Lecture 17 — Fast Compilation

Stanford CS343D (Fall 2021)
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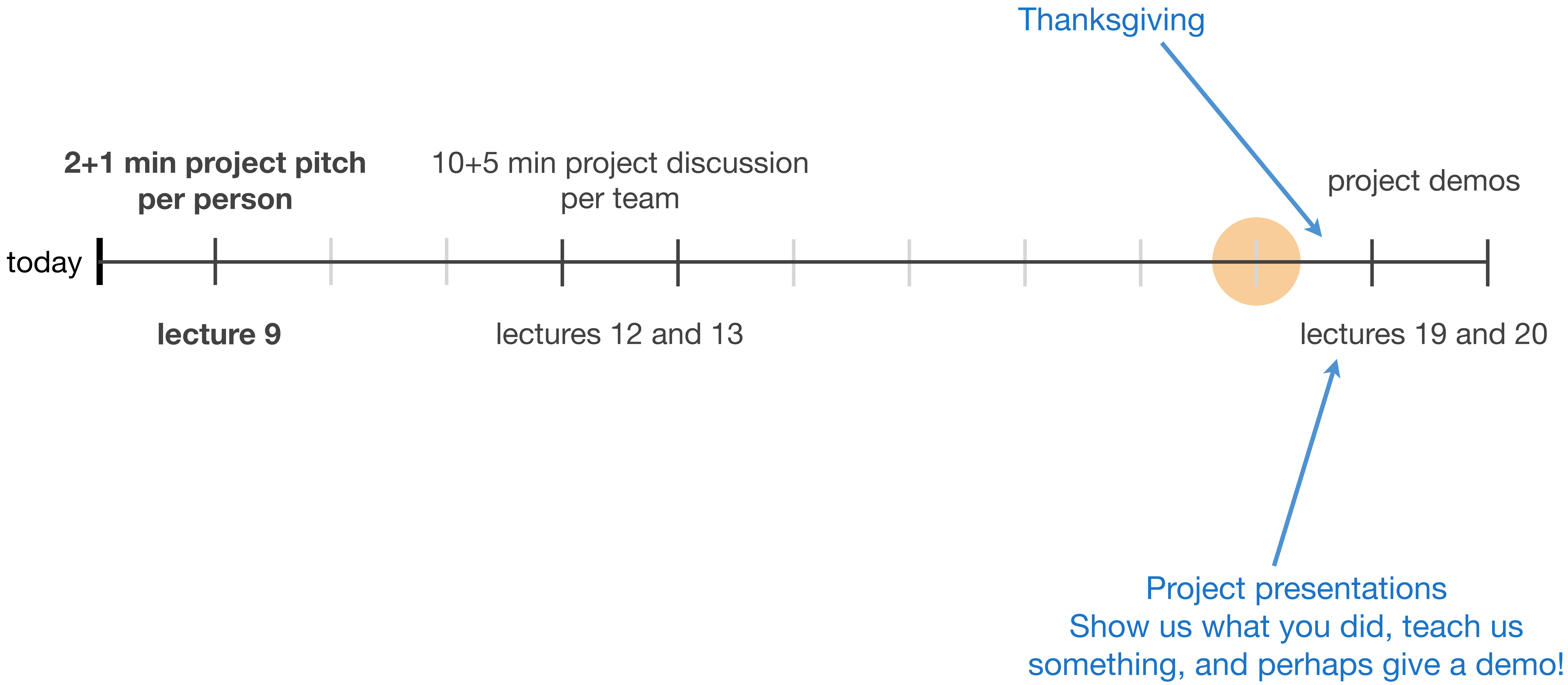
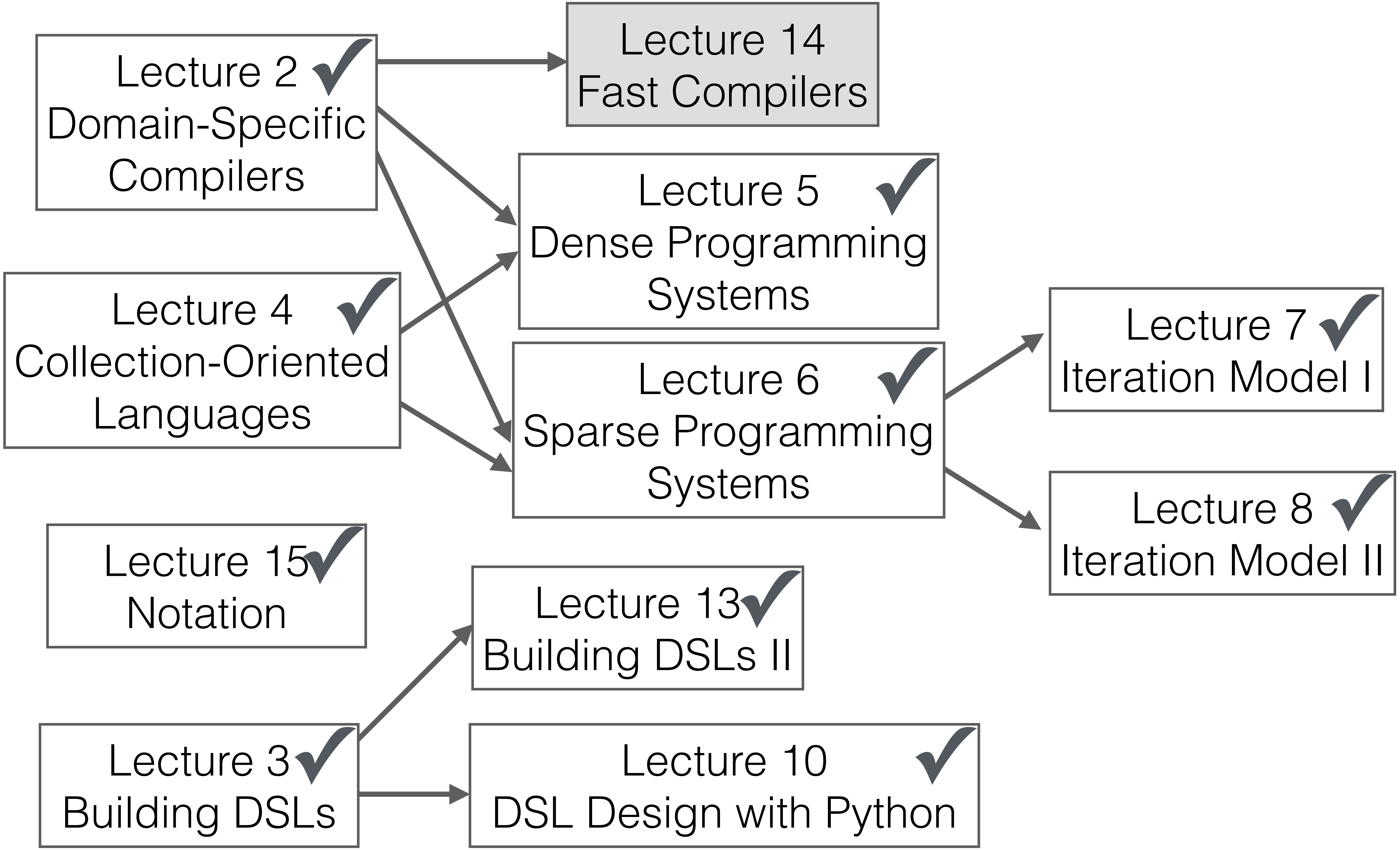
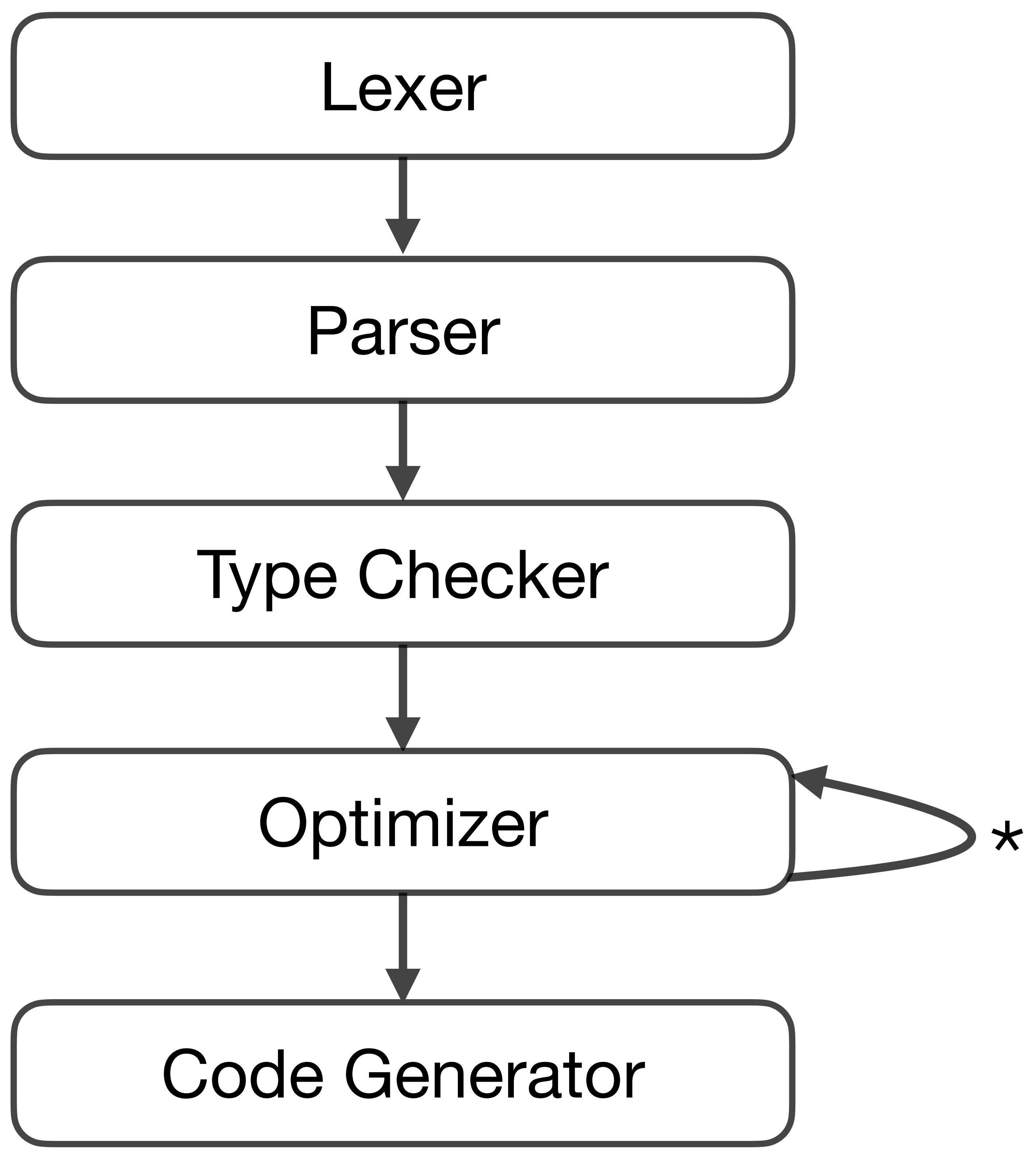
Course Project




