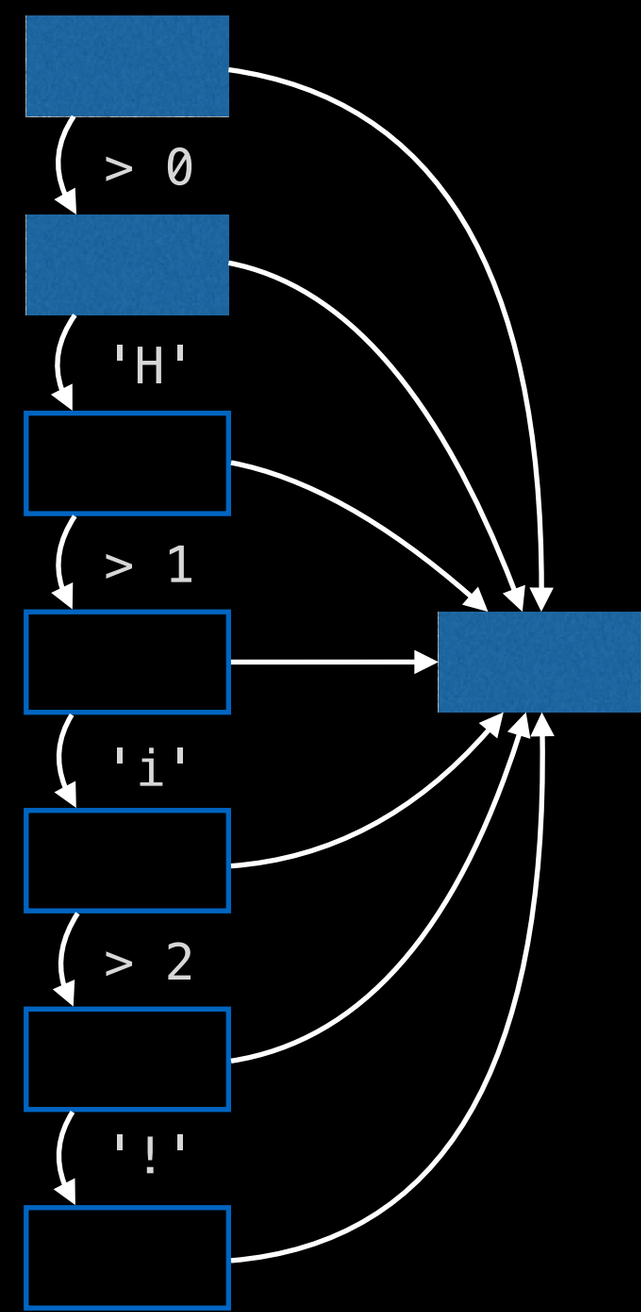
        exit(0);
  return 0;
}
```

Unit: q

Mutations: qZ y

Corpus

q



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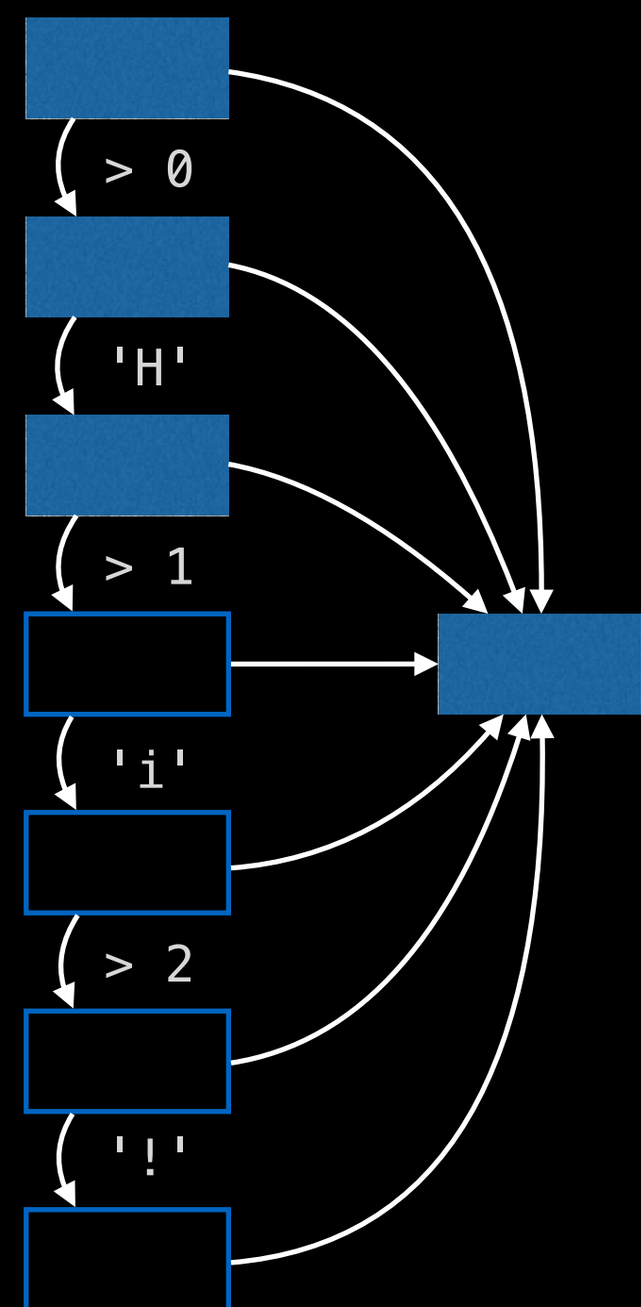
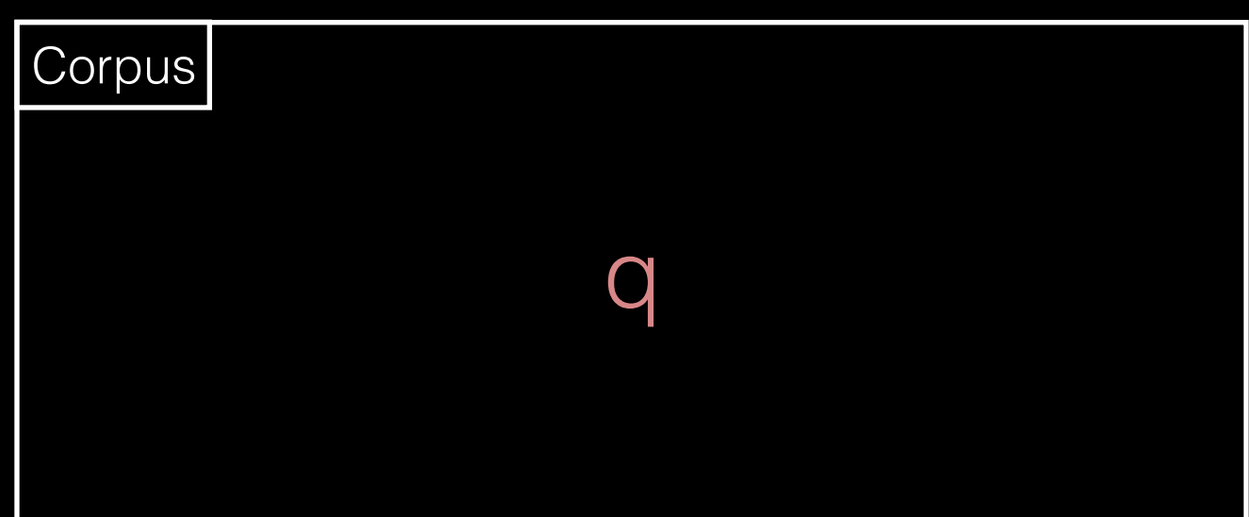


