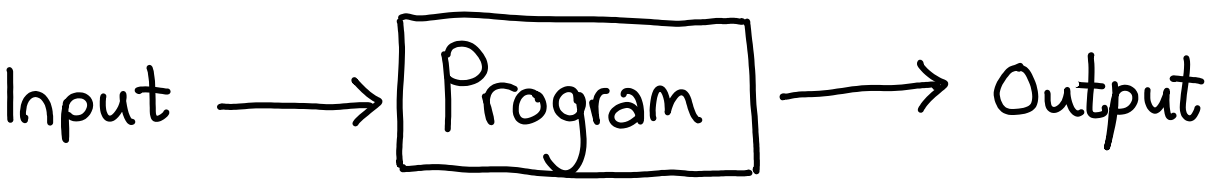
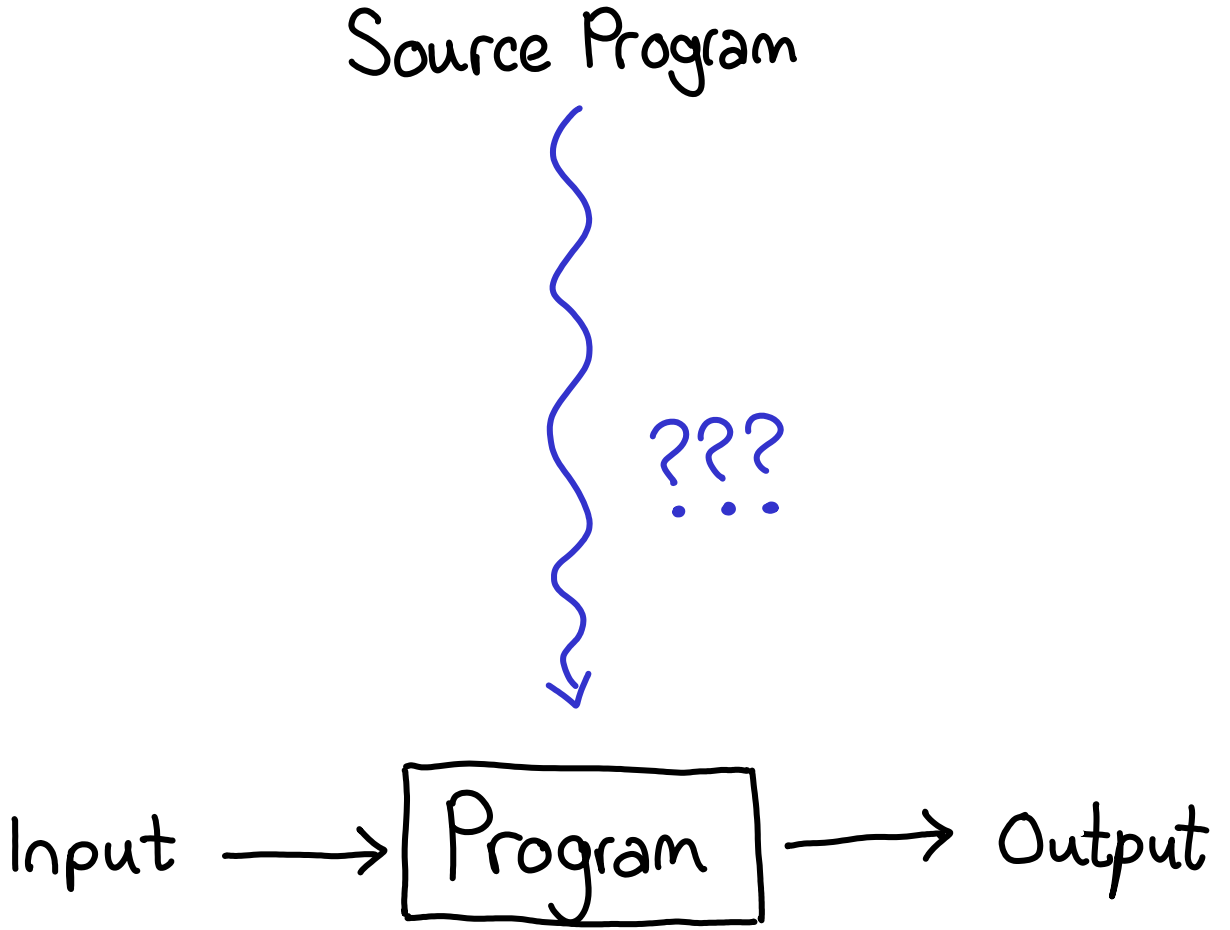
Implementation

Edward Z. Yang

(intro)


Input
Program
Output

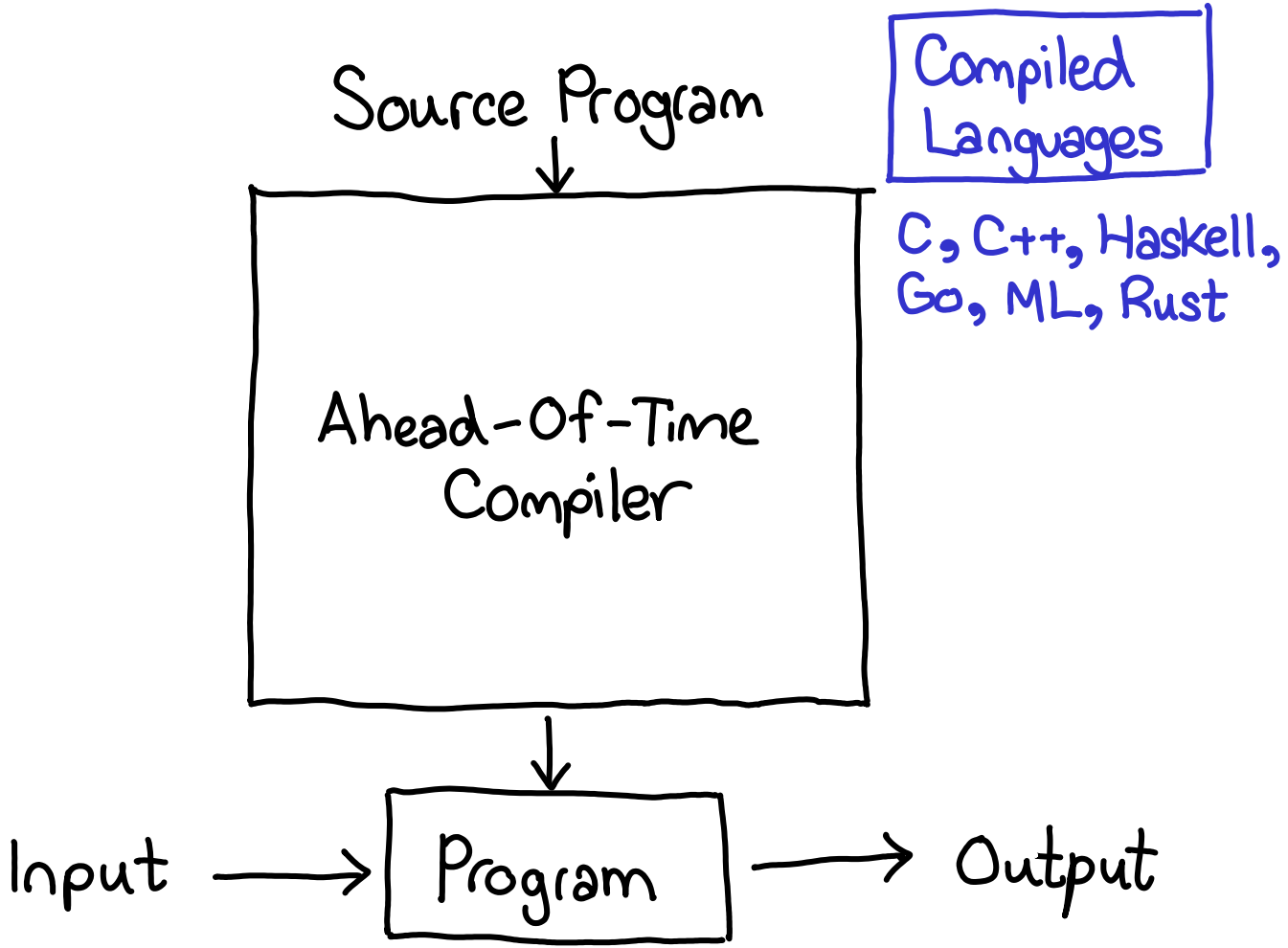

Source Program
???
Input
Program
Output

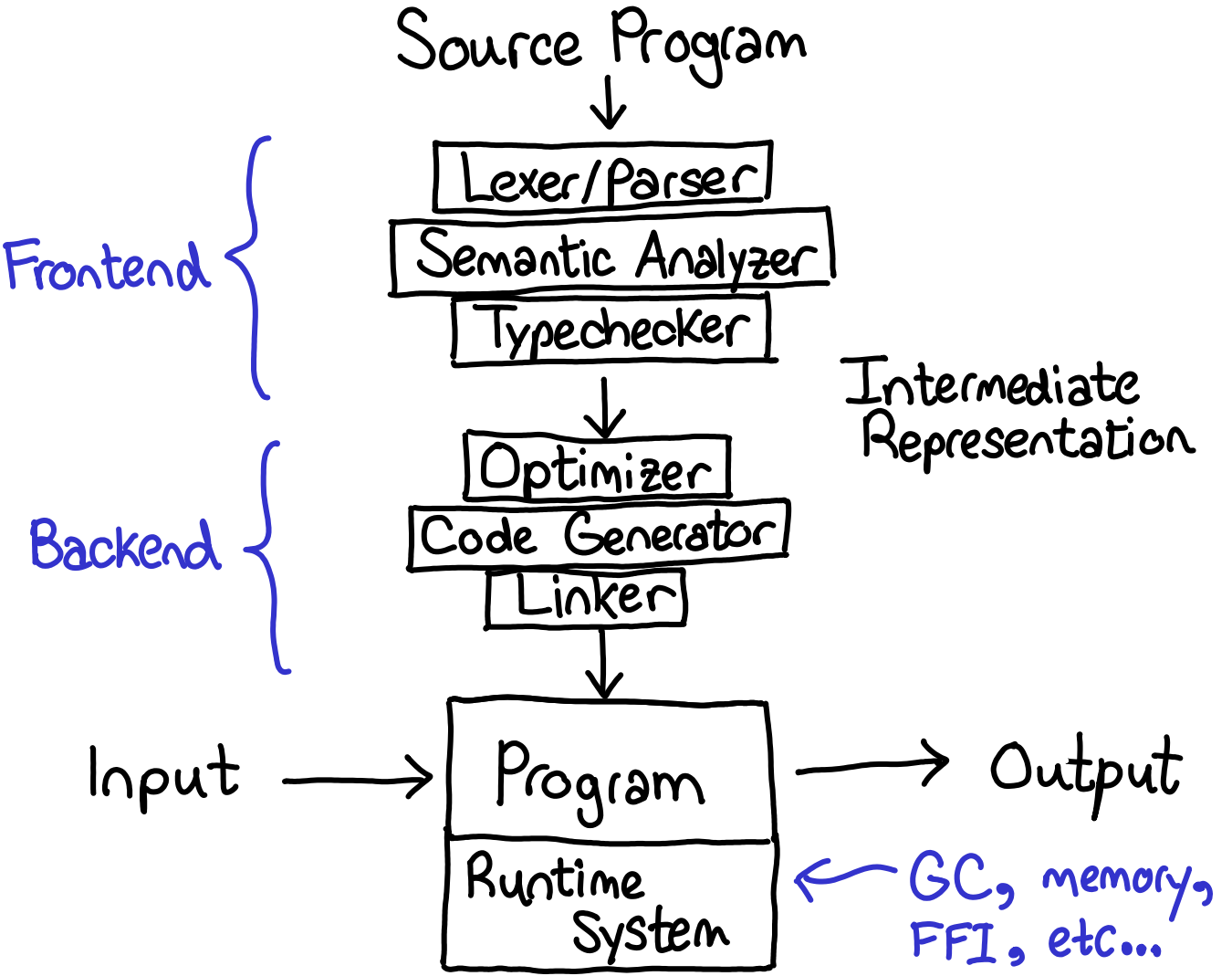
Source Program

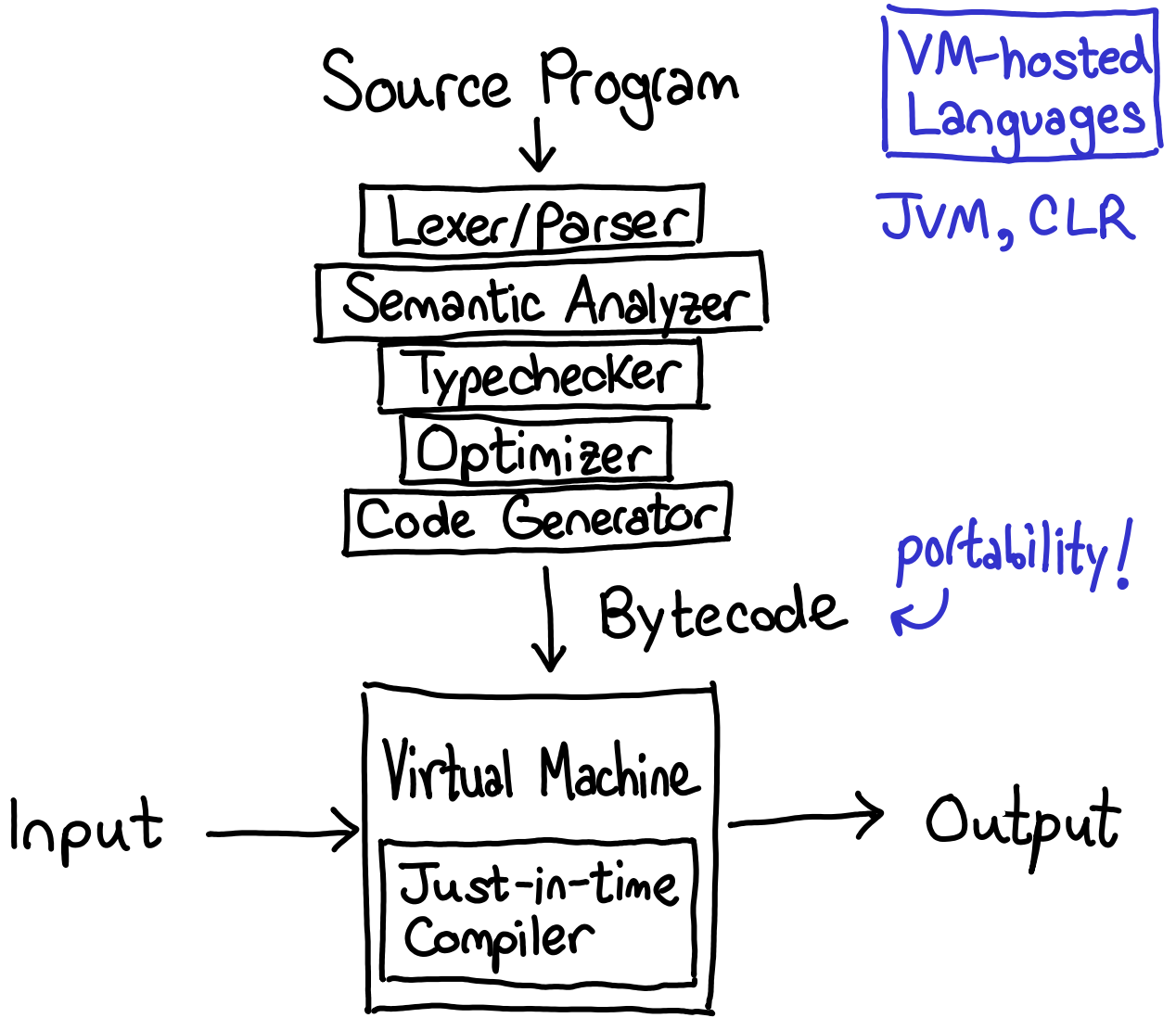
Input → Interpreter → Output

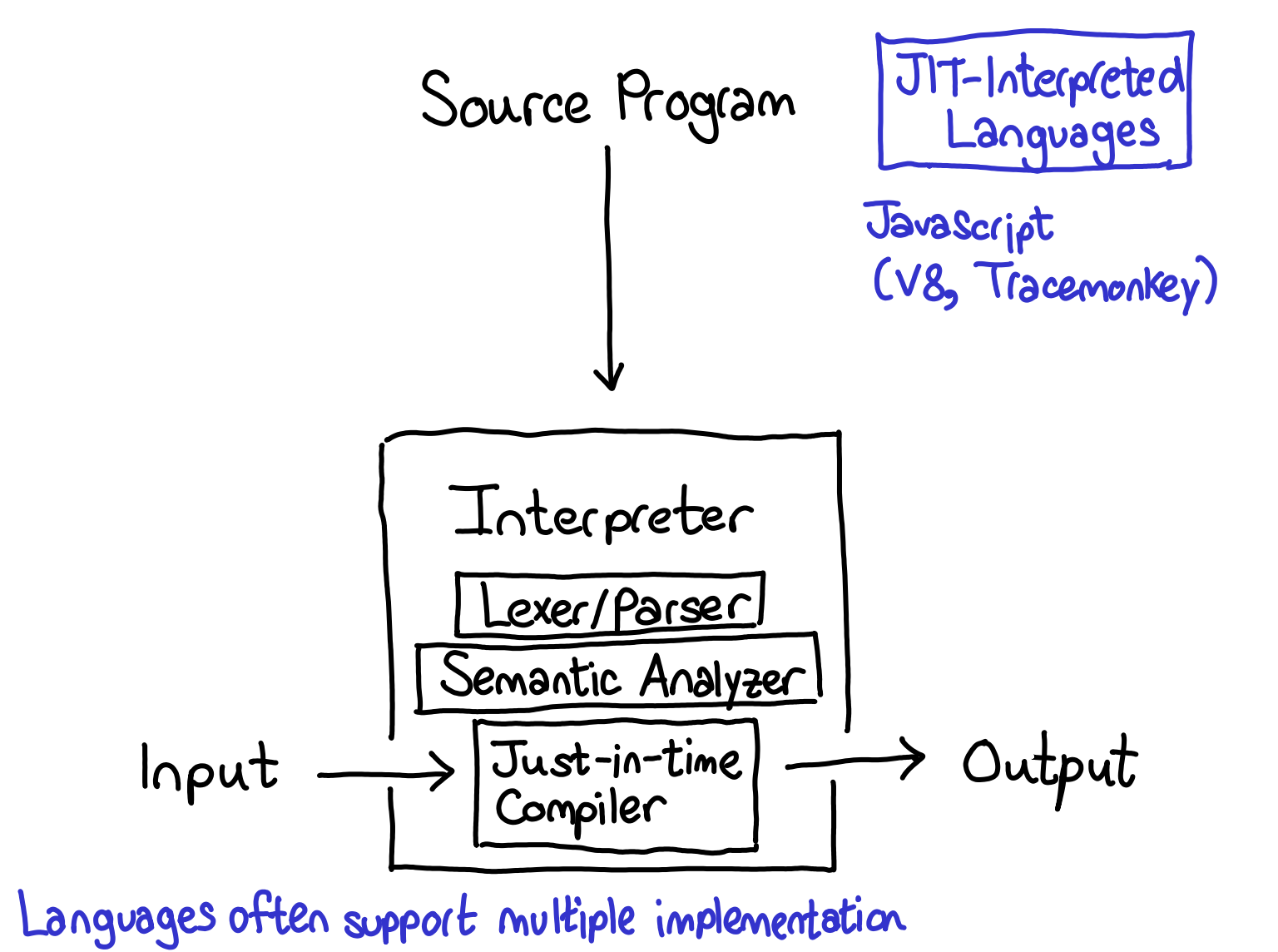
Interpreted Languages

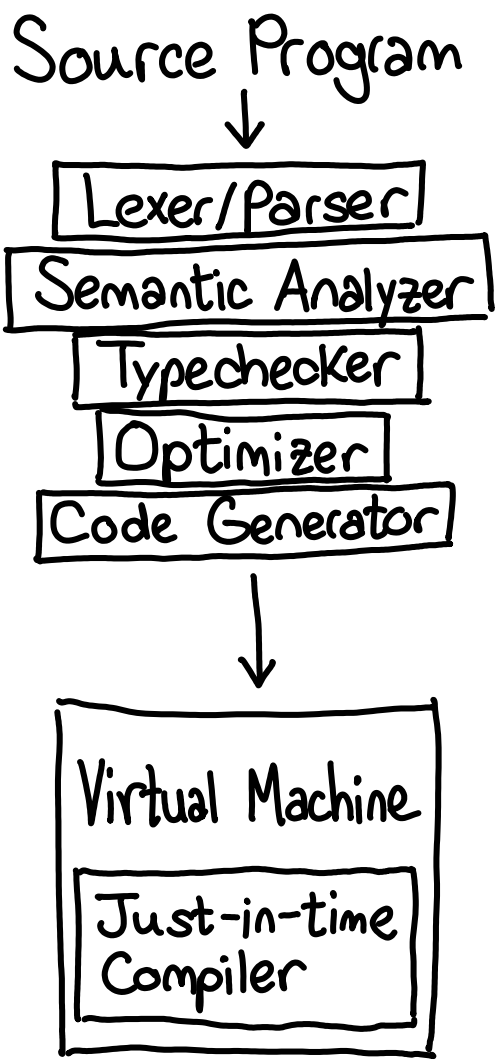
Python, Ruby, PHP, Perl, MATLAB...


