CSE P 501 – Compilers

Memory Management and Garbage Collection

Hal Perkins

Autumn 2021

References

- *Uniprocessor Garbage Collection Techniques*
  Wilson, IWMM 1992 (longish survey)

- *The Garbage Collection Handbook*
  Jones, Hosking, Moss, 2012 (book)

- Earlier version of this lecture by Vijay Menon, CSE 501, Sp09; Jim Hogg, CSE P 501 Sp14

Program Memory

- Typically divided into 3 regions:
  - Global / Static: fixed-size at compile time; exists throughout program lifetime
  - Stack / Automatic: per function, automatically allocated and released (local variables)
  - Heap: Explicitly allocated by programmer (malloc/new/cons)
    - Need to recover / recycle storage for reuse when no longer needed

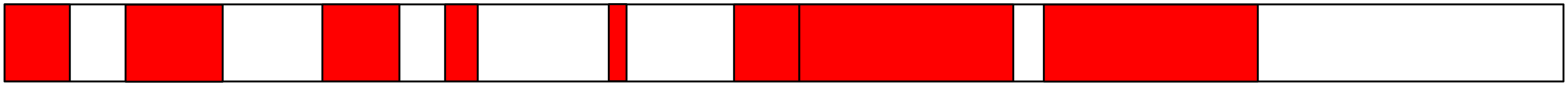
Manual Heap Management

- Programmer calls free/delete when done with storage
- Pro
  - Cheap
  - Precise
- Con
  - How do we enumerate the ways? the pain?
  - Buggy, huge debugging costs, …

Conventional Heap Storage

```
...
char* s = (char*) malloc(50);
...
free(s);
```

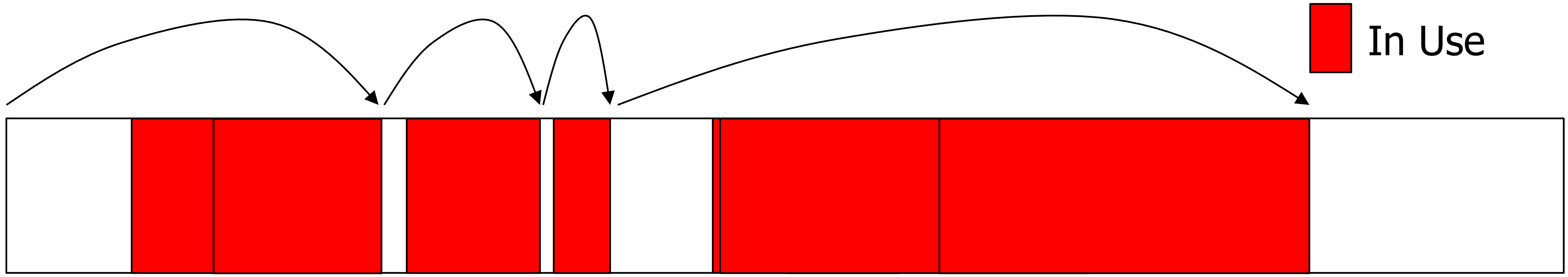
🟥 In Use



C Runtime Heap Memory

- Developer must remember to free memory when no longer required
- Eventual fragmentation => slow to malloc, slow to free

