Efficient and Scalable Parallel Functional Programming Through Disentanglement

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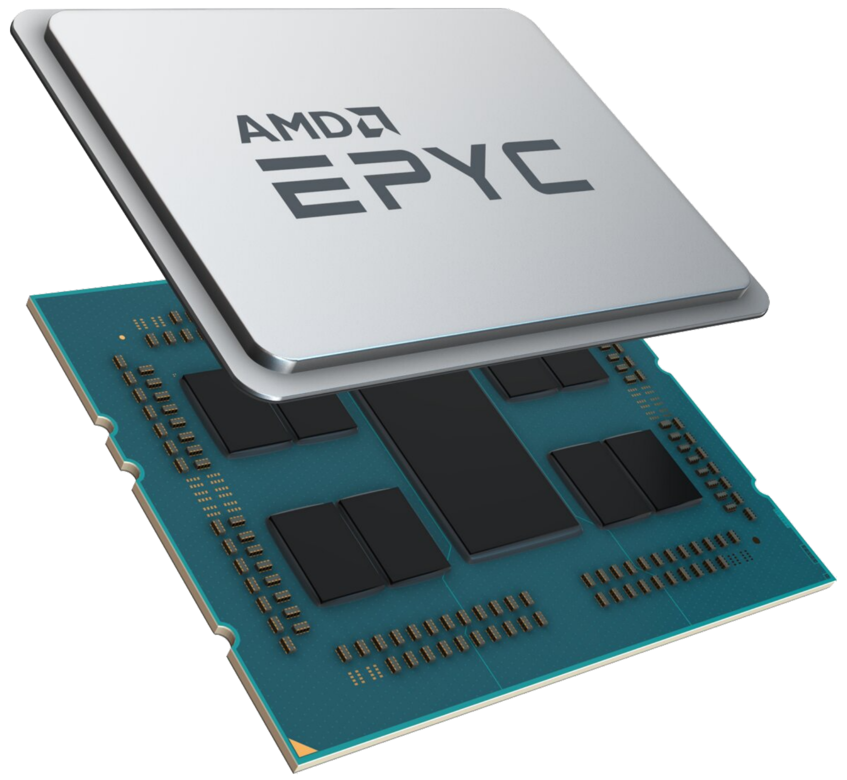
Parallel Hardware Today

Apple A14:
12 cores

Apple S4:
2 cores

AMD Ryzen Threadripper:
16 cores

nVidia
GeForce 3090:
10496 (CUDA) cores



AMD Epyc: 64 cores

4x Intel Xeon E7:
72 cores

Parallel Programming

imperative

mutability (in-place updates)
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

mutability (in-place updates)
manual memory management
race conditions

immutability
automatic memory management
deterministic by default

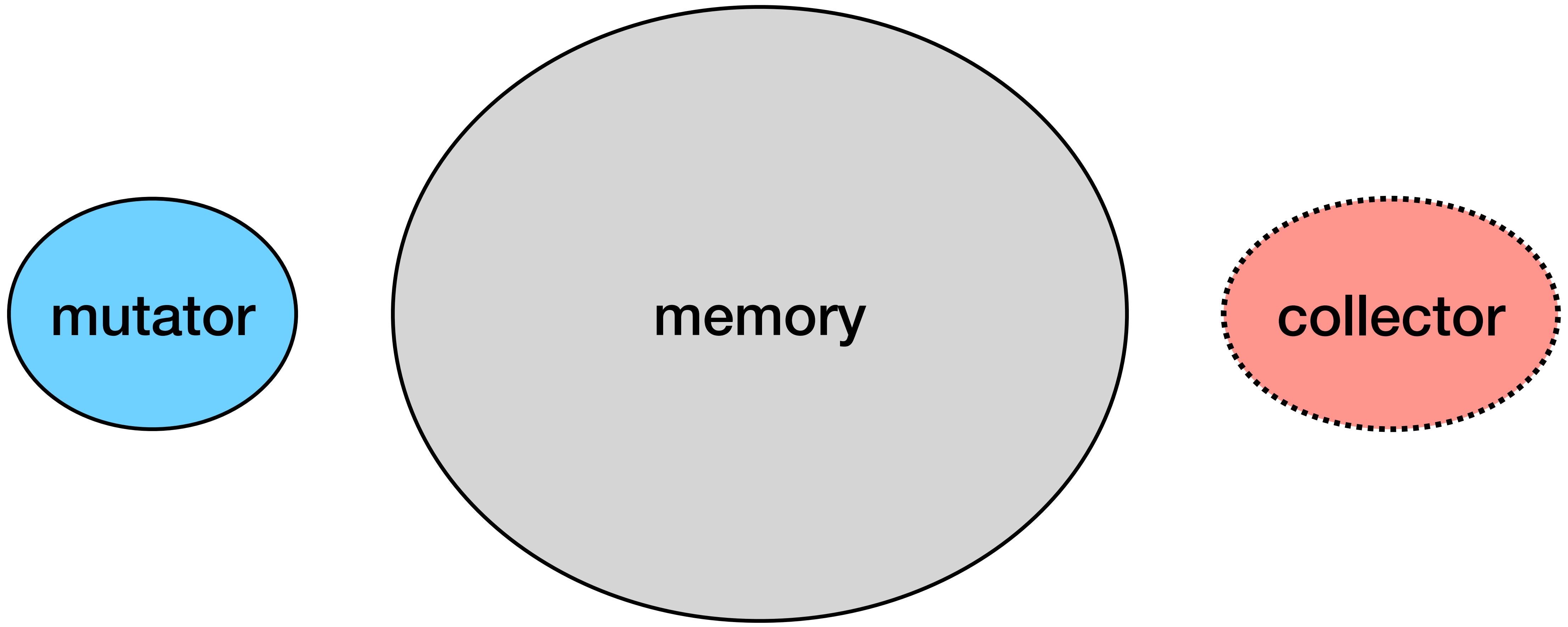
functional

high rate of allocation
heavy reliance on GC

fast

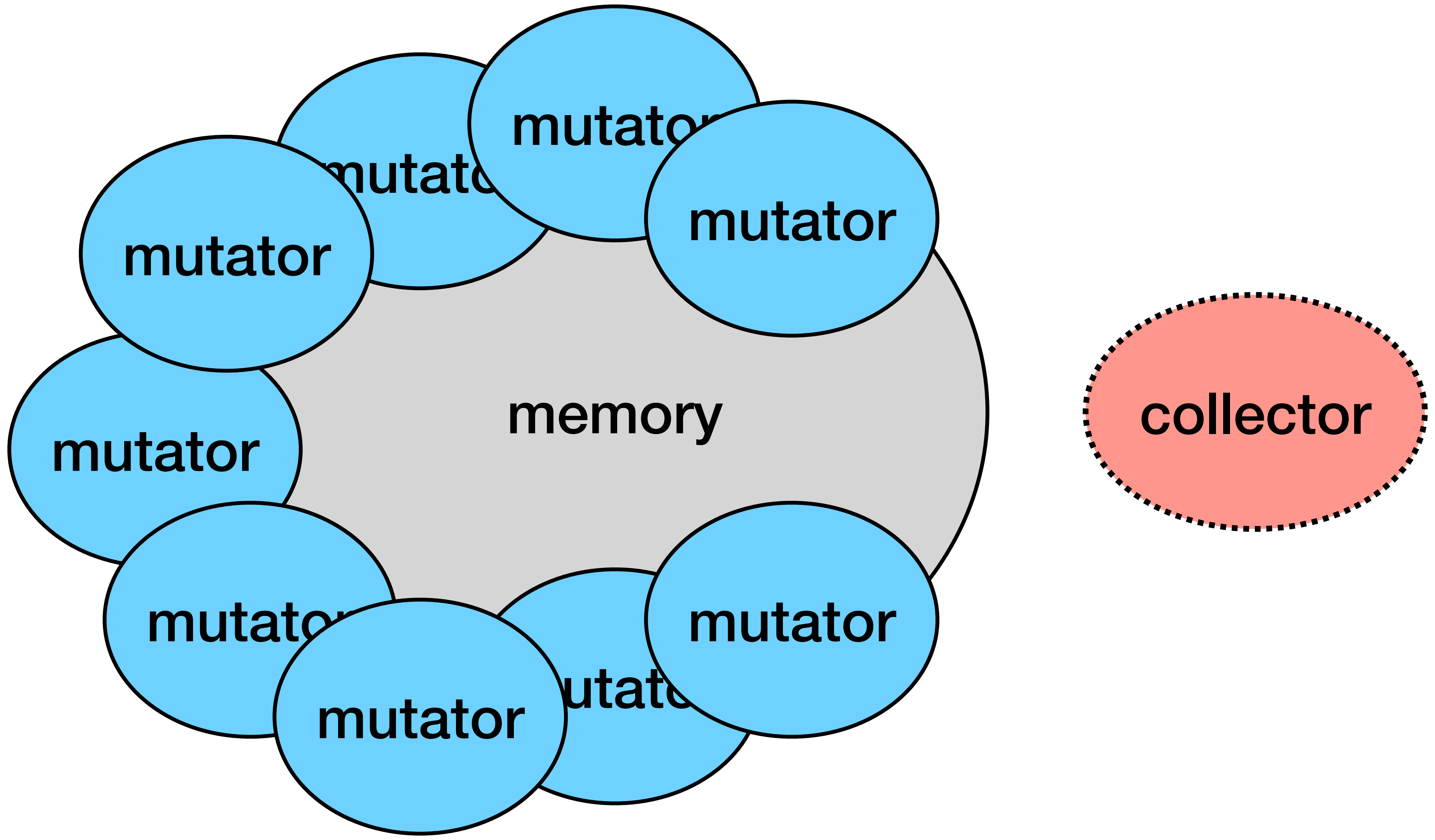
can parallel functional programming be fast and scalable ?

