The Space Cost of Lazy Reference Counting

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invent

Some figures are taken from the corresponding paper in the Proceedings of the 2004 POPL Symposium, and are reproduced by permission of ACM.

Automatic Memory Management

- Tracing garbage collection
  - Periodically trace through all live objects.
  - Reclaim untraced objects.
  - Common in language runtimes.

- Reference Counting
  - Associate count of incoming references with objects.
  - Reclaim object when count reaches zero.
  - Common in OS file systems, some C++ libraries.
  - Used occasionally in language runtimes.

Tradeoffs

- Classic reference count disadvantages:
  - Leaks cyclic garbage.
  - Expensive pointer assignments, (threads!)
- Classic reference count advantages:
  - Faster reuse: better cache behavior.
  - ~~Synchronous/deterministic finalization~~.
  - Possibly better memory utilization.
  - Supports copy avoidance.
  - **Avoids GC pauses?**

Classic Reference Counting

- When creating reference to *p*:

```
incr(p) { count(p)++; }
```

- When deleting a reference to *p*:

```
decr(p) {
  if (--count(p) == 0) {
   invoke decr on embedded references;
   free(p);
  }
}
```

- Pointer assignment requires incr(new) followed by decr(old).
- Count update/test must be atomic.
- Incr/decr usually inserted automatically.

Pauses avoided

```
big = make_huge_linked_tree();
do forever {
    temp = new foo();
}
```

- Each implied incr()/decr() takes constant time.
- No significant pauses during execution.
- Simple tracing GC would trace `big` repeatedly, introducing pauses.

…but only sometimes

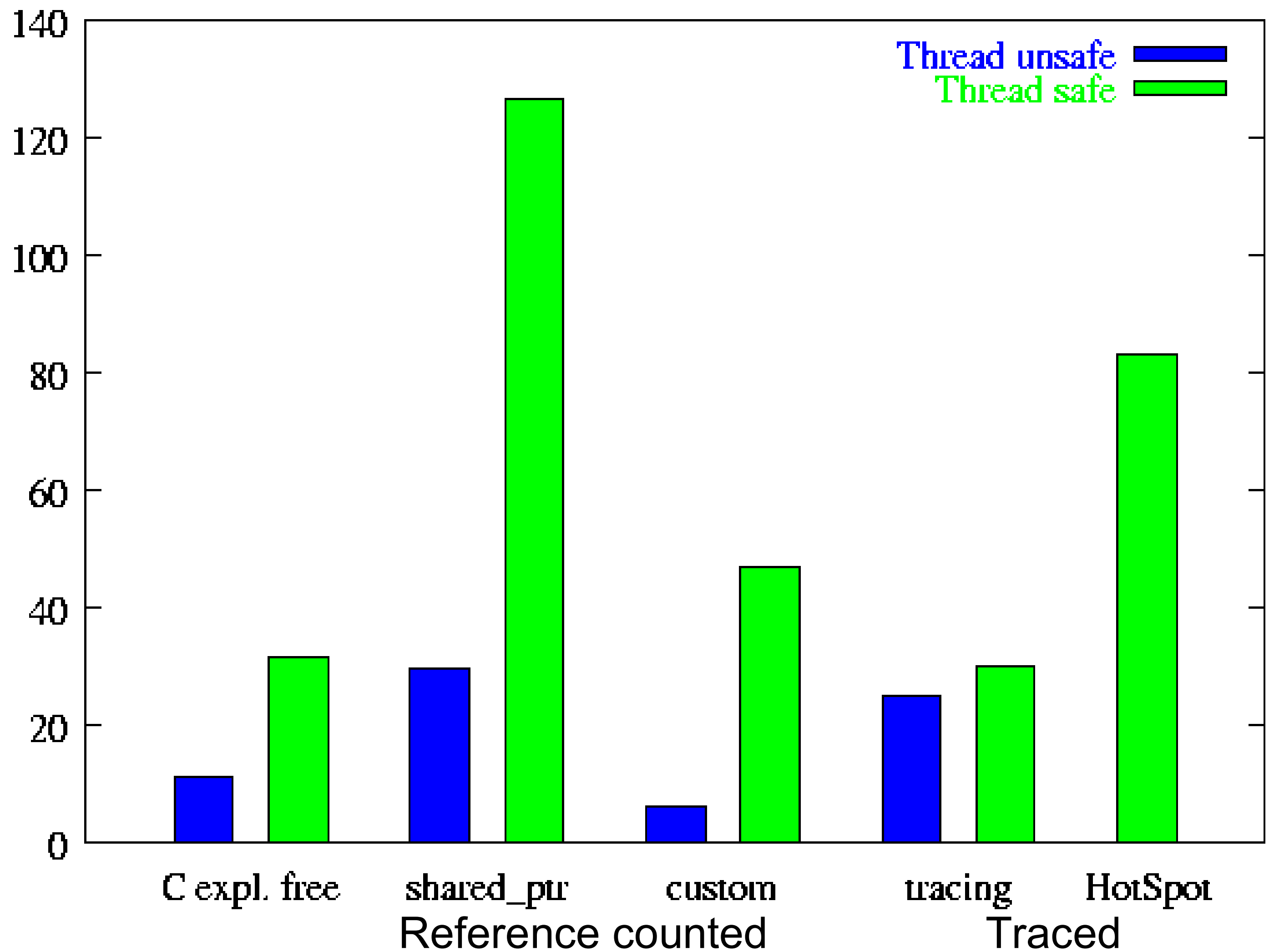
```
do forever {
    tmp = make_huge_linked_tree();
    ...
    big = tmp;
    ...
}
```