Source Program
Compiled Languages
C, C++, Haskell, Go, ML, Rust
Ahead-Of-Time Compiler
Input
Program
Output


Source Program
Lexer/Parser
Semantic Analyzer
Typechecker
Frontend
Intermediate Representation
Optimizer
Code Generator
Linker
Backend
Input
Program
Output
Runtime System
GC, memory, FFI, etc...


Source Program
Lexer/Parser
Semantic Analyzer
Typechecker
Optimizer
Code Generator
Bytecode
Virtual Machine
Just-in-time Compiler
Input
Output
VM-hosted Languages
JVM, CLR
portability!


Source Program
JIT-Interpreted Languages
Javascript (V8, Tracemonkey)
Interpreter
Lexer/Parser
Semantic Analyzer
Input
Just-in-time Compiler
Output
Languages often support multiple implementation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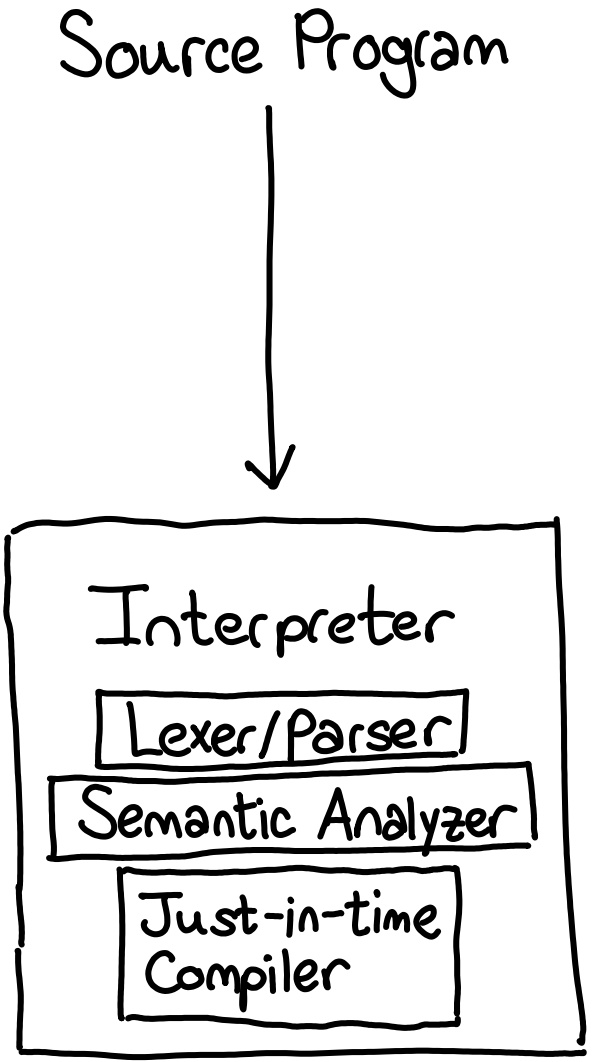
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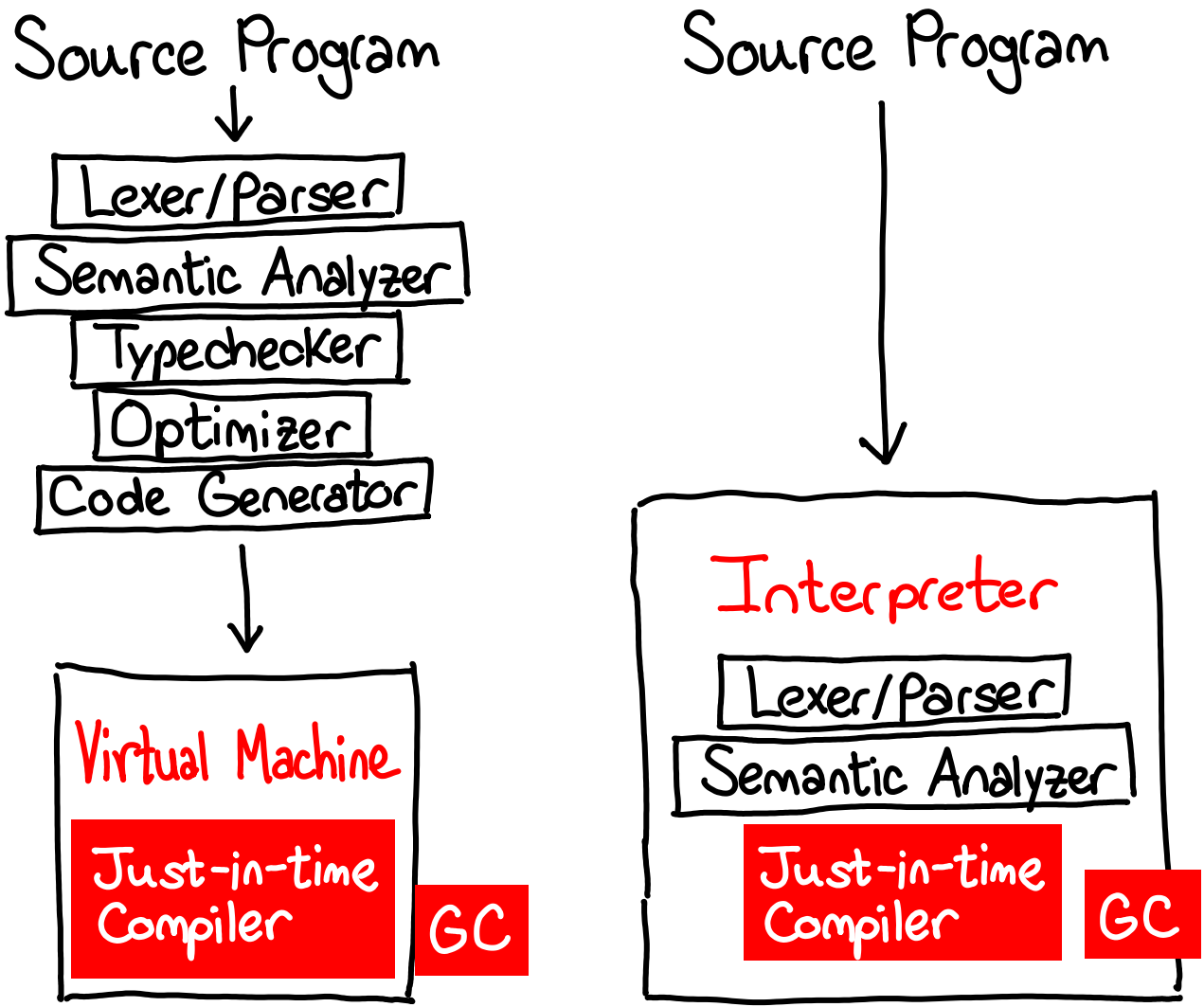
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GC
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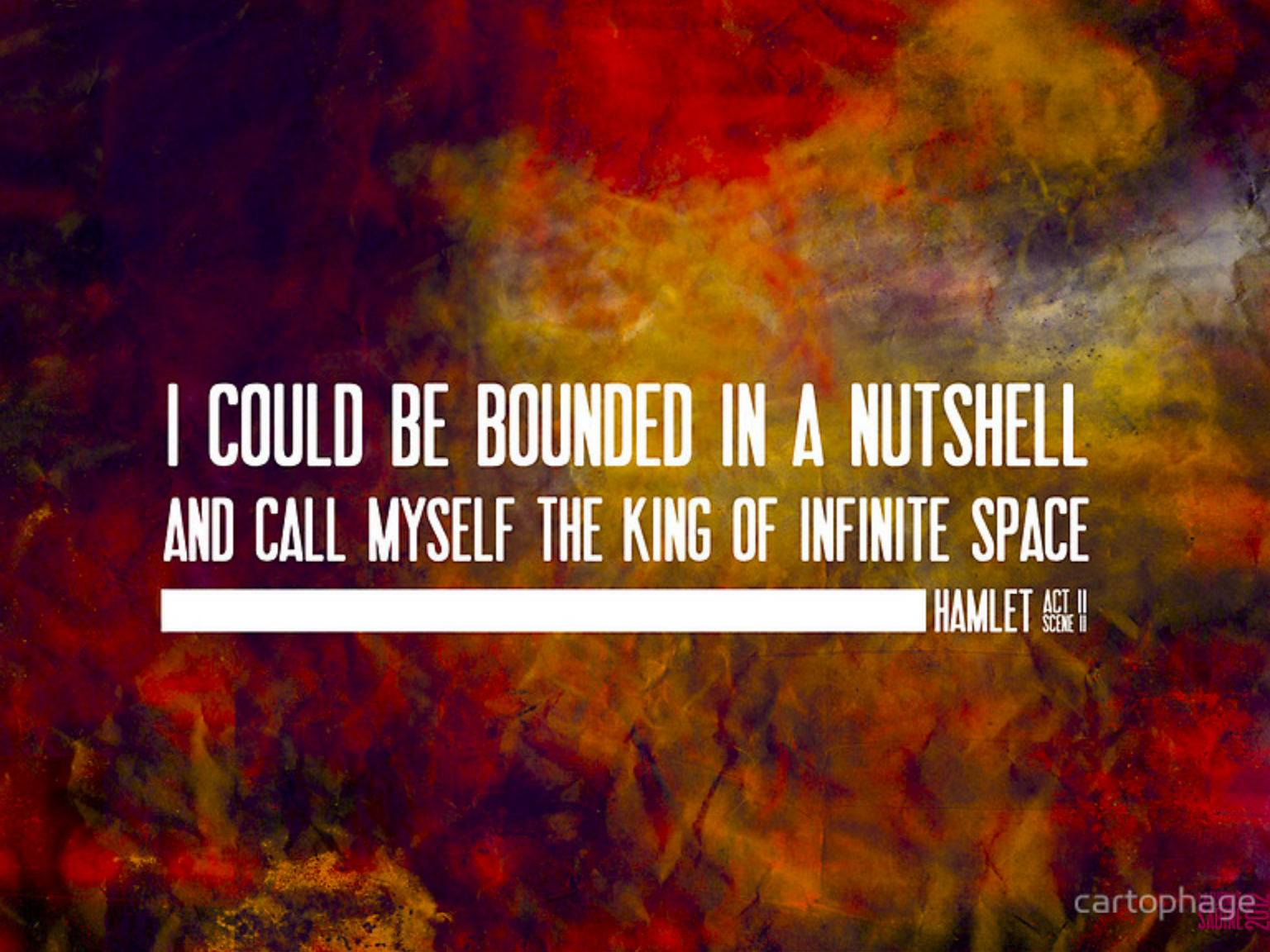
GC

- Garbage Collection

- Dynamic Dispatch in a JIT

  compare with C++ vtables


I COULD BE BOUNDED IN A NUTSHELL
AND CALL MYSELF THE KING OF INFINITE SPACE
HAMLET ACT II SCENE II
cartophage

Lambda Calculus

Activation-record Model

x86 machine architecture

Memory Hierarchy

INFINITE MEMORY

FINITE MEMORY

INFINITE MEMORY

GARBAGE COLLECTION

FINITE MEMORY

& reuse space which provably will never be used again

Managed Memory

Memory Management

allocate

Interface for allocating objects.
Pointers are opaque.

Garbage collection / Reference counting

malloc
free

Interface for explicitly allocating/
deallocating finite memory

Operating System & Hardware

Garbage Collection

- Reference Counting
  - ARC, Perl, PHP, Python
  - The Cycle Problem

- Tracing Collection
  - Java, Haskell, ML, Lisp, Go, JavaScript
    - Mark and Sweep
    - Copying Collection

When I am done using an object, free its memory

How do I know this?

When I am done using an object,

free its memory

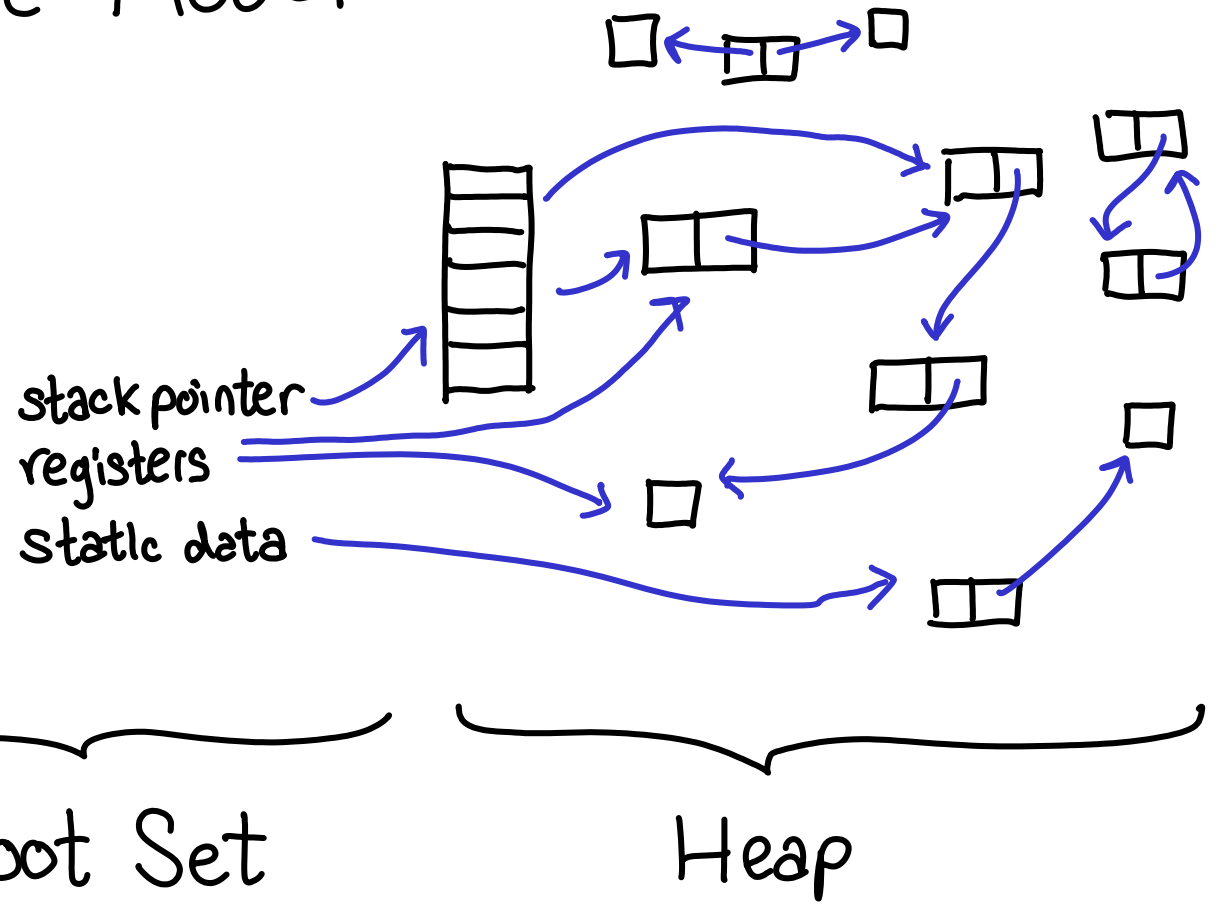
IDEAL

Object has no causal influence on future program execution

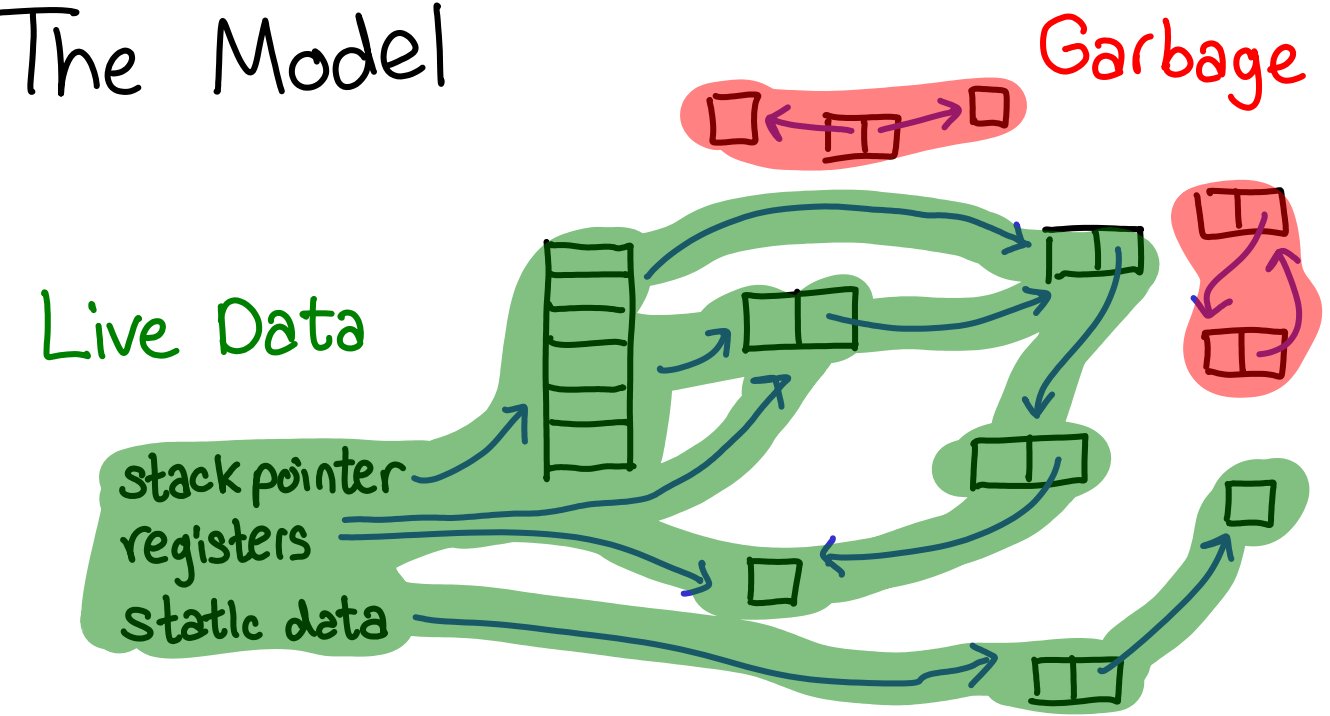
When I am done using an object,

free its memory

The Model



The Model



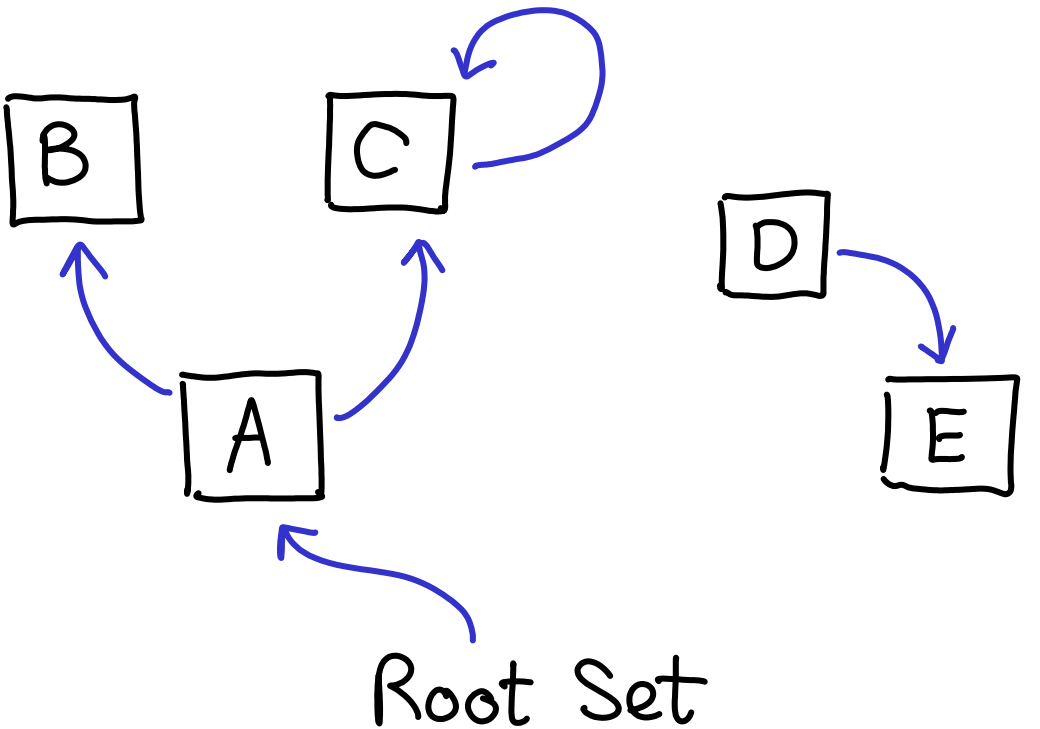
Root Set

Heap

Why must pointer arithmetic be disallowed?

