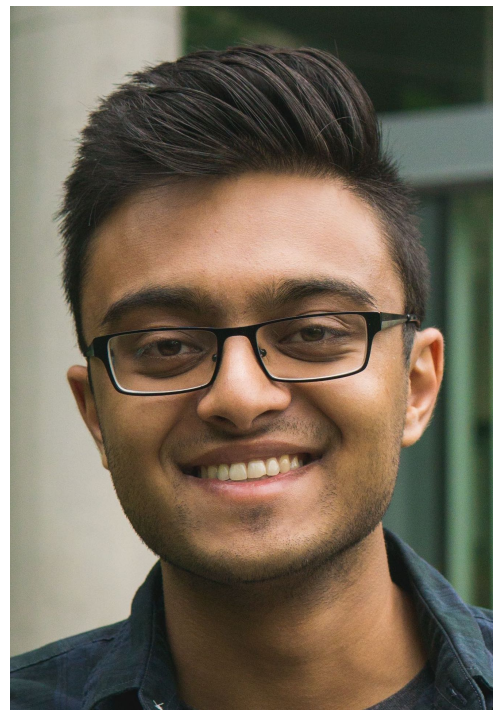
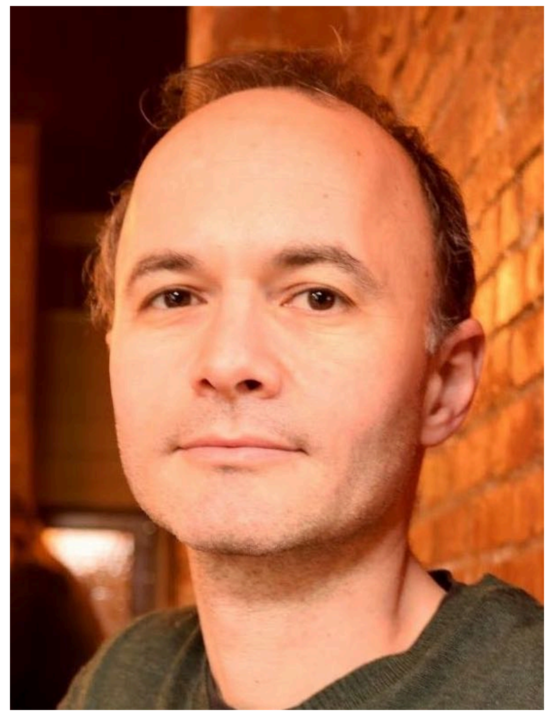
Disentanglement: Provably Efficient Parallel Functional Programming

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Parallel Programming

imperative

mutability
manual memory management
race conditions

immutability
automatic memory management
deterministic by default

functional

fast

can parallel functional programming be fast and scalable ?

slow?

Parallel Programming

imperative

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manual memory management
race conditions

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automatic memory management
deterministic by default

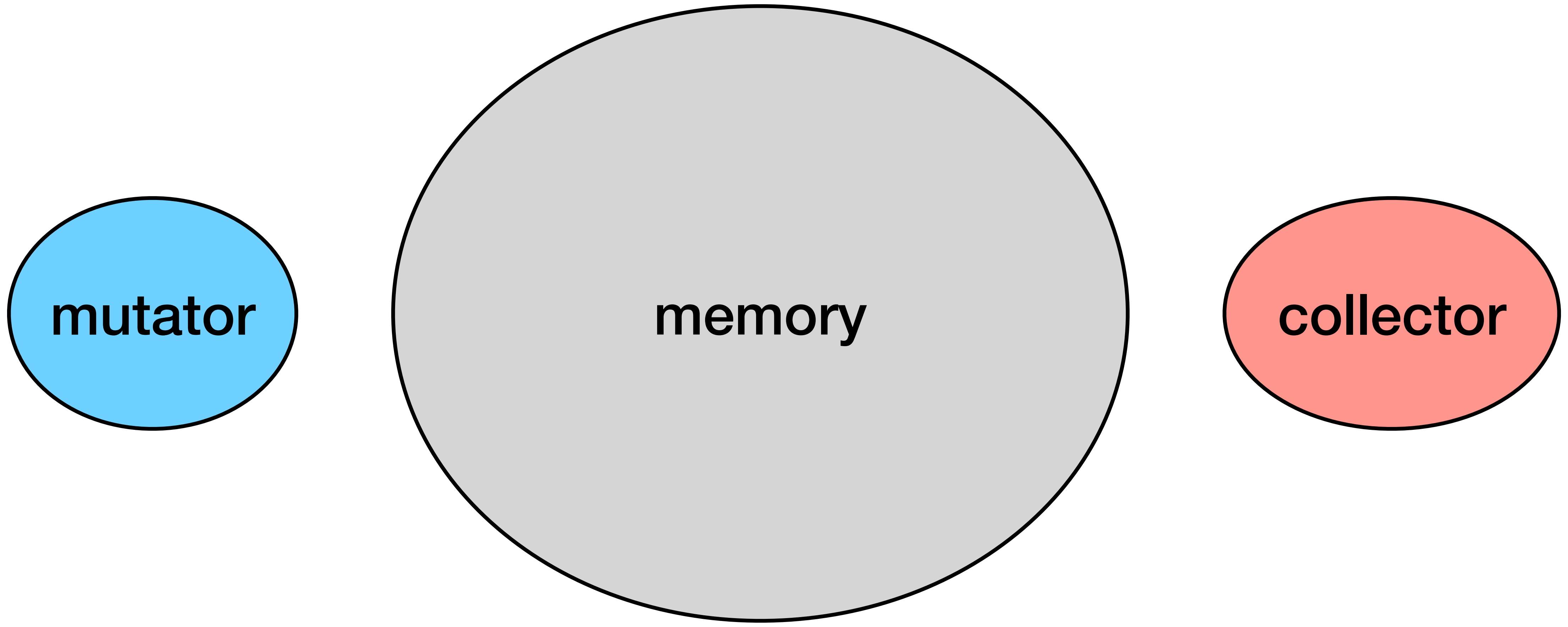
functional

high rate of allocation
heavy reliance on GC

fast

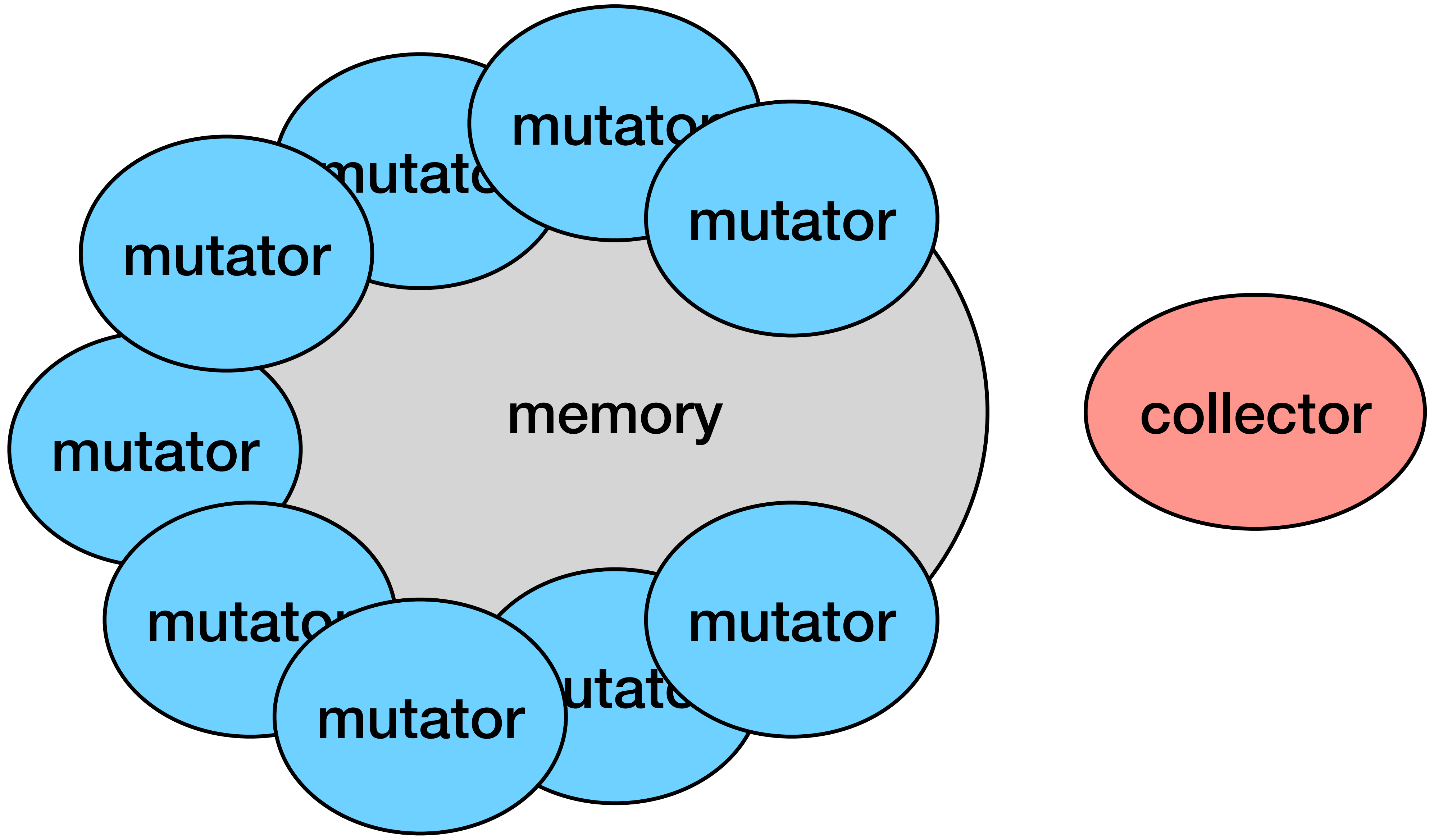
can parallel functional programming be fast and scalable ?

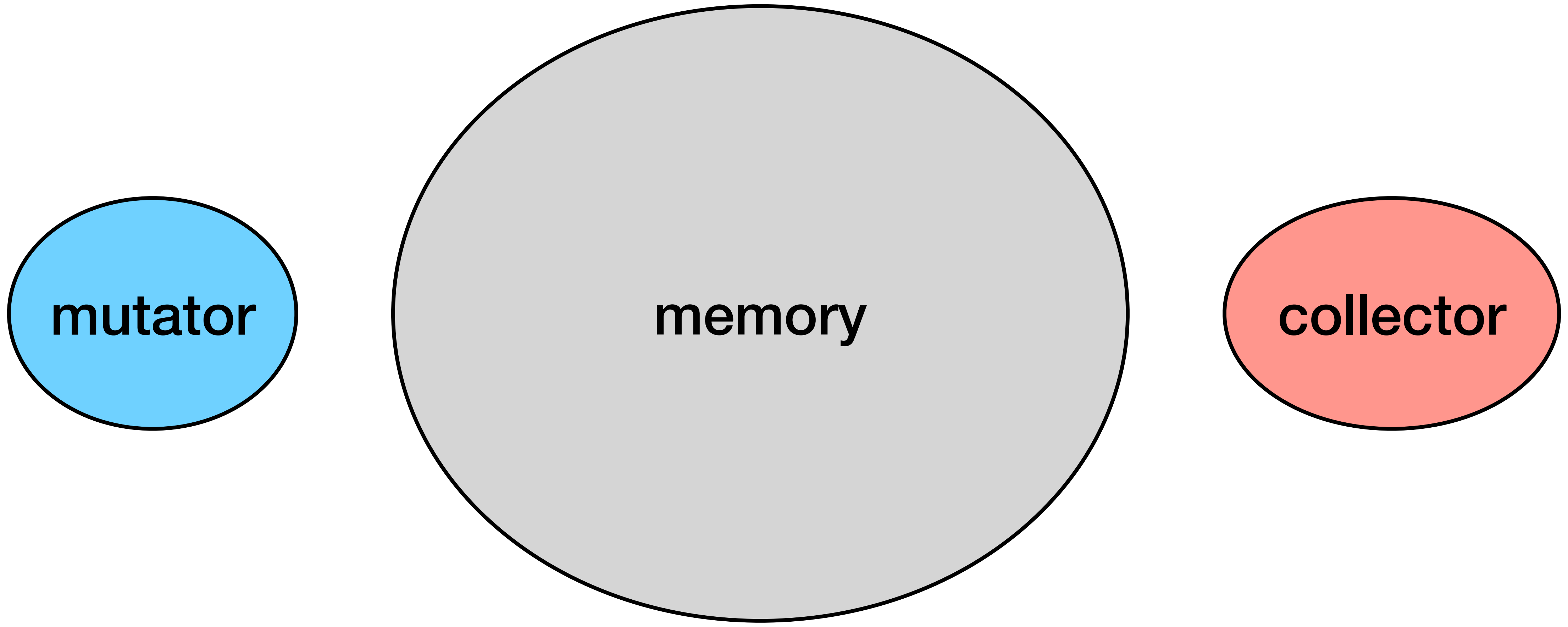
slow?