Heap Storage Fragmentation

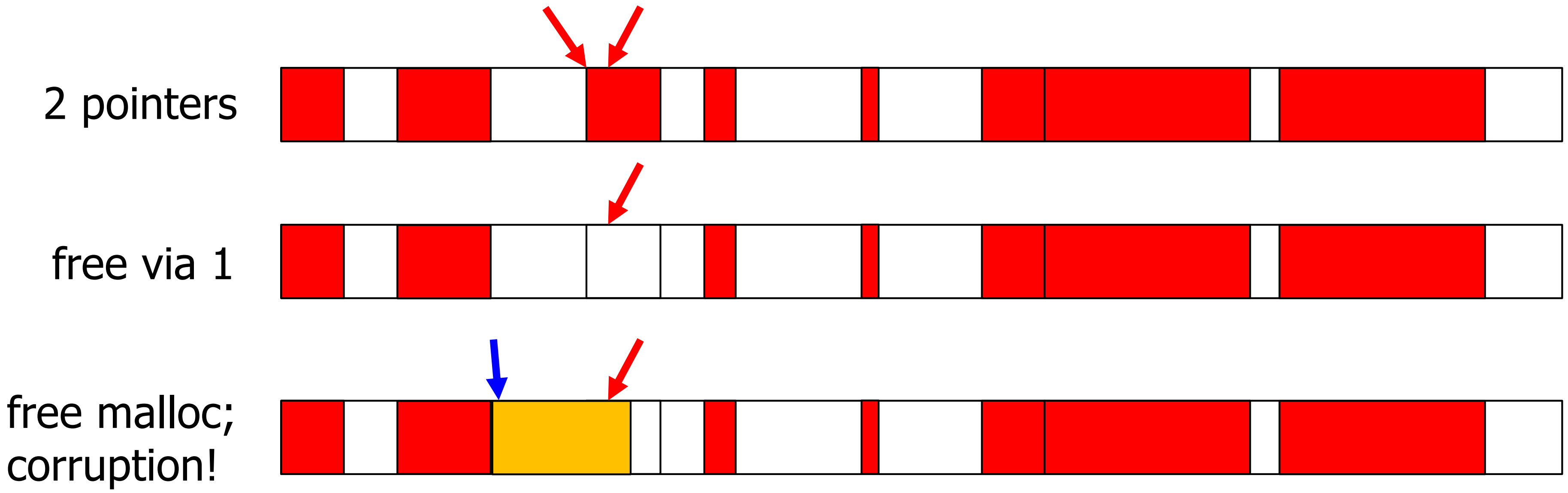


C Runtime Heap Memory

- malloc: walk the freelist to find a slot big enough for current request
- free: adjust freelist; collapse contiguous freespace
- fragmentation: plenty free chunks but none big enough for request
- cannot compact the used space - may contain pointers; may be pointed-at