Reference counting

Count the number of incoming references



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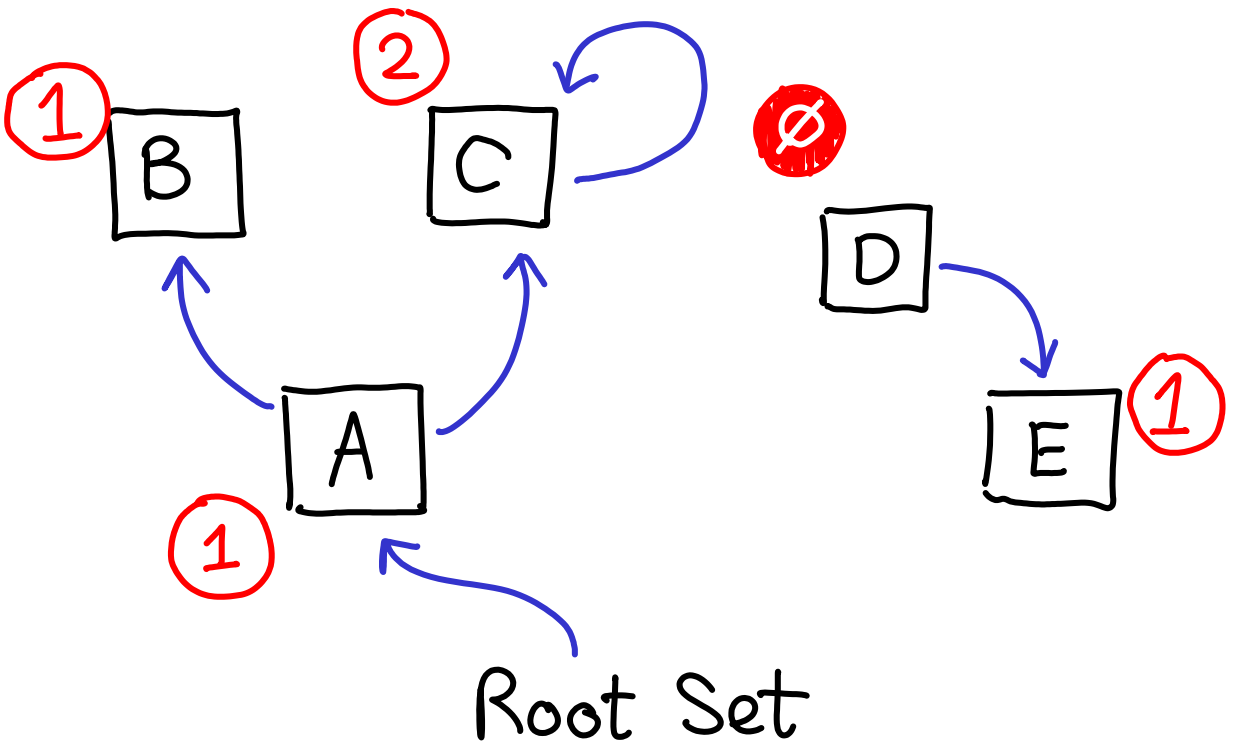

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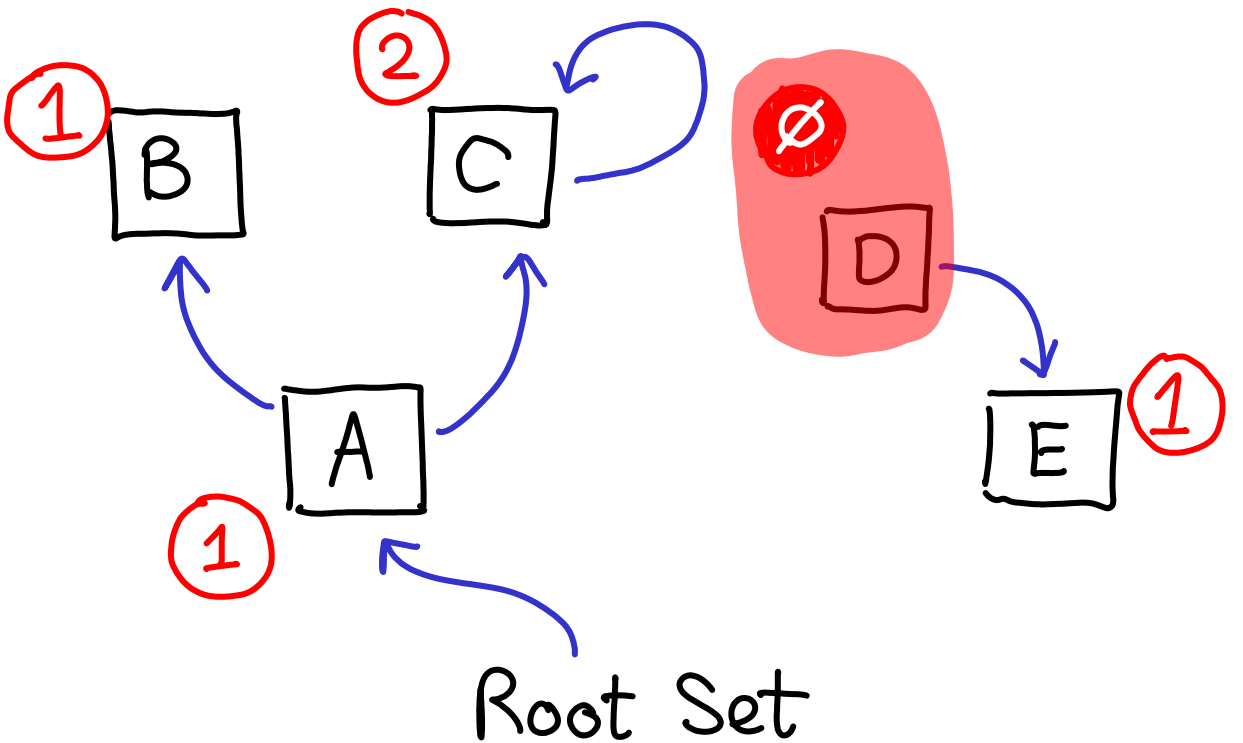

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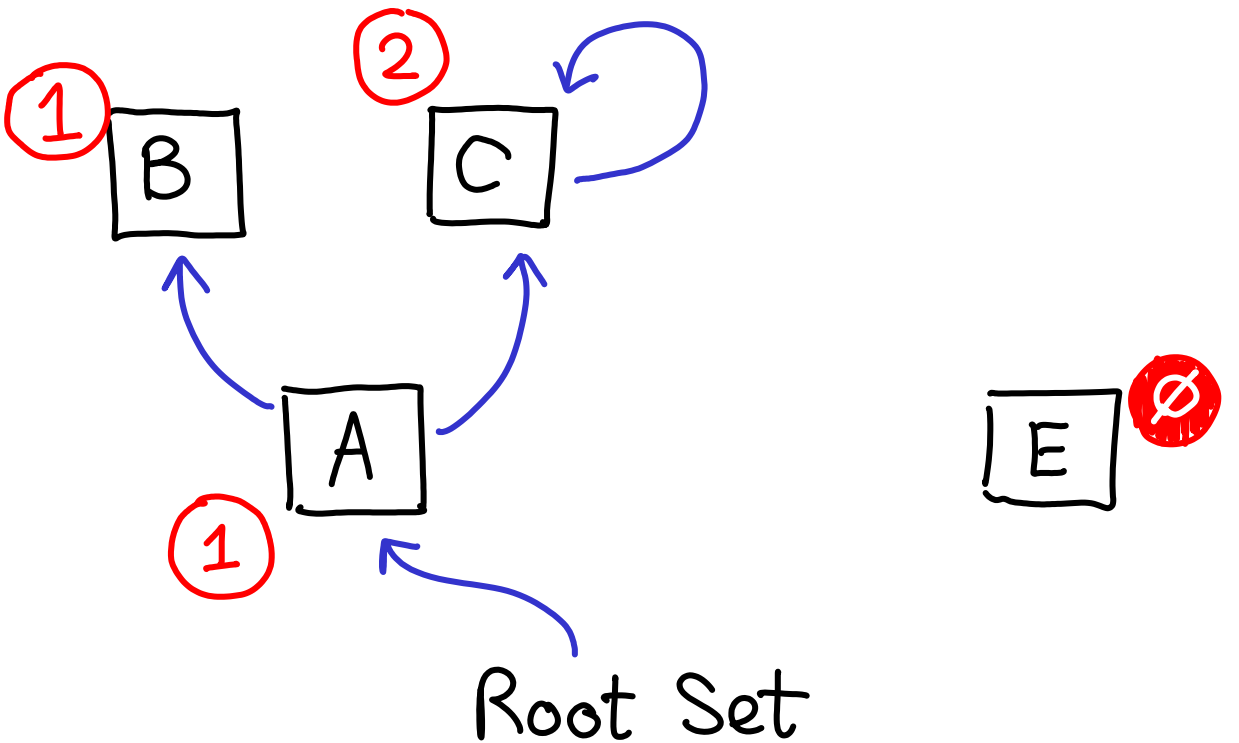

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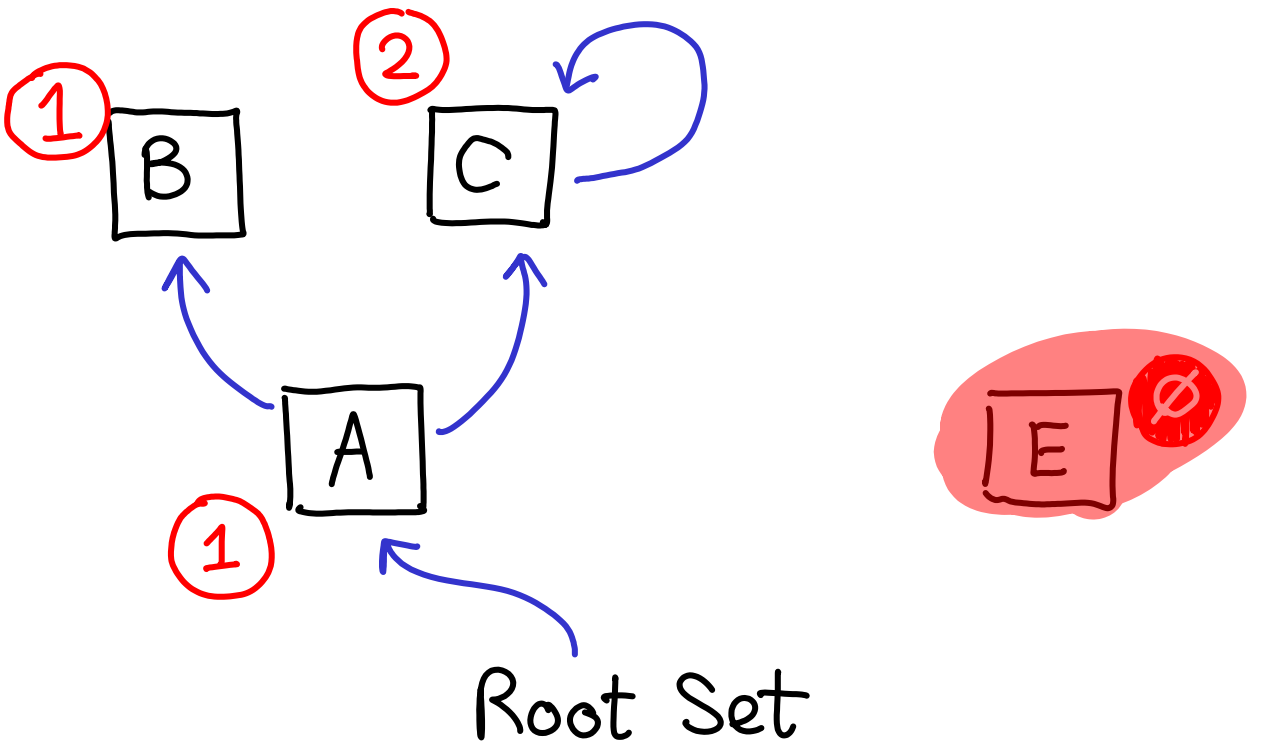

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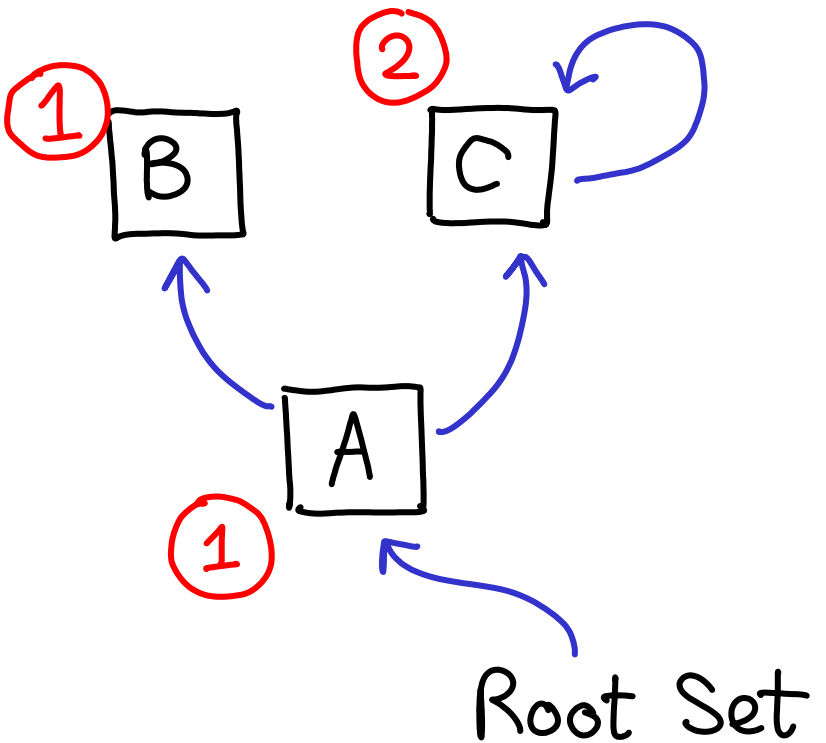

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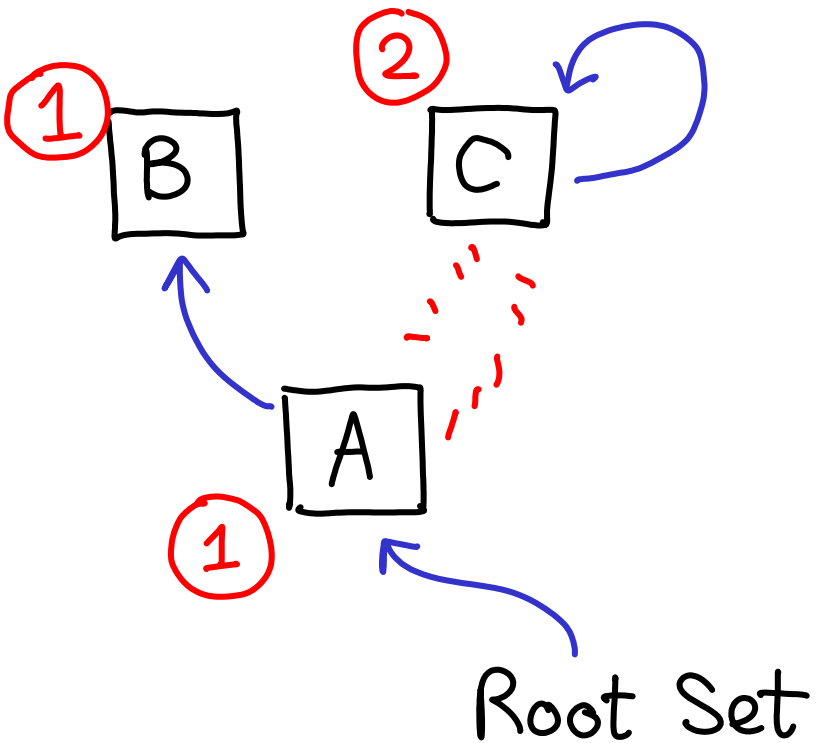

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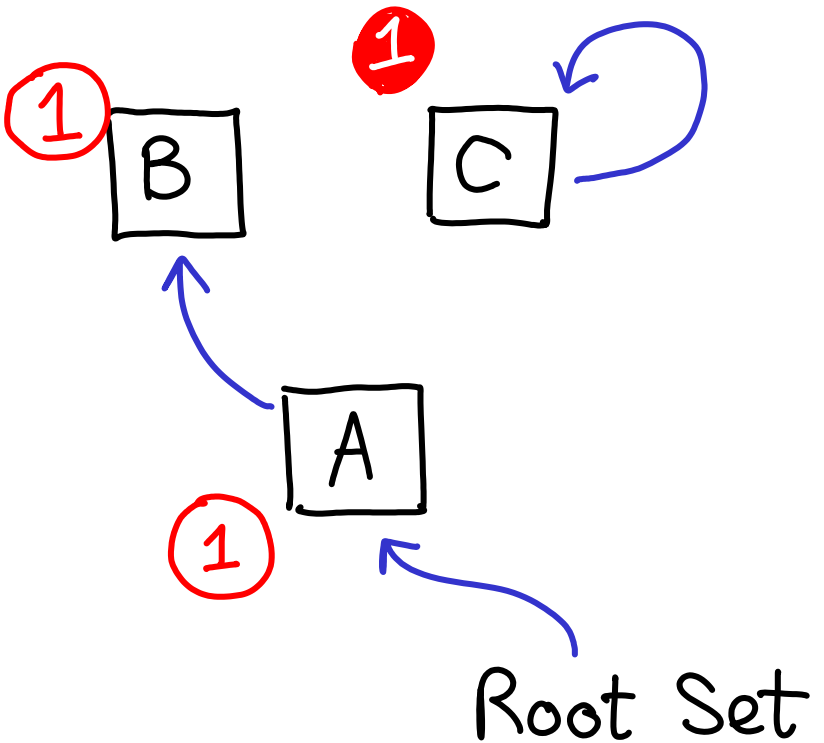

Reference counting

Count the number of incoming references

- ✓ Very easy to implement
- ✓ Objects immediately deallocated
- ✗ Cycles never die! (cycle-breaking)
- ✗ Storing & updating counts is costly
- ✗ Sychronizing updates

