CS412/CS413

Introduction to Compilers

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Lecture 34: Memory Management
16 Apr 08

Outline

- Explicit memory management
- Garbage collection techniques
  - Reference counting
  - Deutsch-Bobrow Deferred Reference Counting
  - Mark and sweep
  - Copying GC
  - Concurrent/incremental GC
  - Generational GC
- See http://www.memorymanagement.org

Explicit Memory Management

- Unix (libc) interface:

  void* malloc(long n) : allocate n bytes of storage on the heap and return its address

  void free(void *addr) : release storage allocated by malloc at address addr

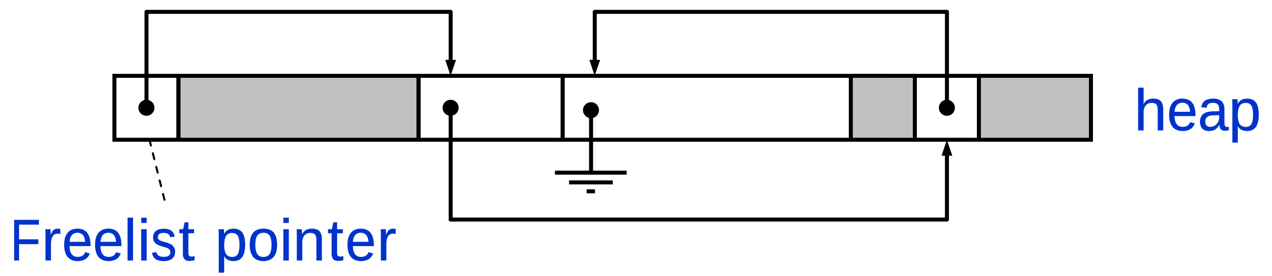
- User-level library manages heap, issues brk calls when necessary

Freelists

- Blocks of unused memory stored in freelist(s)

  malloc: find usable block on freelist

  free: put block onto head of freelist



- Simple, but fragmentation ruins the heap
- External fragmentation = small free blocks become scattered in the heap
  - Cannot allocate a large block even if the sum of all free blocks is larger than the requested size

Buddy System

- Idea 1: freelists for different allocation sizes
  - malloc, free are O(1)
- Idea 2: freelist sizes are powers of two: 2, 4, 8, 16, ...
  - Blocks subdivided recursively: each has buddy
  - Round requested block size to the nearest power of 2
  - Allocate a free block if available
  - Otherwise, (recursively) split a larger block and put all the other blocks in their respective free lists
  - Reverse operation: coalesce (with buddy, if free, not split)
- Internal fragmentation: allocate larger blocks because of rounding
- Trade external fragmentation for internal fragmentation

Explicit Garbage Collection

- Java, C, C++ have new operator / malloc call that allocates new memory
- How do we get memory back when the object is not needed any longer?
- Explicit garbage collection (C, C++)
  - delete operator / free call destroys object, allows reuse of its memory. Programmer decides how to collect garbage
  - makes modular programming difficult—have to know what code "owns" every object so that objects are deleted exactly once