Unit: q

Mutations: qZ y H



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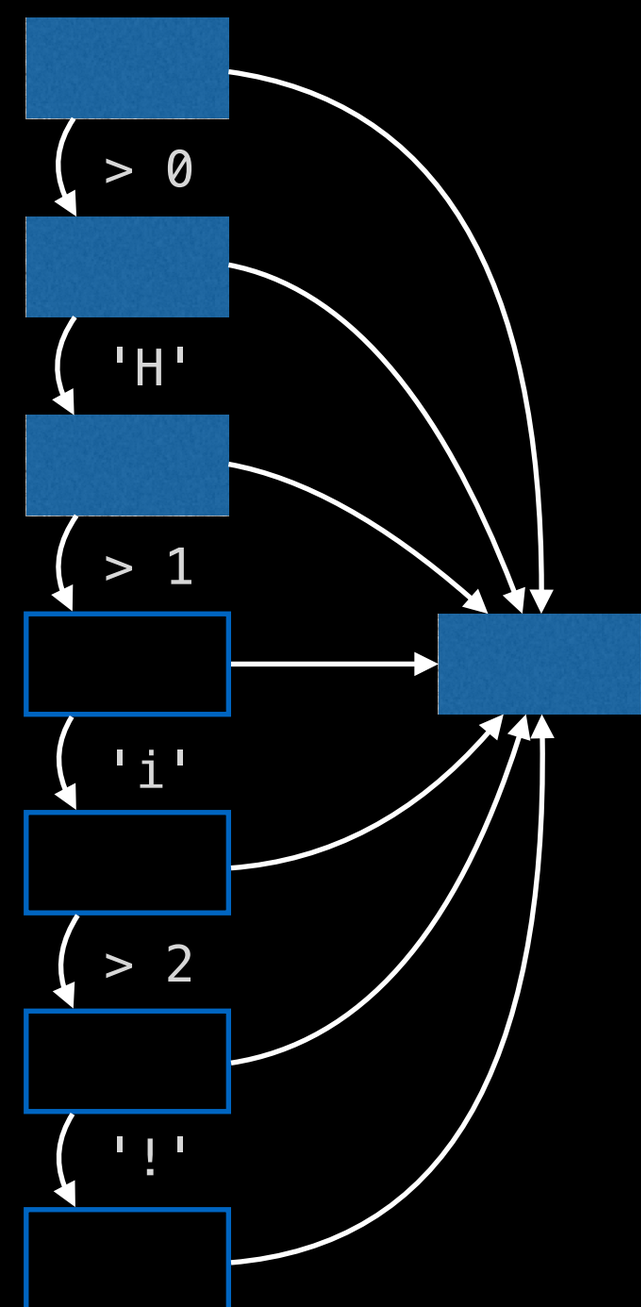
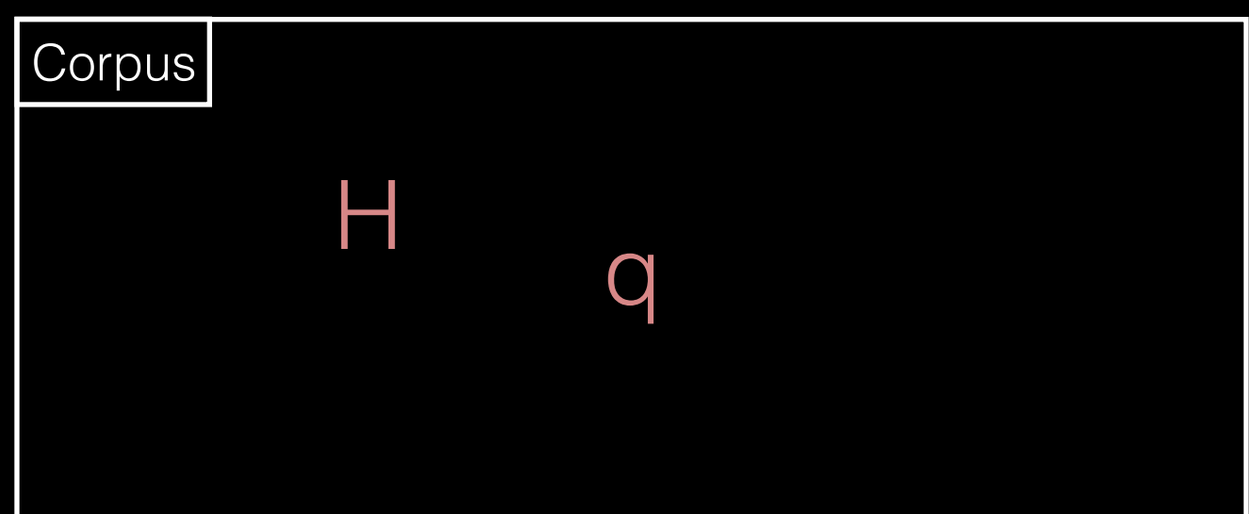


Unit: q

Mutations: qZ y H qm



