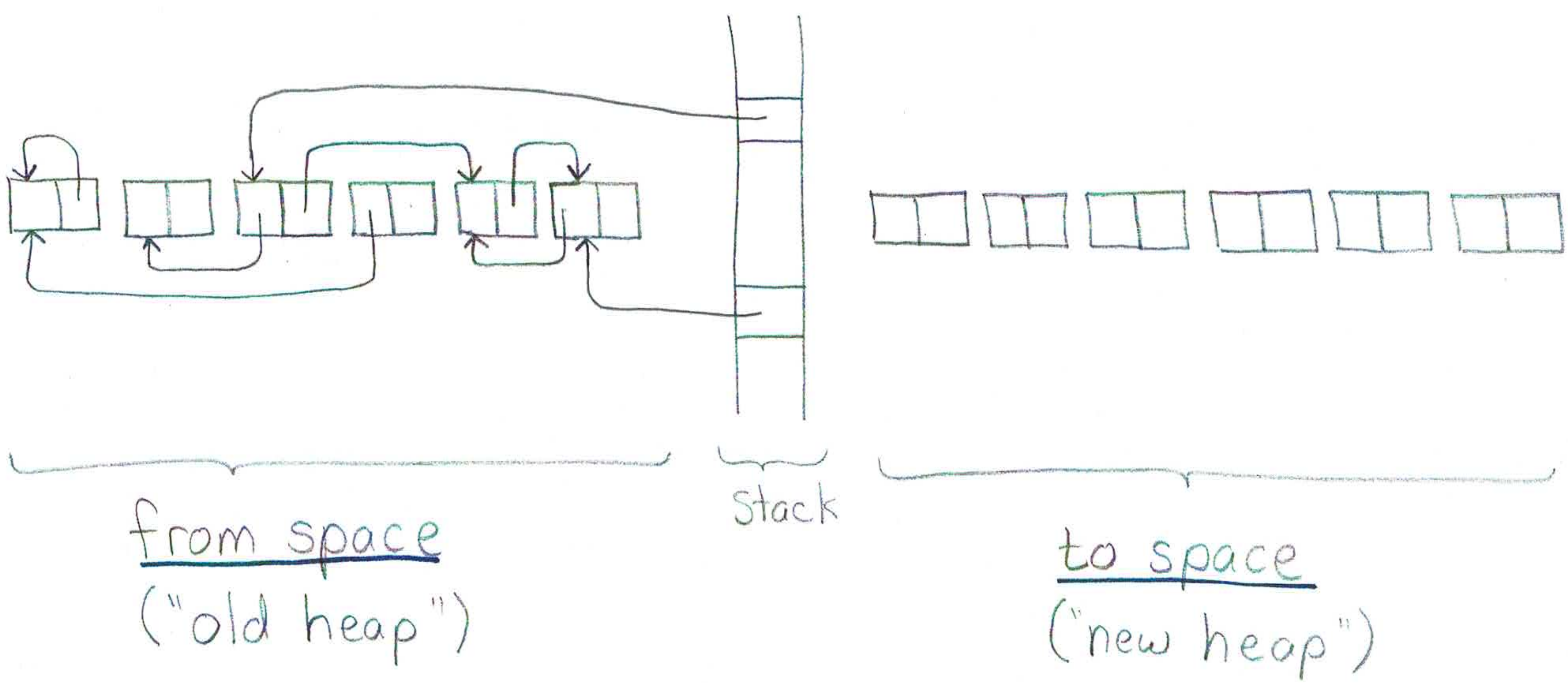
Copying Garbage Collection

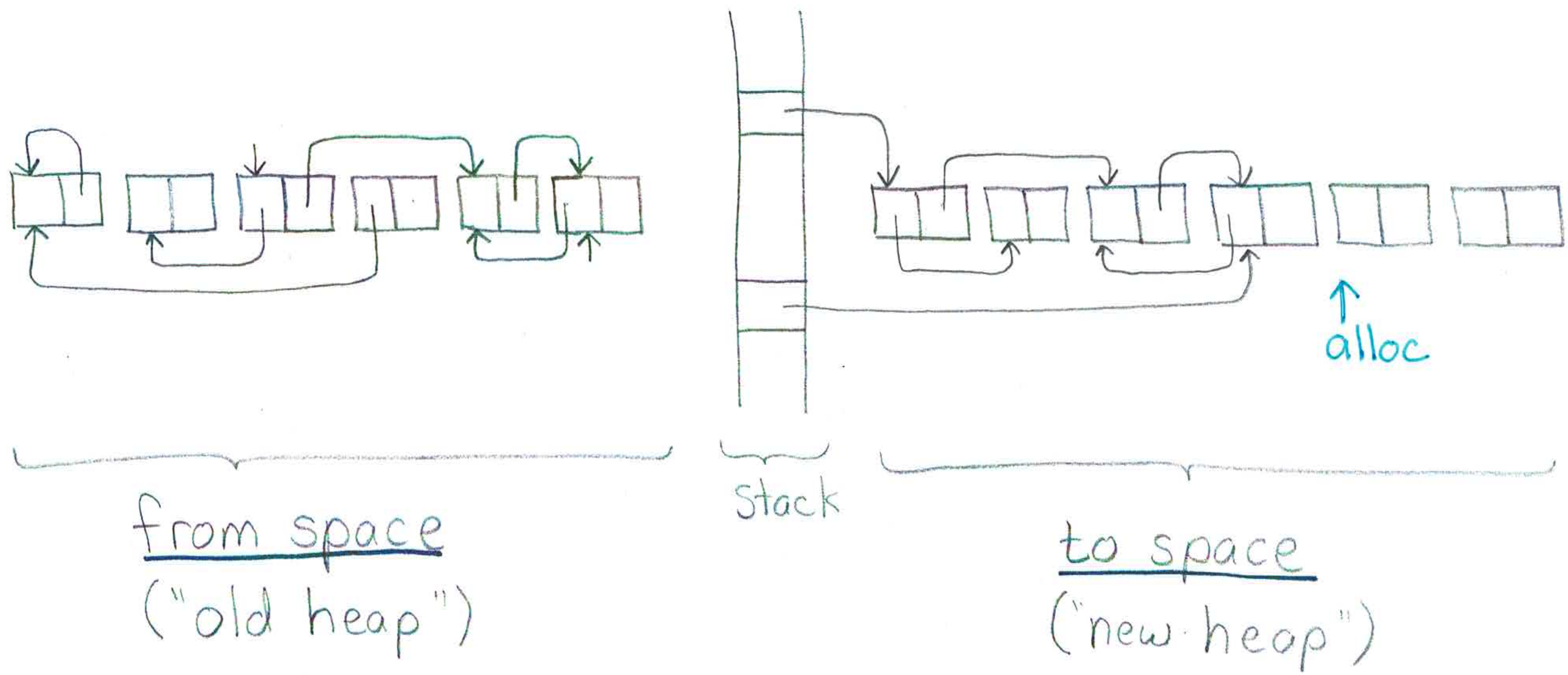
- Recall: use reachability as conservative approx. of when it is safe to reclaim objs.

- Copying is a different take
  - allocate objs until heap is full
  - find all reachable objects and copy them <u>from current heap</u> <u>to new heap</u>
  - reclaim all of old heap (reachable + unreachable)
    - ↳ actually, keep old heap around to serve as the new new heap at next GC
    - ↳ but, this "bulk reuse" of whole heap is faster than reclaiming individual objs (trading space for time)

Copying GC: Example (Simple)



Copying GC: Example (Simple)



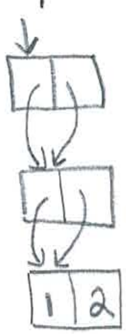
Copying GC: Details

- Copying into a contiguous prefix of to-space leaves a contiguous suffix of to-space available