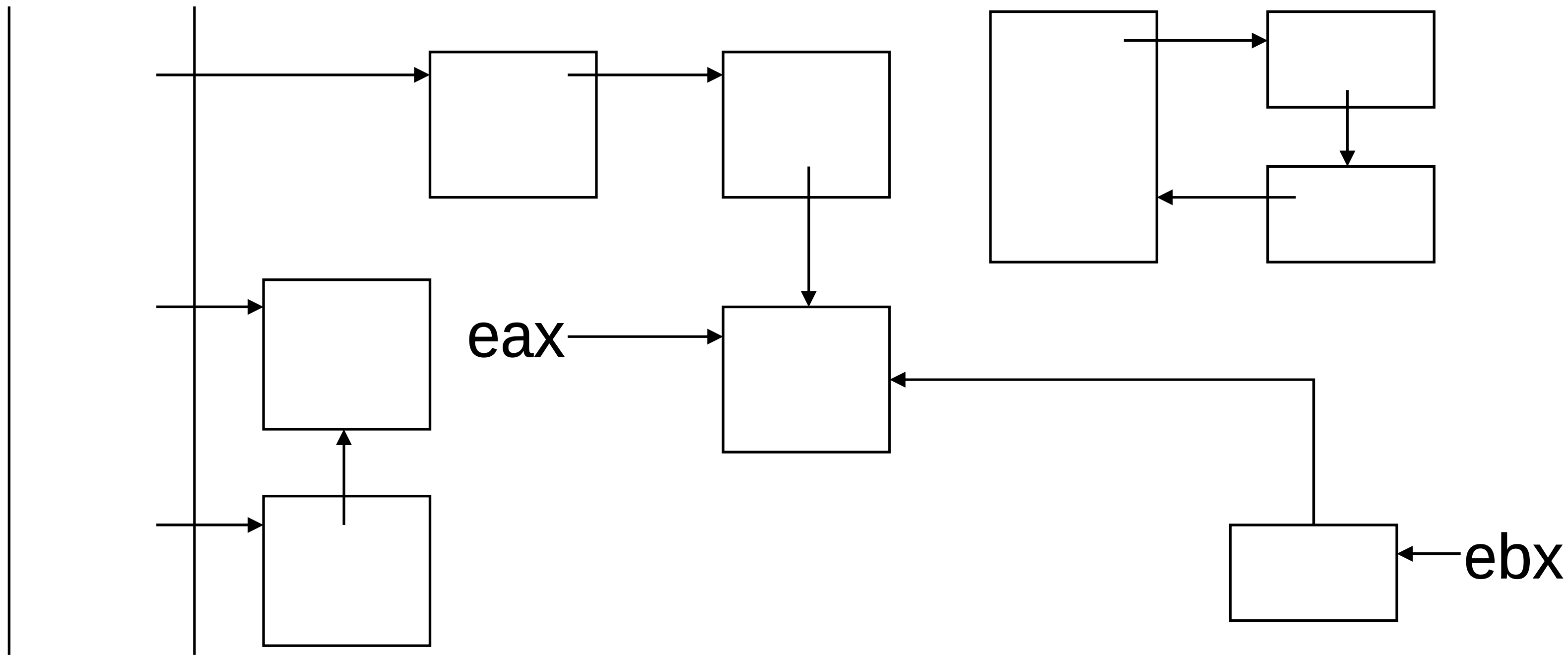
Automatic Garbage Collection

- The other alternative: automatically collect garbage!

- Usually most complex part of the run-time environment
- Want to delete objects automatically if they won't be used again: undecidable
- Conservative: delete only objects that definitely won't be used again
- Reachability: objects definitely won't be used again if there is no way to reach them from root references that are always accessible (globals, stack, registers)

Object Graph

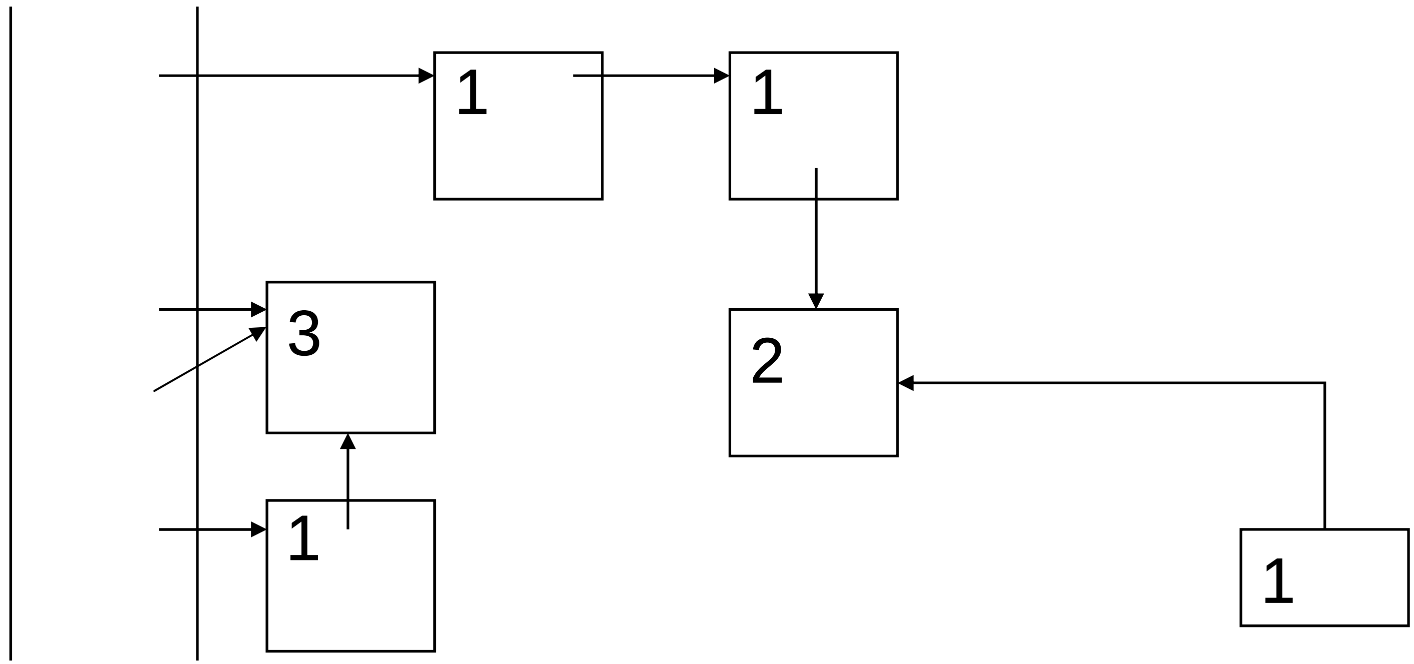
- Stack, registers are treated as the roots of the object graph. Anything not reachable from roots is garbage
- How can non-reachable objects can be reclaimed efficiently? Compiler can help



