Retrofitting a Concurrent GC onto OCaml

KC Sivaramakrishnan

University of Cambridge

OCaml Labs

OCaml

industrial-strength, pragmatic, functional programming language

- Functional core with imperative and object-oriented features
- Native (x86, ARM, …), JavaScript, JVM

Hindley-Milner Type Inference

Powerful module system

Facebook: REASON Infer flow Hack PYRE

Microsoft: Project Everest

Jane Street

The Coq Proof Assistant

MIRAGE OS

OCaml

industrial-strength, pragmatic, functional programming language

No multicore support!

- Native (x86, ARM, …), JavaScript, JVM

Facebook: REASON Infer flow Hack

Microsoft: Project Everest

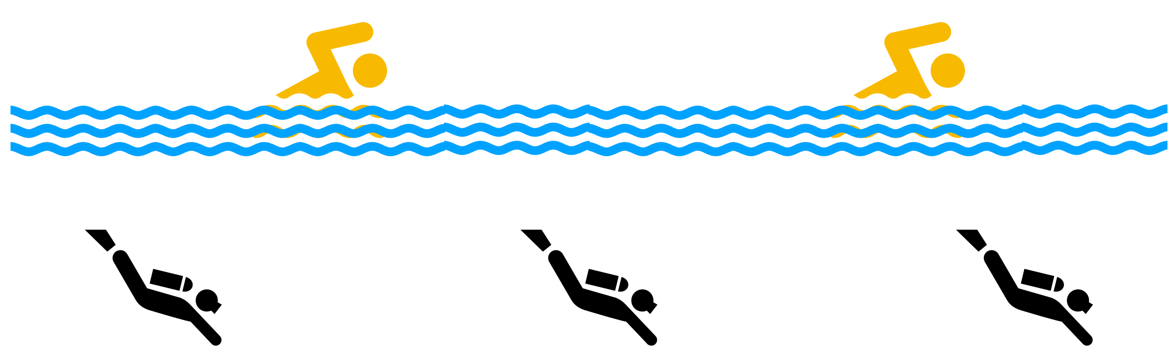
Jane Street

The Coq Proof Assistant

MIRAGE OS

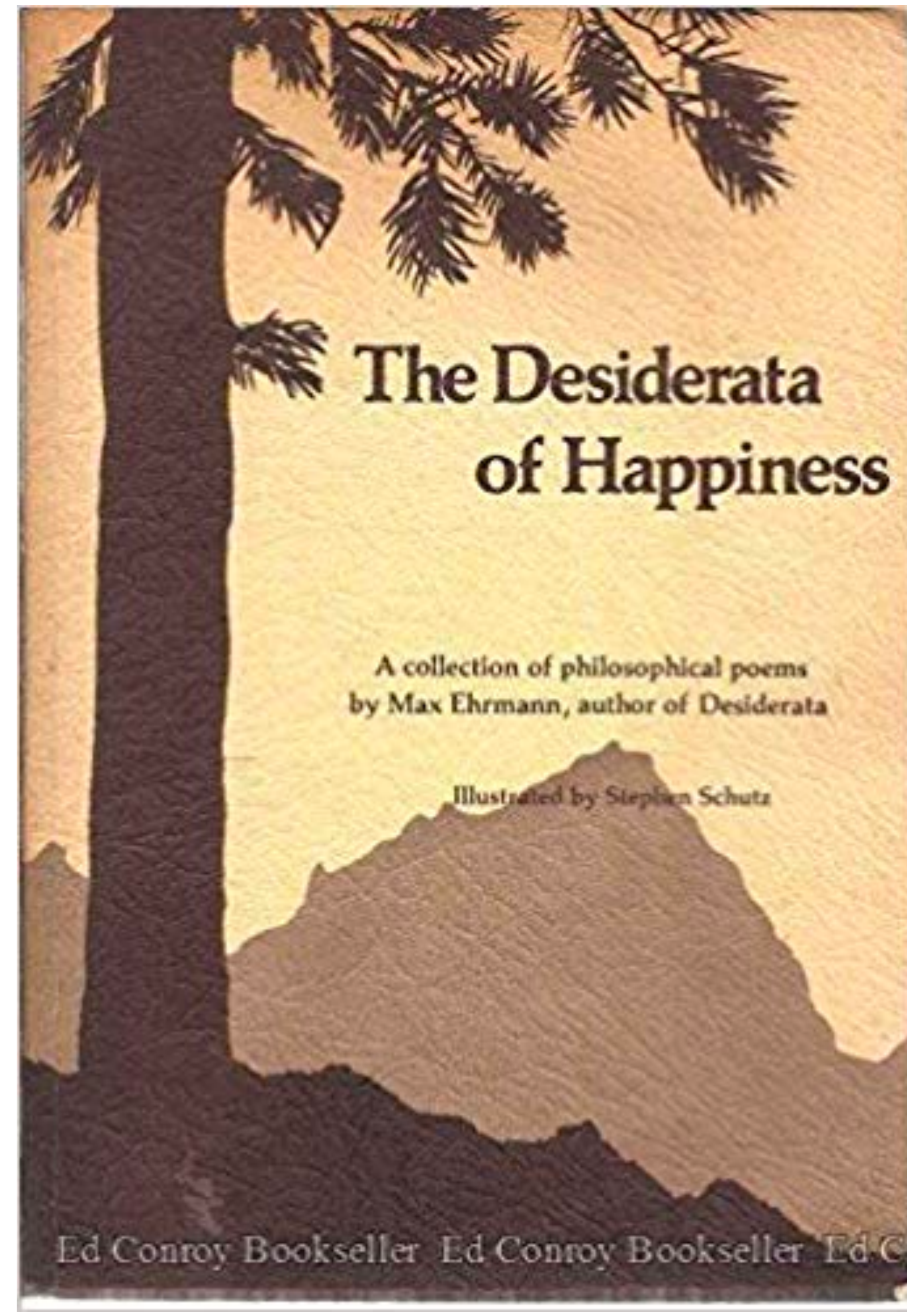
Multicore OCaml

- Native support for *concurrency* and *parallelism* in OCaml
- Lead from OCaml Labs, University of Cambridge
  - Collaborators Stephen Dolan (OCaml Labs), Leo White (Jane Street)
- Expected to hit mainline in late 2019
- In this talk,
  - Overview of Multicore GC, with a few deep dives



