Retrofitting *Parallelism* onto OCaml

"KC" Sivaramakrishnan

IIT MADRAS

OCaml Labs

Tarides

λ 0x1F42B Segfault Systems

OCaml

Industry

ahrefs
docker
Jane Street
SimCorp
FACEBOOK
Tarides
Tezos
Bloomberg

Projects

The Astrée Static Analyzer
flow
hack
COMPCERT

Industry

Projects

No multicore support!

Multicore OCaml

- Adds native support for *concurrency* and *parallelism* to OCaml

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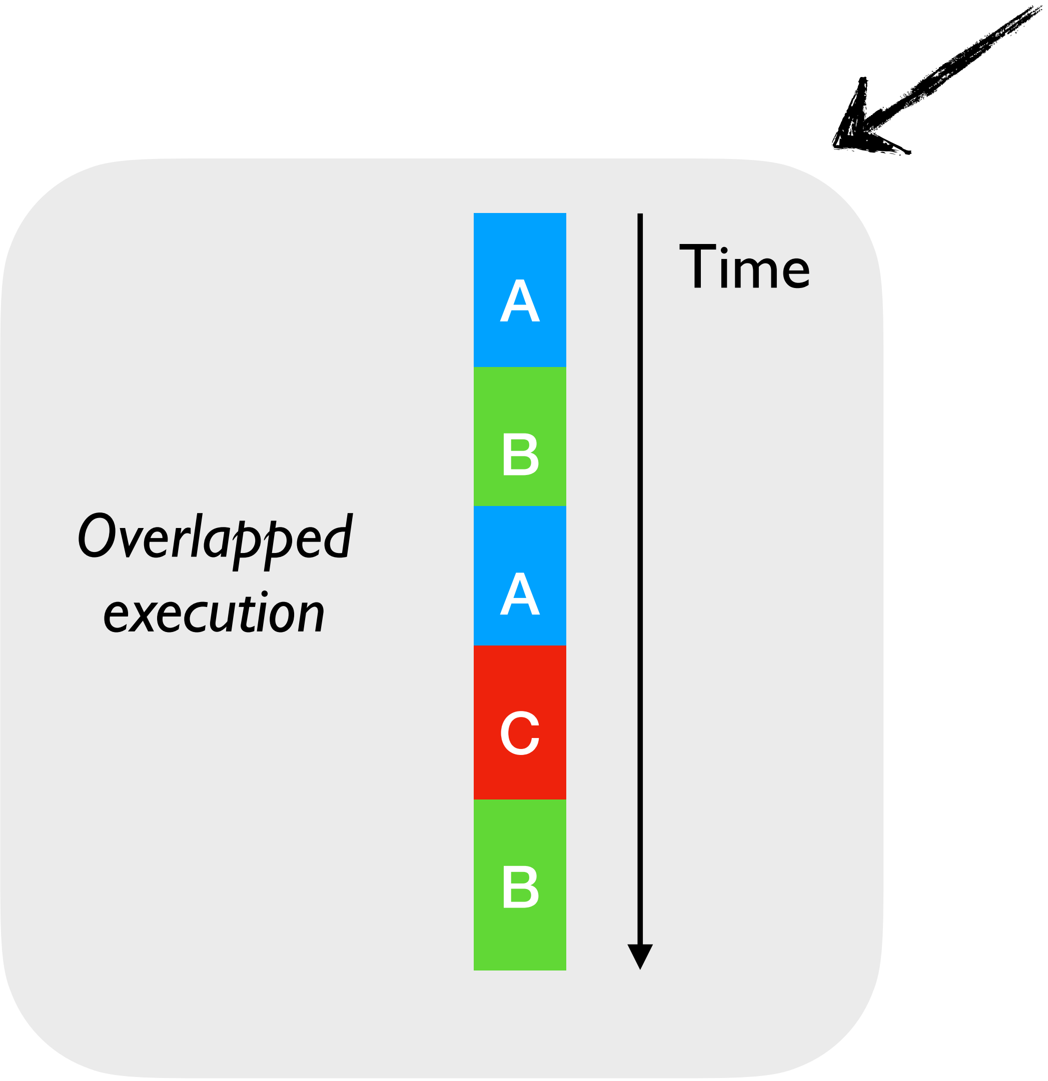

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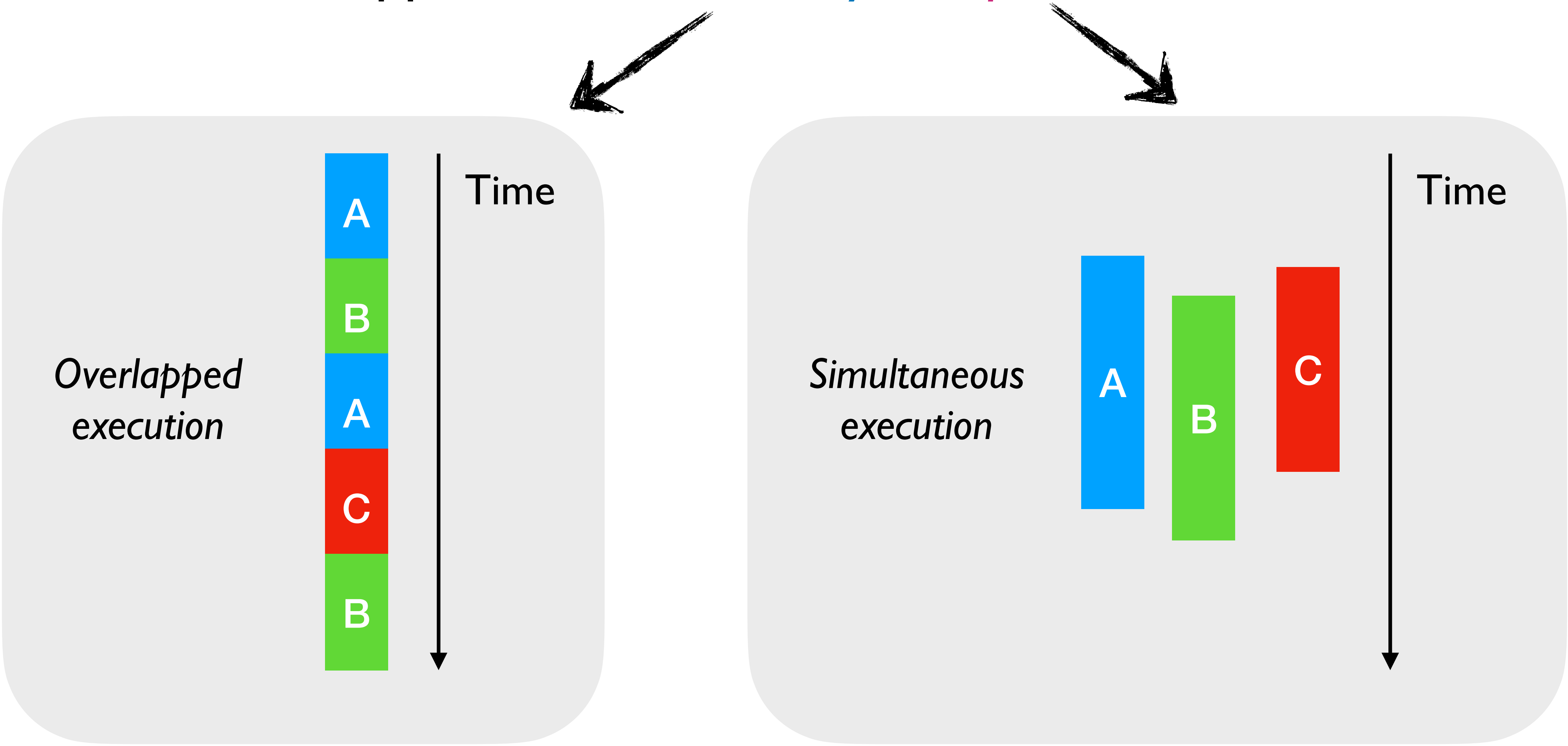

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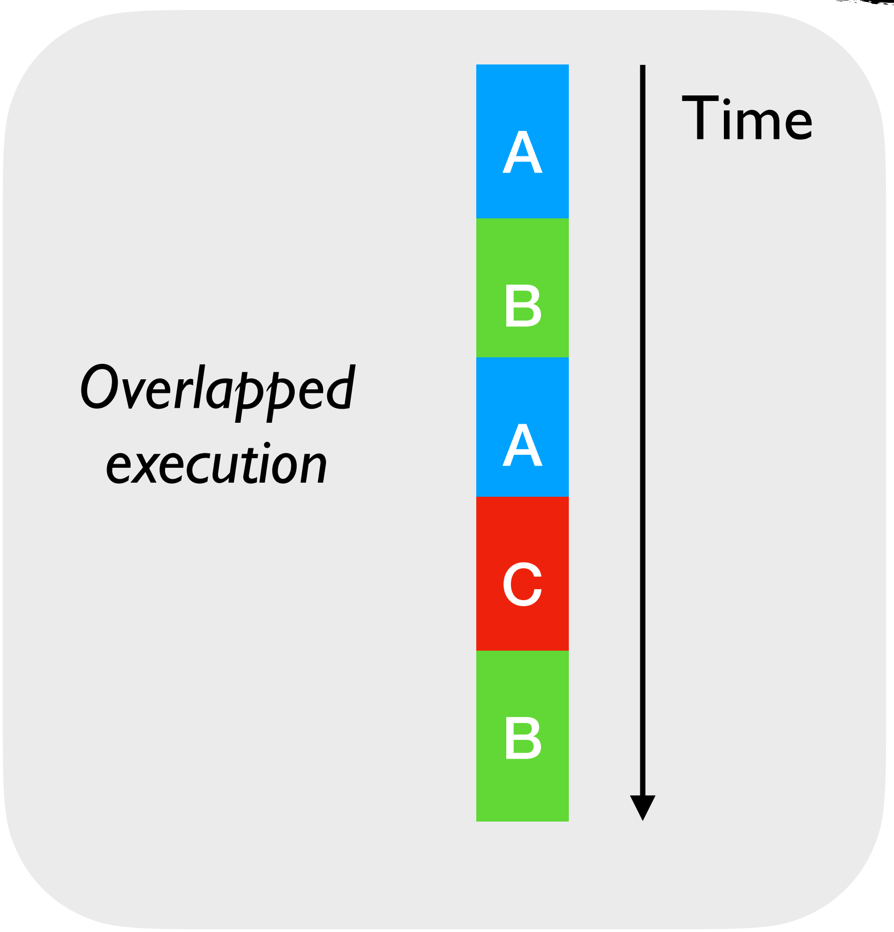

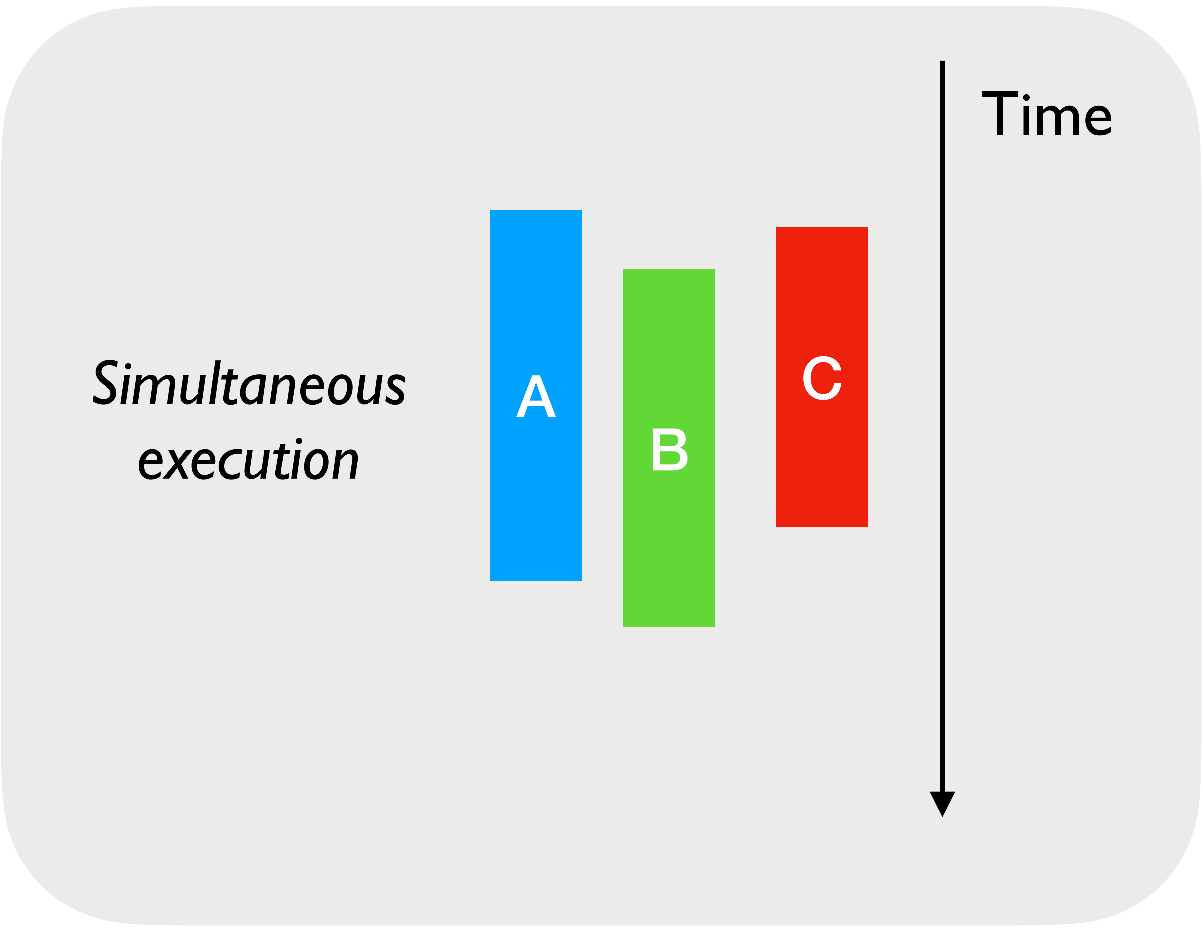

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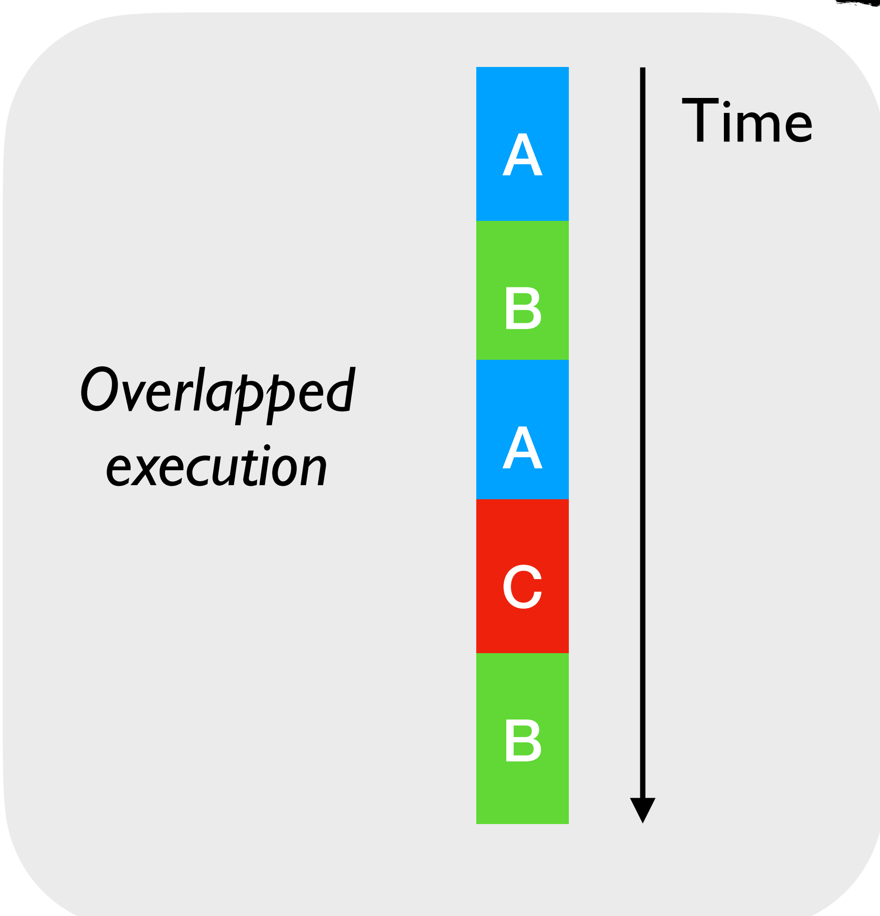