Sequential

Parallel





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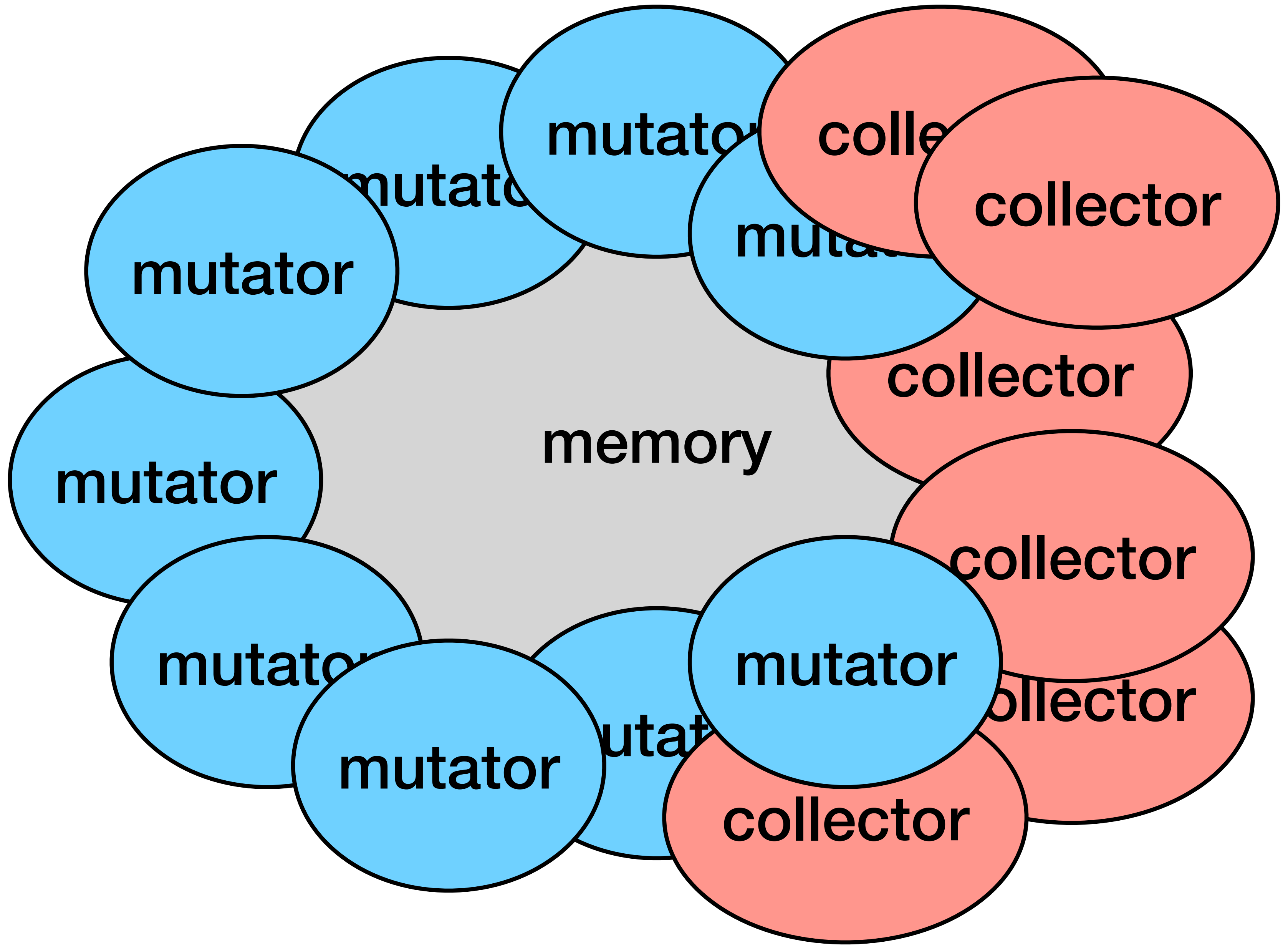
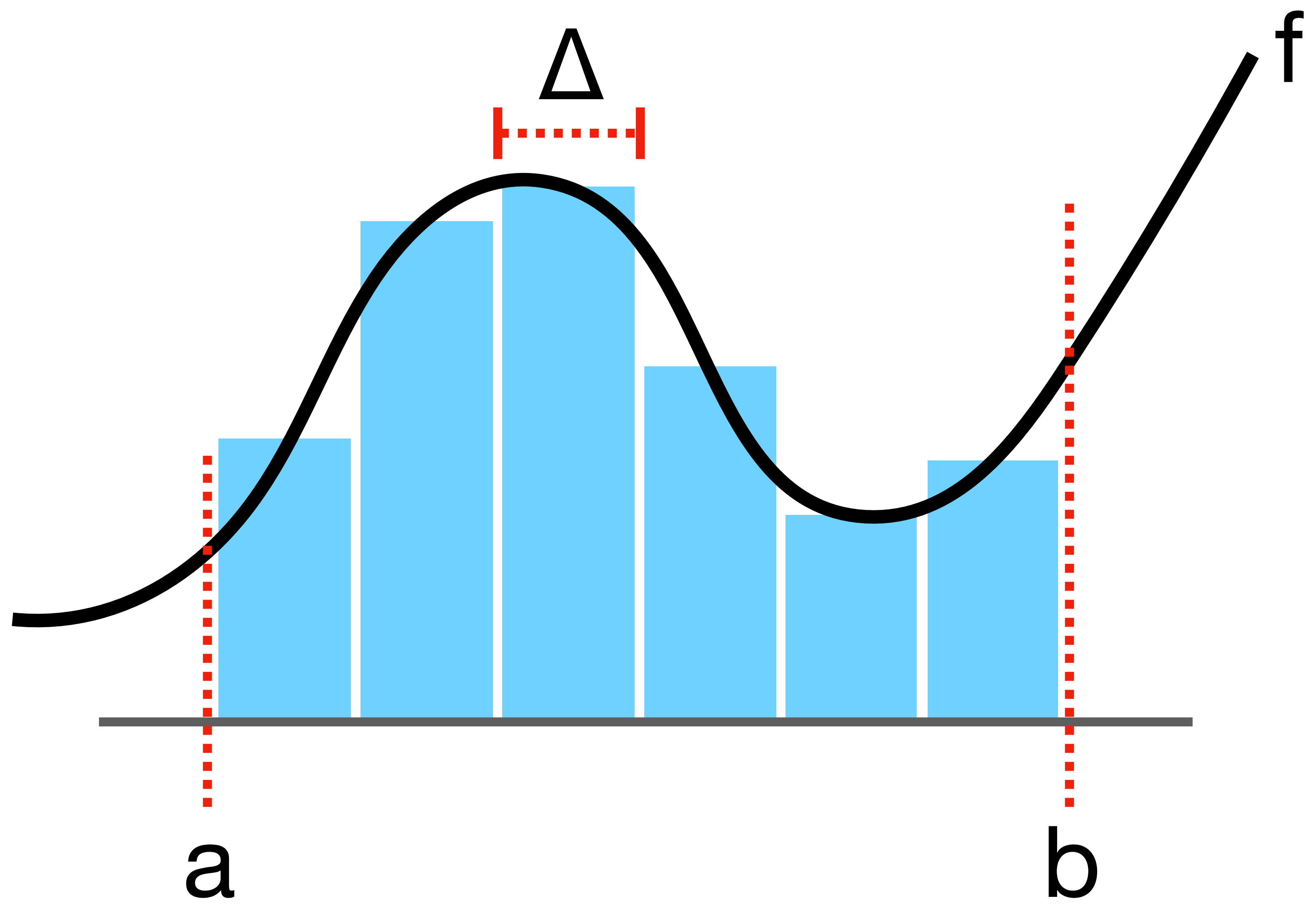


Is there a better way?

Example: Numerical Integration

```
function integrate(f, a, b, n) {
  Δ = (b-a) / n
  heights = tabulate(n, fn i => f(a + Δ/2 + i*Δ) )
  return Δ * reduce(heights, fn (a,b) => a+b )
}
```

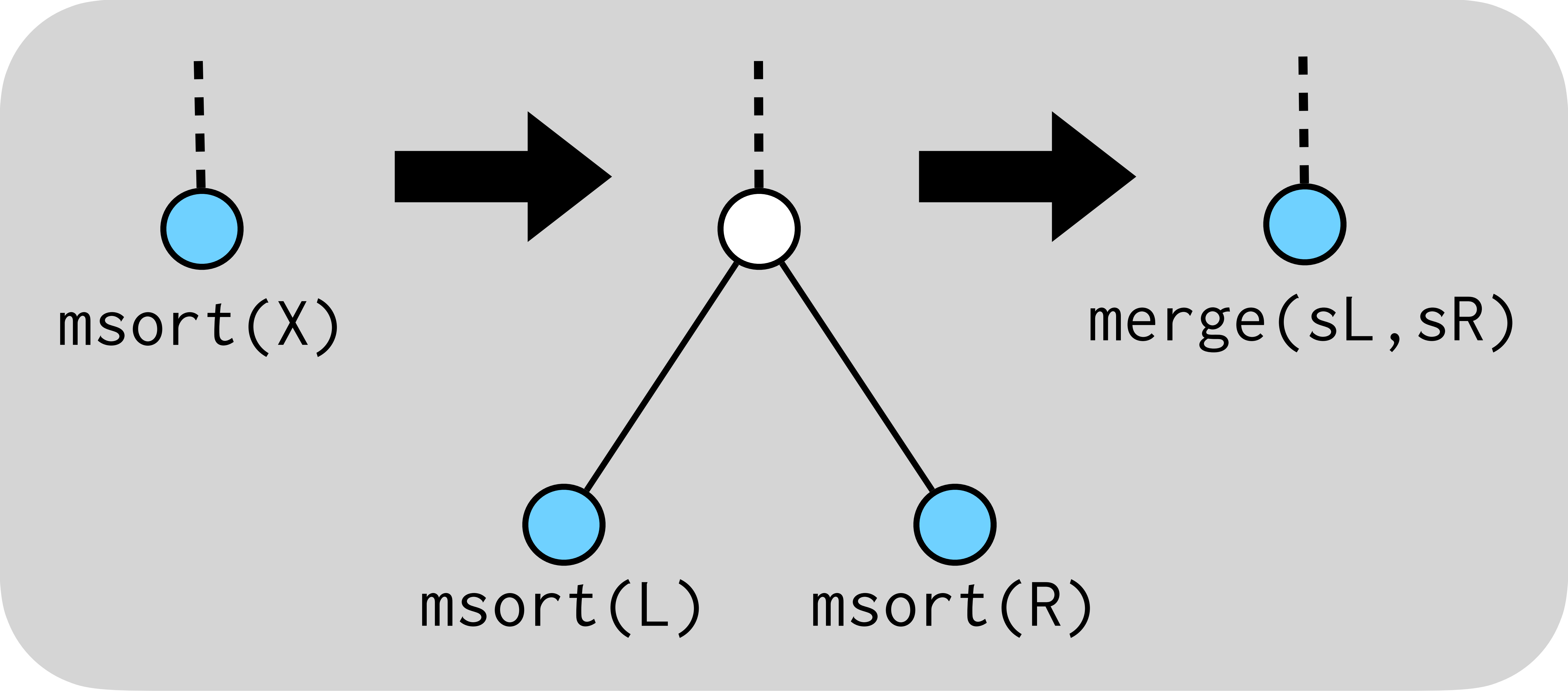


O(n) work
O(log n) span

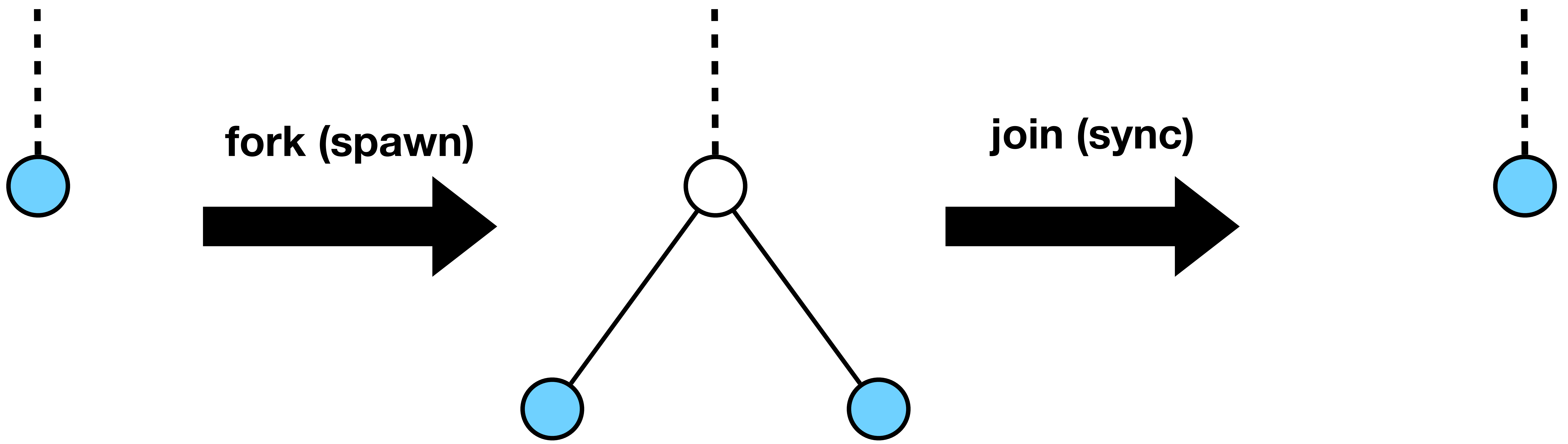
Example: Mergesort

```
function msort(X) {
  if length(X) <= 1 return X
  L, R = split(X)
  sL, sR = par(msort(L), msort(R))
  return merge(sL, sR)
}
```