Multicore OCaml GC: Desiderata

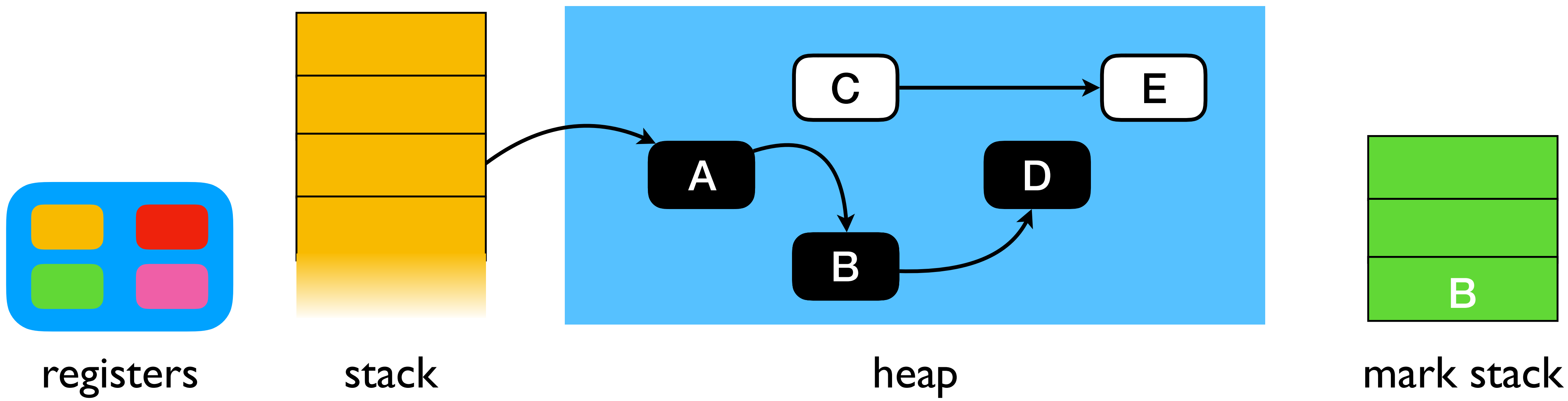
- *Code backwards compatibility*
  - ✦ Do not break existing code
- *Performance backwards compatibility*
  - ✦ Do not slow down existing programs
- *Minimise pause times*
  - ✦ Latency is more important than throughput
- *Performance predictability and stability*
  - ✦ Slow and stable better than fast but unpredictable
- *Minimize knobs*
  - ✦ 90% of programs should run at 90% peak performance by default



Outline

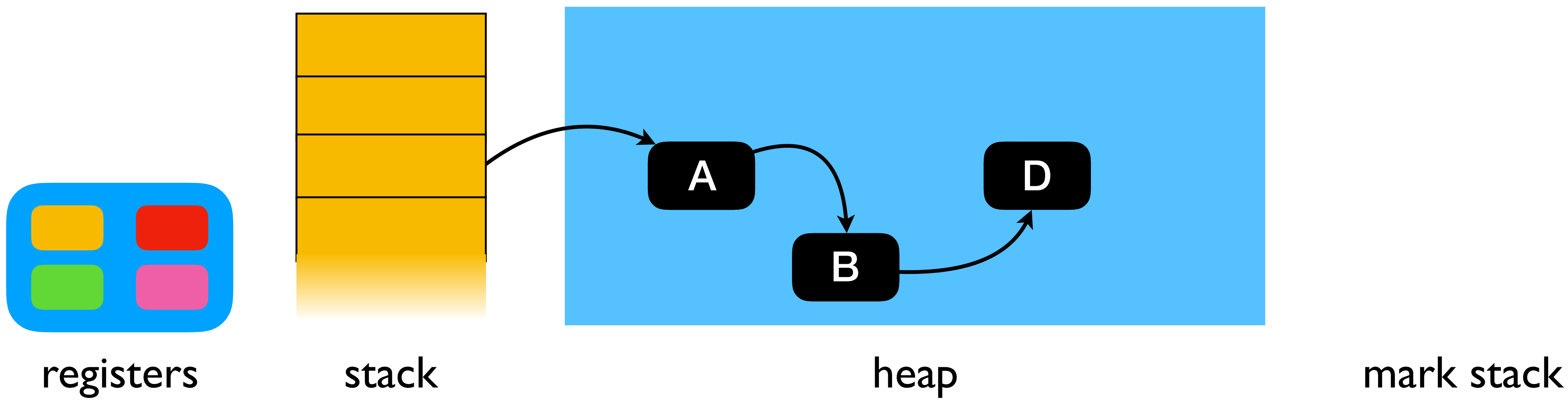
- Difficult to appreciate GC choices in isolation
- Begin with a GC for a *sequential purely functional* language
    - ✦ Gradually add mutations, parallelism and concurrency

Sequential purely functional



- Stop-the-world mark and sweep
- Tri-color marking
  - ✦ States: White (Unmarked), Grey (Marking), Black (Marked)
- White —> Grey (mark stack) —> Black
- Mark stack is empty => *done marking*
  - ✦ Tri-color invariant: *No black object points to a white object*
- Sweeping : walk the heap and free white objects

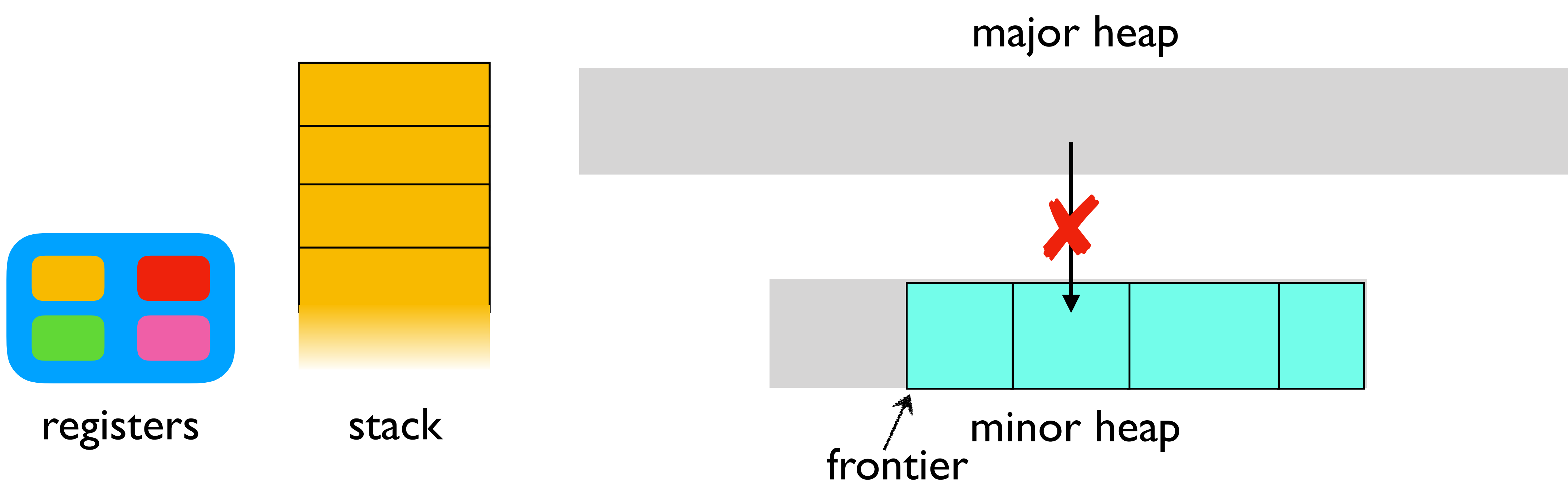
Sequential purely functional



- Pros
  - Simple
  - Can perform the GC incrementally
    - `...|--mutator--|--mark--|--mutator--|--mark--|--mutator--|--sweep--|...`
- Cons
  - Need to maintain free-list of objects => allocations overheads + fragmentation