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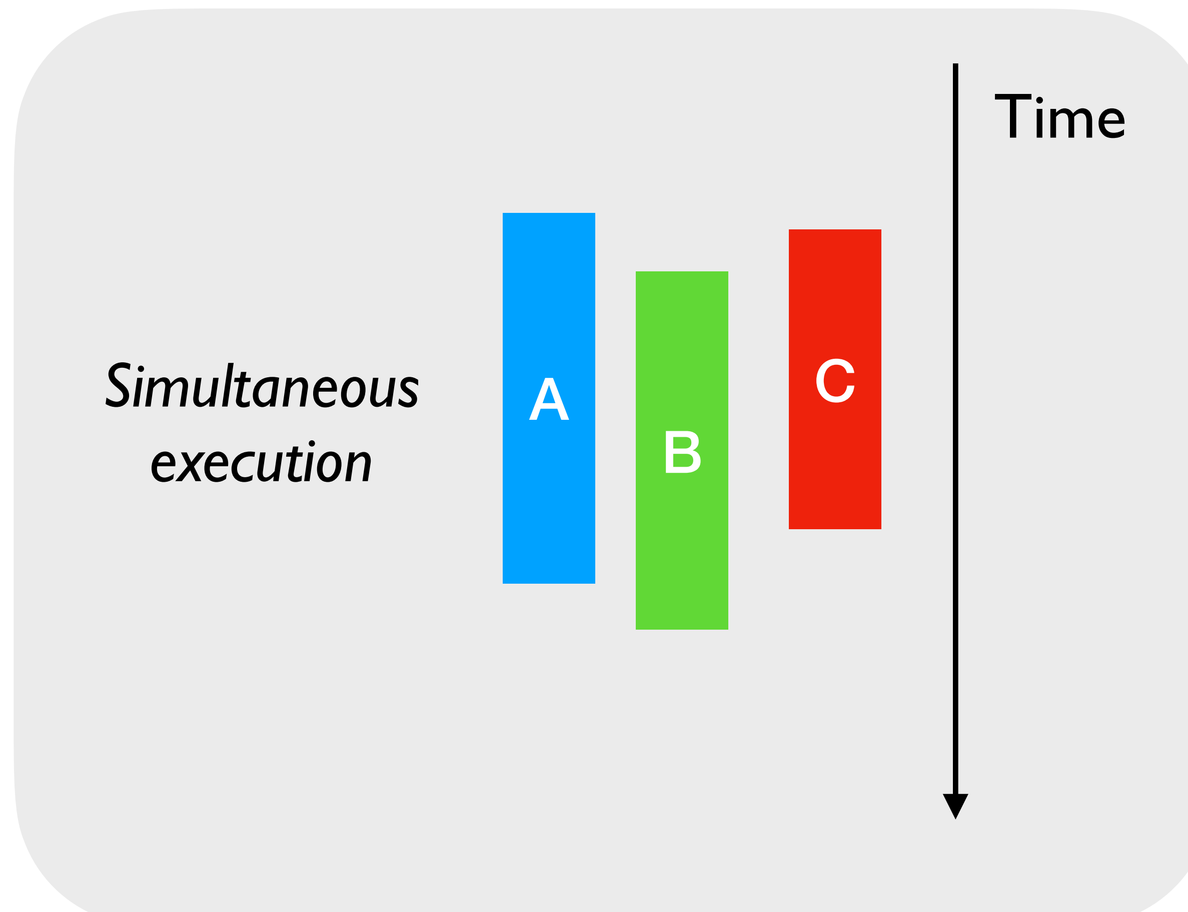