O(n log n) work
O($\log^k$ n) span



Task-Local Heaps



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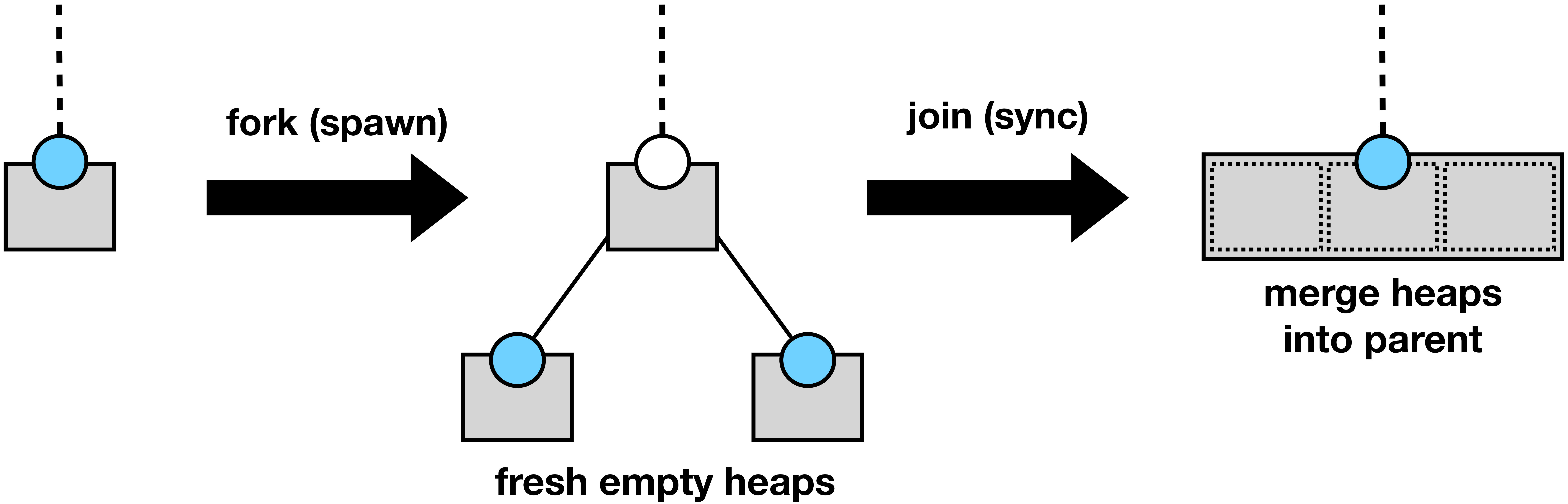
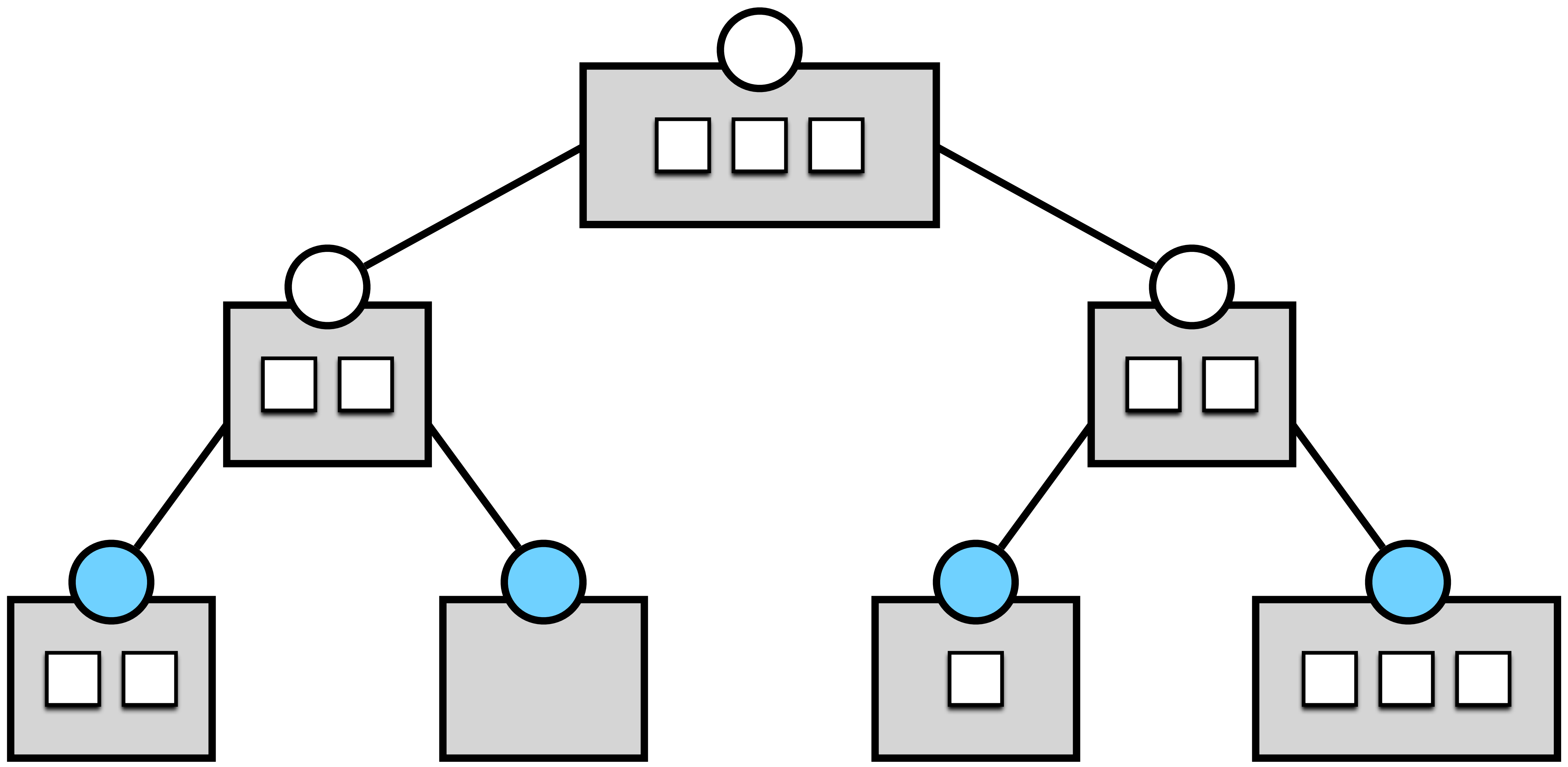


Disentanglement

definition
throughout execution, each task may only use data in **local** or **ancestor** heaps



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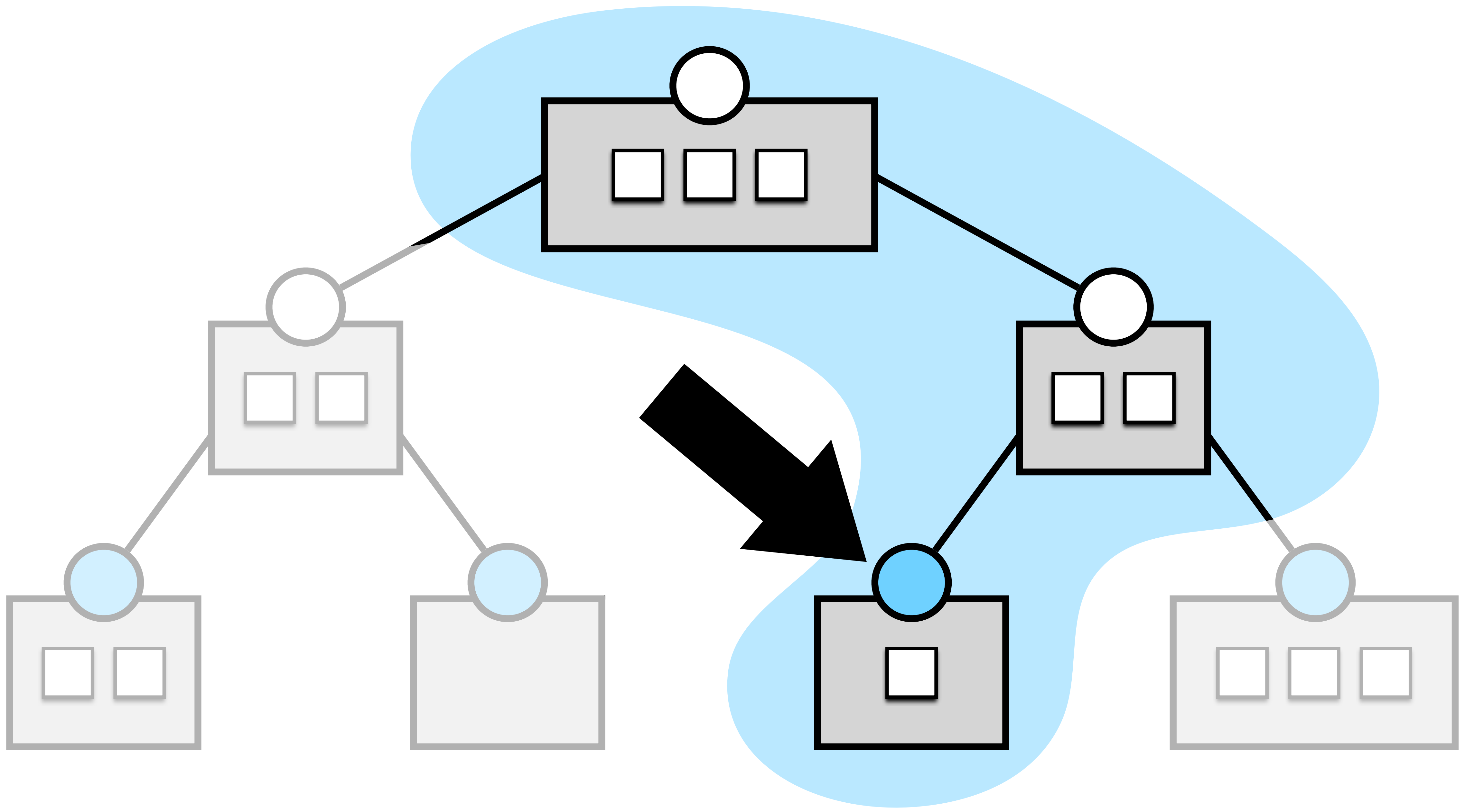