Generational GC

- Generational Hypothesis
  - ✦ Young objects are much more likely to die than old objects



- Minor heap collected by copying collection
  - ✦ Survivors promoted to major heap
  - ✦ Only touches live objects (typically, < 10% of total)
- Roots are registers and stack
  - ✦ purely functional => no pointers from major to minor

Mutations

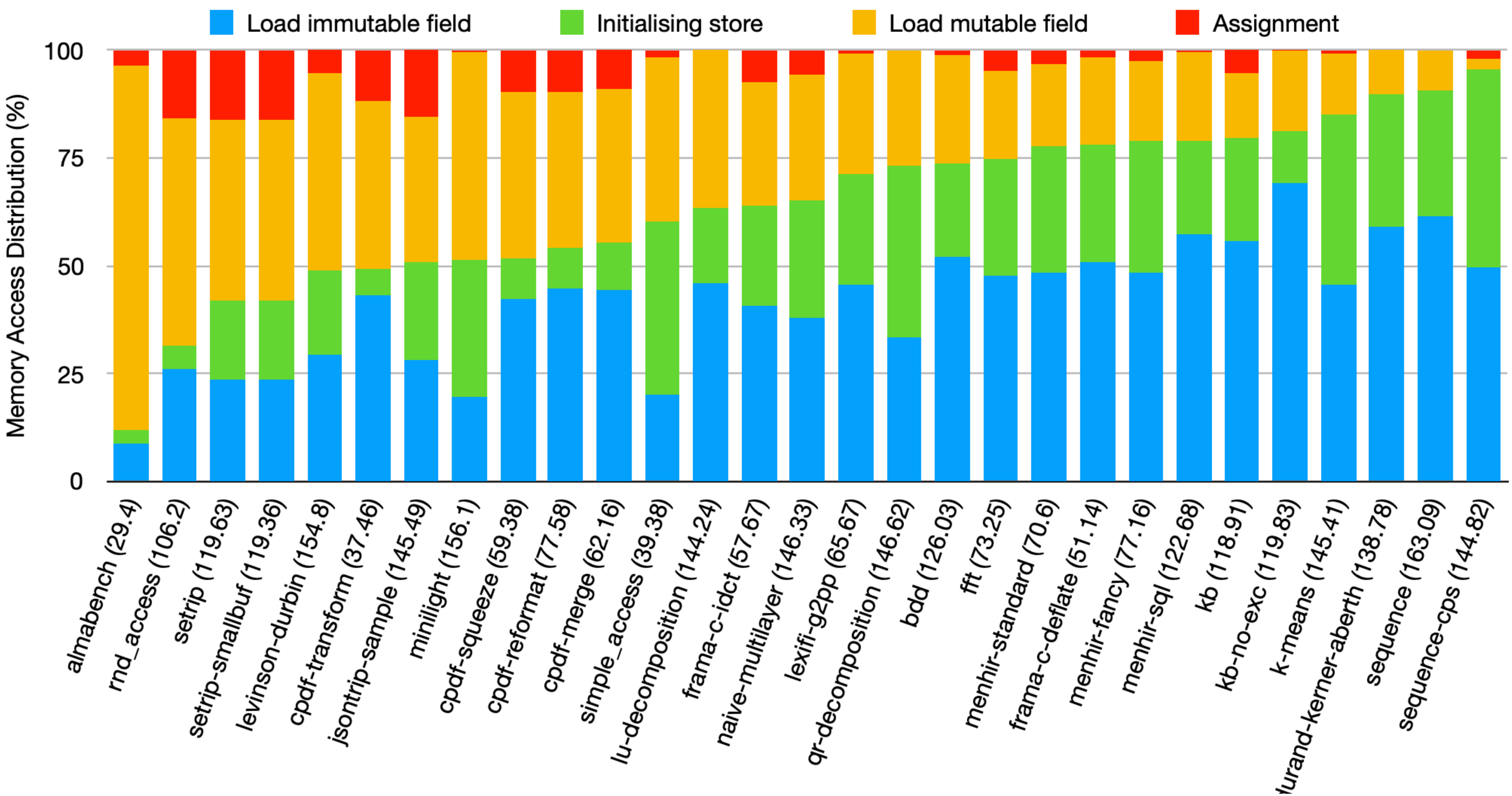
- OCaml does not prohibit mutations
  - ✦ Mutable references, Arrays…
- *Encourages it with syntactic support!*

```
type client_info =
  { addr: Unix.inet_addr;
    port: int;
    user: string;
    credentials: string;
    mutable last_heartbeat_time: Time.t;
    mutable last_heartbeat_status: string;
  }
```

```
let handle_heartbeat cinfo time status =
  cinfo.last_heartbeat_time <- time;
  cinfo.last_heartbeat_status <- status
```

  - ✦ Mutations are pervasive in real-world code

Mutations



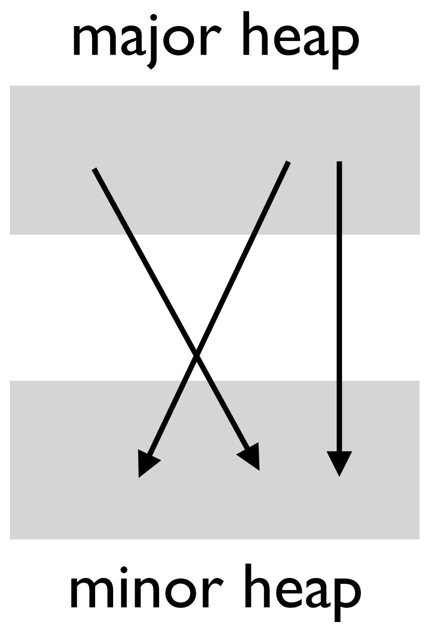
less functional **more functional**

Mutations — Minor GC

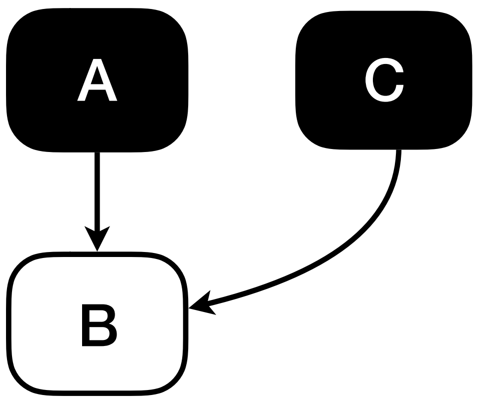
- Old objects might point to young objects
- Must know those pointers for minor GC
  - ✦ (Naively) scan the major GC for such pointers
- Intercept mutations with write barrier

```
(* Before r := x *)
let write_barrier (r, x) =
  if is_major r && is_minor x then
    remembered_set.add r
```

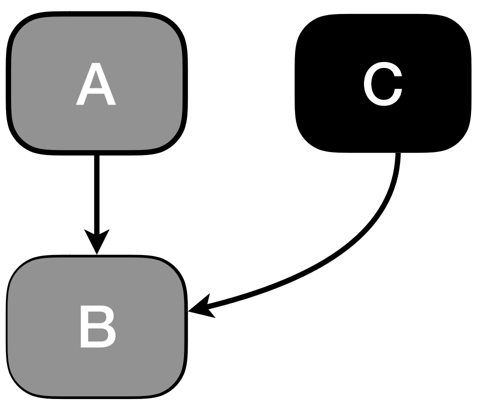
- *Remembered set*
  - ✦ Set of major heap addresses that point to minor heap
  - ✦ Used as root for minor collection
  - ✦ Cleared after minor collection.