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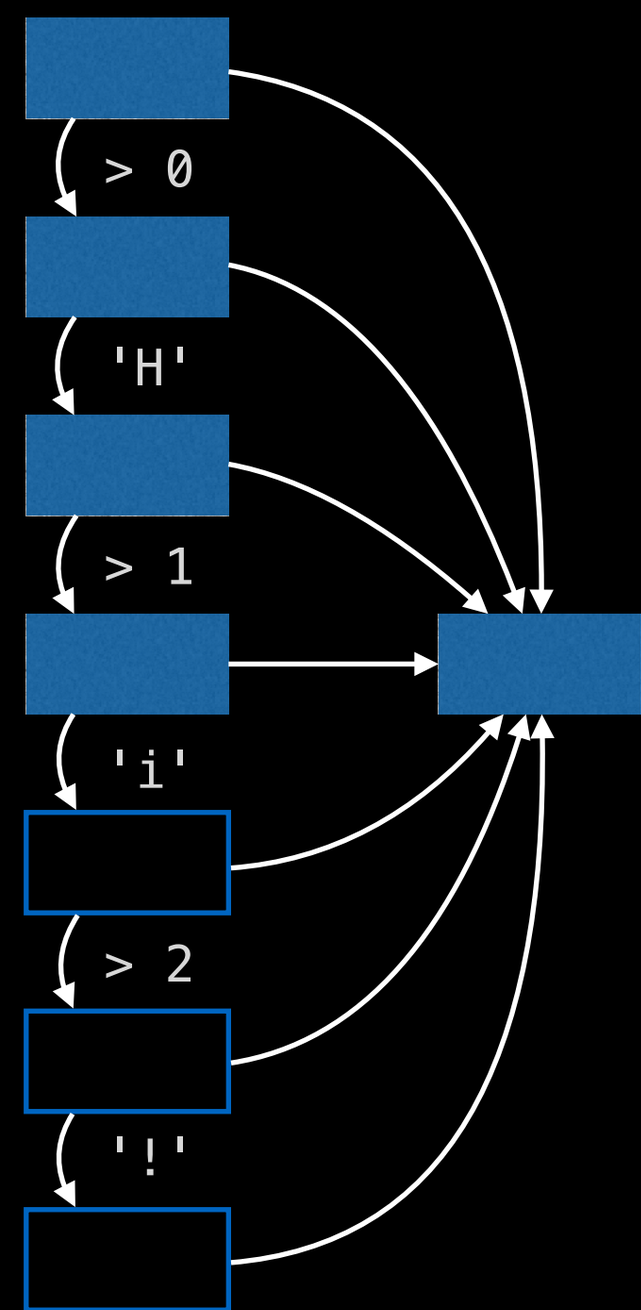
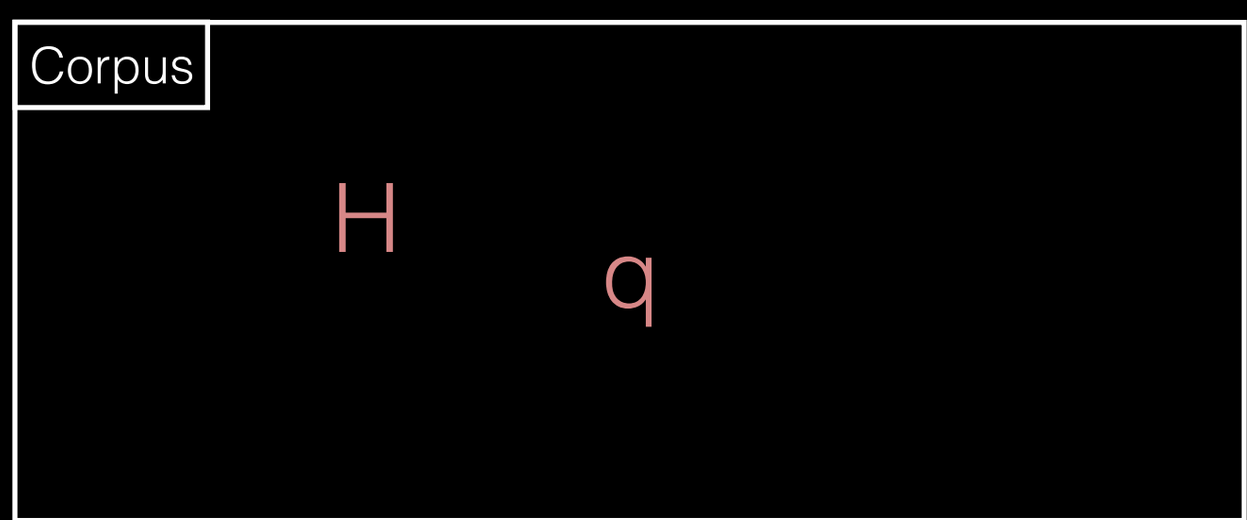


Unit: H

Mutations: HF



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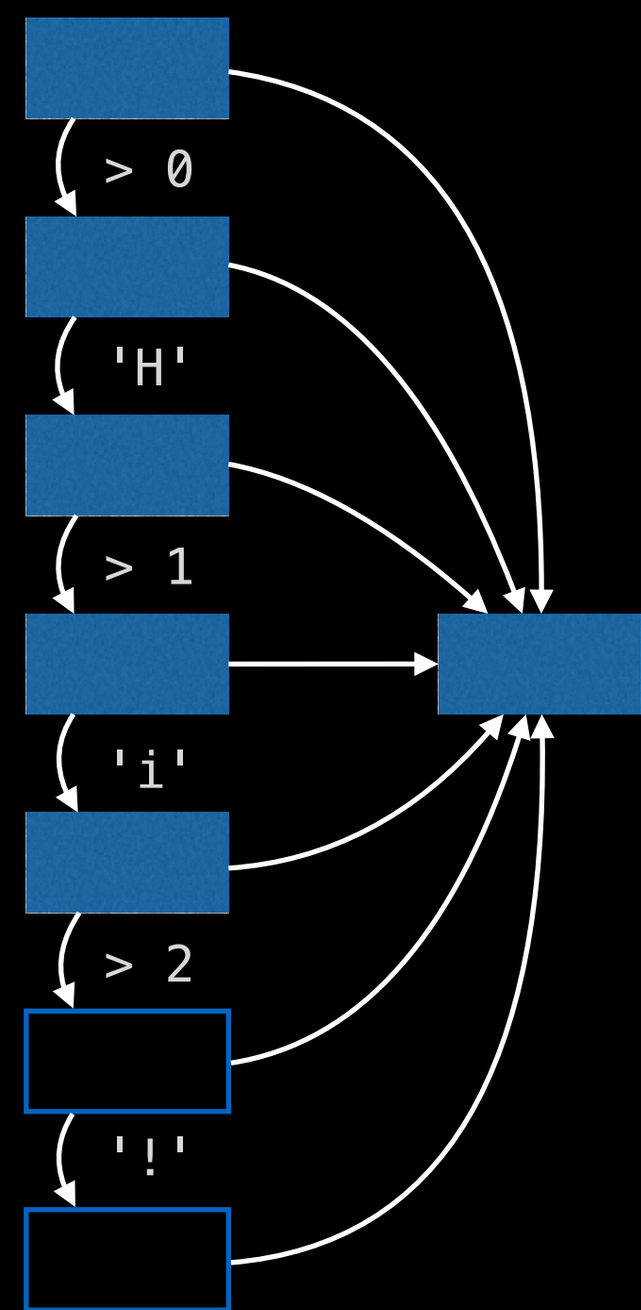
