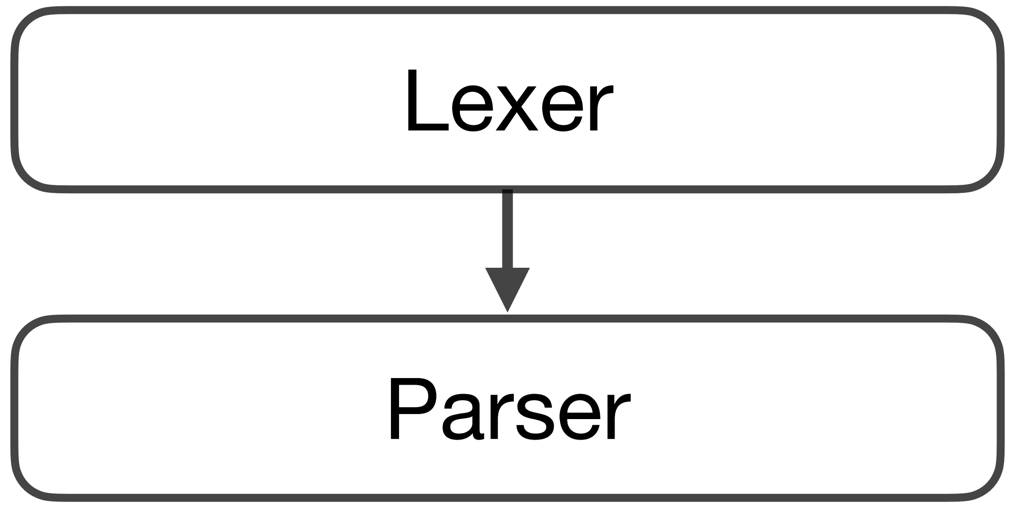
Lecture 10 — Fast Compilation

Stanford CS343D (Winter 2025)
Fred Kjolstad

Classical compiler overview

Lexer

Classical compiler overview



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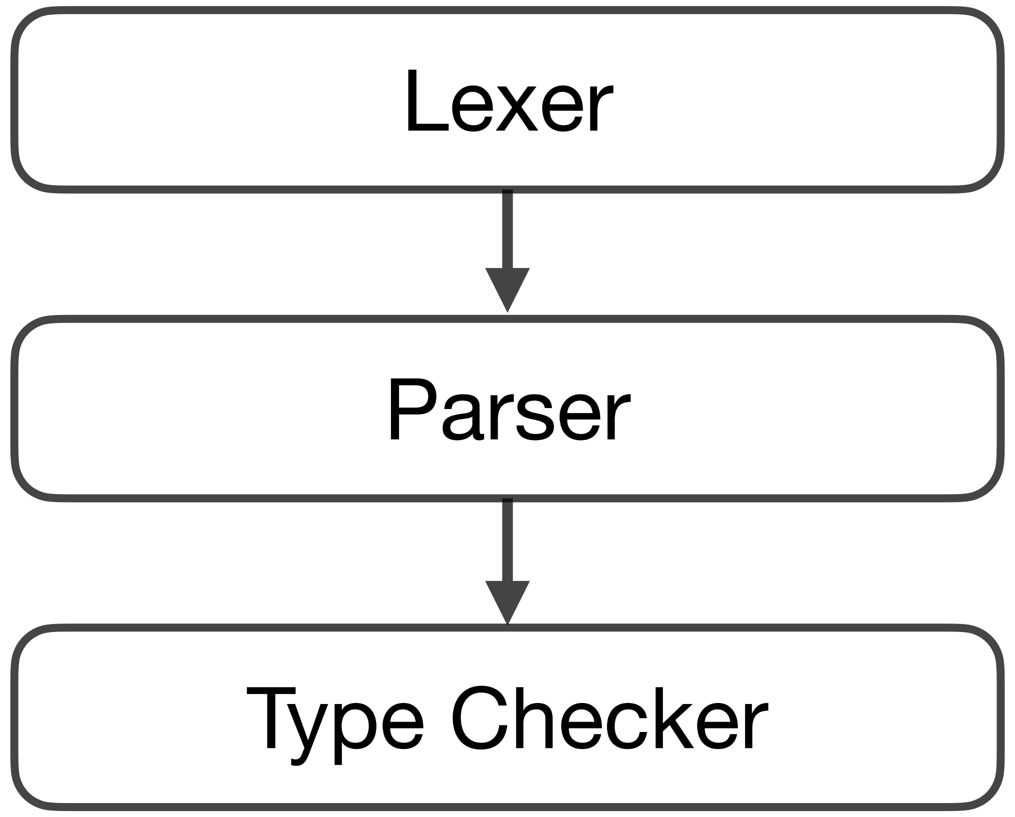

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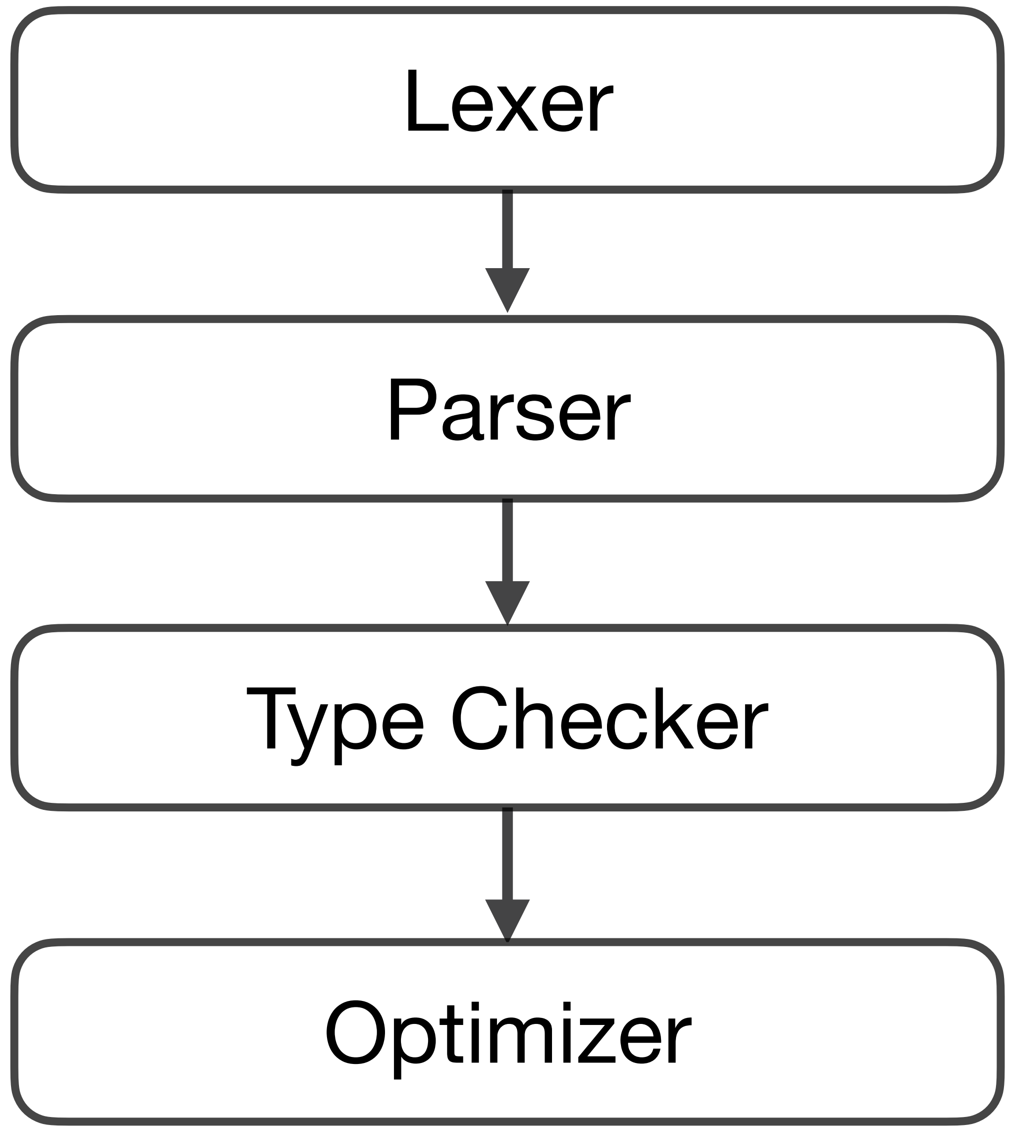

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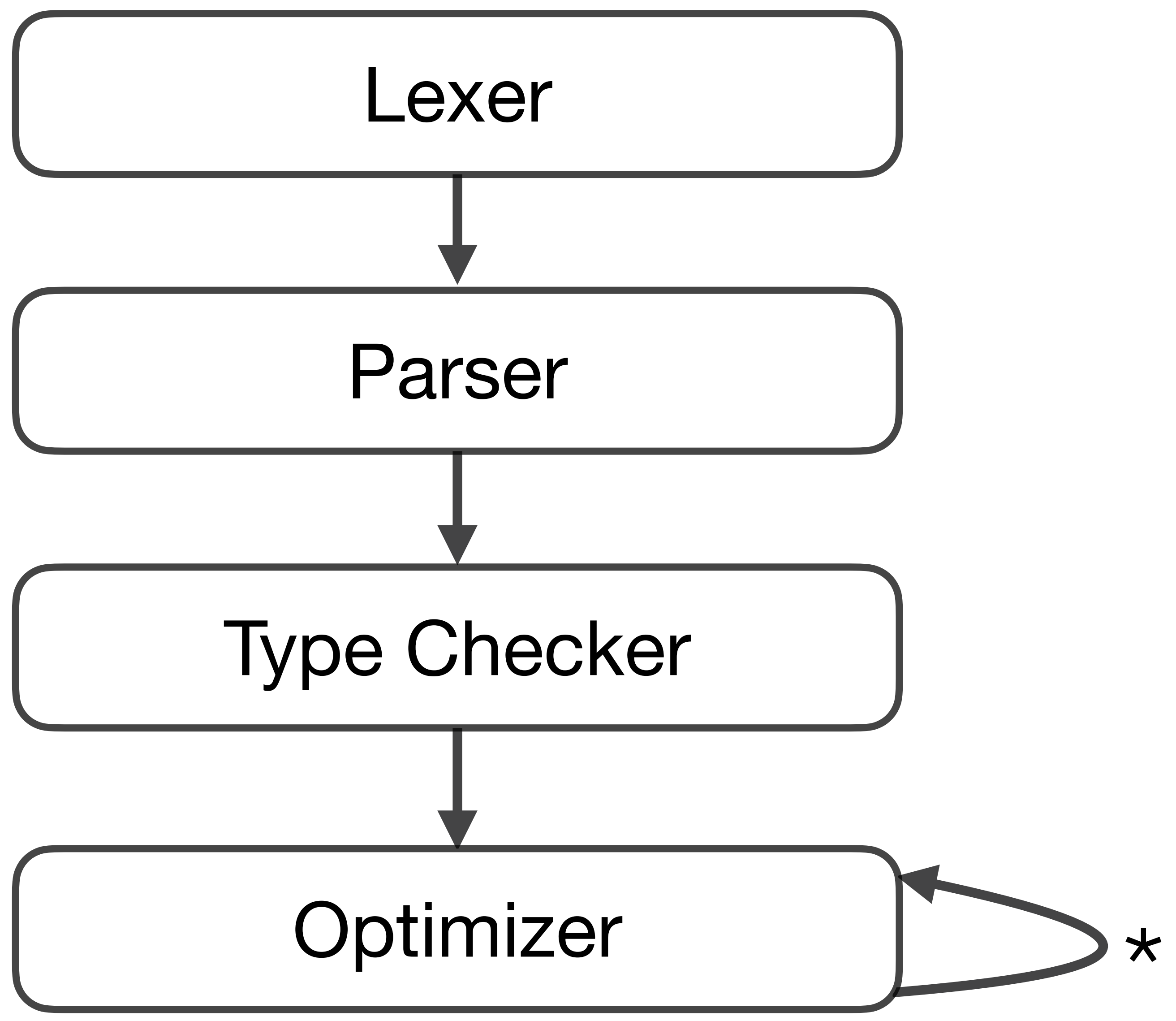

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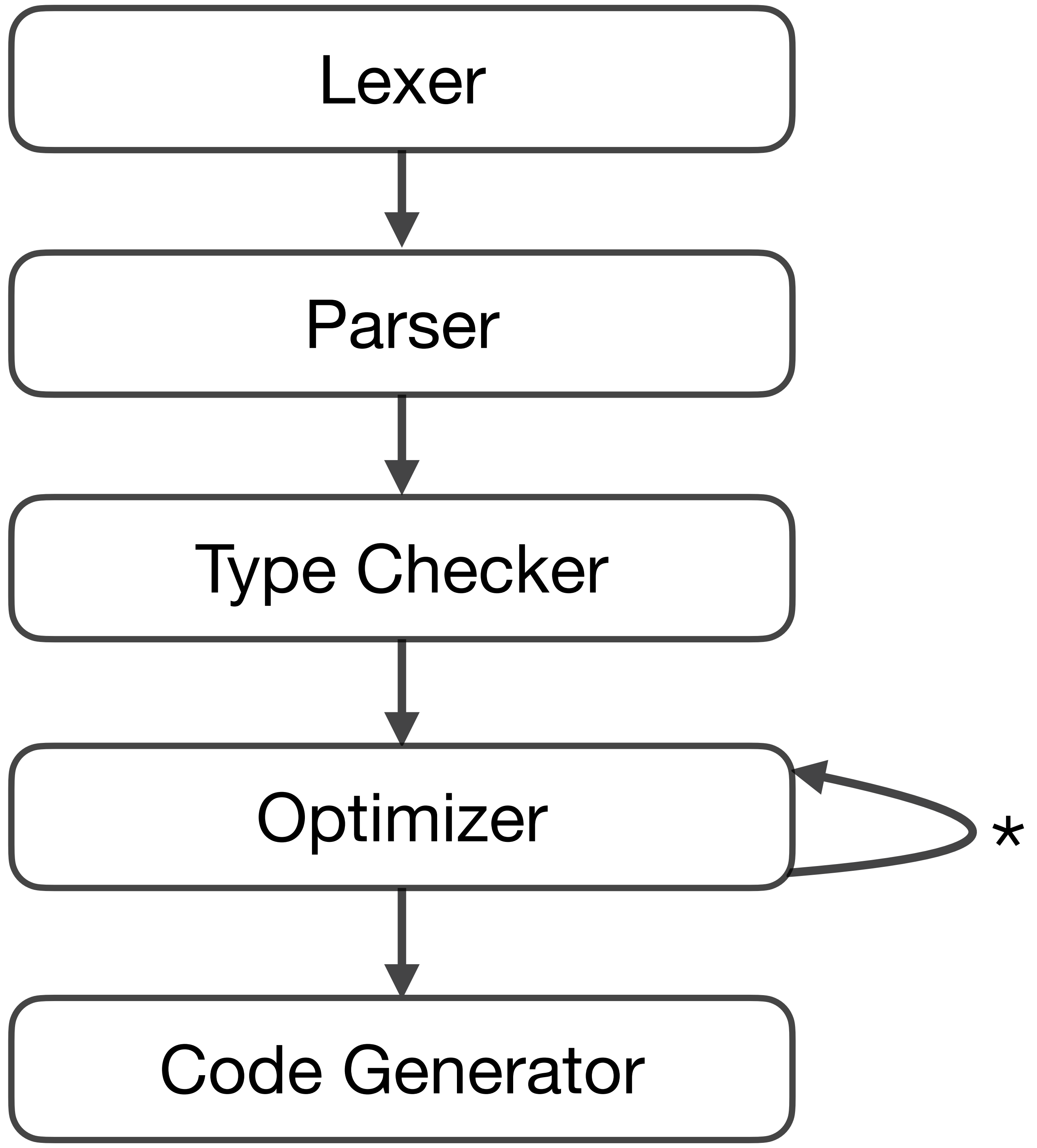