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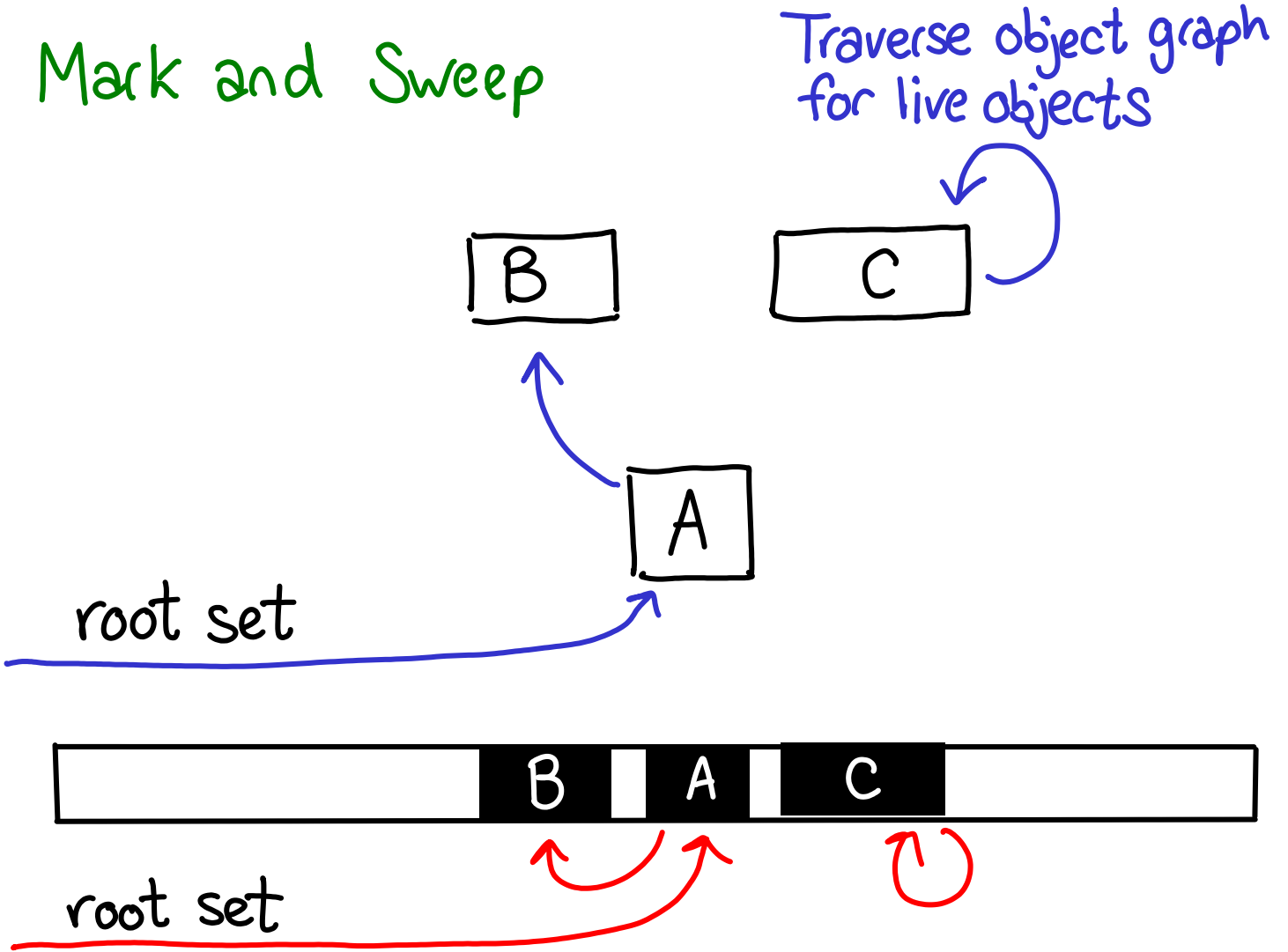
Mark and Sweep



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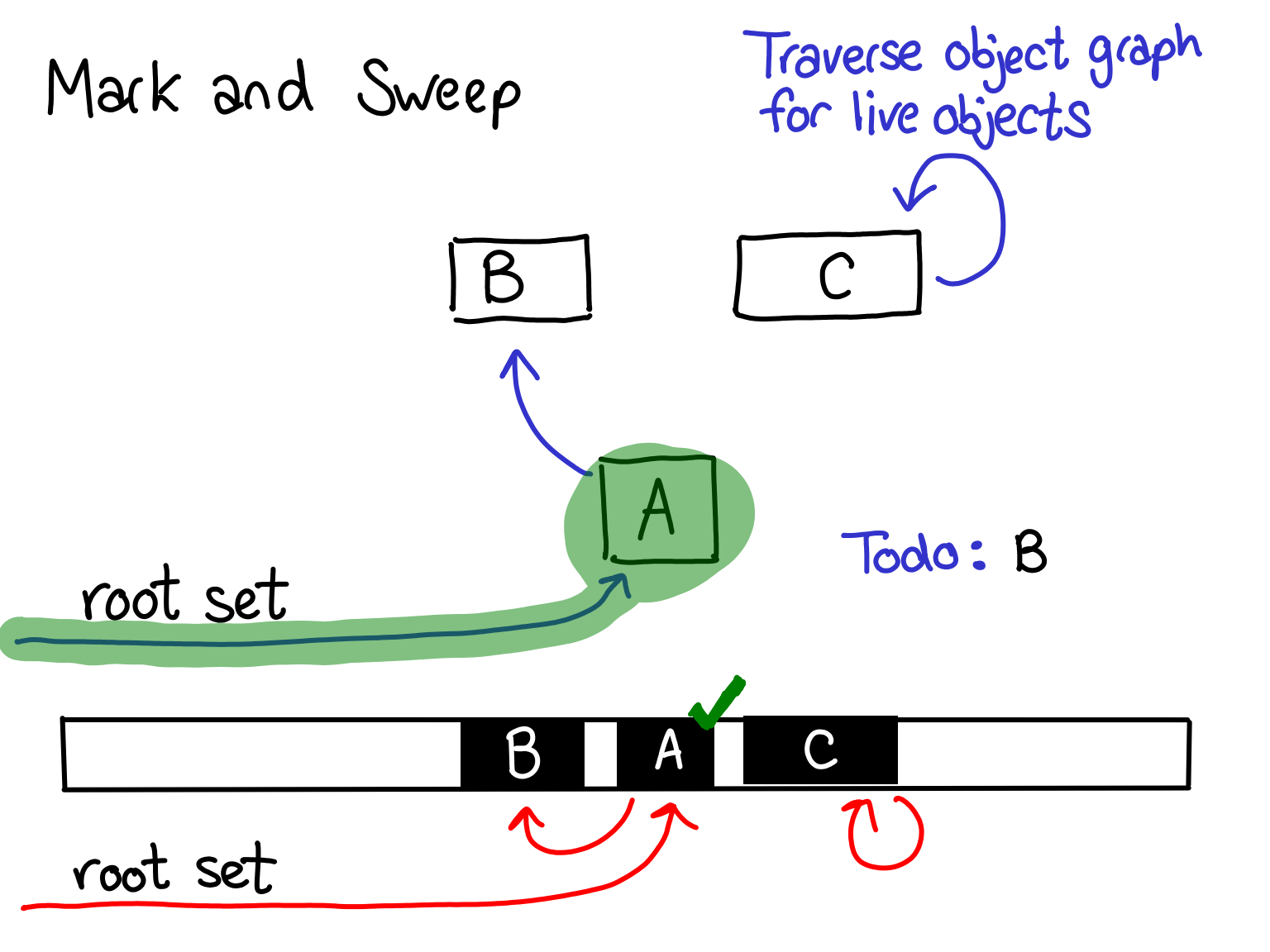

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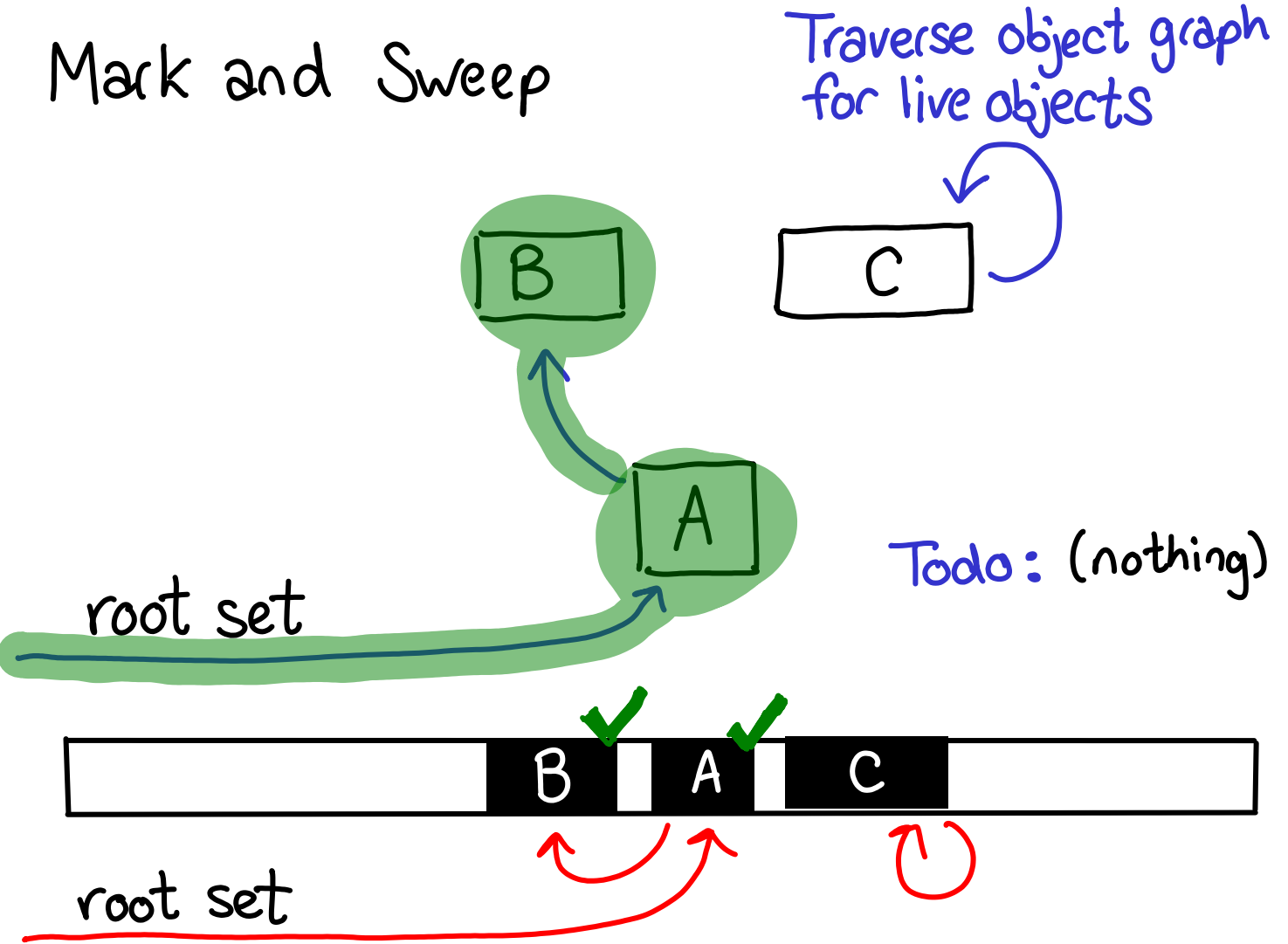
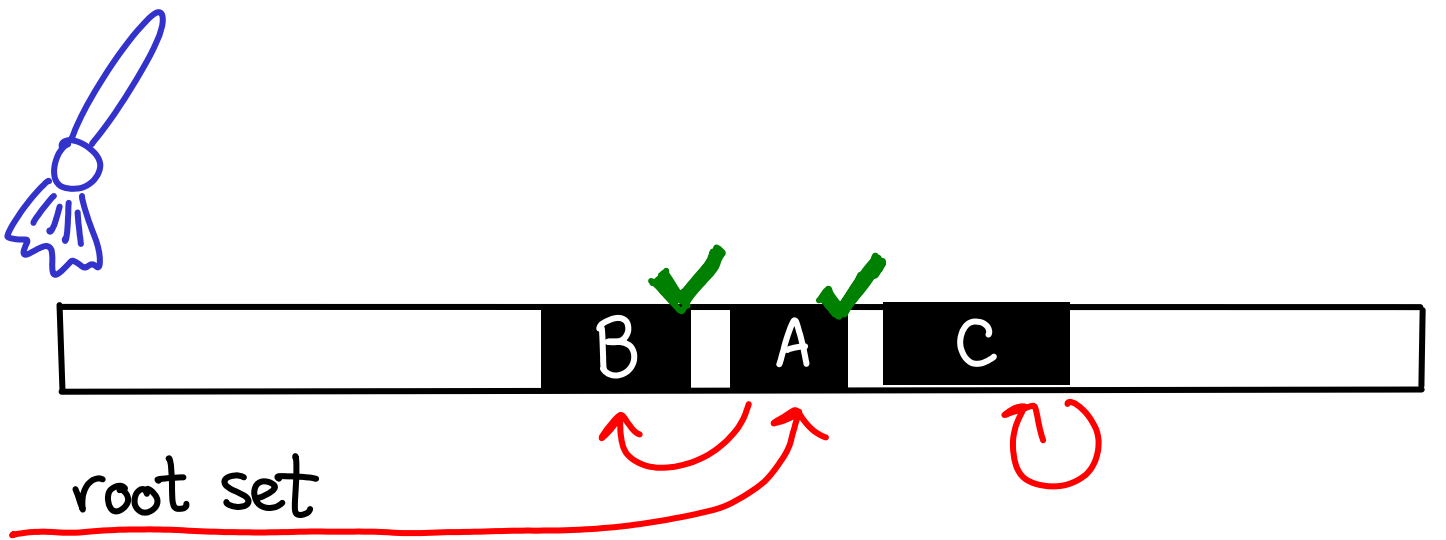


Mark and Sweep

Sweep memory for dead objects



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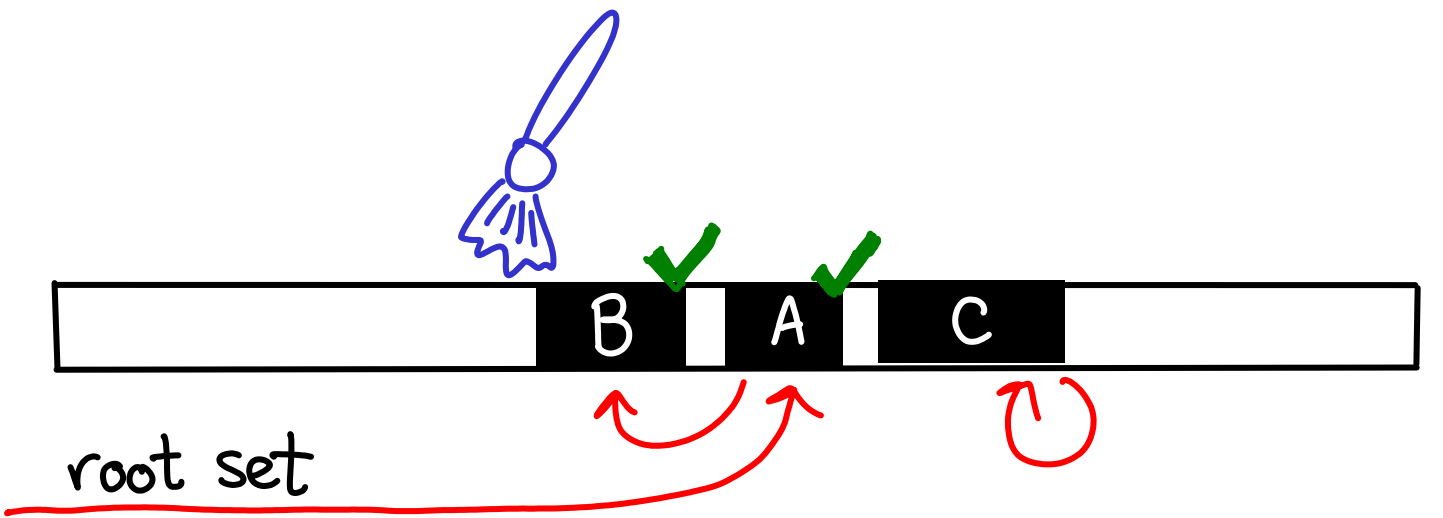

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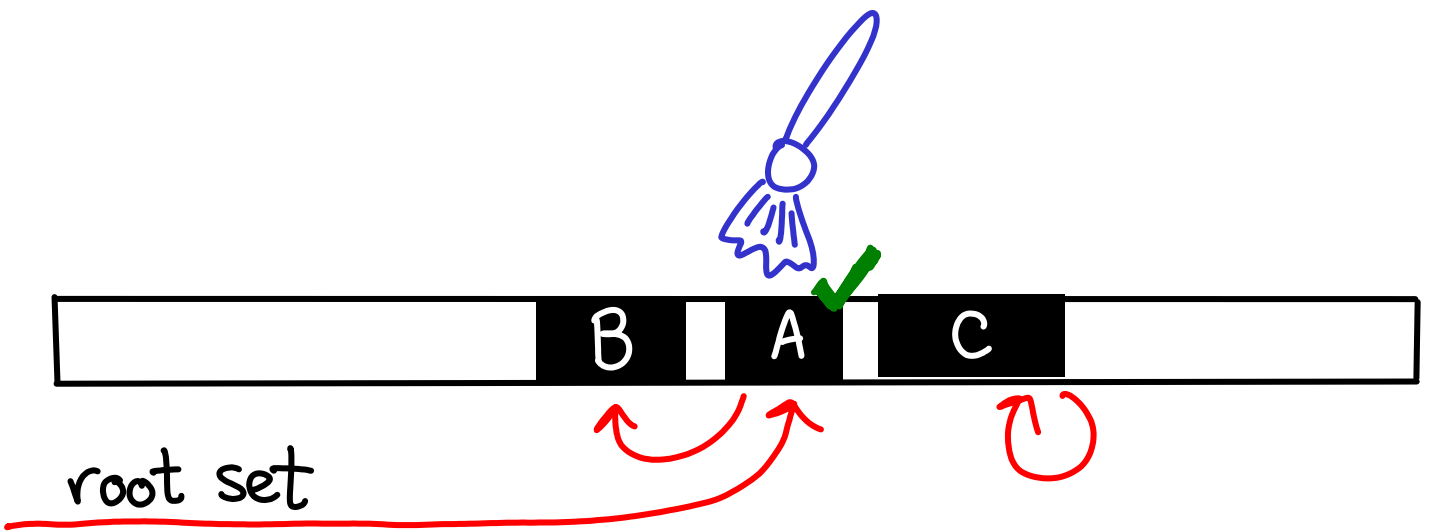

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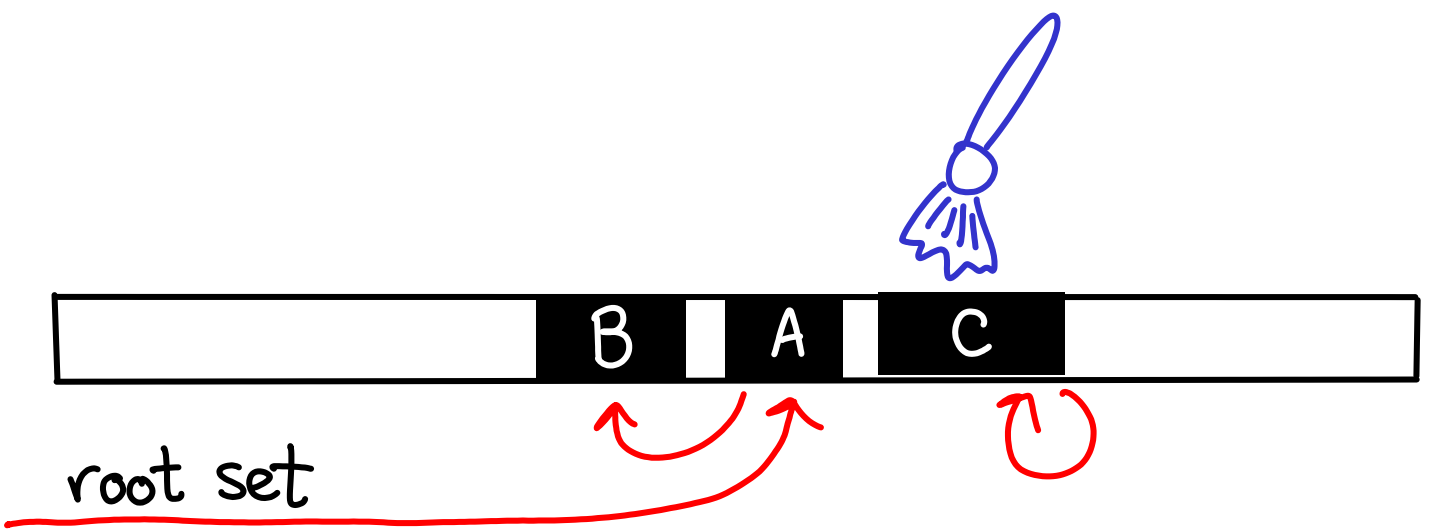