- "`big = tmp`" assignment invokes decr() on old tree.
- Count becomes zero.
- Decr() recurses, deallocating and touching entire tree.
- Effectively a significant pause during assignment.

Tracing vs. ref. counting pauses

- Simple tracing GC stops entire process.
- Classic reference counting stops thread
  - …which may hold critical lock.
- If deallocation time were predictable, we could easily deallocate manually.
  - Pauses are effectively unpredictable.
- Manual deallocation also adds “pauses”.
  - They are usually predictable.
- Recursive decr() calls need atomicity.
  - Usually more sensitive to threading.

Worst case "pause" times for GCBench (msecs, P4 2.0GHz, gcc, Linux)



Lazy deletion

- Decr(p):

```
if (--count(p) == 0)
    add p to to-be-freed;
```

- Before each allocation:

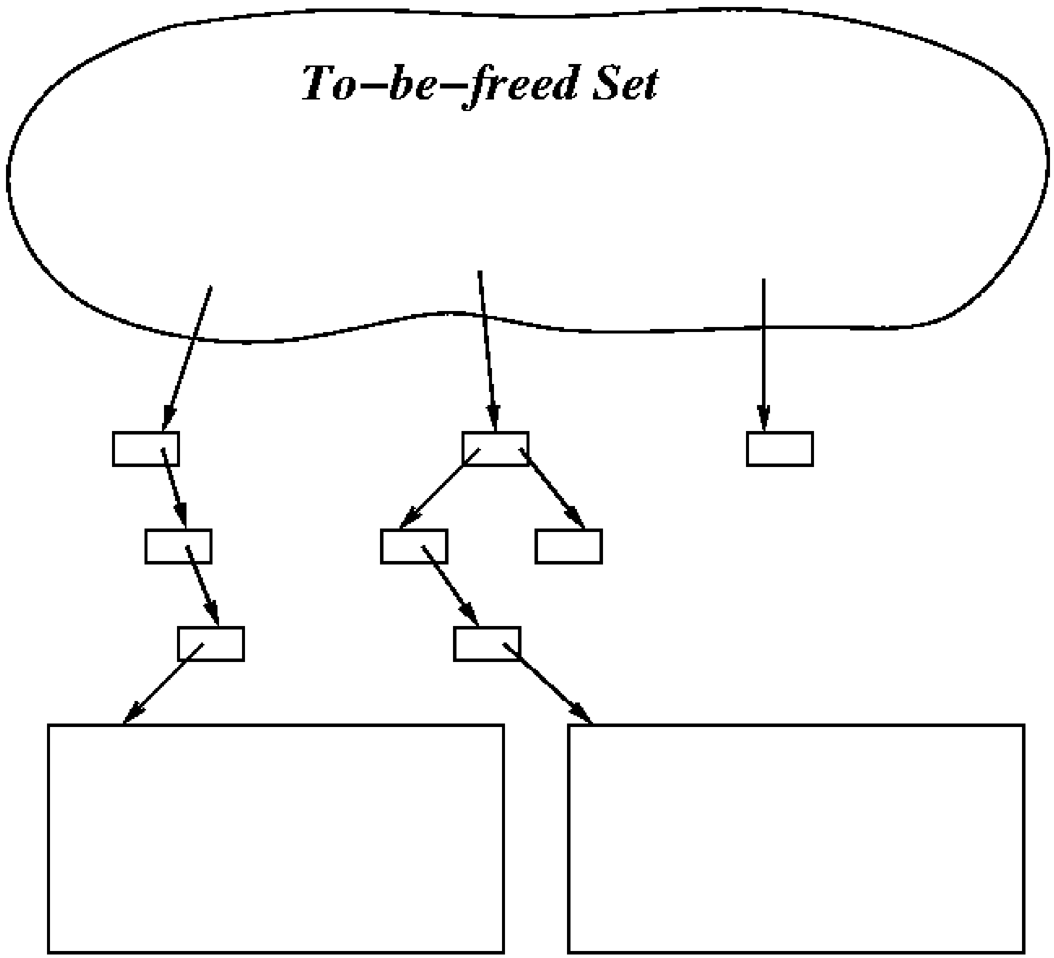
```
q = element of to-be-freed (if any);
invoke decr on embedded references;
free(q);
```