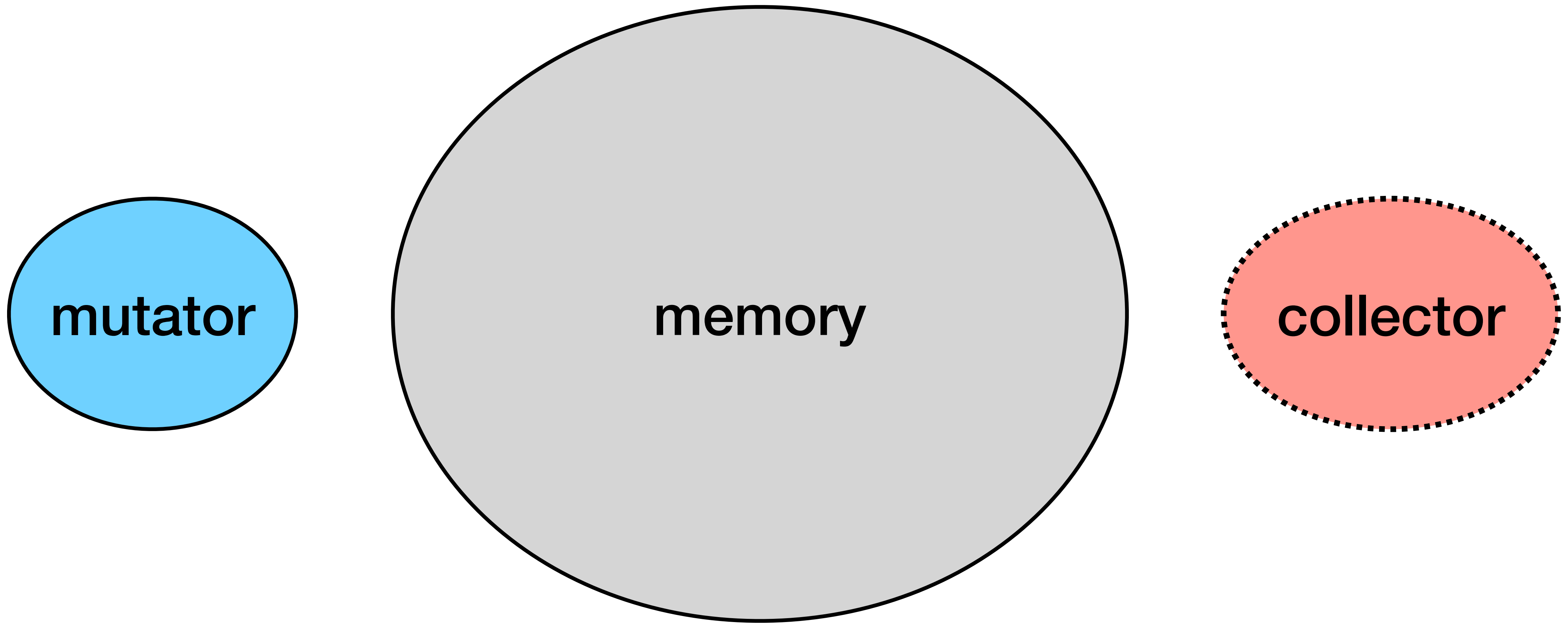
slow?



Sequential

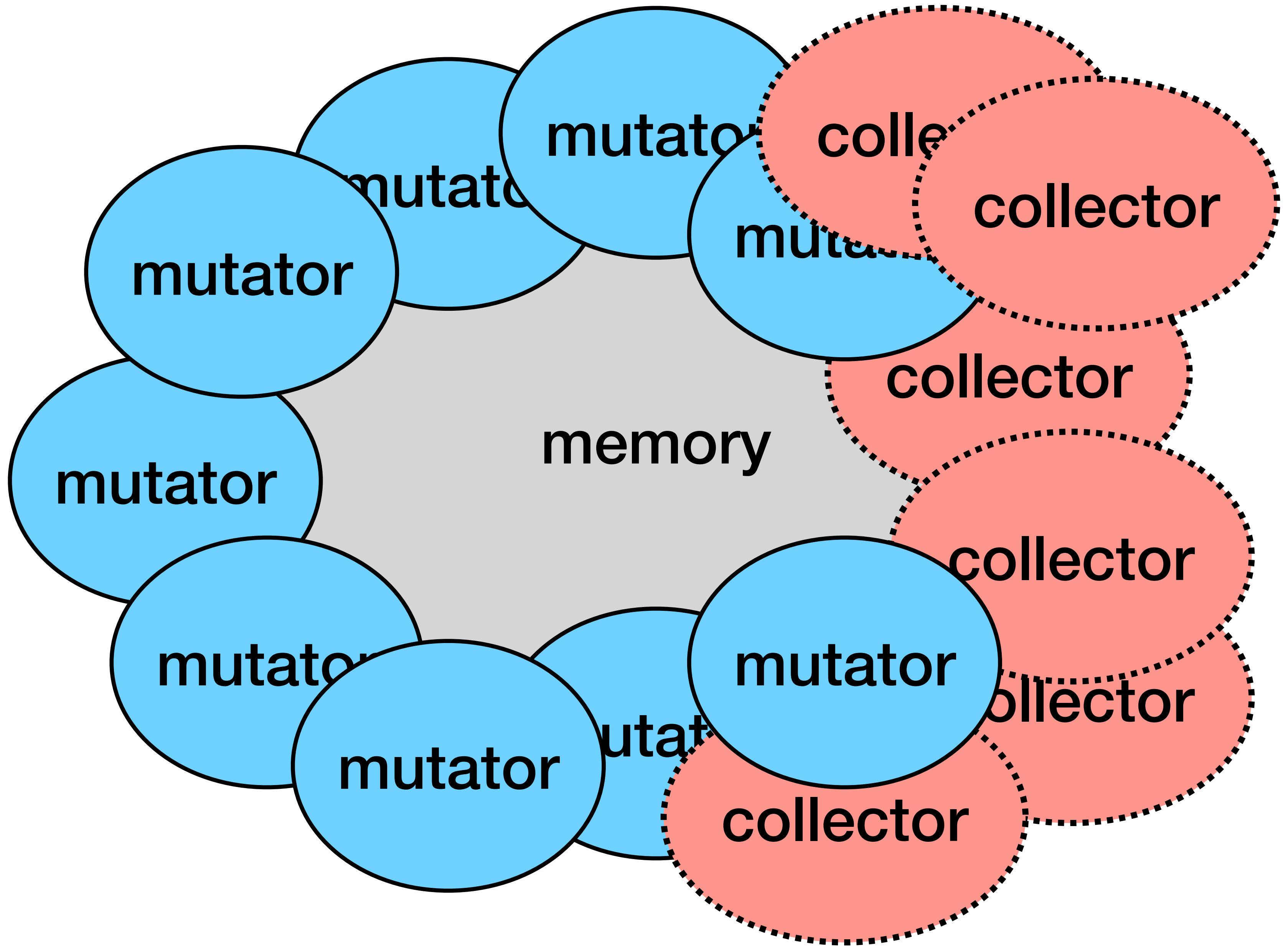
Parallel



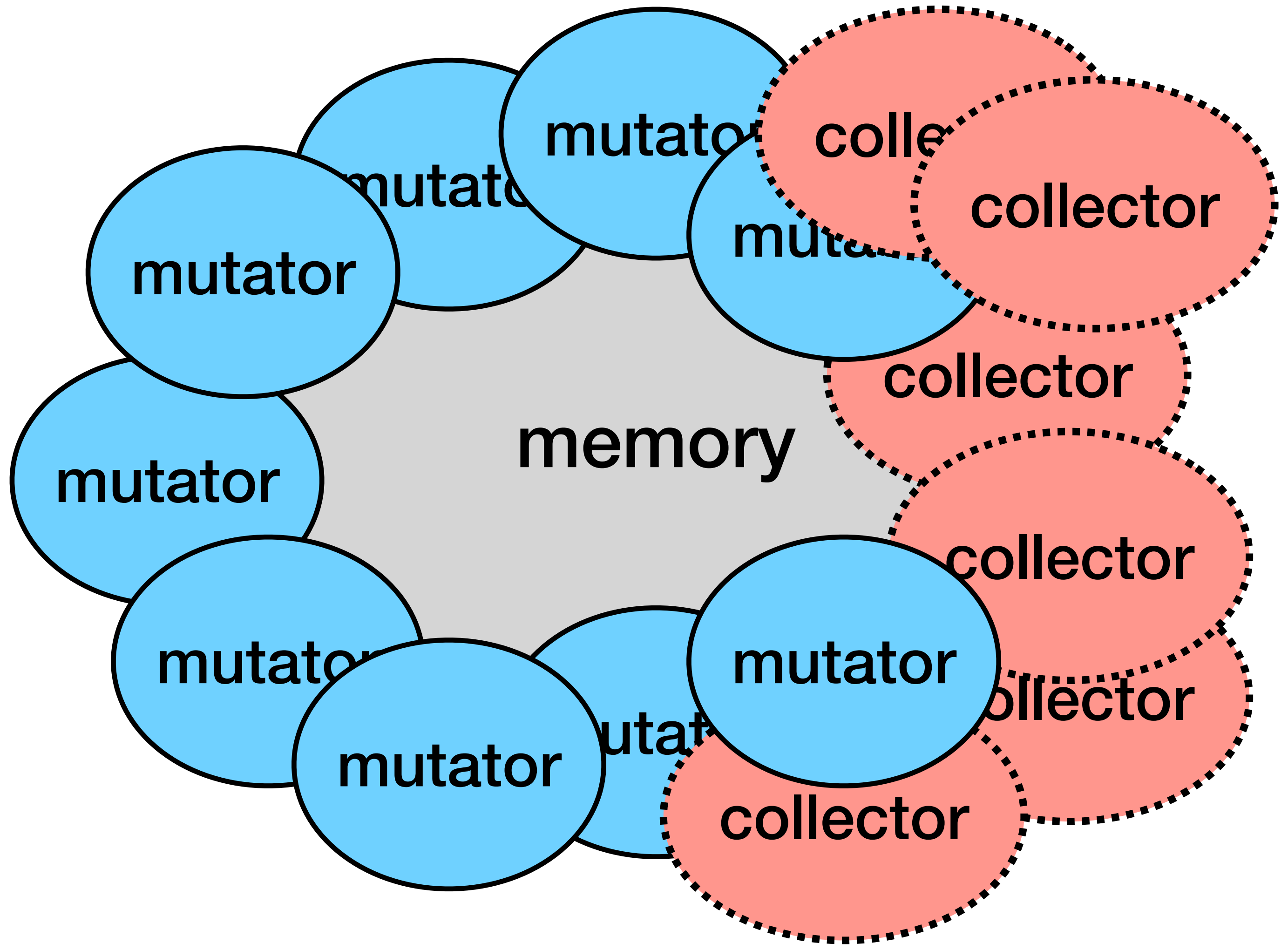


Sequential

Parallel



Is there a better way?