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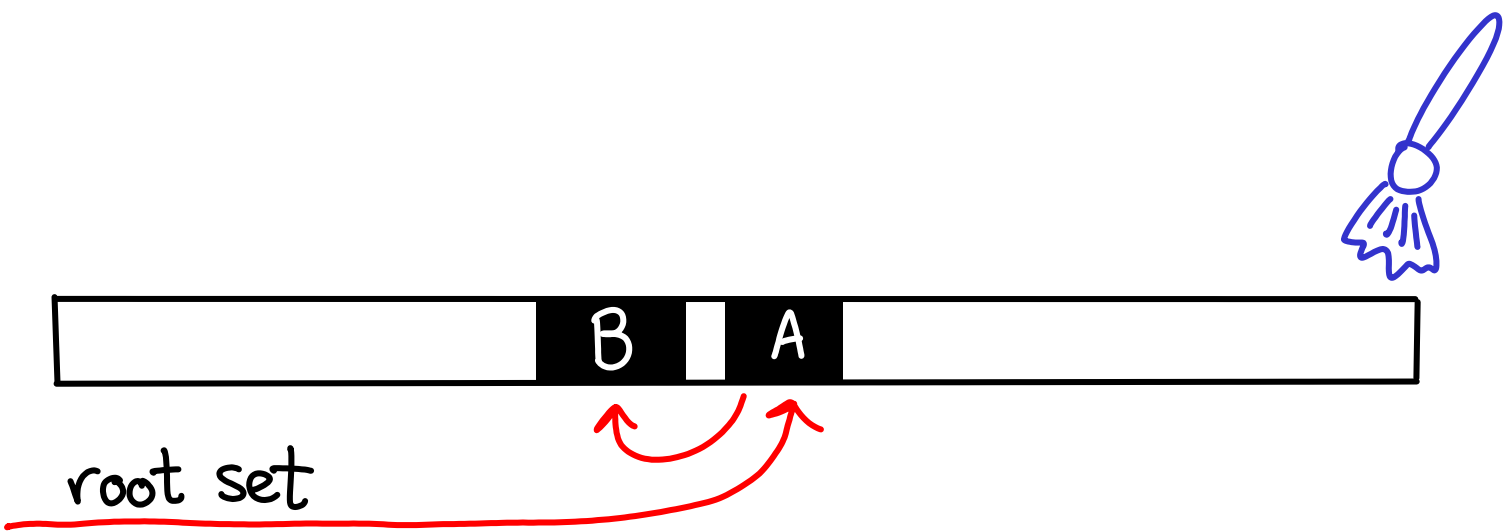

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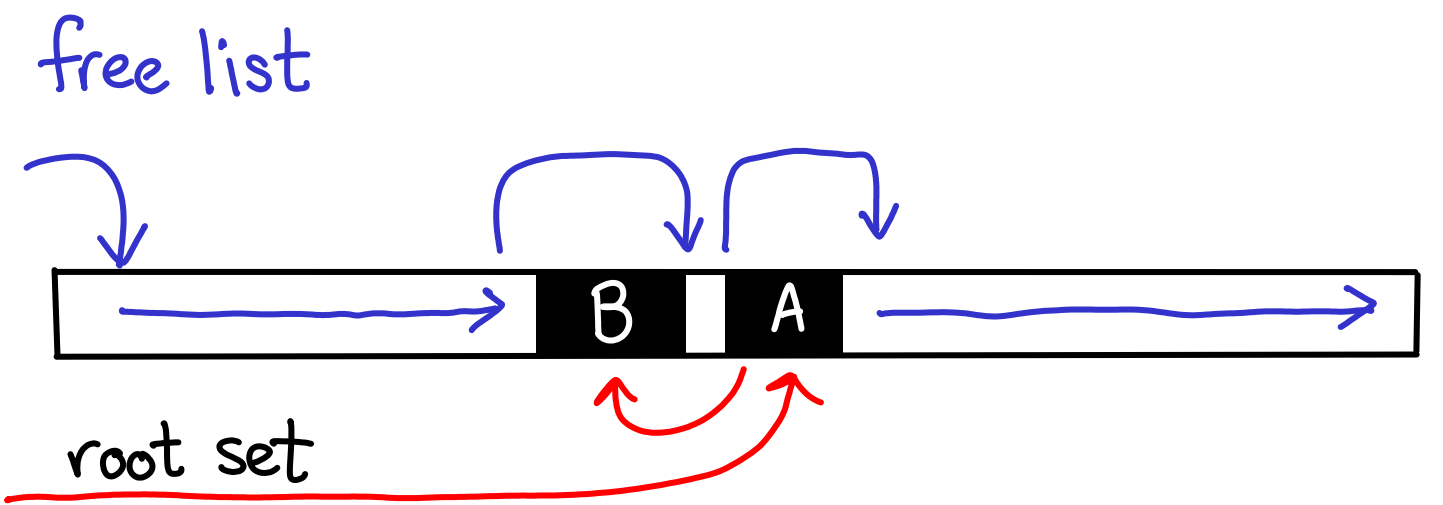

Mark and Sweep

Traverse object graph for live objects

Sweep memory for dead objects

✓ Cycles are handled

✓ No extra bookkeeping

⚠ Naïvely needs to traverse entire heap

⚠ Naïvely leads to fragmentation (can compact)

✗ Needs to store a mark bit

✗ Needs to maintain TODO list

✗ Stop-the-world GC (could refcounting pause?)

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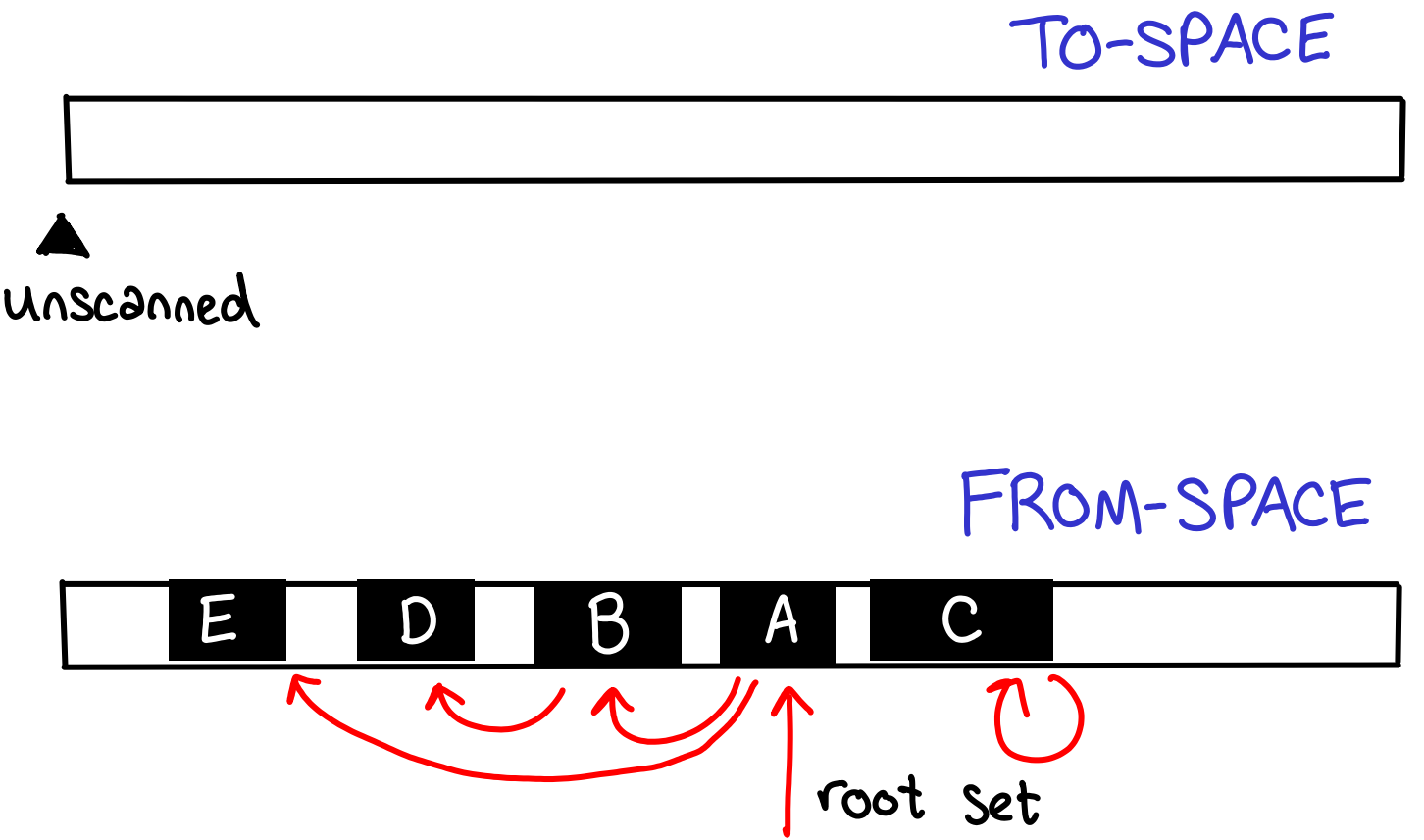
Copying Collection



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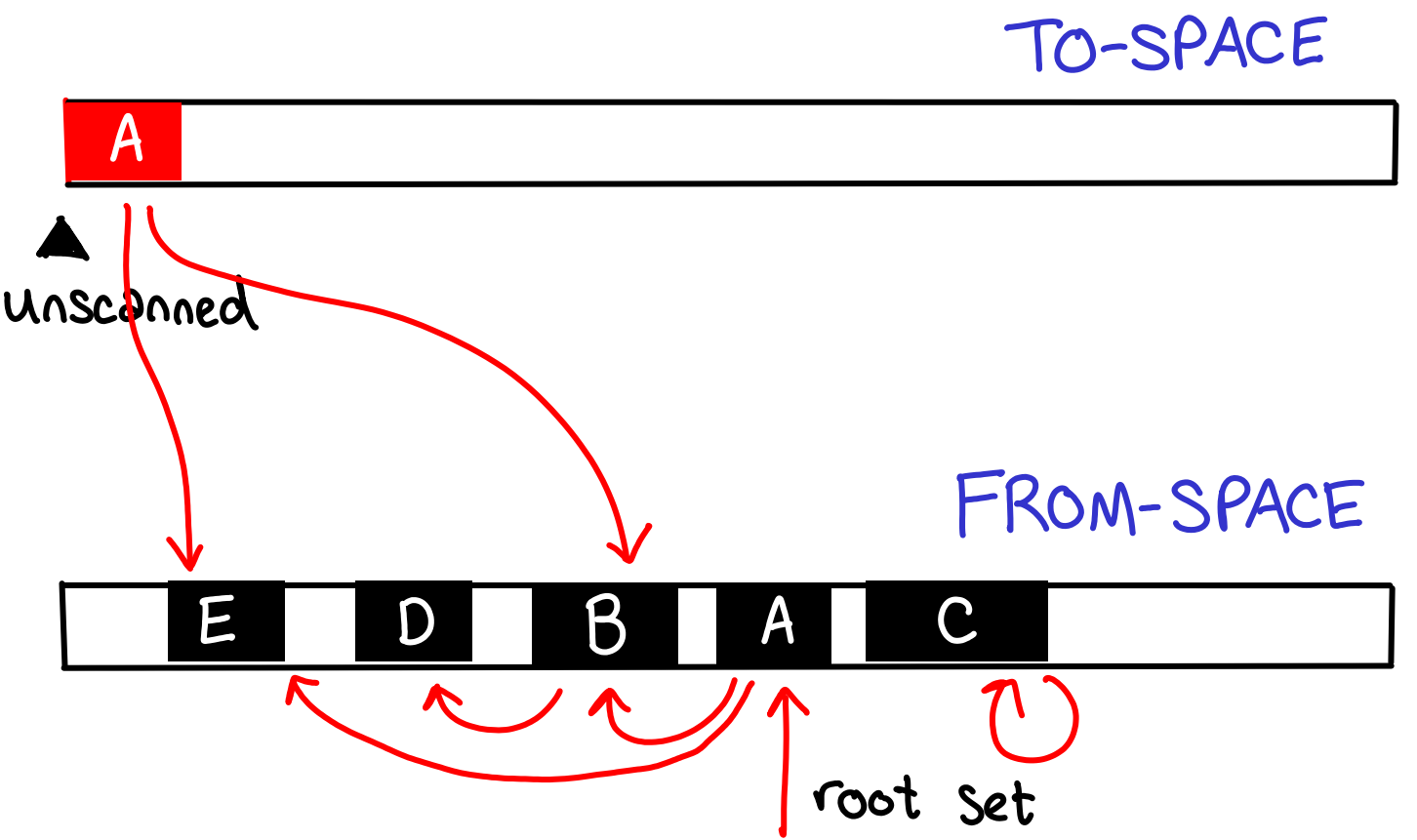

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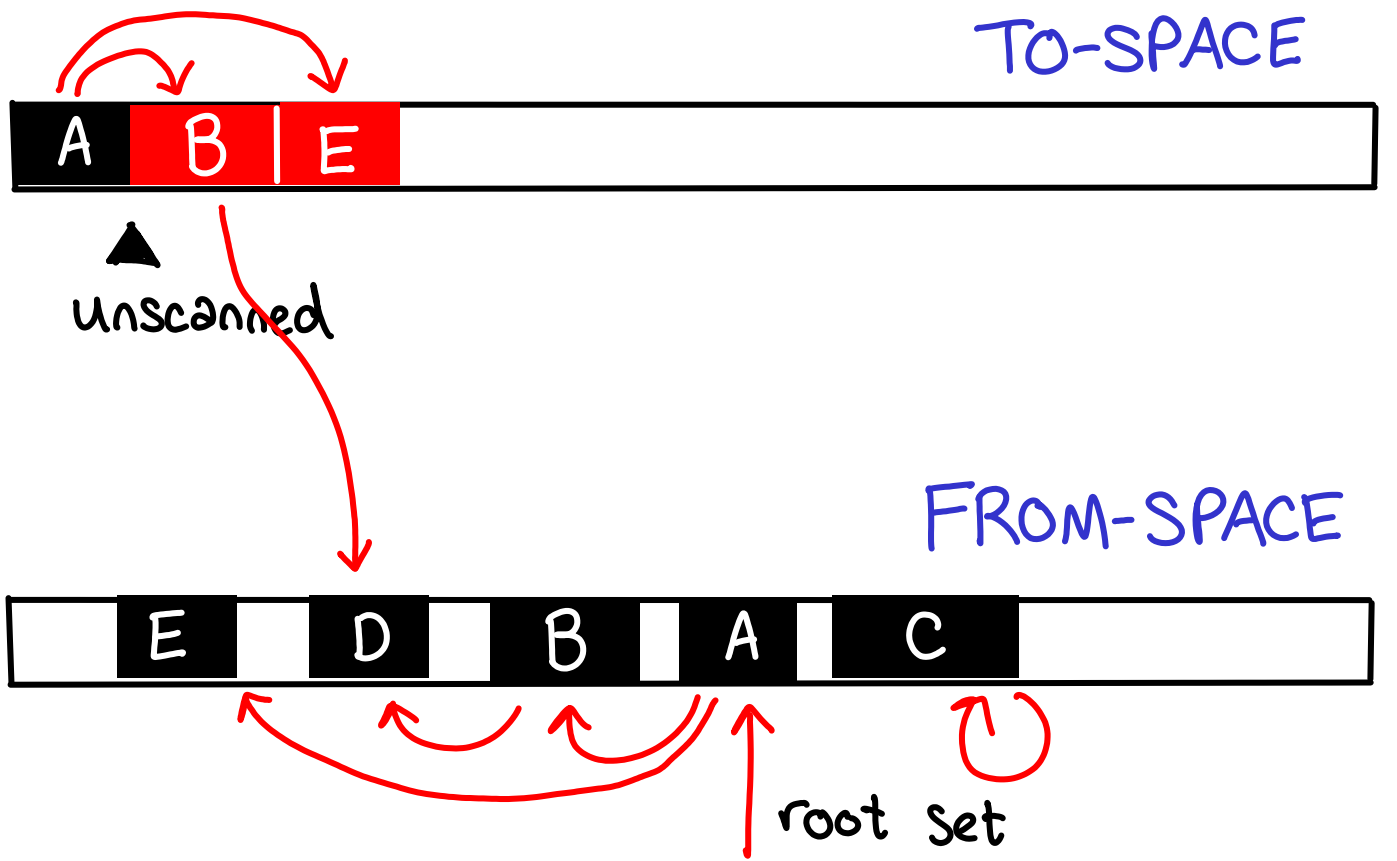

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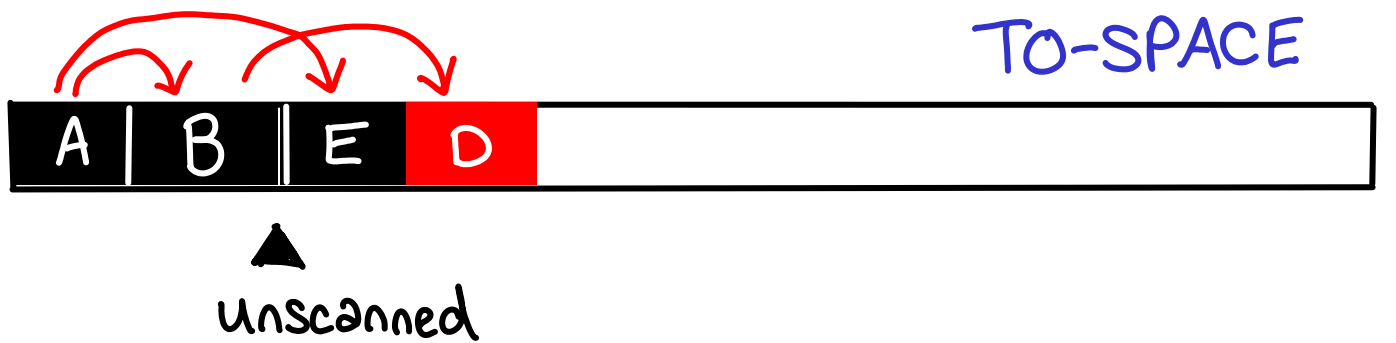

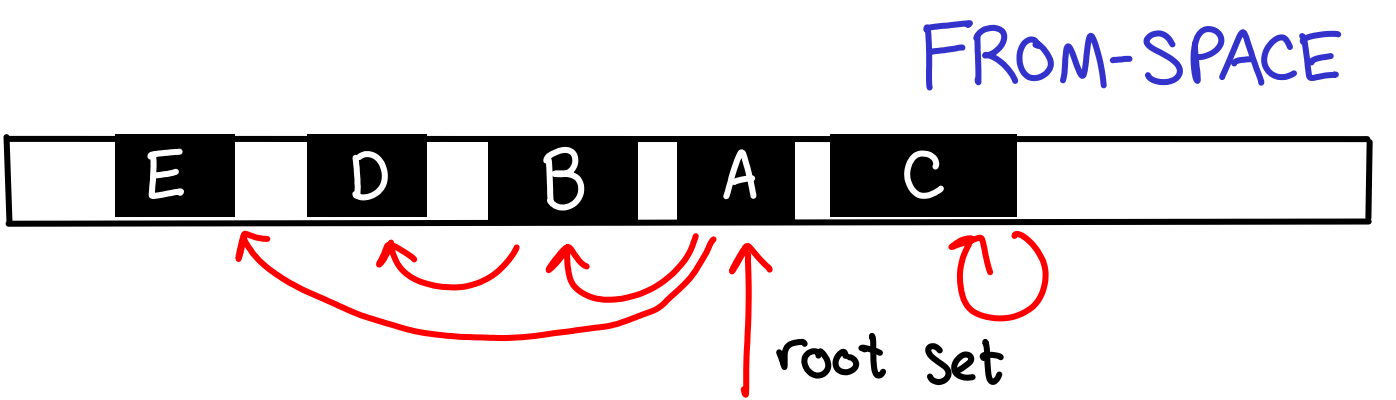

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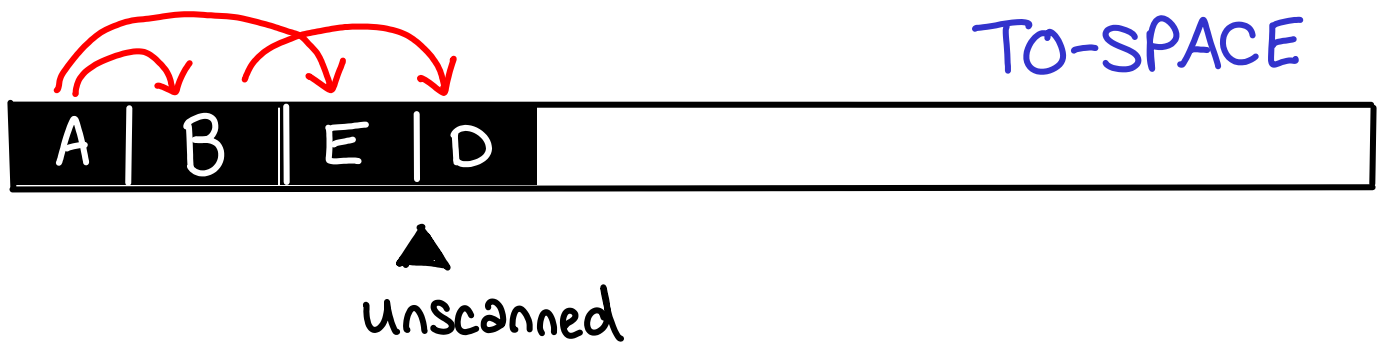