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OCaml 5.0

- Domains and *the runtime system support* for effect handlers will land in OCaml 5.0
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```
opam install 4.12.0+domains+effects
```

Outline of the talk

1. Challenges of adding parallelism to OCaml
2. Deep dive into the new parallel GC for OCaml
3. High-level parallel programming with *Domainslib*

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- Millions of lines of legacy code
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Backwards compatibility before scalability

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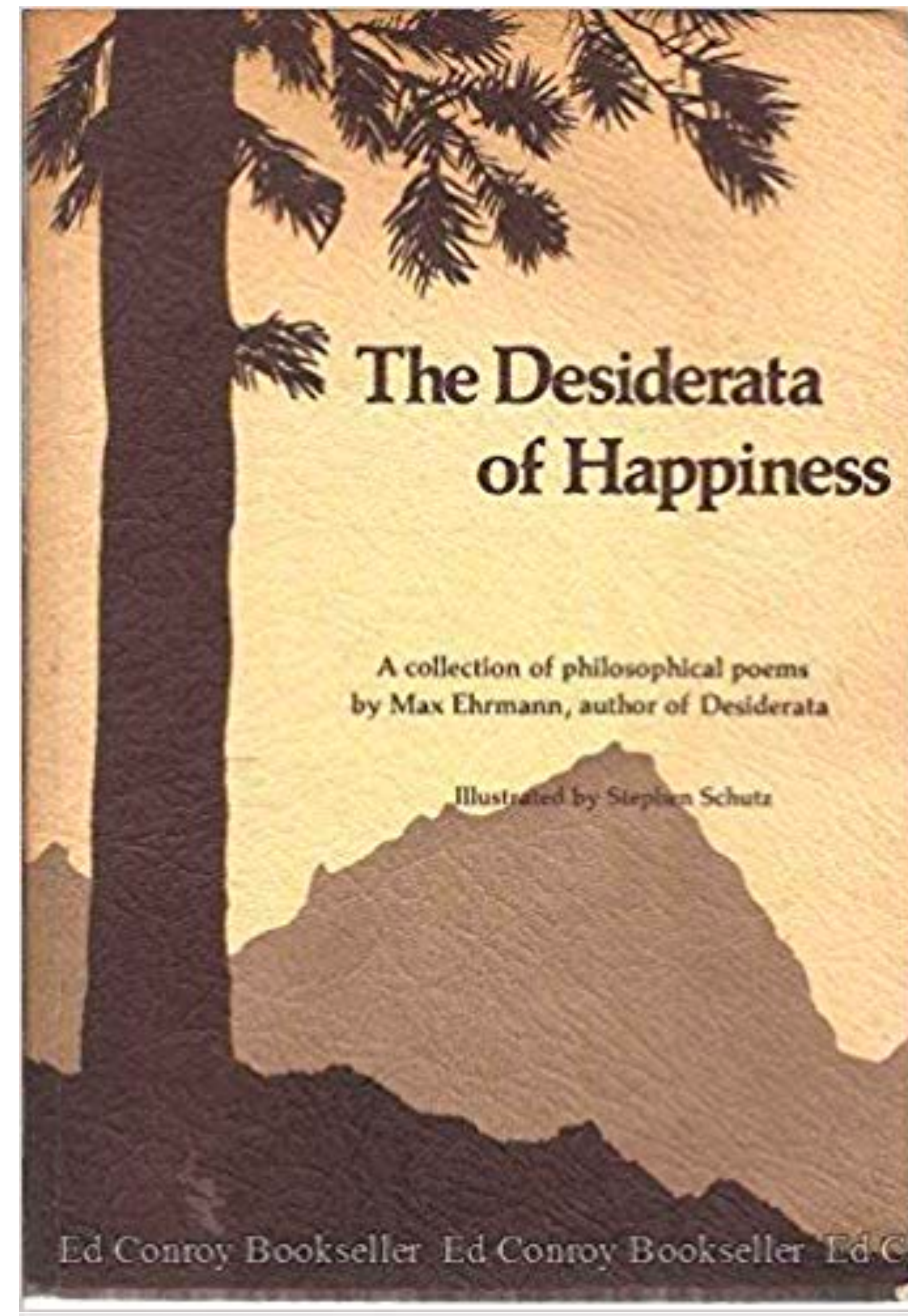

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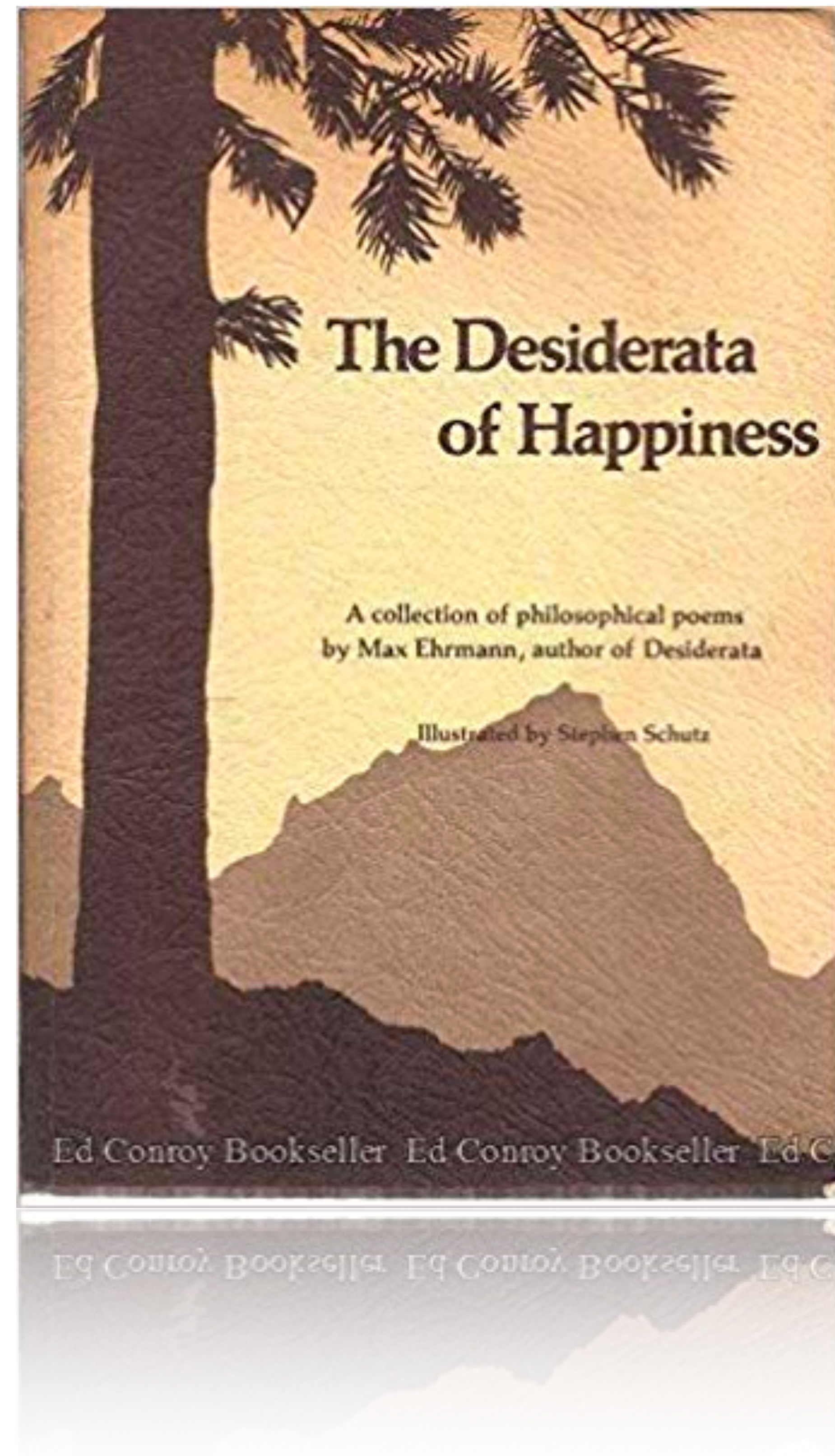

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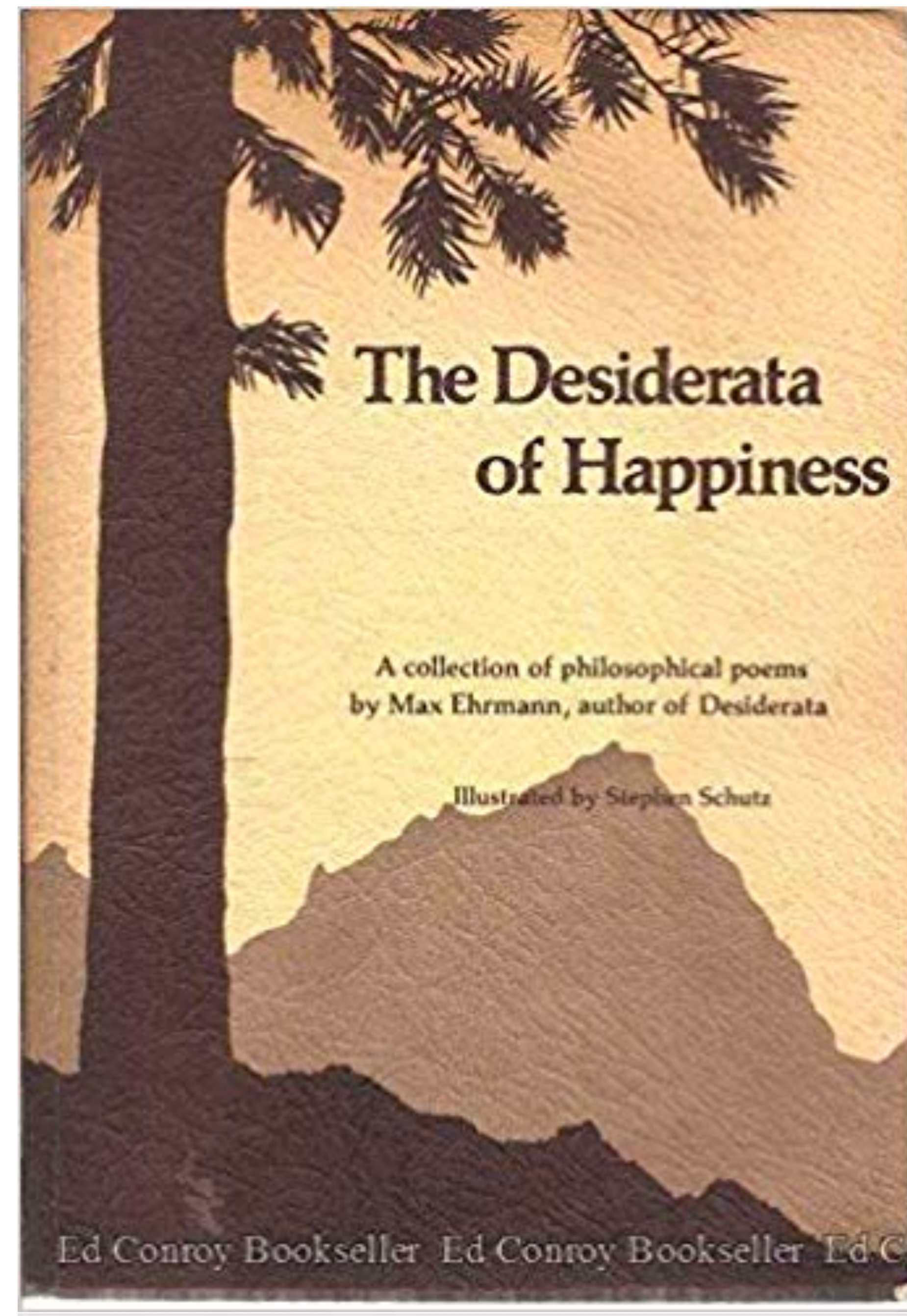

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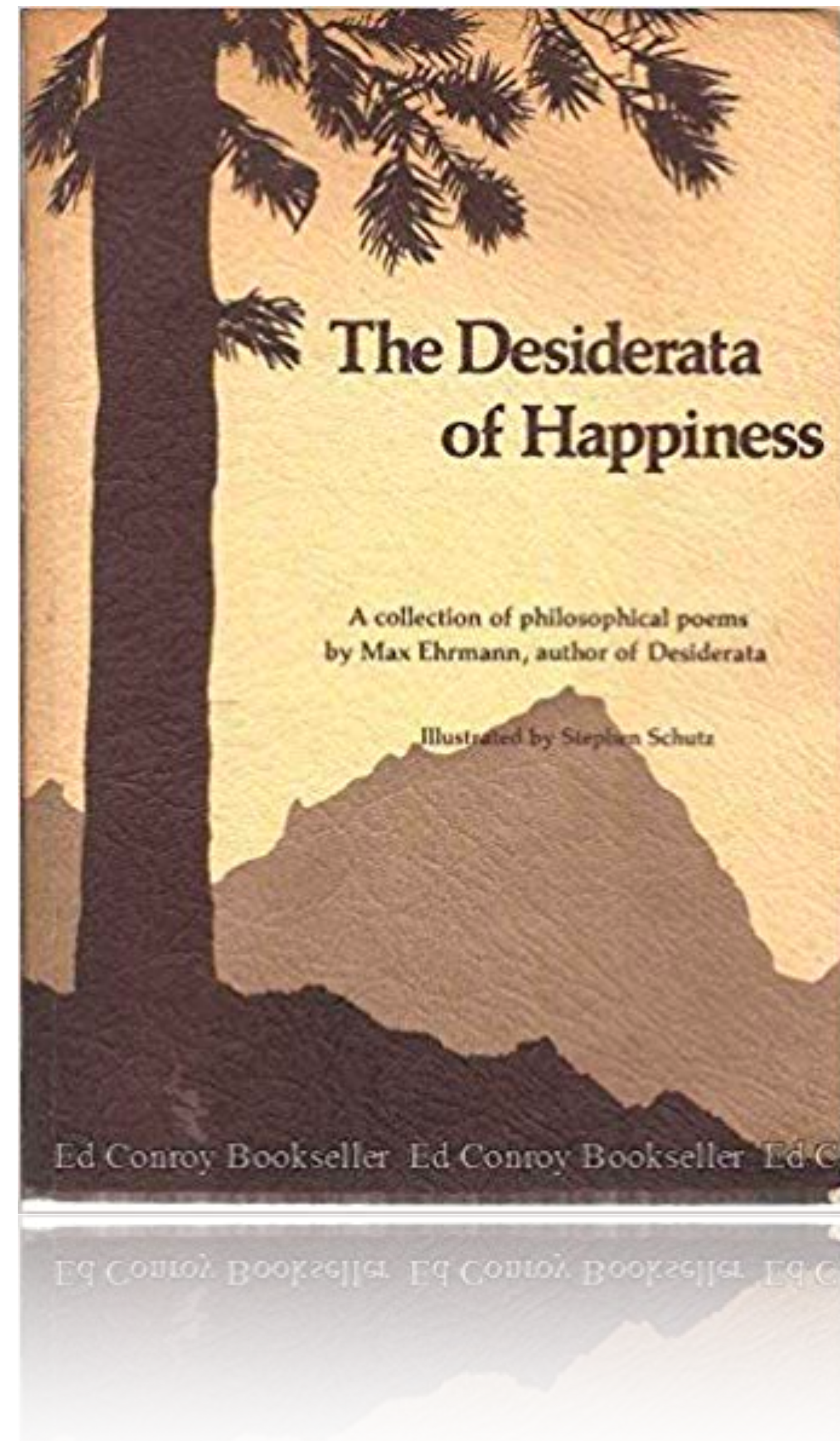

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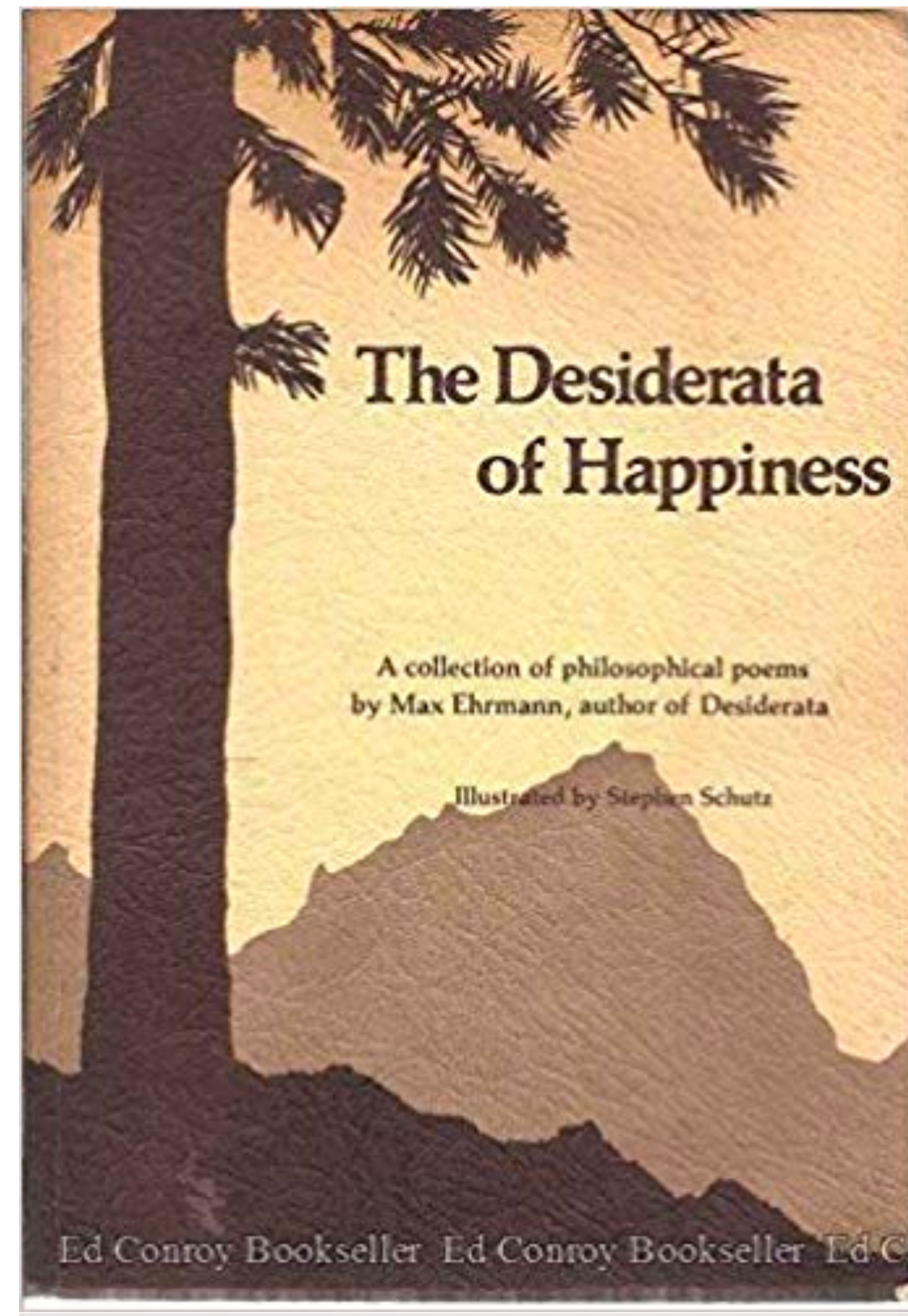
- Performant concurrent and parallel programming abstractions



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  - Domain-local storage