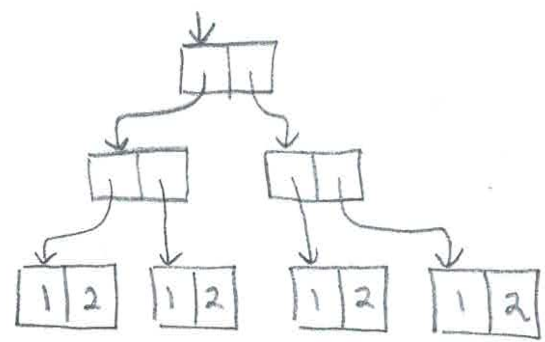
  ↳ use "bump pointer" allocation;
    - at end of copying, alloc ptr at start of available region
    - at allocation, increment alloc ptr by requested size (no fragmentation or irregular obj size issues)
    - much faster than free-list

Copying Collection: Details

- Two issues
  - a recursive copying function would use stack space (don't want to use mem. to reclaim mem.)
  - must preserve sharing



should not be copied as



(would use more space and, with mutation, would change semantics)

- related to both issues, beware of cycles in object graph

Copying Collection: Details

- Solutions (Cheney's Alg)
  - use to-space as a queue of "to be copied" objs
  - when obj. is copied, install forwarding pointer;
    when obj. would be copied again, use forwarding ptr

- Algorithm
  1) Forward roots
     ↳ copy objs pointed to and update pointers
  2) Scan to-space for objs. w/ fields pointing to from-space;
     forward such fields
  3) GC done when all objs in to-space scanned

Copying GC: Example

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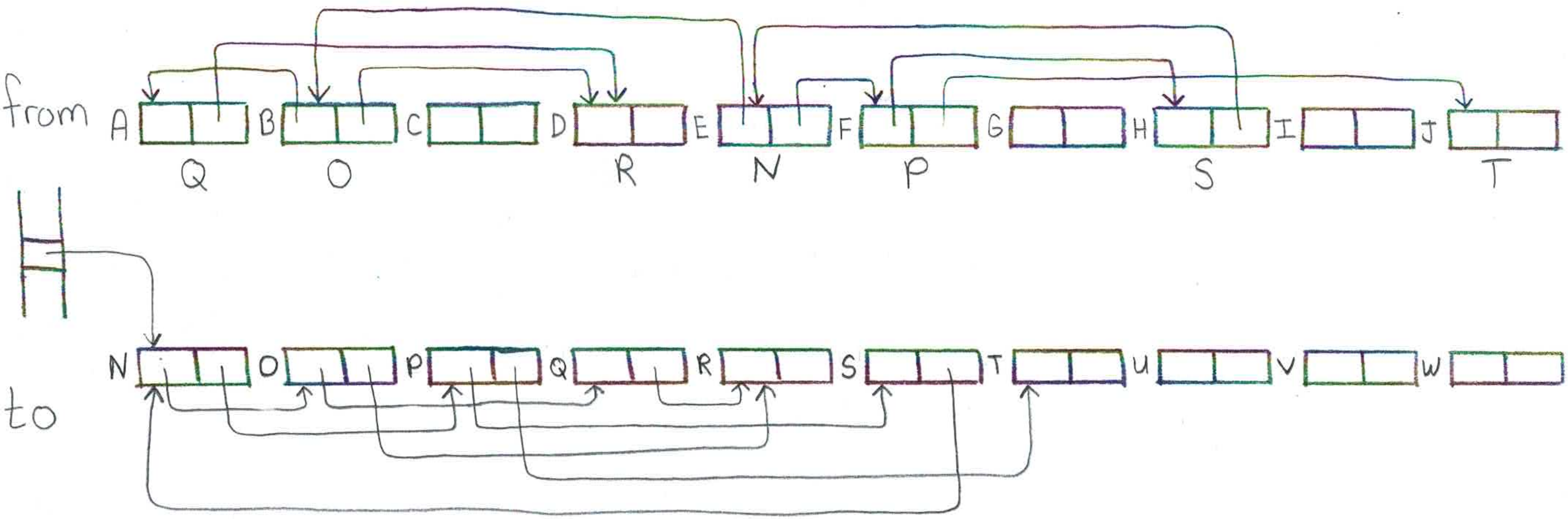