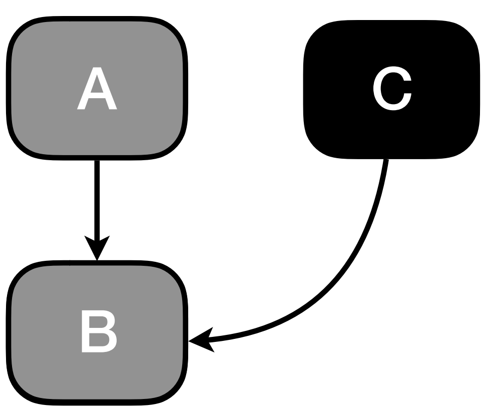
Mutations — Major GC



- Mutations are problematic if both conditions hold
  1. Exists Black —> White
  2. All Grey —> White* —> White paths are deleted



- Insertion/Dijkstra/Incremental barrier prevents 1

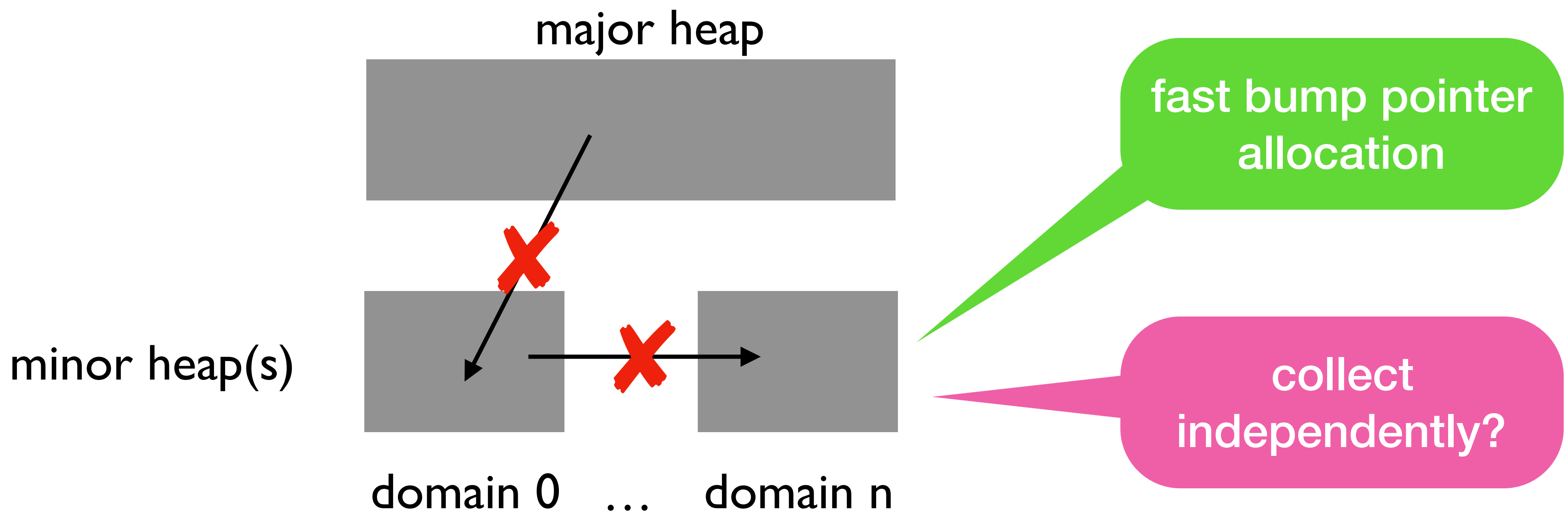


- Deletion/Yuasa/snapshot-at-beginning prevents 2

```
(* Before r := x *)
let write_barrier (r, x) =
  if is_major r && is_minor x then
    remembered_set.add r
  else if is_major r && is_major x then
    mark(!r)
```

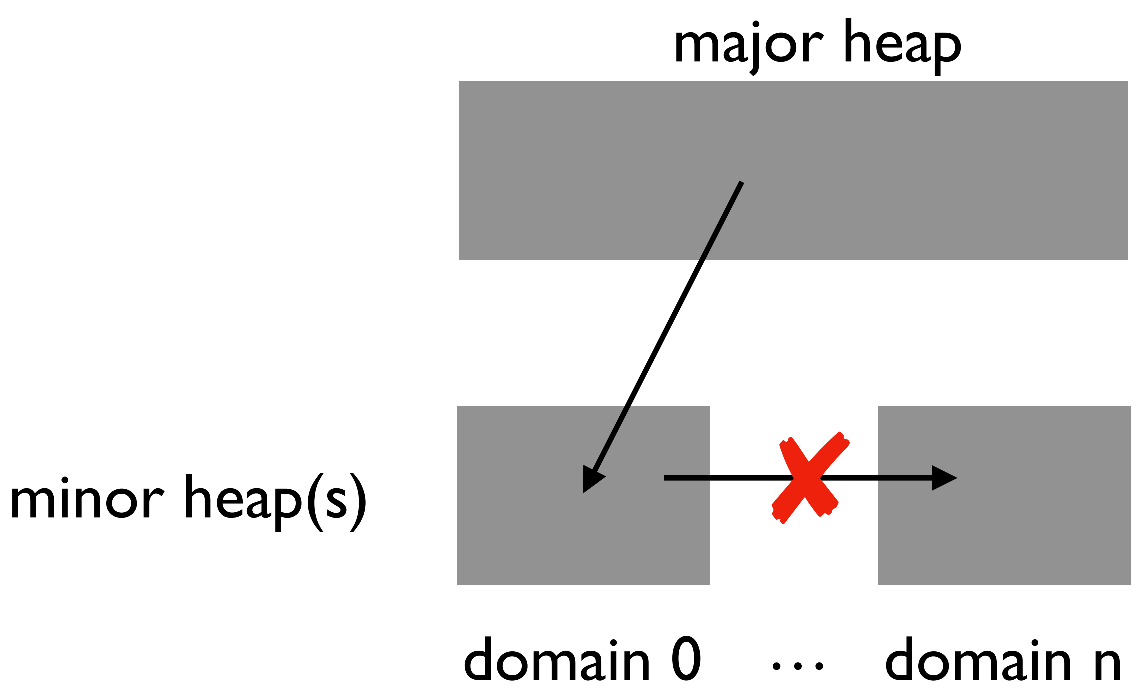
Parallelism — Minor GC

- `Domain.spawn : (unit -> unit) -> unit`



- Invariant: Minor heap objects are only accessed by owning domain
- Doligez-Leroy POPL'93
  - ✦ No pointers between minor heaps
  - ✦ No pointers from major to minor heaps
- Before r := x, if is_major(r) && is_minor(x), then promote(x).
- *Too much promotion.* Ex: work-stealing queue