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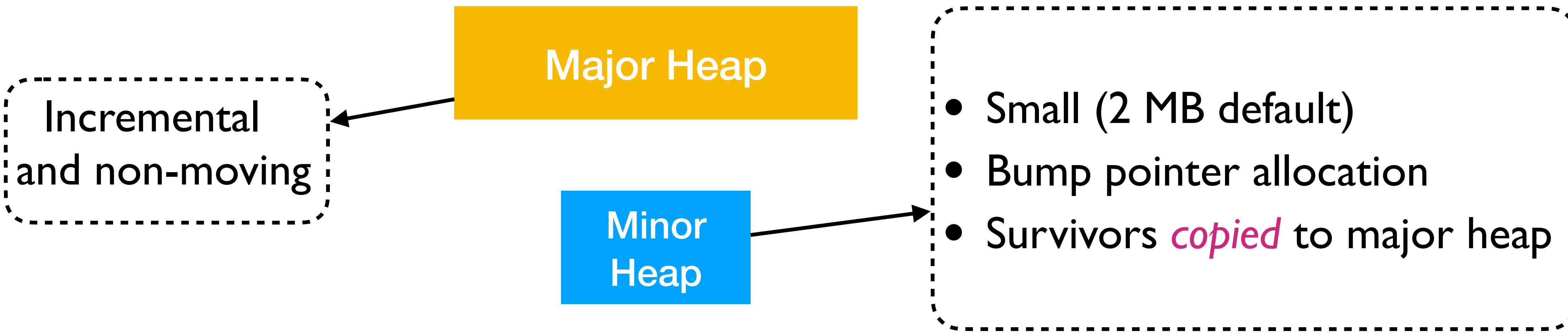
- No restrictions on sharing objects between domains
  - But how does it work?

Stock OCaml GC

- A generational, non-moving, incremental, mark-and-sweep GC



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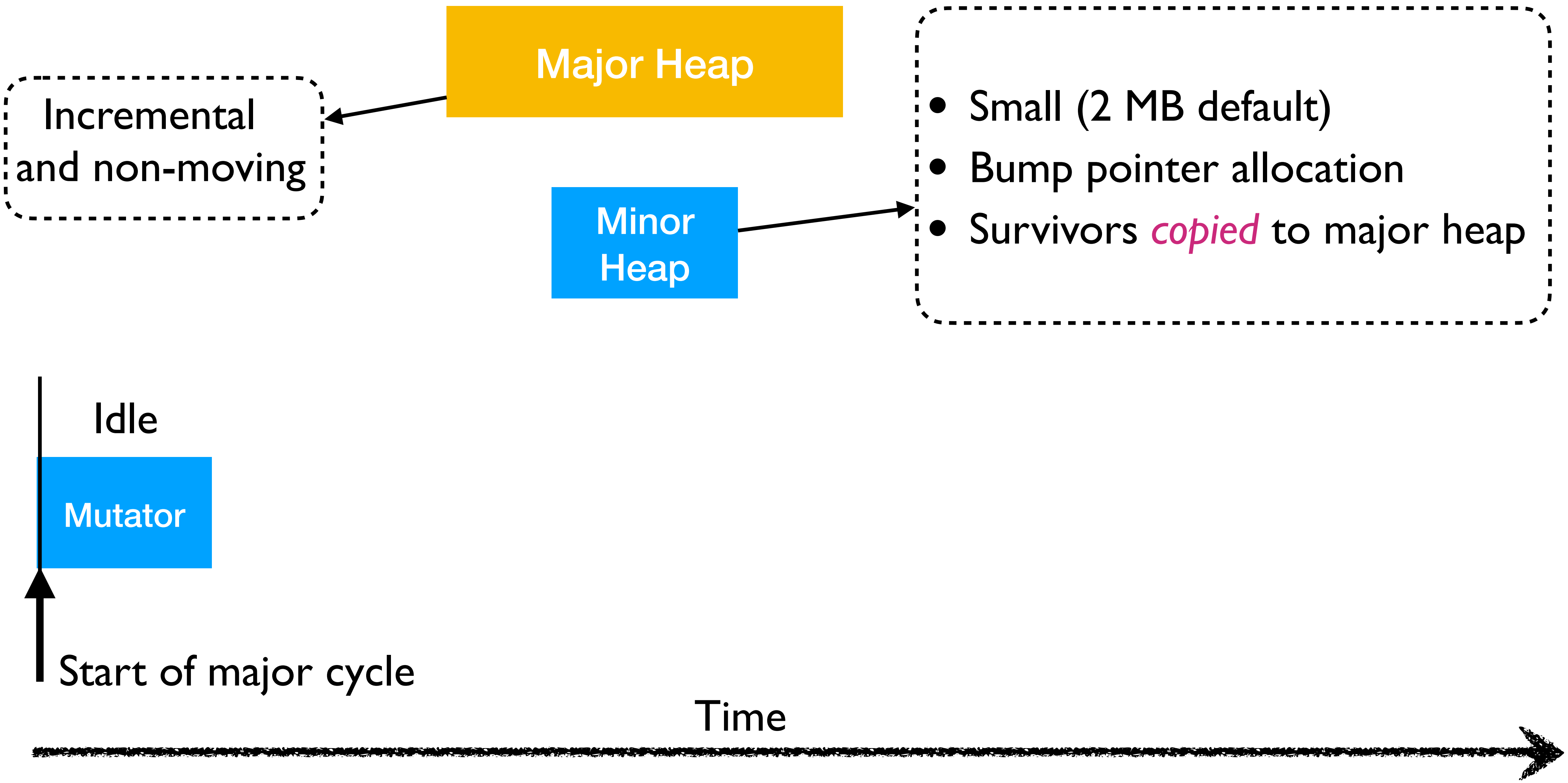

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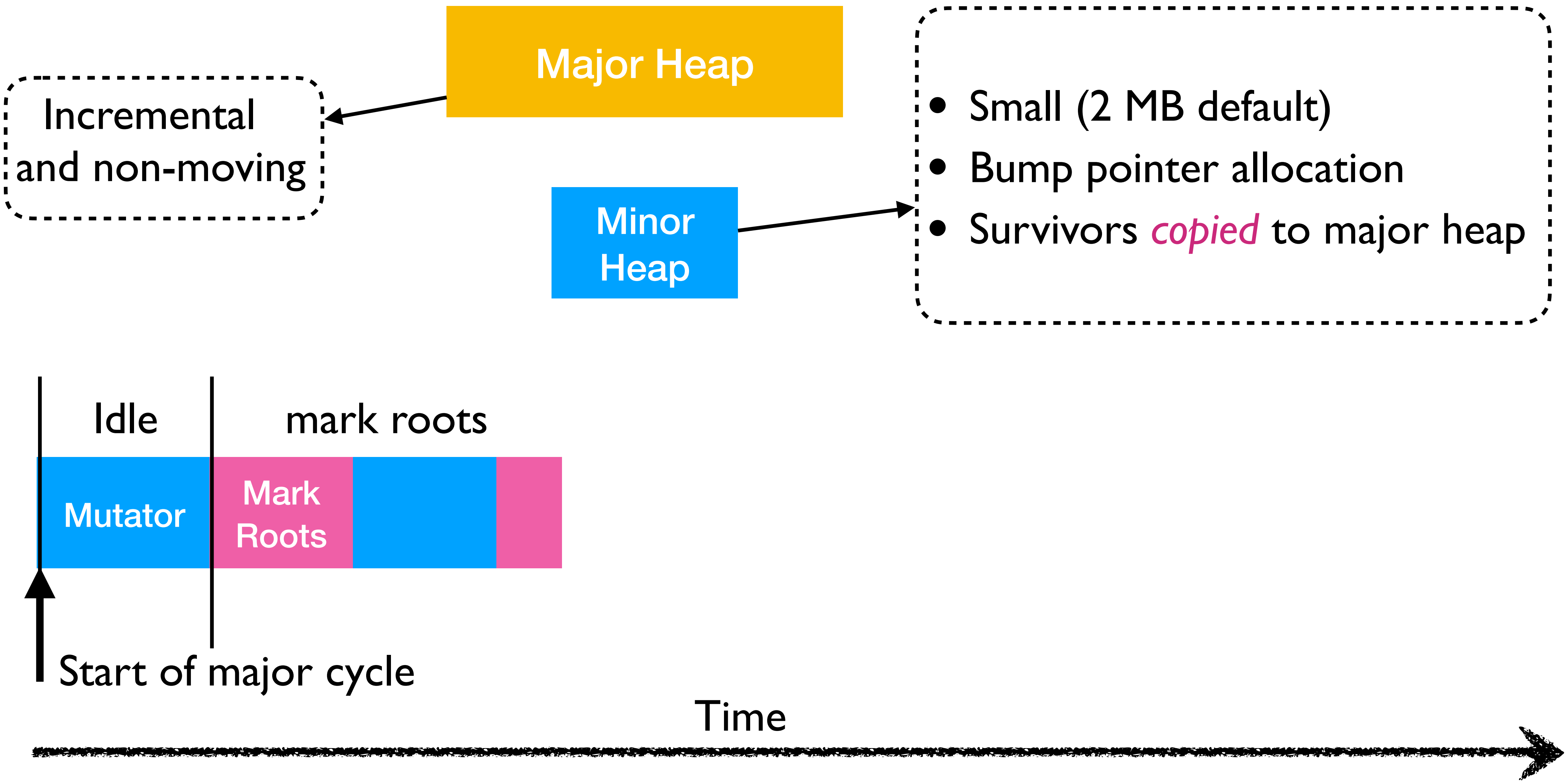

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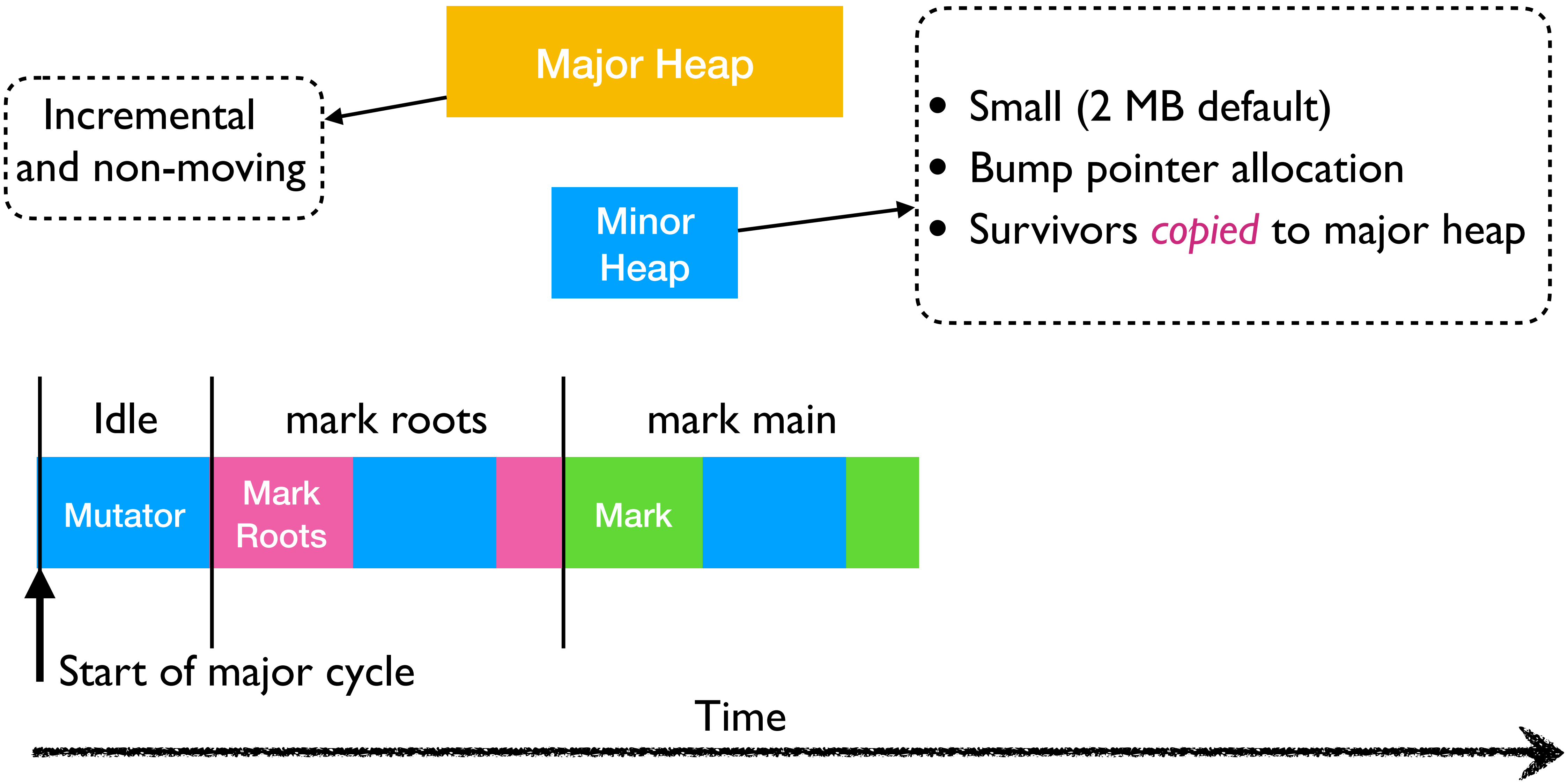

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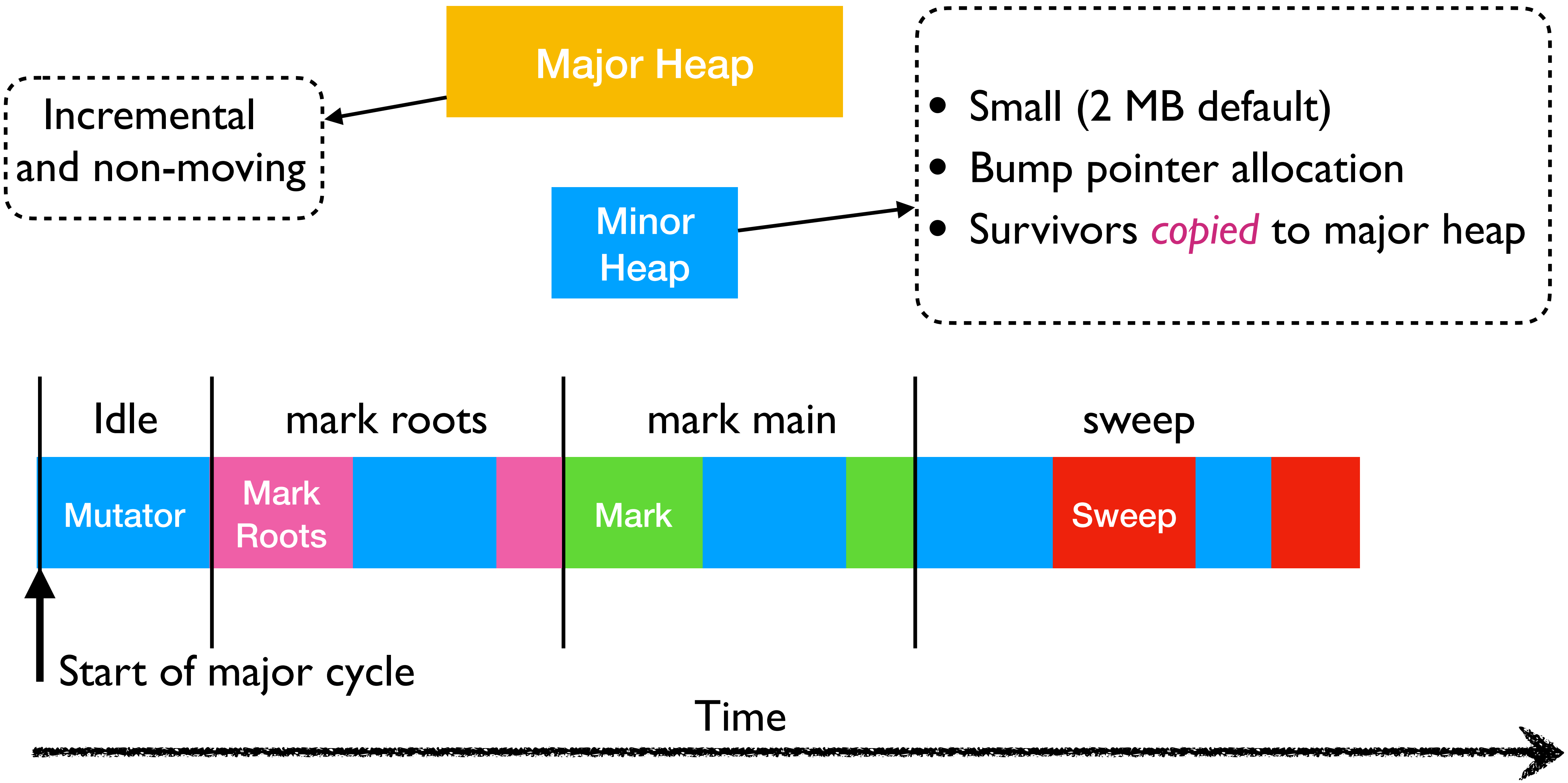

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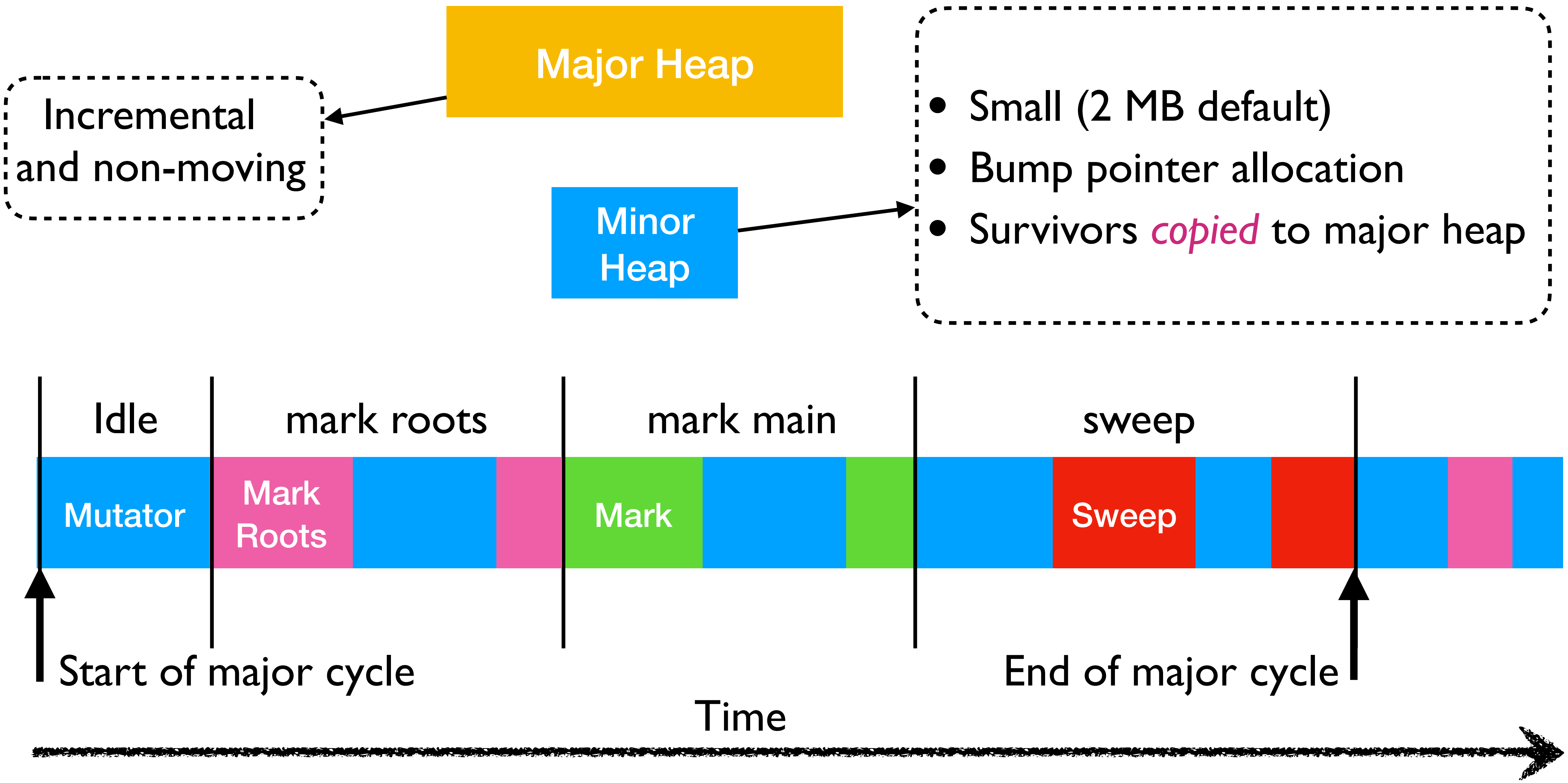

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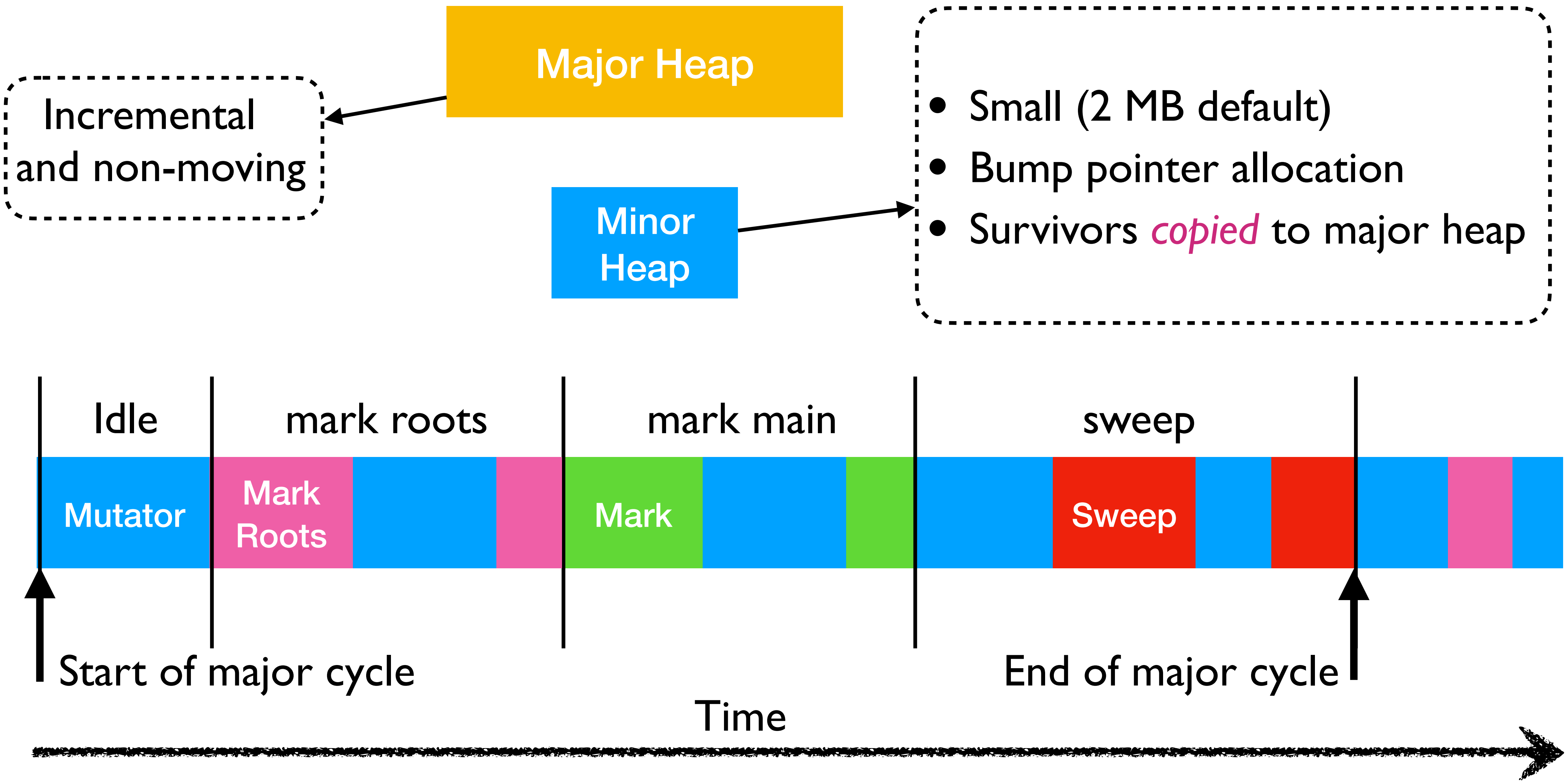

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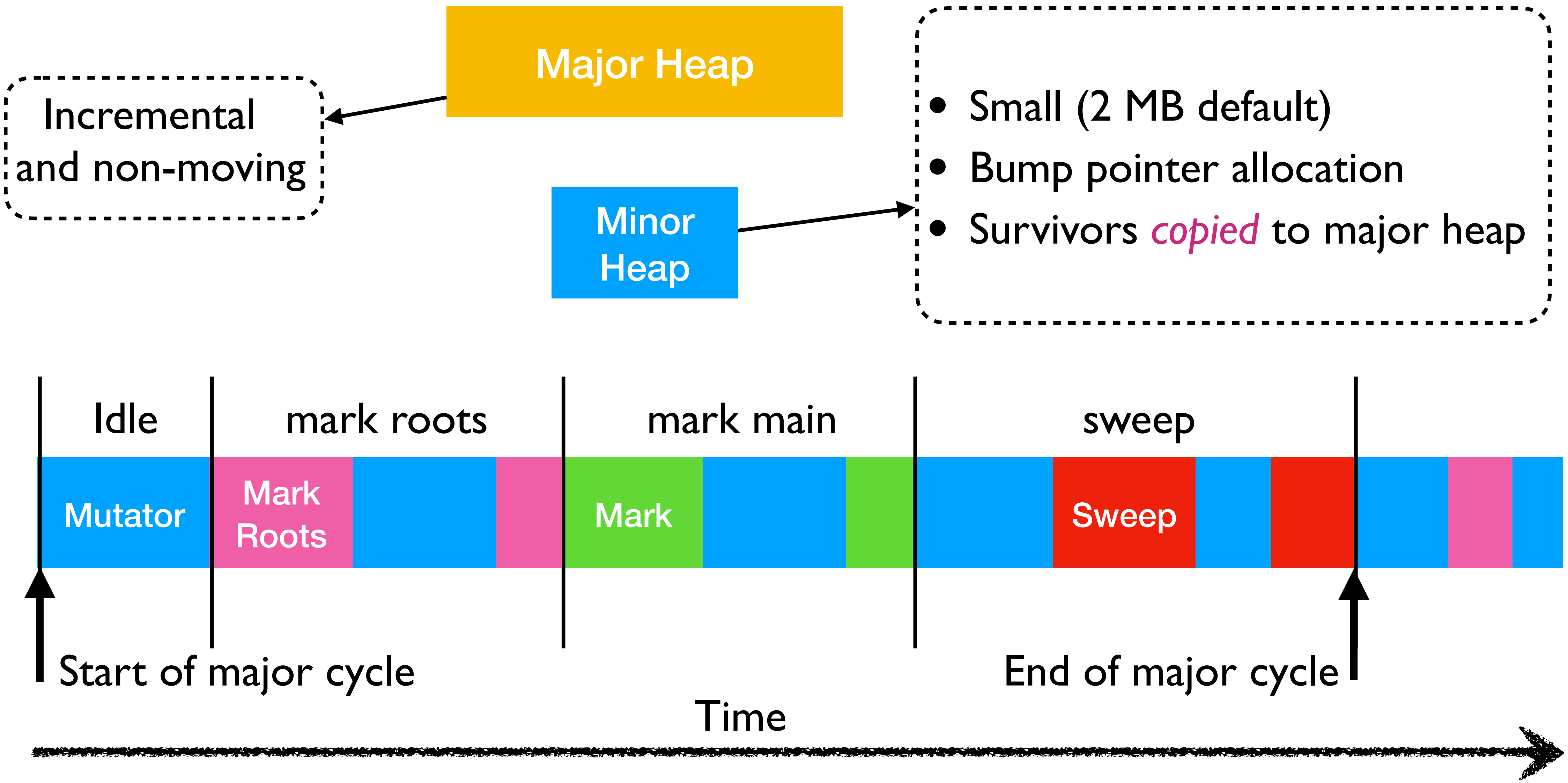
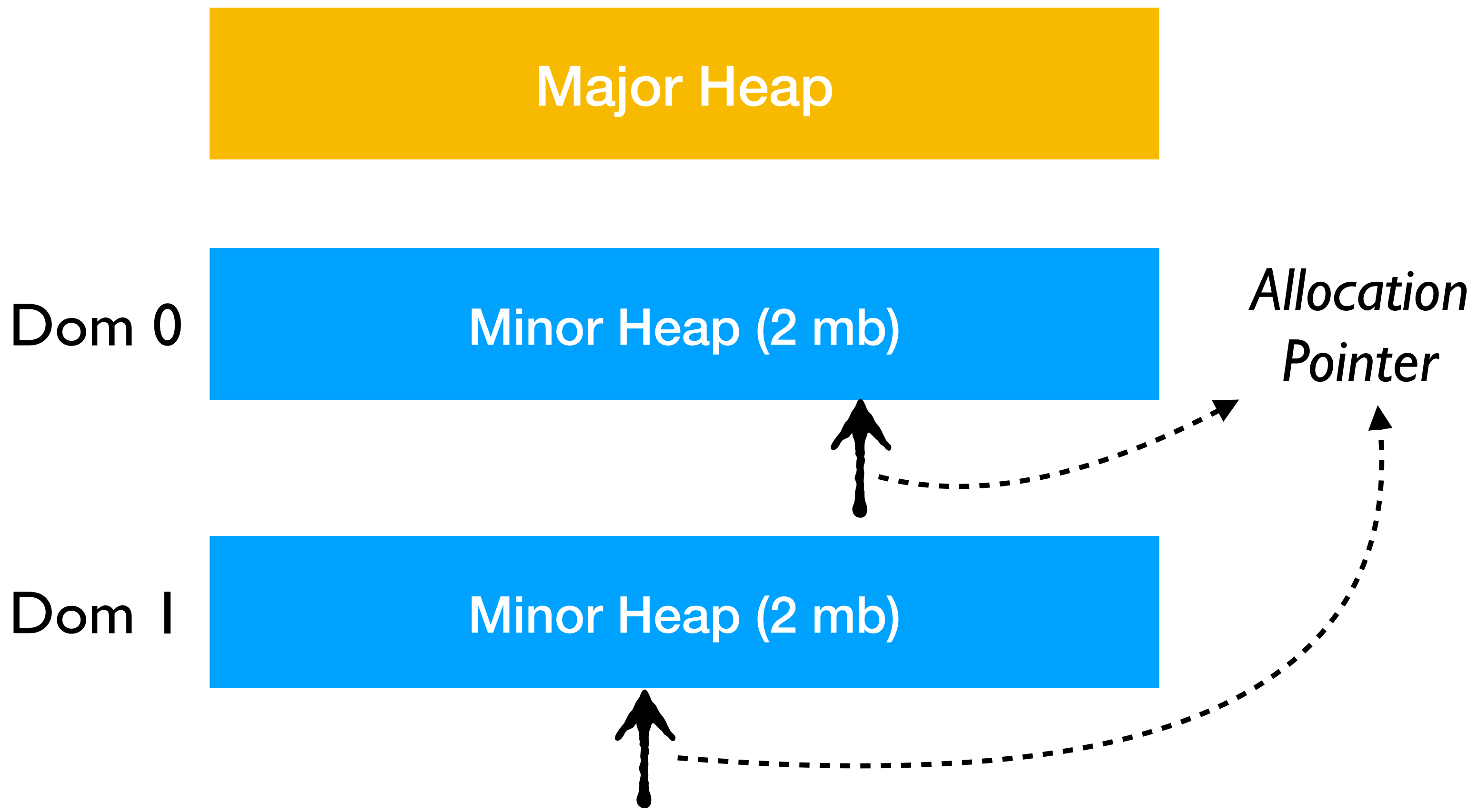


- Fast allocations
- Max GC latency **< 10 ms**, 99th percentile latency **< 1 ms**

Multicore OCaml: Minor GC



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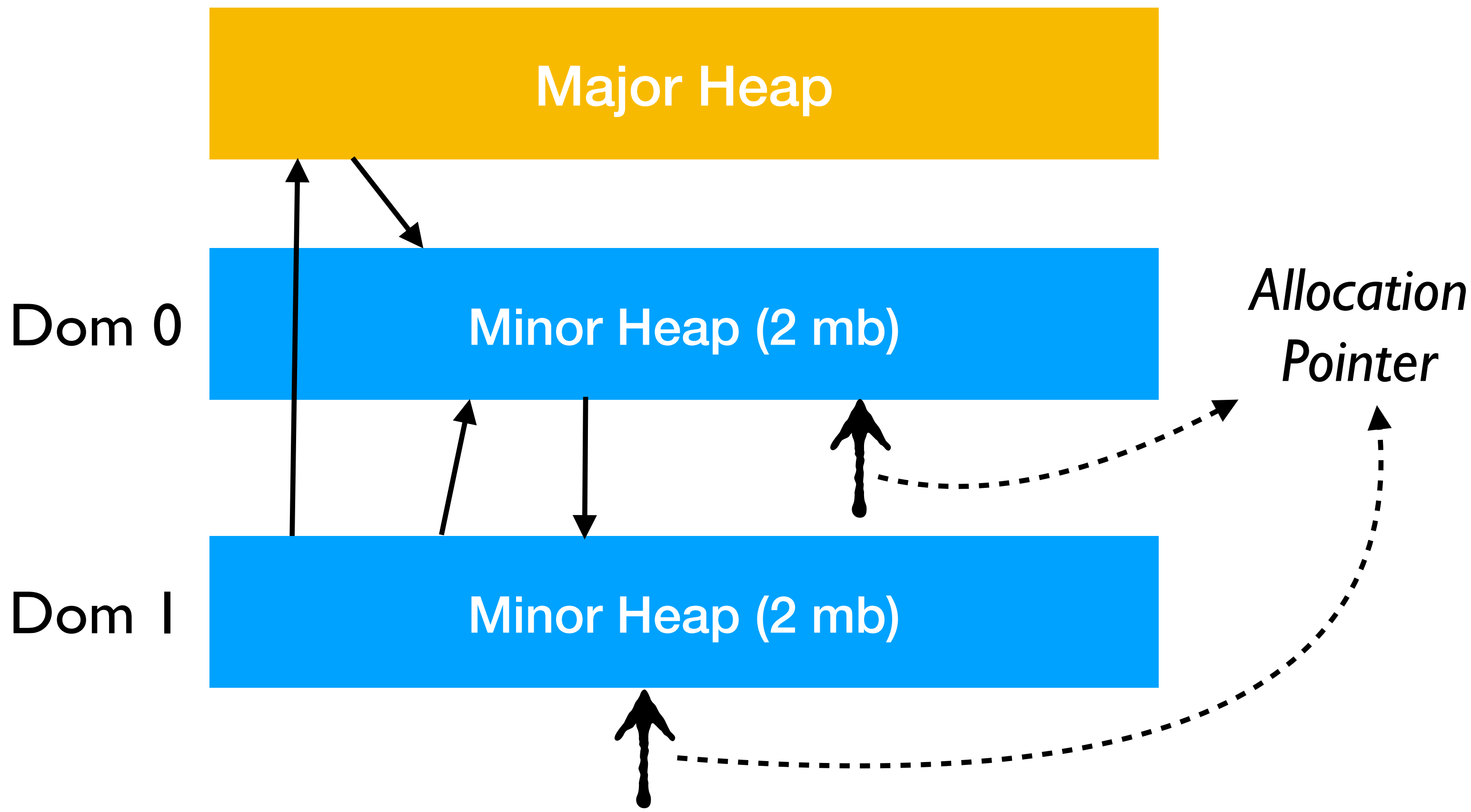

- Private minor heap arenas per domain