Bugs

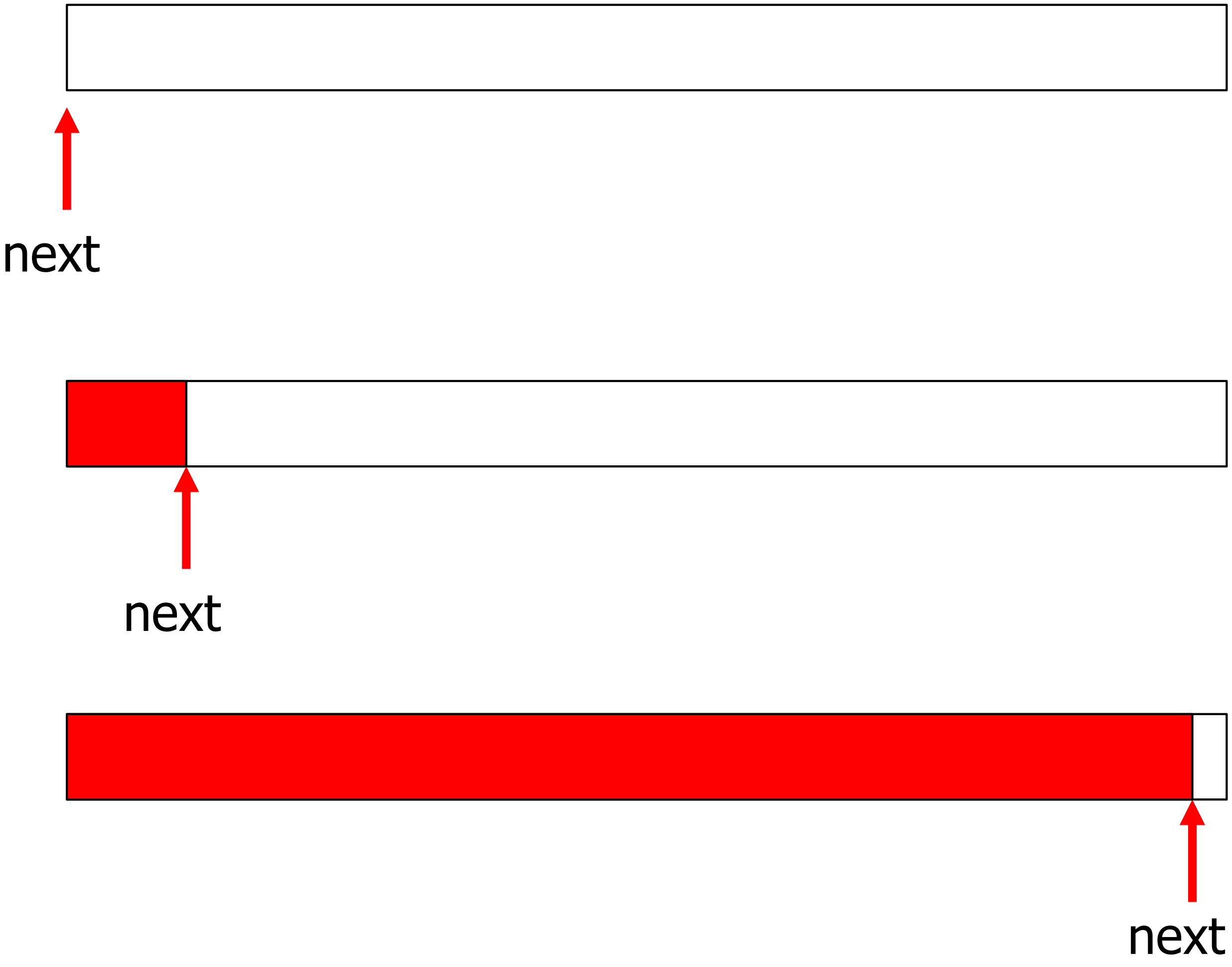
- Forget to free => eventually run out of memory
  - called a "memory leak”
- Call free, but continue to use!
  - called "use-after-free", or "dangling pointer"
  - memory corruption - wrong answers; crash if lucky!
  - major source of security issues
  - detect via "pool poisoning"



Garbage Collection

- Automatically reclaim heap memory no longer in use by the program
  - Simplify programming
  - Better modularity, concurrency
  - Avoids huge problems with dangling pointers
  - Almost required for type safety
  - But not a panacea – still need to watch for stale pointers, GC's version of "memory leaks"
    - i.e., pointers in live data to no-longer-used data