Reference Counting

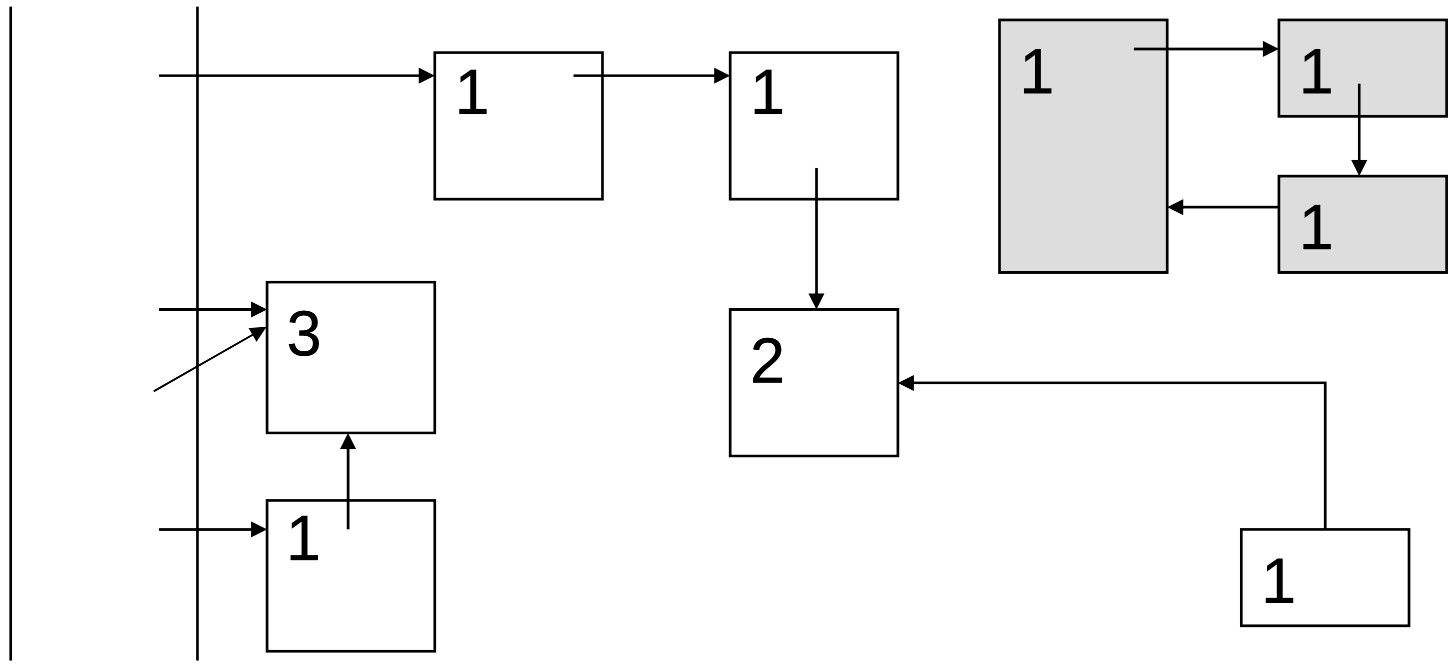
- Idea: associate a reference count with each allocated block (reference count = the number of references (pointers) pointing to the block)
- Keep track of reference counts
  - For an assignment x = Expr;
    - decrement reference count of block referenced by x
    - increment reference count of block Expr references
- When decrement reduces count to zero, object is unreachable; reclaim it.