- Each allocation does one deallocation.

Lazy deletion (contd.)

- Dates back to 1963 paper (Weizenbaum).
- Works well for fixed size objects.
- But for multiple object sizes:
  - No sufficiently large object may be free.
  - Sufficiently large objects may be in to-be-freed set.
  - We may require additional heap size to satisfy allocations.

Hidden space



How much space overhead?

- Ignore fragmentation cost.
- Objects between s_{min} and s_{max} in size.
- We measure space overhead as:

$$\frac{\text{max size of allocated objects (incl. to-be-freed)}}{\text{max size of live objects}}$$

- Fragmentation adds at most a factor of $O(\log(s_{max}/s_{min}))$ to total heap size. (Robson, 1971).

Space overhead (contd.)

- Lazy reference counting cannot increase the number of allocated objects above maximum number of live objects.
- Hence

$$\frac{\text{max allocated size}}{\text{max live size}} \leq \frac{s_{max}}{s_{min}}$$

Main result

- The preceding bound is asymptotically optimal.
- This holds for a large class of variants of the preceding algorithm.
- Smooth tradeoff:

  allocation deallocates *m* items ➔

  bound reduced by factor of *m*

Observations

- It may take a heap of size $\Omega(N^2)$ to accommodate N live bytes.
- If an n byte allocation deallocates at least n bytes, the max number of allocated bytes can't exceed the the max number of live bytes → only fragmentation overhead.
  - May require s_{max}/s_{min} deallocations for a single allocation.

More precise statement

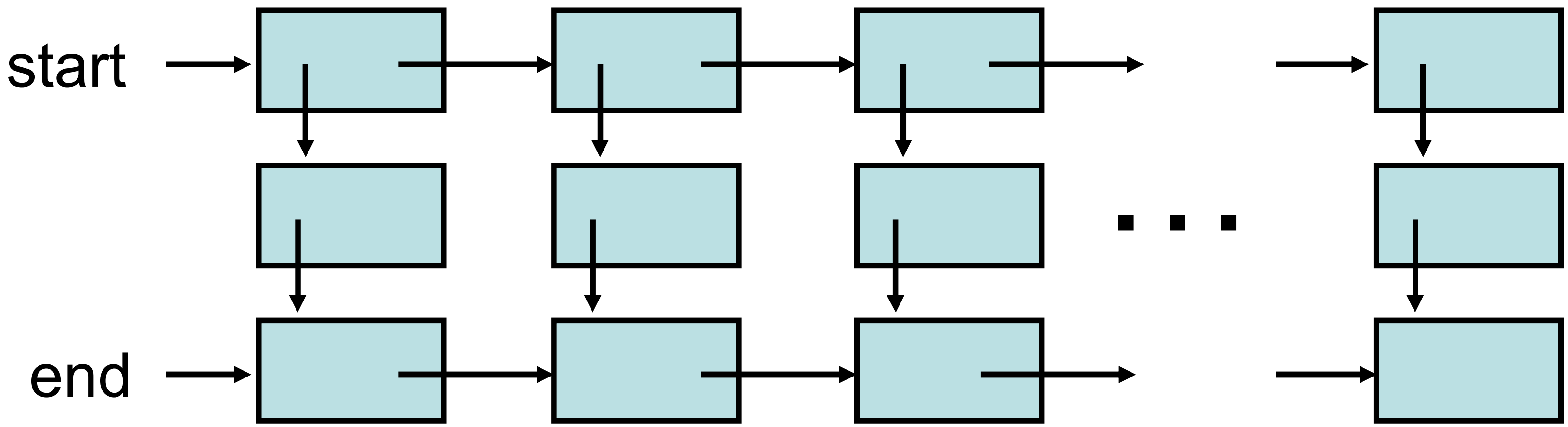
- Assuming that:
  - s_{min} and s_{max} satisfy some assumptions.
    - Affect only constants.
  - We have a "lookahead-free reference count implementation".
  - Every sequence of 1 allocation, 2 incr(), and 2 decr() calls deallocate ≤ m objects.
- There exists a "program" with no more than N referenced (live) bytes, such that:
  - The total number of allocated bytes is at least