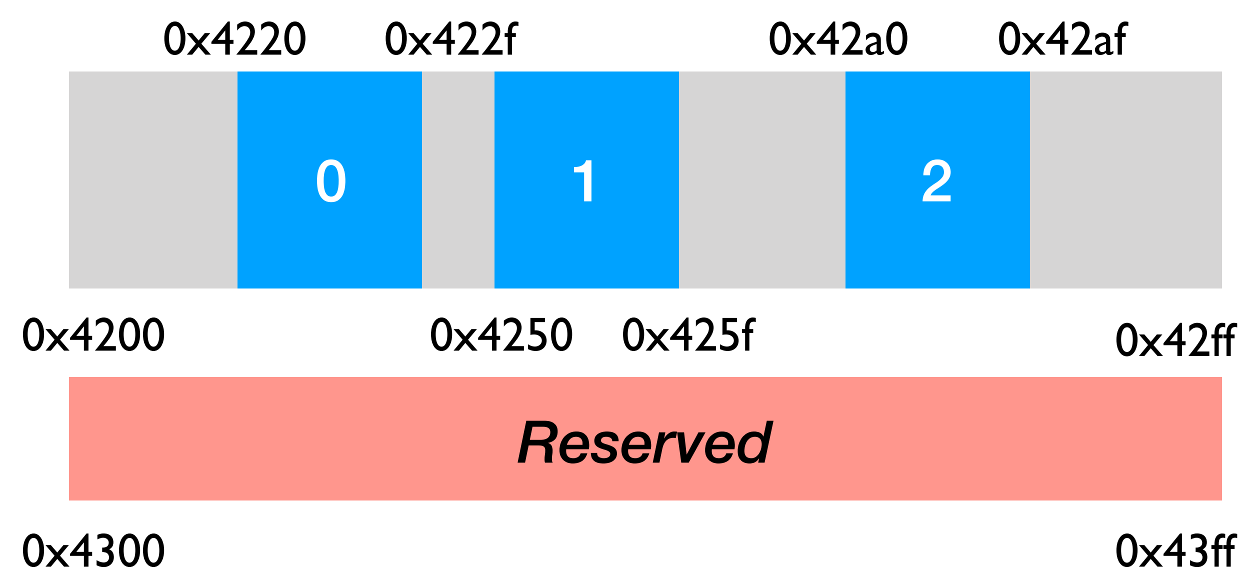
Parallelism — Minor GC



- Weaker invariant
  - ✦ No pointers between minor heaps
  - ✦ *Objects in foreign minor heap are not accessed directly*
- Read barrier. If the value loaded is
  - ✦ integers, object in shared heap or own minor heap => continue
  - ✦ object in foreign minor heap => *Read fault (Interrupt + promote)*

Efficient read barrier check

- Given x, is x an integer[1] or in shared heap[2] or own minor heap[3]
- *Careful VM mapping + bit-twiddling*
- Example: 16-bit address space, `0xPQRS`
  - `Minor area: 0x4200 – 0x42ff`
  - `Domain 0  : 0x4220 – 0x422f`
  - `Domain 1  : 0x4250 – 0x425f`
  - `Domain 2  : 0x42a0 – 0x42af`
  - `Reserved  : 0x4300 – 0x43ff`



- Integer lsb(S) = `0x1`, Minor PQ = `0x42`, R determines domain
- Compare with *template* y, where y lies within minor heap
  - *allocation pointer!*
  - On amd64, allocation pointer is in `r15` register

Efficient read barrier check

```
# %rax holds x (value of interest)
xor %r15, %rax
sub 0x0010, %rax
test 0xff01, %rax
# ZF set => foreign minor
```

Integer

```
# lsb(%rax) = 1
xor %r15, %rax
# lsb(%rax) = 1
sub 0x0010, %rax
# lsb(%rax) = 1
test 0xff01, %rax
# ZF not set
```

Shared heap

```
# PQ(%r15) != PQ(%rax)
xor %r15, %rax
# PQ(%rax) > 1
sub 0x0010, %rax
# PQ(%rax) is non-zero
test 0xff01, %rax
# ZF not set
```

Efficient read barrier check

```
# %rax holds x (value of interest)
xor %r15, %rax
sub 0x0010, %rax
test 0xff01, %rax
# ZF set => foreign minor
```

Own minor heap

```
# PQR(%r15) = PQR(%rax)
xor %r15, %rax
# PQR(%rax) is zero
sub 0x0010, %rax
# PQ(%rax) is non-zero
test 0xff01, %rax
# ZF not set
```

Foreign minor heap

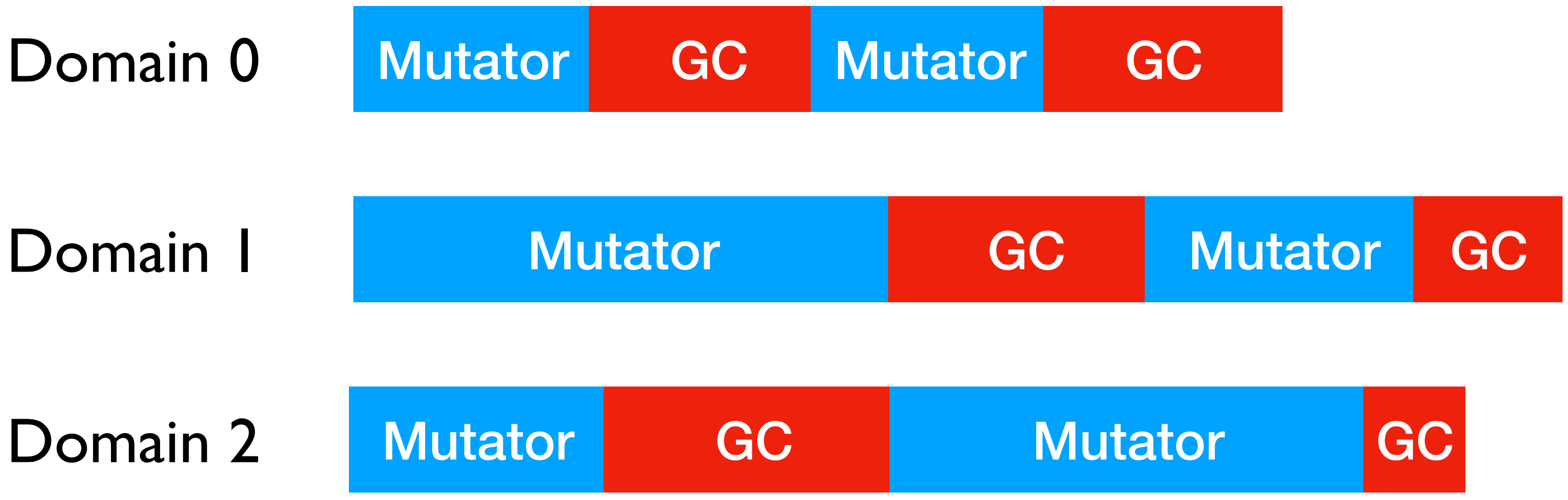
```
# PQ(%r15) = PQ(%rax)
# R(%r15) != R(%rax)
# lsb(%r15) = lsb(%rax) = 0
xor %r15, %rax
# R(%rax) is non-zero
# PQ(%rax) = lsb(%rax) = 0
sub 0x0010, %rax
# PQ(%rax) = lsb(%rax) = 0
test 0xff01, %rax
# ZF set
```