Reference Counts



- ... how about cycles?

Reference Counts



- Reference counting doesn't detect cycles!

Performance Problems

- Consider assignment   x.f = y.
- Without ref-counts: [tx+ off] = ty
- With ref-counts:

```
t1 = [tx + f_off];
c = [t1 + refcnt];
c = c - 1;
[t1 + refcnt] = c;
if (c == 0) call reclaim_object(t1);
c = [ty + refcnt];
c = c + 1;
[ty + refcnt] = c;
[tx + f_off] = ty;
```

- Large run-time overhead
- Result: reference counting not used much by real language implementations

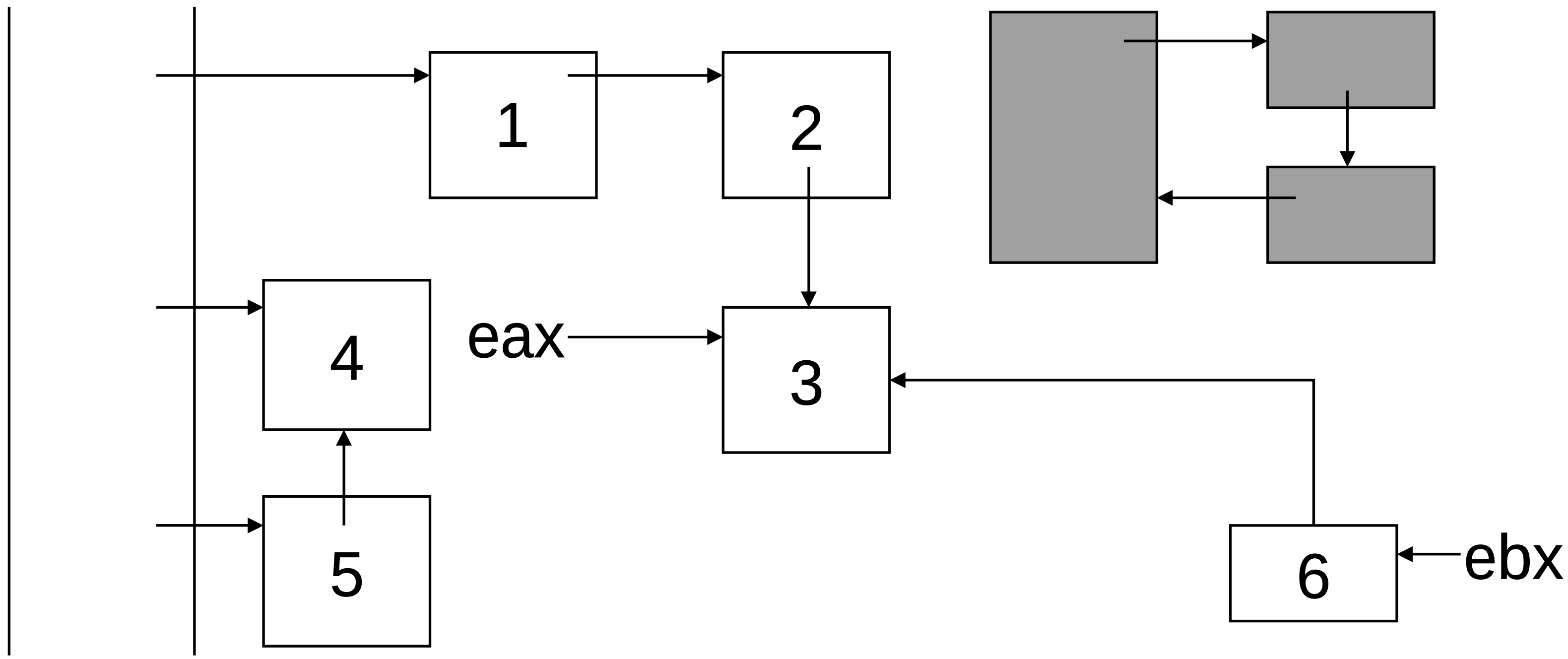
Deutsch-Bobrow Deferred Reference Counting

- Don't count references to nodes from stack
- When reference count drops to 0, insert it into Zero Count Set for deferred collection.
- When Zero Count Set is full:
  - Scan stack, incrementing counts of all nodes it refers to.
  - Scan Zero Count Set, and reclaim any nodes with zero count.
  - Set Zero Count Set to empty.
  - Scan stack, decrementing counts of all nodes it refers to. If reference count drops to 0, insert into Zero Count Set.
  - Increase size of Zero Count Set if it is more full than some threshold.