$$\frac{N \, s_{max}}{2 \, m \, s_{min}}$$

Proof illustration

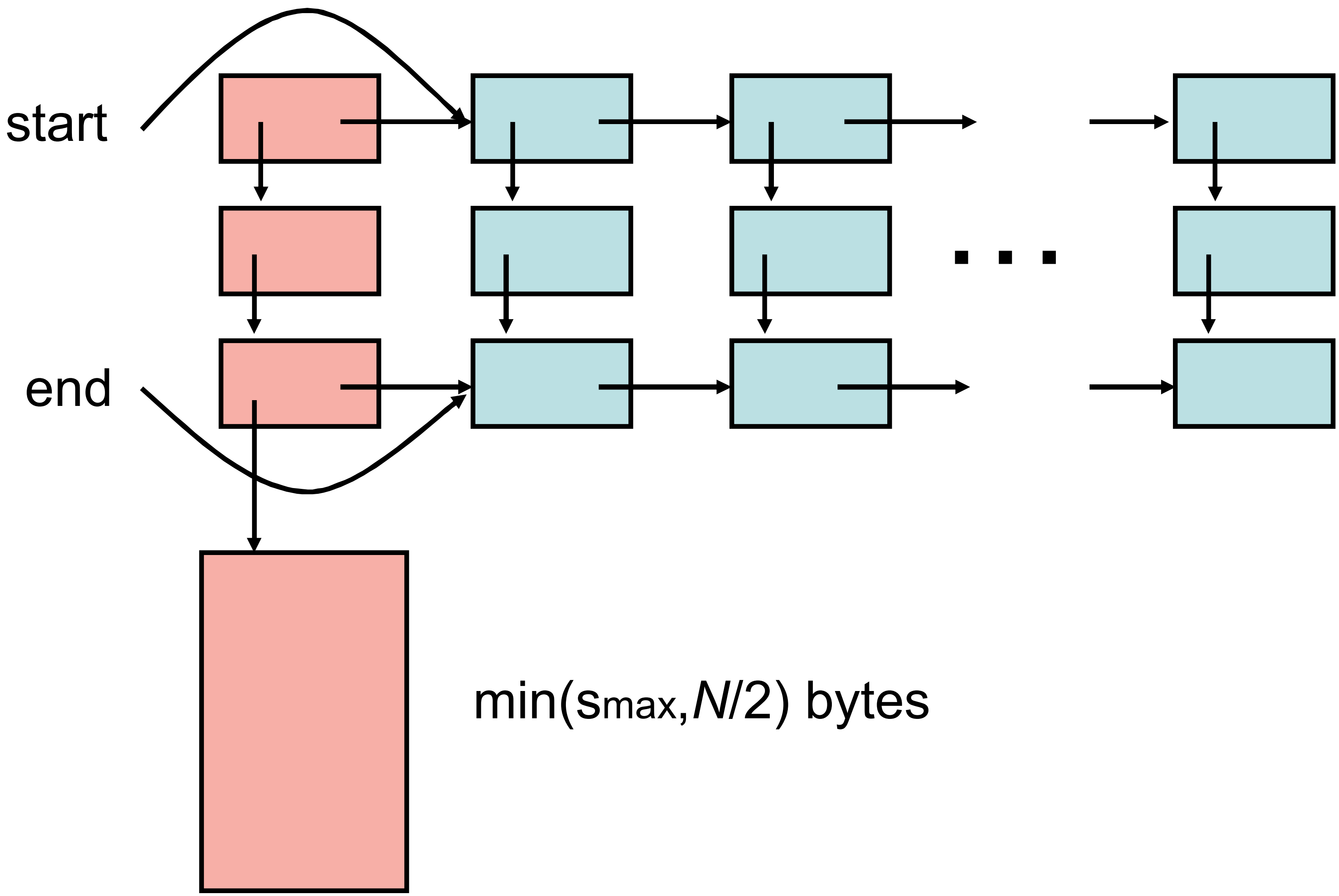
- We construct a program.
- Real proof adapts to deallocation order of reference counting algorithm.
- Here we assume instead:
  - $m = 3$
    - each allocation deallocates 3 *to-be-freed* items.
  - *to-be-freed* set is managed in LIFO order.