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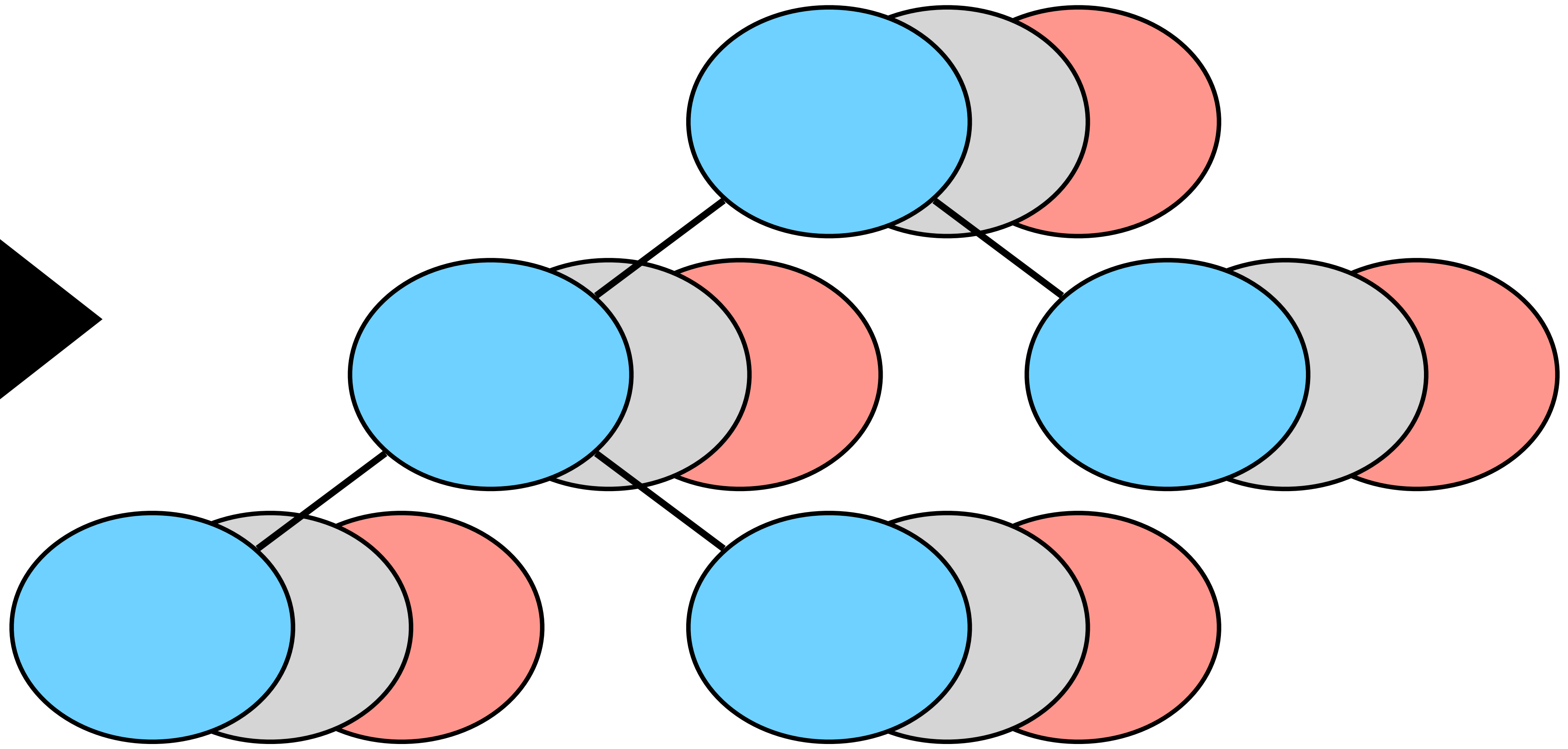


Disentanglement

“concurrent tasks remain oblivious
to each other’s allocations”

MaPLe Compiler

- based on MLton, **full Standard ML language**, extended with

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

- **parallel memory management based on disentanglement**
- used by 500+ students at CMU each year

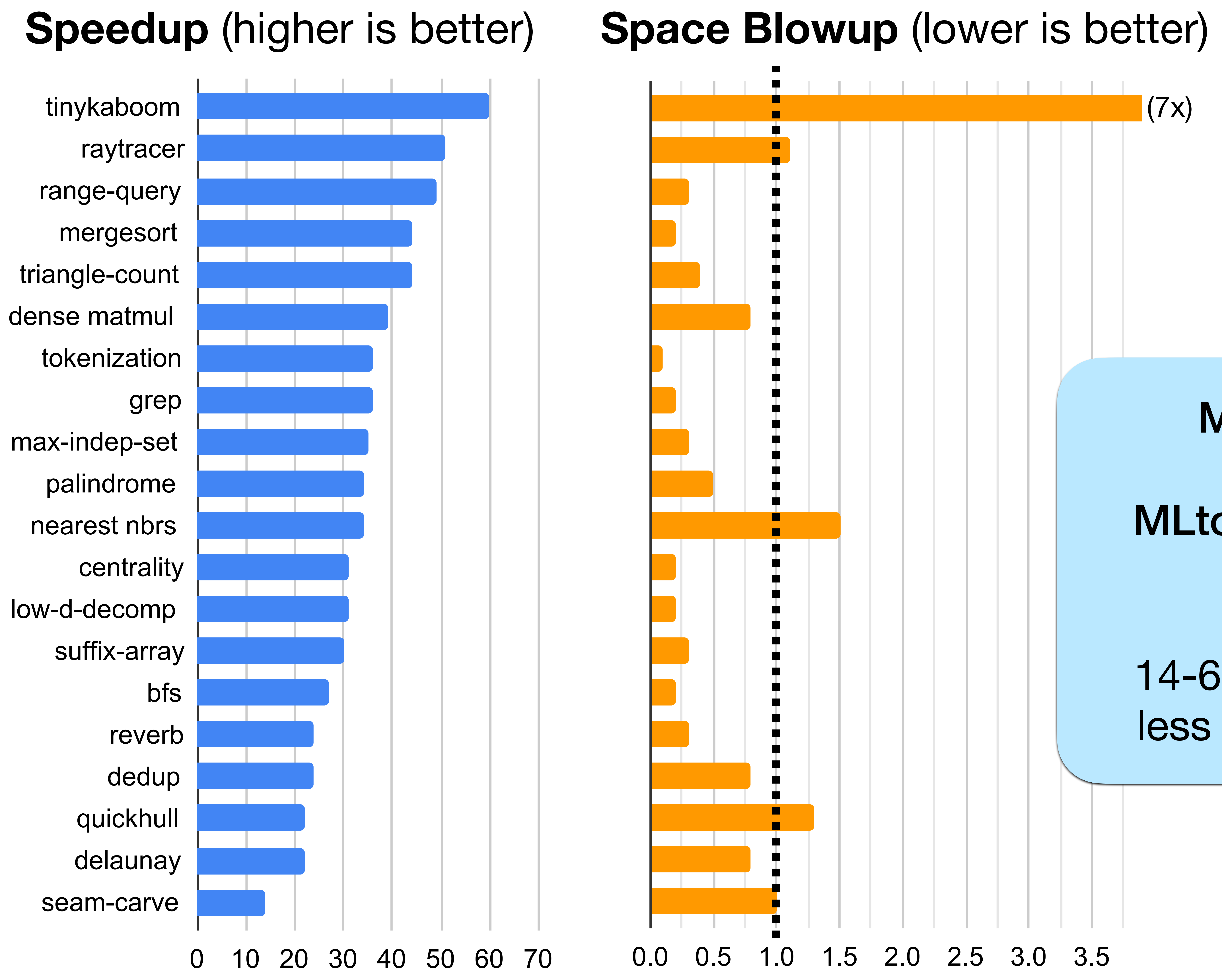
github.com/mpllang/mpl

Parallel ML Benchmark Suite

github.com/mpllang/parallel-ml-bench

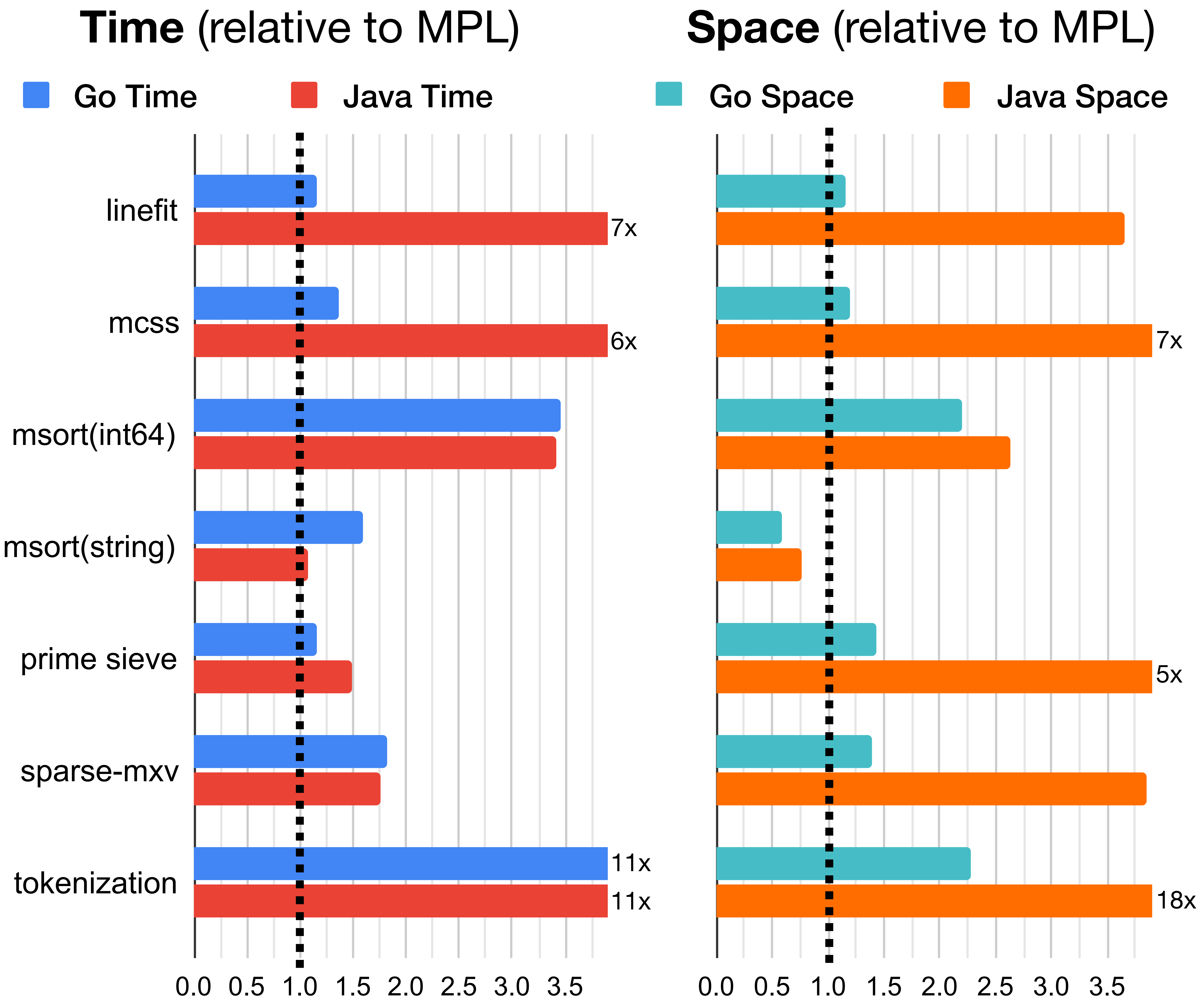
- over 30 state-of-the-art parallel algorithms
  - ported from highly-optimized C++ benchmark suites (PBBS, GBBS, Ligra, PAM, ...)
- **all disentangled**
- MPL has excellent parallel time and space performance
- **same memory footprint as C++** (on average)
- generally **within 2x time of hand-optimized C++**
  - e.g. linefit (±5%), sparse matrix-vector mult (±10%), mergesort (1.3x), nearest-neighbors (1.7x), tokenization (1.7x), delaunay triangulation (2.3x)