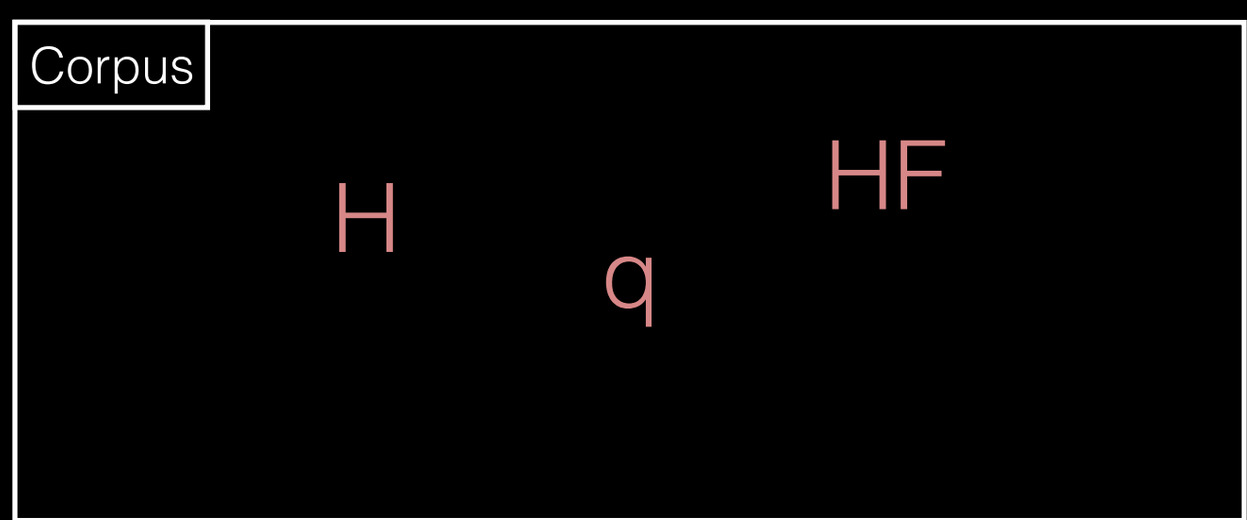


Unit: H

Mutations: HF Hi



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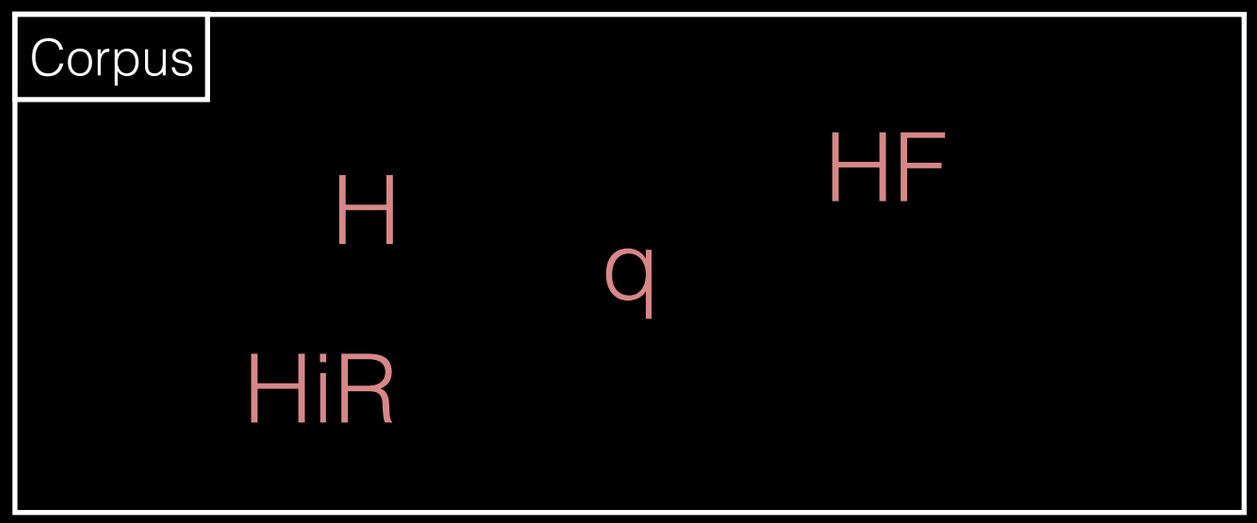
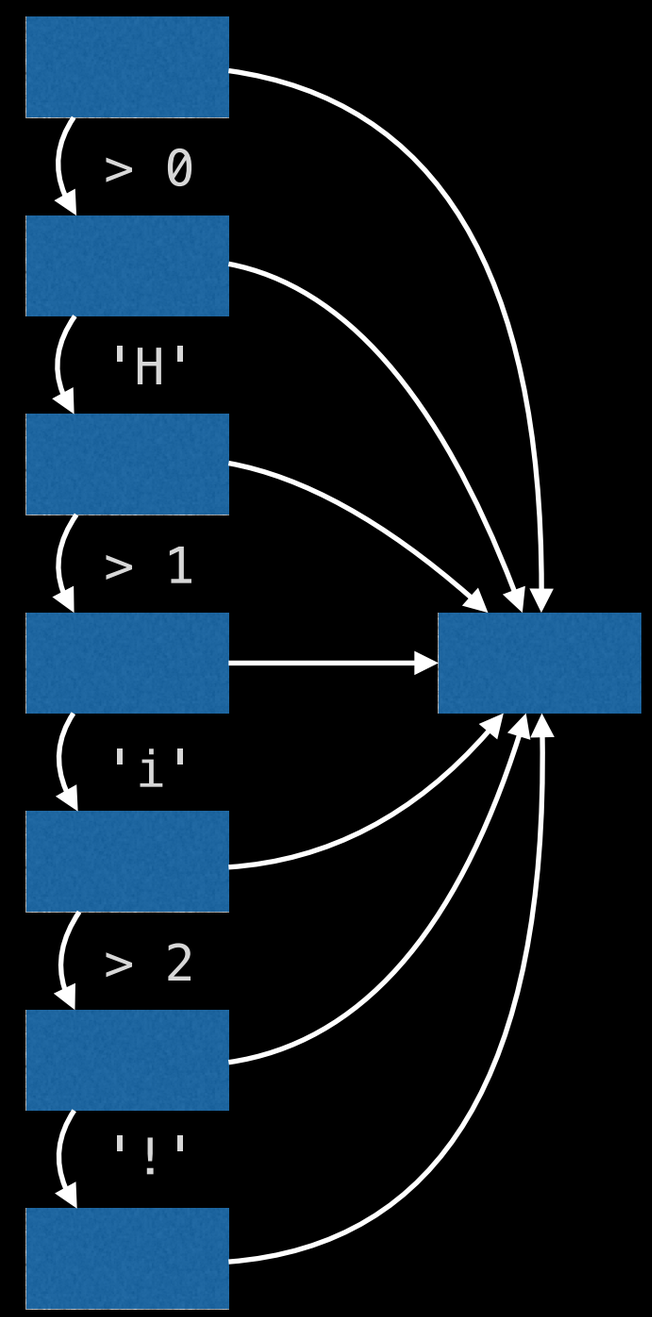
        exit(0);
  return 0;
}
```