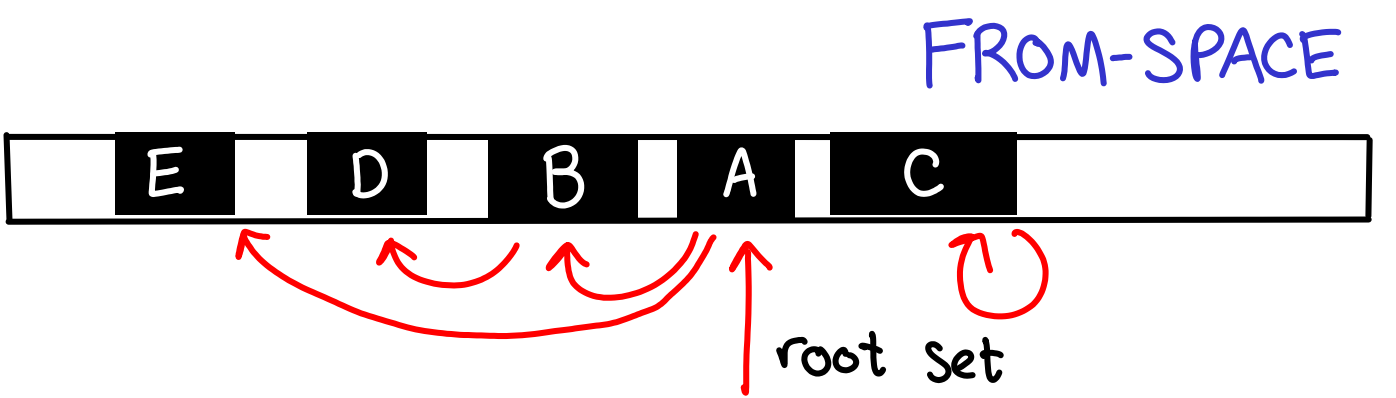

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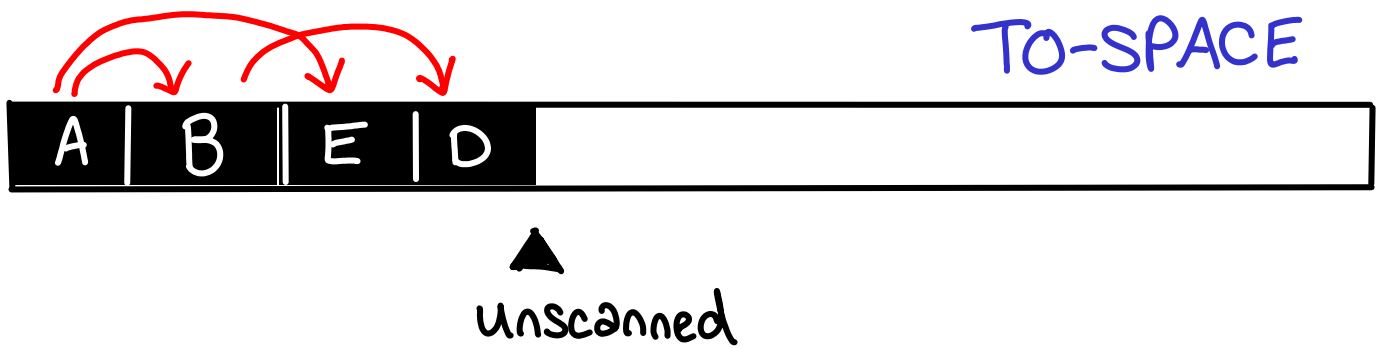
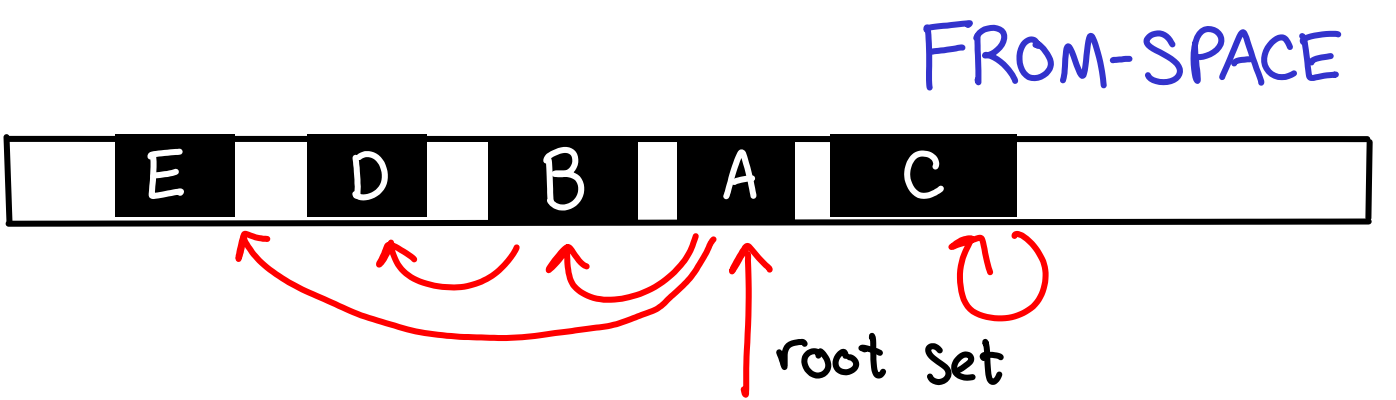




Copying Collection

✓ Compacts data (better locality)

✓ Constant space bookkeeping

✗ Needs x2 available space

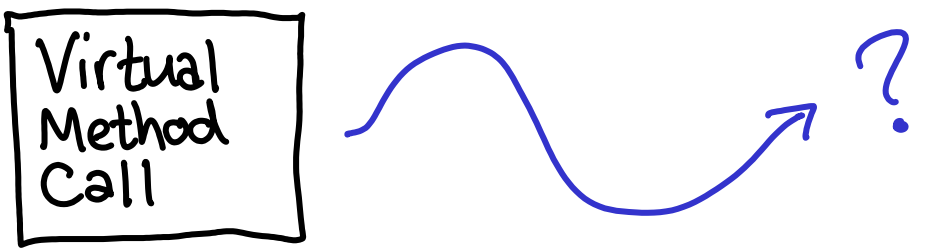
✗ (Still) Stop-the-world GC

Summary: Garbage Collection

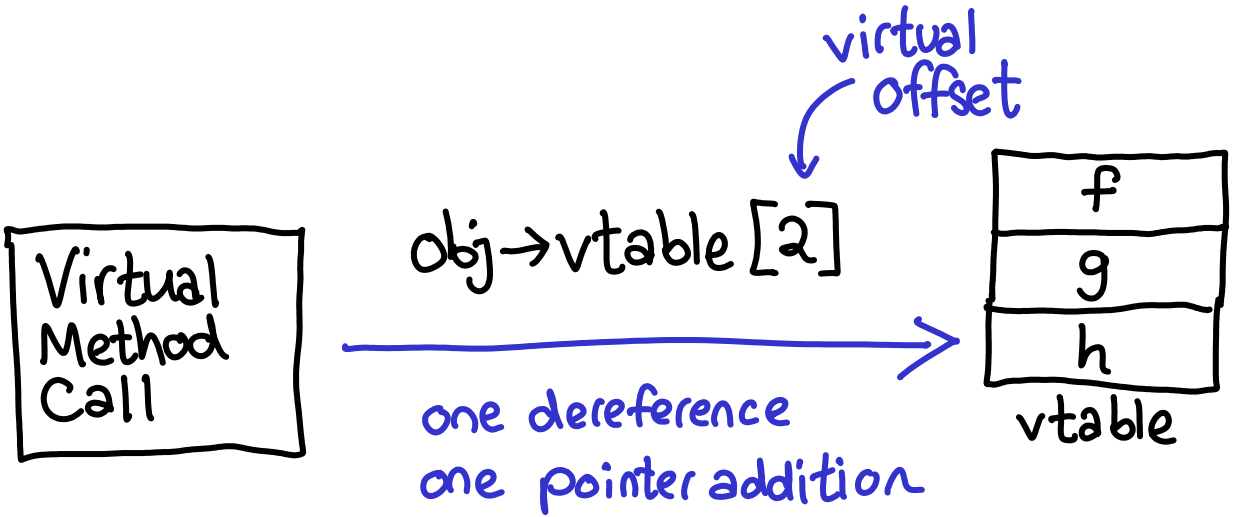
- Provide the ILLUSION of infinite memory
- Liveness based on reachability
- Generational GC (it's hard!)

Dynamic Dispatch

Recap: C++ Virtual Tables



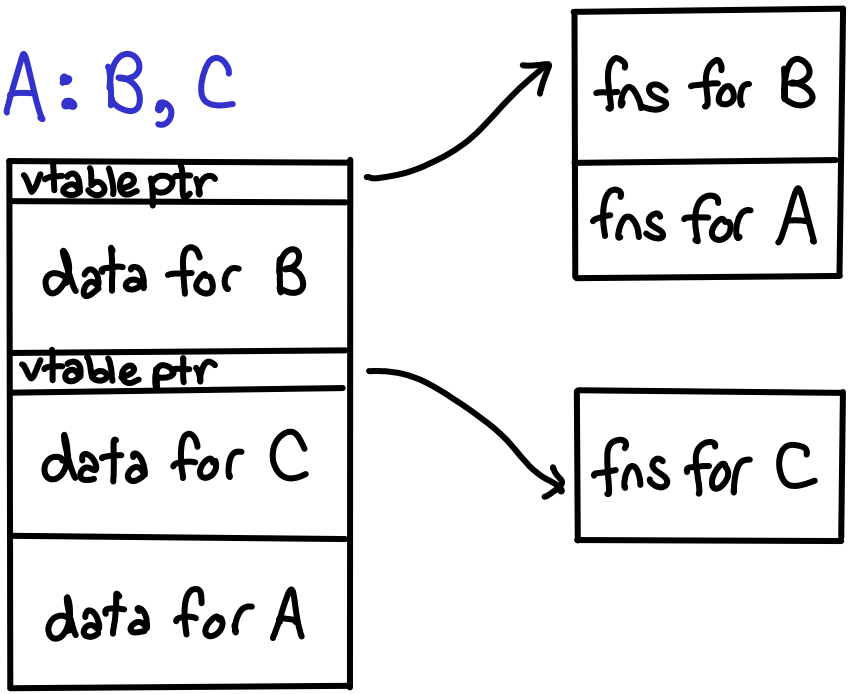
Recap: C++ Virtual Tables



C++ goal: Make virtual dispatch as efficient as possible

Recap: C++ Virtual Tables

class A: B, C



Consequence: Multiple inheritance, but no interfaces

Recap: C++ Virtual Tables

Motivating Problem

```
class A {
    virtual void f();
    virtual void g();
}
```

```
class B {
    virtual void g();
    virtual void f();
}
```

Naive solution: Do a dictionary lookup

Recap: C++ Virtual Tables

Motivating Problem

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class A {
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    virtual void g();
}
```

```
class B {
    virtual void g();
    virtual void f();
}
```

C++ says: Do both layouts

Recap: C++ Virtual Tables

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```

```
class B {
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    virtual void f();
}
```
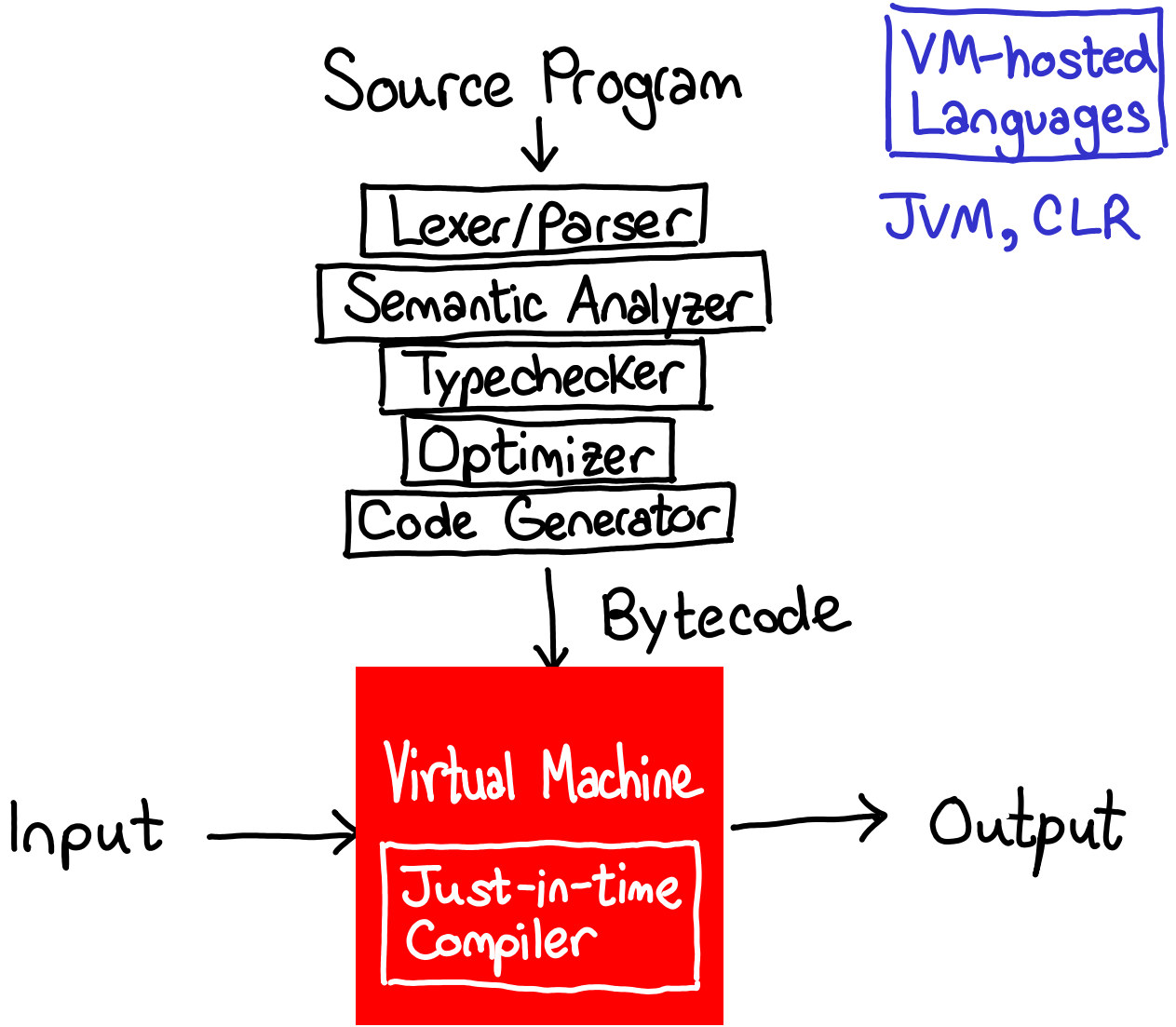

Today: Do a dictionary lookup and cache it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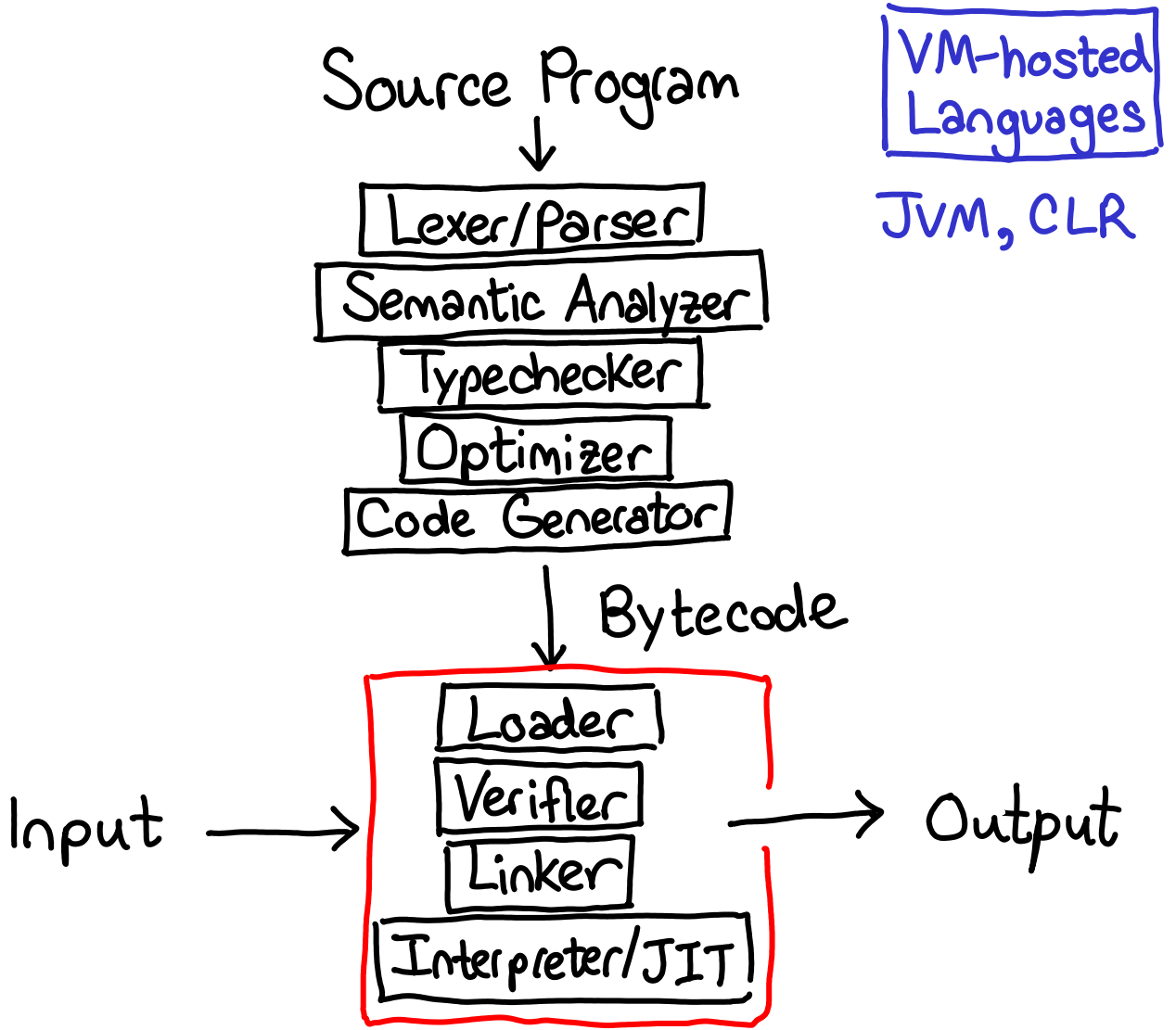
VM-hosted Languages
JVM, CLR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Briefly:

JVM

Loader

On-demand class loading
Search FS for object
Can override default class loader

Verifier

Check if bytecode is valid { valid opcode, valid jump targets, well-typed }

Linker

Add class/interface to runtime
Initialize static fields
Resolve names

Interpreter/JIT

Runtime checks (e.g. bounds checks)

Briefly:

JVM

Bytecode is for a stack machine