Mark and Sweep

- Classic algorithm with two phases
- Phase 1: Mark all reachable objects
  - start from roots and traverse graph forward marking every object reached
- Phase 2: Sweep up the garbage
  - Walk over all allocated objects and check for marks
  - Unmarked objects are reclaimed
  - Marked objects have their marks cleared
  - Optional: compact all live objects in heap

Traversing the Object Graph



Implementing Mark Phase

- Mark and sweep generally implemented as depth-first traversal of object graph
- Has natural recursive implementation
- What happens when we try to mark a long linked list recursively?

Pointer Reversal

- Idea: during DFS, each pointer only followed once. Can reverse pointers after following them -- no stack needed! (Deutsch-Waite-Schorr algorithm)

- Implication: objects are broken while being traversed; all computation over objects must be halted during mark phase (No concurrency allowed)

Cost of Mark and Sweep

- Mark and sweep accesses all memory in use by program
  - Mark phase reads only live (reachable) data
  - Sweep phase reads the all of the data (live + garbage)
- Hence, run time proportional to total amount of data!
- Can pause program for long periods!

Conservative Mark and Sweep

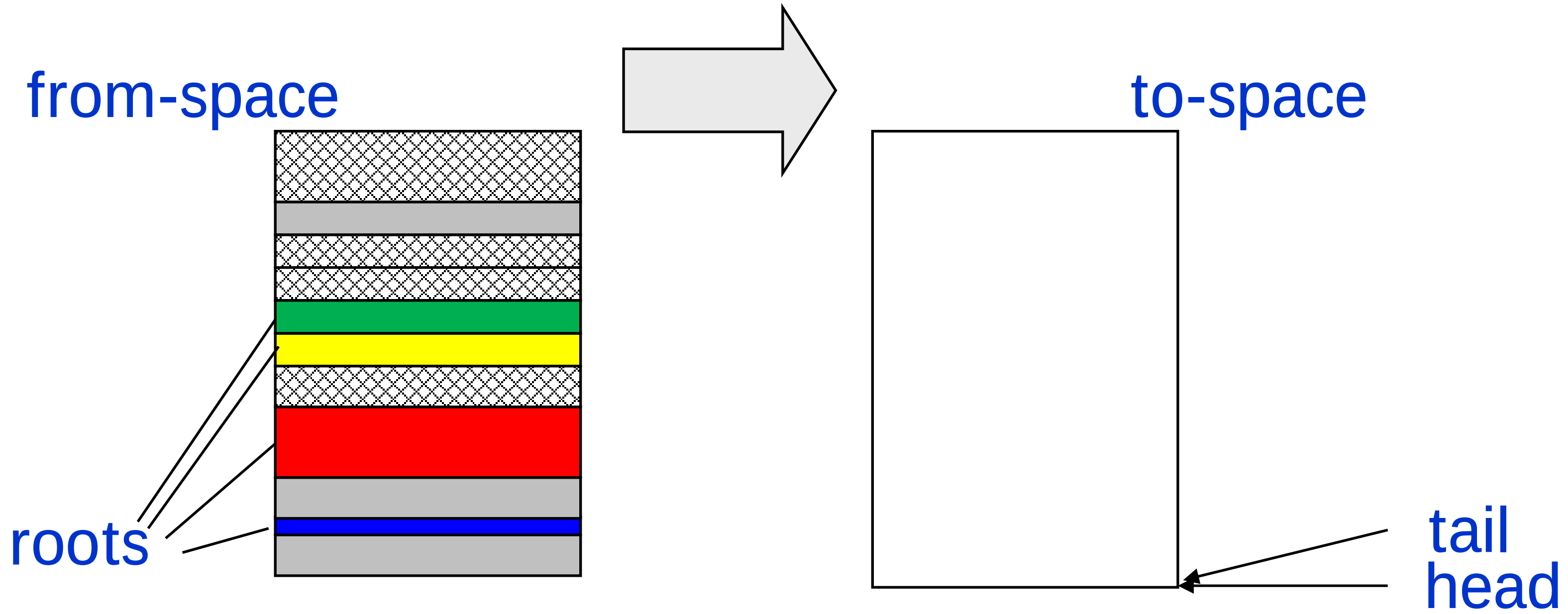
- Allocated storage contains both pointers and non-pointers; integers may look like pointers
- Issues: precise versus conservative collection
- Treating a pointer as a non-pointer: objects may be garbage-collected even though they are still reachable and in use (unsafe)
- Treating a non-pointer as a pointer: objects are not garbage collected even though they are not pointed to (safe, but less precise)
- Conservative collection: assumes things are pointers unless they can't be; requires no language support (works for C!)