graphs	betweenness centrality
	breadth-first search
	minimum spanning tree
	maximum independent set
	low-diameter decomposition
	triangle counting
geometry	delaunay triangulation
	nearest neighbors
	quickhull
	2D range query
images	seam carving
	raytracing
	tinykaboom
	GIF encode+decode
audio	reverb
	WAV encode+decode
text	tokenization
	deduplication
	grep
	word-count
	longest palindrome
	suffix array
numeric	dense+sparse matrix mult
	integration



MPL (72 processors)
vs
MLton (sequential baseline)

14-60x speedup, often with less space (average: -30%)



(higher is better for MPL)

MPL vs Java and Go
(on 72 processors)

average vs Go:
2x faster
30% less space

average vs Java:
3x faster
4x less space

can parallel functional programming be fast and scalable ?

YES:

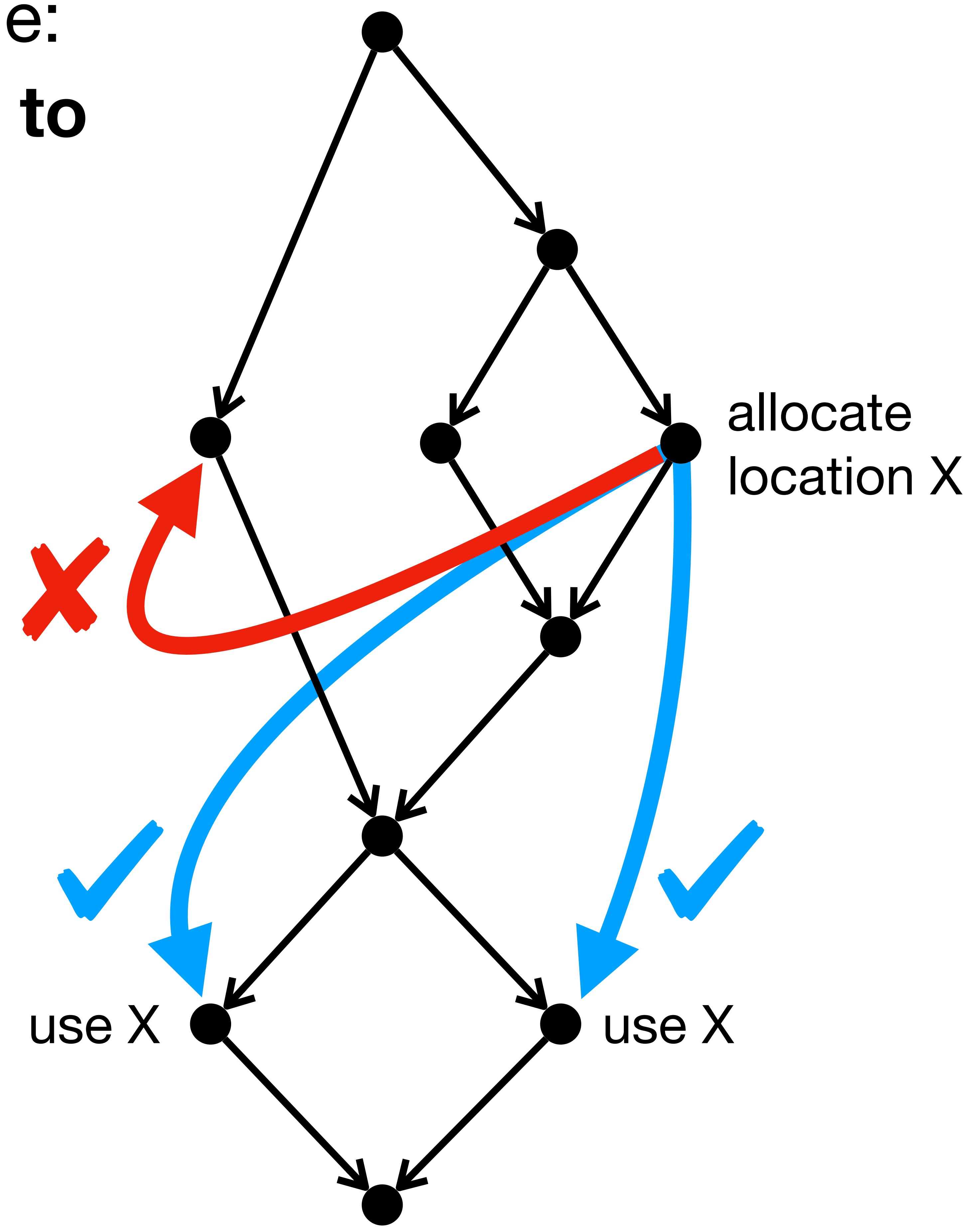
- MPL can outperform existing implementations of parallel languages
- MPL can compete with low-level optimized C++ code

Disentanglement

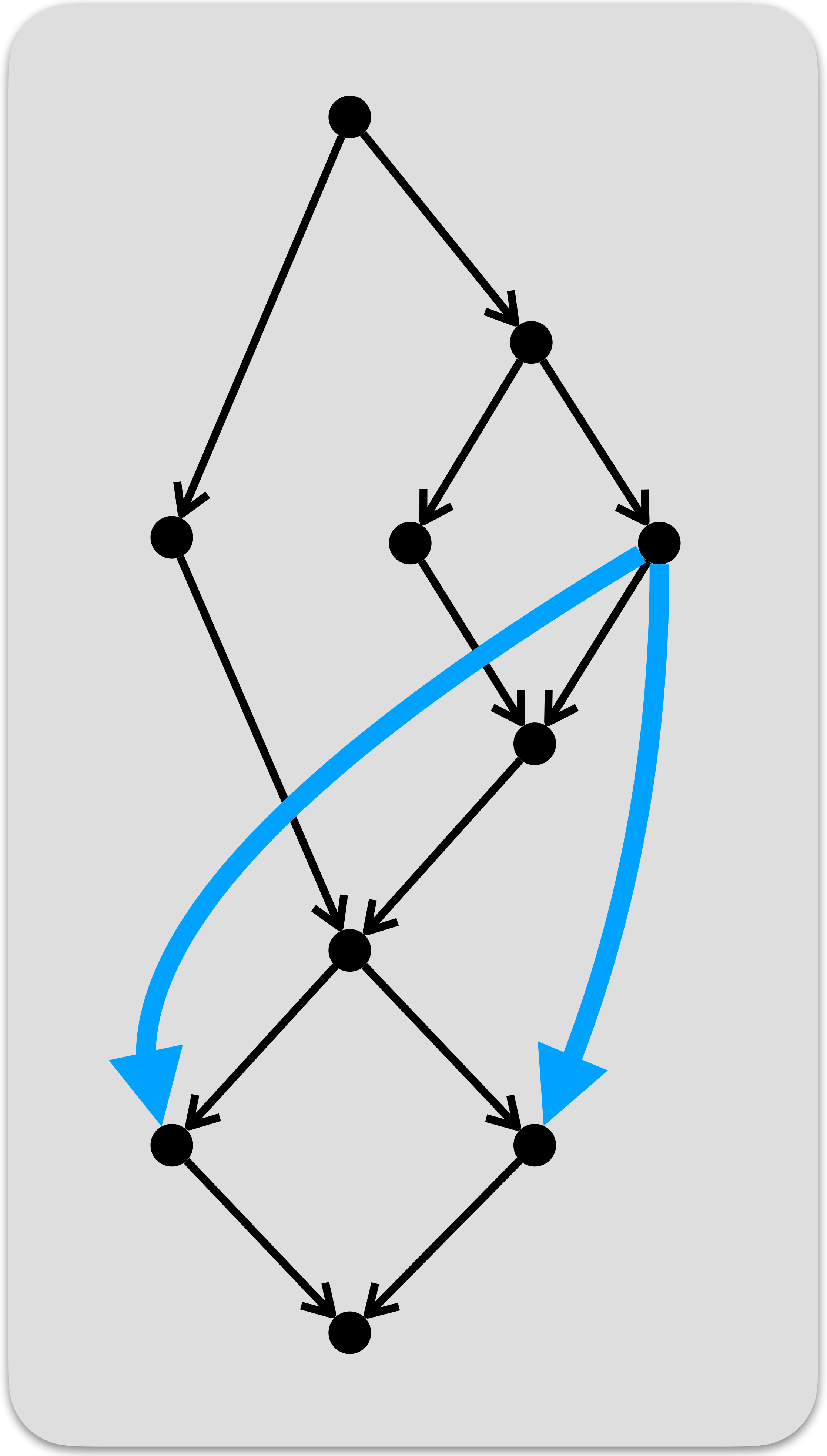
Disentanglement

graphs	betweenness centrality breadth-first search minimum spanning tree maximum independent set low-diameter decomposition triangle counting
geometry	delaunay triangulation nearest neighbors quickhull 2D range query
images	seam carving raytracing tinykaboom GIF encode+decode
audio	reverb WAV encode+decode
text	tokenization deduplication grep word-count longest palindrome suffix array
numeric	dense+sparse matrix mult integration linear regression