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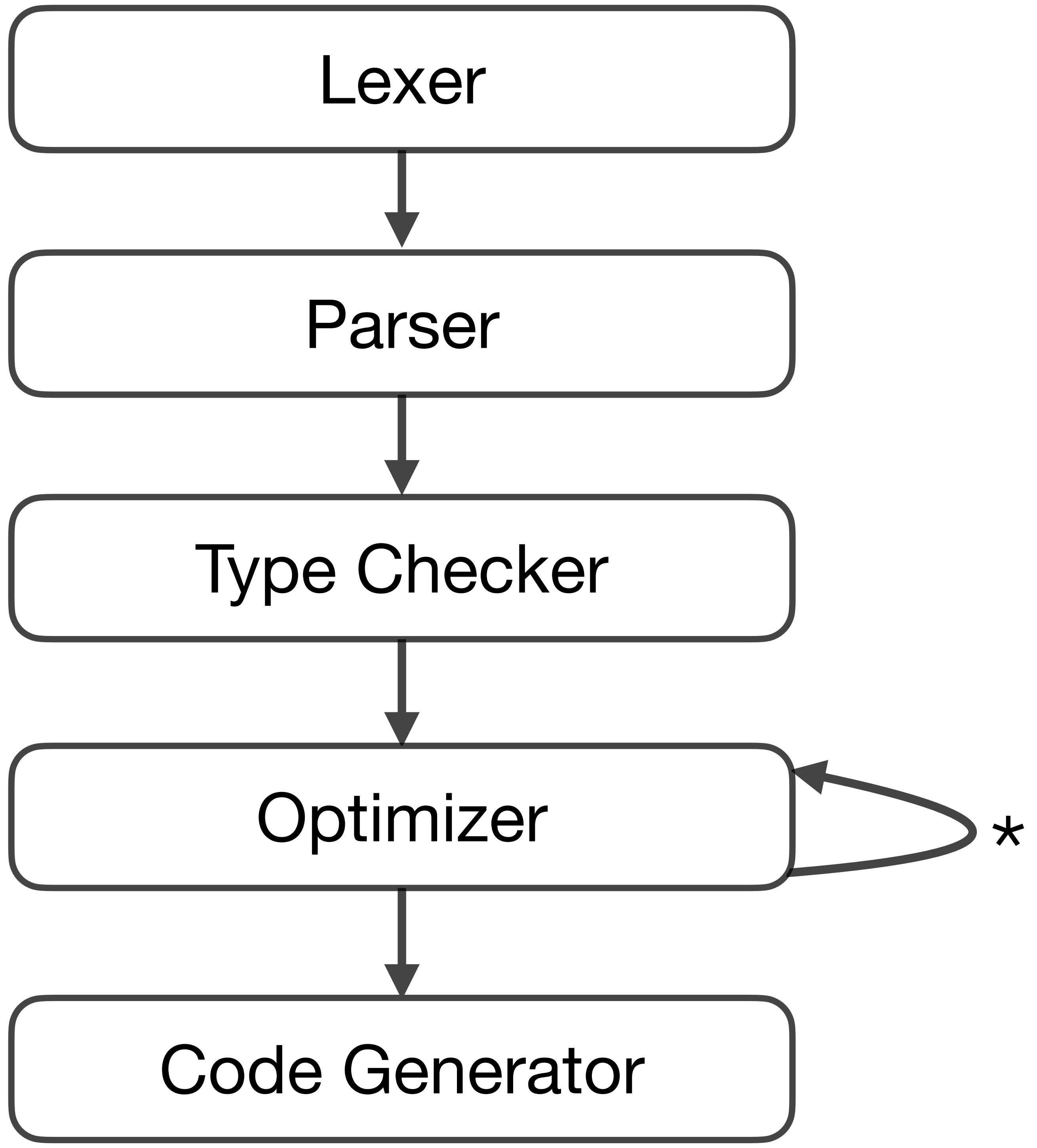
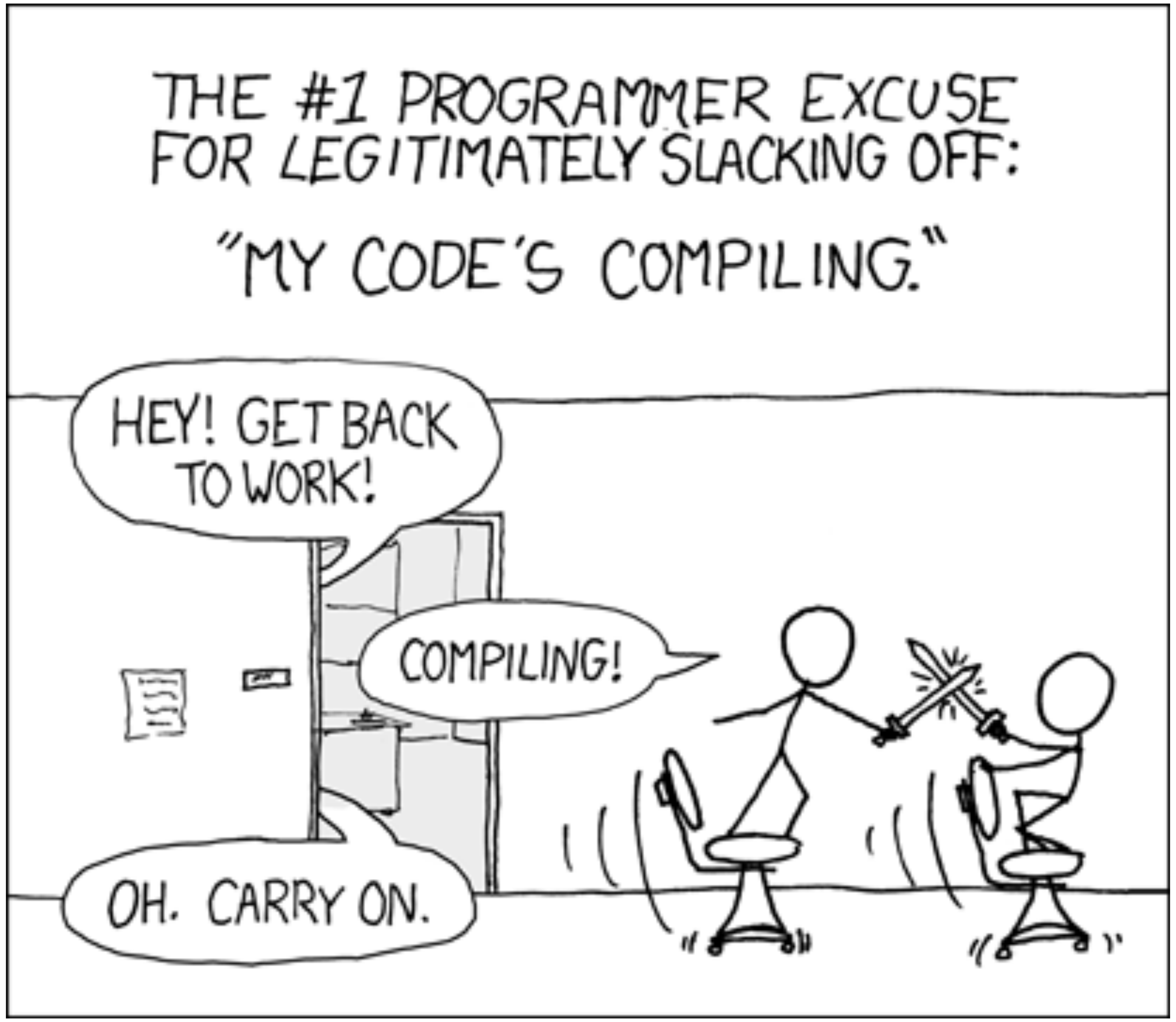


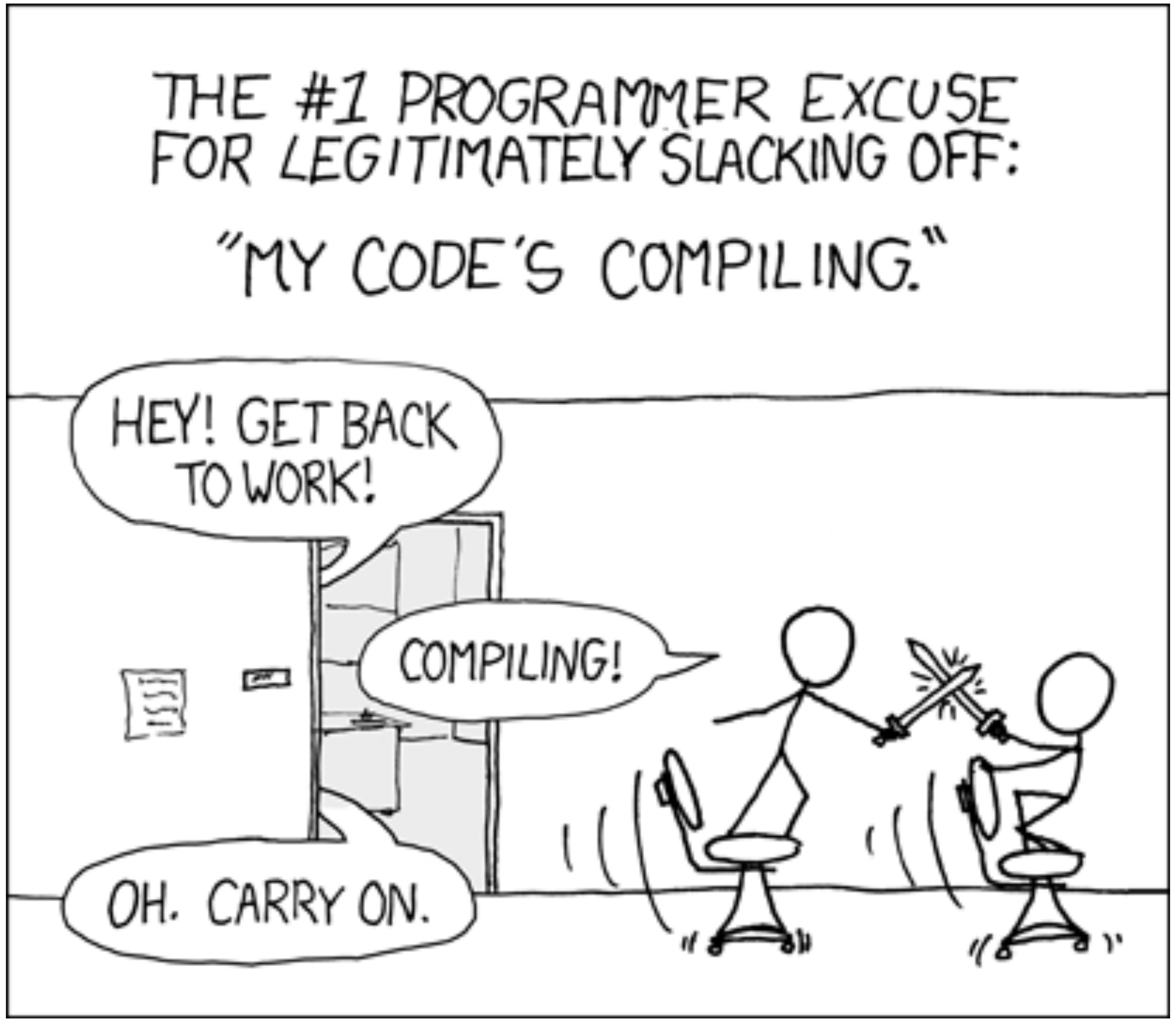
There is a lot of work to compiling optimized code

Compilation times matter



Compilation times matter

- LLVM -O0 vs -O2 (10x difference)



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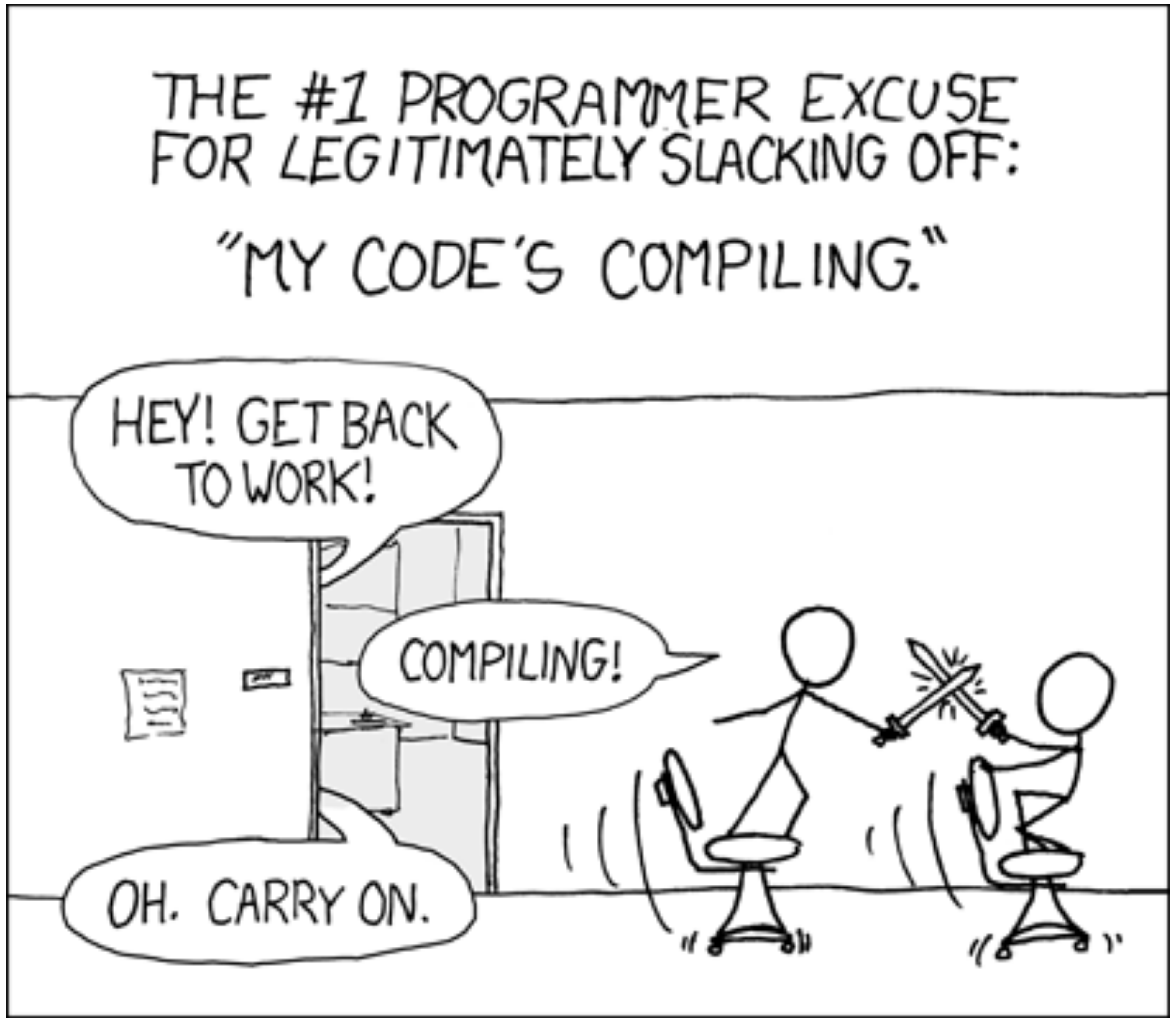
- Scala (large type checking cost)



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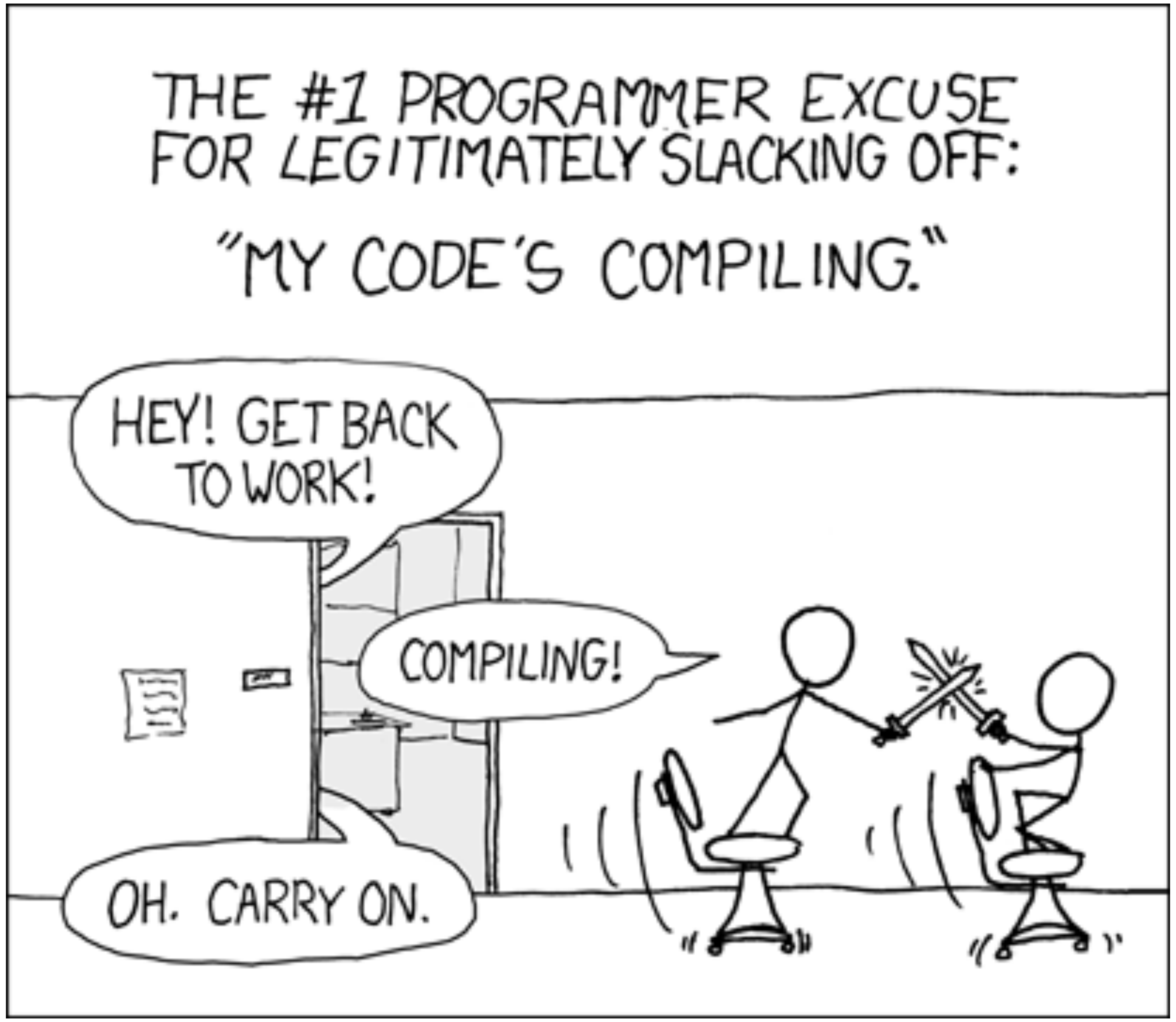

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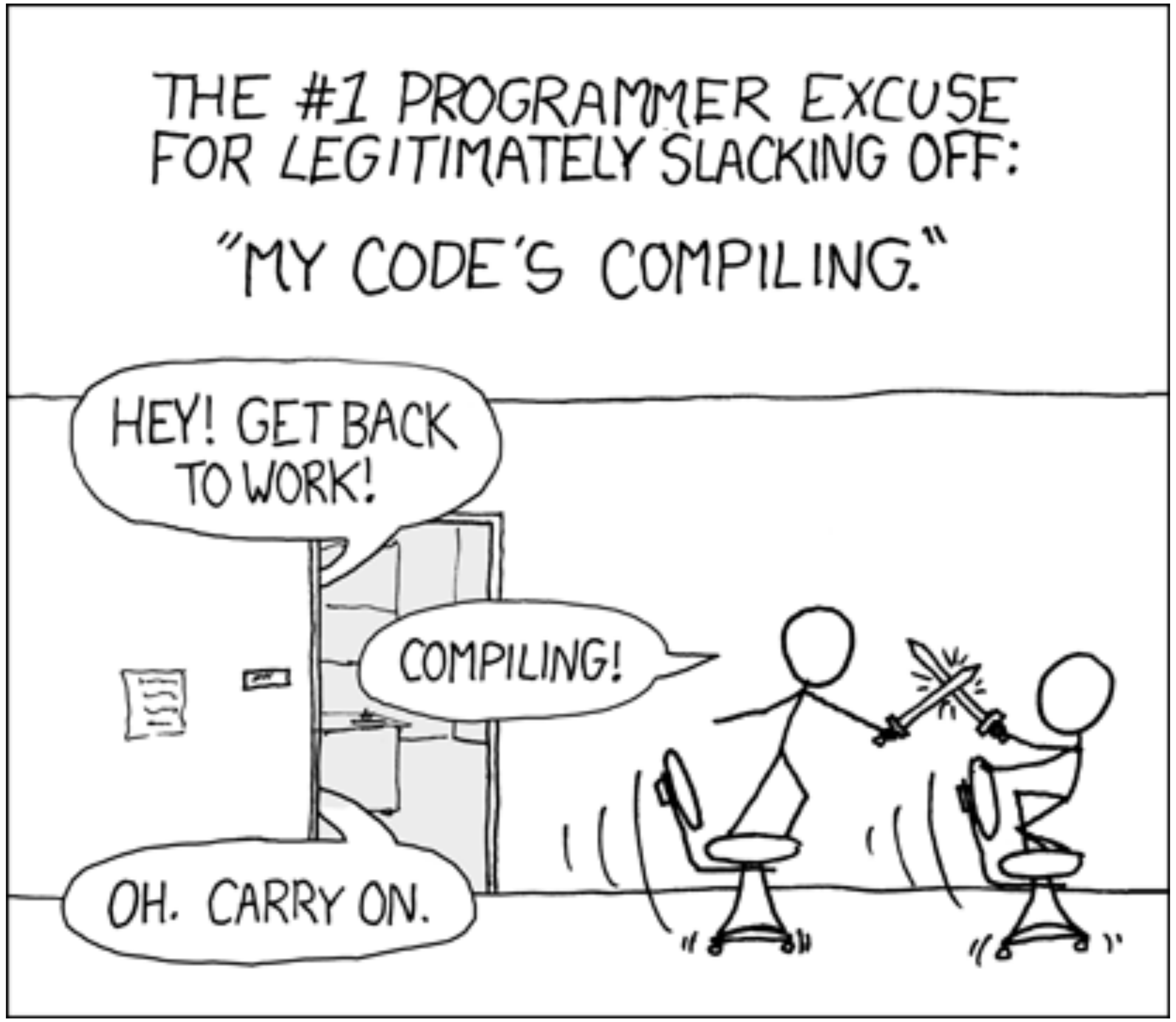