Step 1 – Allocate N/2 bytes in small objects

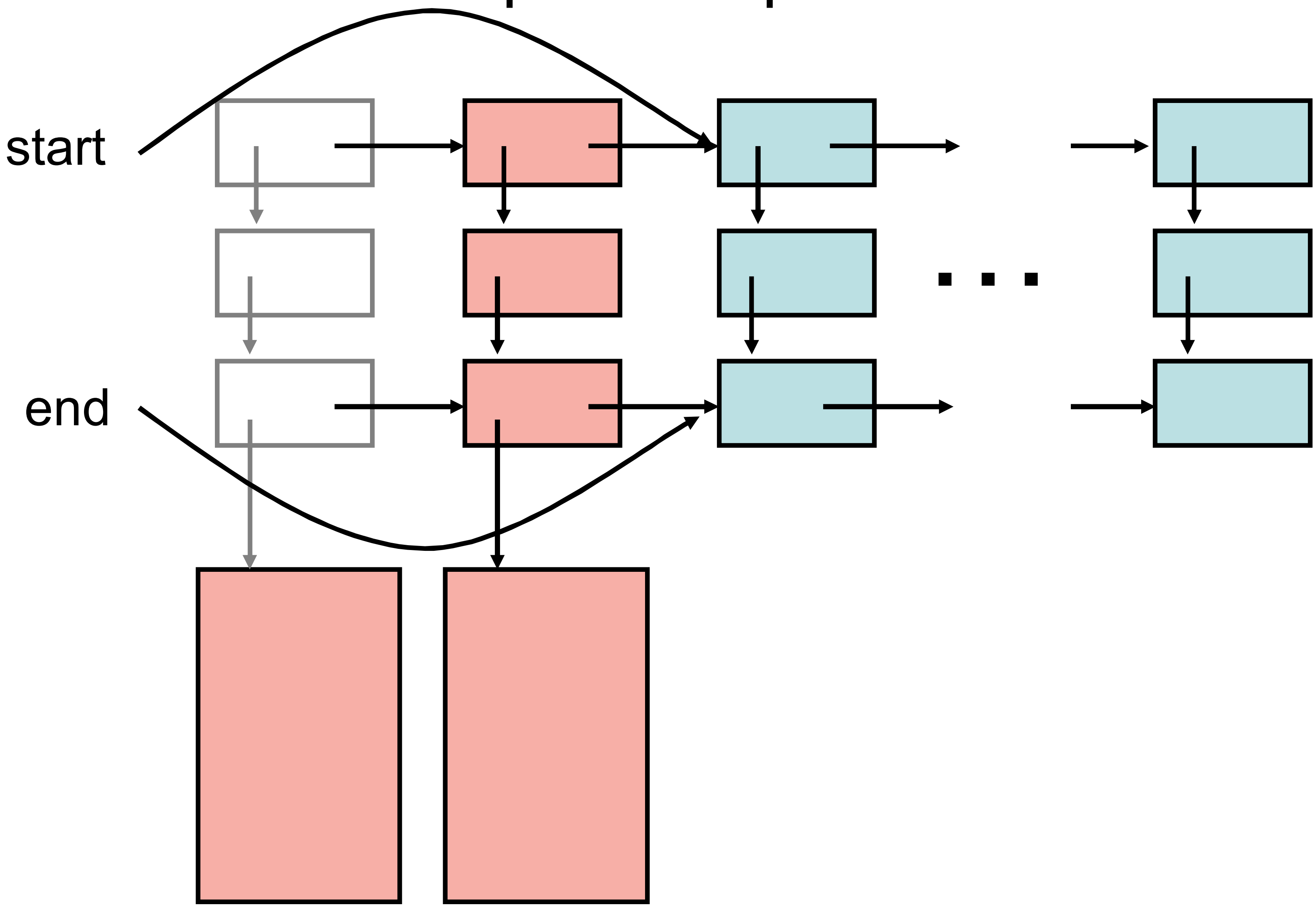


$$\frac{N}{6\,s_{min}} \text{ columns}$$

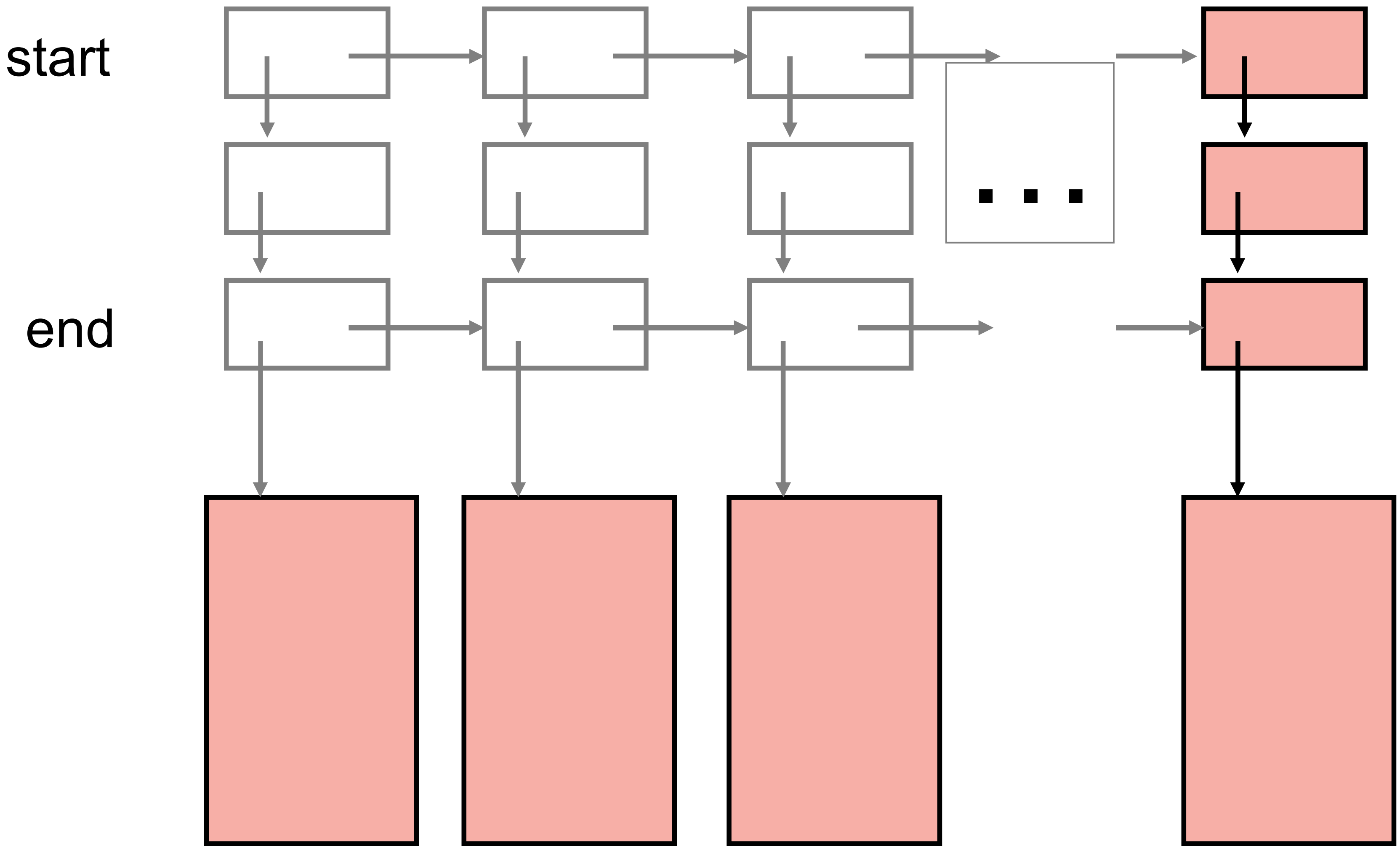
Step 2 – Allocate large object & advance



Step 3 – Repeat



Final State



Conclusions

- In a reference counted system, either:
  - There may be pauses,
  - Allocation takes time proportional to object size (as with tracing), or
  - It incurs a probably unacceptable (though finite) worst-case space overhead.
- The fixed size case is not an anomaly:
  - There is a smooth tradeoff with s_{max}/s_{min}.