Lecture 2 ✓
Domain-Specific Compilers
Lecture 14
Fast Compilers
Lecture 5 ✓
Dense Programming Systems
Lecture 4 ✓
Collection-Oriented Languages
Lecture 6 ✓
Sparse Programming Systems
Lecture 7 ✓
Iteration Model I
Lecture 8 ✓
Iteration Model II
Lecture 15 ✓
Notation
Lecture 13 ✓
Building DSLs II
Lecture 3 ✓
Building DSLs
Lecture 10 ✓
DSL Design with Python

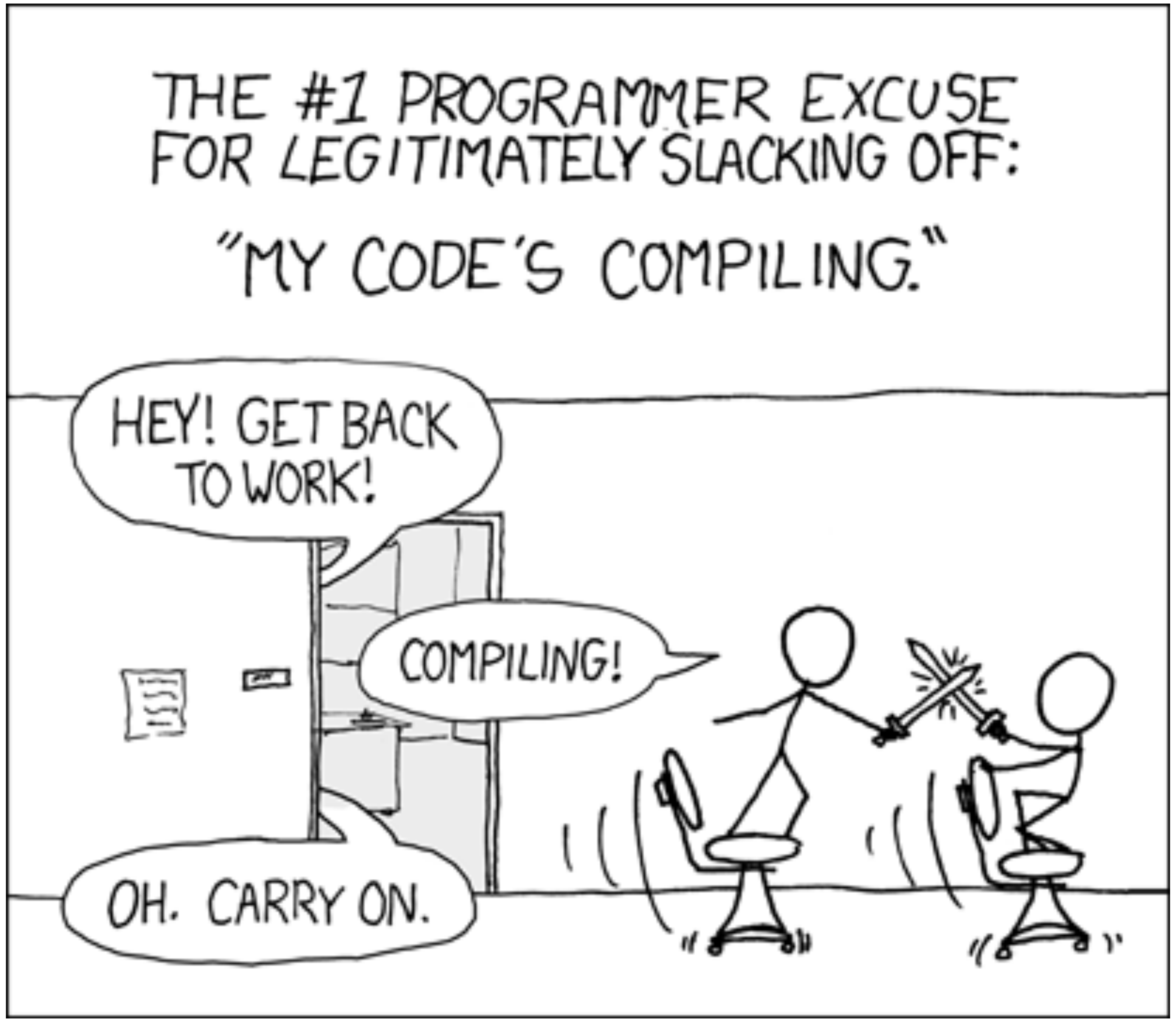
Classical compiler overview