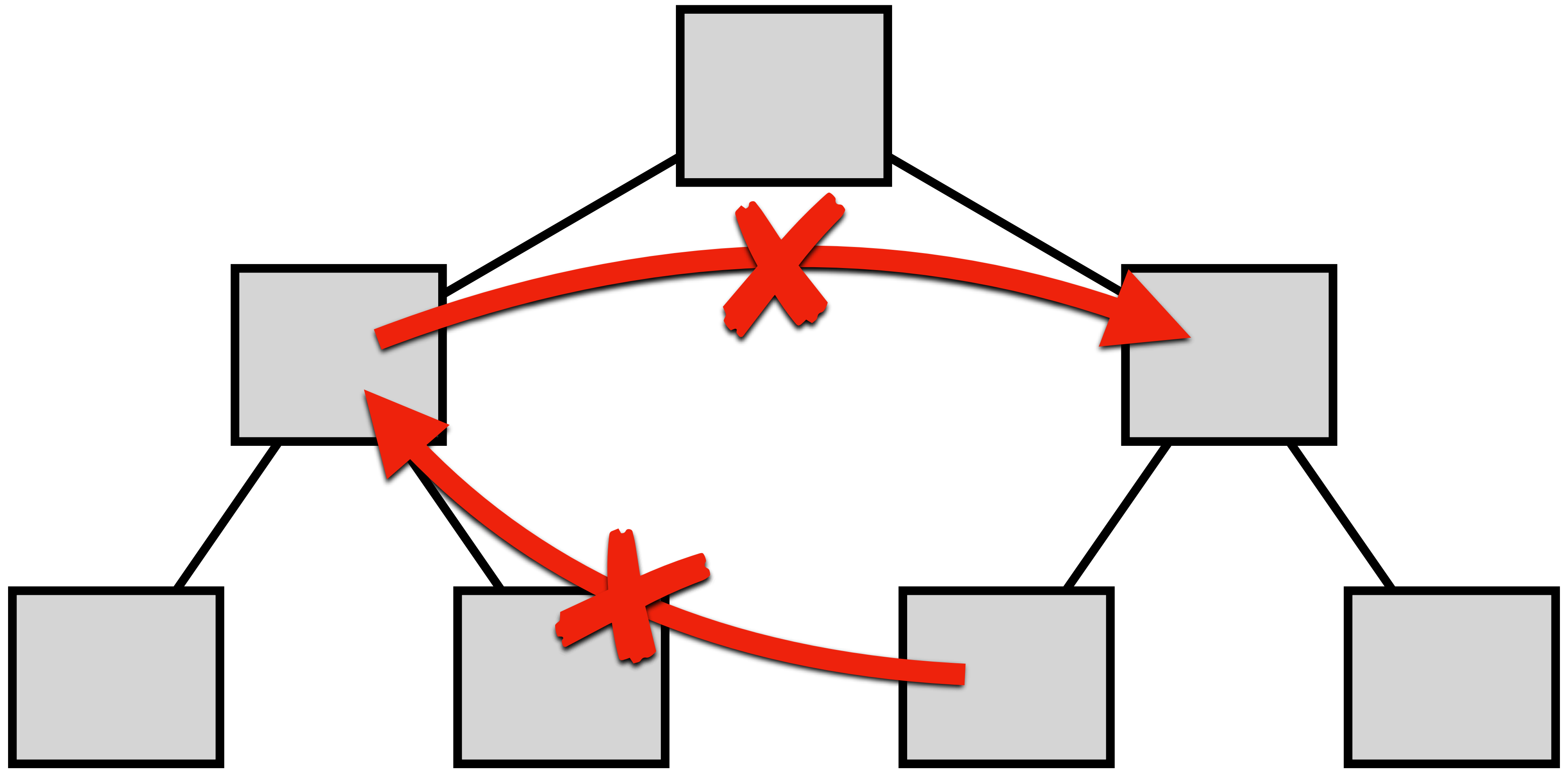
- observed in efficient parallel code: **concurrent tasks are oblivious to each other's allocations**
- in computation graph: **allocation precedes use**
- arbitrary? no: **guaranteed by determinacy-race-freedom** [Westrick et al. 2020]



Disentanglement



How to utilize disentanglement
for improved efficiency and scalability?

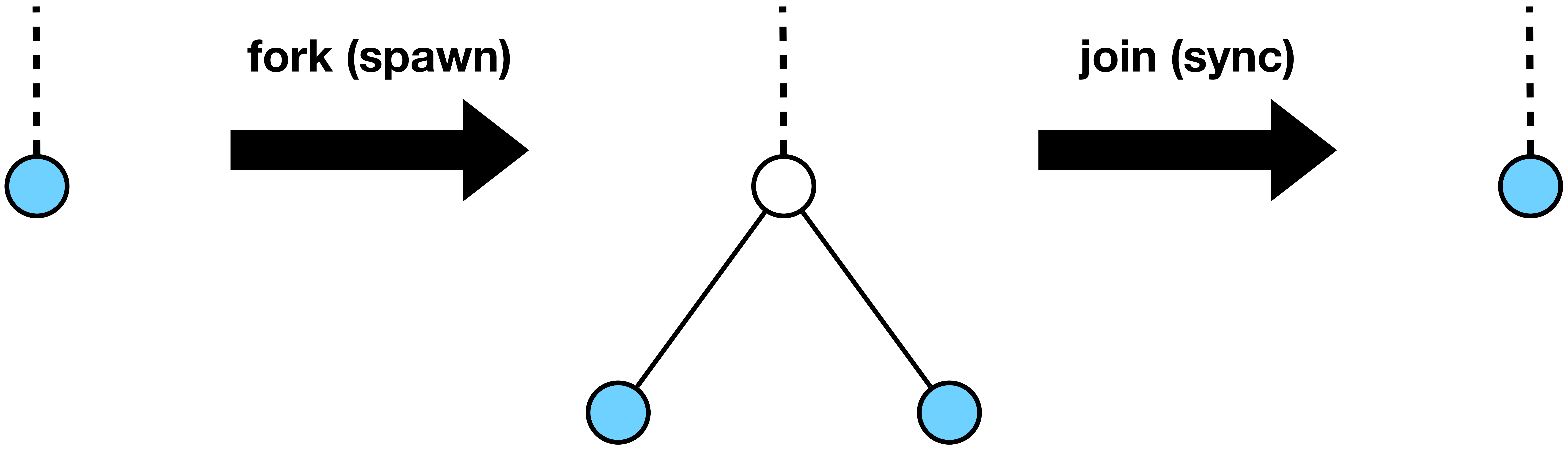


idea: organize memory to reflect structure of parallelism:
concurrent execution ⇔ memory separation

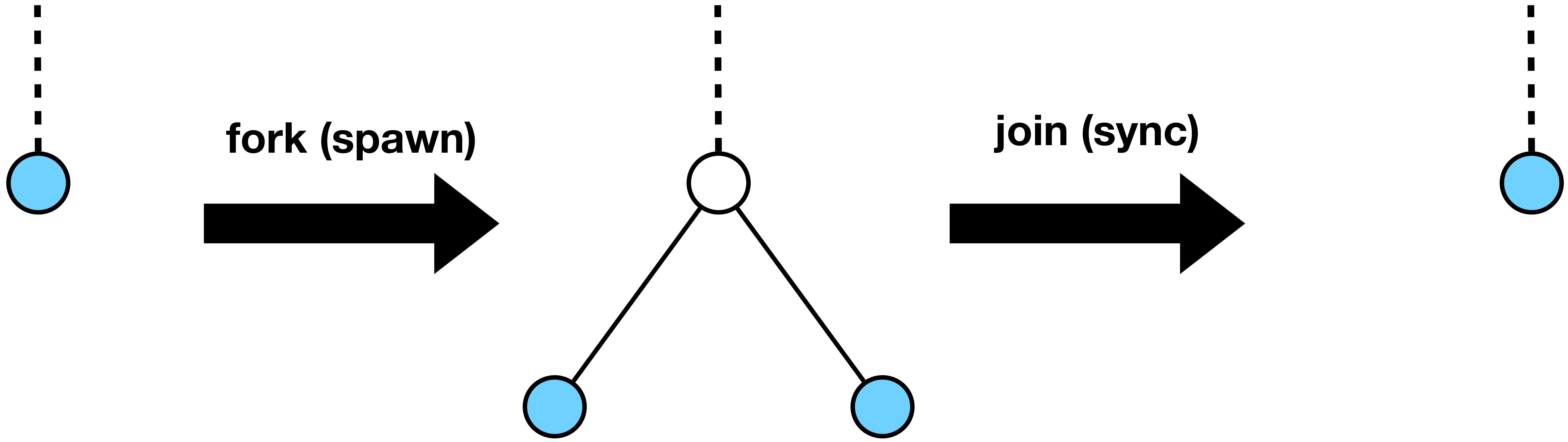
Nested Fork/Join Parallelism

classic and popular (as programming model and/or execution model):

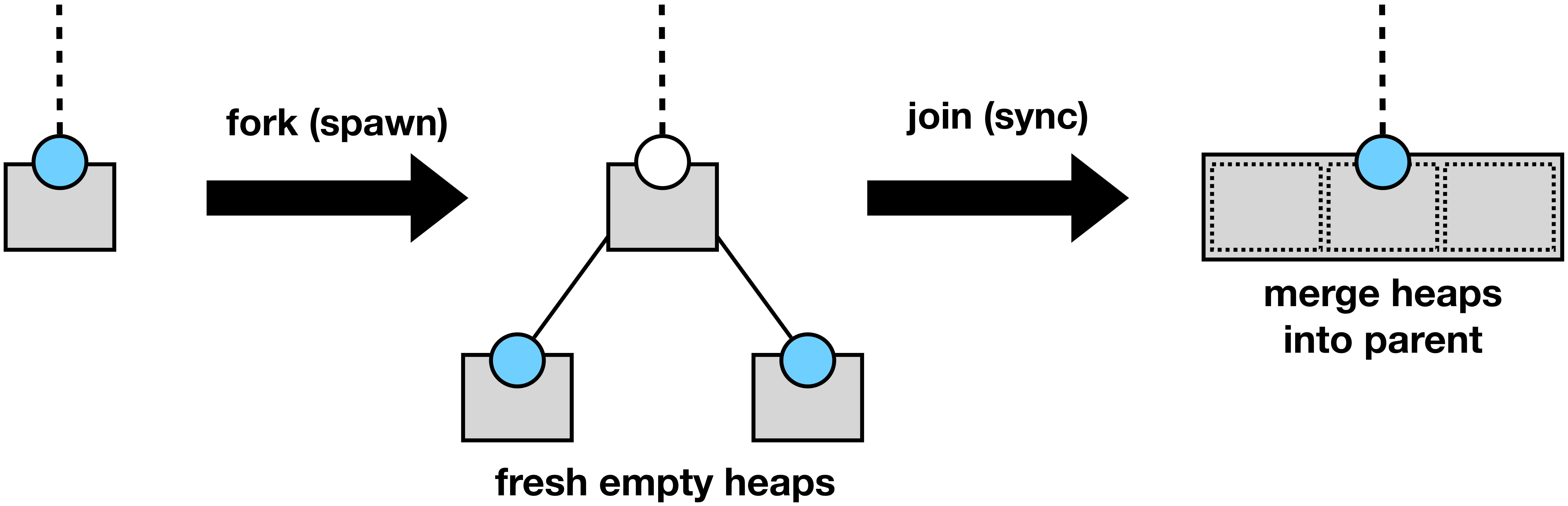
- Cilk, ParlayLib, Intel TBB, Microsoft TPL, OpenMP, Legion, Rayon, Fork/Join Java, Habanero Java, X10, multiLisp, Id, NESL, parallel Haskell, Manticore, Futhark, SML#, etc.