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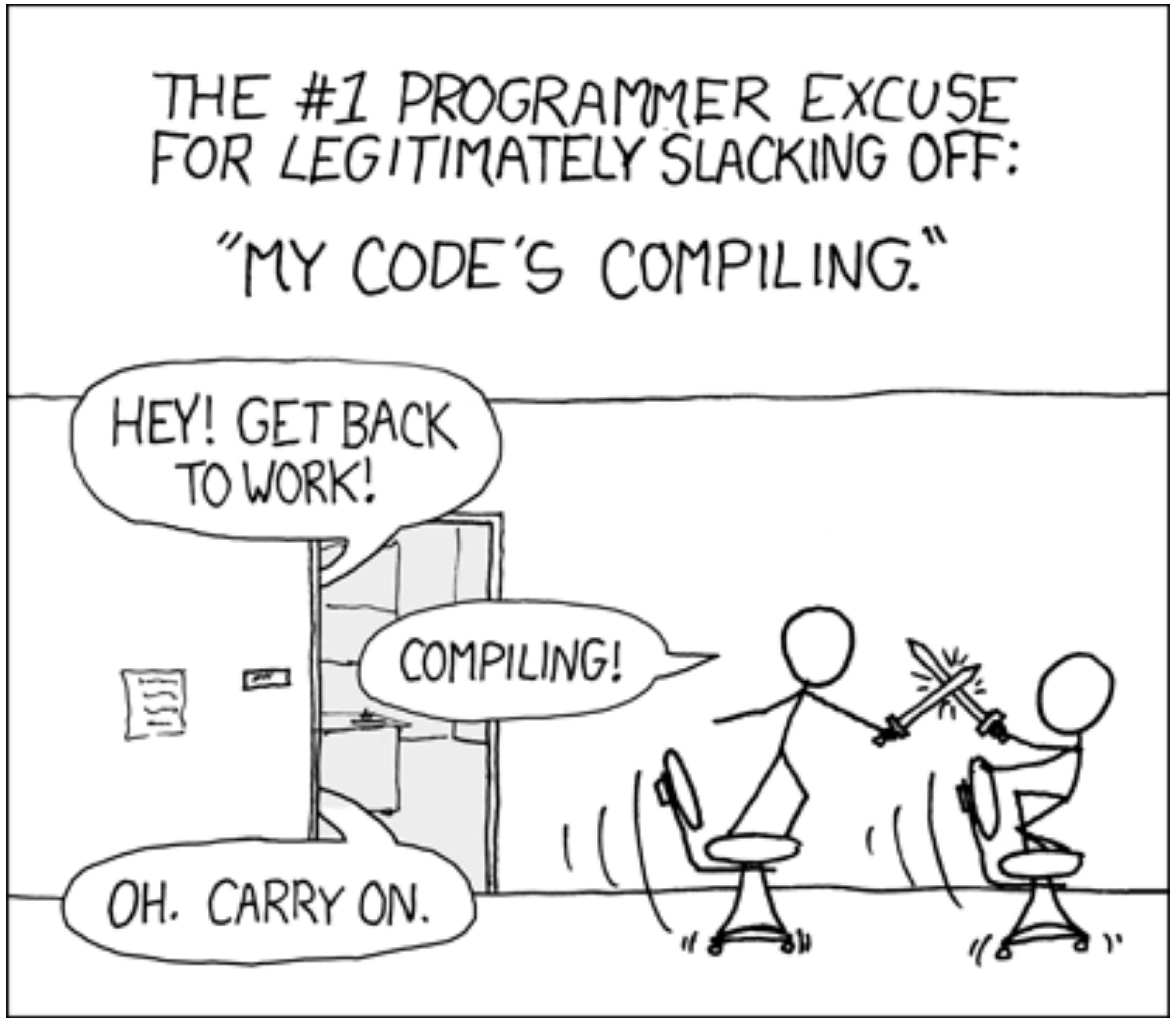

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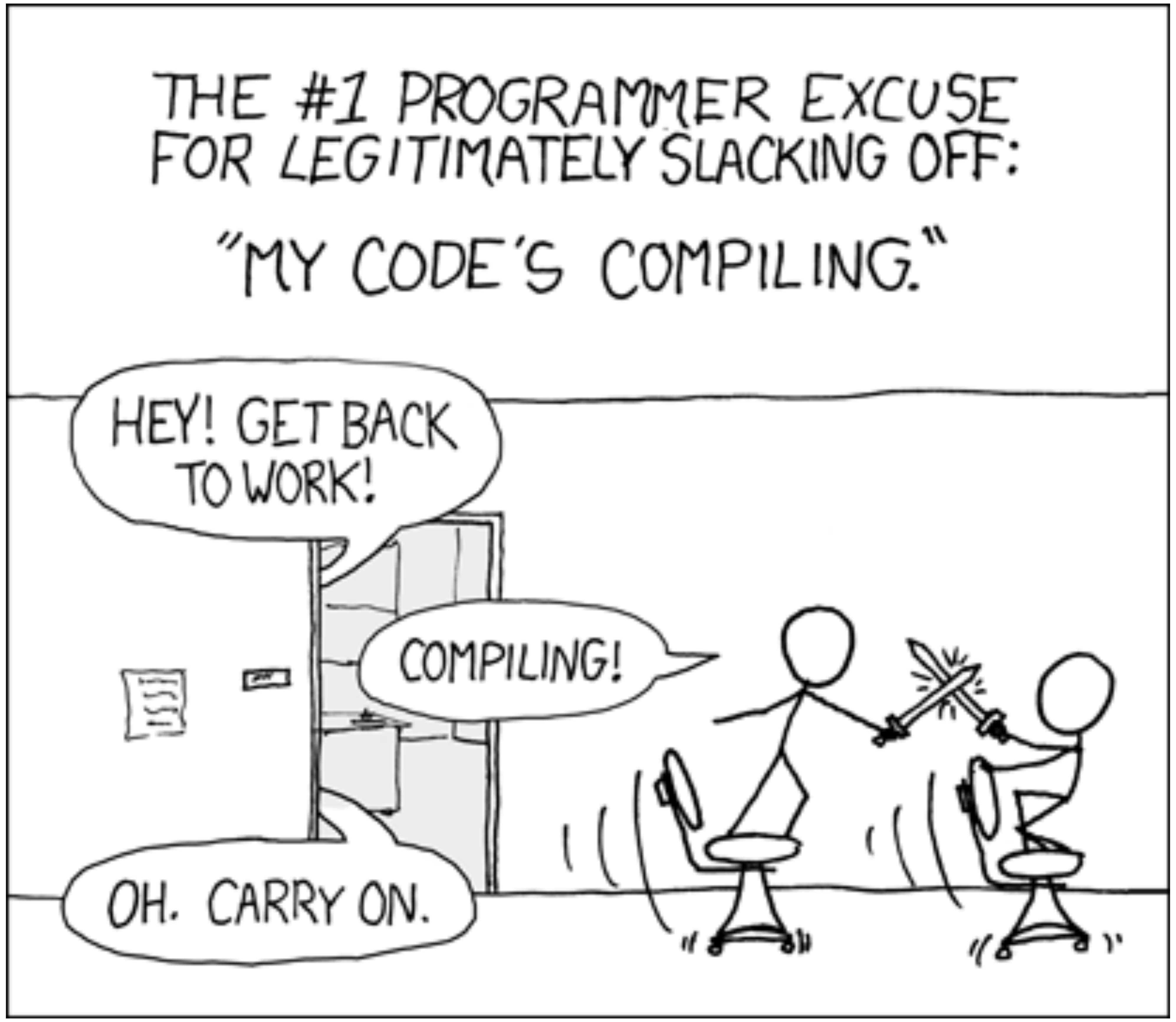
- JIT compilers (compilation at runtime)



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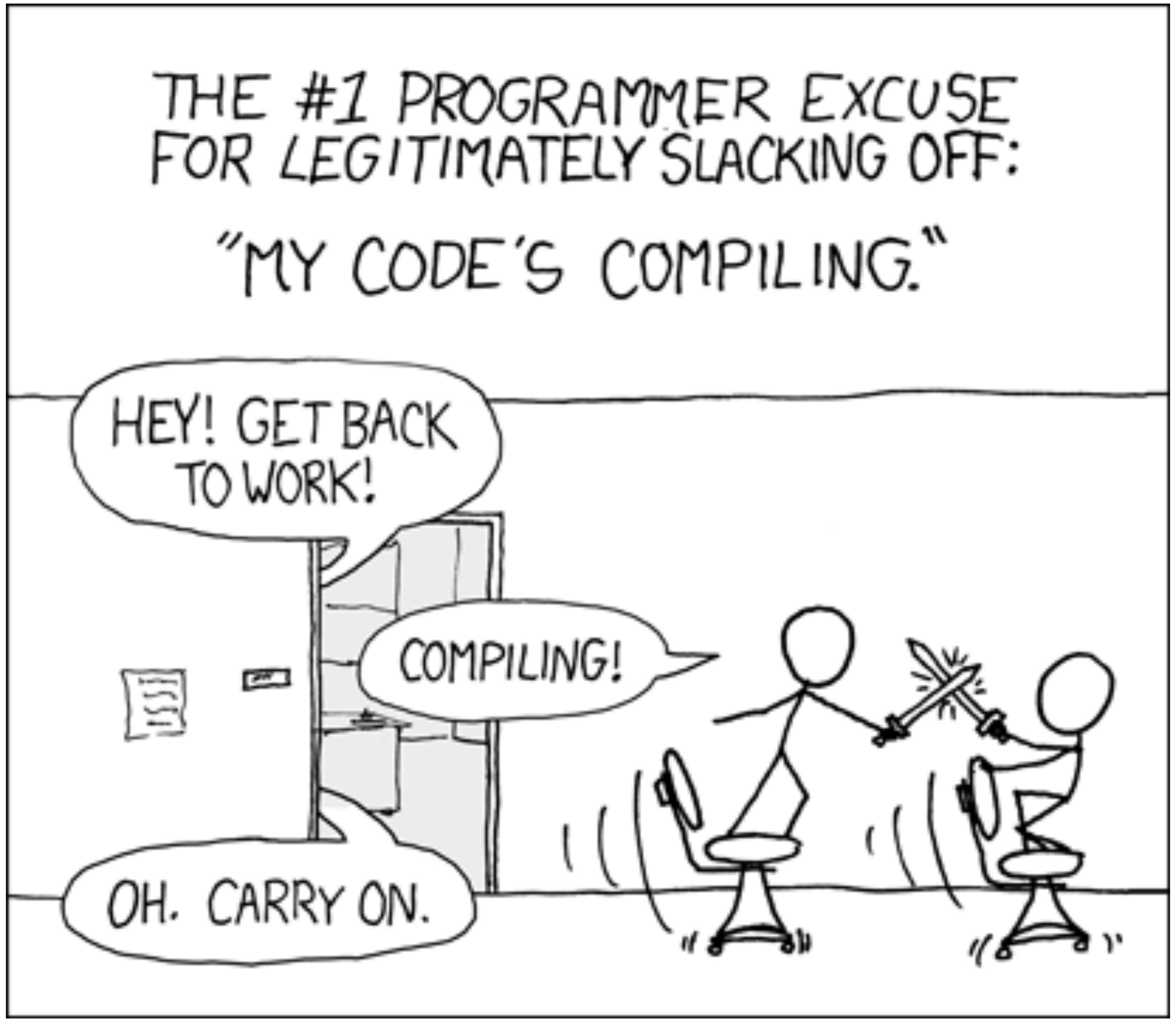
- JIT compilers (compilation at runtime)
- JavaScript (teams of engineers)



How can we speed up compilation? — Let us brainstorm

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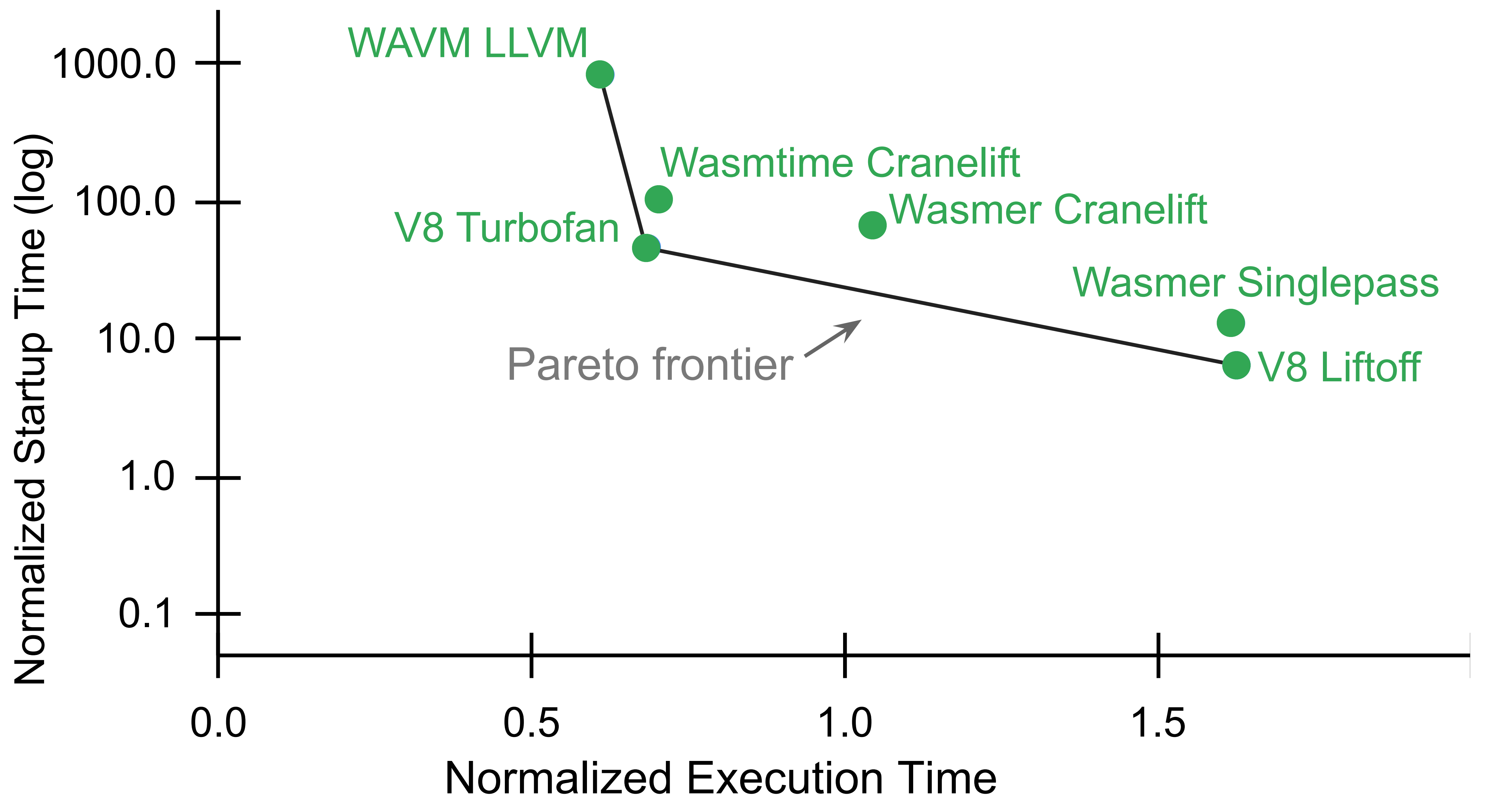
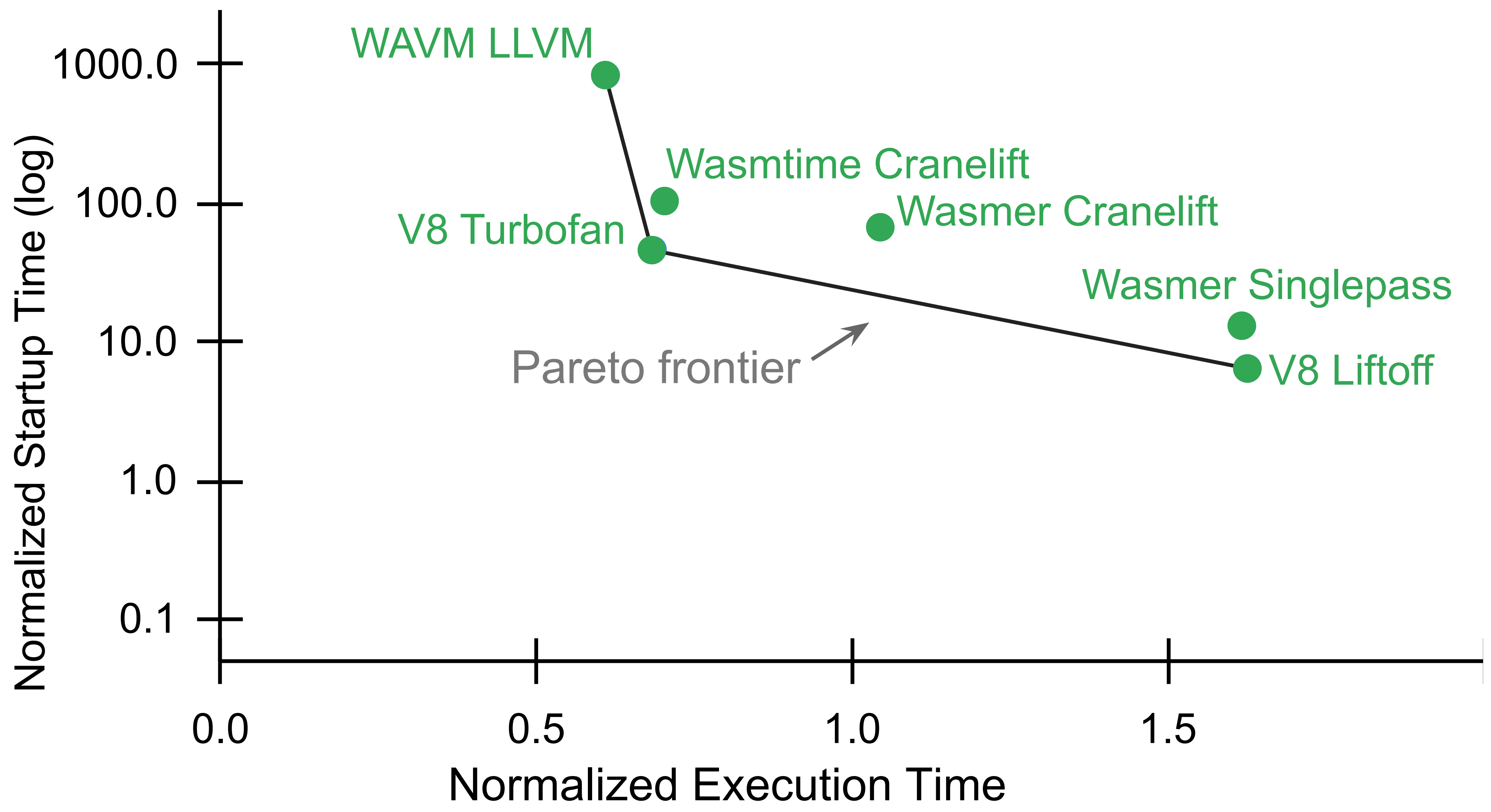
- Multithreading
- Turn off optimization
- Interpretation instead of compilation
- Use bytecode for partial pre-compilation
- Change language: e.g., simplify type system