```
class A {
    int i;
    void f(int val) { i = val+1 ;}
}
```

```
aload 0  ; object ref this
iload 1  ; int val
iconst 1
iadd     ; add val+1
putfield #4 <Field int i>
return
```

Dynamic Dispatch in the JVM

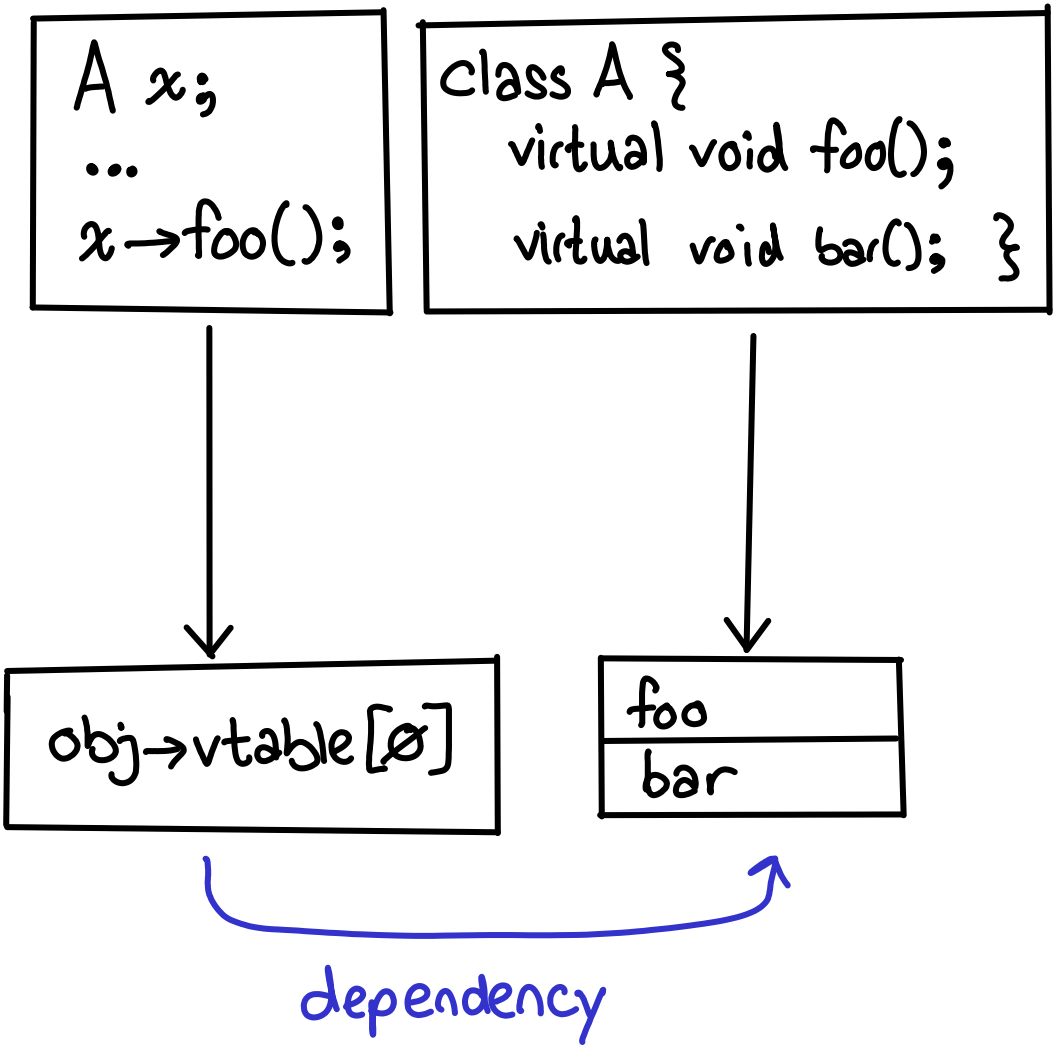
1. invokevirtual — bytecode rewriting
2. invokeinterface — inline caches
3. invokedynamic — polymorphic inline caches

(or Smalltalk or Self)

invokevirtual

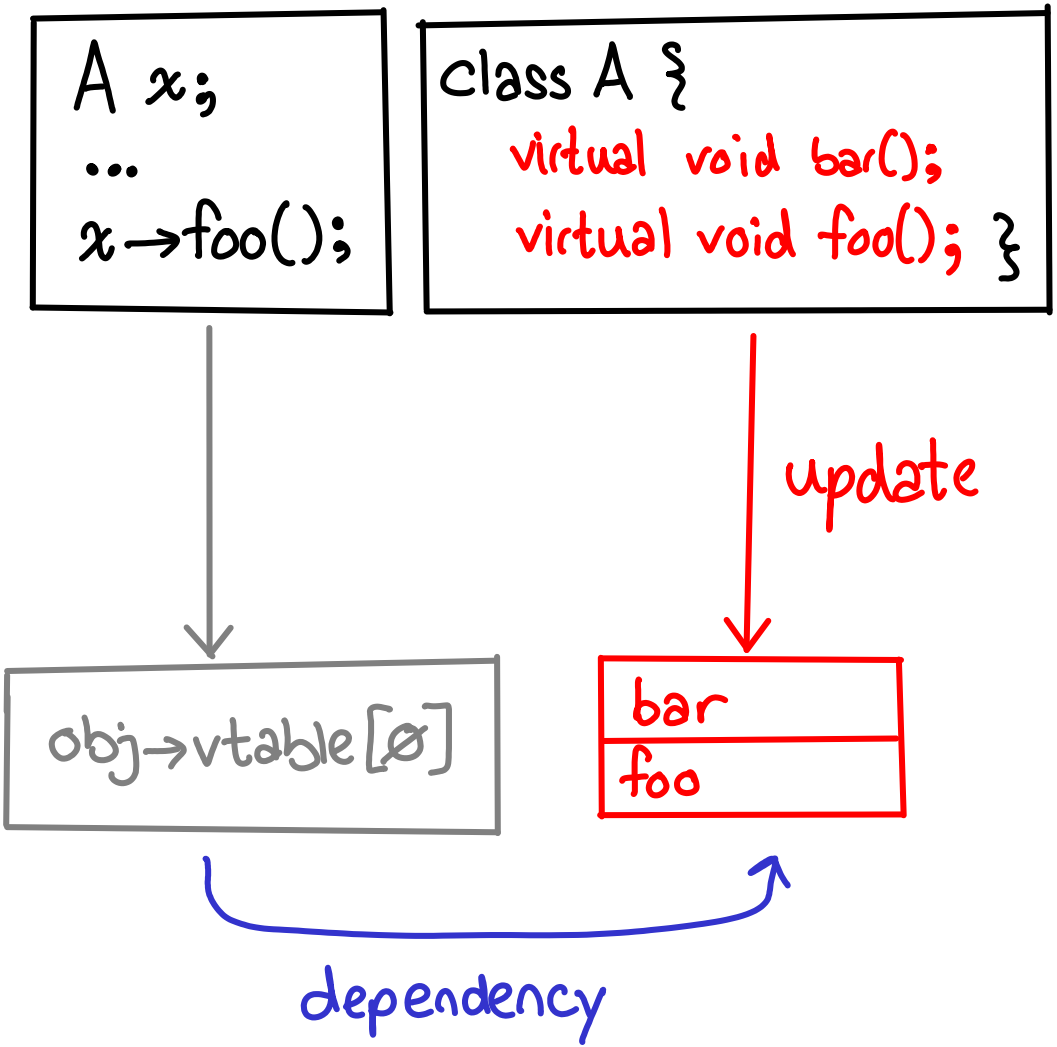
```
A x;
...
x->foo();
```

invokevirtual

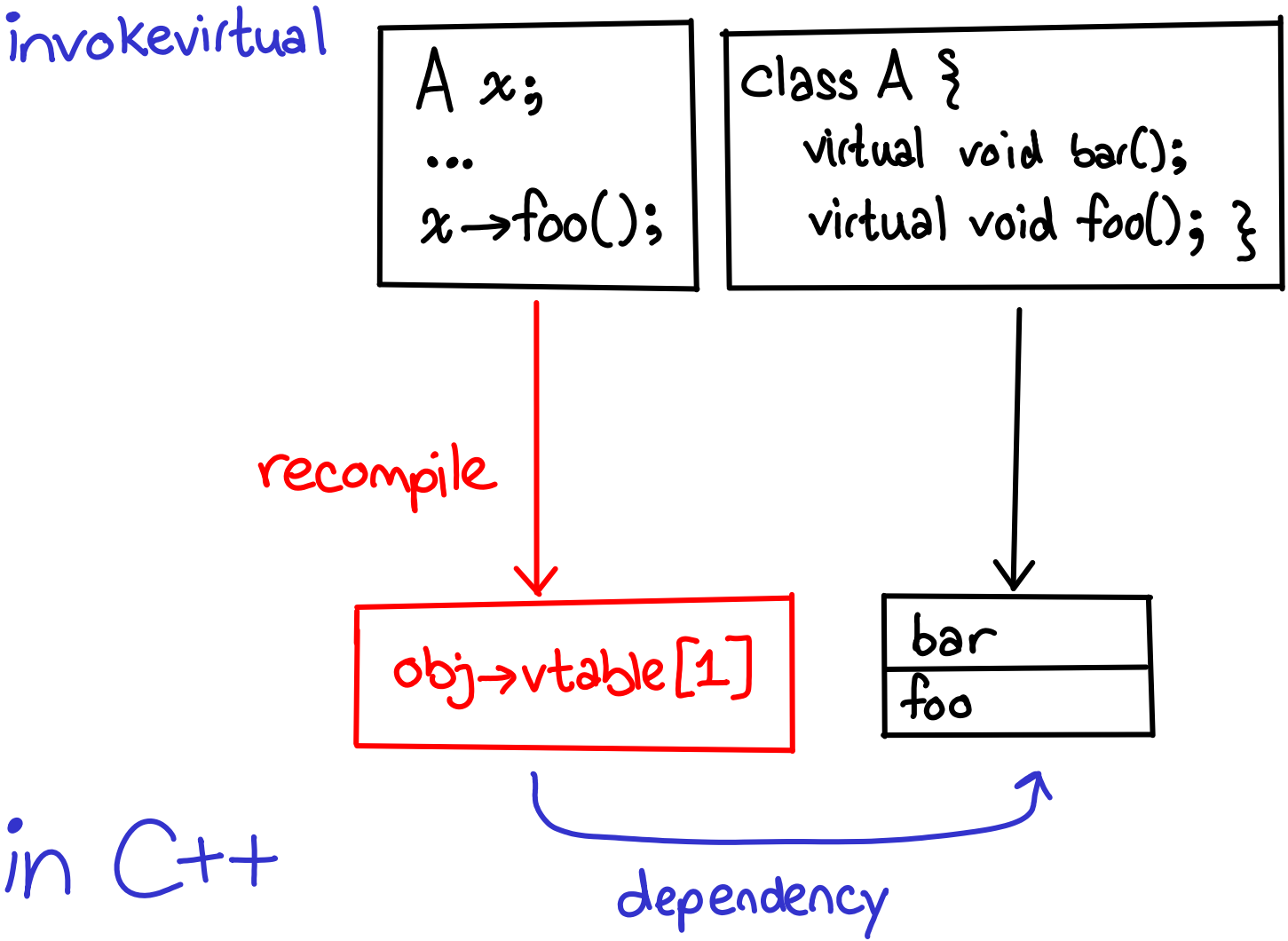


in C++

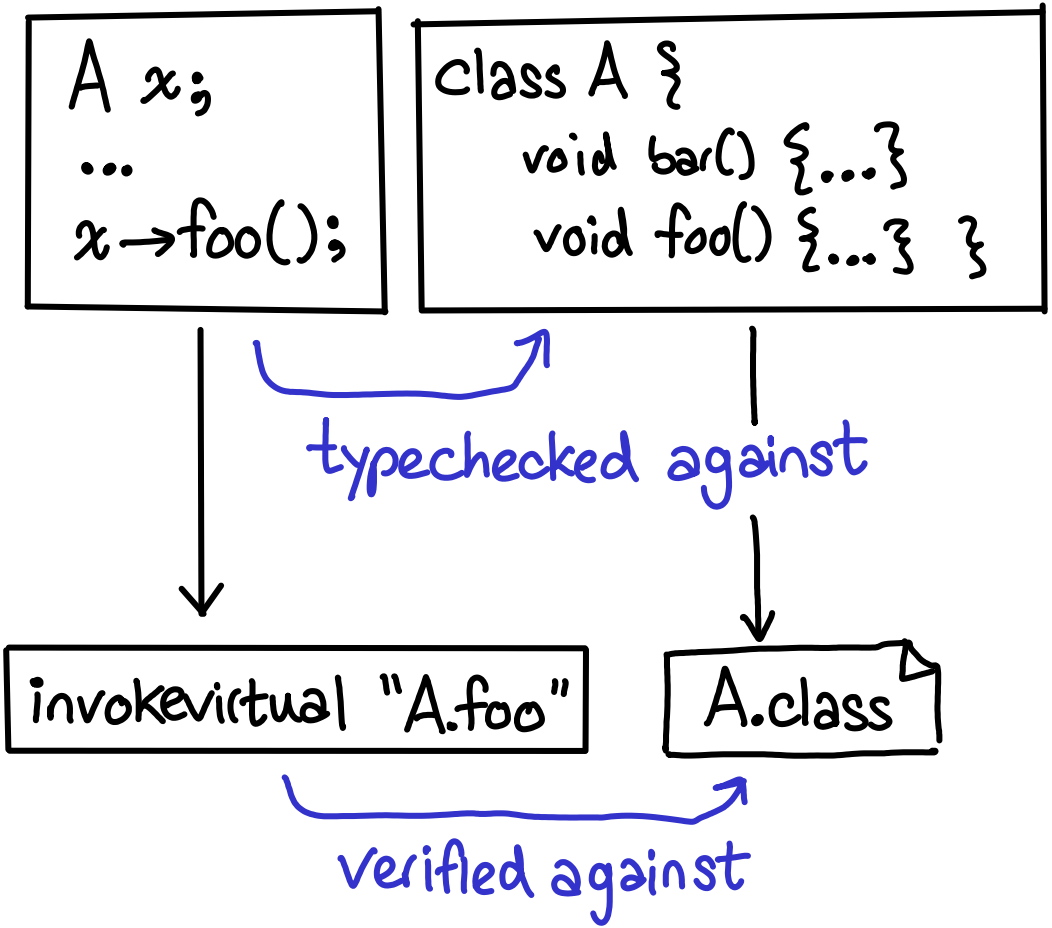
invokevirtual



in C++

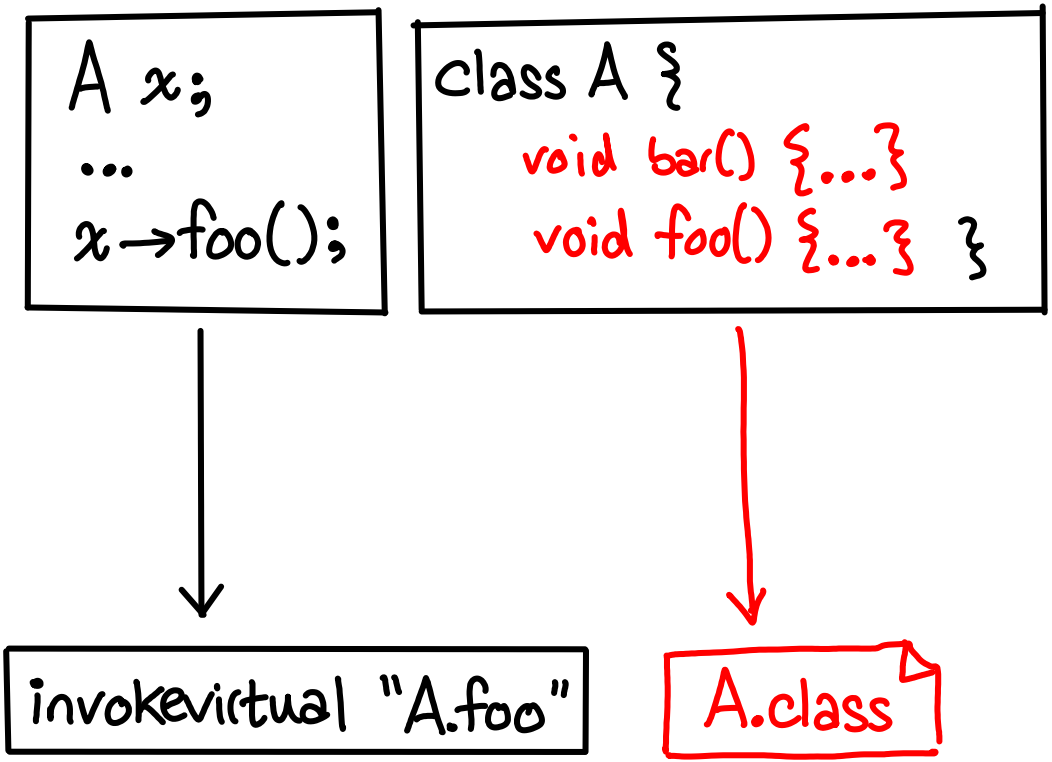

invokevirtual
A x;
...
x->foo();
class A {
virtual void bar();
virtual void foo(); }
recompile
obj->vtable[1]
bar
foo
in C++
dependency

invokevirtual



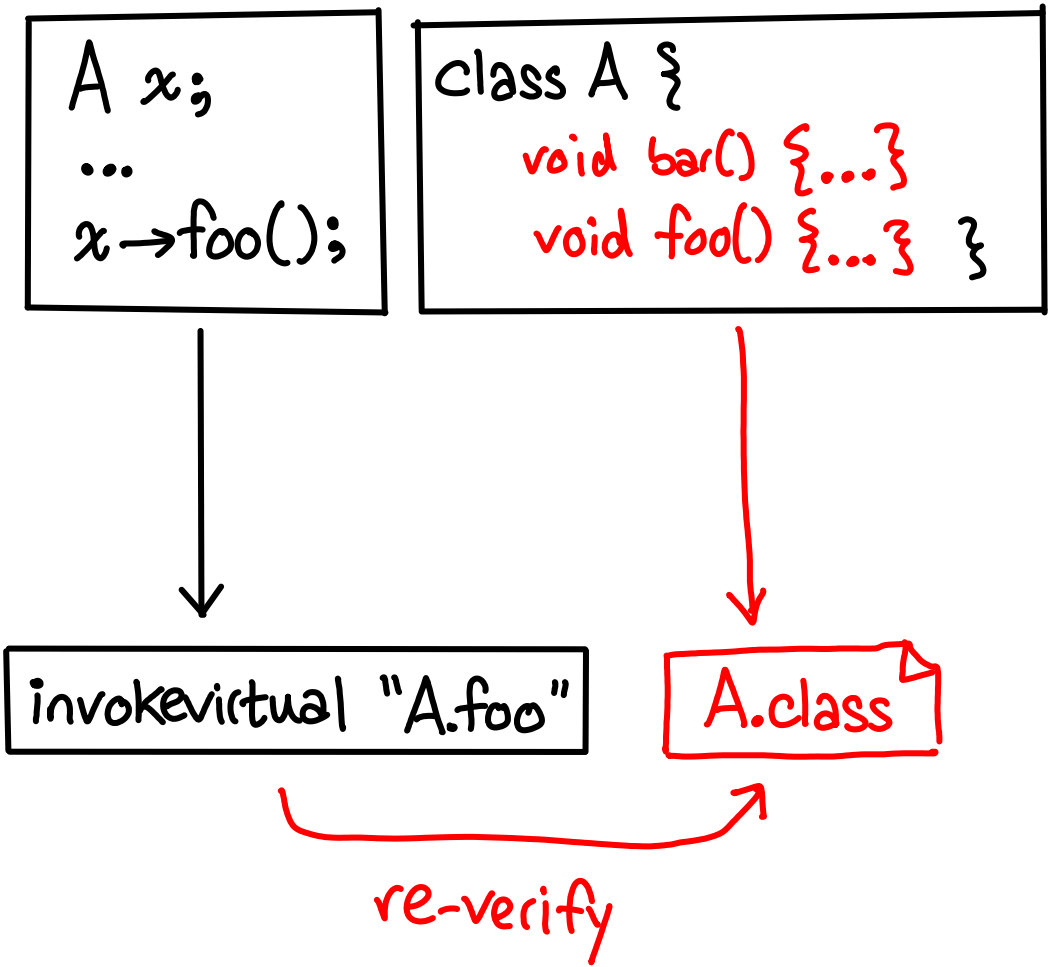
in Java

invokevirtual



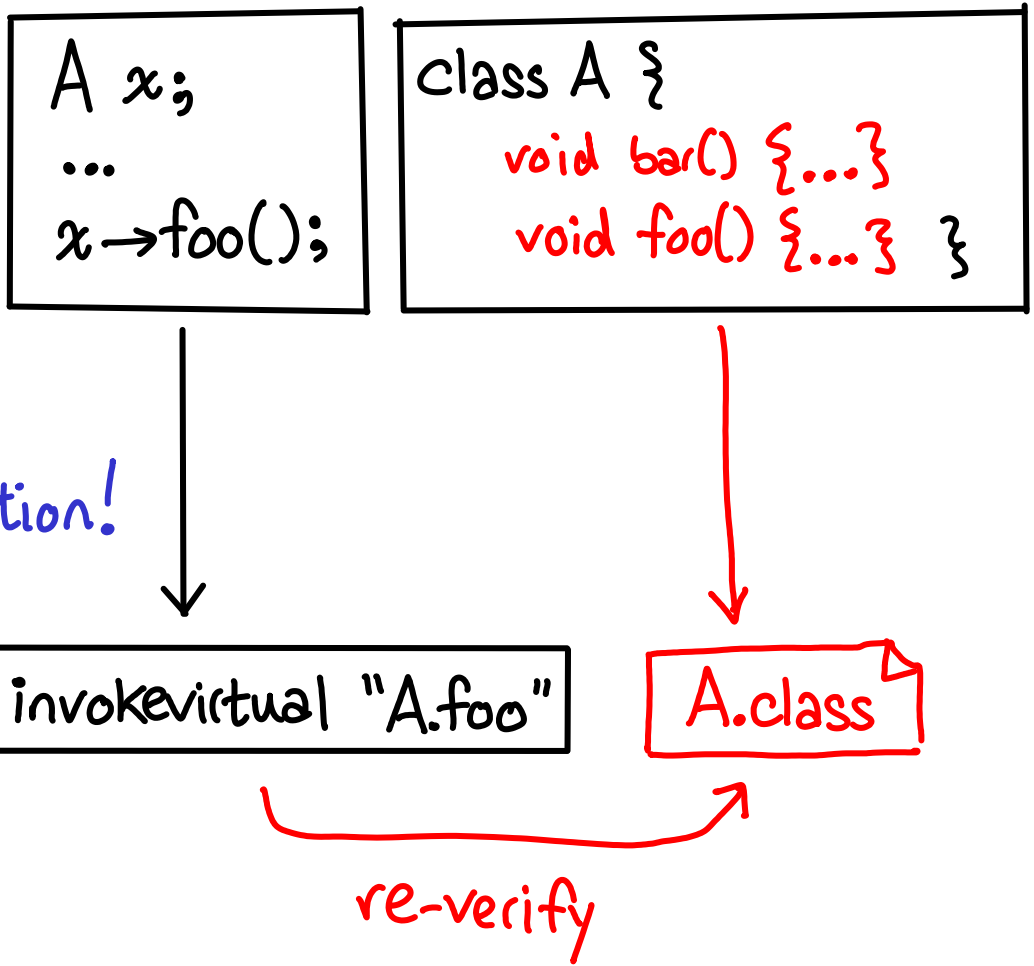
in Java

invokevirtual



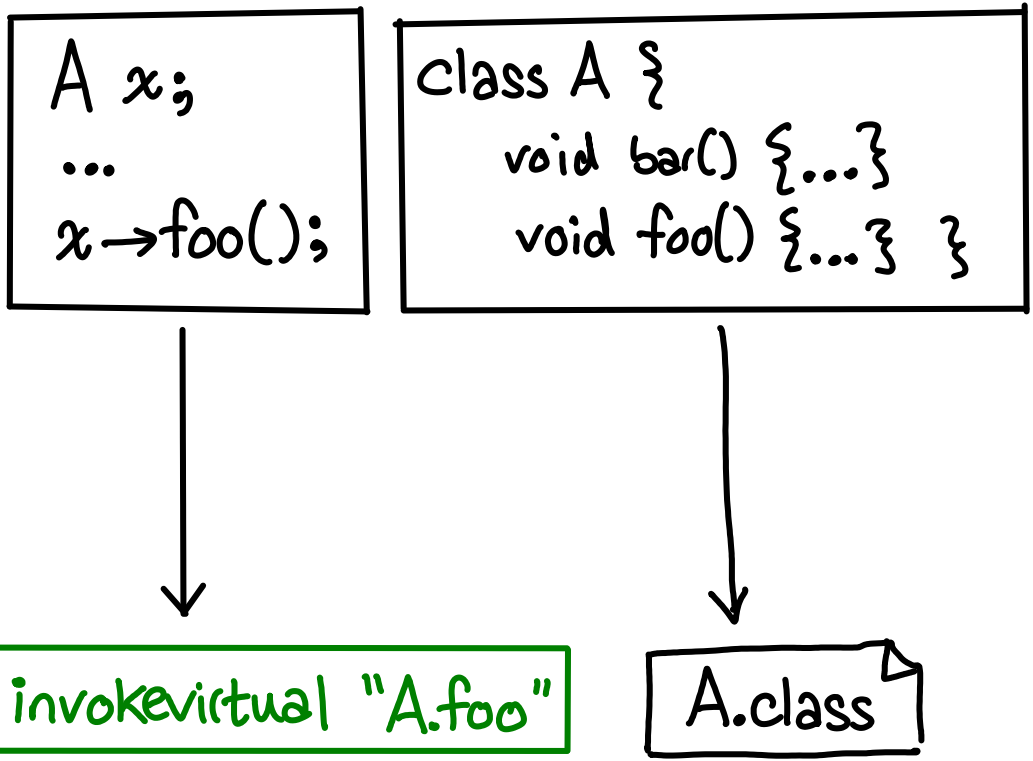
in Java

invokevirtual



in Java

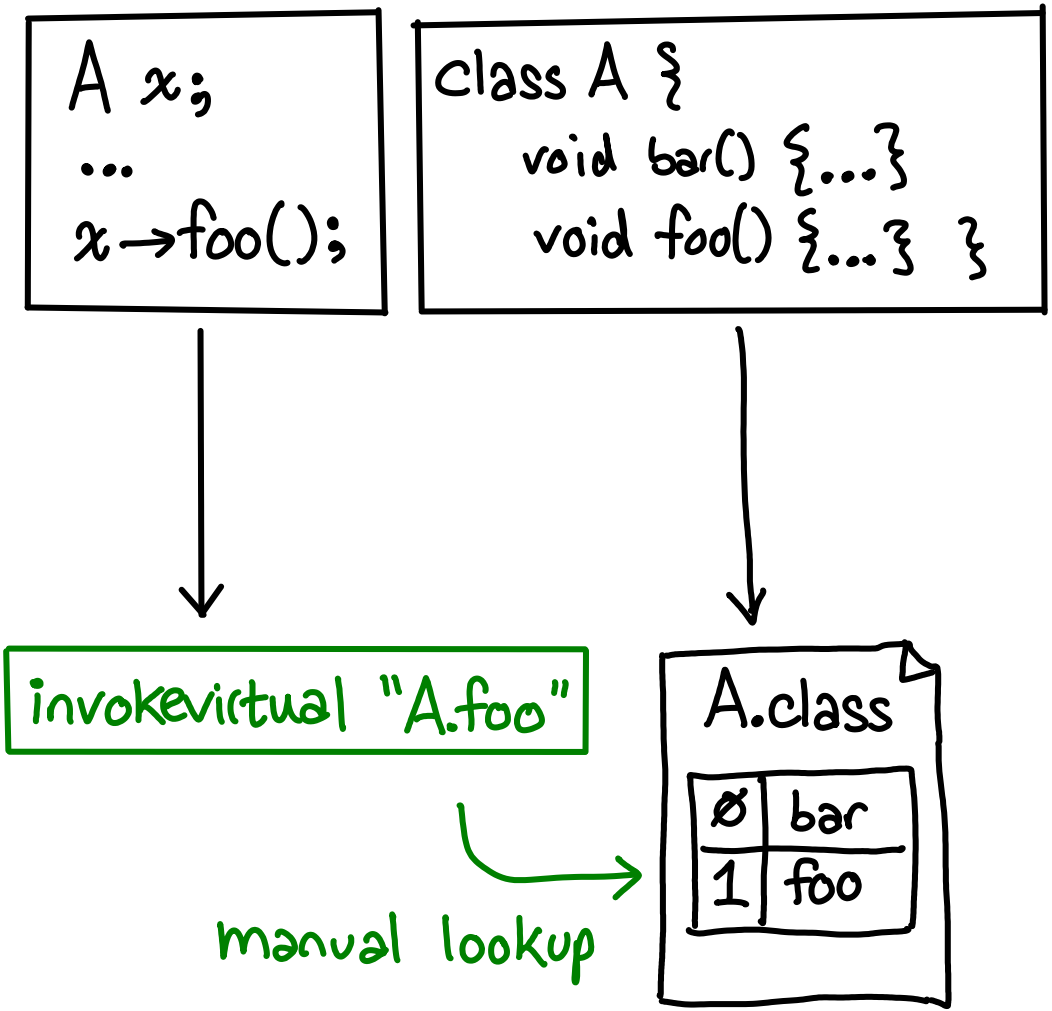
invokevirtual



how do you run this?

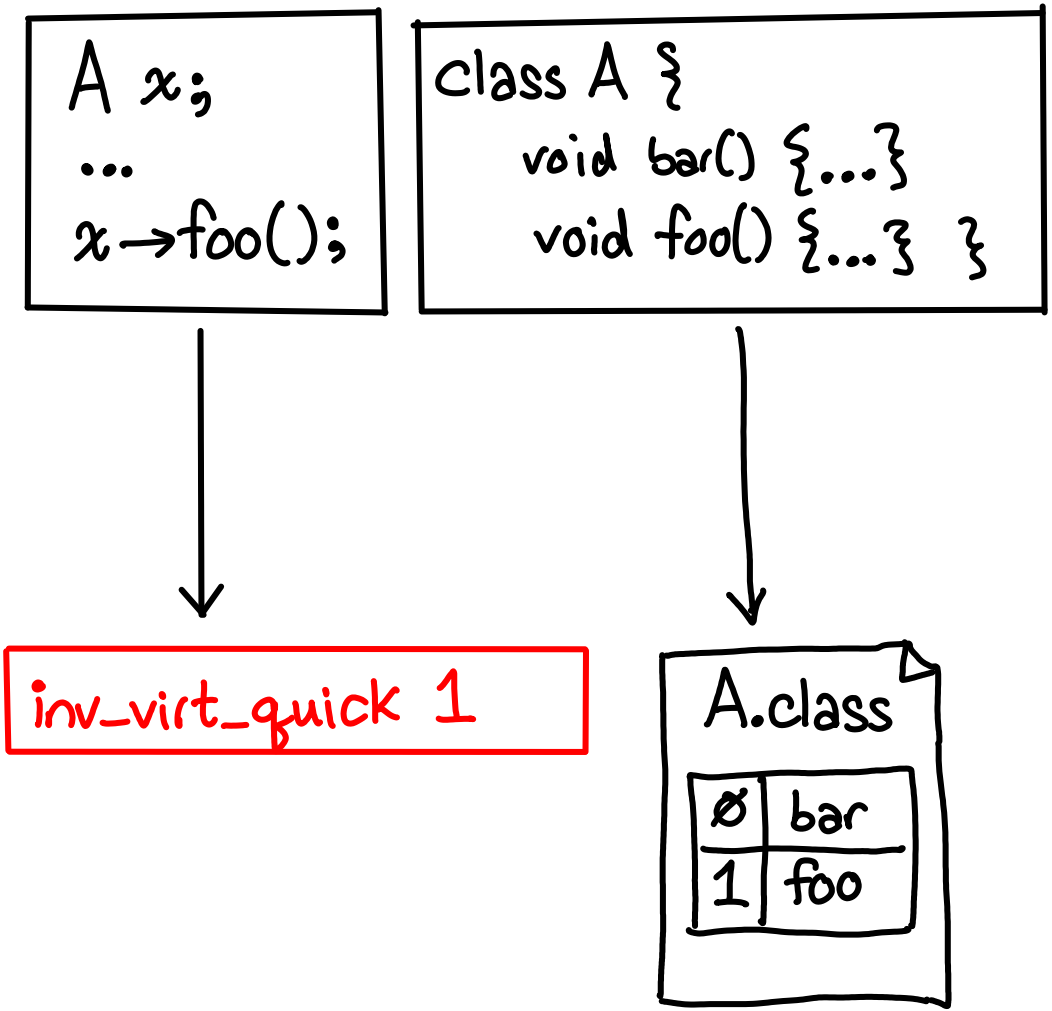
in Java

invokevirtual



in Java

invokevirtual



in Java

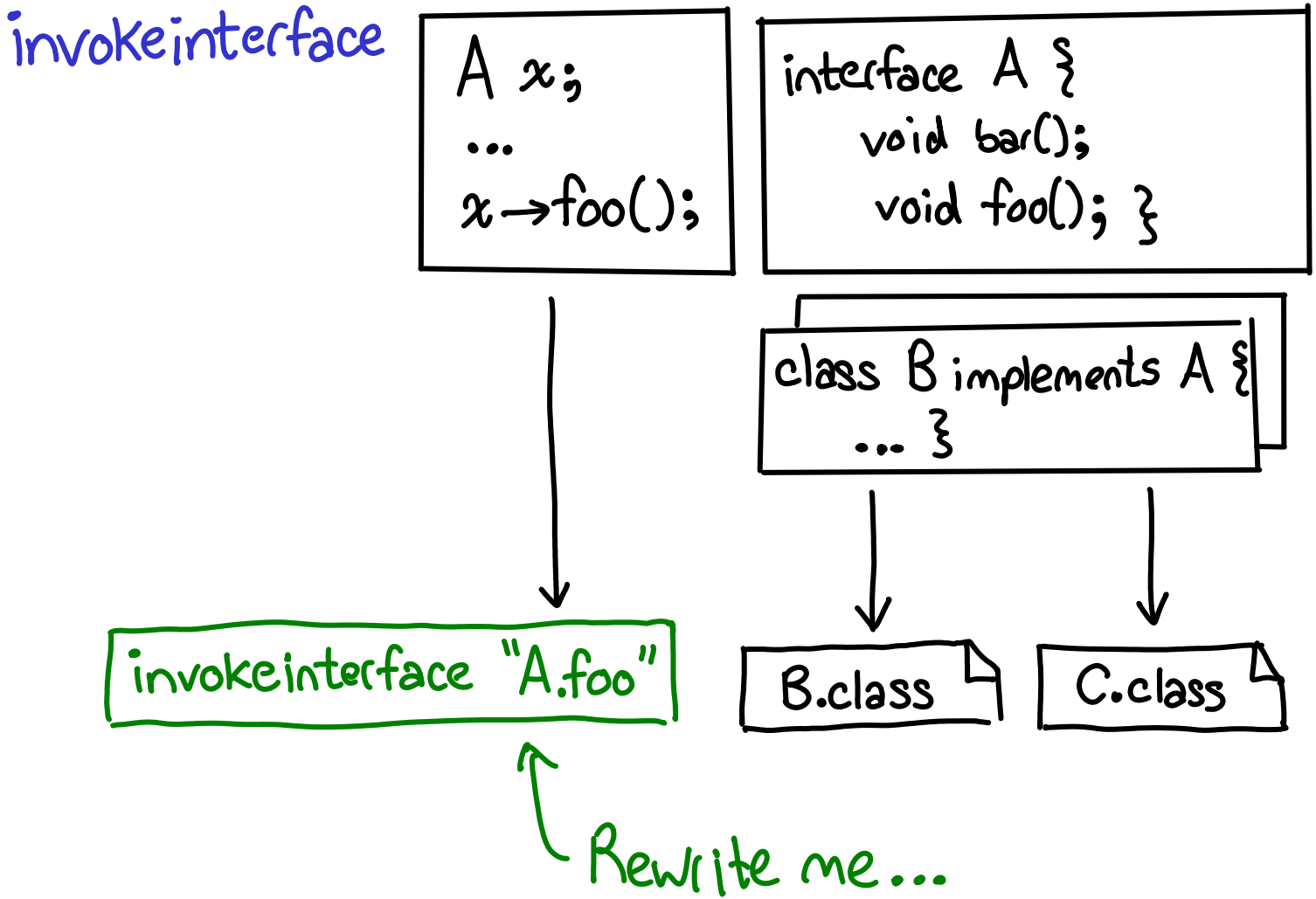
Big Idea #1: Rewrite code to make it more efficient

invokevirtual "A.foo" ⟶ inv_virt_quick 1

⇊

fast, C++-like machine code

What about Interfaces?


invokeinterface
A x;
...
x→foo();
interface A {
void bar();
void foo(); }
class B implements A {
... }
invokeinterface "A.foo"
B.class
C.class
Rewrite me...

invokeinterface

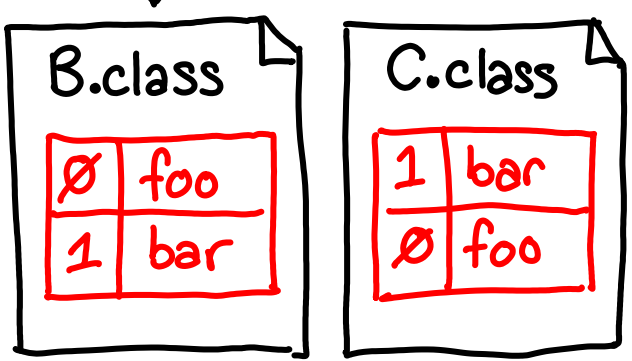
```
A x;
...
x->foo();
```