Task-Local Heaps

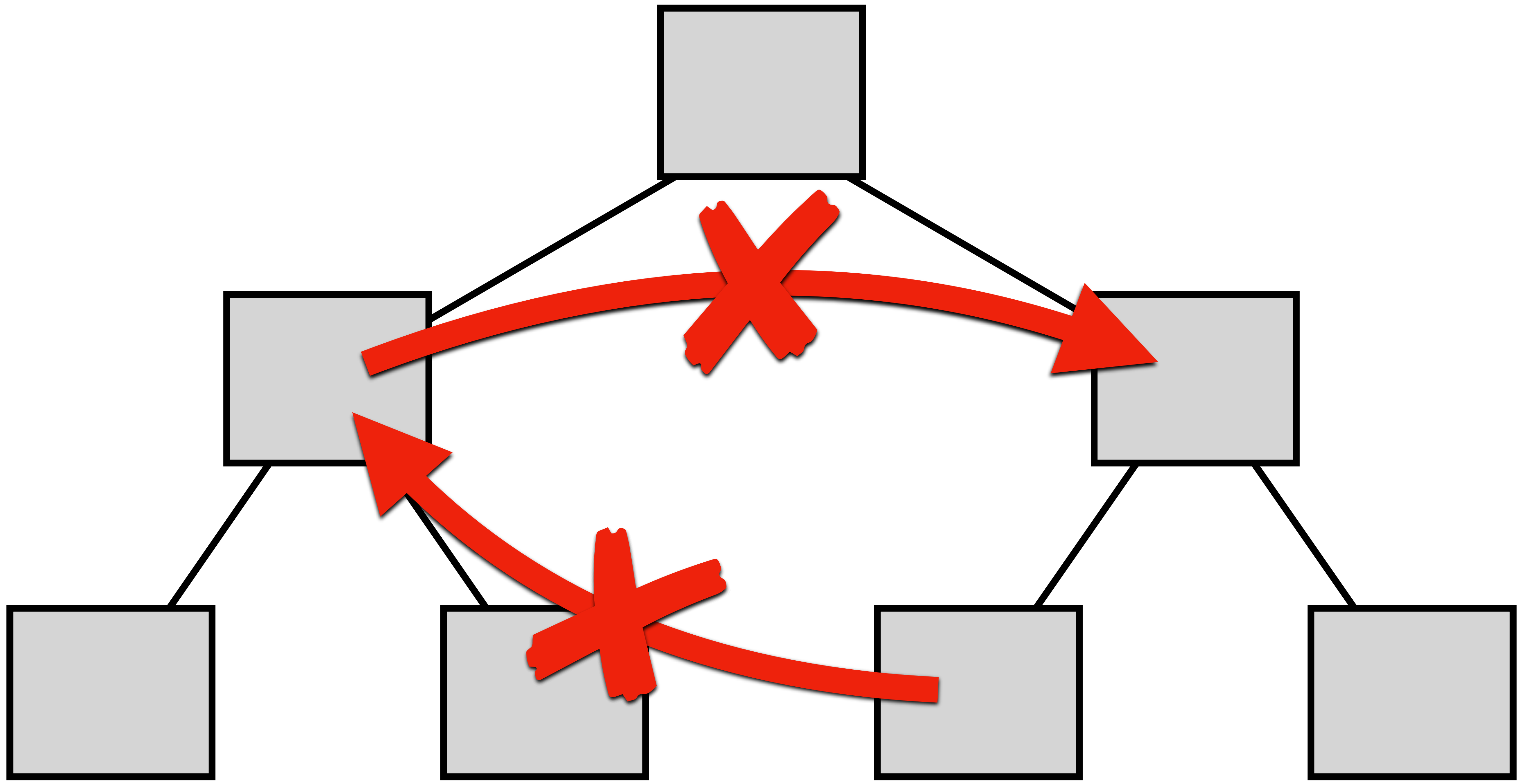


Task-Local Heaps



Disentangled Memory Management

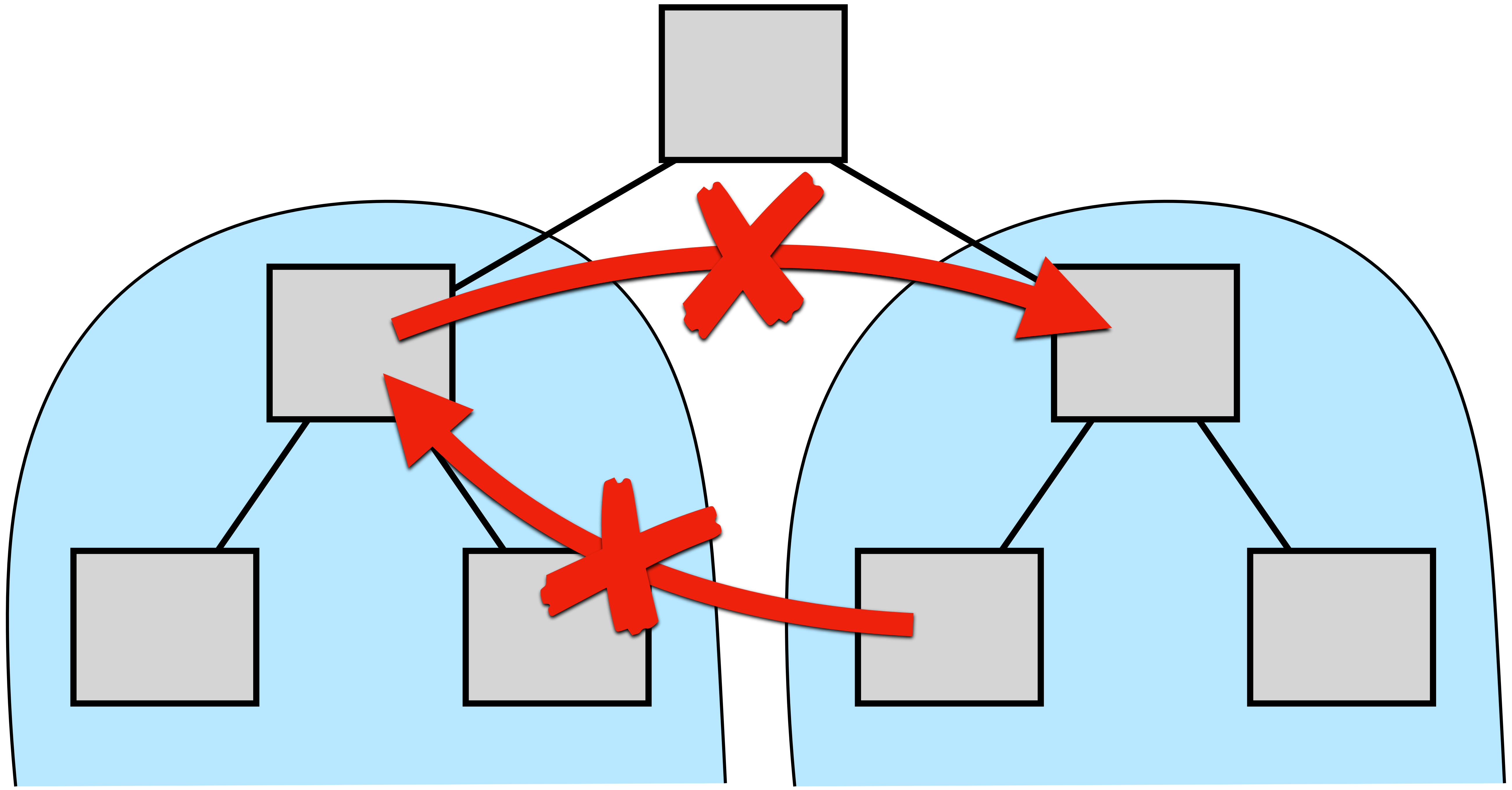
- disentanglement: ***no cross-pointers***
  (up-pointers are down-pointers are allowed)



Disentangled Memory Management

- disentanglement: ***no cross-pointers***
  (up-pointers are down-pointers are allowed)
- subtree collection