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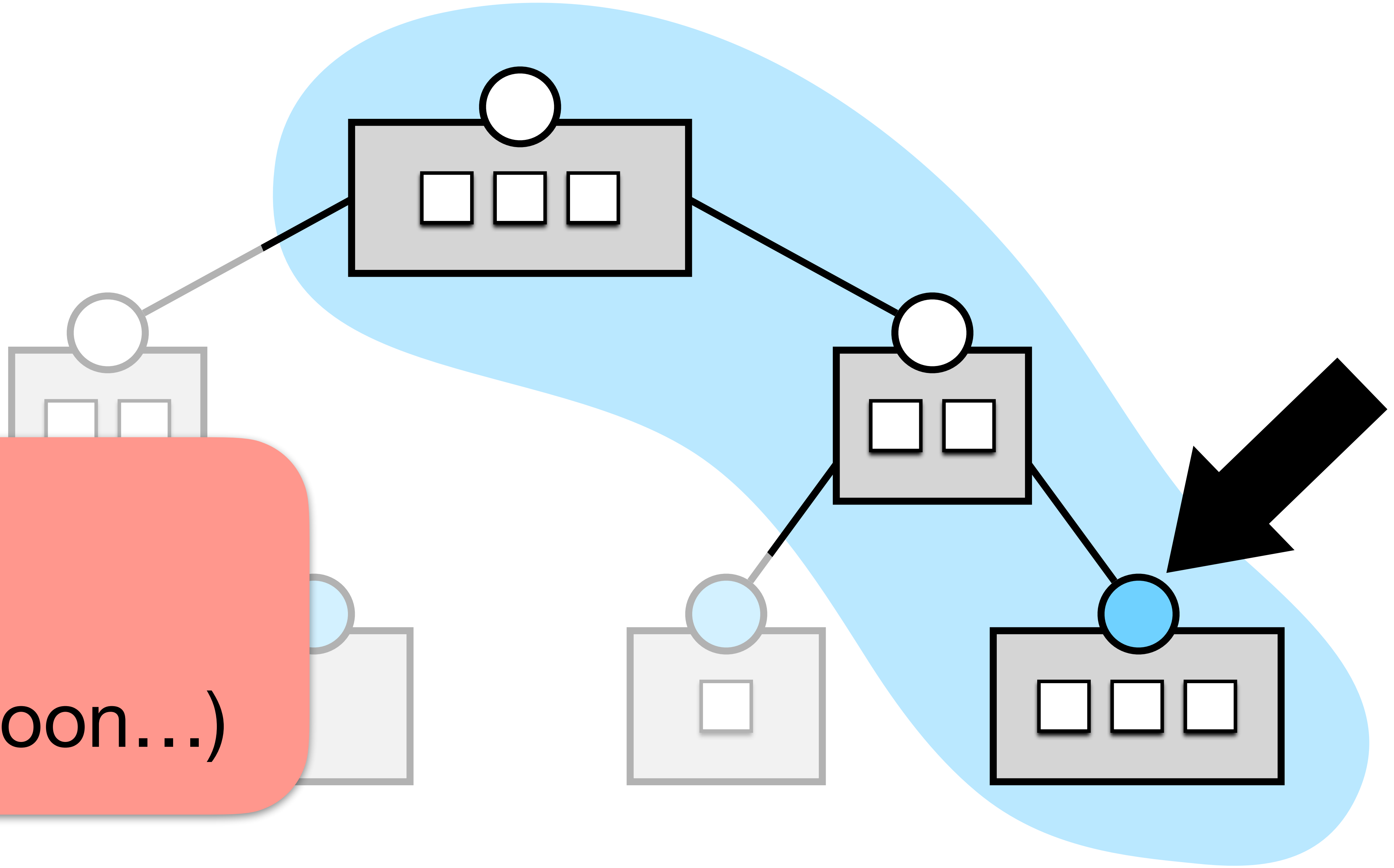
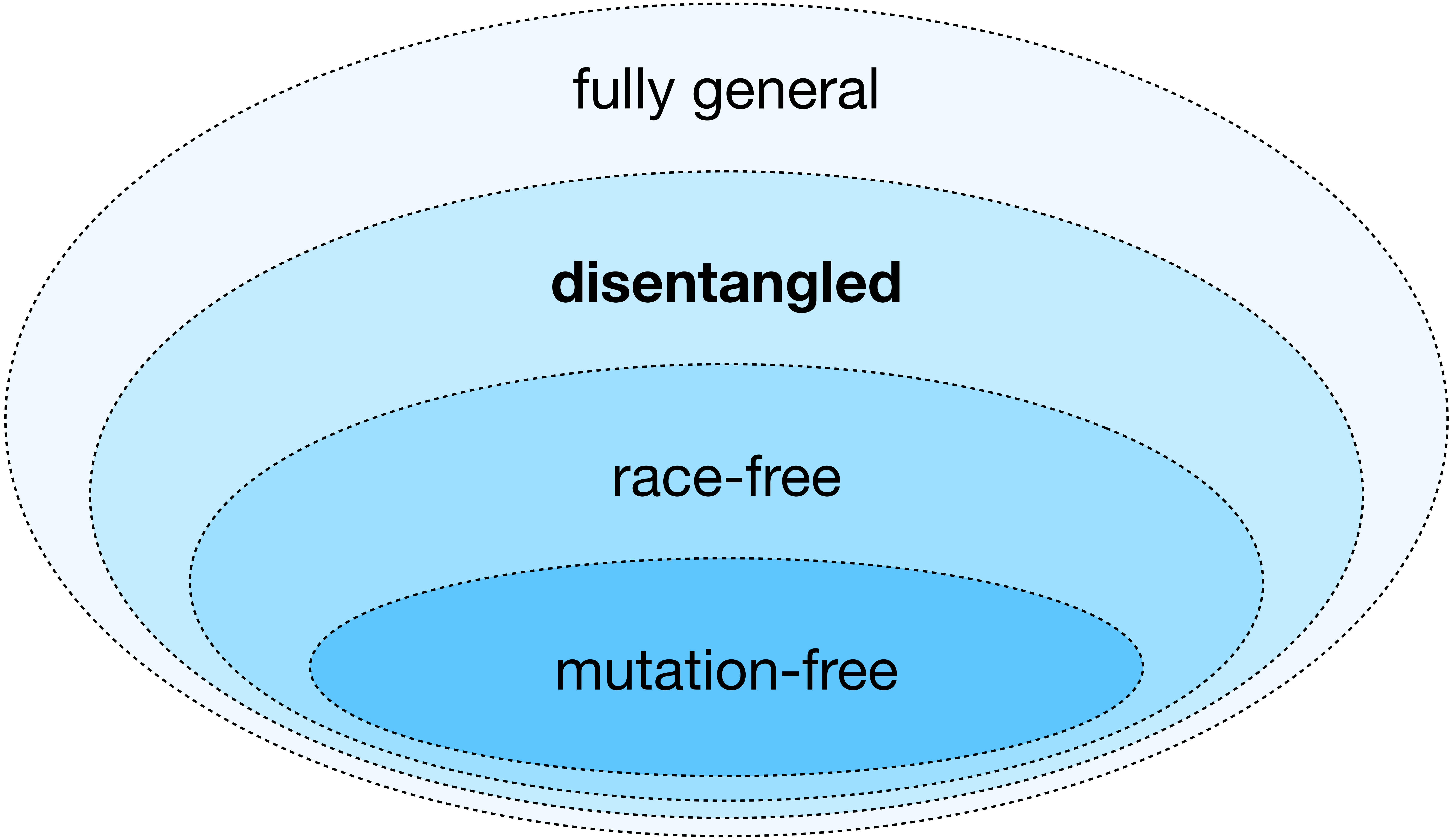


Why do we care?
Hint: parallel GC
(will get back to this soon…)

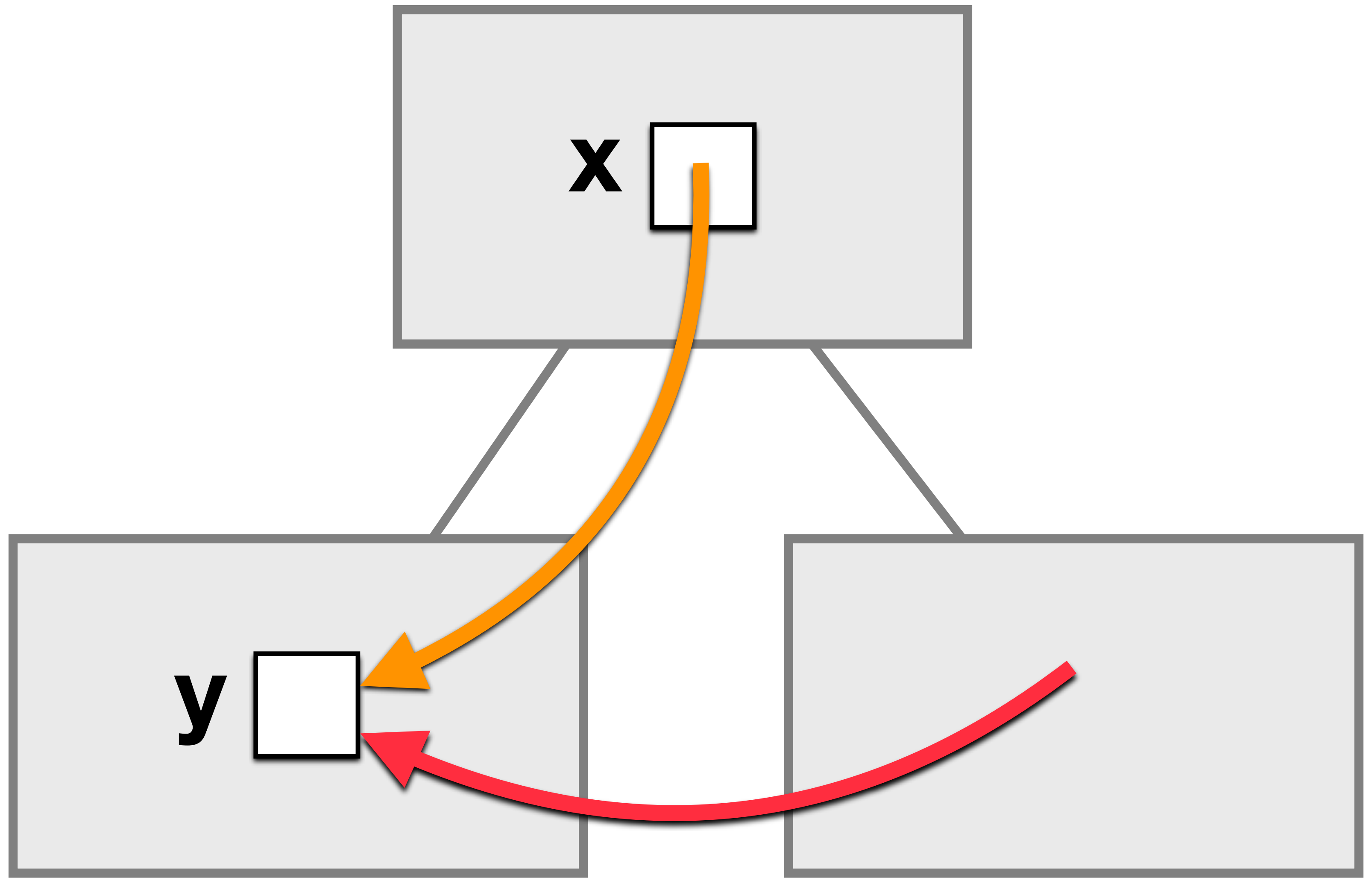
What programs are disentangled?



theorem [Westrick et al., POPL 20]
all race-free programs are disentangled

Intuition

- if entangled, must have read **down-pointer**
- down-pointer must have been created by concurrent write
- so, program has read/write race




```
y = malloc()        |  ...
*x = y              |  ...
...                 |  z = *x
```

Proof Sketch

- **single-step invariant:**
  if location *X* accessible without a race, then *neighbors(X)* are in root-to-leaf path
- carry invariant through race-free execution

Disentanglement in the Wild

Ligra

- BFS
- betweenness centrality
- Bellman-Ford
- *k*-Core
- Page Rank
- maximal independent set
- eccentricity estimation