```
interface A {
    void bar();
    void foo(); }
```

```
class B implements A {
    ... }
```

???

to what?!



invokeinterface

```
A x;
...
x->foo();
```

```
interface A {
    void bar();
    void foo(); }
```

```
class B implements A {
    ... }
```

inv_int_quick "A.foo"

B.class	
0	foo
1	bar

C.class	
1	bar
0	foo

can we pick a specific implementation?

invokeinterface

cache

inv_int_quick "A.foo" <B.foo addr>

```
        if (this.class == B) {
fastpath:   directly invoke <B.foo addr>
        } else {
slowpath:   invoke interface "A.foo"
        }
```

Big Idea #2: A cache lookup can be built into the rewritten code, an inline cache

invokeinterface

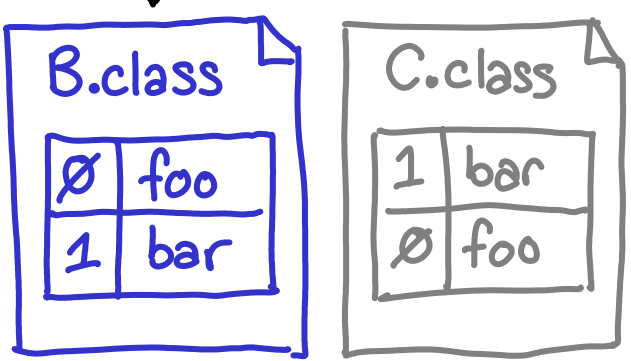
```
A x;
...
x->foo();
```

```
interface A {
    void bar();
    void foo(); }
```

```
class B implements A {
    ... }
```

What if this is the ONLY class loaded which implements A?

(Singleton class)



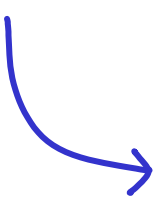
invokeinterface

inv_int_quicker <B.foo addr>

fastpath: directly invoke <B.foo addr>

call on A will always be B,
omit conditional

Corollary: Rewritten code does not have to be fully general, if you invalidate it when necessary.



Class Hierarchy Analysis

invokedynamic

In dynamic languages, usually have <10 distinct underlying types

Big Idea #3: Cache them all!

invokedynamic : Polymorphic Inline Cache

slow: invoke dynamic lookup handler

invokedynamic : Polymorphic Inline Cache

```
        if (this.class ==A) {
            directly invoke <A handler>
        } else {
slow:       invoke dynamic lookup handler
        }
```

invokedynamic : Polymorphic Inline Cache

```
        if (this.class == A) {
            directly invoke <A handler>
        if (this.class == B) {
            directly invoke <B handler>
        } else {
slow:       invoke dynamic lookup handler
        }
```

invokedynamic : Polymorphic Inline Cache

```
if (this.class == A) {
    directly invoke <A handler>
if (this.class == B) {
    directly invoke <B handler>
if (this.class == C) {
    directly invoke <C handler>
} else {
slow:   invoke dynamic lookup handler
}
```

invokedynamic : Polymorphic Inline Cache

```
if (this.class == A) {
    directly invoke <A handler>
if (this.class == B) {
    directly invoke <B handler>
if (this.class == C) {
    directly invoke <C handler>
} else {
slow:   invoke dynamic lookup handler
}
```

order by freq.

invokedynamic : Polymorphic Inline Cache

orlginated in Self

dynamically typed OOP language

PICs $\longmapsto$ 37% perf improvement

Summary:

JIT codegen = Flexibility

allows Java/JavaScript engines to avoid paying too much for indirection

(end)