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- Pointers permitted between minor arenas and major heap

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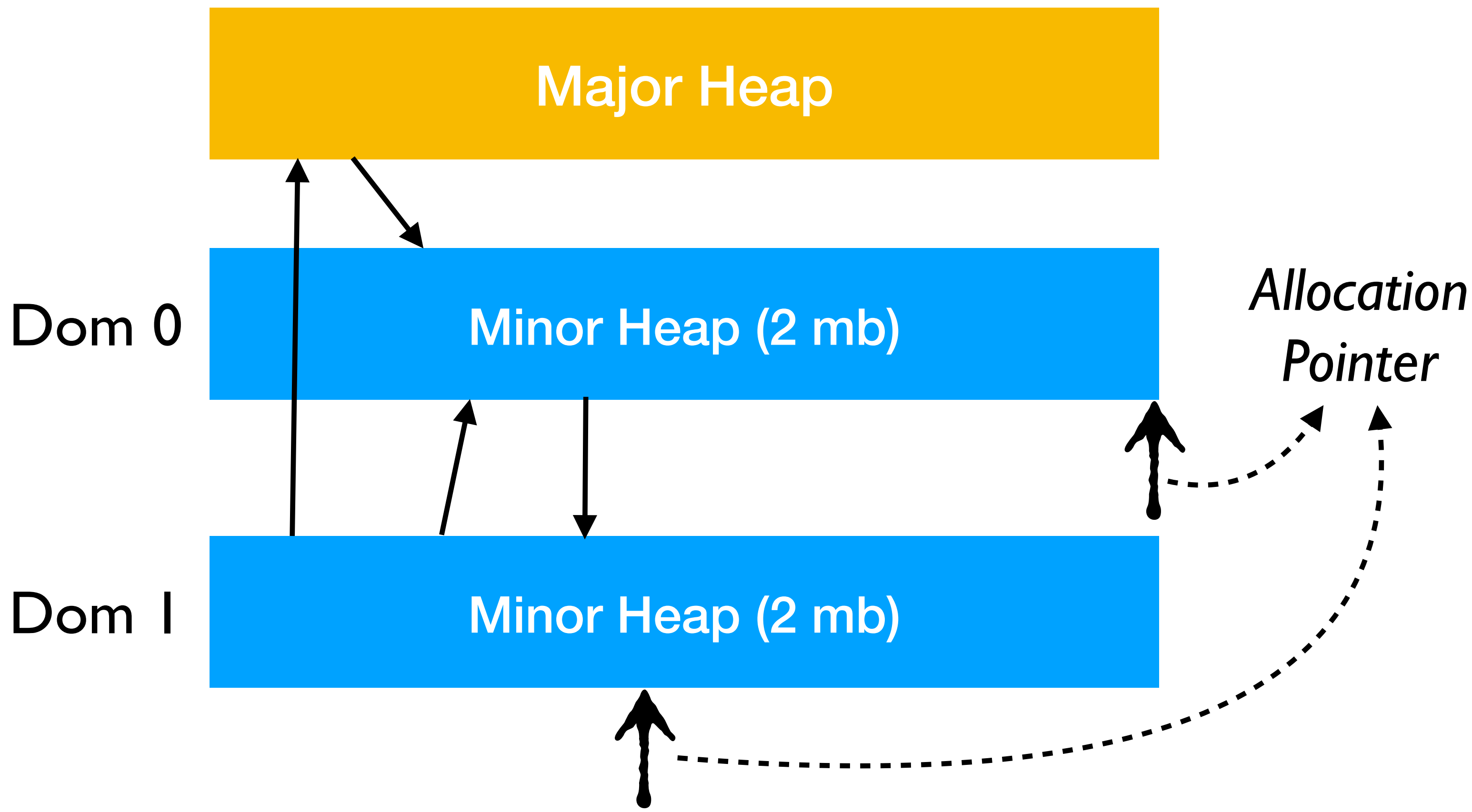

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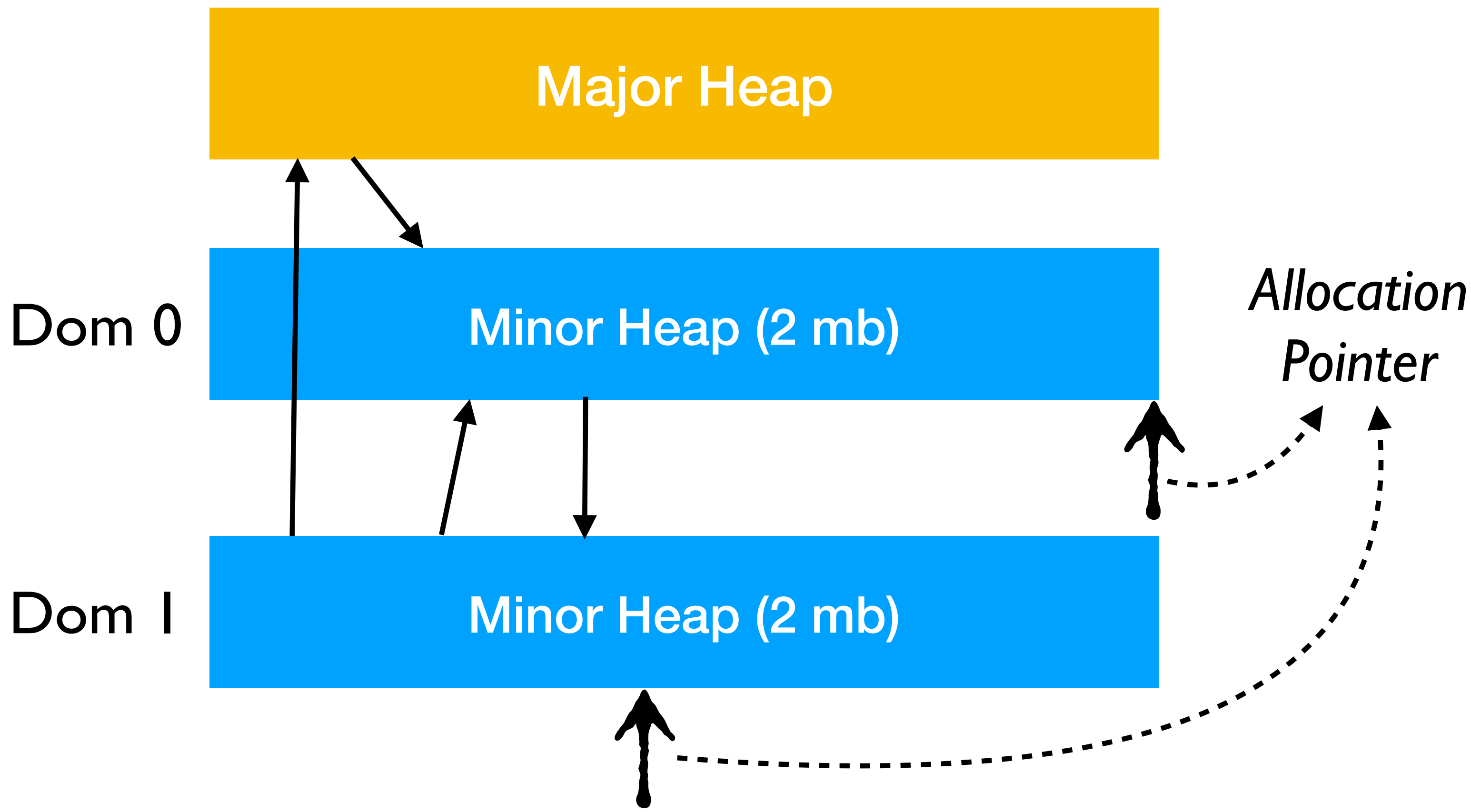

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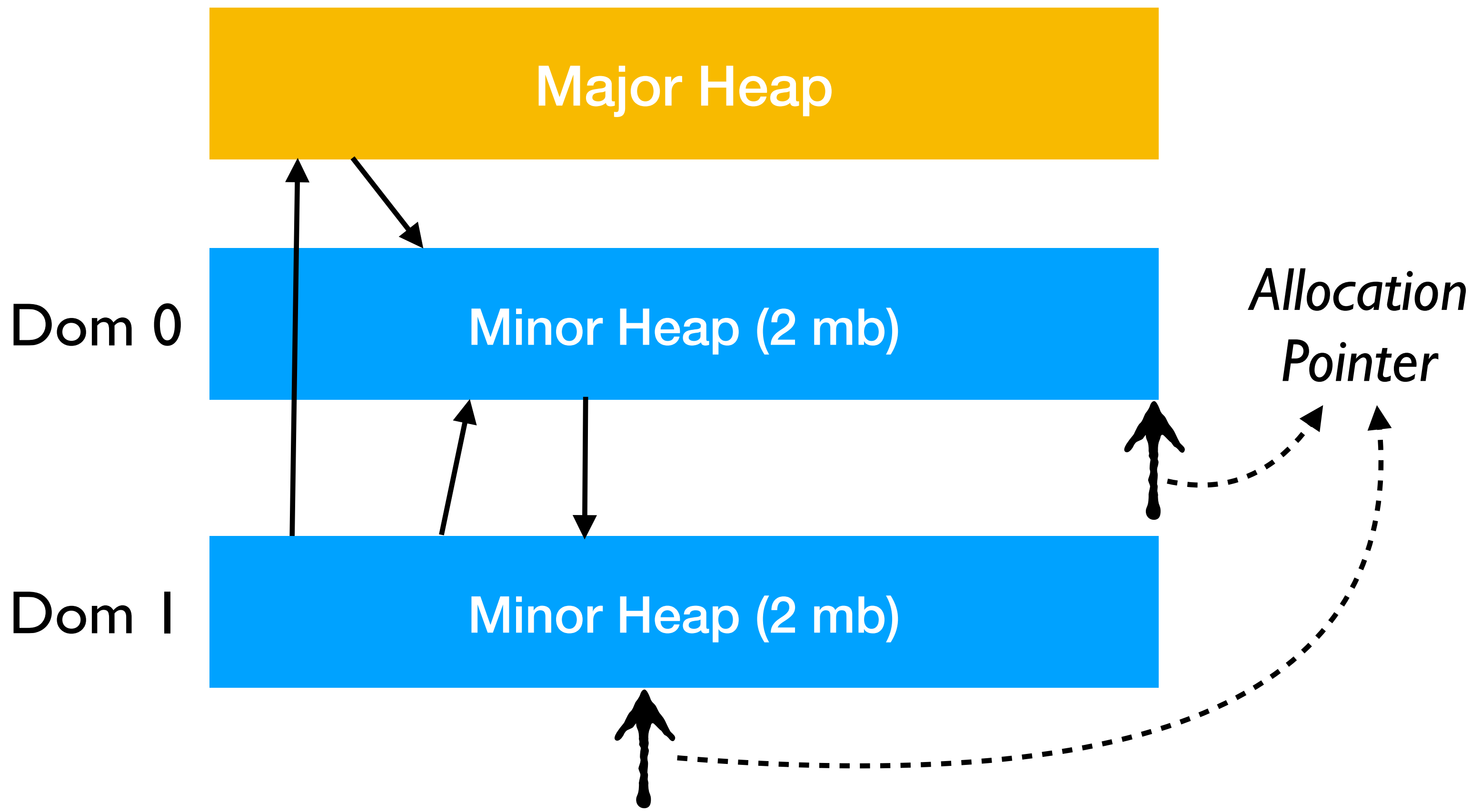

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- On 24 cores, ~10 ms pauses for completing stop-the-world minor GC

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- Sequential performance on par with OCaml's recent *best-fit* allocator

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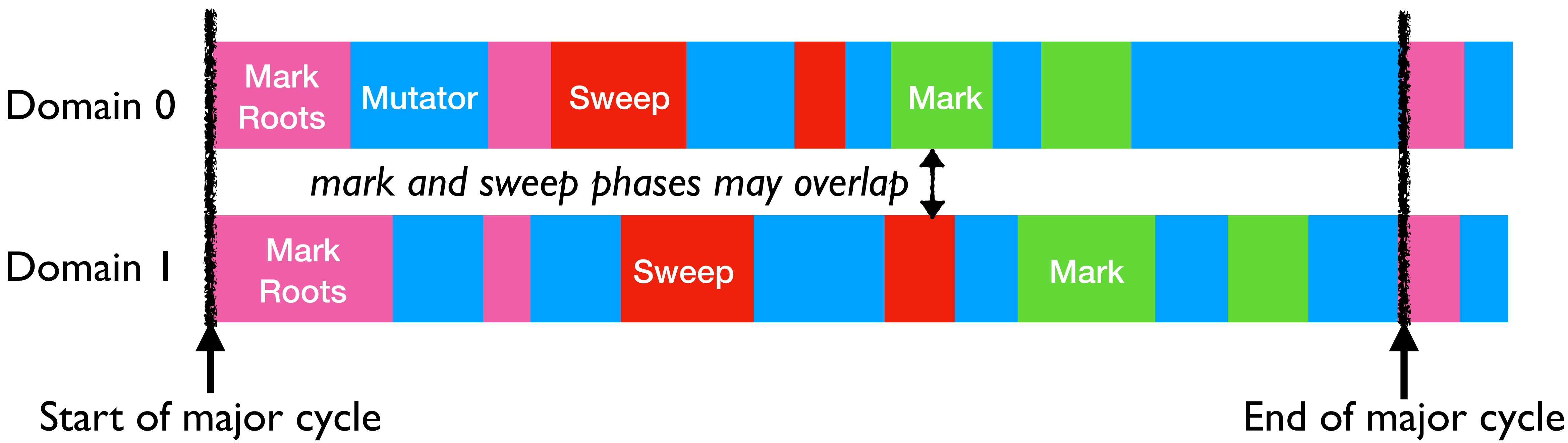

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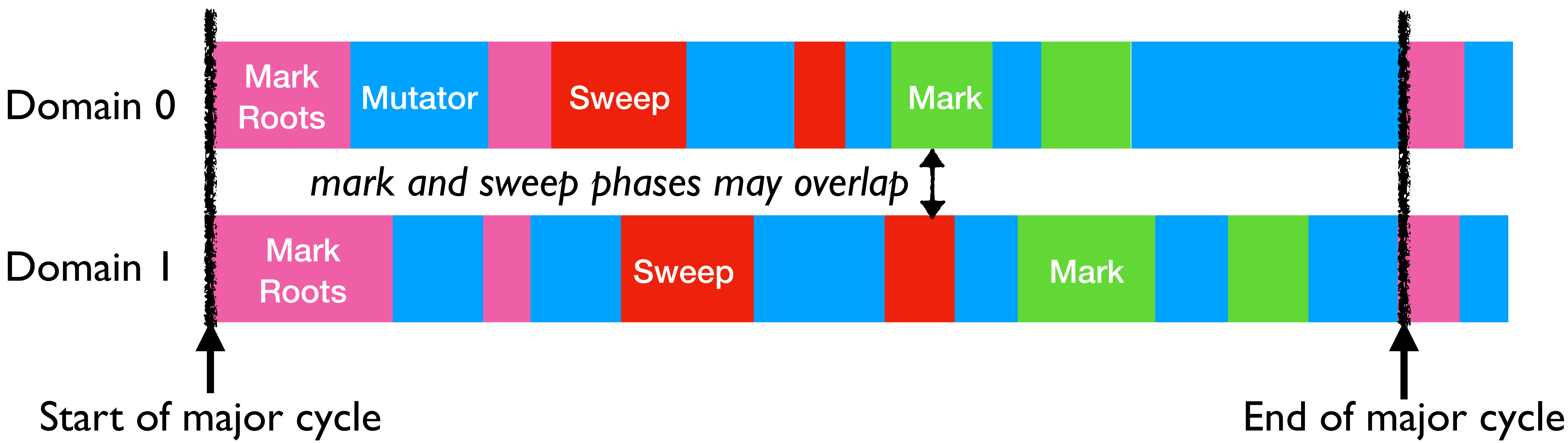

- Marking: Unmarked → Marked Sweeping: Garbage → Free
  - ✦ Marking is *racy* but uses plain *non-atomic stores and idempotent*

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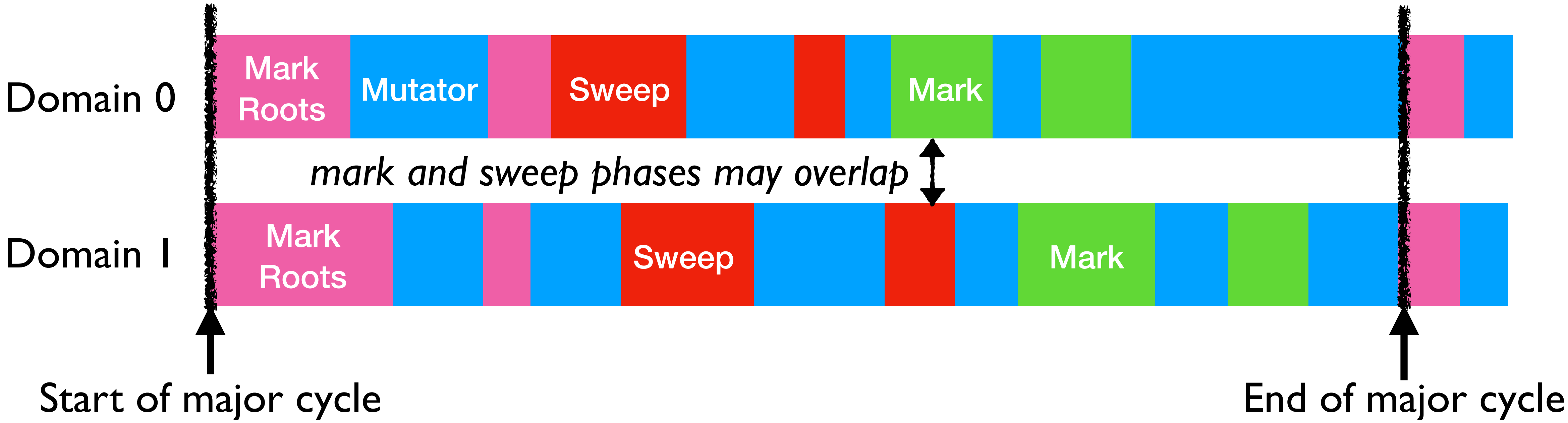

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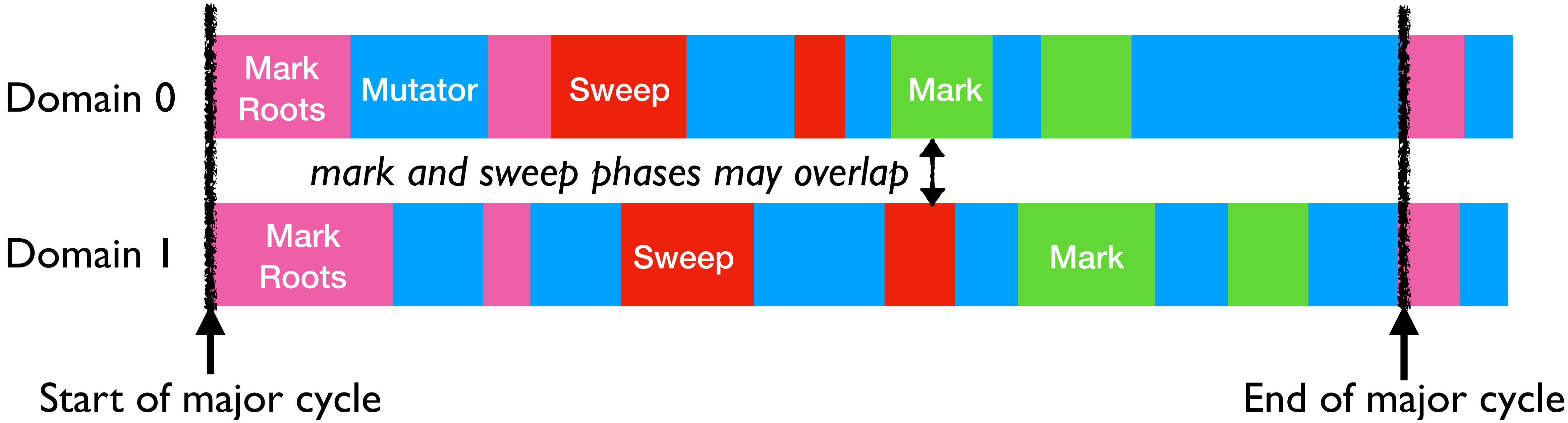