Read fault

Parallelism — Major GC

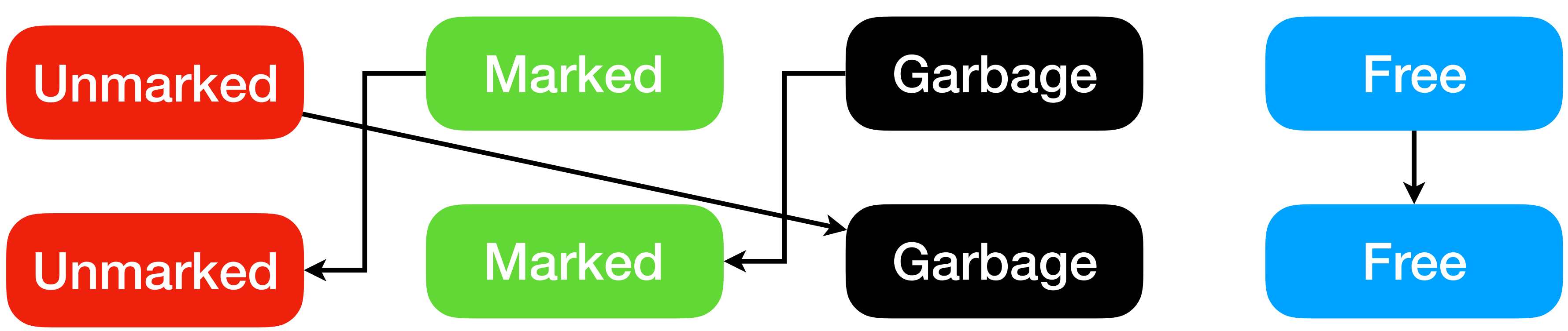
- OCaml's GC is *incremental*

- Multicore OCaml's GC needs to be *concurrent* *(and incremental)*
  - ✦ *Parallel collectors have high latency budget*



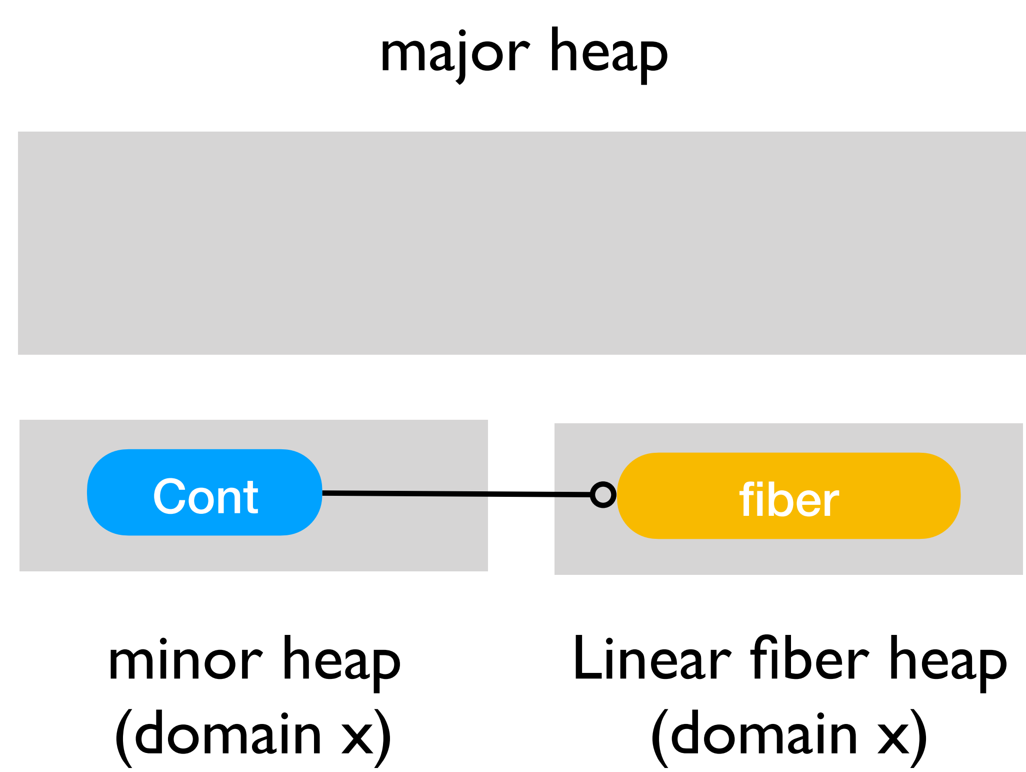
Parallelism — Major GC

- Design based on VCGC from Inferno project (ISMM’98)
  - ✦ Allows mutator, marker, sweeper threads to concurrently
- In Multicore OCaml,
  - ✦ States Unmarked Marked Garbage Free
  - ✦ Domains alternate between mutator and gc thread
  - ✦ Marking: Unmarked → Marked Sweeping: Garbage → Free
  - ✦ Marking is *racy* but *idempotent*
- Marking & Sweeping done ⇒ stop-the-world



