Cheaply writing a fast interpreter

Code at https://github.com/ndmitchell/interpret

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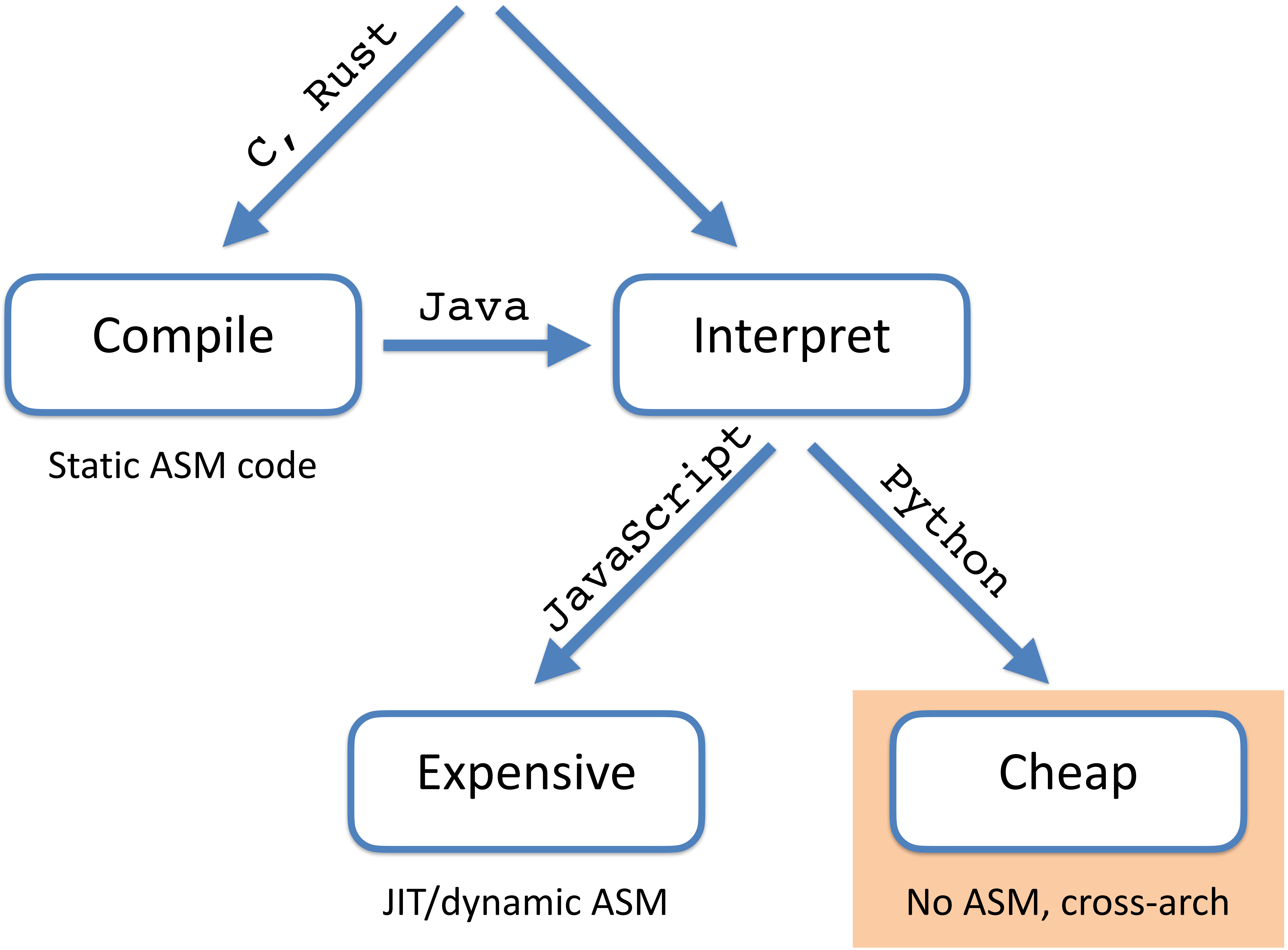
The options

Given a language, we can:



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This talk

Cheap interpreters

- Low cost of development and maintenance
- No Assembly (ASM) writing (may be some reading)
- Can do better! But at cost (v8, Lua)

An example: Starlark (aka deterministic Python)

- Used by Buck/Bazel build systems for config
- How would we go about writing an interpreter in Rust for Starlark?

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Approach

Possible alternatives

- AST (abstract syntax tree) interpretation
- Bytecode (threaded?)
- Closure generation
- Intermediates: Native, Stack, Registers?
- Packed/Unpacked?