There is a lot of work to compiling optimized code

Compilation times matter

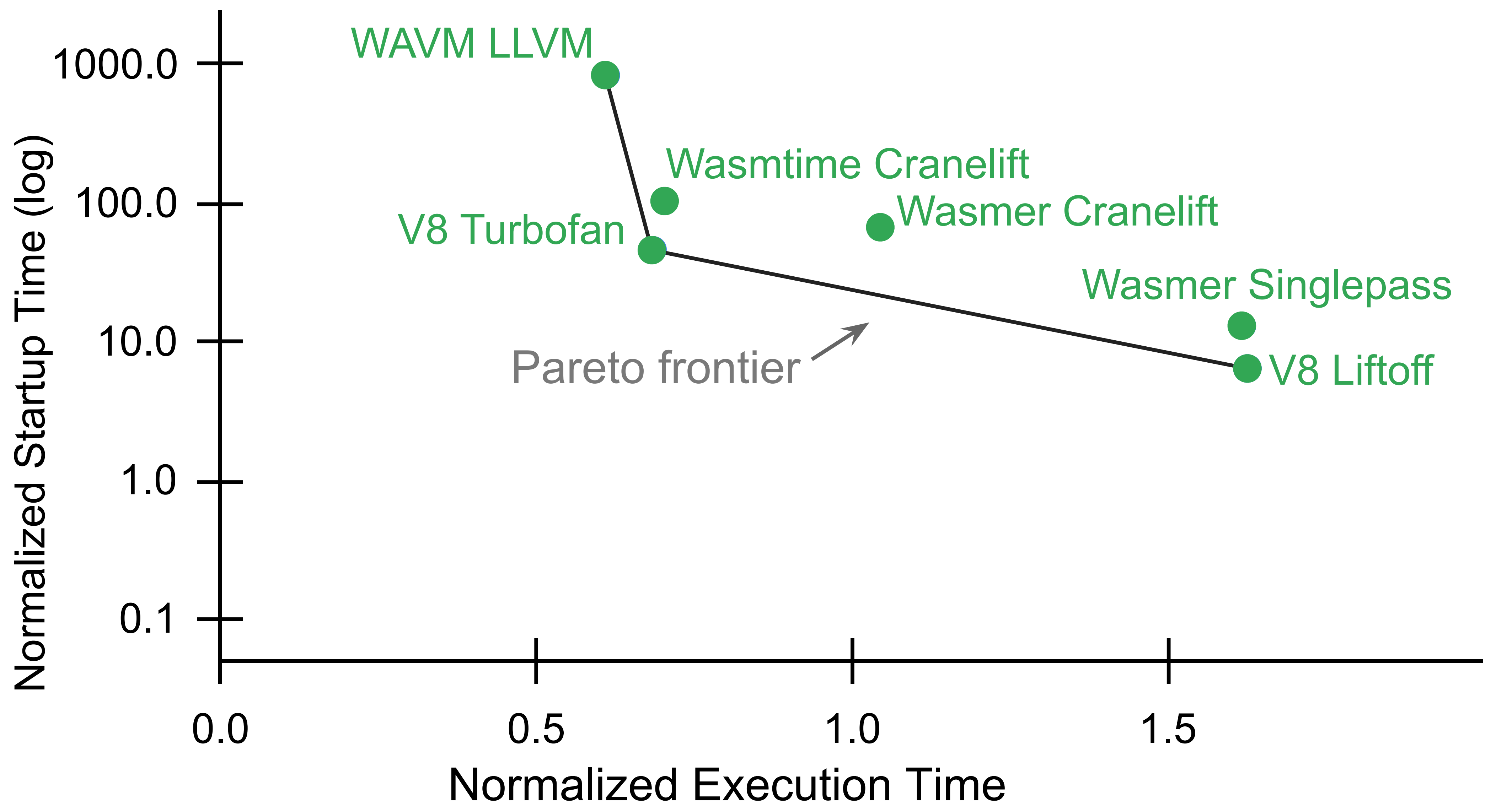
- JIT compilers (compilation at runtime)
- LLVM -O0 vs -O2 (10x difference)
- Scala (large type checking cost)
- JavaScript (teams of engineers)
- WebAssembly (51s for AutoCAD)
- Databases (4.5s for TPC Q19 query)
- Taco (generated expressions)



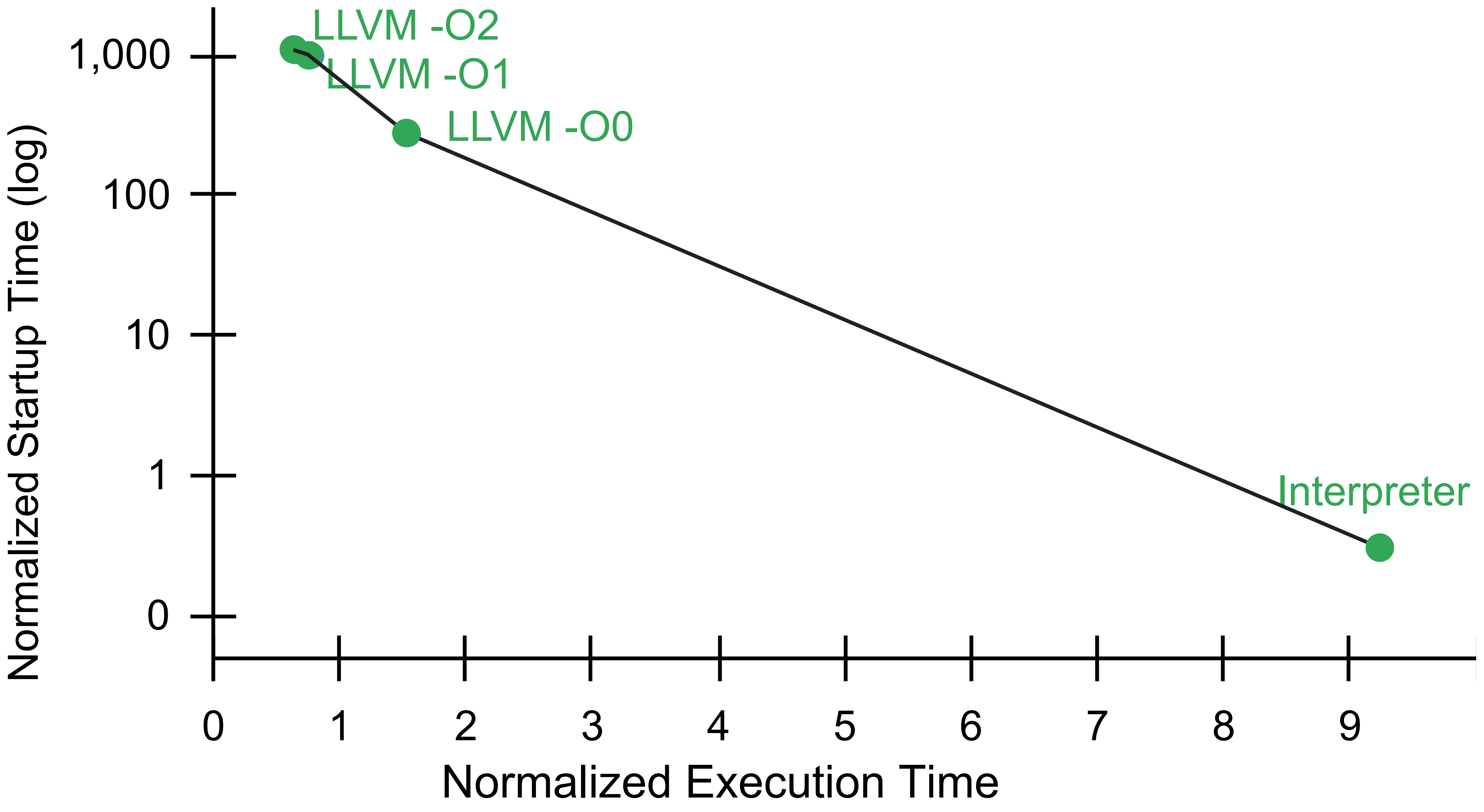
How can we speed up compilation? — Let us brainstorm