Tradeoff between compilation time and code performance



WebAssembly (PolyBench benchmarks)

Tradeoff between compilation time and code performance



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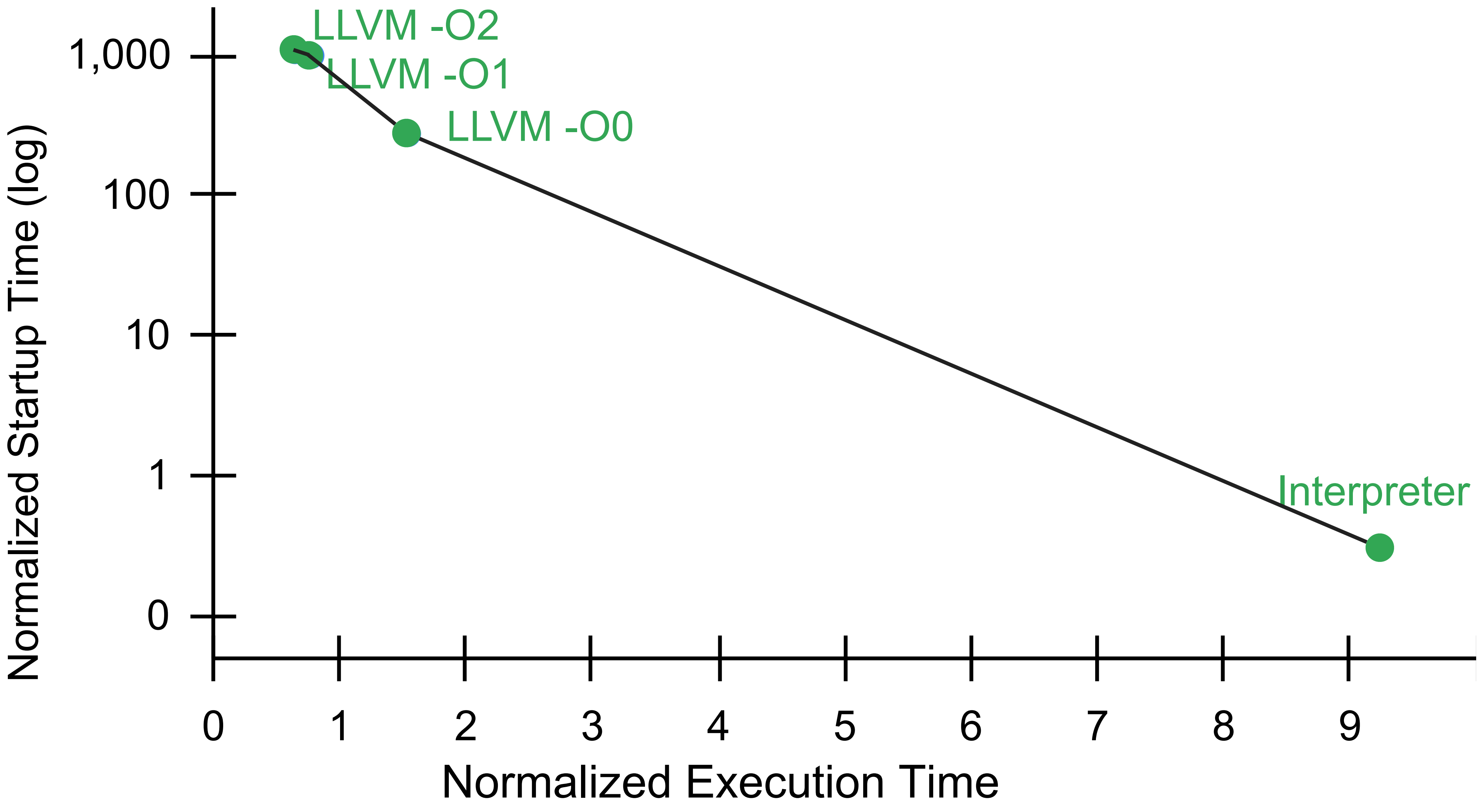

Imperative Language (TPC-H Q6)

Idea: Two-tiered execution

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Tier 1: Fast startup

- Interpreter
- LLVM -O0
- Baseline single-pass compilers

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Tier 2: Fast execution

- Java HotSpot JIT Compiler
- LLVM -O2
- Google V8 TurboFan

Idea: Two-tiered execution

Tier 1: Fast startup

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- Baseline single-pass compilers

Tier 2: Fast execution

- Java HotSpot JIT Compiler
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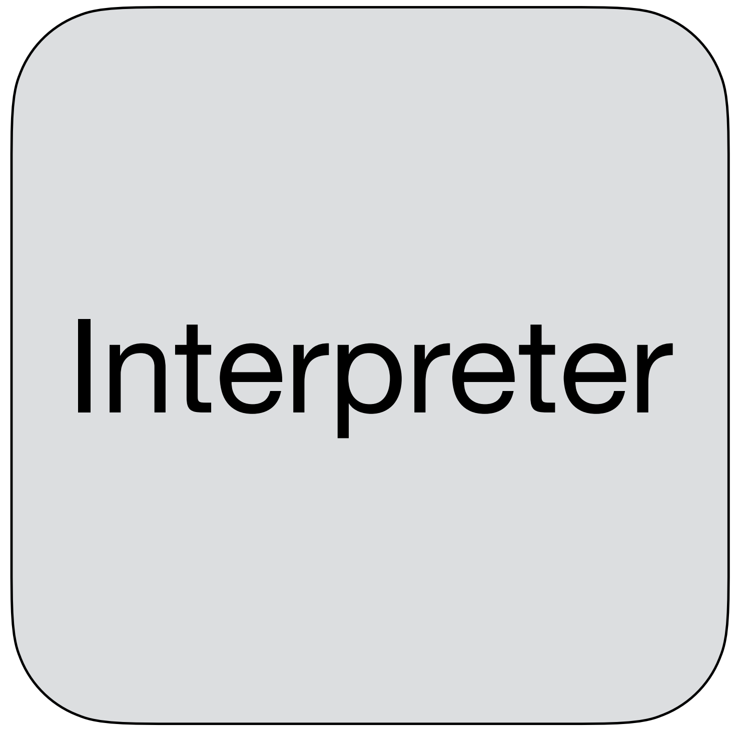
Used in many dynamic language VMs, compilers, and databases

Examples: Java, JavaScript, Lua, WebAssembly, Databases

JavaScript Virtual Machine

JavaScript Virtual Machine



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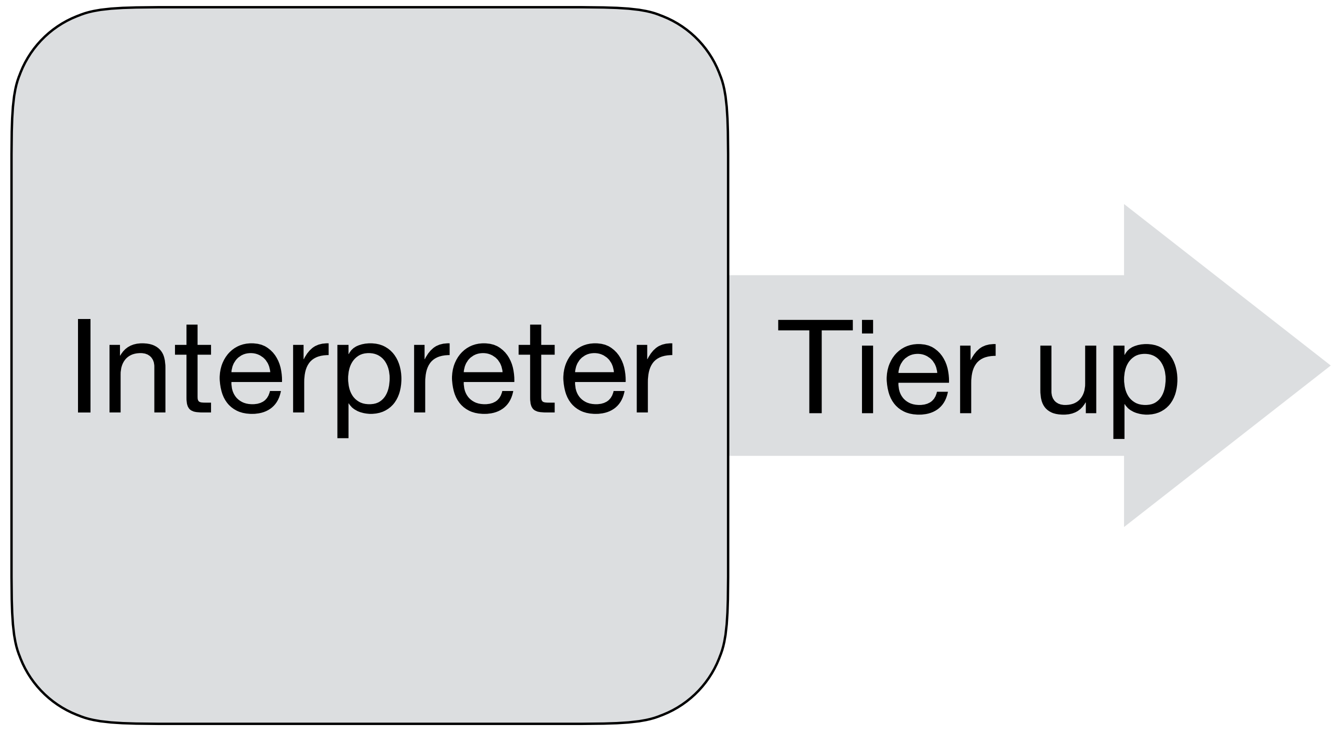

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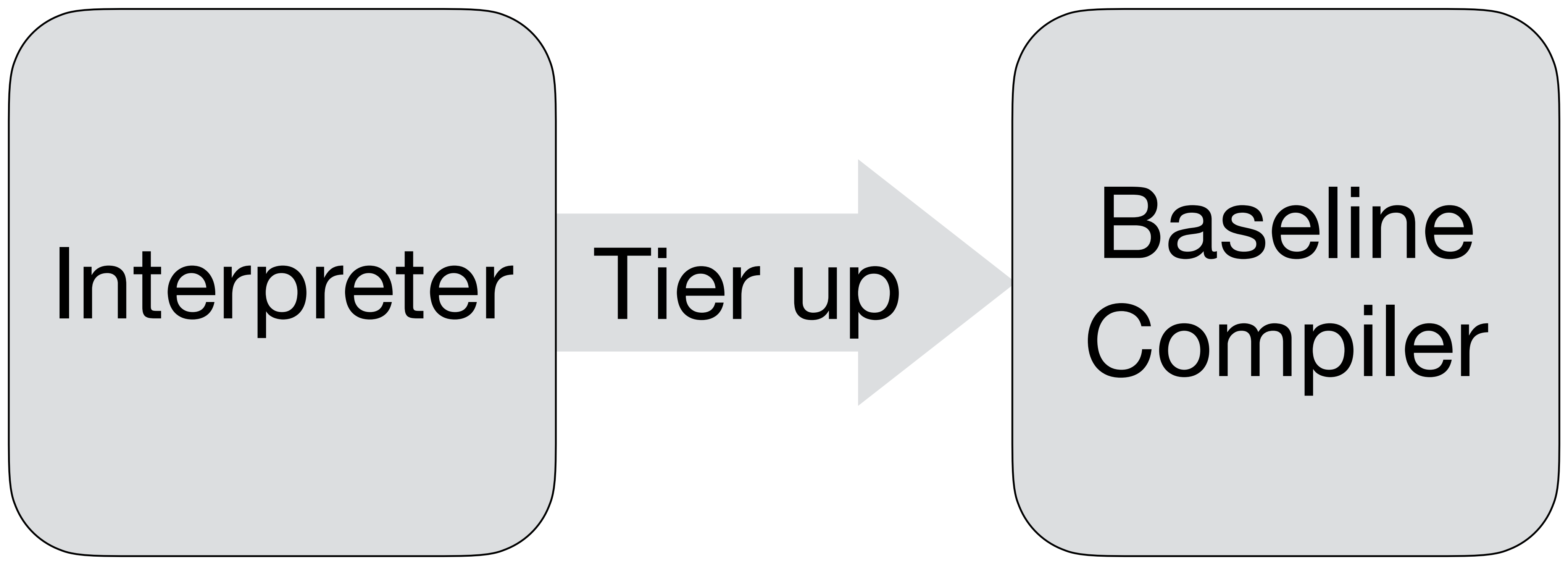

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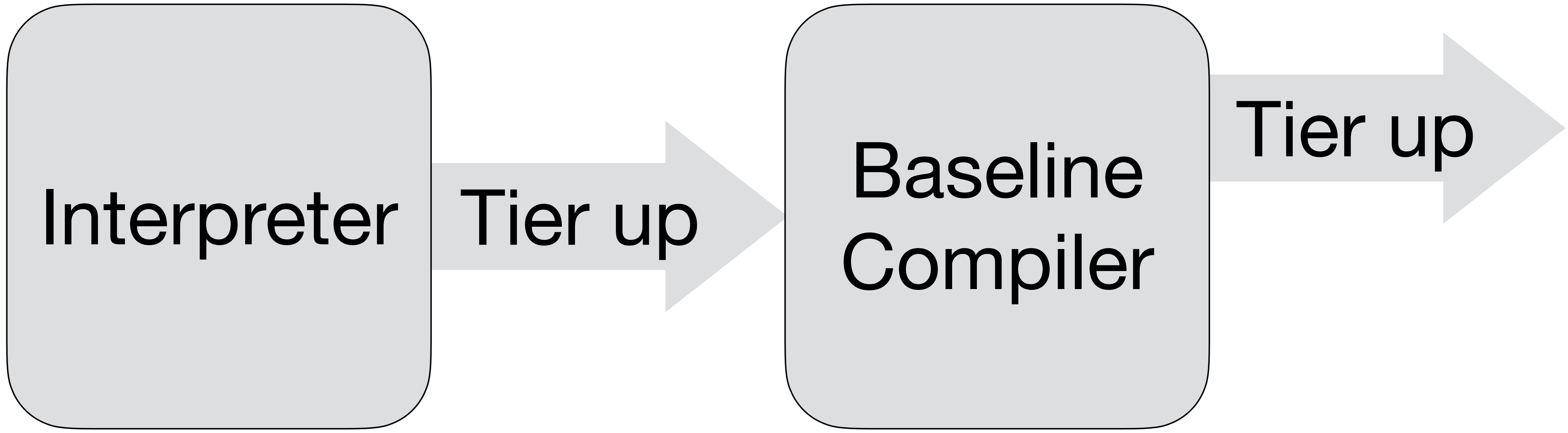

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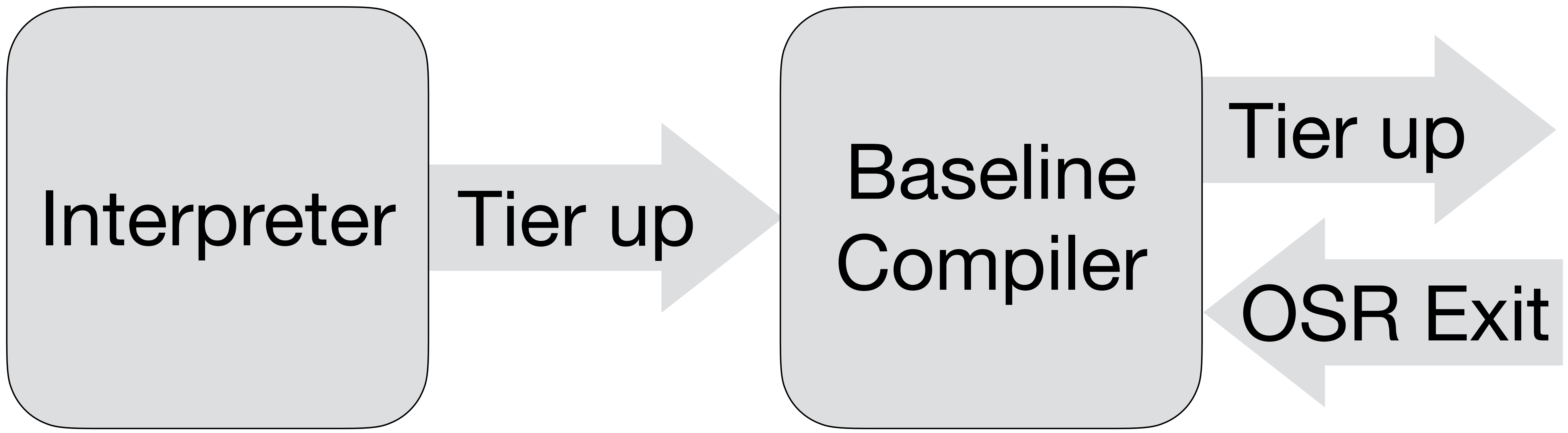