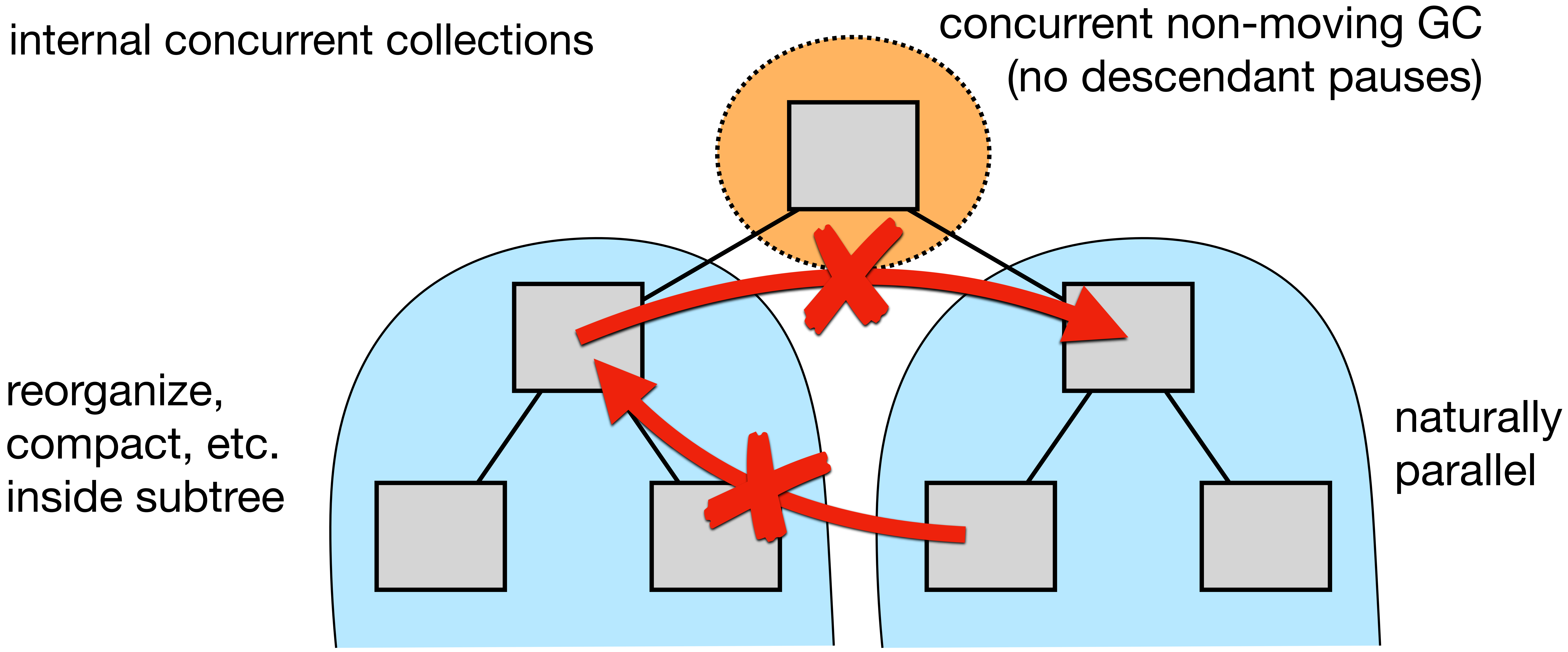
reorganize,
compact, etc.
inside subtree



naturally
parallel

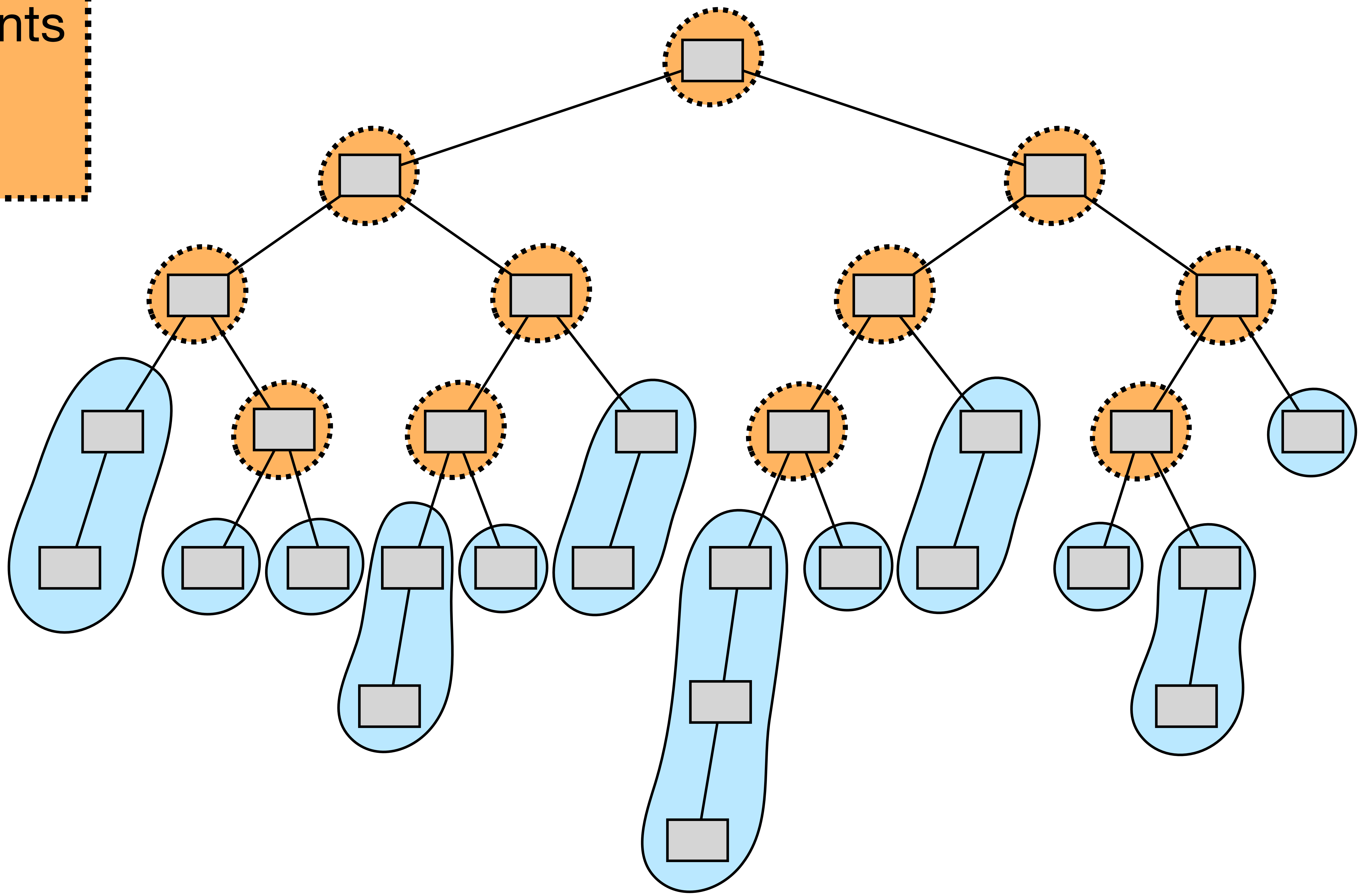
Disentangled Memory Management

- disentanglement: ***no cross-pointers***
  (up-pointers are down-pointers are allowed)
- subtree collection
- internal concurrent collections



CGC
- heaps with at least 2 active descendants
- concurrent non-moving mark-sweep
- snapshot-at-the-beginning (SATB)

LGC
- heaps local to one processor
- compactifying (copying) GC



Notes:

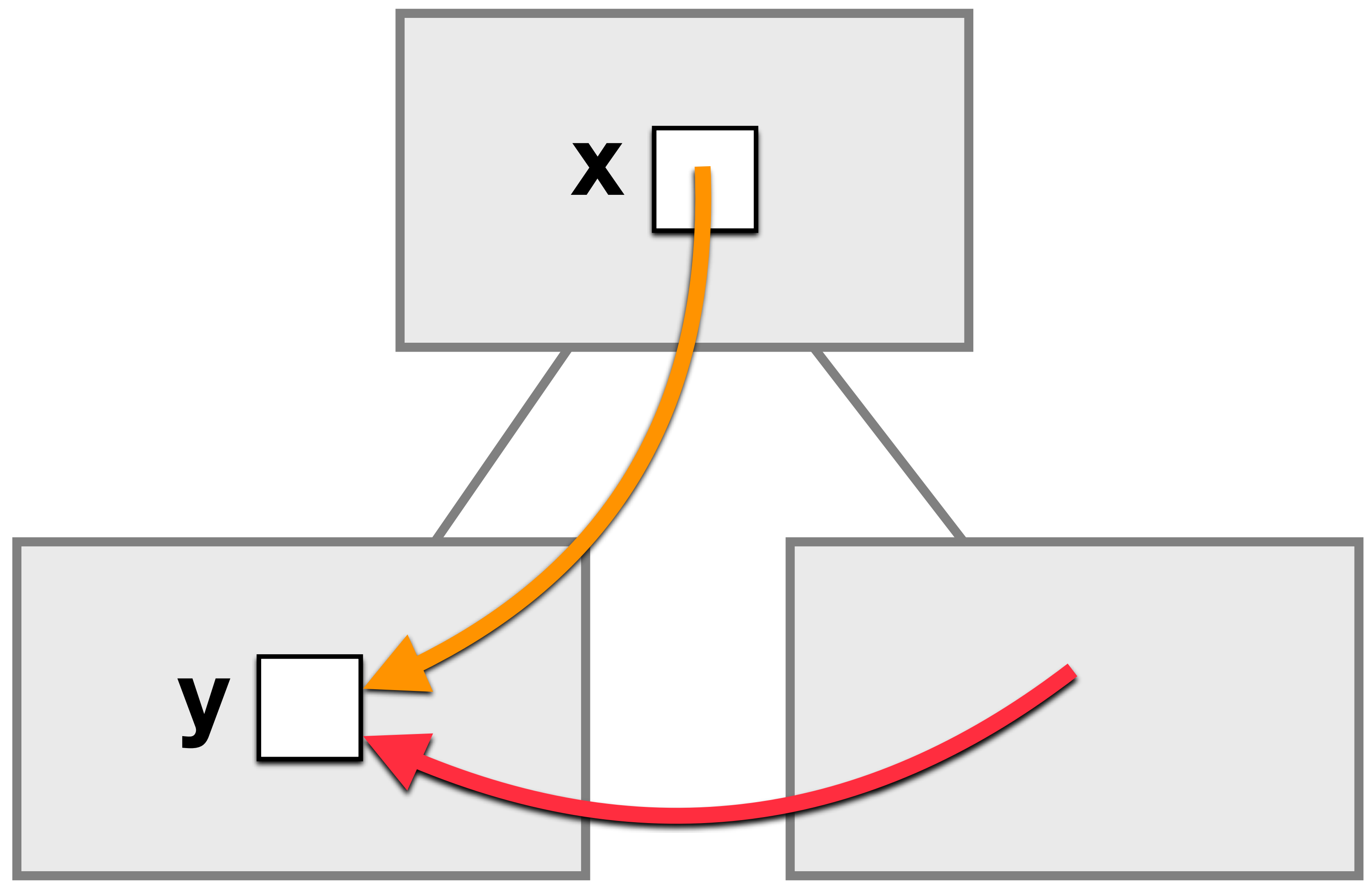
- write barrier for remembered sets (for SATB, and down-pointers)
- **never stops the world**
- **no promotions necessary**
- LGC+CGC ➞ provable efficiency [Arora et al. 2021]