Concurrency

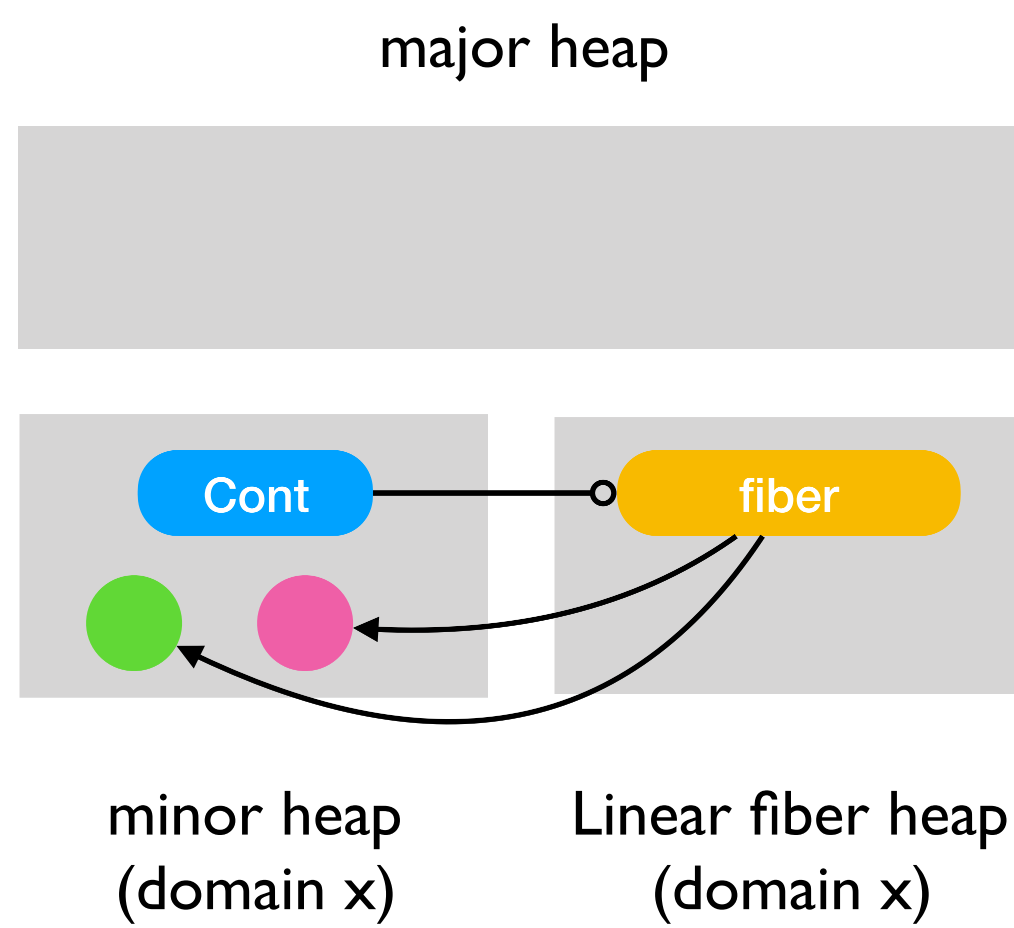
- Fibers: vm-threads, *linear* delimited continuations
- Stack segments managed on the heap



- Every fiber has a *unique* reference from a continuation object
  - ✦ *Fibers freed when continuations are swept*
- *No write barriers on fiber stack operations (push & pop)*

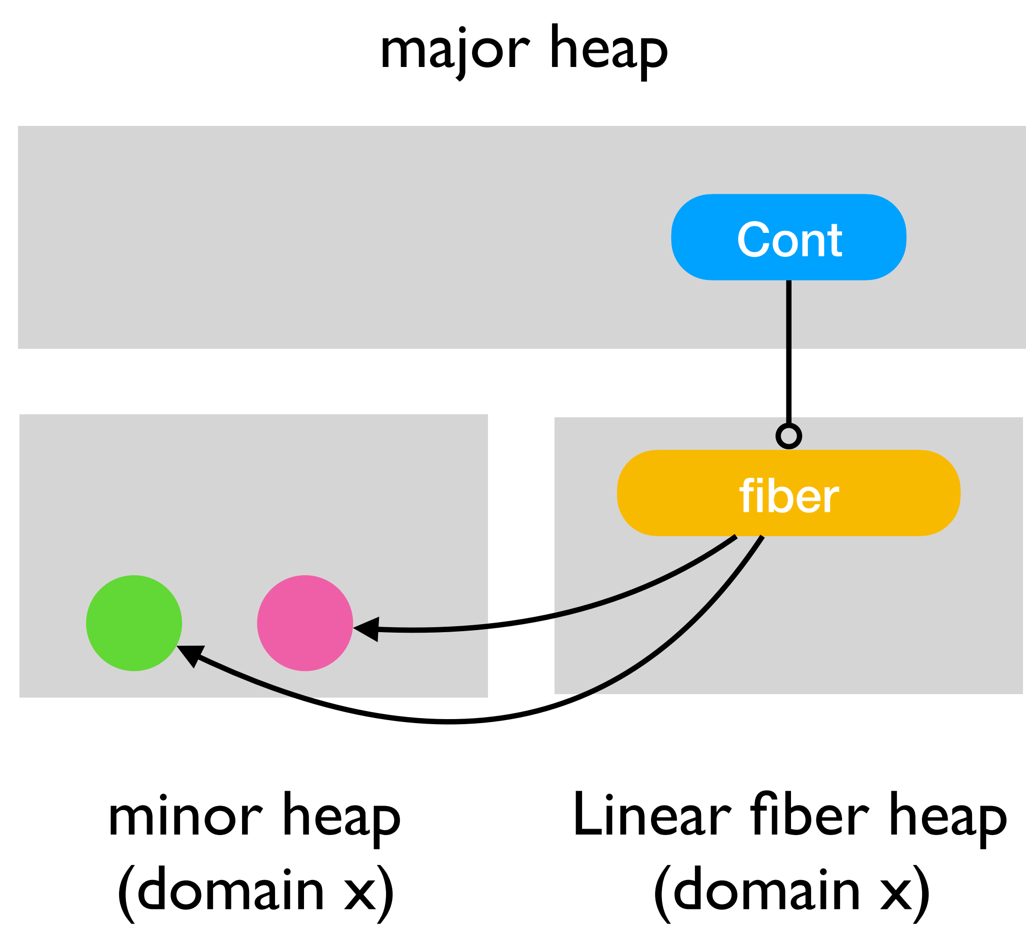
Concurrency — Minor GC

- Fibers may point to minor heap objects
  - ✦ *which fibers to scan among 1000s? (no write barriers on fiber stacks)*
- Fresh continuation object for every fiber suspension
  - ✦ *Continuation in minor heap => fiber suspended in current minor cycle*