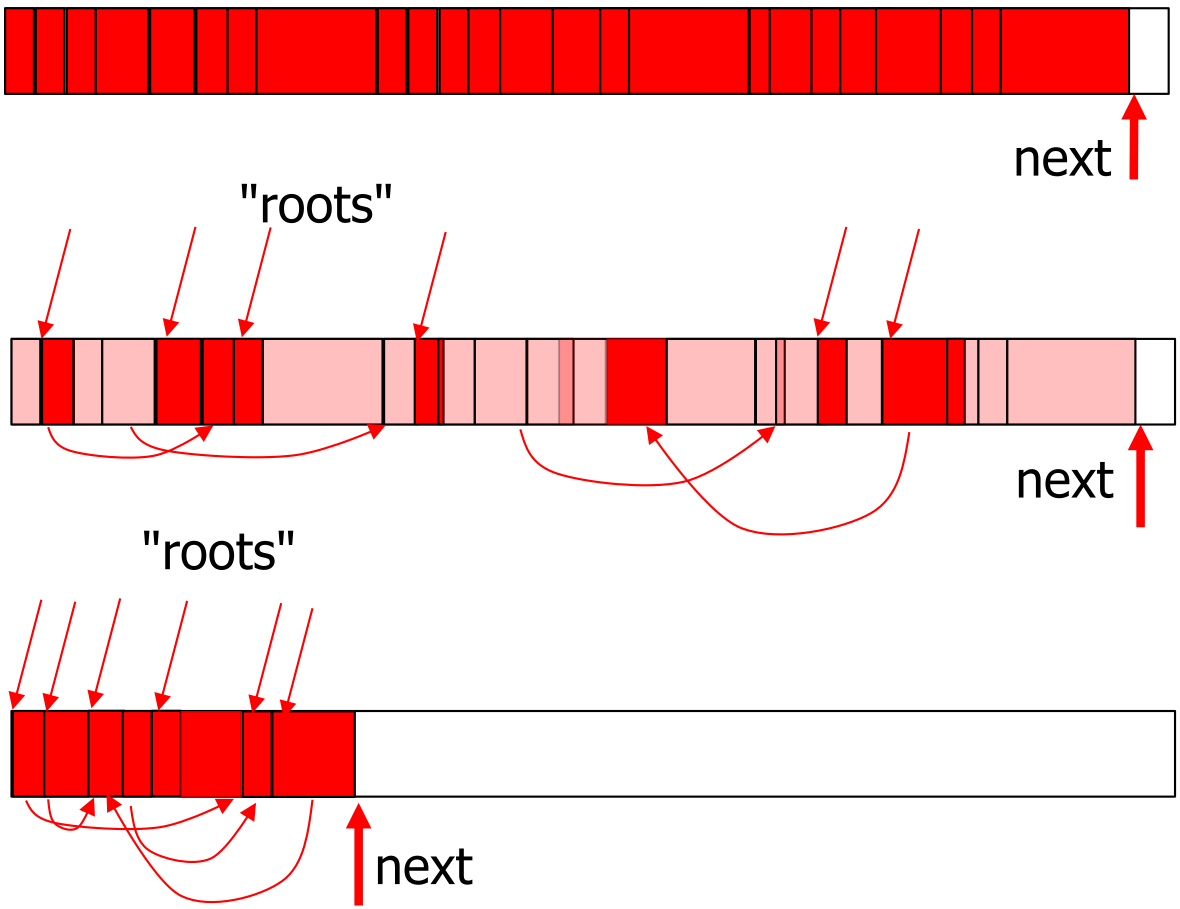
Garbage Collection



Allocate an object; fast!

Allocate more objects;
and one more, please?

Garbage Collection



Allocate another object

Trace reachable objects

Compact unreachables; update *all* pointers

GC does not find garbage: it finds live objects and ignores all other memory

Heap Characteristics

- Most objects are small (< 128 bytes)
- Object-oriented and functional code allocates a huge number of short-lived objects
- Want allocation, recycling to be fast and low overhead
  - Serious engineering required

Allocation

- Usually multiple free lists organized by size for small objects (8, 16, 24, 32, … depends on alignment); additional list for large blocks
  - Regular malloc does exactly the same
- Allocation
  - Grab a free object from the right free list
  - No more memory of the right size triggers a collection

What is Garbage?

- An object is *live* if it is still in use
- GC needs to be conservative
  - OK to keep memory no longer in use
  - Not ok to reclaim something that is live
- An object is *garbage* if it is not live

Reachability

- *Root set* : the set of global and local (stack + register) variables visible to active procedures
- Heap objects are *reachable* if:
  - They are directly accessible from the root set
  - They are accessible from another reachable heap object (pointers/references)
- Liveness implies reachability (conservative approximation)
- Not reachable implies garbage