- 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)



Imperative Language (TPC-H Q6)

Idea: Two-tiered execution

Tier 1: Fast startup

- Interpreter
- LLVM -O0
- Baseline compilers (bytecode)

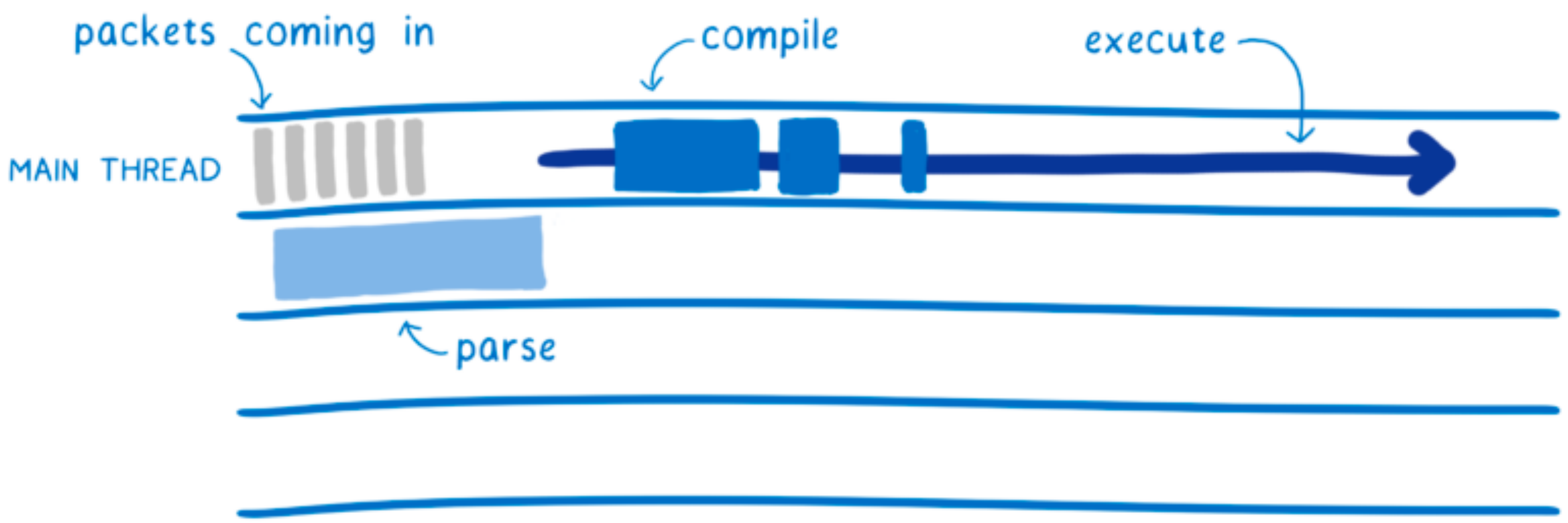
Tier 2: Fast execution

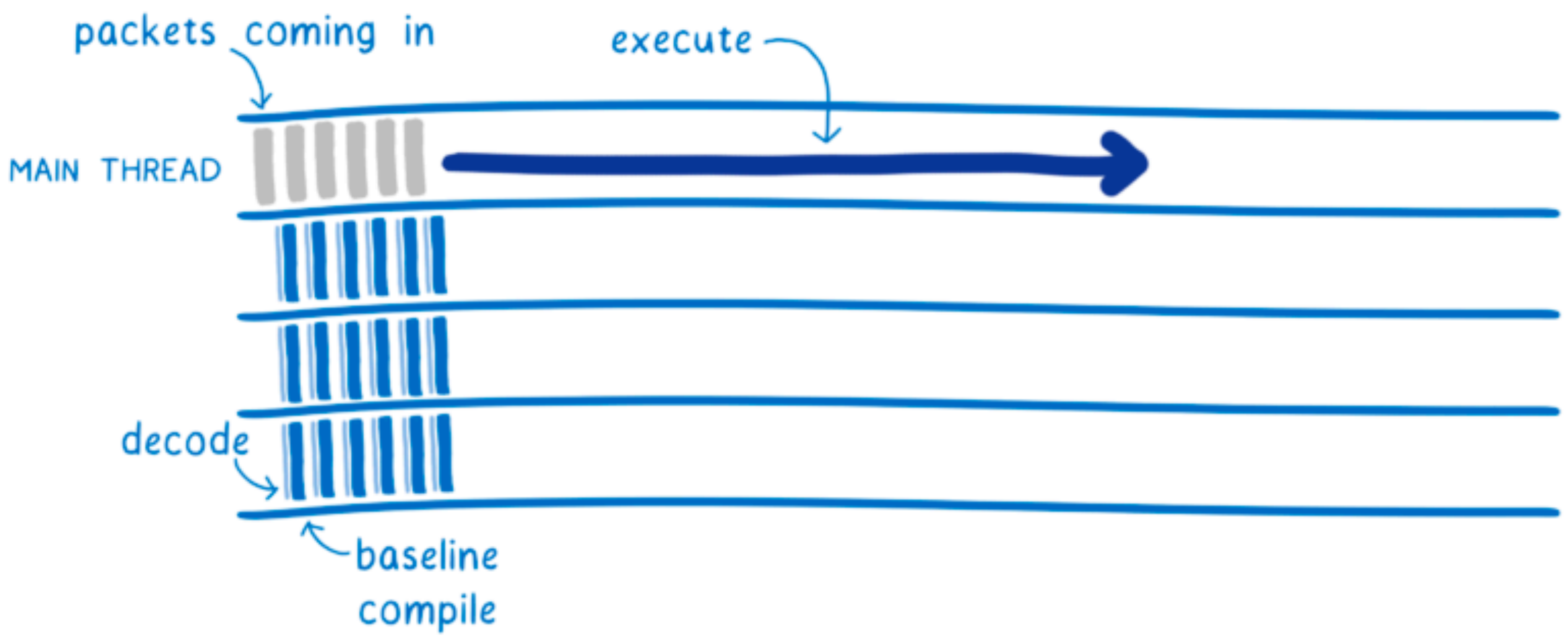
- Java HotSpot JIT Compiler
- LLVM -O2
- Google V8 TurboFan