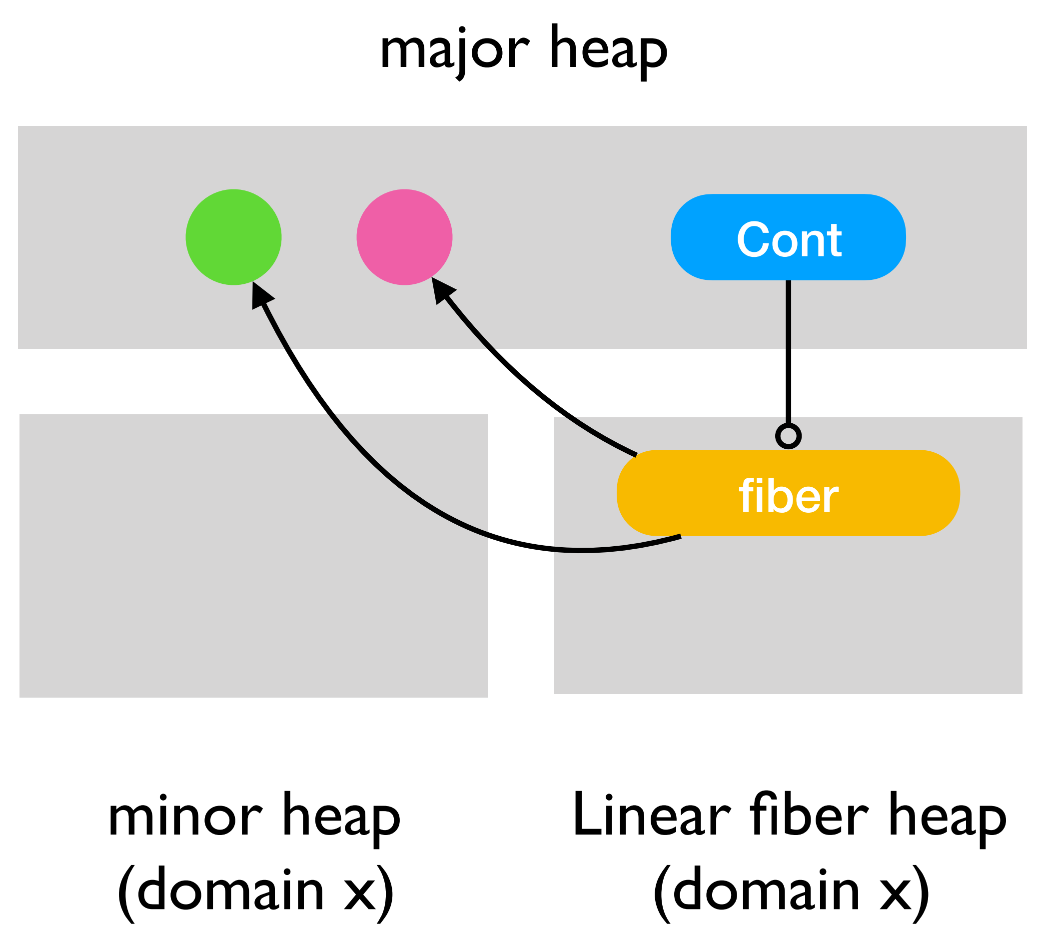
Concurrency — Minor GC

- Fibers may point to minor heap objects
  - *which fibers to scan among 1000s? (no write barriers on fiber stacks)*
- Fresh continuation object for every fiber suspension
  - *Continuation in minor heap => fiber suspended in current minor cycle*



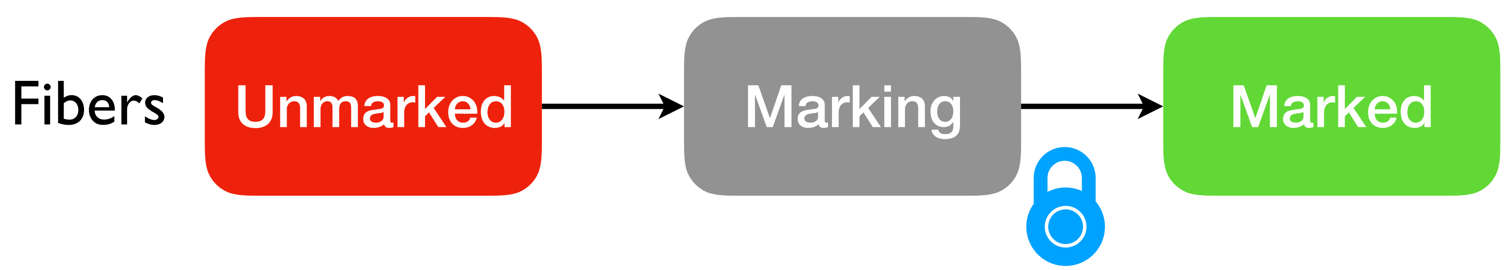
Concurrency — Minor GC

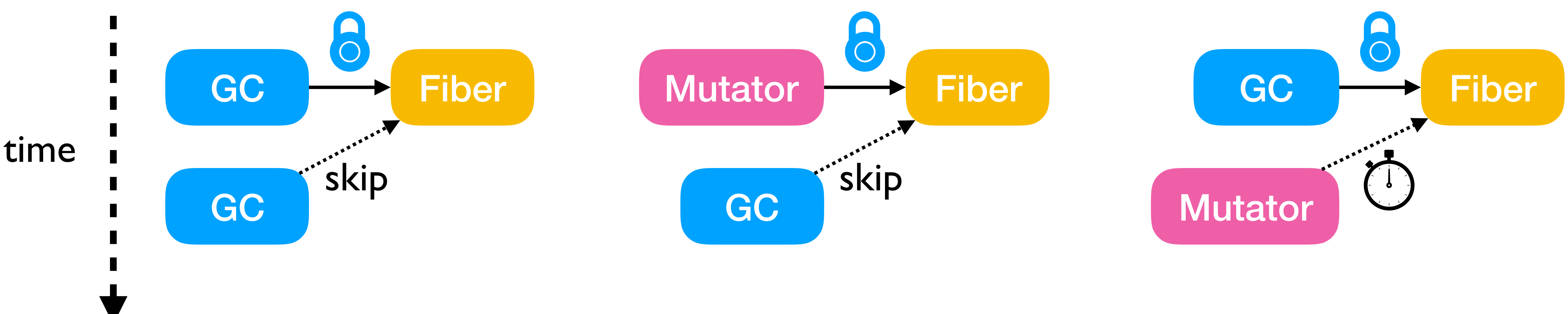
- Fibers may point to minor heap objects
  - *which fibers to scan among 1000s? (no write barriers on fiber stacks)*
- Fresh continuation object for every fiber suspension
  - *Continuation in minor heap => fiber suspended in current minor cycle*



Concurrency — Major GC

- (Multicore) OCaml uses deletion barrier
  - ✦ Fiber stack pop is a deletion *(but no write barrier)*
- Before switching to unmarked fiber, *complete* marking the fiber
- Marking is racy
  - ✦ *For fibers, race between mutator (context switch) and gc (marking) unsafe*





Performance

- Serial performance
  - ✦ Multicore benchmarking CI: http://ocamllabs.io/multicore/
- Parallel Benchmarks
  - ✦ Multicore http server, model-checker, mathematical kernels…
  - ✦ Intel Core i9 (x86_64), 8 domains (parallel threads)
- Latency is our primary concern
  - ✦ Minor GC pause times (trunk & multicore) = ~1-2 ms
  - ✦ Avg. 50th percentile pause times = ~4 ms (1-2 ms on trunk)
  - ✦ Avg. 95th percentile pause times = ~7 ms (3-4 ms on trunk)
- Throughput is easier => add more domains

Summary

- Multicore OCaml GC
  - Optimise for latency first, throughput next
  - Independent minor GCs + concurrent mark-and-sweep
- Various other research directions in Multicore OCaml project
  - Concurrency through *Algebraic Effects and Handlers* *[TFP'17]*
  - *OCaml Memory Model* *[PLDI'18]*
  - *Reagents*: STM + channel communication + Hardware transactions (Intel TSX) [OCaml'16]

Questions?

https://github.com/ocamllabs/ocaml-multicore

http://kcsrk.info