Unit: Hi

Mutations: Hh xi HiR Hi!





Fuzzers in LLVM

- clang-fuzzer
- clang-format-fuzzer
- llvm-as-fuzzer
- llvm-mc-fuzzer
- ... but no llc-fuzzer

Beyond Parser Bugs

```
static void g(){}
signed*Qwchar_t;
overridedouble++!=~;inline-=}y=^bitand{;*=or;goto*&&k}==n
int XS/=~char16_t&s<=const_cast<Xchar*>(thread_local3+=char32_t
```

Beyond Parser Bugs

```
@a2 = global i8 addrspace(1)*@0 = private constant i32 0 @1 =
private constant i32 1
@2 = private alias i32* @d0
@3 = @a
@a = ad private aeflias i32* @1ine internal h2dden vodrsid @fun
ction() {
entry:
ret void
}pac
e(1) global i8 0
```

Structured Fuzzing

```
 00000000  64 65 66 69 6e 65 20 76  6f 69 64 20 40 66 28 29  |define void @f()|
 00000010  20 7b 0a 42 42 3a 0a 20  20 25 4c 32 20 3d 20 6c  | {.BB:.  %L2 = l|
-00000020  6f 61 64 20 69 31 2c 20  69 31 2a 20 75 6e 64 65  |oad i1, i1* unde|
+00000020  6f 61 64 20 69 38 2c 20  69 38 2a 20 75 6e 64 65  |oad i8, i8* unde|
 00000030  66 0a 20 20 62 72 20 6c  61 62 65 6c 20 25 42 42  |f.  br label %BB|
 00000040  35 0a 0a 42 42 39 3a 0a  20 20 25 4c 36 20 3d 20  |5..BB9:.  %L6 = |
-00000050  6c 6f 61 64 20 69 31 2c  20 69 31 2a 20 75 6e 64  |load i1, i1* und|
+00000050  6c 6f 61 64 20 69 38 2c  20 69 38 2a 20 75 6e 64  |load i8, i8* und|
 00000060  65 66 0a 20 20 25 42 38  20 3d 20 73 64 69 76 20  |ef.  %B8 = sdiv |
-00000070  69 31 20 25 4c 36 2c 20  25 4c 32 0a 20 20 25 41  |i1 %L6, %L2.  %A|
+00000070  69 38 20 25 4c 36 2c 20  25 4c 32 0a 20 20 25 41  |i8 %L6, %L2.  %A|
 00000080  37 20 3d 20 61 6c 6c 6f  63 61 20 66 6c 6f 61 74  |7 = alloca float|
 00000090  0a 20 20 25 41 34 20 3d  20 61 6c 6c 6f 63 61 20  |.  %A4 = alloca |
```