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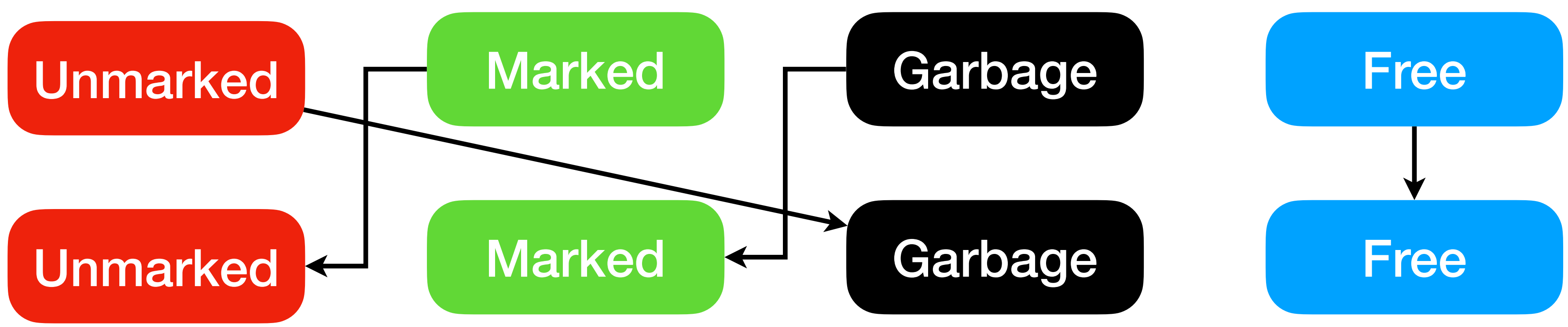

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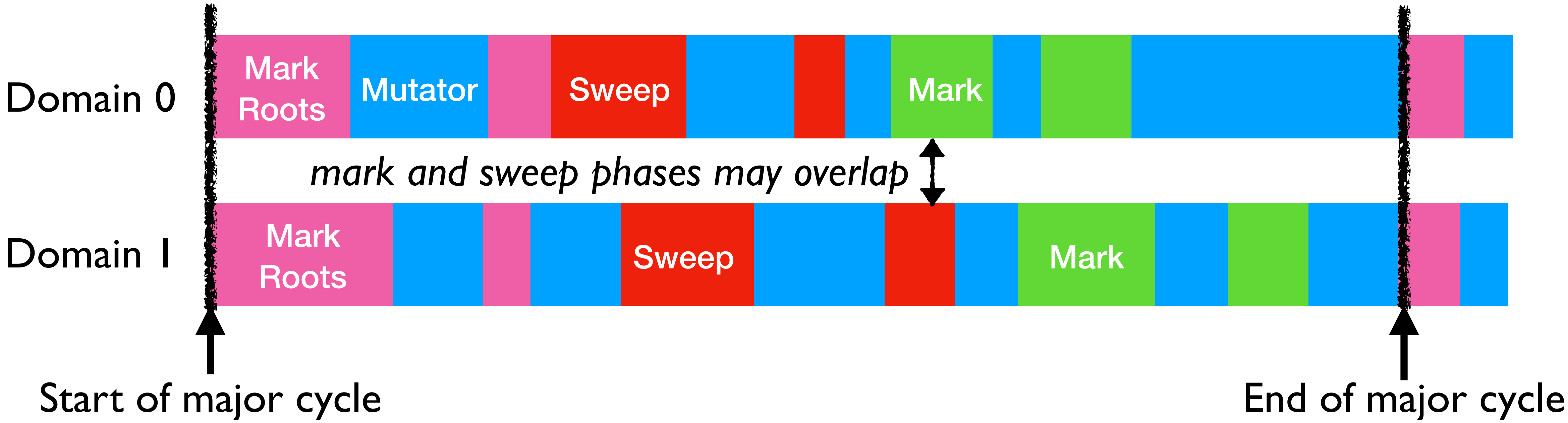

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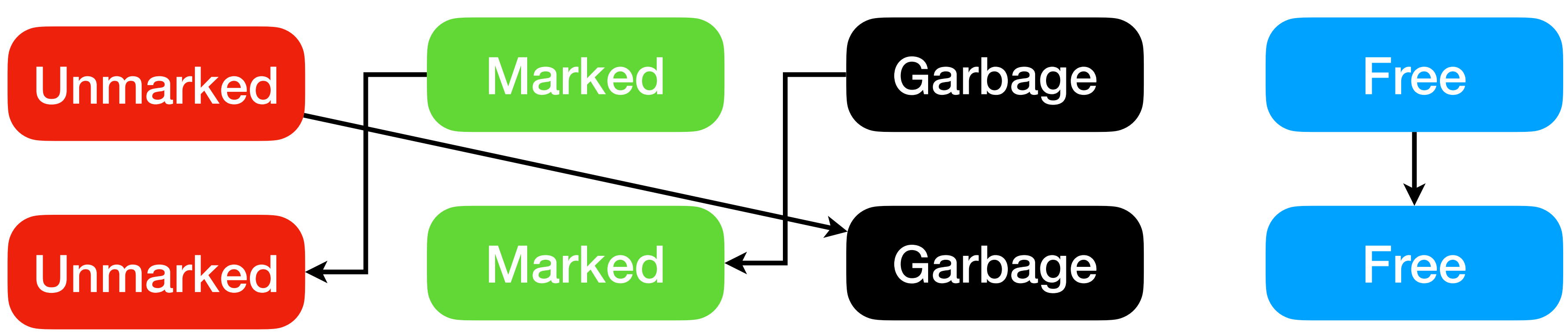
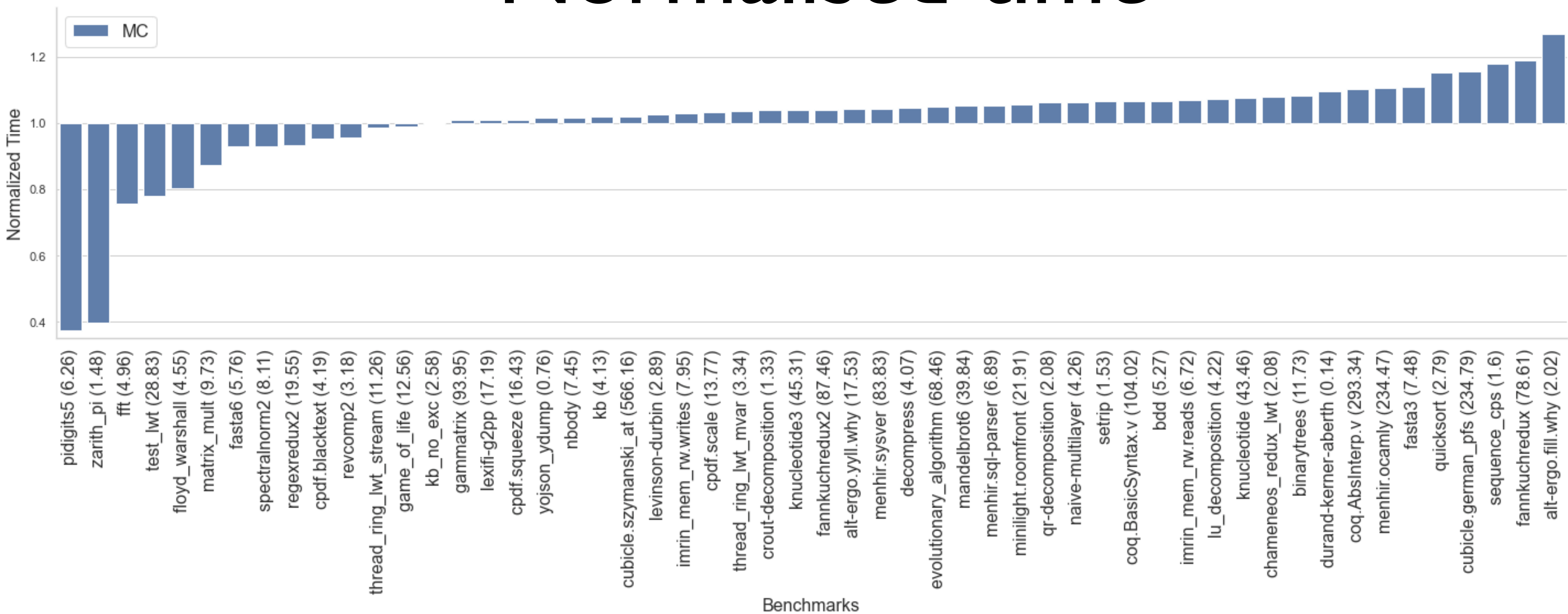


- Stop-the-world pauses are ~5 ms on 24 cores

Sequential Performance: Normalised time



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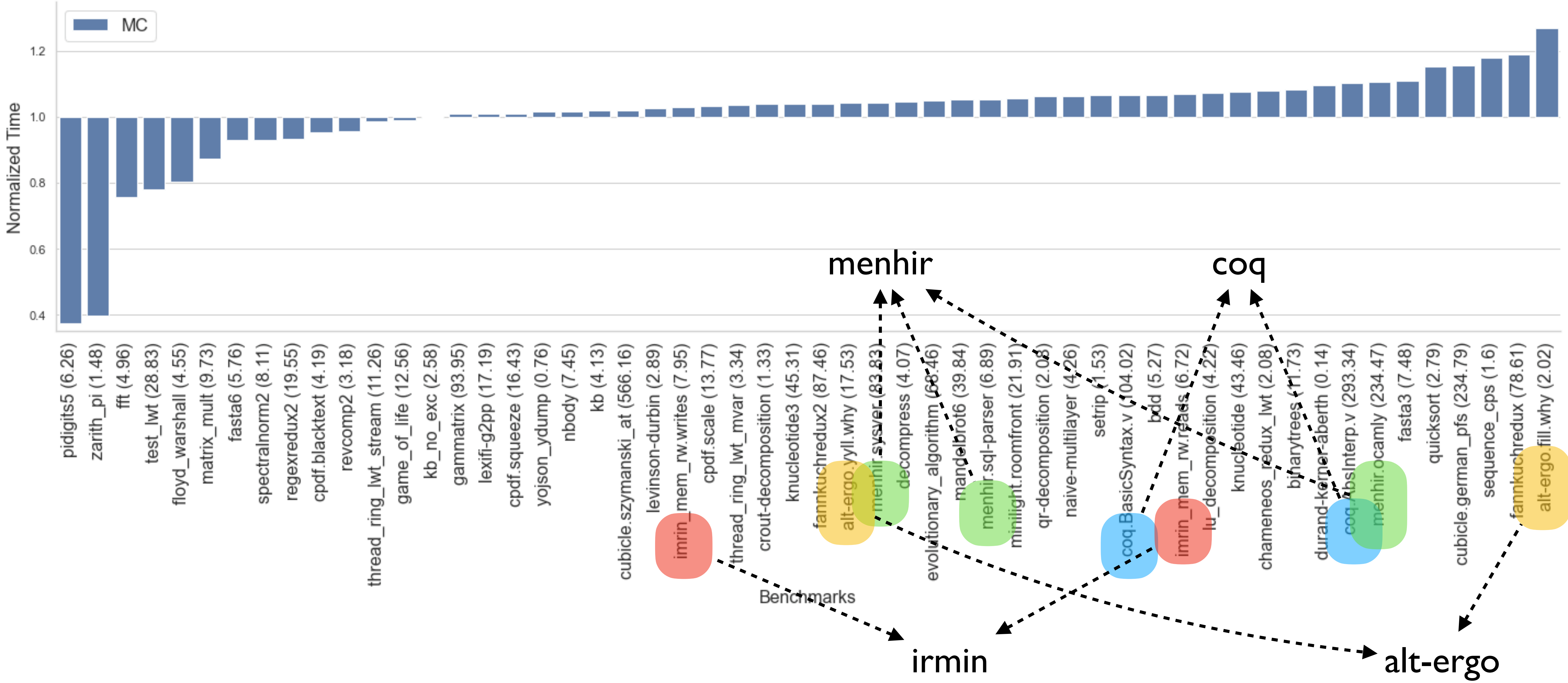

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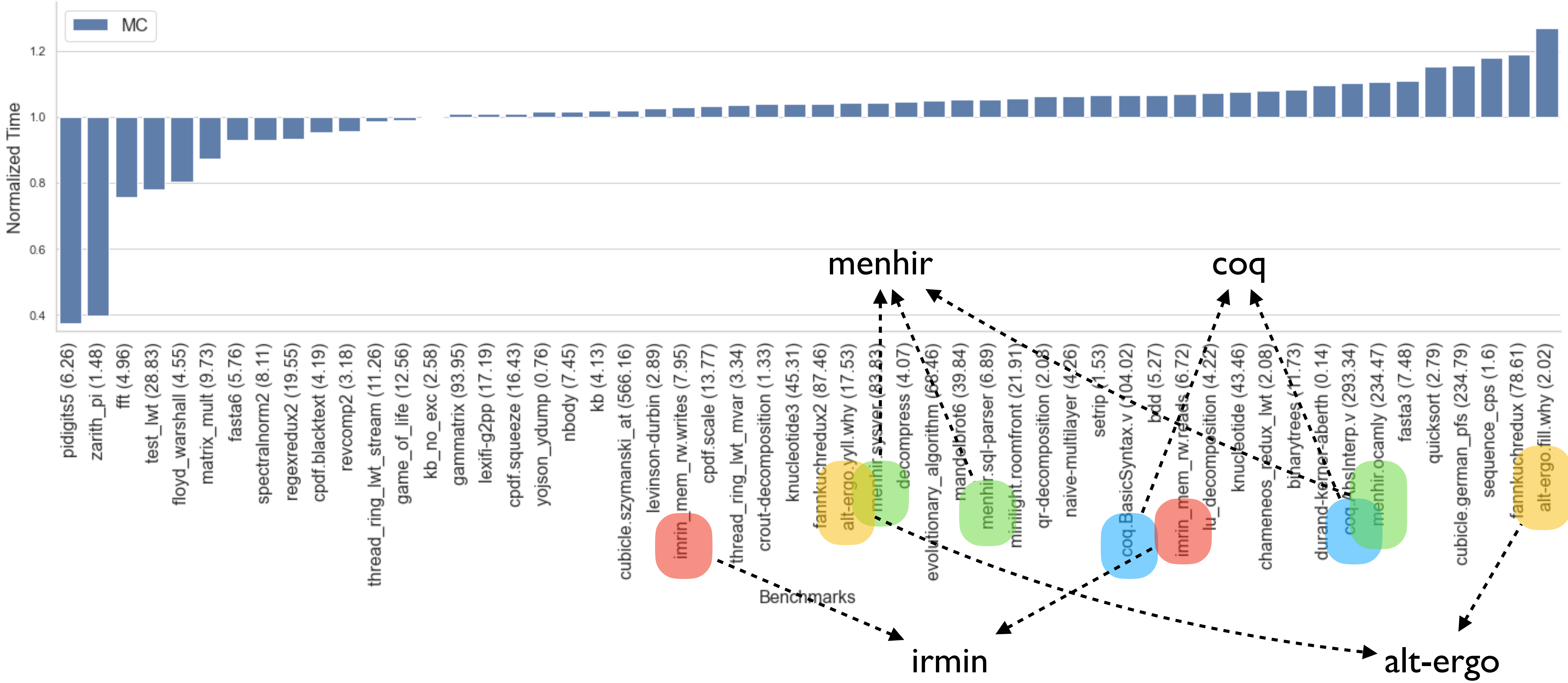
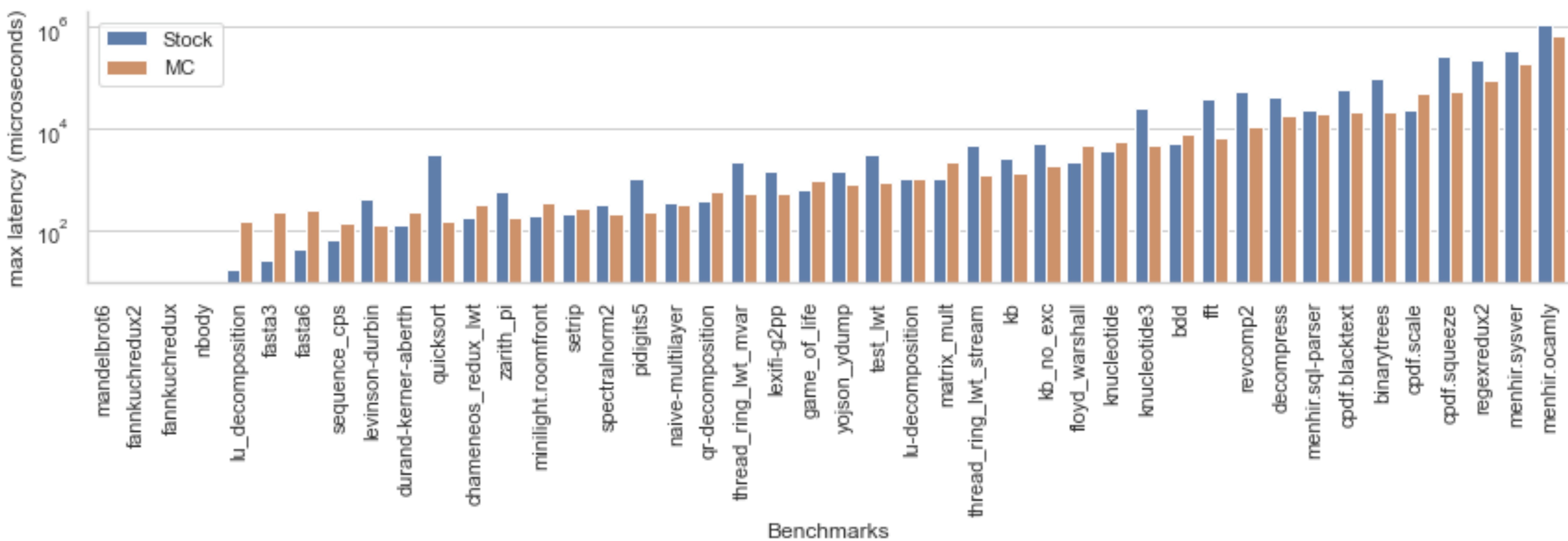


- ~1% faster than stock (geomean of normalised running times)
  - Difference under measurement noise mostly
  - Outliers due to difference in allocators

Sequential Performance: Max pause time



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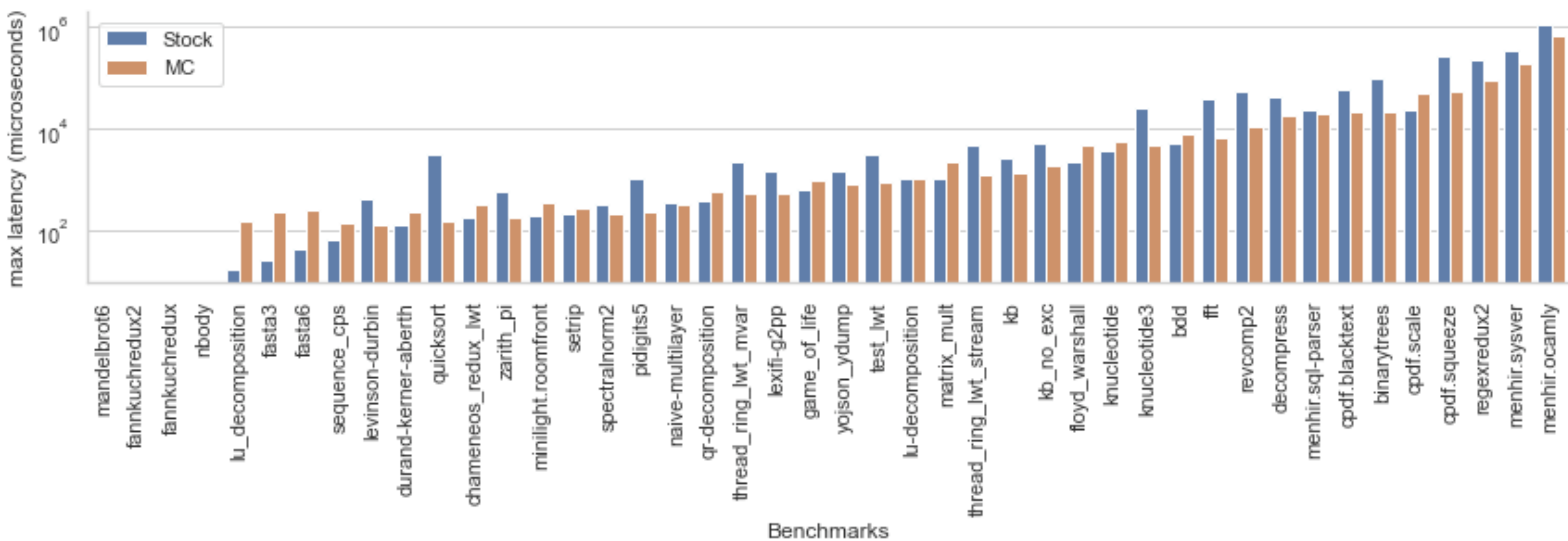

- *Pausetimes are lower under Multicore OCaml than stock OCaml*

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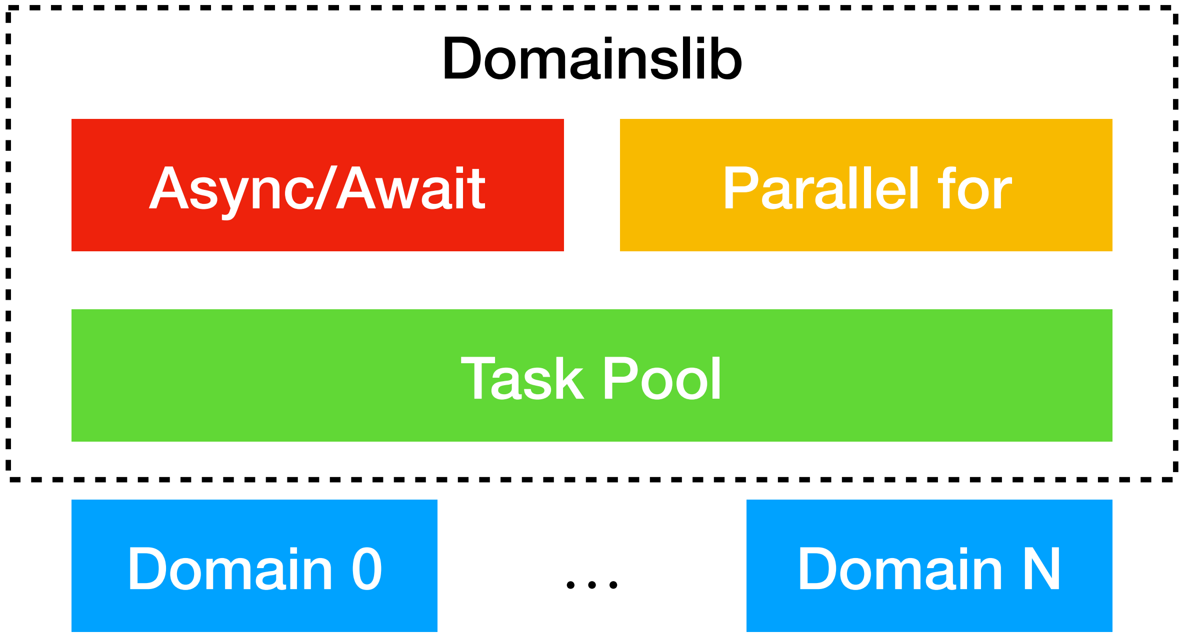

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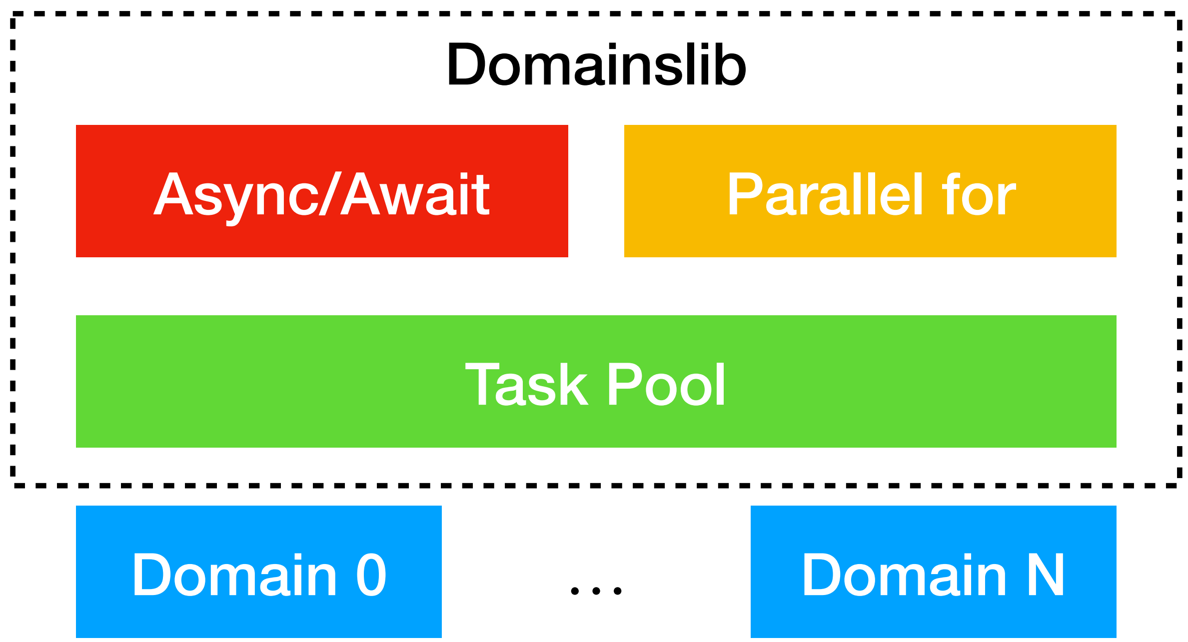

Let's look at examples!

Recursive Fibonacci - Sequential