PBBS

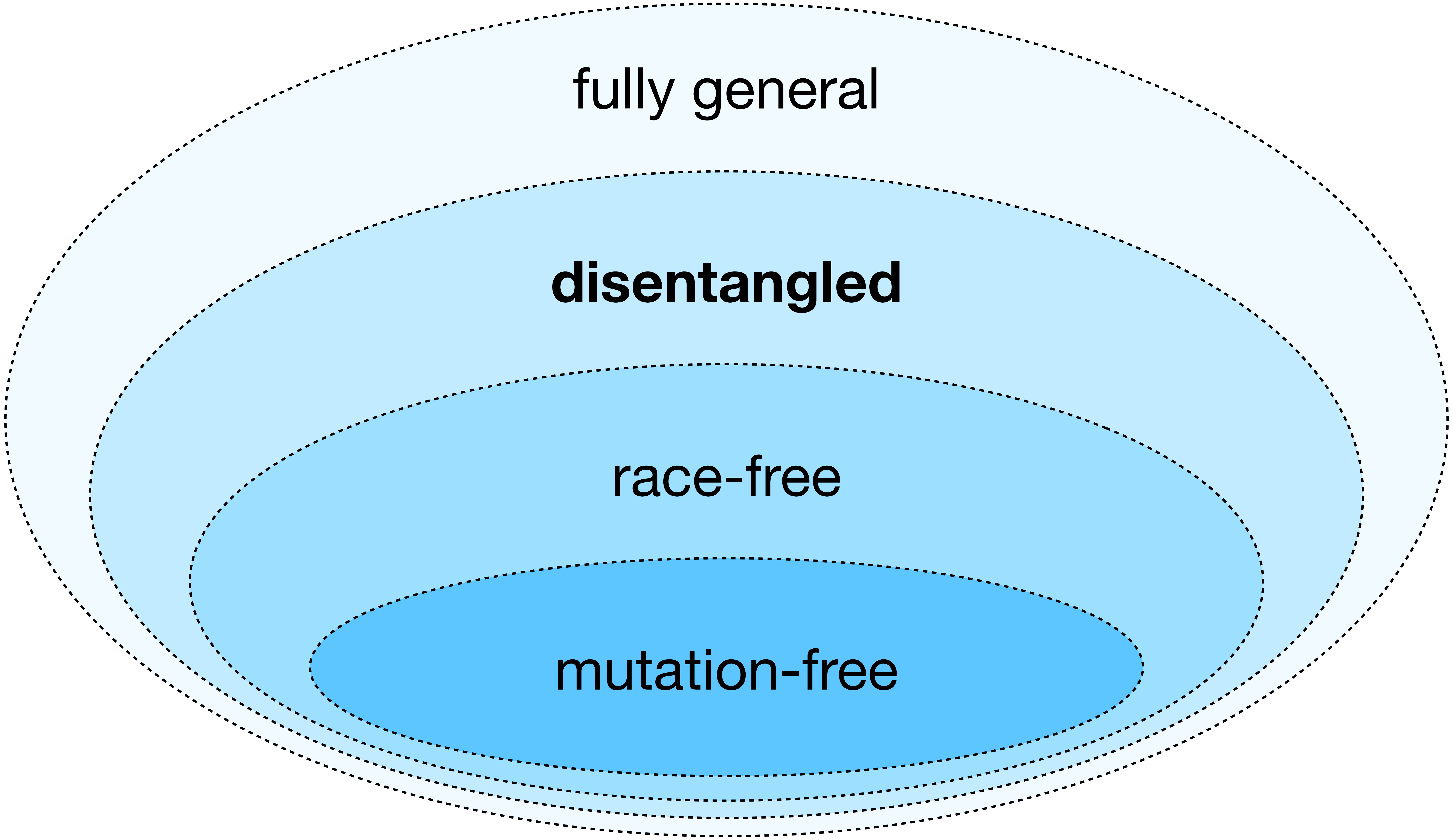
- quickhull
- deduplication
- sorting
- minimum spanning forest
- suffix array
- Barnes-Hut
- nearest neighbors
- ray casting

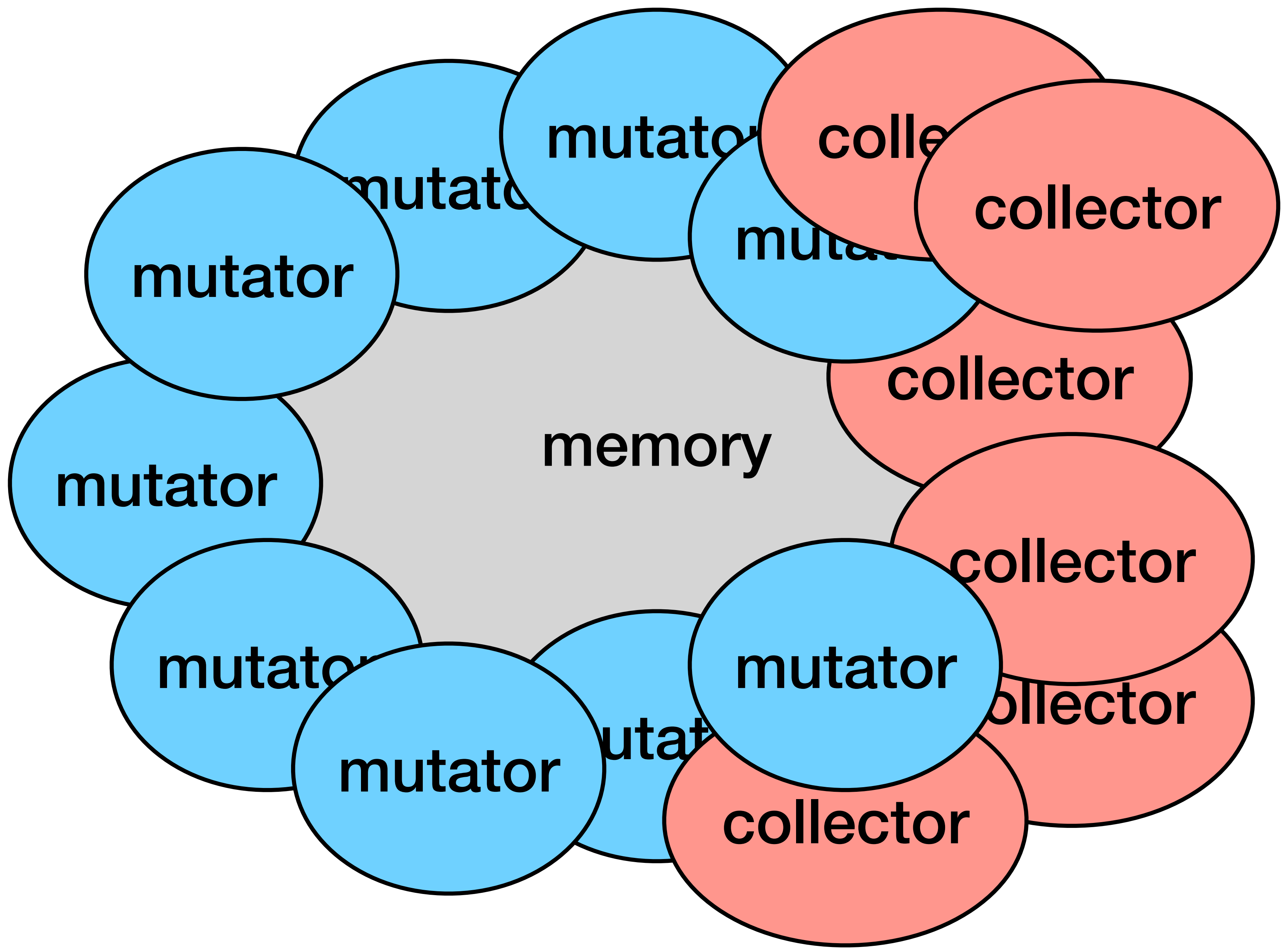
all disentangled

(and likely others too)

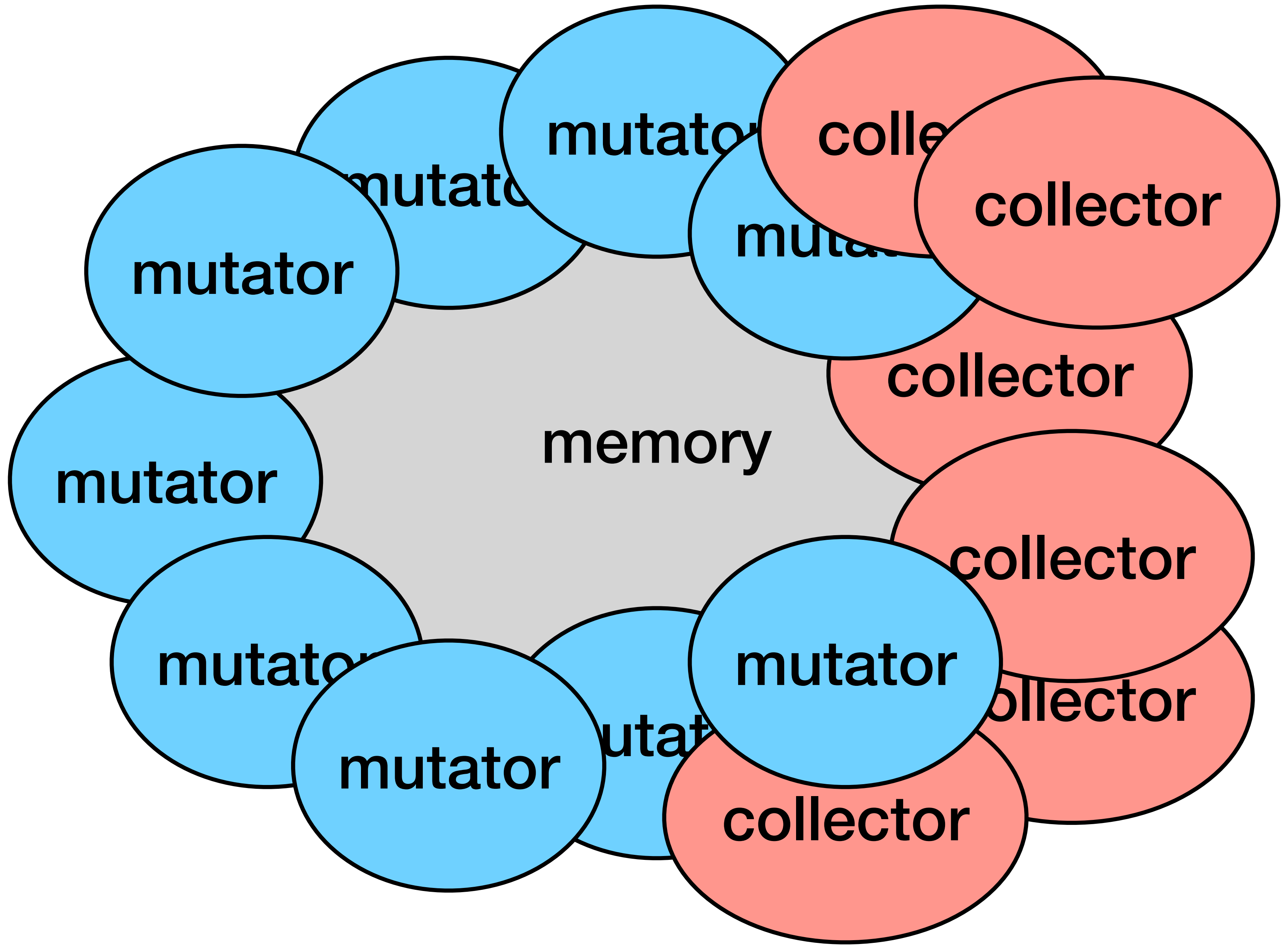
many benign races

What programs are disentangled?