Ensuring Disentanglement

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

Intuition

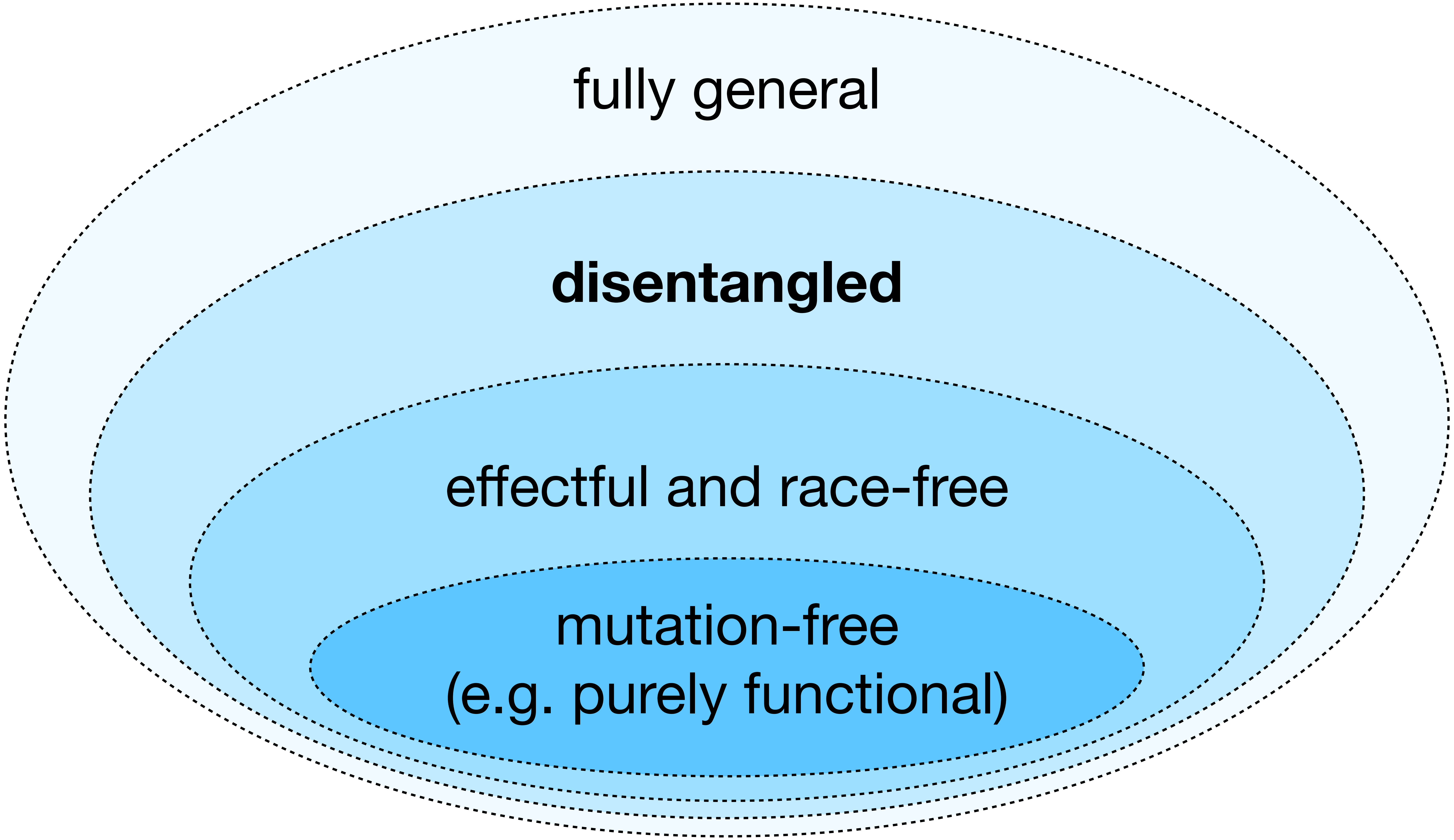
- if entangled, must be a **read/write** race
- **write:** creates down-pointer
- **read:** discovers data across




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

Proof idea

- **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


fully general
disentangled
effectful and race-free
mutation-free
(e.g. purely functional)

Entanglement Detection

Algorithm

- build computation graph during execution
- annotate allocated locations with current vertex
- check **results of memory reads**
  - disentangled: result allocated before current vertex ✓
  - otherwise, **entanglement detected** ✗

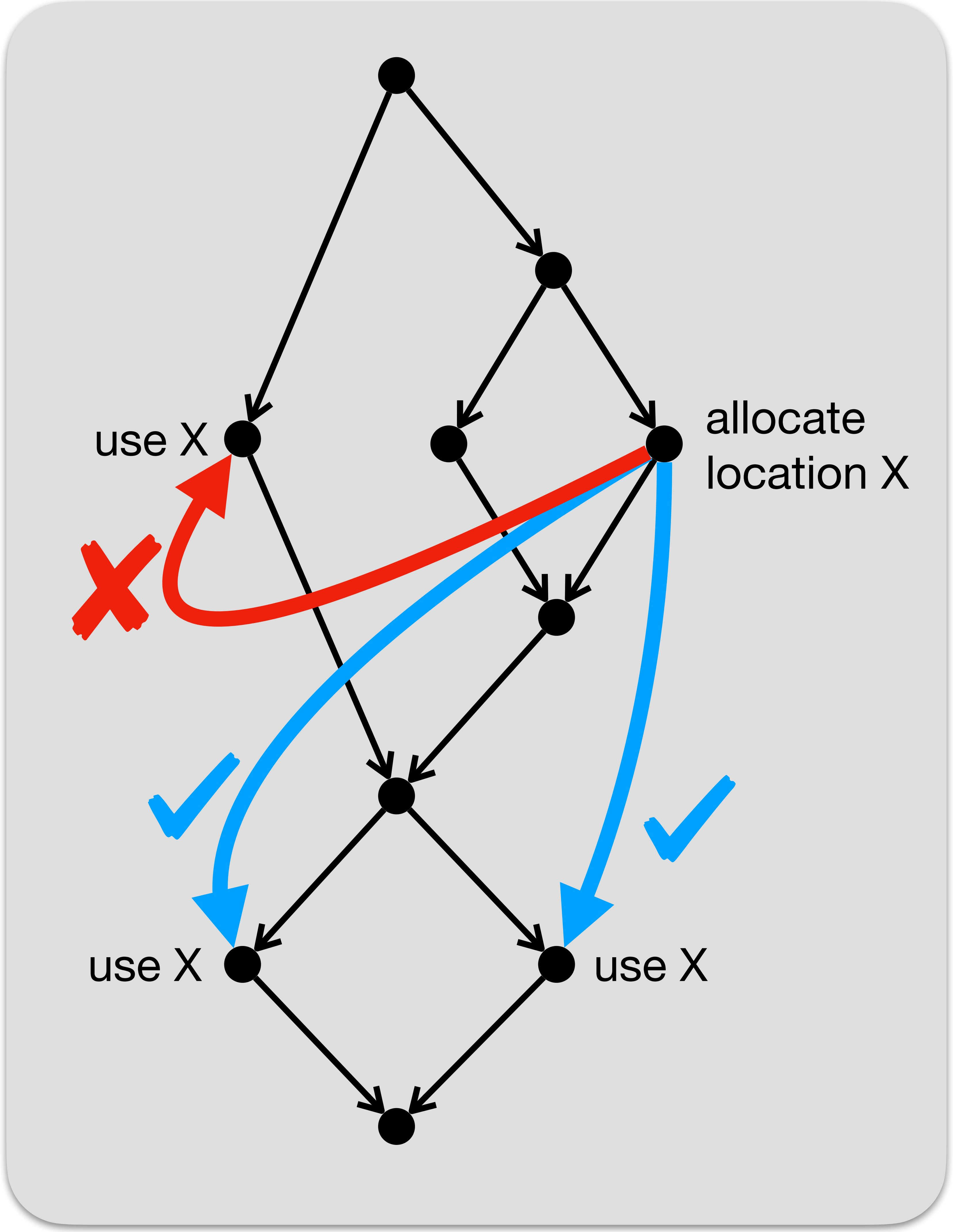
sound (no missed alarms) and **complete** (no false alarms)

provably efficient (work, span, and space)

[Westrick et al. ICFP 22]

Implementation and Evaluation:

- nearly zero overhead (±5%) for both time and space
- read-barrier on mutable pointers only
- SP-order maintenance



Writing Disentangled Programs

Writing Disentangled Programs

pure library interface

tabulate	filter
map	flatten
reduce	merge
scan	…

fast implementation w/ “local” effects

…

purely functional, parallel, disentangled algorithms

```
fun mergesort(X) =
  if length(X) <= granularity then
    quicksort(X)
  else
    let
      val (L,R) = split(X)
      val (sL,sR) = par(fn _ => mergesort(L),
                        fn _ => mergesort(R))
    in
      merge(sL,sR)
    end
```

no need to know about disentanglement!

only 10% more time+memory than hand-optimized

Writing Disentangled Programs

pure library interface

tabulate, map, reduce, scan, filter, flatten, merge, ...

fast implementation w/ “local” effects

...

purely functional, parallel, disentangled algorithms

15-210 (Undergrad Course)
Parallel and Sequential
Data Structures and Algorithms

- parentheses matching
- max contiguous subsequence
- prime sieve
- sorting
- order statistics
- range query
- graph search
- connected components
- shortest paths
- minimum spanning forest
- dynamic programming
- hashing
- ...

no need to know about disentanglement!

Writing Disentangled Programs

pure library interface

tabulate
map
reduce
scan
filter
flatten
merge
...

fast implementation w/ "local" effects

...

~~purely~~ mostly functional, parallel, disentangled algorithms

```
fun forwardBFS(G,s) =
  let
    fun outEdges(u) = map(fn v => (u,v), neighbors(G,u))
    val parents = tabulate(numVertices(G), fn v => -1)
    fun tryVisit(u,v) =
      if compareAndSwap(parents,v,-1,u) then SOME(v) else NONE
    fun search(F) =
      if length(F) = 0 then ()
      else search(filterOp(tryVisit, flatten(map(outEdges, F))))
  in
    tryVisit(s,s);
    search(singleton(s));
    parents
  end
```

Summary

disentanglement

- "concurrent tasks remain oblivious to each other's allocations"
- common property, guaranteed by race-freedom, functional programming
- enables fully parallel memory management and GC

MaPLe implementation

- fast, scalable, and space-efficient
- competitive with low-level imperative code

`github.com/mpllang/mpl`

Future / Ongoing work

- static enforcement of disentanglement (e.g. type system)
- dynamic "entanglement management"
- distributed computing