Structured Fuzzing

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 00000030  66 0a 20 20 62 72 20 6c  61 62 65 6c 20 25 42 42  |f.  br label %BB|
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 00000060  65 66 0a 20 20 25 42 38  20 3d 20 73 64 69 76 20  |ef.  %B8 = sdiv |
-00000070  69 31 20 25 4c 36 2c 20  25 4c 32 0a 20 20 25 41  |i1 %L6, %L2.  %A|
+00000070  69 38 20 25 4c 36 2c 20  25 4c 32 0a 20 20 25 41  |i8 %L6, %L2.  %A|
 00000080  37 20 3d 20 61 6c 6c 6f  63 61 20 66 6c 6f 61 74  |7 = alloca float|
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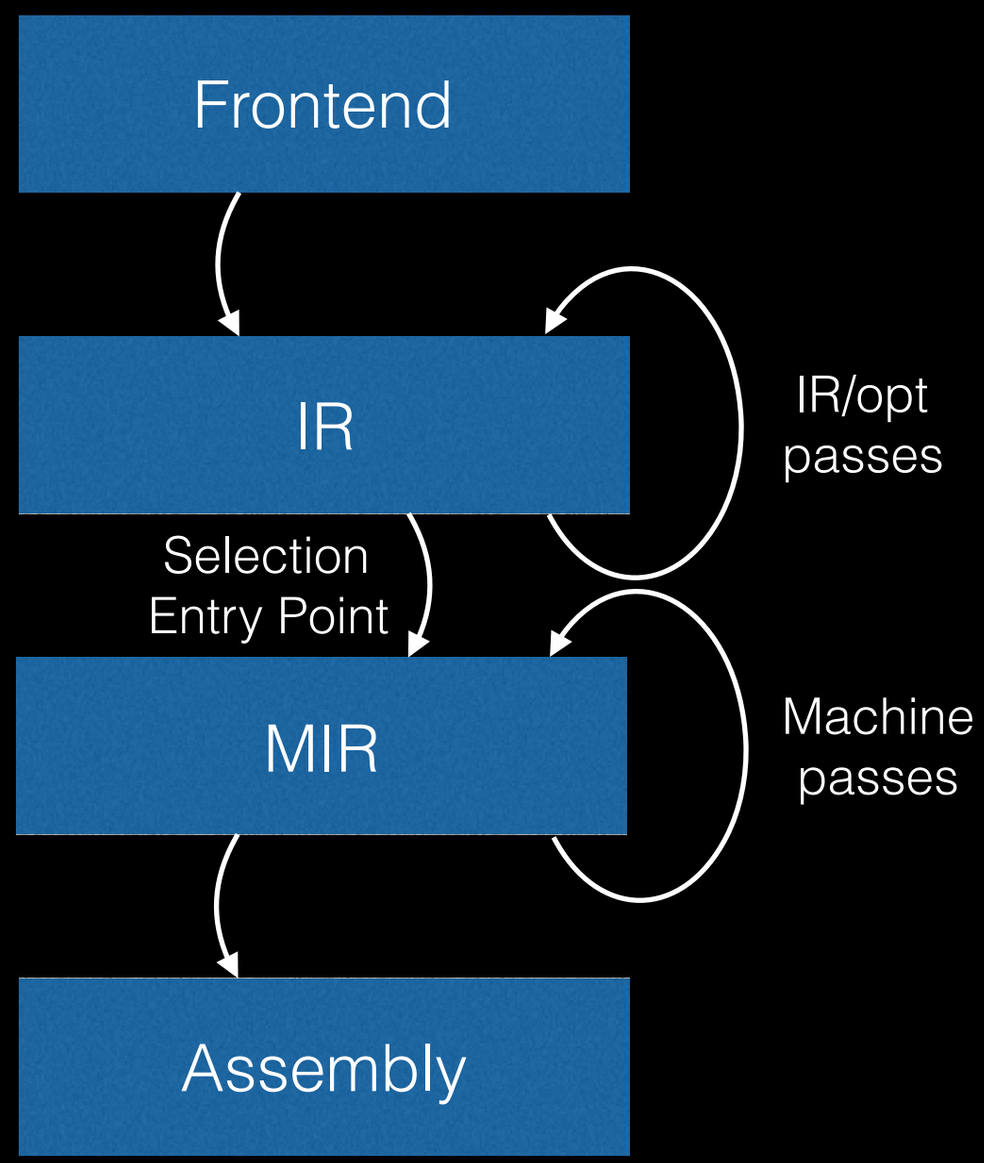
 00000090  0a 20 20 25 41 34 20 3d  20 61 6c 6c 6f 63 61 20  |.  %A4 = alloca |
```

Custom Mutator API

```
// Optional user-provided custom mutator.
// Mutates raw data in [Data, Data+Size) inplace.
// Returns the new size, which is not greater than MaxSize.
// Given the same Seed produces the same mutation.
size_t LLVMFuzzerCustomMutator(uint8_t *Data,
                               size_t Size,
                               size_t MaxSize,
                               unsigned int Seed);
```

Where to Mutate?



llvm-stress

- Random IR generator
- Used for new backends and FastISel
- Excellent for bringup, forgotten later

LLVM IR Mutator

- Work in terms of operations on SSA values
- Each operation has sources and a sink
- Sinks should be side effects to avoid dead code
- It's safe to disconnect sinks and DCE at will

Adding one operation

- Divide a block into potential sources and sinks