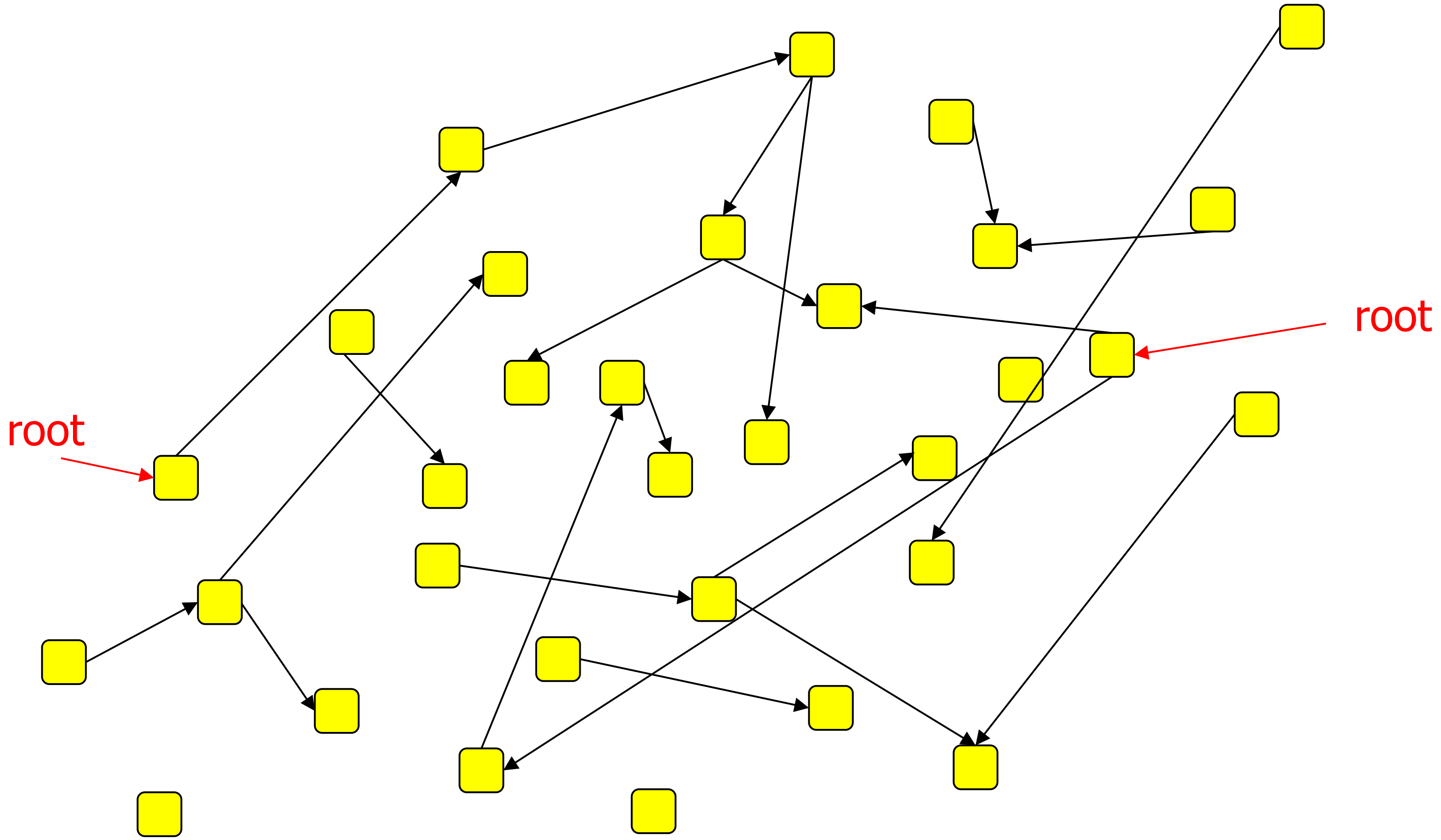
Tracing Collectors

- Mark the objects reachable from the root set, then perform a transitive closure to find all reachable objects
- All unmarked objects are dead and can be reclaimed
- Various algorithms: mark-sweep, copying, generational…