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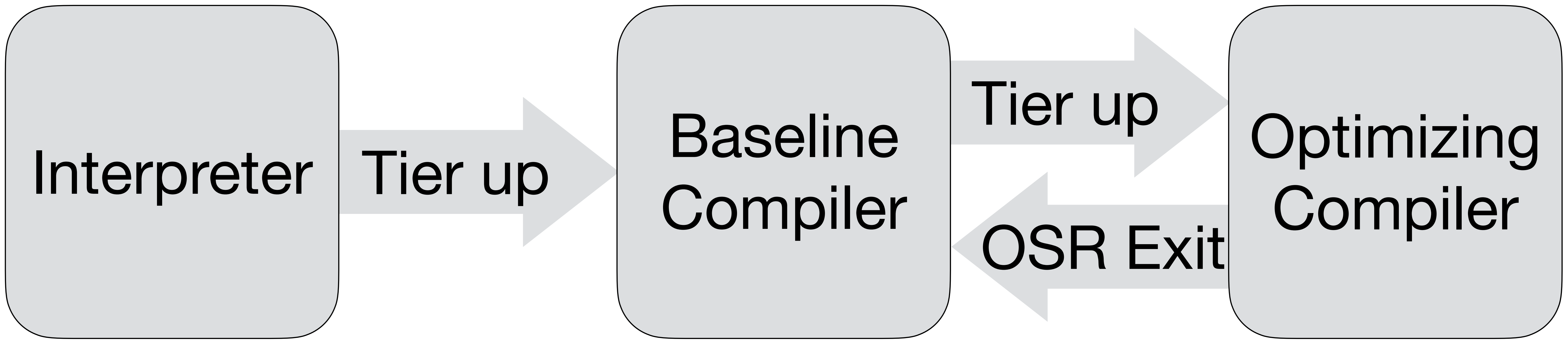

(e.g., type speculation)

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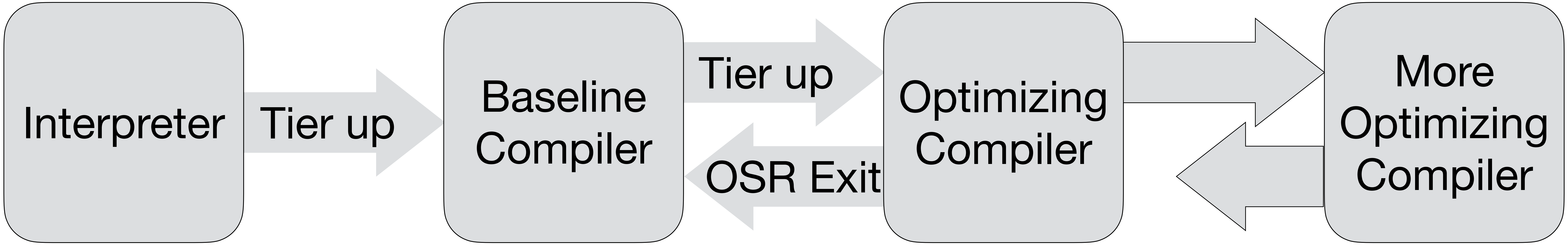

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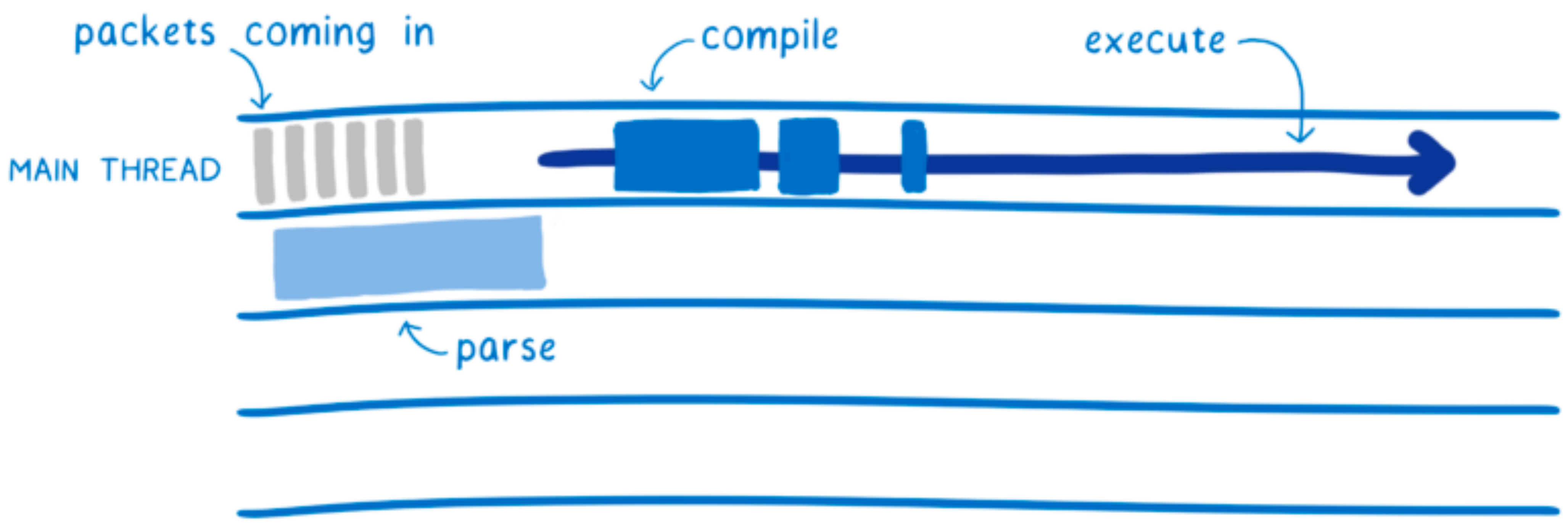
Baseline compiler web example



Figures borrowed from Lin Clark
https://hacks.mozilla.org/2018/01/making-webassembly-even-faster-firefoxs-new-

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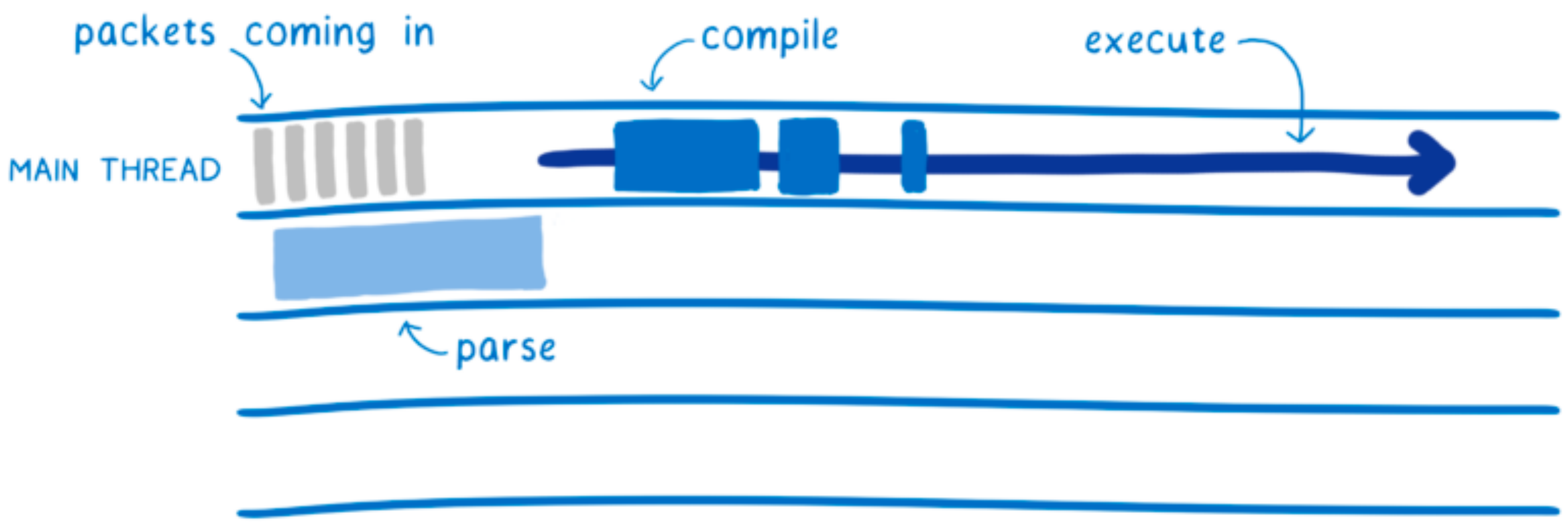

200ms can be perceived by users and cause them to visit a webpage less frequently

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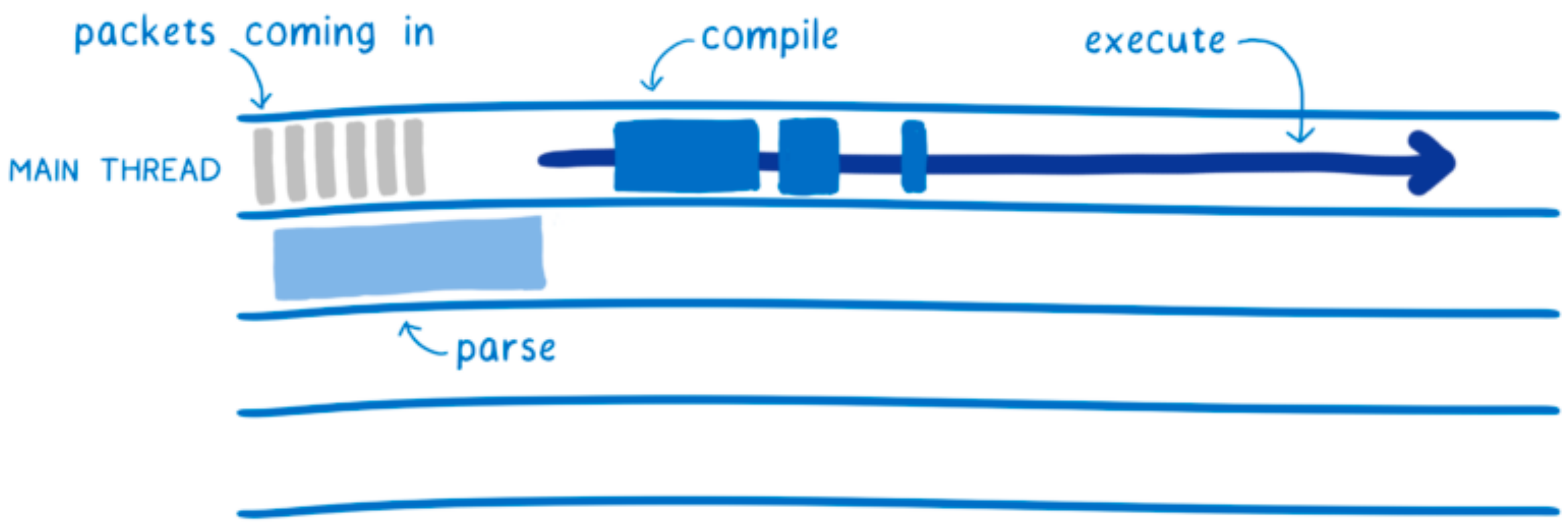

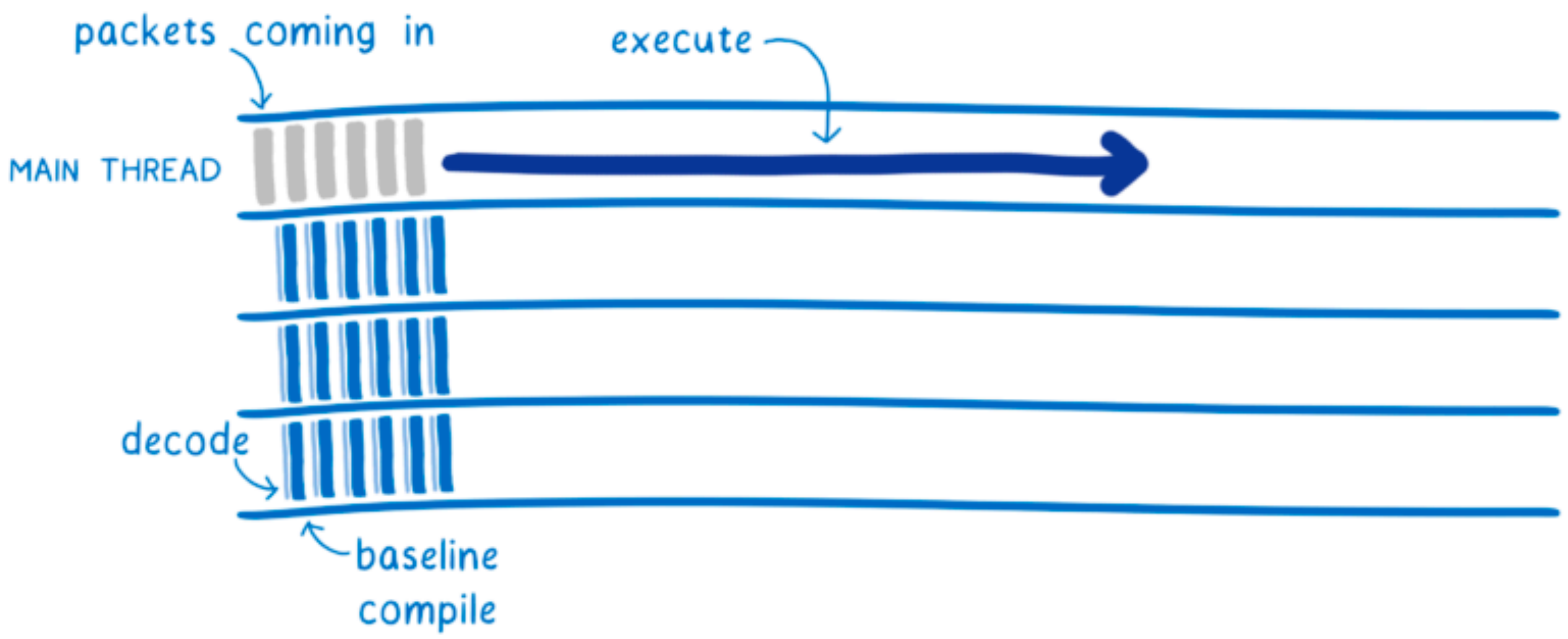

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Baseline compiler web example

WebAssembly (sent in binary)

```
(func (param i32) (result i32)
  local.get 0
  i32.eqz
  if (result i32)
      i32.const 1
  else
      local.get 0
      local.get 0
      i32.const -1
      i32.add
      call 0
      i32.mul
  end)
```

Baseline compiler web example

WebAssembly (sent in binary)

Baseline Compilation

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Baseline compiler rule (Firefox)

```
void BaseCompiler::emitAddI32() {

    RegI32 r, rs;
    pop2xI32(&r, &rs);
    masm.add32(rs, r);
    freeI32(rs);
    pushI32(r);

}
```

Baseline compiler web example

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      call 0
      i32.mul
  end)
```

Baseline compiler rule (Firefox)