Is there a better way?


mutator
mutator
memory
mutator
mutator
collector
collector
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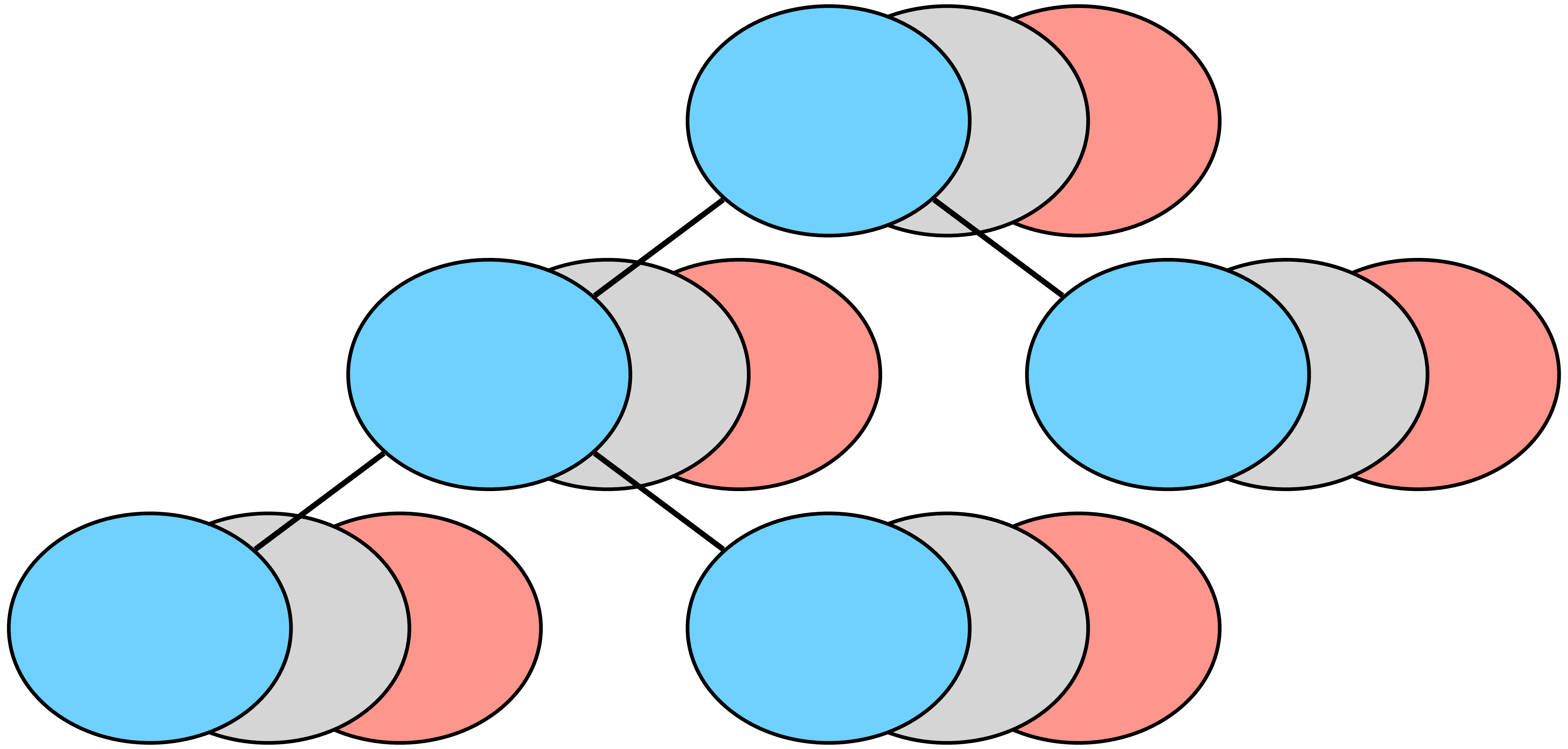
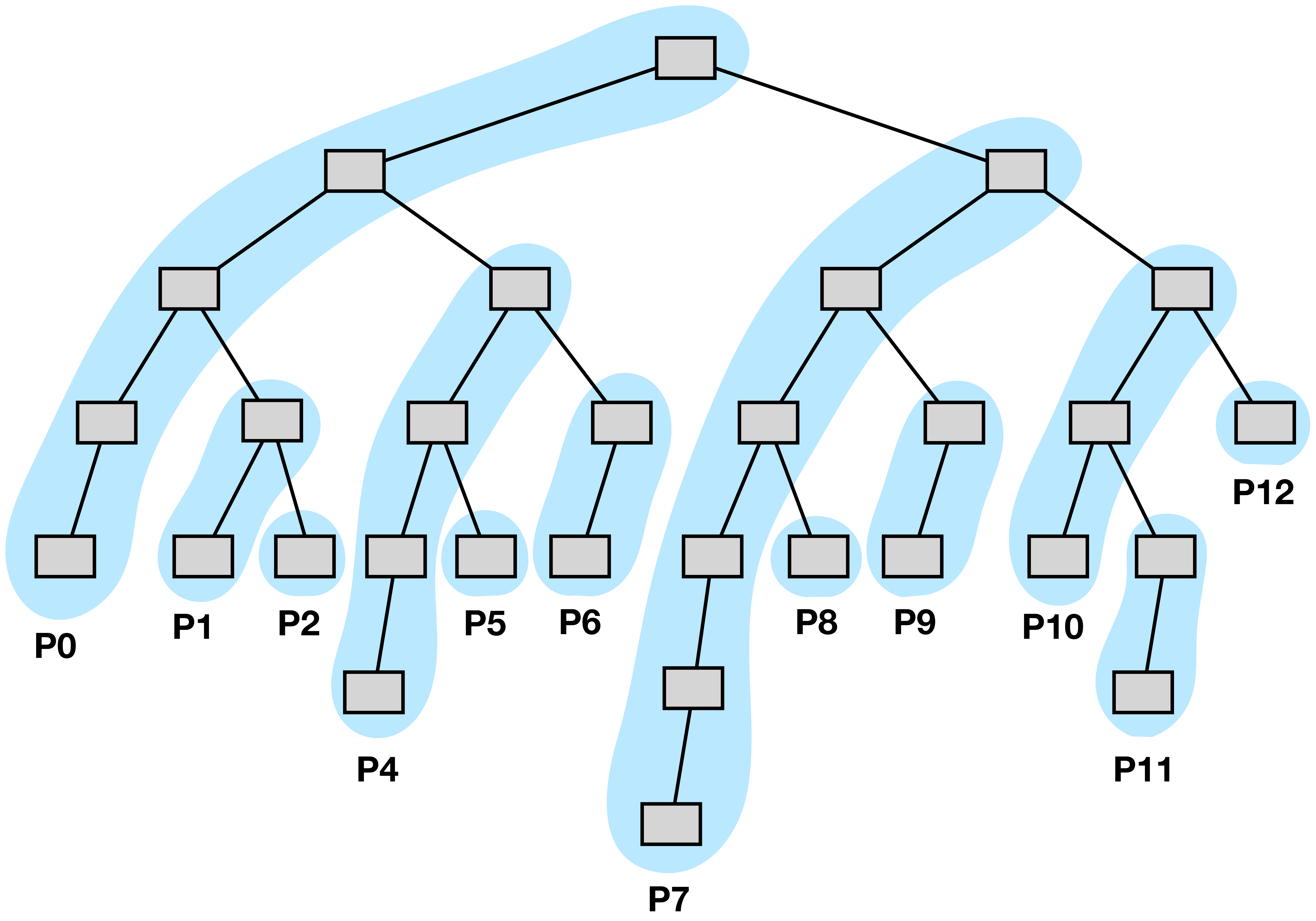
collector



Heap Scheduling

- goal: assign heaps to processors
- each processor manages its own memory



Heap Scheduling

- goal: assign heaps to processors
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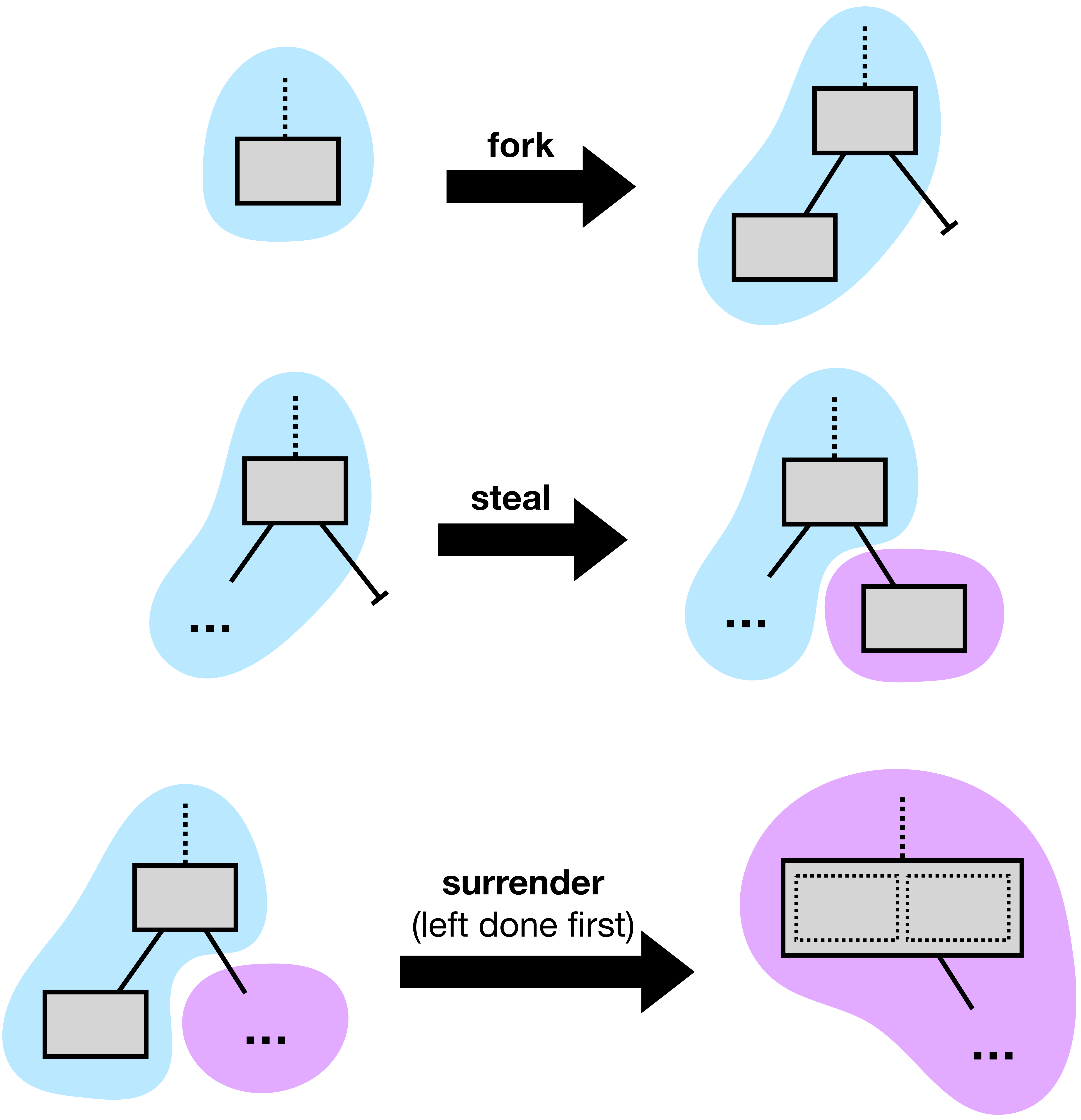
- **integrate closely with thread scheduling** (work-stealing)
  - **fork**: new heap on left, assign to *same* proc
  - **steal:** new heap on right, assign to *new* proc
  - **surrender**: at join, give heaps to sibling