```
let rec fib n =
  if n < 2 then 1
  else fib (n-1) + fib (n-2)
```

Recursive Fibonacci - Parallel

```
module T = Domainslib.Task
```

```
let fib n =
  let pool = T.setup_pool
    ~num_additional_domains:(num_domains - 1) in
  let res = fib_par pool n in
  T.teardown_pool pool;
  res
```

Recursive Fibonacci - Parallel

```
module T = Domainslib.Task




let rec fib_par pool n =
  if n <= 40 then fib_seq n
  else
    let a = T.async pool (fun _ -> fib_par pool (n-1)) in
    let b = T.async pool (fun _ -> fib_par pool (n-2)) in
    T.await pool a + T.await pool b

let fib n =
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Performance: fib(48)

Cores	Time (Seconds)	Vs Serial	Vs Self
1	37.787	0.98	1
2	19.034	1.94	1.99
4	9.723	3.8	3.89
8	5.023	7.36	7.52
16	2.914	12.68	12.97
24	2.201	**16.79**	**17.17**

Conway's Game of Life

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```
let next () =
  ...
  for x = 0 to board_size - 1 do
    for y = 0 to board_size - 1 do
      next_board.(x).(y) <- next_cell cur_board x y
    done
  done;
  ...
```

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  done;
  ...

let next () =
  ...
  T.parallel_for pool ~start:0 ~finish:(board_size - 1)
    ~body:(fun x ->
       for y = 0 to board_size - 1 do
         next_board.(x).(y) <- next_cell cur_board x y
       done);
  ...
```