↑alloc

↑scan

Copying GC: Details

- ptr alloc(sz)
```
ptr alloc(sz) { res = alloc;
                alloc = alloc + sz;
                return res;
              }
```

- ptr forward(p)
```
ptr forward(p) { if (p->fwd != NULL) {
                     return (p->fwd);
                 }
                 q = alloc(p->sz);
                 memcpy(q, p, p->sz);
                 p->fwd = q;
                 return q;
               }
```

Copying GC: Details

- scan() {
```
scan() { while (scan < alloc) {
            p = scan
            foreach f in fields(p) {
              p->f = forward(p->f);
            }
            scan = scan + p->sz;
          }
        }
```

Copying: Analysis

- Per object overhead
- Allocation cost
- Pause time
  - higher constant factors due to writes/copying
- Notes
  - ½ of heap unused when not GCing
  - BFS graph traversal
    may affect locality
  - Objects with long lifetimes may be copied many times
    (but most objects die young)
    ↳ motivation for generational copying collection

Heap Resizing

- What happens if a GC does not reclaim many objs?
  - ↳ Will need to GC again very soon.
- What happens if a GC does not reclaim any objs?
  - ↳ Will need to grow heap.
- Recall: H - size of heap

  L - amount of live data

  $\gamma = H/L$ - ratio of heap size to live data

  $1/\gamma$ - fraction of heap occupied by live objs

- if γ too small
  - ↳ frequent GCs (and % of program time in GC very high)

Heap Resizing

- Start with a small heap, and grow in response to growth of live data
- After each collection, compute L and γ.

  If γ too small, then increase H (by requesting mem. from OS)

  If γ too large, then shrink H (by returning mem. to OS)

  ↳ Why give mem. back? "play nice" w/ other programs
  fit into physical memory

  ⇒ Maintain a roughly constant γ
- Mark-Sweep performs well w/ $\gamma > 2$
- Copying performs well w/ $\gamma > 3$
- Production systems often target $\gamma \approx 8$

Advanced Features of GCs

- The mark-sweep and copying GCs are very basic
  - ↳ pause times are a major concern

- Incremental: do a few steps of GC
  after every few steps of program execution
  or at each allocation by program
  - \+ if enough GC steps done often enough,
    then no long pauses (just very many very short ones)
  - − more complicated relationship b/w GC and mutator
    - ↳ GC must be prepared for changes to heap made by mutator

- Real-time: stronger version of incremental,
  guarantee max pause time in any time window
  - \+ req'd for certain applications
  - − usually very conservative (reserve much more time
    than typically needed
    to defend against worst case)

Advanced Features of GCs

- Concurrent: GC executes at the same time as mutator (in a separate thread)
  + if GC runs fast enough, then low/no pause times
  - complex coordination b/w GC and mutator
- Parallel: GC executes using multiple threads (but mutator paused)
  + lower pause times (b/c GC work split b/w threads)
  - complex coordination b/w GC threads
    ↳ for good performance, want to balance work among threads (but can be hard: how to parallelize marking a long list?)
- Concurrent + Parallel: GC executes using multiple threads at the same time as mutator
  + better pause times
  - complex coordination among GC and mutator threads

Advanced Features of GCs

- Many of these features work best w/ mark-sweep
  - ↳ non-moving makes coordination w/ mutator easier
- Many, many variants and novel GCs
- Remains an active area of research
  - Prog. Lang. Design and Implementation (PLDI)
  - International Symposium on Mem. Mgmt. (ISMM)
  - International Conf. on Functional Prog. (ICFP)
  - Obj. Oriented Prog., Systems, Langs., and Apps. (OOPSLA)

  } Conferences

  - The Garbage Collection Handbook
    by Hosking, Moss, and Jones