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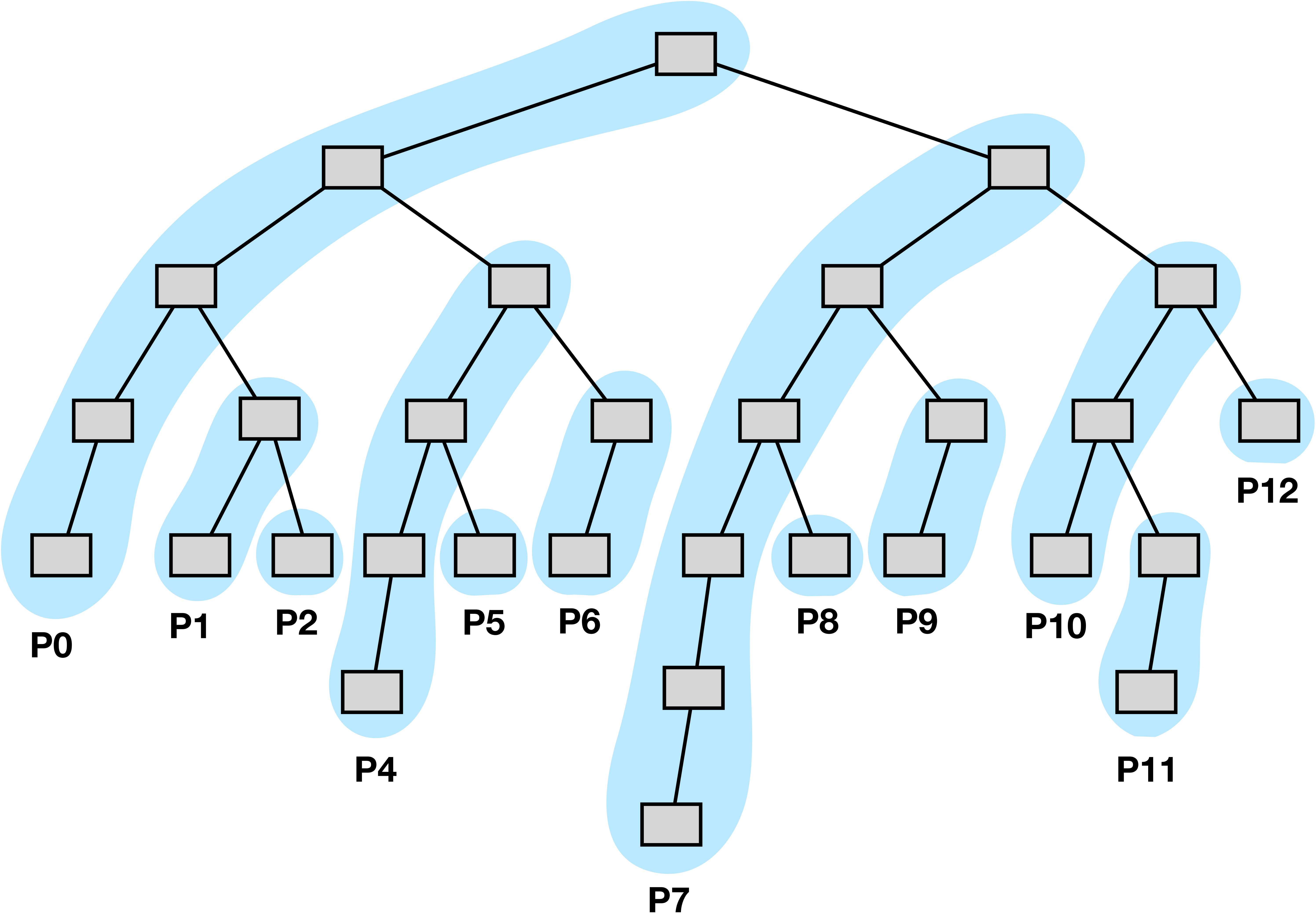
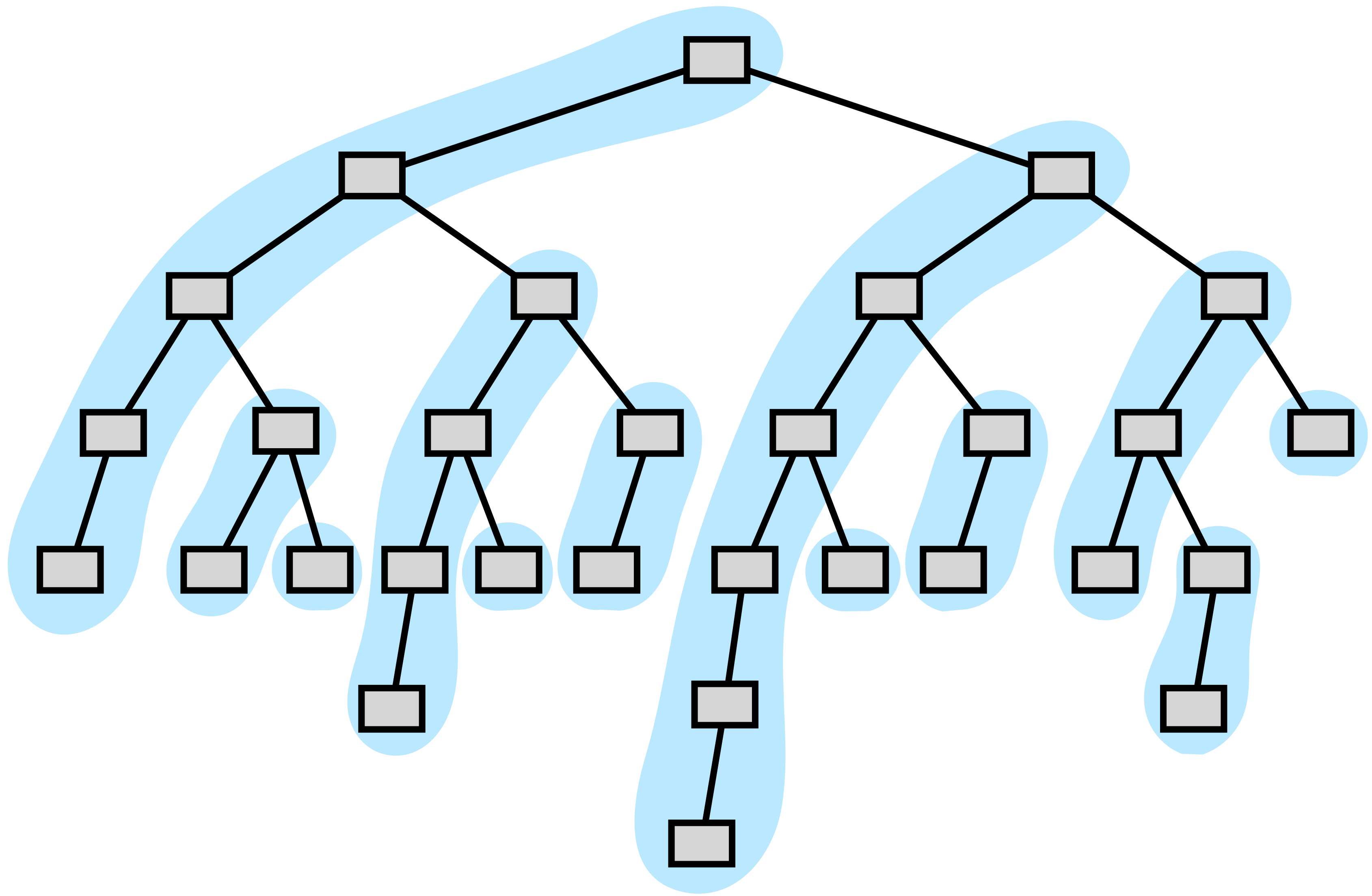


Collection Policy



algorithm
- each processor ***p*** has local counter L_p
- when cumulative size of ***p***'s heaps exceeds $k{\cdot}L_p$:
  - processor ***p*** performs GC on its heaps
  - set L_p to amount of memory that survives

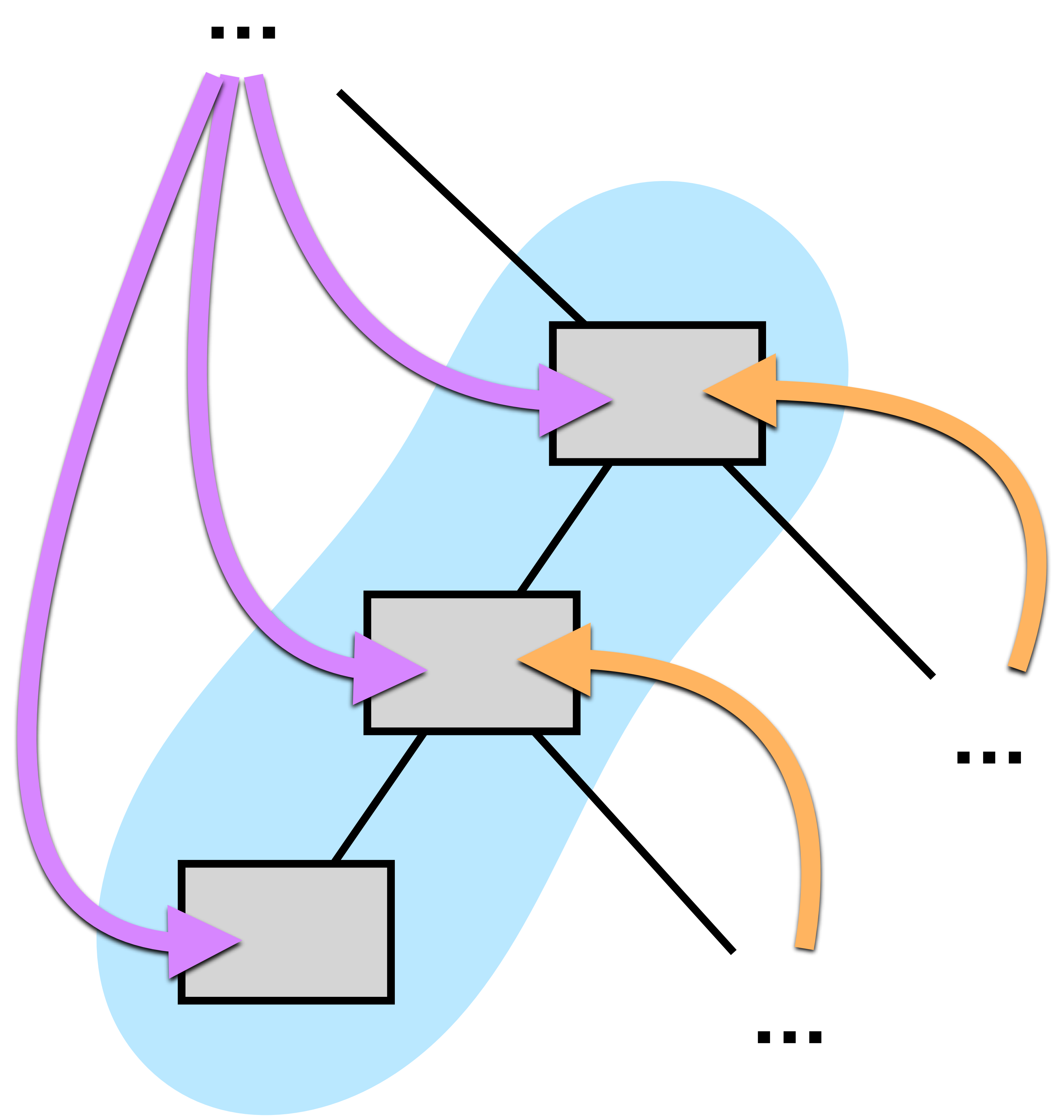
theorem [Arora et al., POPL 21]
a race-free program with work ***W*** and sequential space R^* requires $O(P{\cdot}R^*)$ space and $O(W + P{\cdot}R^*)$ work, including costs of memory management

Key ideas:

- after surrender, heaps resemble sequential execution
  - left-before-right, or right-before-left?
  - "unordered reachable space" R^* allows for both
- local counters L_p cannot exceed R^*

Disentangled Garbage Collection

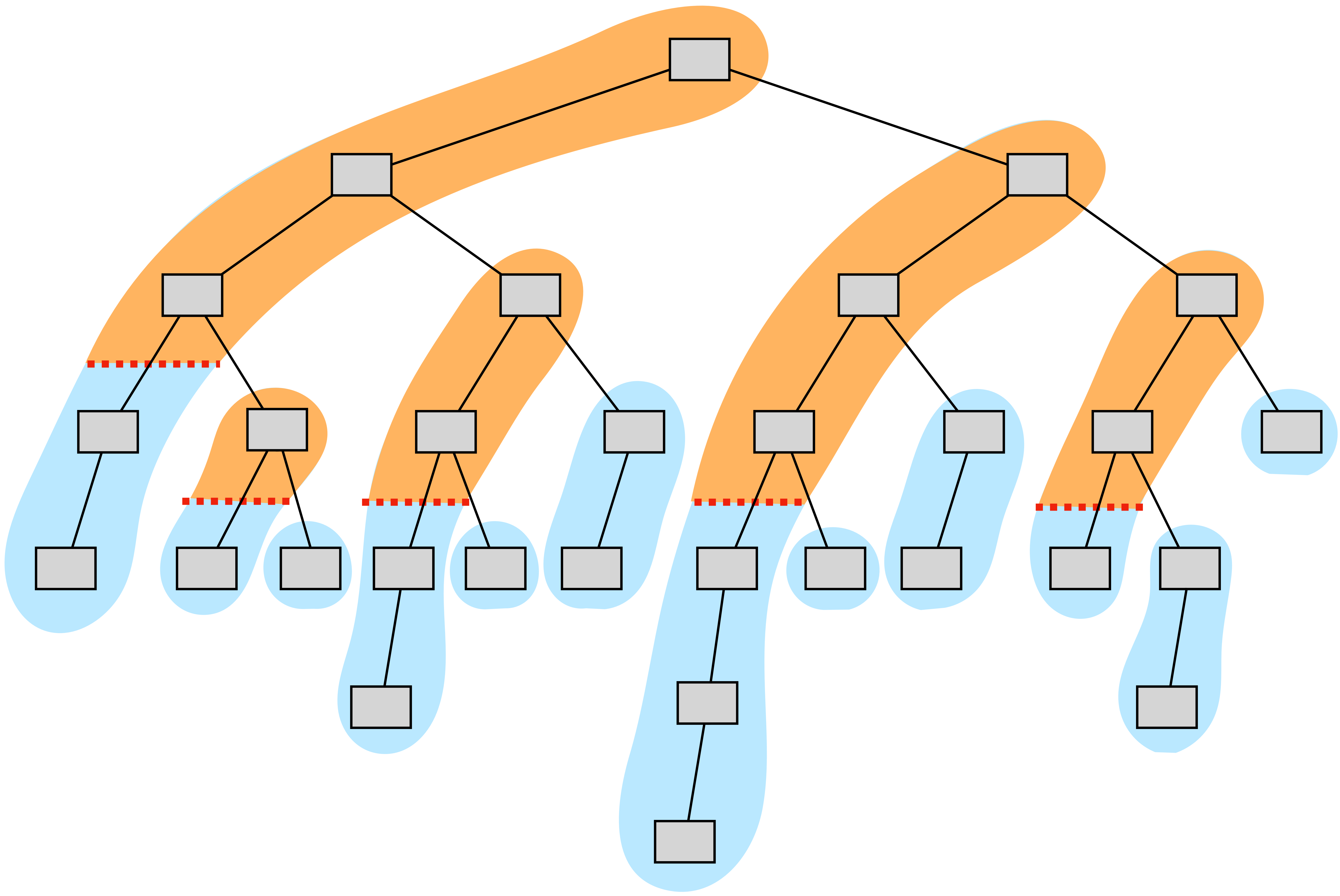
- every pointer points ***up*** or ***down***
  - ***disentanglement: no cross-pointers***
- leaves are active tasks with GC roots (think of these as up-pointers)
- write-barrier remembers down-pointers
- **snapshot-at-fork** summarizes up-pointers from stolen children
  - closure of right-side forked task is good enough (doesn't violate local ***R**** bound!)
  - write-barrier preserves reachability