Used in basically all JIT compilers and databases

Examples: Java, JavaScript, WebAssembly, Databases

Baseline compiler web example





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

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

Baseline compiler web example

Baseline Compilation

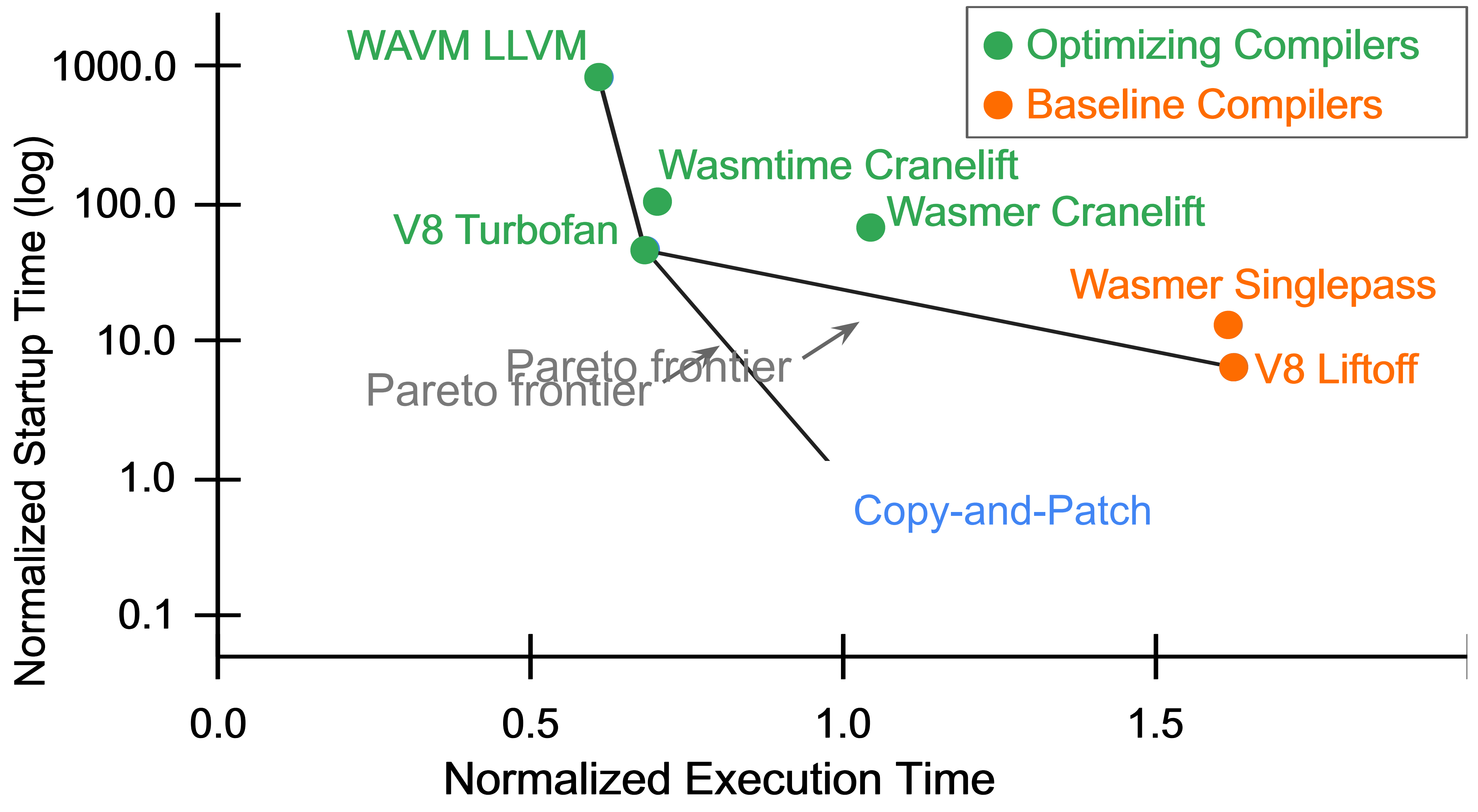
WebAssembly (sent in binary)

```
(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)
```

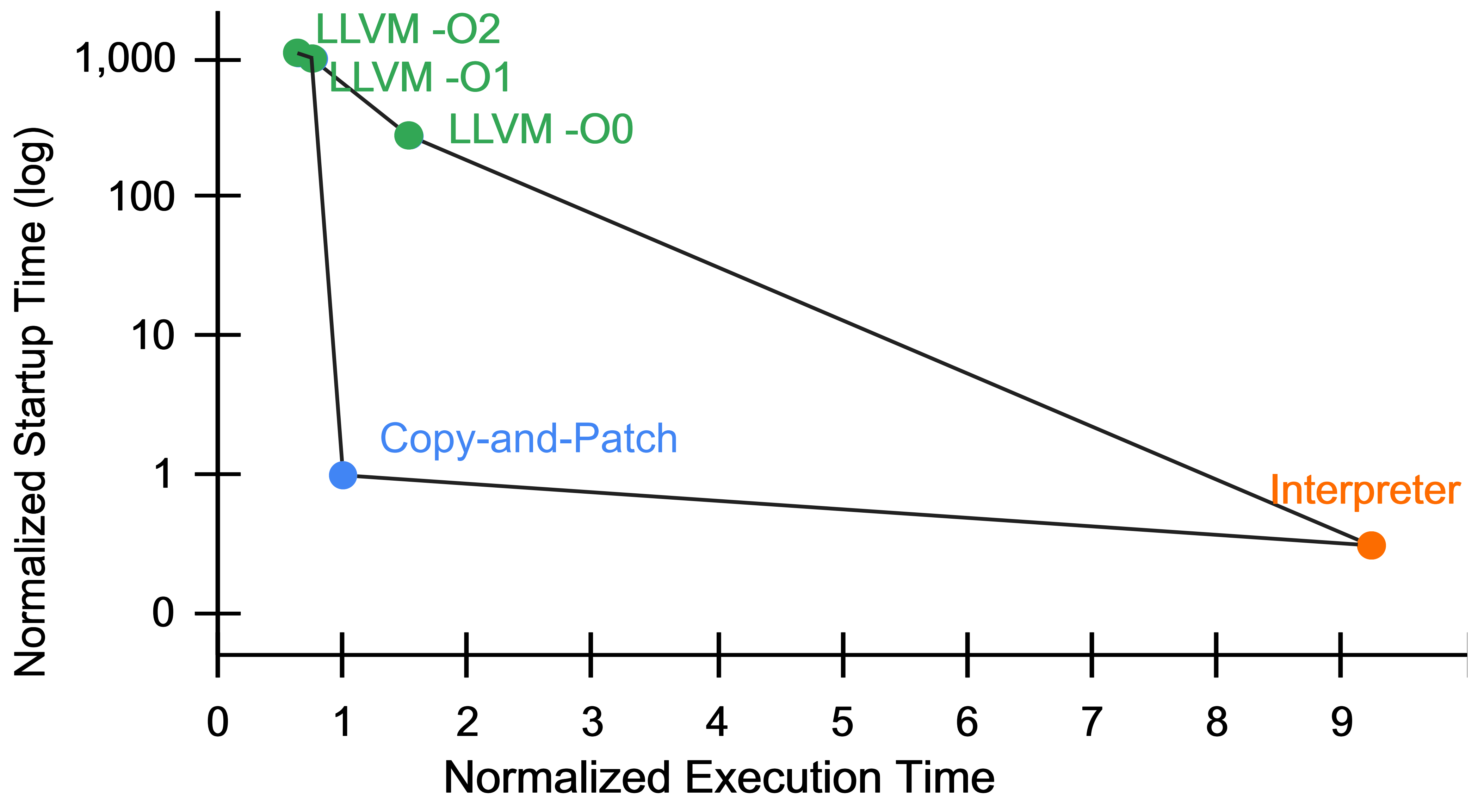
Baseline compiler rule (Firefox)

```
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);
    pushI32(r);
  }
}
```