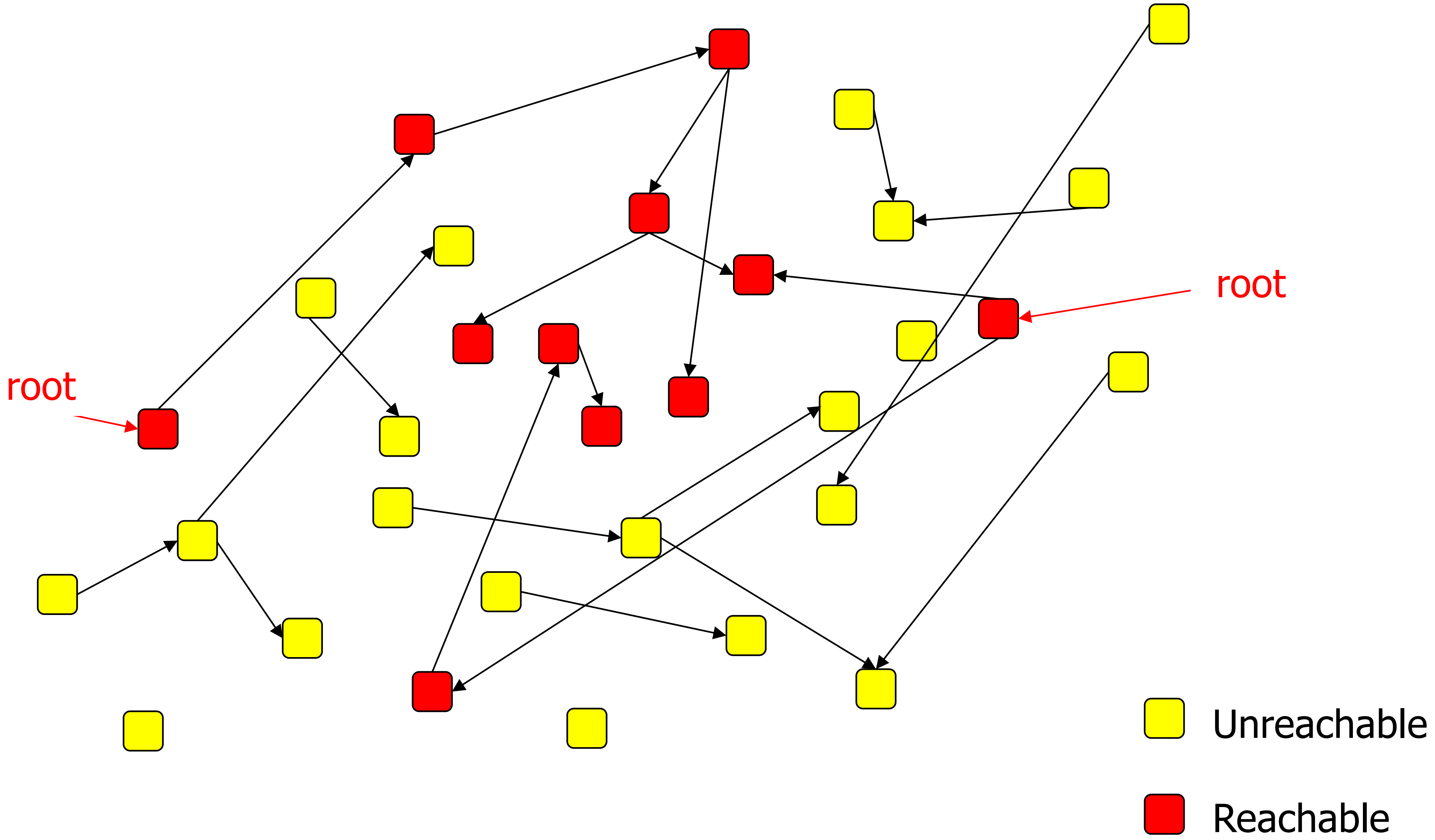
Mark-Sweep Collection

- Mark phase – find the live objects
  - Transitive closure from root set marking all live objects
- Sweep phase
  - Sweep memory for unmarked objects and return to appropriate free list(s)