```
define void @f() {
BB:
  %L1 = load i16, i16* undef
  %L2 = load i16, i16* undef
  %B1 = lshr i16 %L1, %L2
  store i16 %B1, i16* undef
  ret void
}
```

Adding one operation

- Divide a block into potential sources and sinks

```
define void @f() {
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  %L2 = load i16, i16* undef
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```

Adding one operation

- Divide a block into potential sources and sinks
- Choose or create one source

```
define void @f() {
BB:
→ %L1 = load i16, i16* undef
  %L2 = load i16, i16* undef
  ---------------------------
  %B1 = lshr i16 %L1, %L2
  store i16 %B1, i16* undef
  ret void
}
```

Adding one operation

- Divide a block into potential sources and sinks
- Choose or create one source
- Choose an operation

```
define void @f() {
BB:
  %L1 = load i16, i16* undef
  %L2 = load i16, i16* undef
  %B2 = add i16 %L1, ?
  %B1 = lshr i16 %L1, %L2
  store i16 %B1, i16* undef
  ret void
}
```

Adding one operation

- Divide a block into potential sources and sinks
- Choose or create one source
- Choose an operation
- Fill in the other sources

```
define void @f() {
BB:
  %L1 = load i16, i16* undef
  %L2 = load i16, i16* undef
  %B2 = add i16 %L1, %L1
  %B1 = lshr i16 %L1, %L2
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```

Adding one operation

- Divide a block into potential sources and sinks
- Choose or create one source
- Choose an operation
- Fill in the other sources
- Steal an argument of a later operation as a sink

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  %B2 = add i16 %L1, %L1
  %B1 = lshr i16 %L1, %L2 ←
  store i16 %B1, i16* undef
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  store i16 %B1, i16* undef
  ret void
}
```

Adding one operation

- Divide a block into potential sources and sinks
- Choose or create one source
- Choose an operation
- Fill in the other sources
- Steal an argument of a later operation as a sink
- Clean up dead code

```
define void @f() {
BB:
  %L1 = load i16, i16* undef
  %B2 = add i16 %L1, %L1
  %B1 = lshr i16 %L1, %B2
  store i16 %B1, i16* undef
  ret void
}
```

Splitting Blocks

```
BB:
  %L7 = load i1, i1* undef
  br label %BB5
```

```
BB5:
  %L6 = load i1, i1* undef
  %B8 = sdiv i1 %L6, %L7
  %A7 = alloca float
  %A4 = alloca float
  %L5 = load float, float* %A4
  %A1 = alloca float
  %L3 = load float, float* %A1
  %L1 = load i32, i32* undef
  %B6 = frem float %L3, %L5
  %A = alloca i32
  %L = load i32, i32* %A
  %B = xor i32 %L, %L1
  %B1 = xor i32 %B, %B
  store i32 %B1, i32* %A
  store float %B6, float* %A7
  store i1 %B8, i1* undef
  ret void
```

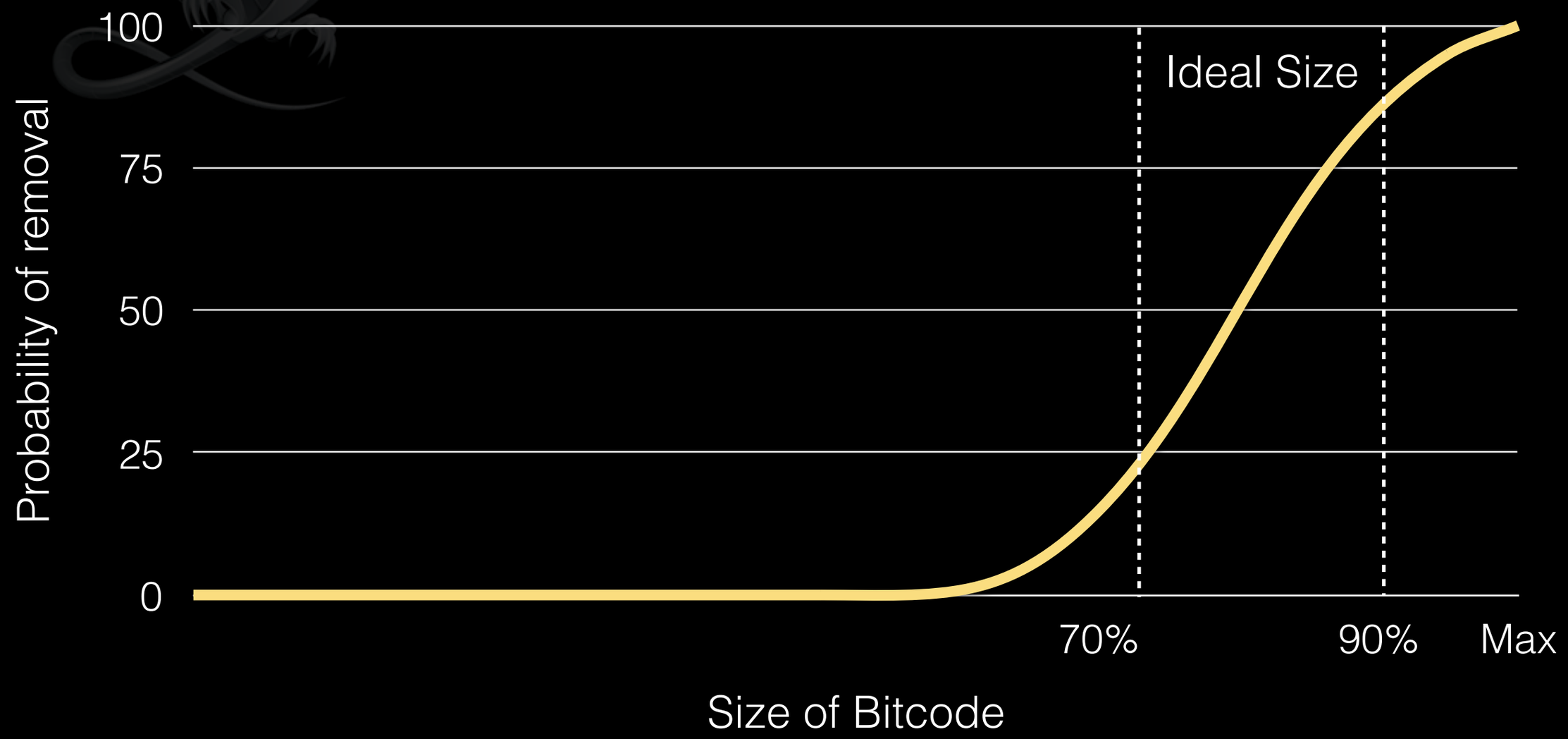
→

```
BB:
  %L7 = load i1, i1* undef
  br label %BB5
```

```
BB5:
  %L6 = load i1, i1* undef
  %B8 = sdiv i1 %L6, %L7
  %A7 = alloca float
  %A4 = alloca float
  br i1 %B8, label %BB5, label %BB1
```

```
BB1:
  %L5 = load float, float* %A4
  %A1 = alloca float
  %L3 = load float, float* %A1
  %L1 = load i32, i32* undef
  %B6 = frem float %L3, %L5
  %A = alloca i32
  %L = load i32, i32* %A
  %B = xor i32 %L, %L1
  %B1 = xor i32 %B, %B
  store i32 %B1, i32* %A
  store float %B6, float* %A7
  store i1 %B8, i1* undef
  ret void
```