Disentangled Garbage Collection

internal
- has to be concurrent GC
- non-moving mark-sweep

local
- no concurrency
- compactifying (copying) GC



MaPLe

- based on MLton compiler for Standard ML
- full Standard ML language, extended with fork-join library

```
val par: (unit -> ‘a) * (unit -> ‘b) -> ‘a * ‘b
```

- used by 500+ students at Carnegie Mellon University each year

github.com/MPLLang/mpl

Sorting Shootout

	T_1	T_{72}
C++ std::sort	8.8	–
Cilk samplesort	7.9	0.16
Cilk mergesort	12.7	0.24
MPL (Ours) mergesort	18.8	0.37
Go samplesort	27.2	0.52
Java mergesort	11.0	0.63
Haskell/C mergesort	10.6	1.3

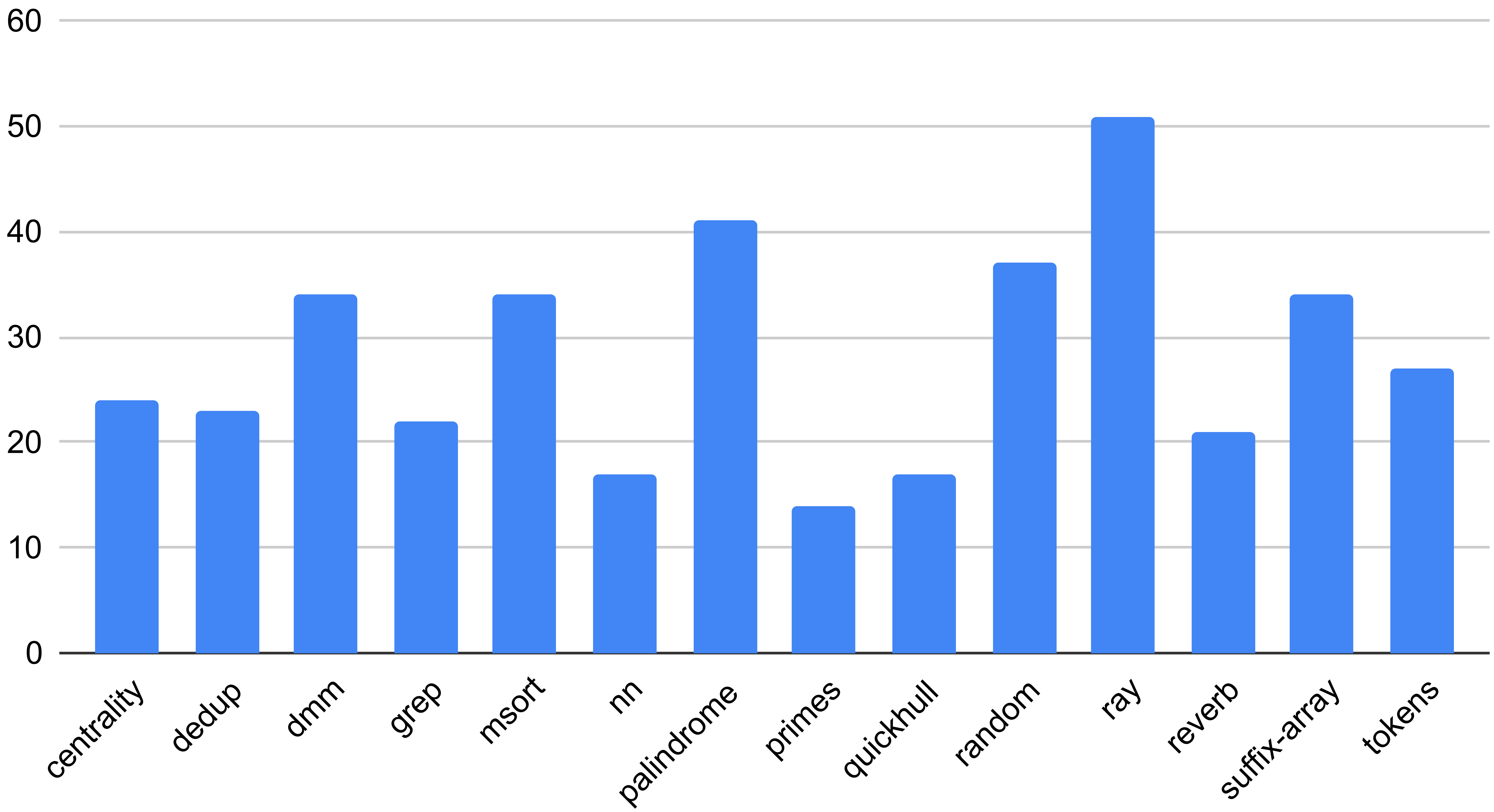
~24x speedup over C++ std::sort

2nd fastest, only behind C++/Cilk

40% faster than Go

70% faster than Java

Speedups

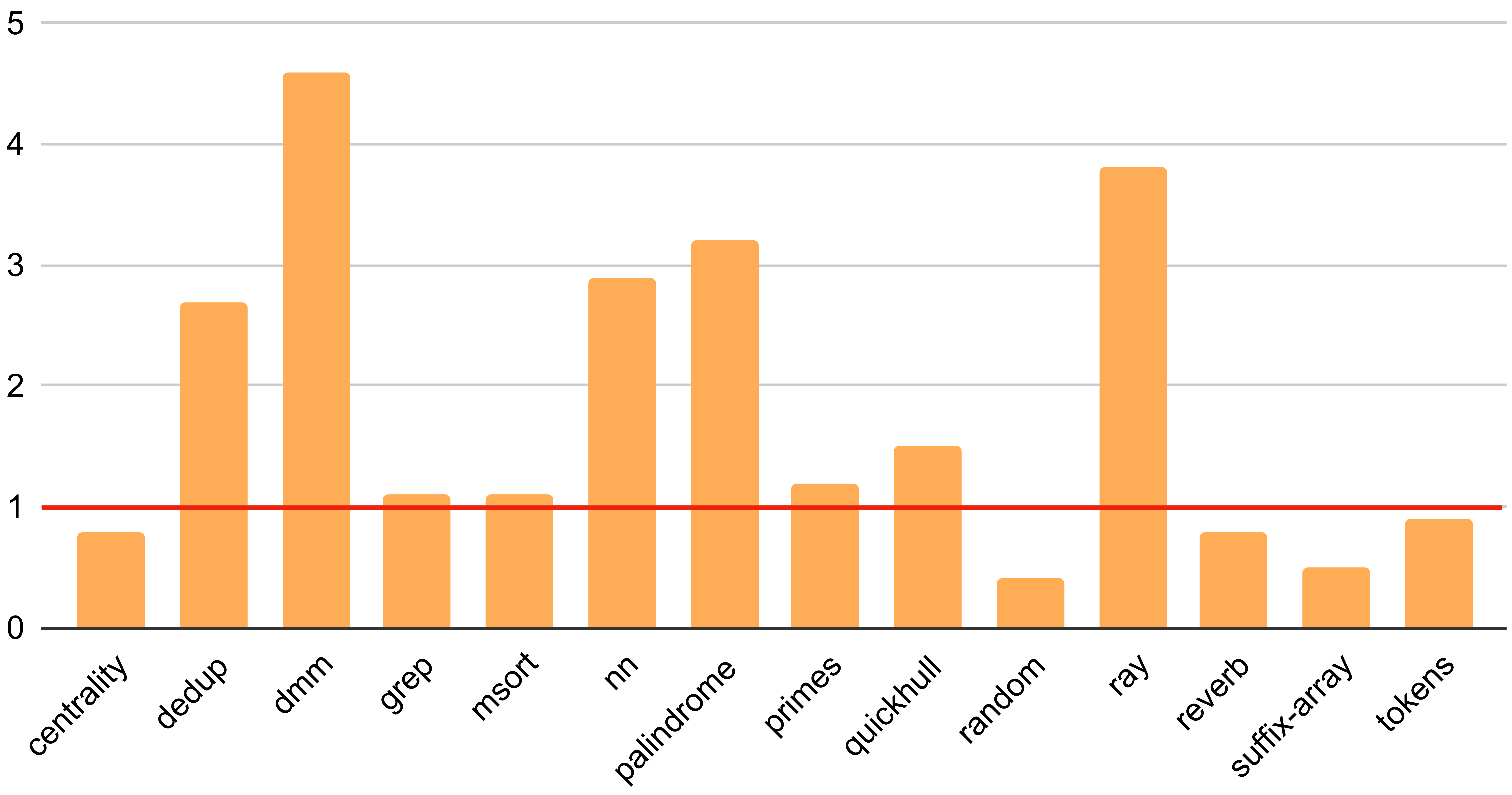


PBBS-style benchmarks

70 procs

relative to MLton

Space Overheads



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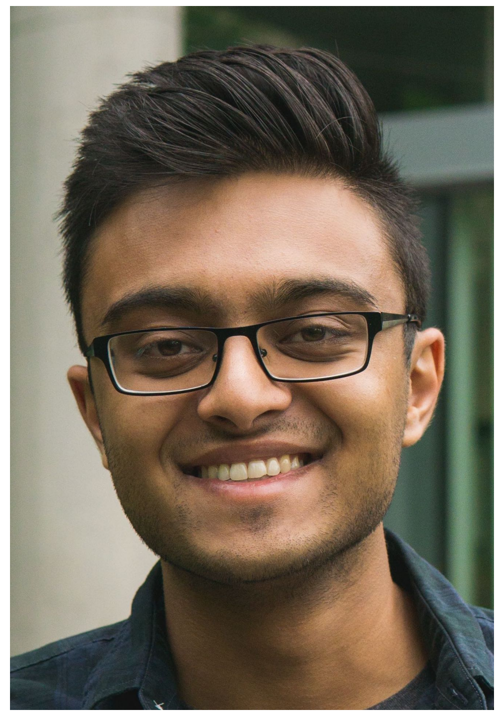
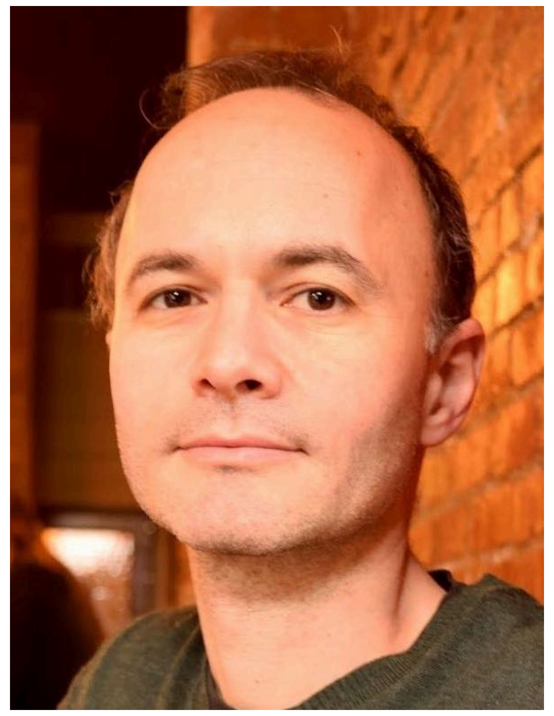
Thanks!





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