```
void BaseCompiler::emitAddI32() {
  int32_t c;
  if (popConstI32(&c)) {
    RegI32 r = popI32();
    masm.add32(Imm32(c), r);
    pushI32(r);
  } else {
    RegI32 r, rs;
    pop2xI32(&r, &rs);
    masm.add32(rs, r);
    freeI32(rs);
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  }
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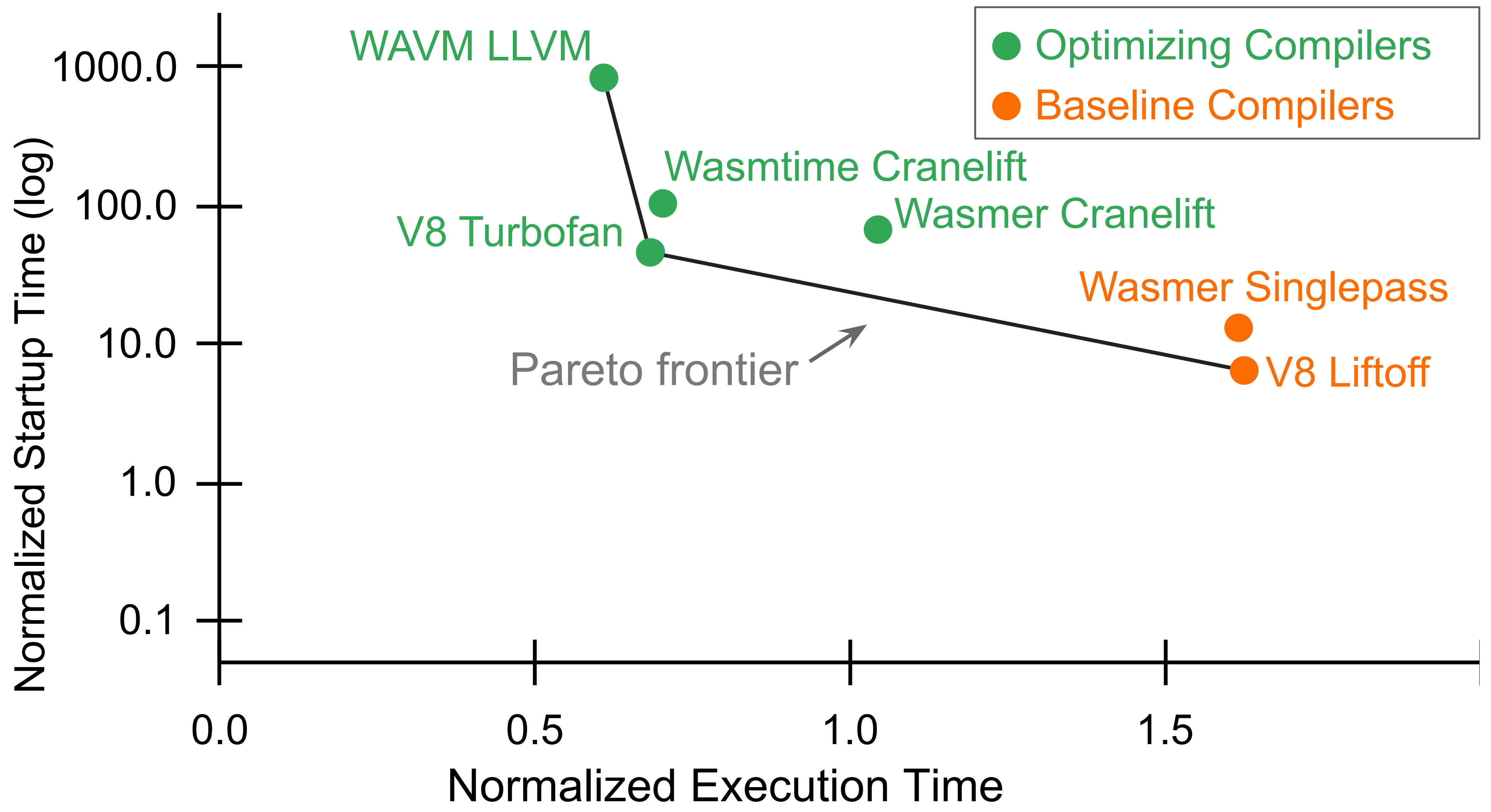
```

Copy-and-Patch is a fast baseline compilation algorithm



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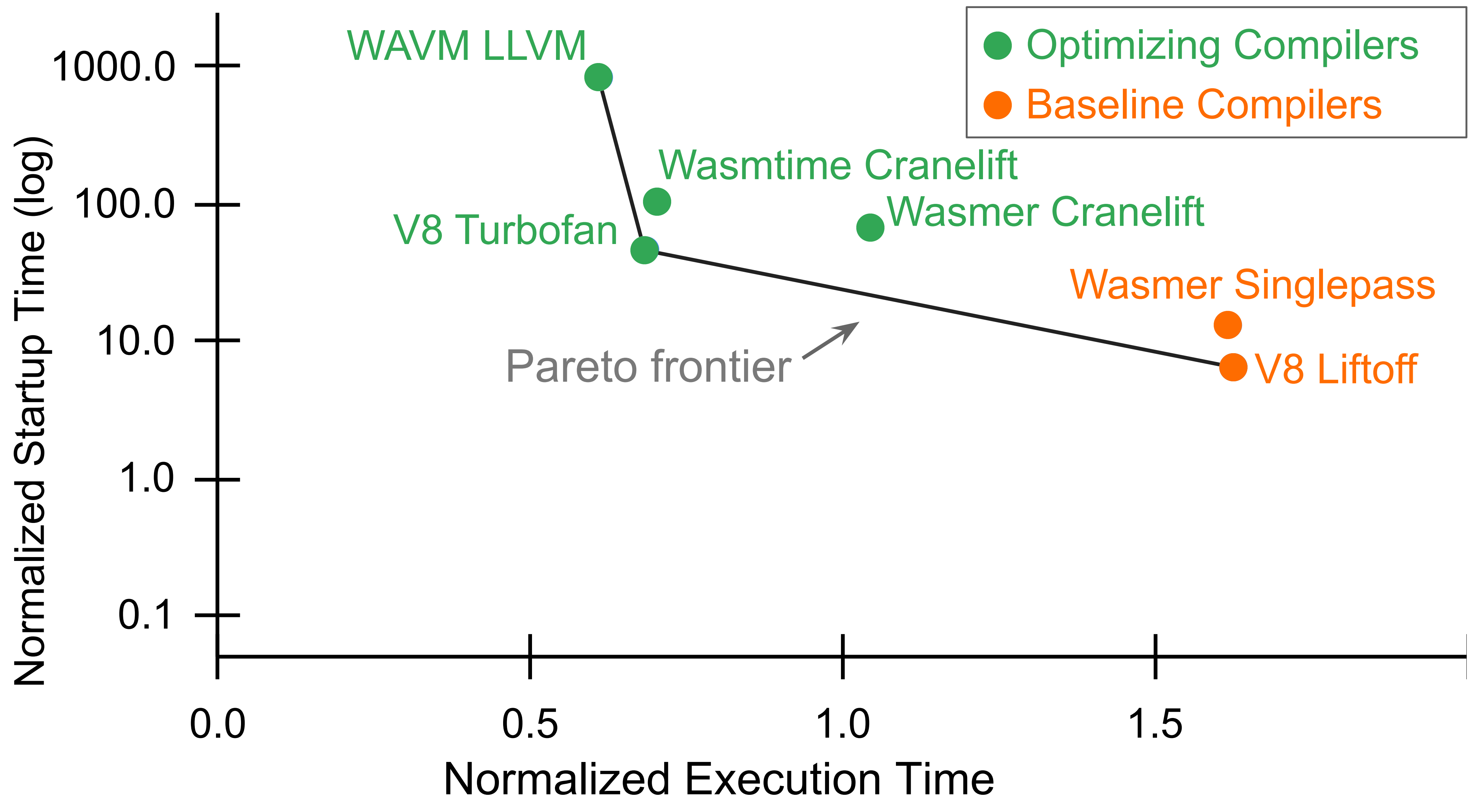

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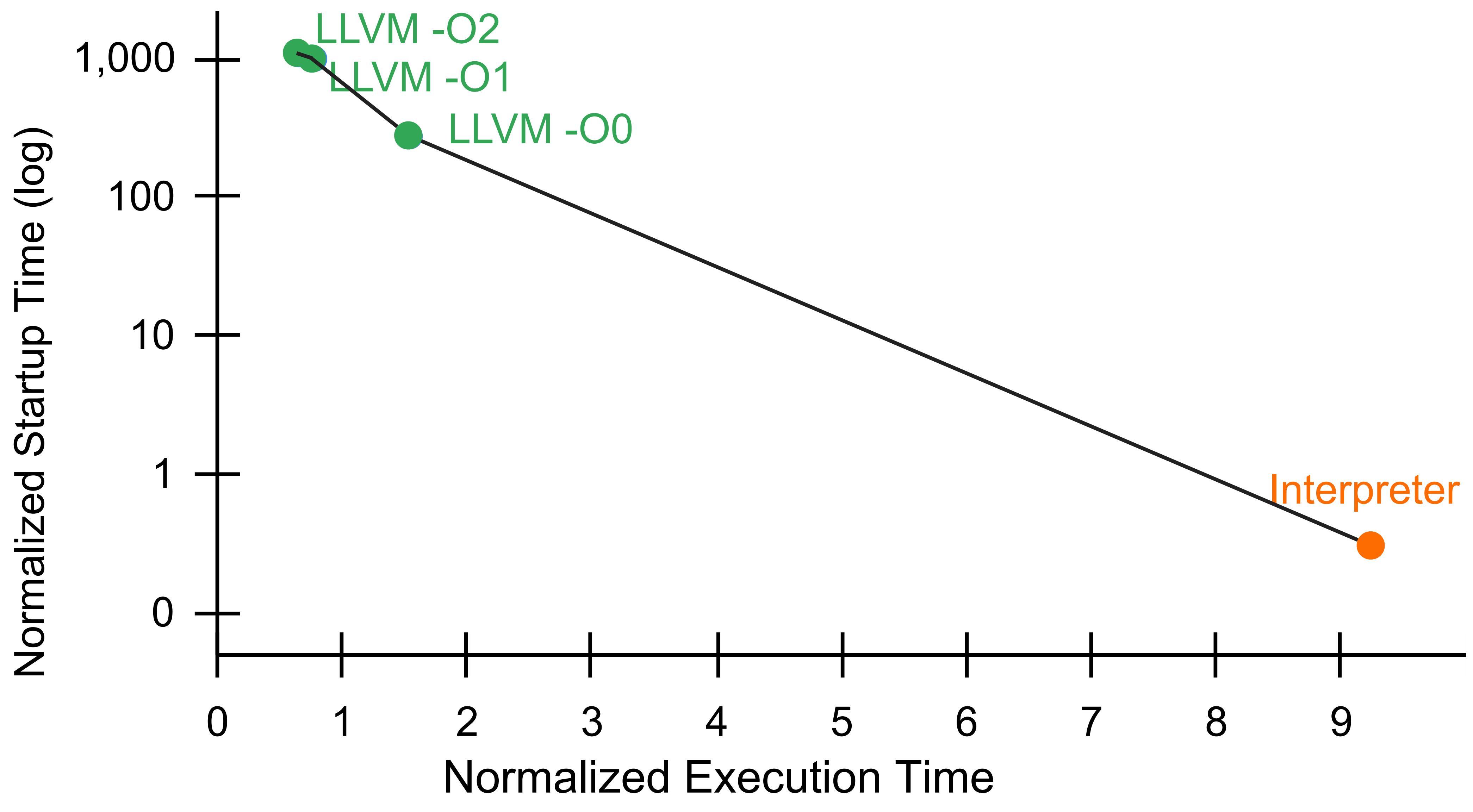

Imperative Language (TPC-H Q6)

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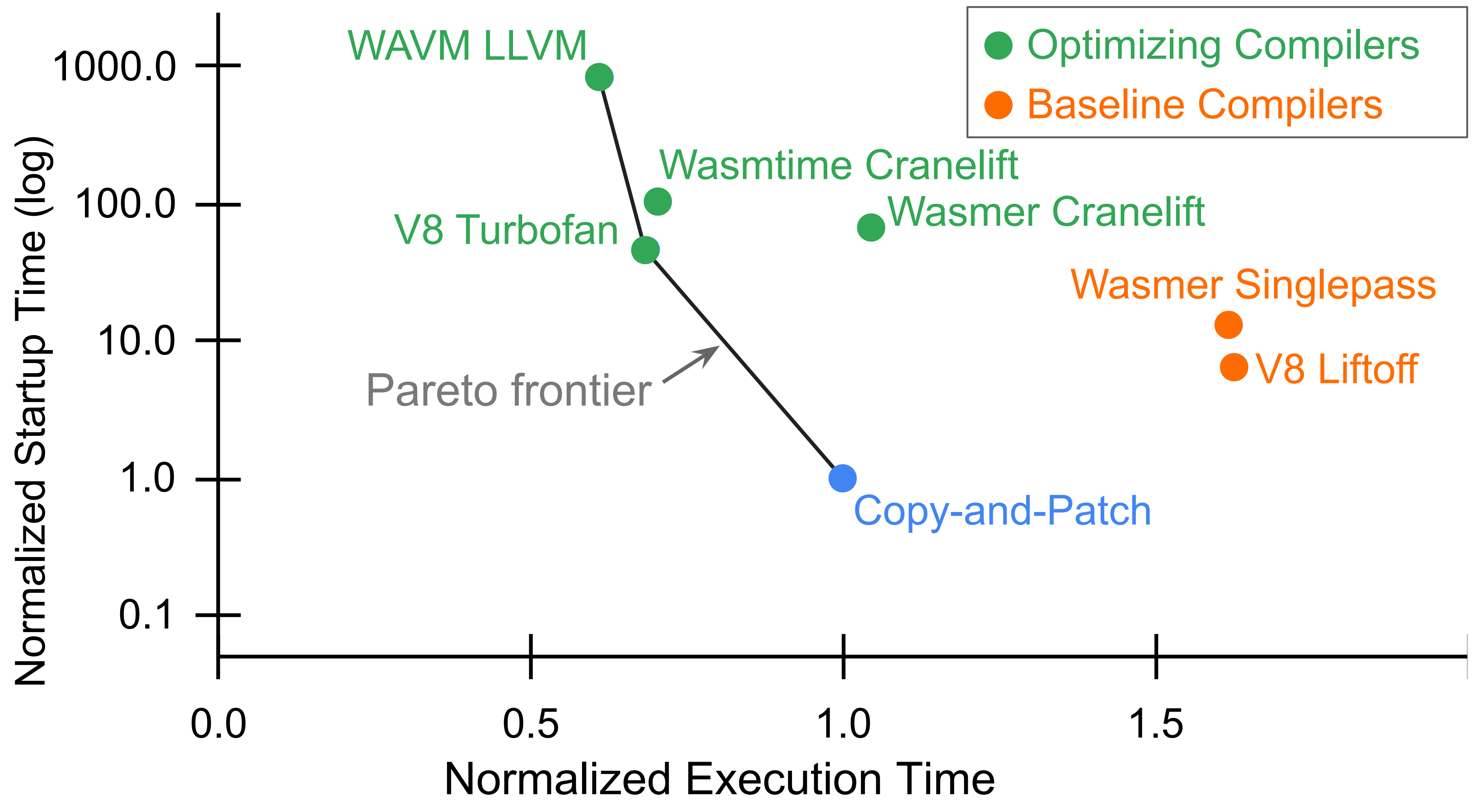

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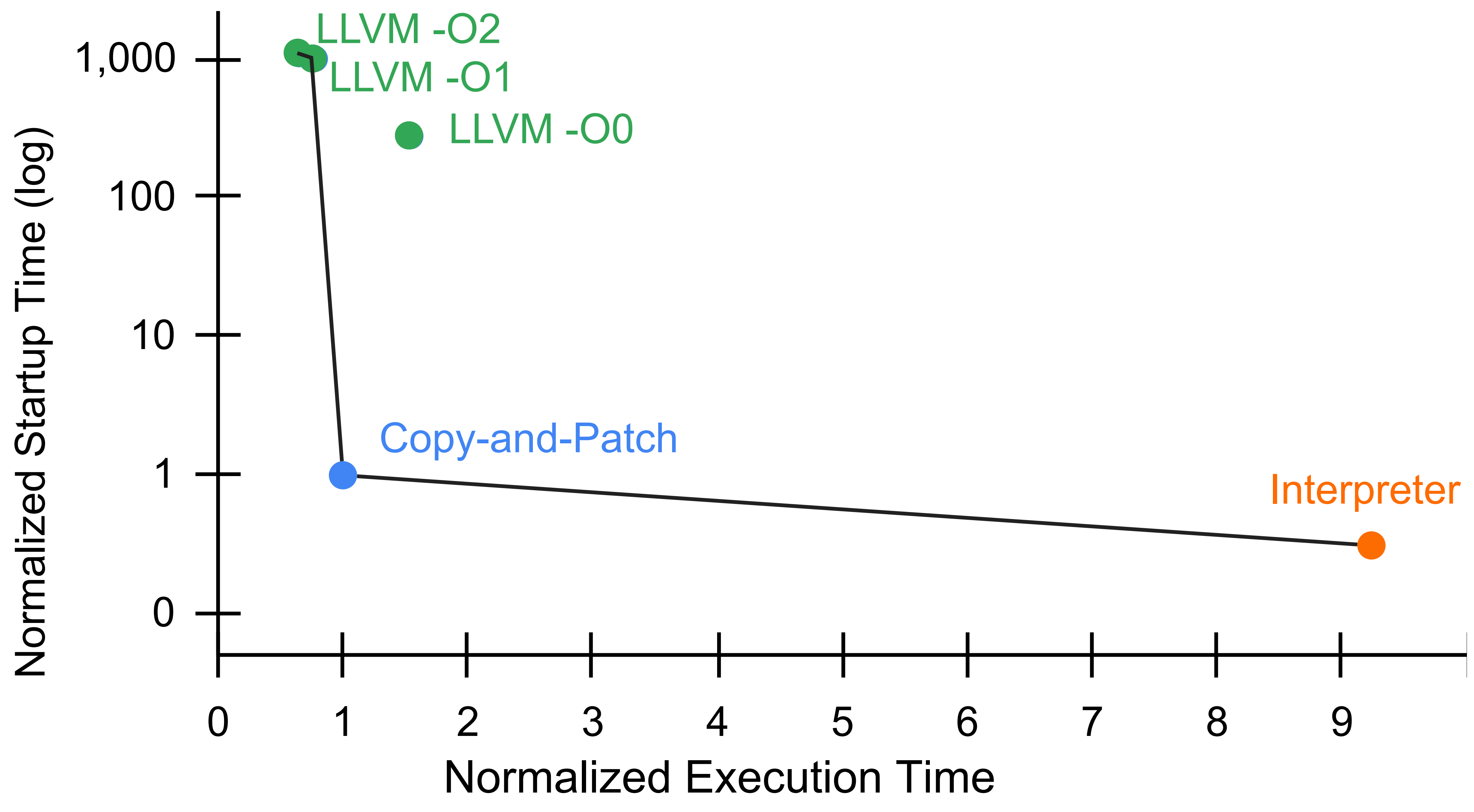
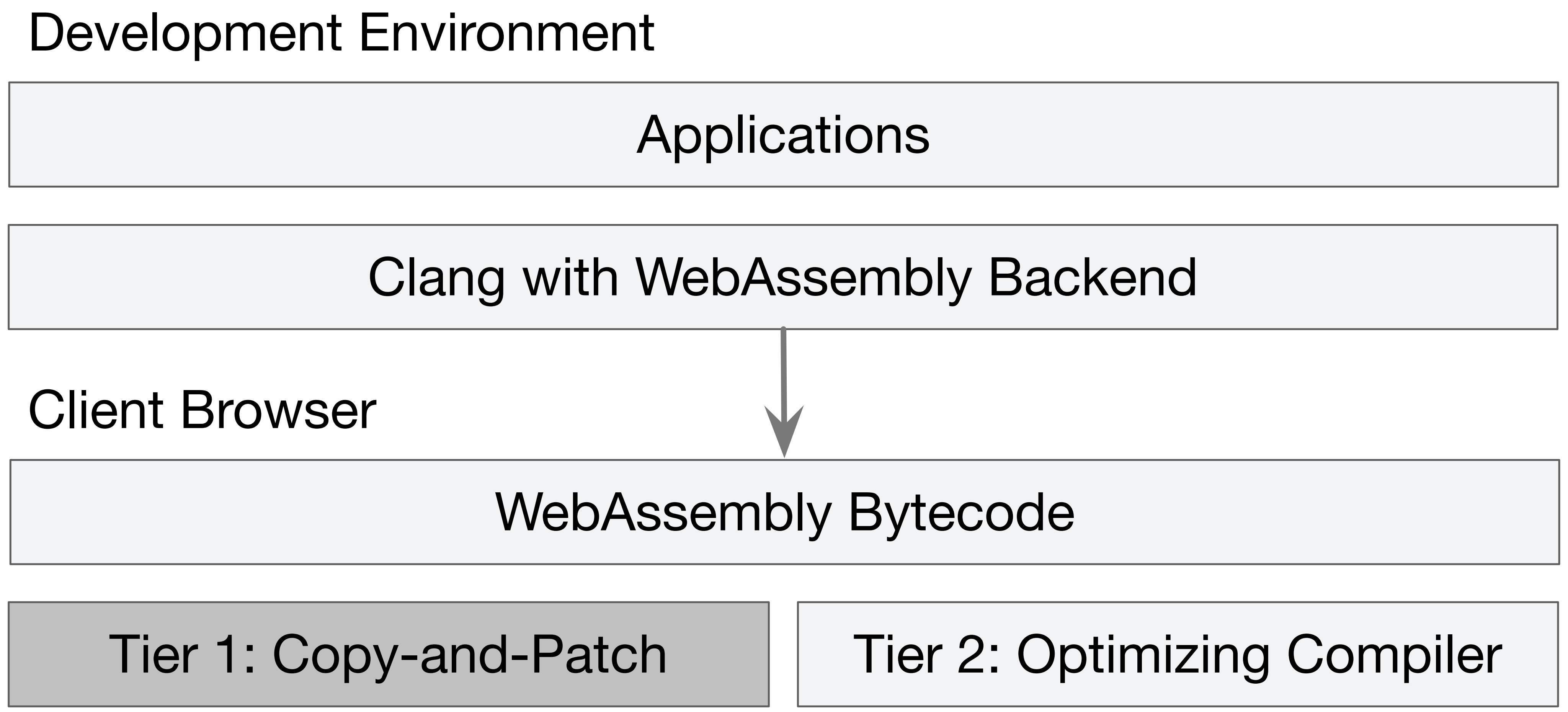


Imperative Language (TPC-H Q6)

Two use cases

WebAssembly



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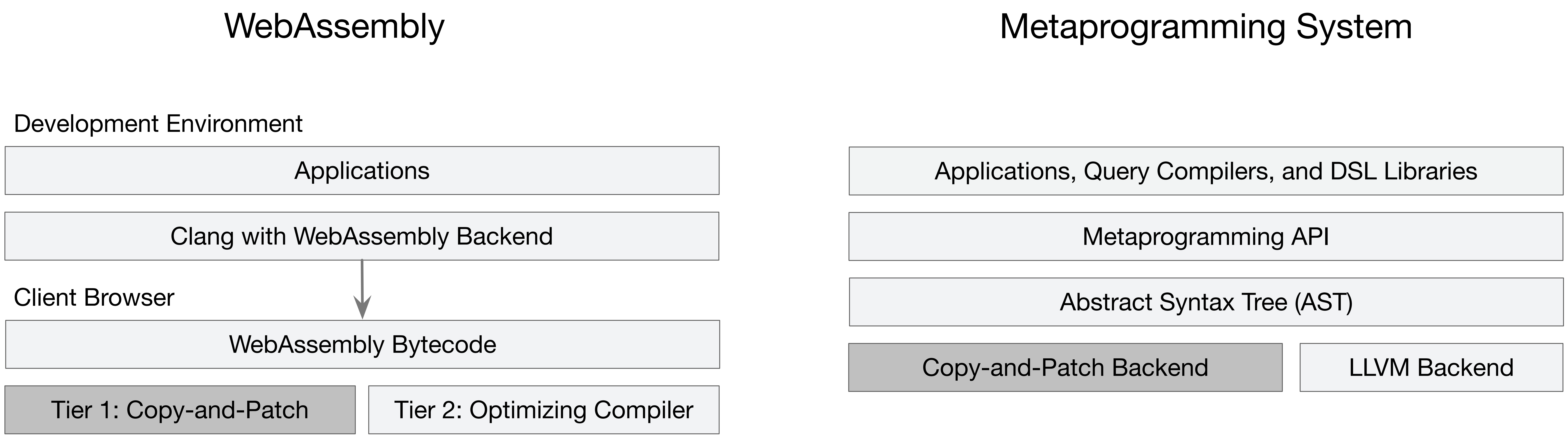

Idea 1: precompile all language constructs

Library of precompiled language constructs

`add`

`sub` `neg`

`load` `mul`

`for` `if`

`while`

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(missing stack offsets and jump targets)

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For each AST node:

1. Hash lookup

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At compile-time

<u>For each AST node:</u>

1. Hash lookup
2. Binary code copy

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For each AST node:

1. Hash lookup
2. Binary code copy
3. Patch in stack offsets and jump targets

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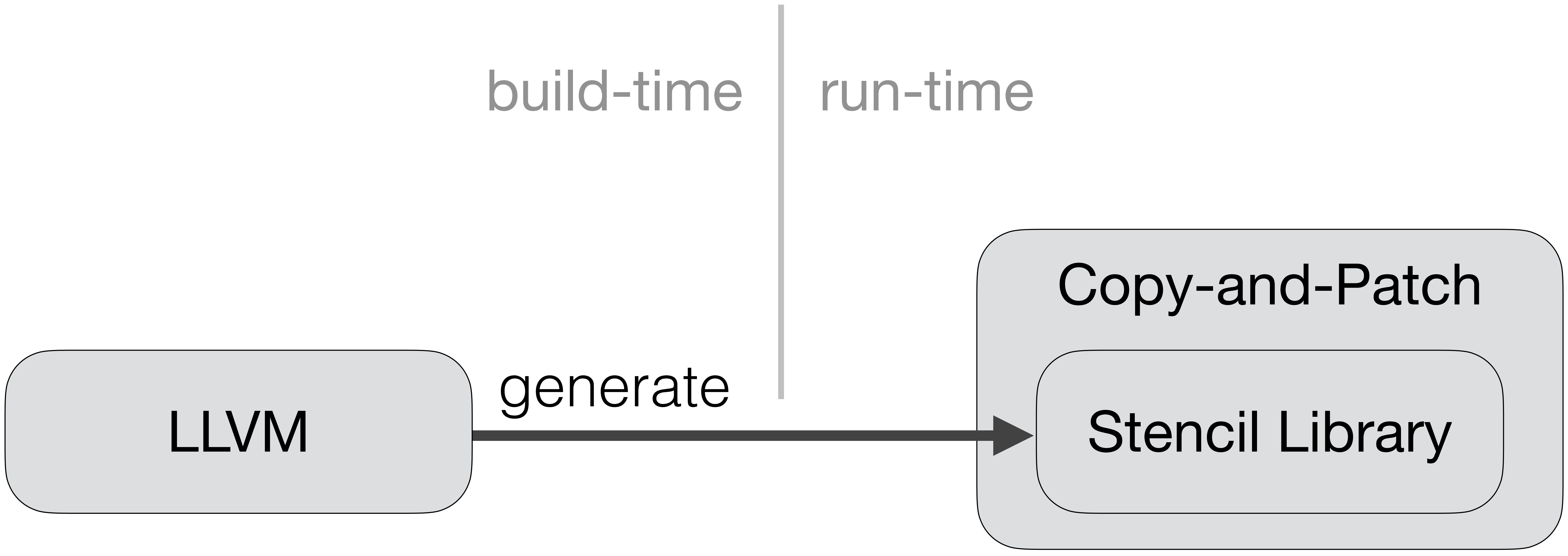

Most performance comes from two optimizations (80/20 rule)

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- 80% of the performance gain comes from **two** optimizations
  1. Instruction selection
  2. Register Allocation

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Idea 2: Instruction Selection

Precompile specialized stencil variants for constants and super-nodes

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`while`

…

Idea 2: Instruction Selection

Precompile specialized stencil variants for constants and super-nodes

Library of precompiled language constructs