Removing Code



Finding Bugs

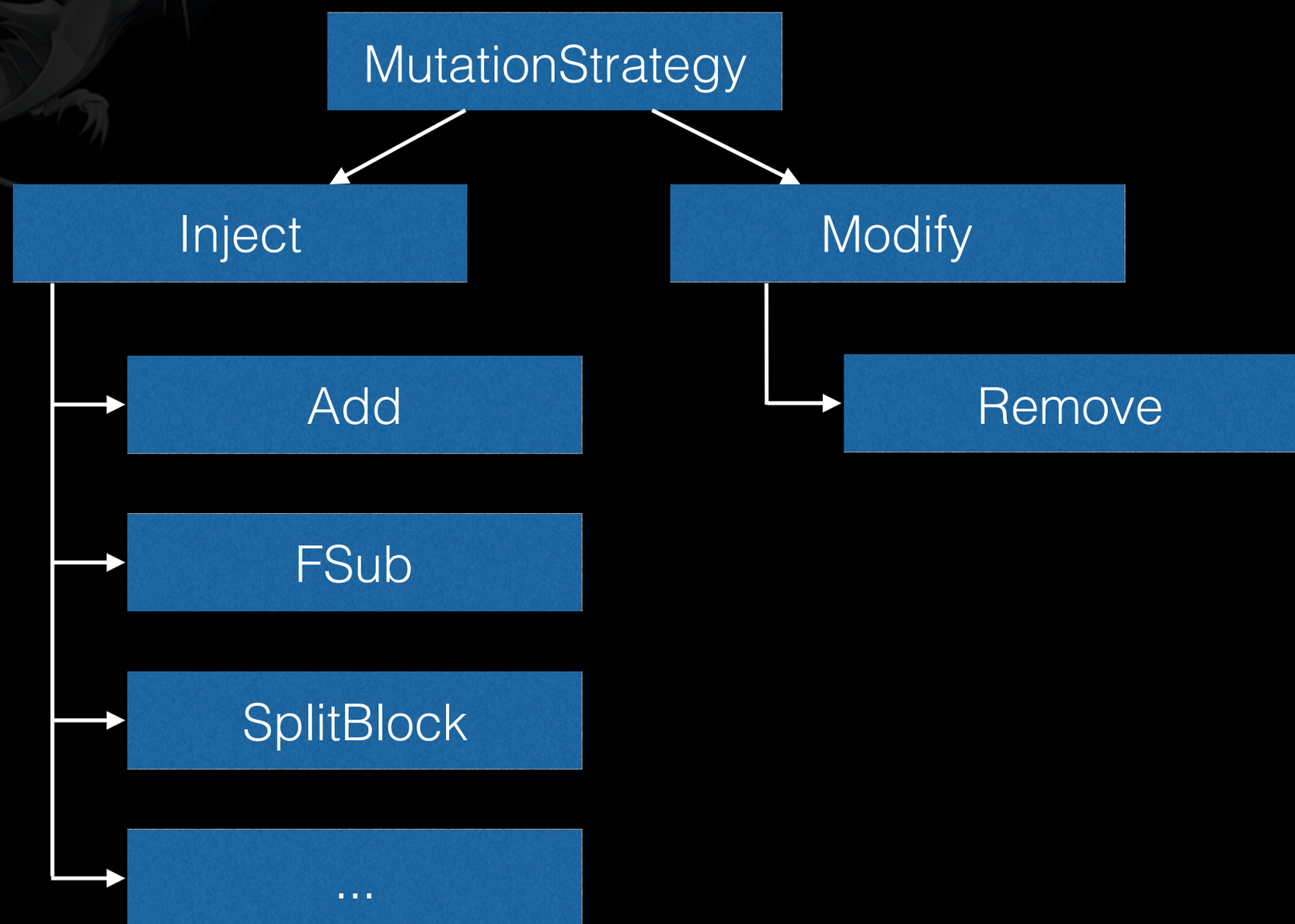
Correctness Checks

- Garbage in, garbage out
- Comparing instruction selectors
- Semantics-preserving mutations

Mutation Library

- Legal types are configurable
- New operations follow a simple interface
- Mix and match the operations you want

Mutation Library



Results

- Found various AArch64 GlobalISel bugs
- SelectionDAG is surprisingly hard to crash
- Test your own backends today
- IR mutator library available for other fuzzers

Questions?