Copy-and-Patch is a fast baseline compilation algorithm

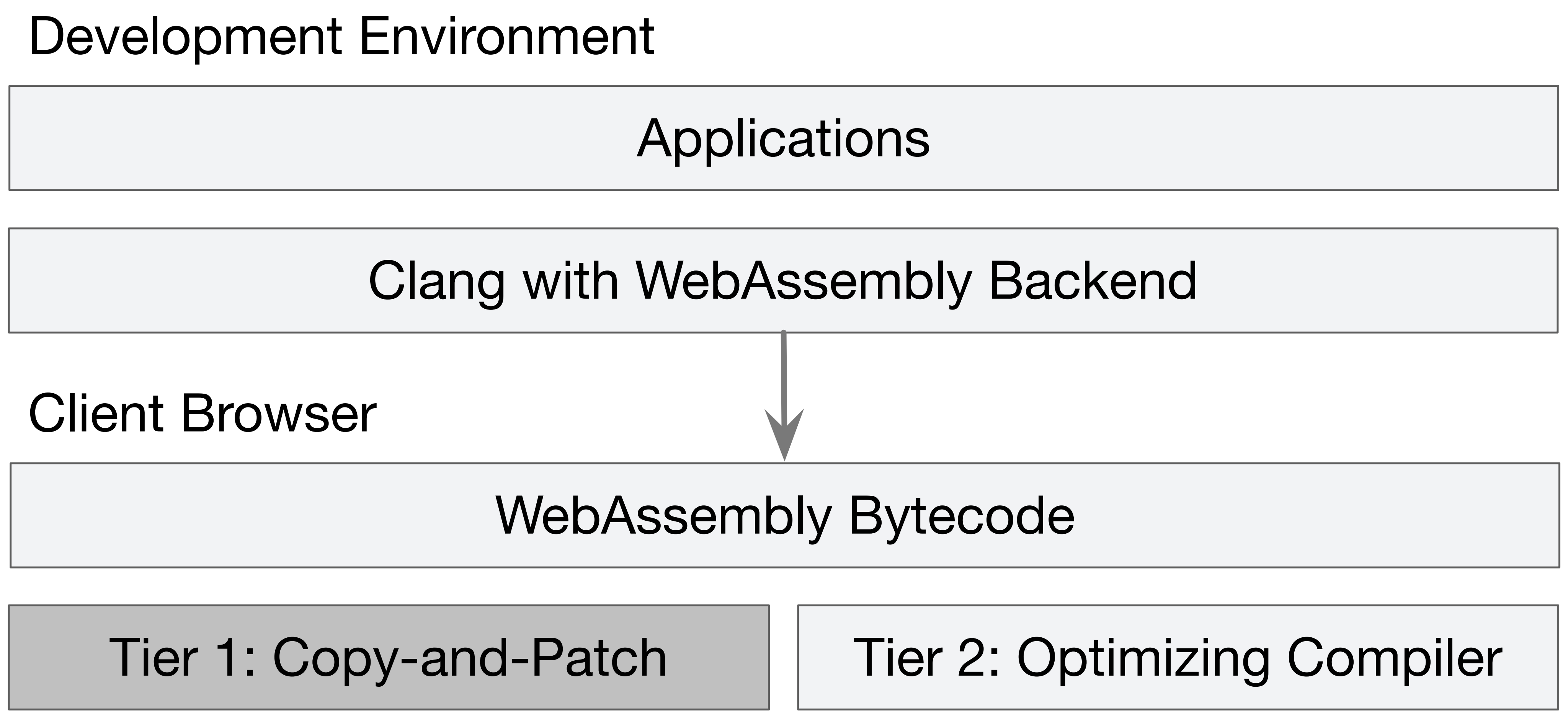


WebAssembly (PolyBench benchmarks)

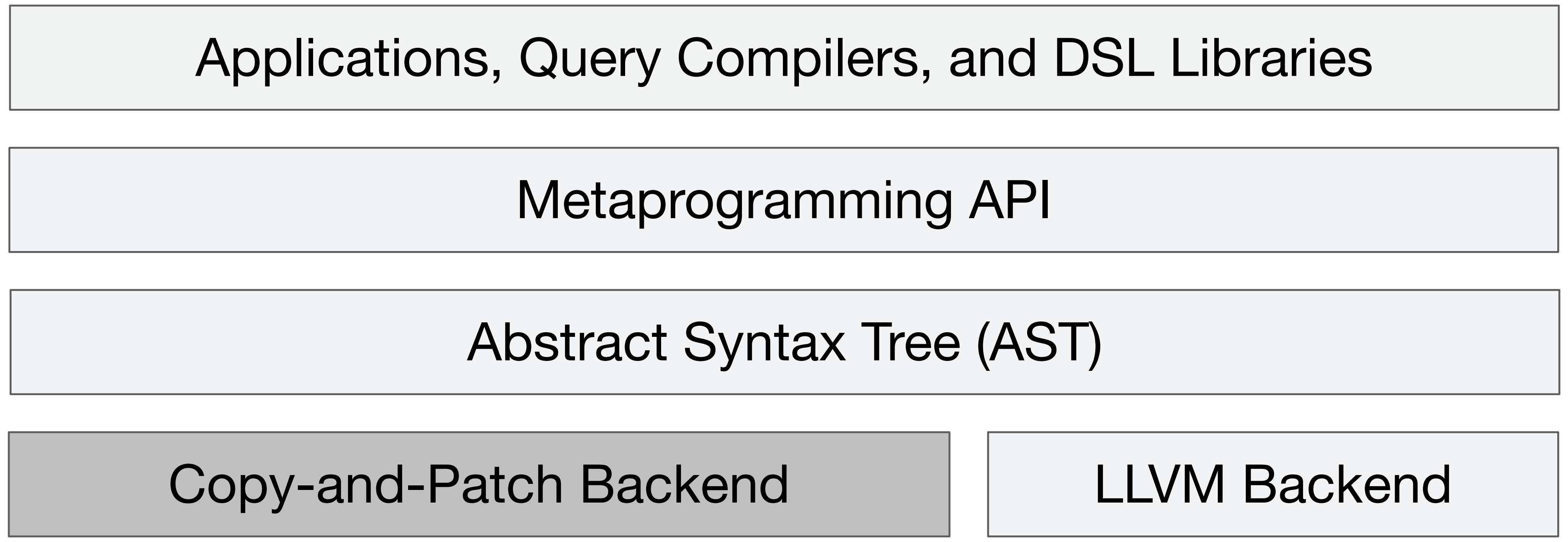


Imperative Language (TPC-H Q6)

Two of many use cases



WebAssembly



Metaprogramming System

Idea 1: precompile all language constructs

Library of precompiled language constructs

`add`

`sub` `neg`

`load` `mul`

`for` `if`

`while`

...

(missing stack offsets and jump targets)

At compile-time

For each AST node:

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

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

- Vilfredo Pareto: “80% of the consequences come from 20% of causes”
- 80% of the performance gain comes from **only two** optimizations
  1. Instruction selection
  2. Register Allocation

According to Vladimir Makarov (GCC developer): https://developers.redhat.com/blog/2020/01/20/mir-a-lightweight-jit-compiler-project#lightweight_jit_compiler_project_goals

Idea 2: Instruction Selection

Precompile specialized stencil variants for super-nodes and constants

Library of precompiled language constructs

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

At compile-time

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

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

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
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