```
add(const, const)
add(stack, const)
mul_add(stack,stack)
load
sub(stack,stack)
load_offset
for
if
if_leq
while
...
```

Idea 2: Instruction Selection

Precompile specialized stencil variants for constants and super-nodes

Library of precompiled language constructs

At compile-time

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For each AST node:

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<u>For each AST node:</u>

1. Supernode Tree search
2. Hash lookup

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For each AST node:

1. Supernode Tree search
2. Hash lookup
3. Binary code copy

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At compile-time

For each AST node:

1. Supernode Tree search
2. Hash lookup
3. Binary code copy
4. Patch in stack offsets, jump targets, and constants

Idea 3: Register Allocation

Precompile specialized stencil variants that use different registers

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```

Idea 3: Register Allocation

Precompile specialized stencil variants that use different registers

Library of precompiled language constructs

```
add(const, const)
add(stack, const)    add(r1, r2)
mul_add(stack,stack)
                      add(r1, const)
load
sub(stack,stack)   load_offset
for   if   if_leq
while
...
```

Idea 3: Register Allocation

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At compile-time

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                      add(r1, const)
load
sub(stack,stack)  load_offset
for  if  if_leq
while
...
```

At compile-time

<u>For each AST node:</u>

1. Supernode Tree search

Idea 3: Register Allocation

Precompile specialized stencil variants that use different registers

Library of precompiled language constructs

```
add(const, const)
add(stack, const)    add(r1, r2)
mul_add(stack,stack)
                      add(r1, const)
load
sub(stack,stack)   load_offset
for    if    if_leq
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...
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At compile-time

<u>For each AST node:</u>

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Precompile specialized stencil variants that use different registers

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`add(const, const)`

`add(stack, const)`

`add(r1, r2)`

`mul_add(stack,stack)`

`add(r1, const)`

`load`

`sub(stack,stack)`

`load_offset`

`for`

`if`

`if_leq`

`while`

...

At compile-time

For each AST node:

1. Supernode Tree search
2. Expression register allocation
3. Hash lookup

Idea 3: Register Allocation

Precompile specialized stencil variants that use different registers

Library of precompiled language constructs

```
add(const, const)
add(stack, const)    add(r1, r2)
mul_add(stack,stack)
add(r1, const)
load
sub(stack,stack)    load_offset
for    if    if_leq
while
...
```

At compile-time

For each AST node:

1. Supernode Tree search
2. Expression register allocation
3. Hash lookup
4. Binary code copy

Idea 3: Register Allocation

Precompile specialized stencil variants that use different registers

Library of precompiled language constructs

```
add(const, const)
add(stack, const)    add(r1, r2)
mul_add(stack,stack)
add(r1, const)
load
sub(stack,stack)    load_offset
for    if    if_leq
while
...
```

At compile-time

<u>For each AST node:</u>

1. Supernode Tree search
2. Expression register allocation
3. Hash lookup
4. Binary code copy
5. Patch in stack offsets, jump targets, and constants

Compile a large stencil variant library for use during compilation

Created at compiler build time, used to compile at runtime

WebAssembly

- 1666 stencils
- 30 kilobytes
- <1 minute to compile

High-Level Imperative Language

- 98,831 stencils
- 17.5 megabytes
- 14 minutes to compile

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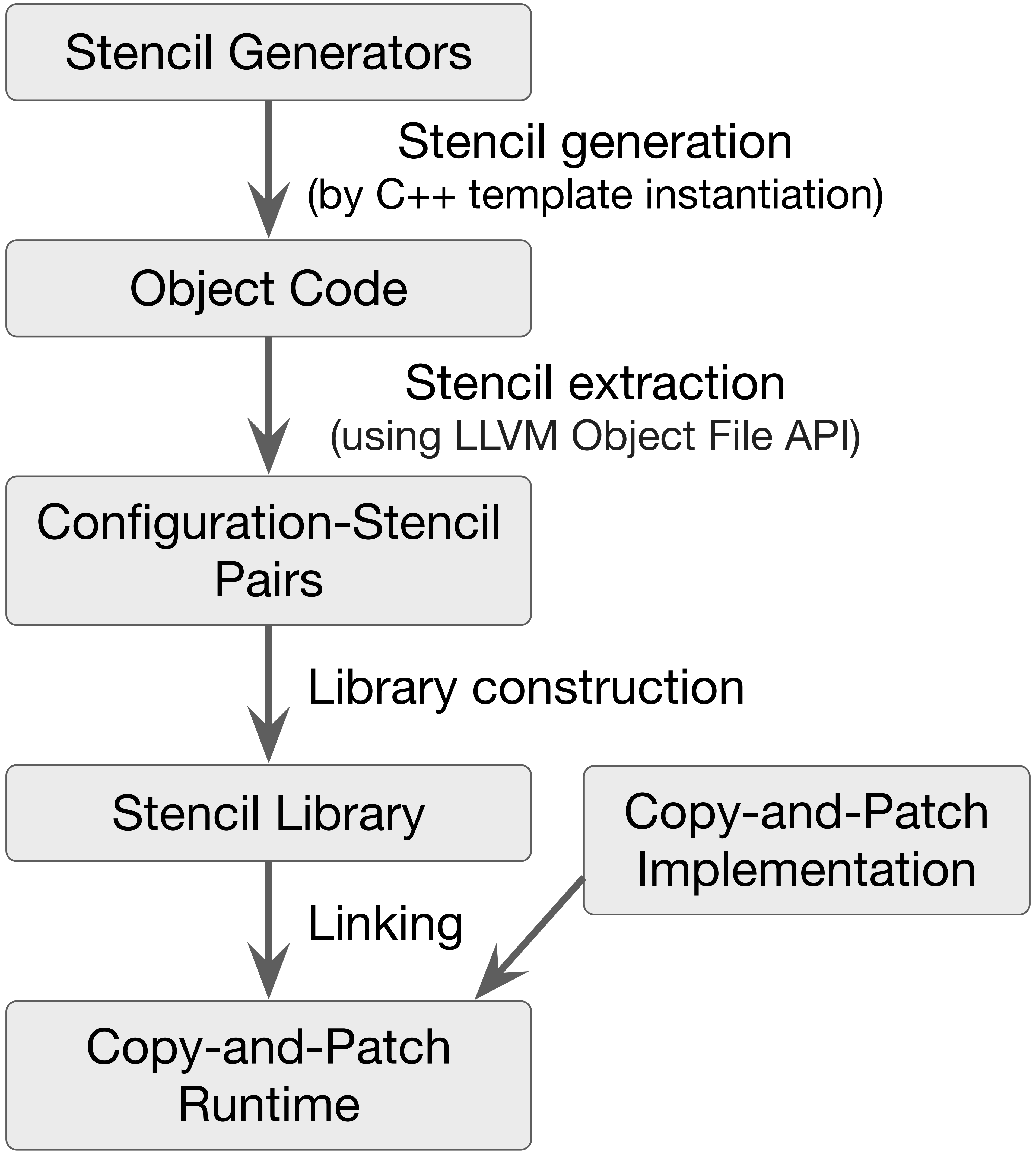
How can we create all of these stencils?

We write variant groups in C++ using templates and Clang+LLVM compiles them for us



Variants

```
void eq_int(uintptr_t stack, int lhs, int rhs) {
  bool result = (lhs == rhs);
  (void(*)(uintptr_t, bool) 1 )(stack, result);
}
```

Variants

Registers operands lhs and rhs

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void eq_int(uintptr_t stack, int lhs, int rhs) {
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Variants

Registers operands lhs and rhs

```
void eq_int(uintptr_t stack, int lhs, int rhs) {
  bool result = (lhs == rhs);
  (void(*)(uintptr_t, bool) [1] )(stack, result);
}
```

Call next operation

Variants

Registers operands lhs and rhs

```
void eq_int(uintptr_t stack, int lhs, int rhs) {
  bool result = (lhs == rhs);
  (void(*)(uintptr_t, bool) 1 )(stack, result);
}
```

Call next operation

```
void eq_int_lvar_rconst(uintptr_t stack) {
  int lhs = *(int*)(stack + 1 );
  int rhs = 2 ;
  bool result = (lhs == rhs);
  (void(*)(uintptr_t, bool) 3 )(stack, result);
}
```

Variants

Registers operands lhs and rhs

```
void eq_int(uintptr_t stack, int lhs, int rhs) {
  bool result = (lhs == rhs);
  (void(*)(uintptr_t, bool) [1] )(stack, result);
}
```

Call next operation

```
void eq_int_lvar_rconst(uintptr_t stack) {
  int lhs = *(int*)(stack + [1]);
  int rhs = [2];
  bool result = (lhs == rhs);
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}
```

Stack operand

Variants

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void eq_int(uintptr_t stack, int lhs, int rhs) {
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Call next operation

```
void eq_int_lvar_rconst(uintptr_t stack) {
  int lhs = *(int*)(stack + [1] );
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  bool result = (lhs == rhs);
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}
```

Stack operand

Constant

Variants

Registers operands lhs and rhs

```
void eq_int(uintptr_t stack, int lhs, int rhs) {
  bool result = (lhs == rhs);
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}
```

Call next operation

```
void eq_int_lvar_rconst(uintptr_t stack) {
  int lhs = *(int*)(stack + 1 );
  int rhs = 2 ;
  bool result = (lhs == rhs);
  (void(*)(uintptr_t, bool) 3 )(stack, result);
}
```

Stack operand

Constant

```
void if(uintptr_t stack, bool test) {
  if (test)
    (void(*)(uintptr_t) 1 )(stack);
  else
    (void(*)(uintptr_t) 2 )(stack);
}
```

Variants

Registers operands lhs and rhs

```
void eq_int(uintptr_t stack, int lhs, int rhs) {
  bool result = (lhs == rhs);
  (void(*)(uintptr_t, bool) [1] )(stack, result);
}
```

Call next operation

```
void eq_int_lvar_rconst(uintptr_t stack) {
  int lhs = *(int*)(stack + [1]);
  int rhs = [2];
  bool result = (lhs == rhs);
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}
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Stack operand

Constant

```
void if(uintptr_t stack, bool test) {
  if (test)
    (void(*)(uintptr_t) [1] )(stack);
  else
    (void(*)(uintptr_t) [2] )(stack);
}
```

```
void eq_int_pt(uintptr_t stack, uint64_t r1, int rhs) {
  int lhs = [1];
  bool result = (lhs == rhs);
  (void(*)(uintptr_t,uint64_t,bool) [2] )(stack, r1, result);
}
```

Variants

Registers operands lhs and rhs

```
void eq_int(uintptr_t stack, int lhs, int rhs) {
  bool result = (lhs == rhs);
  (void(*)(uintptr_t, bool) 1 )(stack, result);
}
```

Call next operation

```
void eq_int_lvar_rconst(uintptr_t stack) {
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Stack operand

Constant

```
void if(uintptr_t stack, bool test) {
  if (test)
    (void(*)(uintptr_t) 1 )(stack);
  else
    (void(*)(uintptr_t) 2 )(stack);
}
```

```
void eq_int_pt(uintptr_t stack, uint64_t r1, int rhs) {
  int lhs = 1 ;
  bool result = (lhs == rhs);
  (void(*)(uintptr_t,uint64_t,bool) 2 )(stack, r1, result);
}
```

Register communicated
from a previous operation
to a later operations

Continuation-passing style and tail call optimization

Typical recursive interpreter code

```
int evaluate()
{
    int lhs = evaluate_lhs();
    int rhs = evaluate_rhs();
    return lhs + rhs;
}
```

Continuation-passing style and tail call optimization

Typical recursive interpreter code

```
int evaluate()
{
    int lhs = evaluate_lhs();
    int rhs = evaluate_rhs();
    return lhs + rhs;
}
```

Faster continuation-passing style

```
(a + b) == c
```

Register pass-through

```
void stencil1(uintptr_t stack) {
  int x = /* assign value to x */;
  (void(*)(uintptr_t, int) □ )(stack, x);
}

void stencil2(uintptr_t stack, uint64_t x) {
   // computation unrelated to x
   (void(*)(uintptr_t, uint64_t) □ )(stack, x);
}

void stencil3(uintptr_t stack, int x) {
   // do something with x
}
```

Hack: use C++ extern keyword to locate holes in generated code