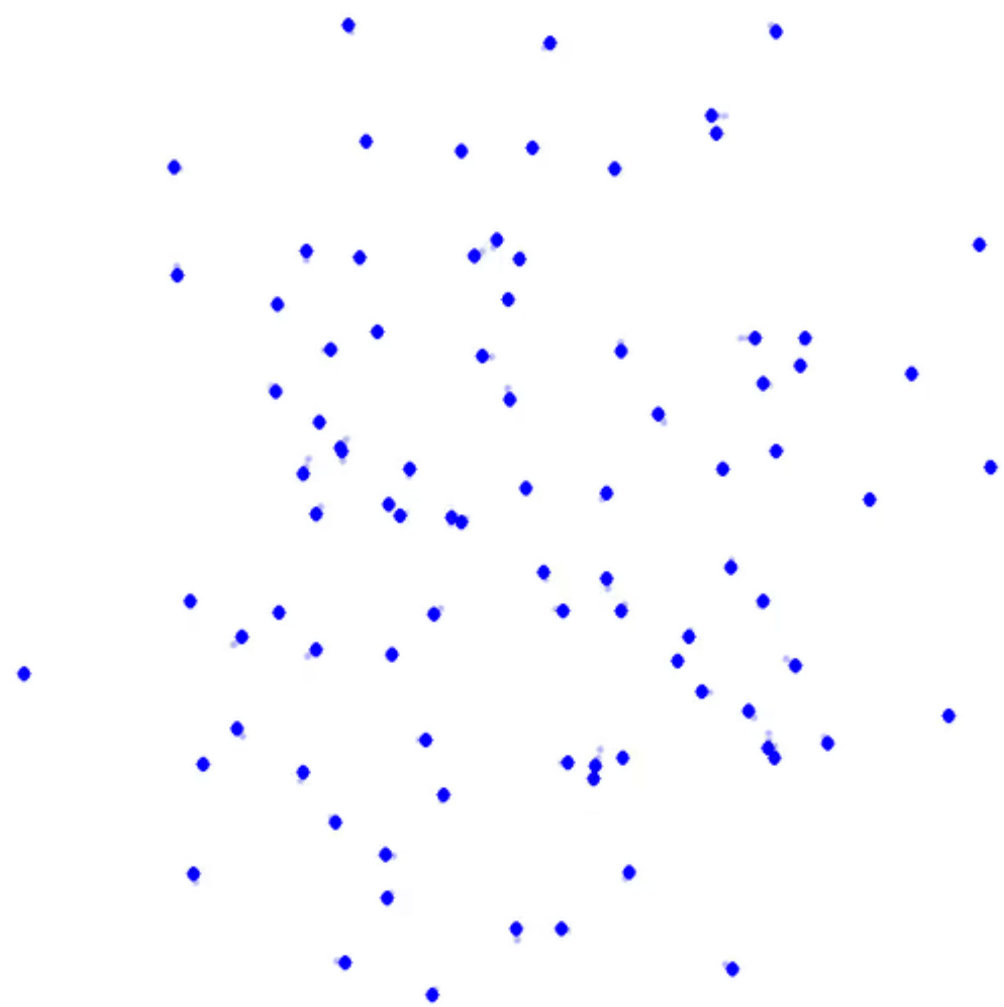
Performance: Game of Life

Board size = 1024, Iterations = 512

Cores	Time (Seconds)	Vs Serial	Vs Self
1	24.326	1	1
2	12.290	1.980	1.98
4	6.260	3.890	3.89
8	3.238	7.51	7.51
16	1.726	14.09	14.09
24	1.212	**20.07**	**20.07**

Performance Hacking: N-body

- Simulates the orbits of large number of astronomical objects
- Taken from computer language benchmarks game



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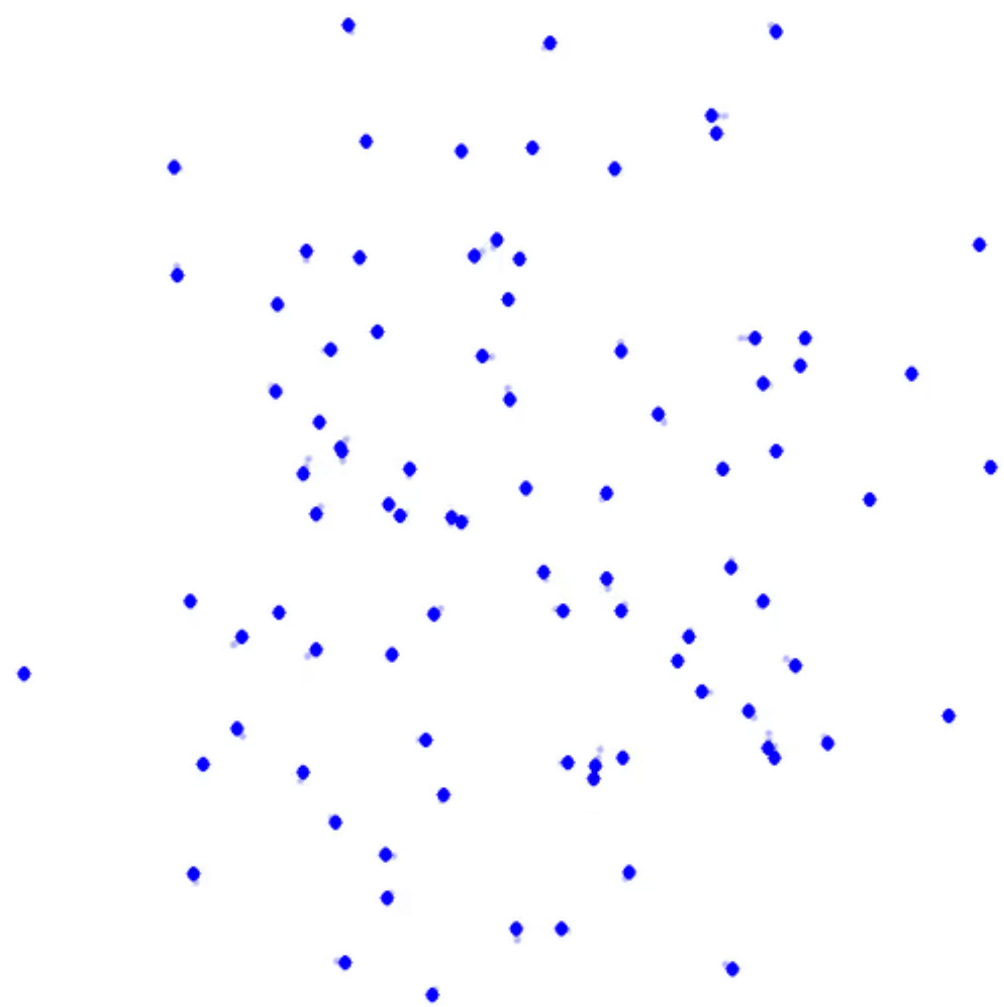

Sequential N-body

```
let advance bodies dt =
  for i = 0 to Array.length bodies - 1 do
    let b = bodies.(i) in
    for j = 0 to Array.length bodies - 1 do
      let b' = bodies.(j) in
      if (i!=j) then begin
        let dx = b.x -. b'.x  and dy = b.y -. b'.y  and dz = b.z -. b'.z in
        let dist2 = dx *. dx +. dy *. dy +. dz *. dz in
        let mag = dt /. (dist2 *. sqrt(dist2)) in
        b.vx <- b.vx -. dx *. b'.mass *. mag;
        b.vy <- b.vy -. dy *. b'.mass *. mag;
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      end
    done
  done;
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$ perf record ./nbody.exe
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```

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$ perf record ./nbody.exe
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```

```
Samples: 17K of event 'cycles:uppp', Event count (approx.): 12363186877
Overhead  Command    Shared Object      Symbol
  99.87%  nbody.exe  nbody.exe          [.] camlDune__exe__Nbody__advance_230
   0.12%  nbody.exe  nbody.exe          [.] camlDune__exe__Nbody__energy_246
   0.00%  nbody.exe  nbody.exe          [.] camlStdlib__domain__get_355
   0.00%  nbody.exe  [kernel]           [k] 0xffffffffb44009e7
```

Parallel N-Body

```
let advance pool bodies dt =
  T.parallel_for pool
    ~start:0
    ~finish:(num_bodies - 1)
    ~body:(fun i ->
      let b = bodies.(i) in
      for j = 0 to Array.length bodies - 1 do
        let b' = bodies.(j) in
        if (i!=j) then begin
          let dx = b.x -. b'.x  and dy = b.y -. b'.y  and dz = b.z -. b'.z in
          let dist2 = dx *. dx +. dy *. dy +. dz *. dz in
          let mag = dt /. (dist2 *. sqrt(dist2)) in
          b.vx <- b.vx -. dx *. b'.mass *. mag;
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- ~5X speedup on 8 cores compared to sequential version.

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- *Can we do better?*

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        end
      done);
```

- ~5X speedup on 8 cores compared to sequential version.
- *Can we do better?*
- All the domains writing to the same shared array *bodies* in the inner loop
  - Leads to poor cache behaviour

Parallel N-Body (cache friendly)

```
let advance pool bodies dt =
  T.parallel_for pool
    ~start:0
    ~finish:(num_bodies - 1)
    ~body:(fun i ->
      let b = bodies.(i) in
      let vx, vy, vz = ref b.vx, ref b.vy, ref b.vz in
      for j = 0 to Array.length bodies - 1 do
        let b' = bodies.(j) in
        if (i!=j) then begin
          let dx = b.x -. b'.x  and dy = b.y -. b'.y  and dz = b.z -. b'.z in
          let dist2 = dx *. dx +. dy *. dy +. dz *. dz in
          let mag = dt /. (dist2 *. sqrt(dist2)) in
          vx := !vx -. dx *. b'.mass *. mag;
          vy := !vy -. dy *. b'.mass *. mag;
          vz := !vz -. dz *. b'.mass *. mag;
        end
      done;
      b.vx <- !vx;
      b.vy <- !vy;
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          vx := !vx -. dx *. b'.mass *. mag;
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        end
      done;
      b.vx <- !vx;
      b.vy <- !vy;
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```

- 22% faster than the unoptimised version

Parallel N-Body (cache friendly)

```
kc@kaveri:~/temp/nbody$ perf stat -e cycles,cycle_activity.cycles_no_execute,cycle_activity.stalls_mem_any,
mem_load_uops_l3_miss_retired.remote_hitm ./_build/default/nbody_multicore.exe 8
10745700105645904.000000000
10745765317367518.000000000

 Performance counter stats for './_build/default/nbody_multicore.exe 8':

    16,919,777,849      cycles
     4,099,415,910      cycle_activity.cycles_no_execute
     3,864,941,761      cycle_activity.stalls_mem_any
         1,374,487      mem_load_uops_l3_miss_retired.remote_hitm

       0.861178677 seconds time elapsed

kc@kaveri:~/temp/nbody$ perf stat -e cycles,cycle_activity.cycles_no_execute,cycle_activity.stalls_mem_any,
mem_load_uops_l3_miss_retired.remote_hitm ./_build/default/nbody_multicore_optimised.exe 8
10745700105645904.000000000
10745765317367518.000000000

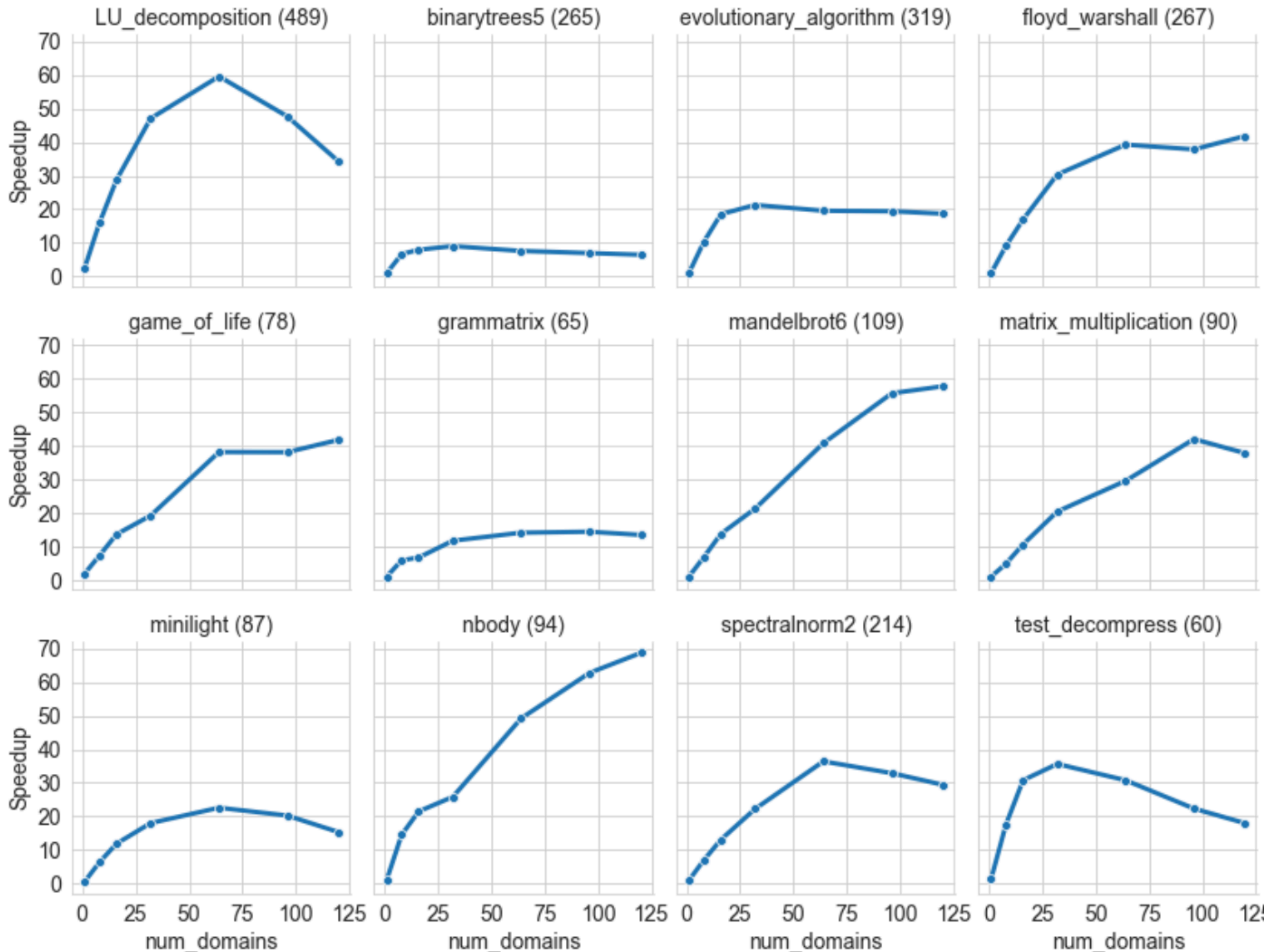
 Performance counter stats for './_build/default/nbody_multicore_optimised.exe 8':

    13,993,448,825      cycles
     2,926,815,349      cycle_activity.cycles_no_execute
     2,844,213,127      cycle_activity.stalls_mem_any
           409,388      mem_load_uops_l3_miss_retired.remote_hitm

       0.701971803 seconds time elapsed
```

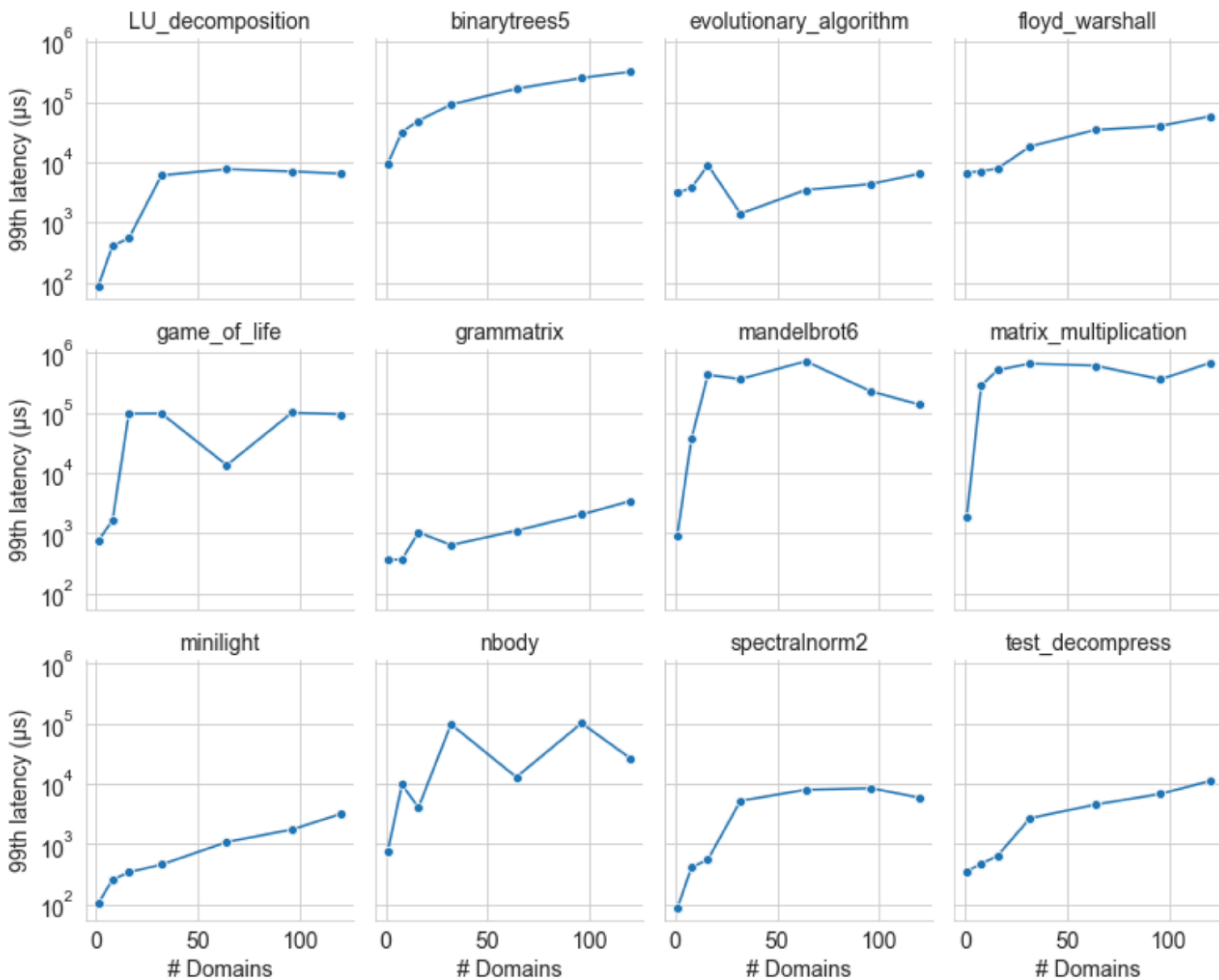
https://www.brendangregg.com/linuxperf.html

Parallel Scalability



On 4 x 32-core AMD EPYC 7551

Parallel Latency



Summary

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- Sivaramakrishnan et al, "*Retrofitting Parallelism onto OCaml*", ICFP 2020