GC Start



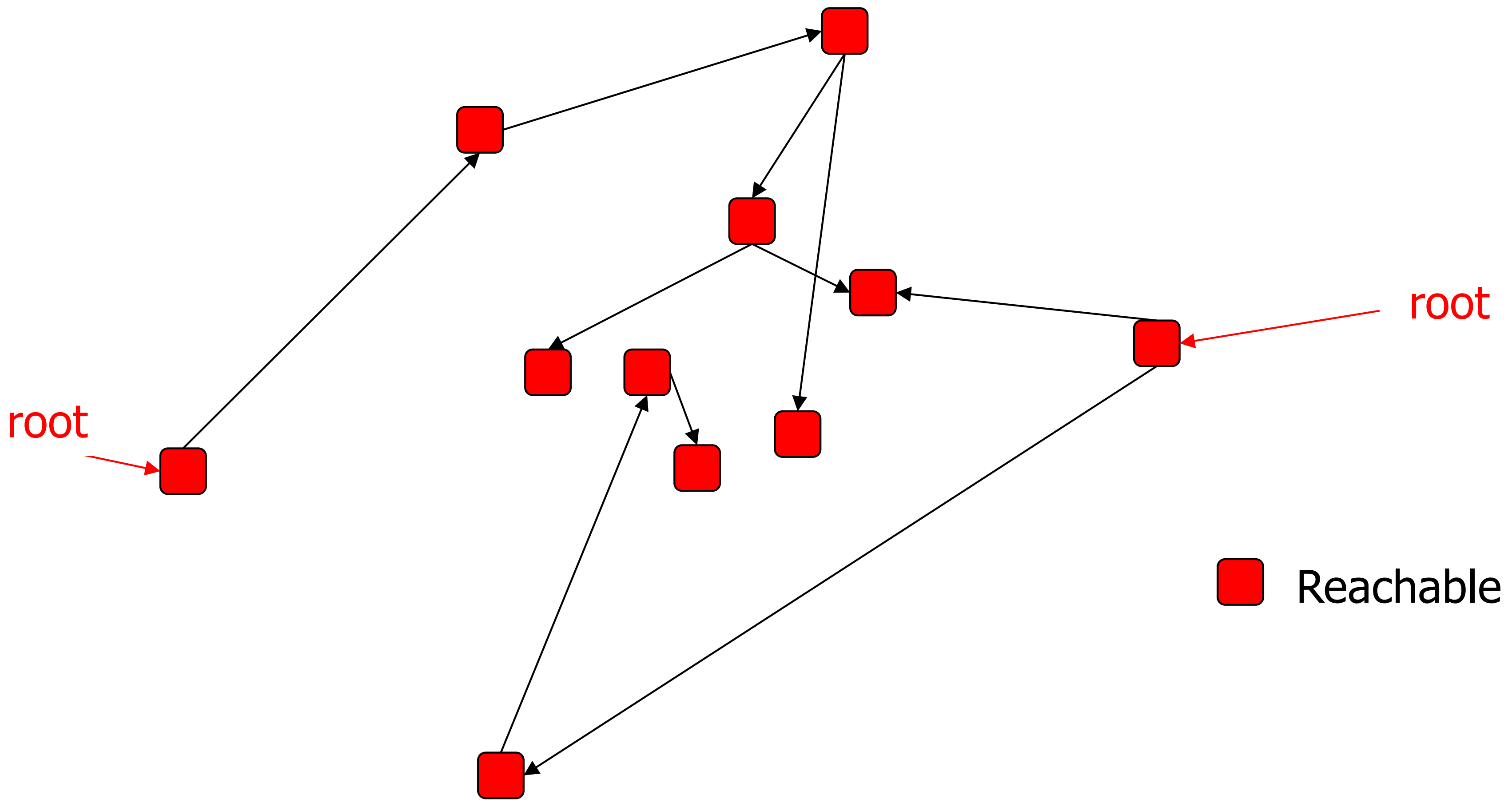
GC Mark Phase



🟨 Unreachable

🟥 Reachable

GC Sweep Phase



With memory free, now allocate space for object that provoked the GC

Reachability

- Compiler produces:
  - A *stack-map* at *GC safe points*
    - *Stack map:* enumerate global variables, stack variables, live registers (tricky stuff! Why?)
    - *GC safe points:* new(), method entry, method exit, back edges (thread switch points)
      - Stop all threads at one of their GC safe points and then ok to do a collection
  - *Type information blocks*
    - Identifies reference fields in objects (to trace the heap)