High-Level Imperative Language

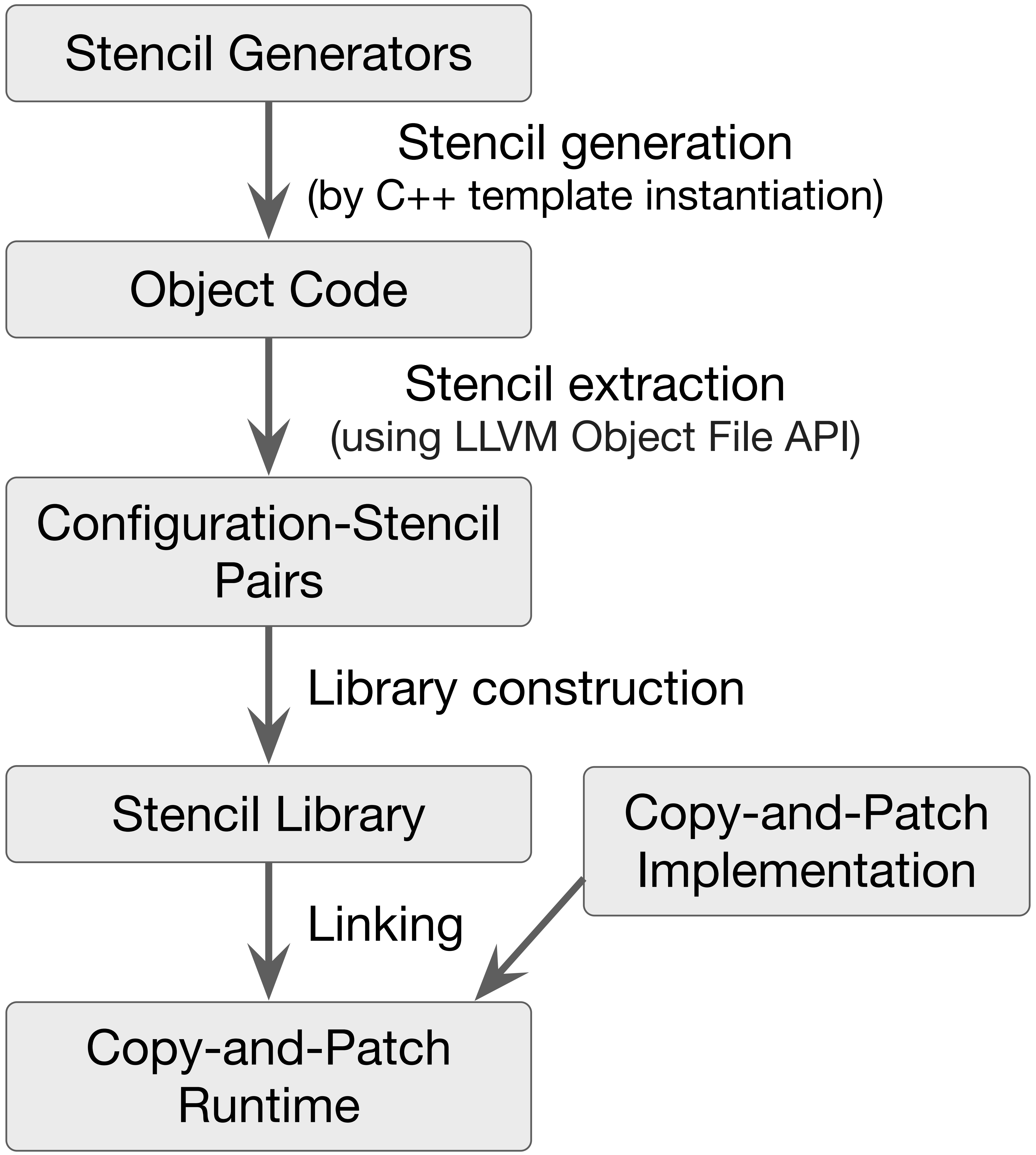
- 98,831 stencils
- 17.5 megabytes
- 14 minutes to compile

WebAssembly

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

How can we create all of these stencils?

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



We write variants in C++ and Clang+LLVM compiles them

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);
}
```

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

Register pass-through

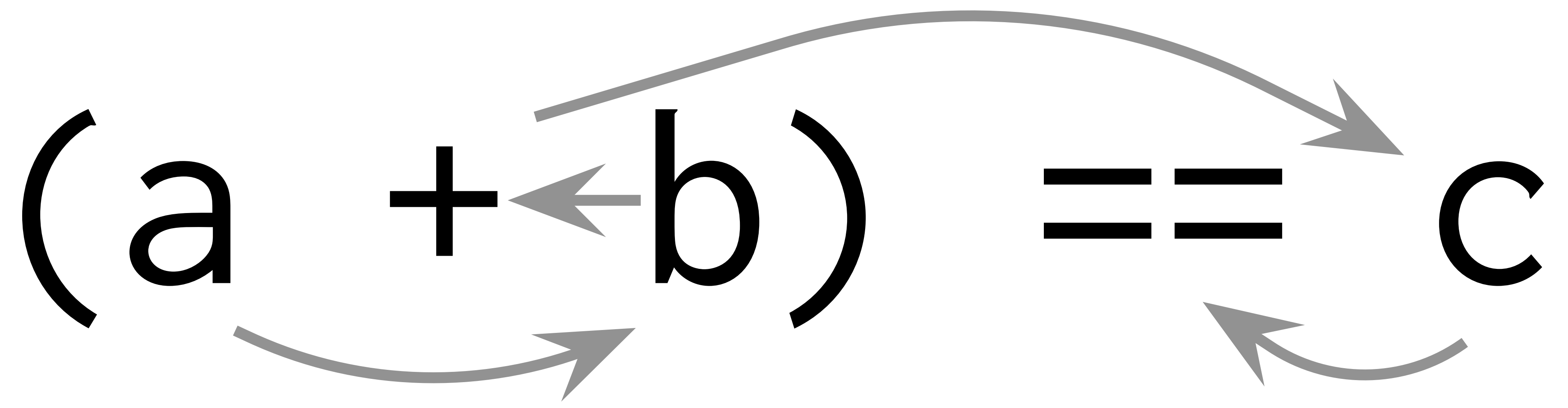
```
void stencil1(uintptr_t stack) {
  int x = /* assign value to x */;
  (void(*)(uintptr_t, int)    )(stack, x);
}

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
}
```

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



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;
}
```

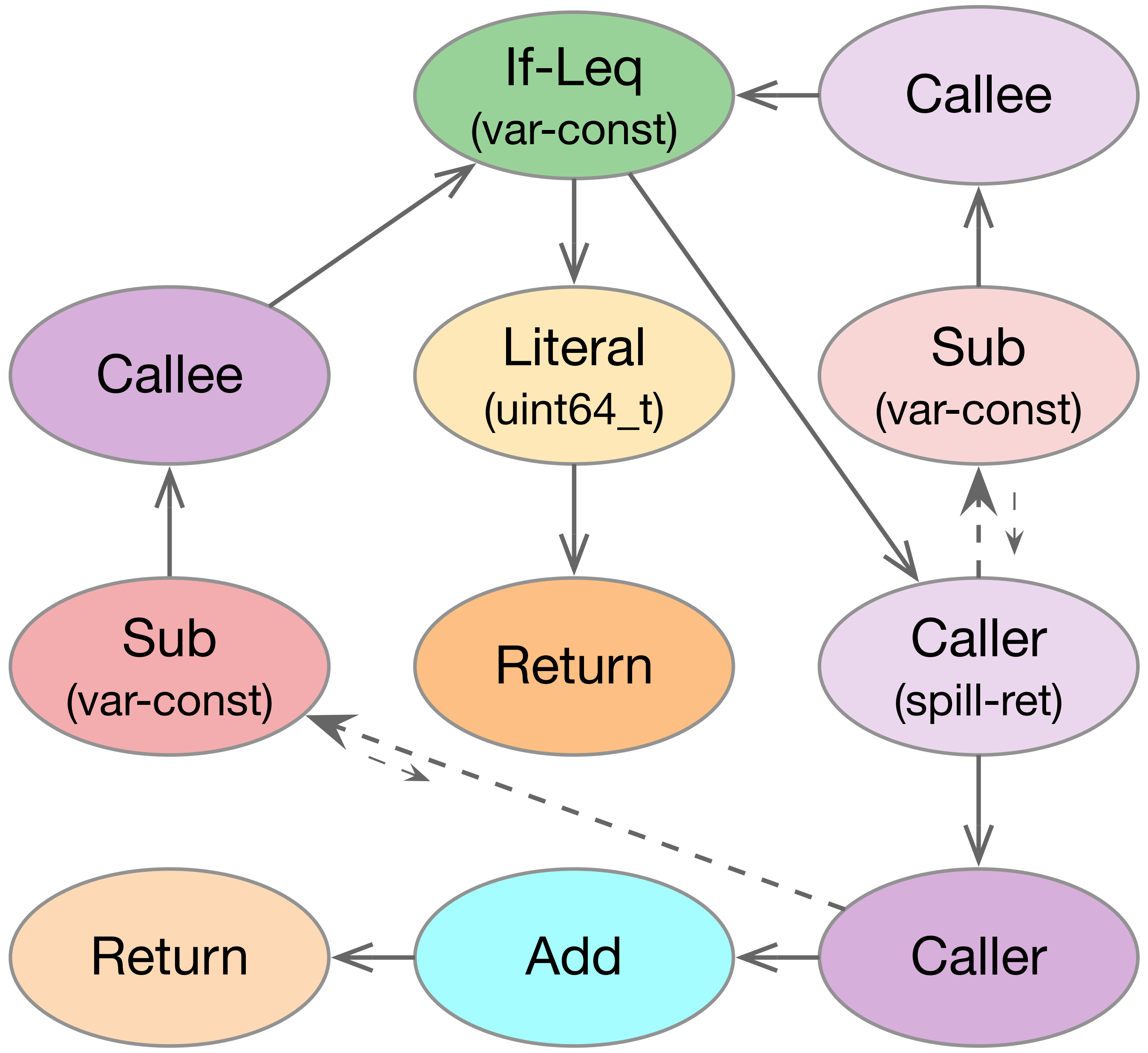
1. C++ compiler generates an object file
2. The linker can link object files to any definition of the extern calls
3. The object file thus contains information to locate them in the binary code
4. We can use this information to locate holes in stencils for later patching