Benchmarks

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Example

```
x = 100;
for (i = 1000; i != 0; i--) {
    x = x + 4 + x + 3;
    x = x + 2 + 4;
}
x
```

Deliberately use only +, to emphasise interpreter overhead
In reality, an expensive atoms might make all this noise

Walk AST

```
fn f(x: &Expr, vs: V) -> i64 {
  match x {
    Lit(i) => *i,
    Var(u) => vs[u],
    Add(x, y) =>
      f(x, vs) + f(y, vs),
    Assign(u, e) =>
      vs[u] = f(e, vs),
    …
```

Guess

What performance penalty?

Do the obvious things:

- Use unchecked array access
- Convert variables to indices
- No allocation
- Rust -O

(All these are always done in this talk)

What is the performance penalty?

570x

1 day

2.5 minutes

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Fairness

What did it do?

```
x = x + 4 + x + 3;
x = x + 2 + 4;
```

↓

```
x = x + x + 13;
```

Make add a `noinline` function call
More representative of real work

6.4x

6 minutes

1 minute

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AST walk

AST

Rust

What does it do?

- Match on AST nodes
- Perform operations

Could we match on AST nodes only once?

- Yes! Generate closures once, run closures
- Closure = function pointer + data

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Closures

AST

Closure

Rust

```
type K = Box<dyn Fn(V) -> i64>;

fn f(x: &Expr) -> K {
  match x {
    Lit(i) => {
      let i = *i;
      box move |_| i;
    }
    Add(x, y) => {
      let x = f(x);
      let y = f(y);
      box move |v| x(v) + y(v)
    }
```

Storage

AST

Closure

Rust

Where do intermediates go?

With AST/Closure we reuse the native/Rust stack

- `f(x, …) + f(y, …)`

What could we do instead? Explicit:

Stack

- Access the top
- PUSH 1
- ADD
  - Pop top 2
  - Push their sum

Registers

- Access by index
- r9 = 1
- r7 = r2 + r9

Bytecode

AST

BCode

Closure

Rust

With a stack

```
PUSH   -1
GET    $i
ADD
SET    $i
```

Put variables at the bottom of the stack

```
loop {
  match tape.next() {
    PUSH => stack.push(tape.next()),
    ADD => stack.push(
      stack.pop() + stack.pop()),
    …
```

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ASM view

AST

BCode

Closure

Rust

What happens on each op?

```
loop {
  match tape.next() {
  LOOKUP match[tape.next()]
  JUMP '_
    …
    BODY
  }
  JUMP 'loop
}
```

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ASM view

AST

BCode

Closure

Rust

What would be optimal?

- Can’t generate new ASM on the fly
  - The definition of a “Cheap” interpreter
- Must have a finite number of parameterisable chunks of ASM
- Must JUMP between them - but only one JUMP

Sometimes known as “direct threading”

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C++ (GCC)

AST

BCode

Closure

Rust

Computed goto

```
static const Tape tape =
  {&&push, 1, &&add, &&set, 8, …};

push:
  stack.push(tape.next());
  goto tape.next();
add:
  stack.push(
    stack.pop() + stack.pop());
  goto tape.next();
set:
```

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Rust

AST

BCode

Closure

Stack

Rust

Faking computed Goto

- Tail calls are compiled to JUMP
  - On x86_64, with -O
  - Not guaranteed 🙁 (can abstract it)
  - But is compositional 🙂

```
fn add(stack: Stack, tape: Tape) {
  stack.push(
    stack.pop() + stack.pop);
  let k = tape.next();
  k(stack, tape);
}
```

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Even faster

AST

BCode

Closure

Stack

Reg

Rust

Use registers

- Longer instructions, but fewer
- Less adjusting the stack

```
PUSH x
PUSH 1
ADD
```

5 words
3 instructions

```
r2 = 1
r3 = r1 + r2
```

3 + 4 words
1 + 1 instructions

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What else?

AST

BCode

Closure

Stack

Reg

Rust

Didn't work

- Use compact tape instead of word-aligned
  - A few percent slowdown
- A better register allocator (less registers)
  - No difference on this particular benchmark

Would work

- Transform the code first (e.g. 2 + 4 => 6)
- Use "bigger" fragments (e.g. add3)
- Generate fresh assembly at runtime

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Conclusion

AST

- 6.4x penalty
- Lowest effort, cleanest code

BCode

Closure

- 4.8x penalty
- More effort, but not *much* more

Stack

Reg

- 1.4x penalty
- Requires register allocator
- Uses unsafe operations (register indexing)
- Much more effort, but much better result

Rust