Mark-Sweep Evaluation

- Pro
  - Space efficiency
  - Incremental object reclamation
- Con
  - Relatively slower allocation time (free lists vs. “next chunk of heap”)
  - Can have poor locality of objects allocated at around the same time
  - Redundant work rescanning long-lived objects
  - “Stop the world I want to collect”

Semispace Copying Collector

- Idea: Divide memory in half
  - Storage allocated from one half of memory
  - When full, copy live objects from old half (“from space”) to unused half (“to space”) & swap semispaces
- Fast allocation – next chunk of to-space
- Requires copying collection of entire heap when collection needed

Semispace collection

- Same notion of root set and reachable as in mark-sweep collector
- Copy each object when first encountered
- Install forwarding pointers in from-space referring to new copy in to-space
- Transitive closure: follow pointers, copy, and update as it scans
- Reclaims entire “from space” in one shot
  - Swap from- and to-space when copy done

Semispace Copying Collector Evaluation

- Pro
  - Fast allocation
  - Locality of objects allocated at same time
  - Locality of objects connected by pointers (can use depth-first or other strategies during the mark-copy phase)
- Con
  - Wastes half of (virtual?) memory
    - Other copying/compacting collectors solve some of this
    - Be careful with VM – don't want compacting to thrash
  - Redundant work rescanning long-lived objects
  - "Stop the world I want to collect"

Generational Collectors

- Generational hypothesis: young objects die more quickly than older ones (Lieberman & Hewitt ‘83, Ungar ‘84)
- Most pointers are from younger to older objects (Appel ‘89, Zorn ‘90)
- So, organize heap into young and old regions, collect young space more often

Generational Collector

- Divide heap into two spaces: young, old
- Allocate new objects in young space
- When young space fills up, collect it and copy surviving objects to old space
  - Engineering: use write barriers to avoid having to scan all of old space on quick collections – most pointers that cross the boundary are from young objects to old
  - Refinement: require objects to survive at least a few collections before copying
- When old space fills, collect both
- Often use multiple generations, not just two

GC Tradeoffs

- Performance
  - Mark-sweep often faster than semispace
  - Generational better than both
- Mutator (i.e., user program) performance
  - Semispace is often fastest
  - Generational is better than mark-sweep
- Overall: generational is a good balance
- But: we still “stop the world” to collect

Advanced GC and Research Areas

- Parallel/concurrent garbage collection
  - Found in some production collectors
    - Tricky stuff – can’t debug it into correctness – there be theorems here
- Locality issues
  - Object collocation
  - GC-time analysis
- Distributed GC

Compiler & Runtime Support

- GC tightly coupled with safe runtime (e.g., Java, CLR, functional languages)
  - Total knowledge of pointers (type safety)
  - Tagged objects with type information
  - Compiler maps for information
  - Objects can be moved; forwarding pointers

What about unsafe languages? (e.g., C/C++)

- Boehm/Weiser collector: GC still possible *without* compiler/runtime cooperation(!)
  - New versions of malloc (& free) + GC to manage heap
  - If it looks like a pointer, it's a pointer
  - Mark-sweep only – GC doesn't move anything
  - Allows GC in C/C++ but constraints on pointer bit-twiddling
  - Surprisingly effective, particularly if program uses pointers as in a type-safe language (e.g., no pointer mangling, no (void*)int tricks, etc.)

Boehm/Weiser Collector

- Useful for development/debugging
  - Less burden on compiler/runtime implementor
- Used in various Java and .net prototypes, research implementations, production code if sufficiently effective
- Similar ideas for various tools to detect memory leaks, etc.

A bit of perspective…

- Automatic GC has been around since LISP I in 1958
- Ubiquitous in functional and object-oriented programming communities for decades
- Mainstream since Java(?) (mid-90s)
- Now conventional wisdom?