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);
}
```

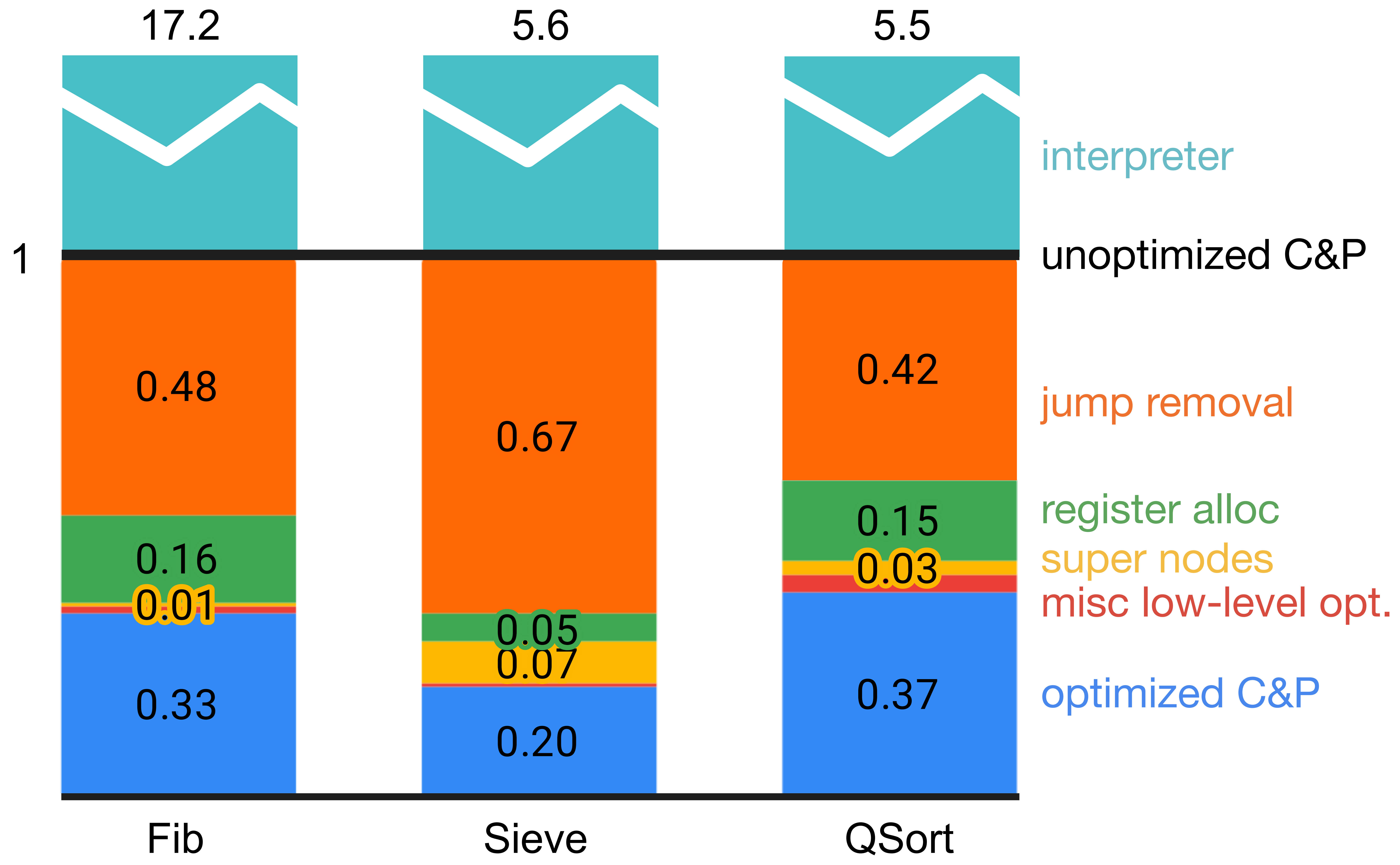
Fibonacci compilation example

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

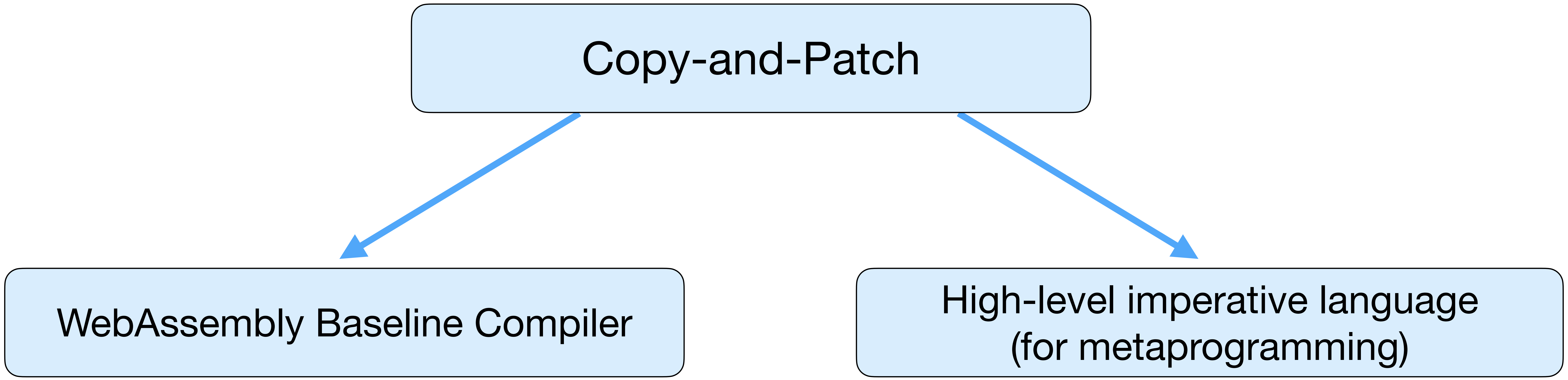



```
00:  mov    0x8(%r13),%r12d
07:  mov    $0x2,%eax
0c:  sub    %eax,%r12d
0f:  mov    %r12d,0x8(%rbp)
13:  mov    %rbp,%r13
20:  mov    $0x2,%eax          <- fib function entry
25:  cmp    %eax,0x8(%r13)
2c:  jg     40
32:  movabs $0x1,%rbp
3c:  mov    %rbp,%rax
3f:  retq
40:  sub    $0x38,%rsp
44:  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



	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

	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