```
extern int evaluate_lhs();
extern int evaluate_rhs();
int evaluate()
{
    int lhs = evaluate_lhs();
    int rhs = evaluate_rhs();
    return lhs + rhs;
}
```

Hack: use C++ extern keyword to locate holes in generated code

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extern int evaluate_lhs();
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1. C++ compiler generates an object file

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1. C++ compiler generates an object file
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1. C++ compiler generates an object file
2. The linker can link object files to any definition of the extern calls
3. The object file thus contains information to locate them in the binary code
4. We can use this information to locate holes in stencils for later patching

Using templates we can generate groups of variants

```
struct ArithAdd {
  template<typename T /* OperandType */,
           bool spillOutput,
           NumPassthroughs numPassThroughs,
           typename... Passthroughs>
  static void g(uintptr_t stack, Passthroughs... pt, T a, T b) {
    T c = a + b;
    if constexpr (! spillOutput) {
      DEF_CONTINUATON_0(void(*)(uintptr_t, Passthroughs...,T));
      CONTINUATON_0(stack, pt..., c);  // continuation
    } else {
      DEF_CONSTANT_1(uint64_t);
      *(T*)(stack + CONSTANT_1) = c;
      DEF_CONTINUATON_0(void(*)(uintptr_t, Passthroughs...));
      CONTINUATON_0(stack, pt...);     // continuation
    }
  }

  template<typename T /* OperandType */,
           bool spillOutput,
           NumPassthroughs numPassThroughs>
  static constexpr bool f() {
    if (numPt > numMaxPassthroughs - 2) return false;
    return !std::is_same<T, void>::value;
  }

  static auto metavars() {
    return createMetaVarList(
      typeMetaVar(),
      boolMetaVar(),
      enumMetaVar<NumPassthroughs::X_END_OF_ENUM>());
  }
};

extern "C" void generate(StencilList* result) {
  runStencilGenerator<ArithAdd>(result);
}
```

Fibonacci compilation example

```
If(n <= 2).Then(
  Return(1ULL)
).Else(
  Return(Call<FibFn>("fib", n-1)
       + Call<FibFn>("fib", n-2))
)
```

Fibonacci compilation example

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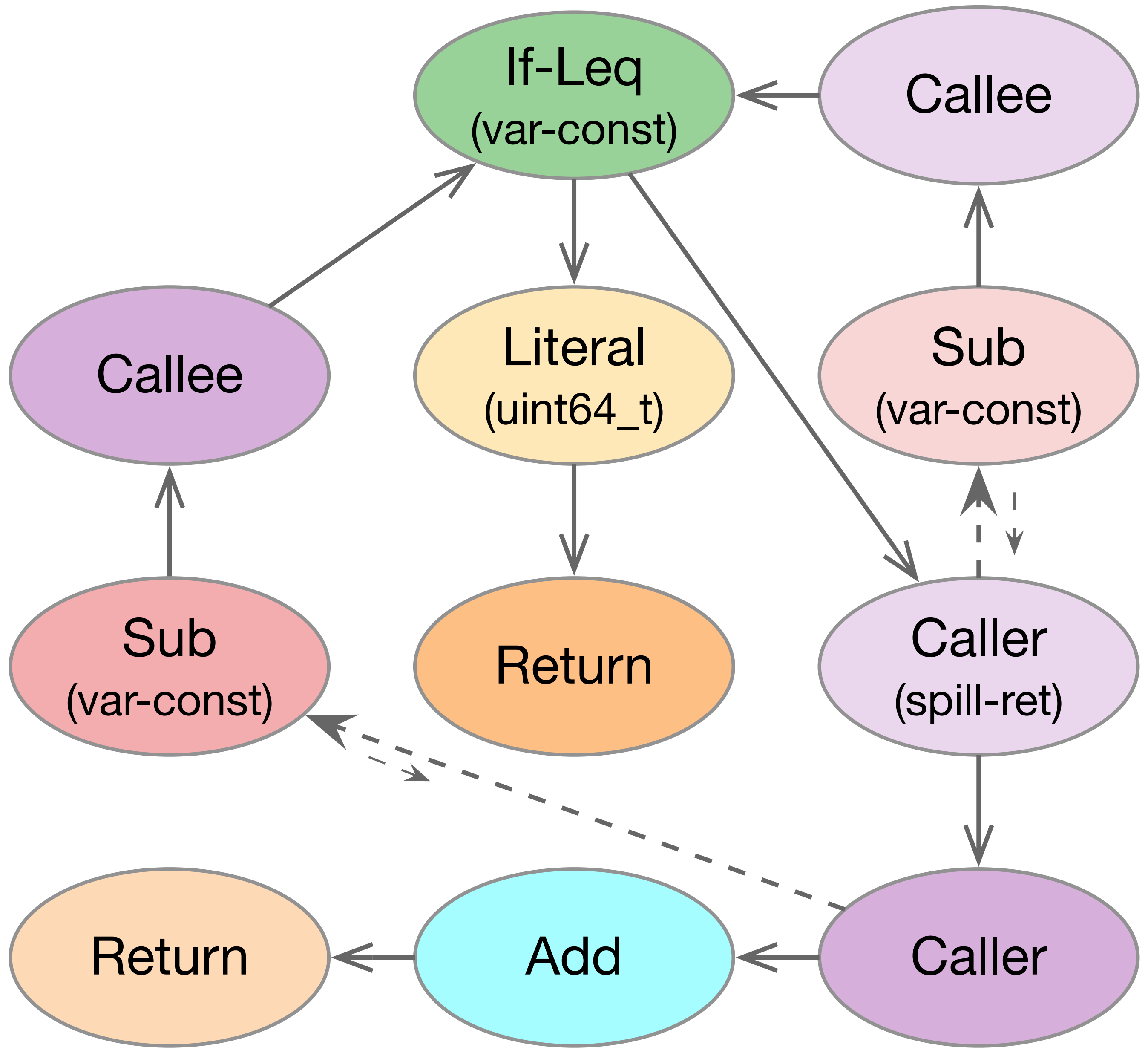

Fibonacci compilation example

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If(n <= 2).Then(
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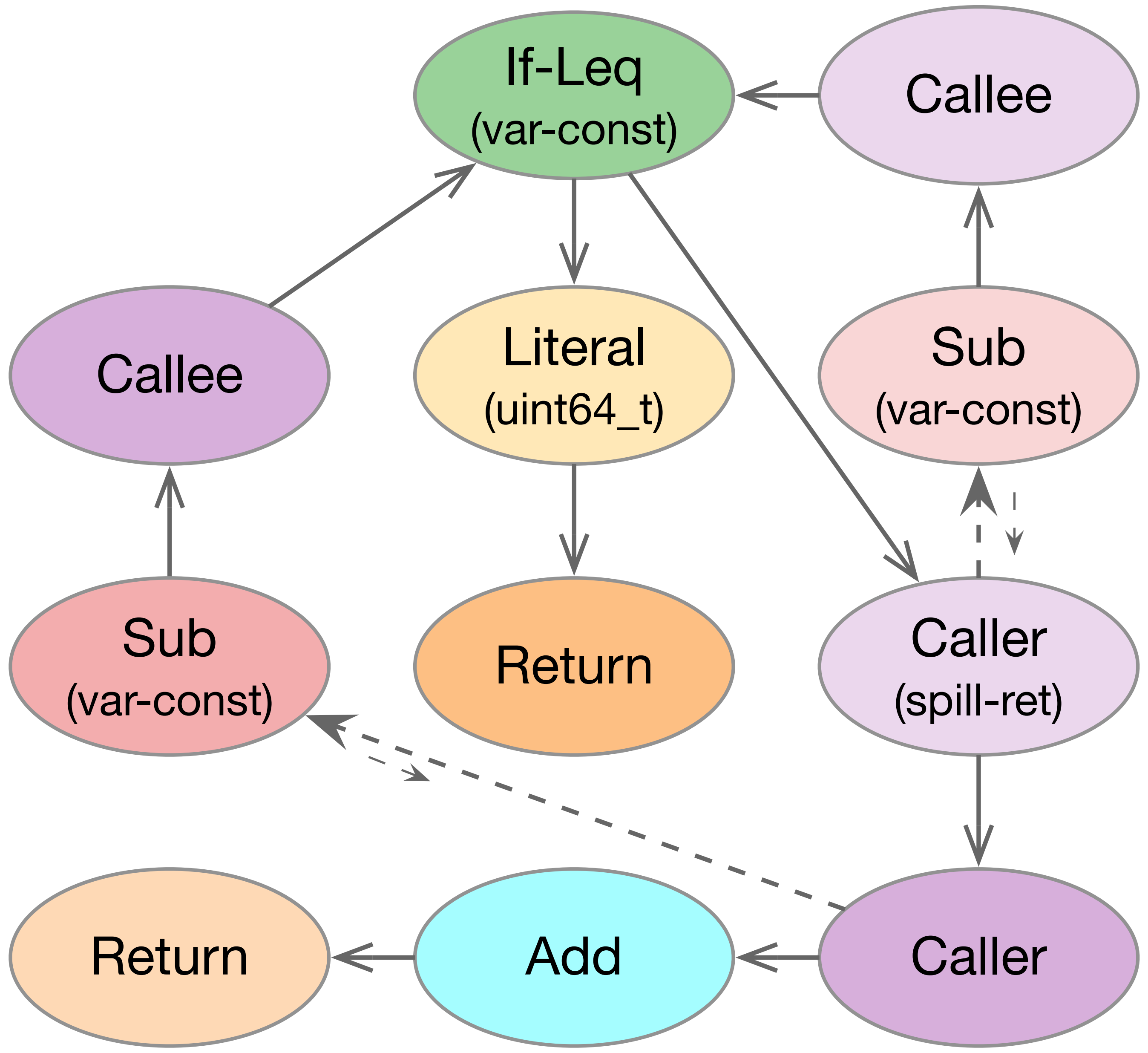
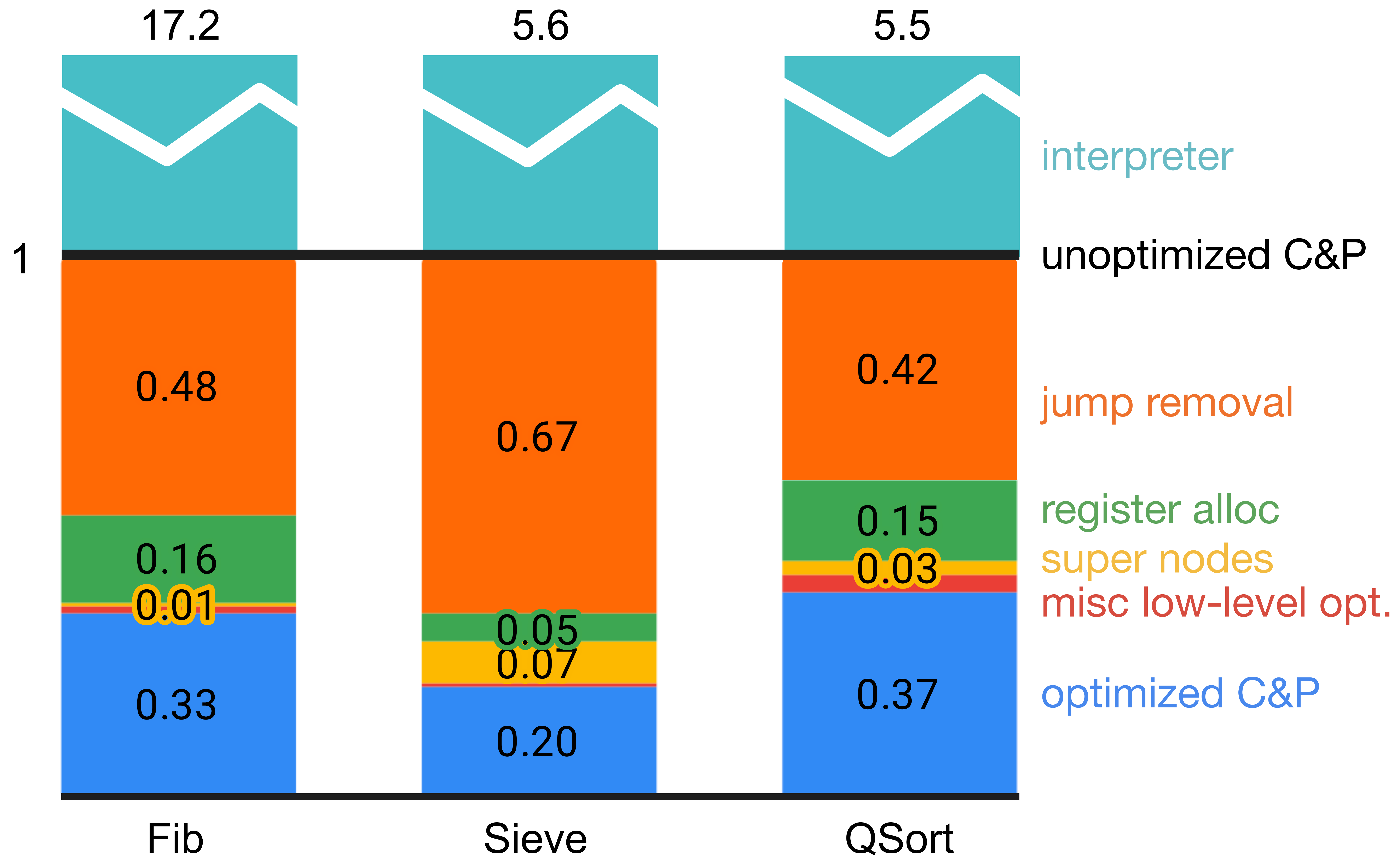



```
00:  mov    0x8(%r13),%r12d
07:  mov    $0x2,%eax
0c:  sub    %eax,%r12d
0f:  mov    %r12d,0x8(%rbp)
13:  mov    %rbp,%r13
20:  mov    $0x2,%eax          <- fib function entry
25:  cmp    %eax,0x8(%r13)
2c:  jg     40
32:  movabs $0x1,%rbp
3c:  mov    %rbp,%rax
3f:  retq
40:  sub    $0x38,%rsp
44:  mov    %r13,0x8(%rsp)
49:  lea    0x10(%rsp),%rbp
4e:  callq  90
53:  mov    0x8(%rsp),%r13
58:  mov    %rax,0x10(%r13)    <- only spilled value
5f:  add    $0x38,%rsp
63:  sub    $0x38,%rsp
67:  mov    %r13,0x8(%rsp)
6c:  lea    0x10(%rsp),%rbp
71:  callq  00
76:  mov    0x8(%rsp),%r13
7b:  mov    %rax,%rbp
7e:  add    $0x38,%rsp         <- jumps between consecutive code blocks are removed
82:  add    0x10(%r13),%rbp
89:  mov    %rbp,%rax
8c:  retq
90:  mov    0x8(%r13),%r12d
97:  mov    $0x1,%eax
9c:  sub    %eax,%r12d
9f:  mov    %r12d,0x8(%rbp)
a3:  mov    %rbp,%r13
a6:  jmpq   20
```

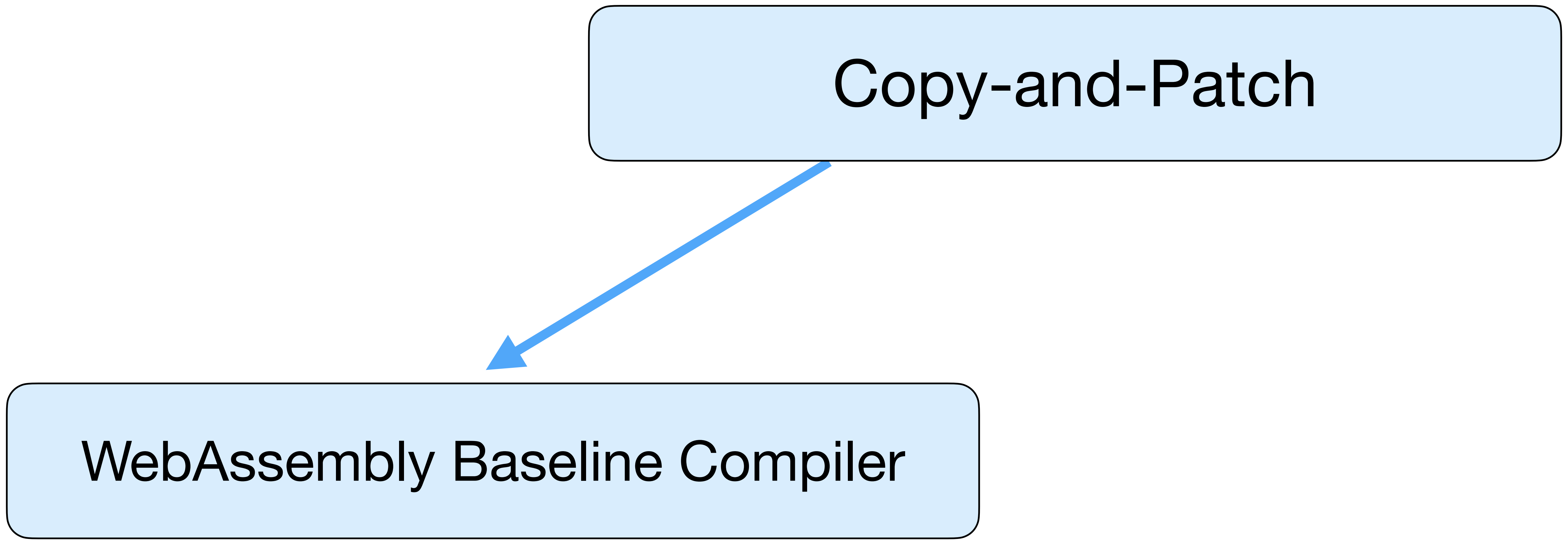
Execution performance breakdown



Final copy-and-patch performance

Copy-and-Patch

Final copy-and-patch performance



	Compilation Speedup	Execution Speedup
Google Chrome Liftoff (baseline compiler)	4.9 – 6.5	1.46 – 1.63
Google Chrome TurboFan (optimizing compiler)	30 – 47 (small module) 88 – 91 (large module)	0.69 – 0.85

Final copy-and-patch performance

Copy-and-Patch

WebAssembly Baseline Compiler

High-level imperative language
(for metaprogramming)

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Google Chrome Liftoff (baseline compiler)	4.9 – 6.5	1.46 – 1.63
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	Compilation Speedup	Execution Speedup
Interpreter	0.3 – 0.5	6 – 36
LLVM -O0	79 – 267	1.02 – 1.57
LLVM -O2	936 – 1384	0.61 – 0.96