Copying Collection

- Like mark & sweep: collects all garbage
- Basic idea: use two memory heaps
  - one heap in use by program
  - other sits idle until GC requires it
- GC mechanism:
  - copy all live objects from active heap (from-space) to the other (to-space)
  - dead objects discarded during the copy process
  - heaps then switch roles
- Issue: must rewrite referencing relations between objects

Copying Collection (Cheney)

- Initialize to-space as empty queue.



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- Initialize to-space as empty queue.
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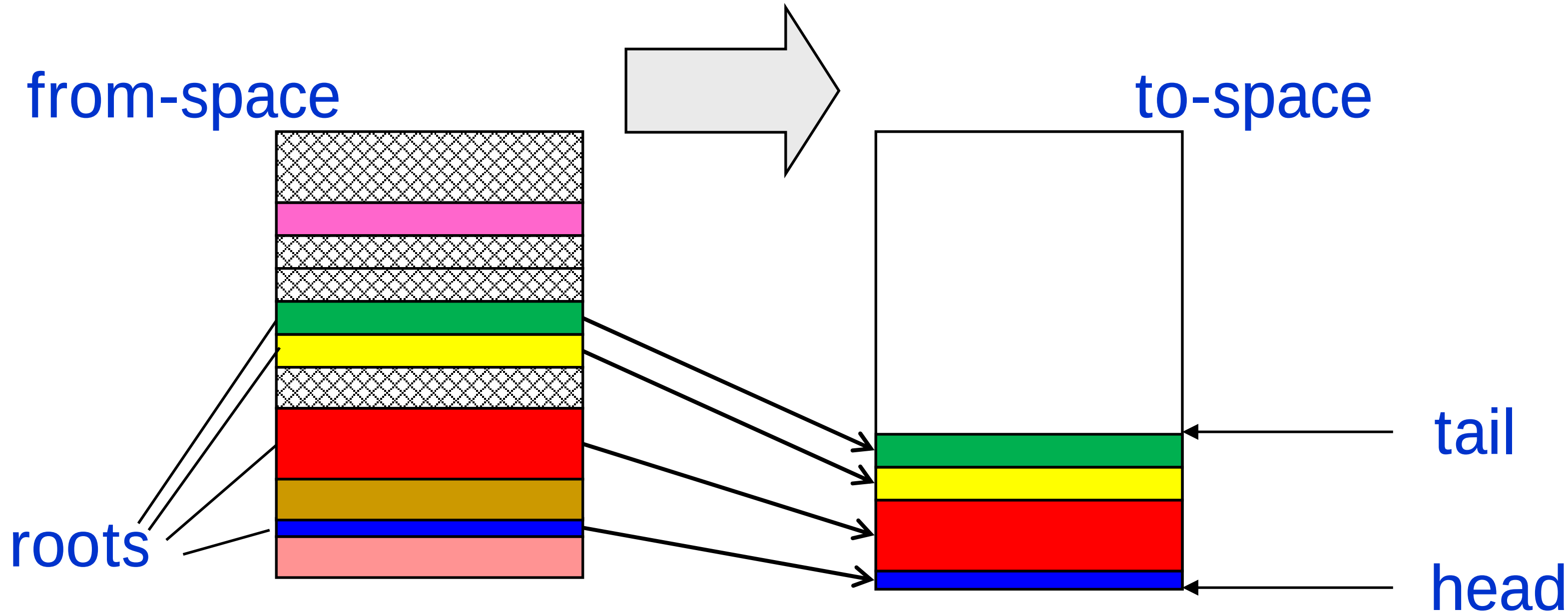

Copy operation leaves forwarding pointer in copied from-space object to the copy in to-space.

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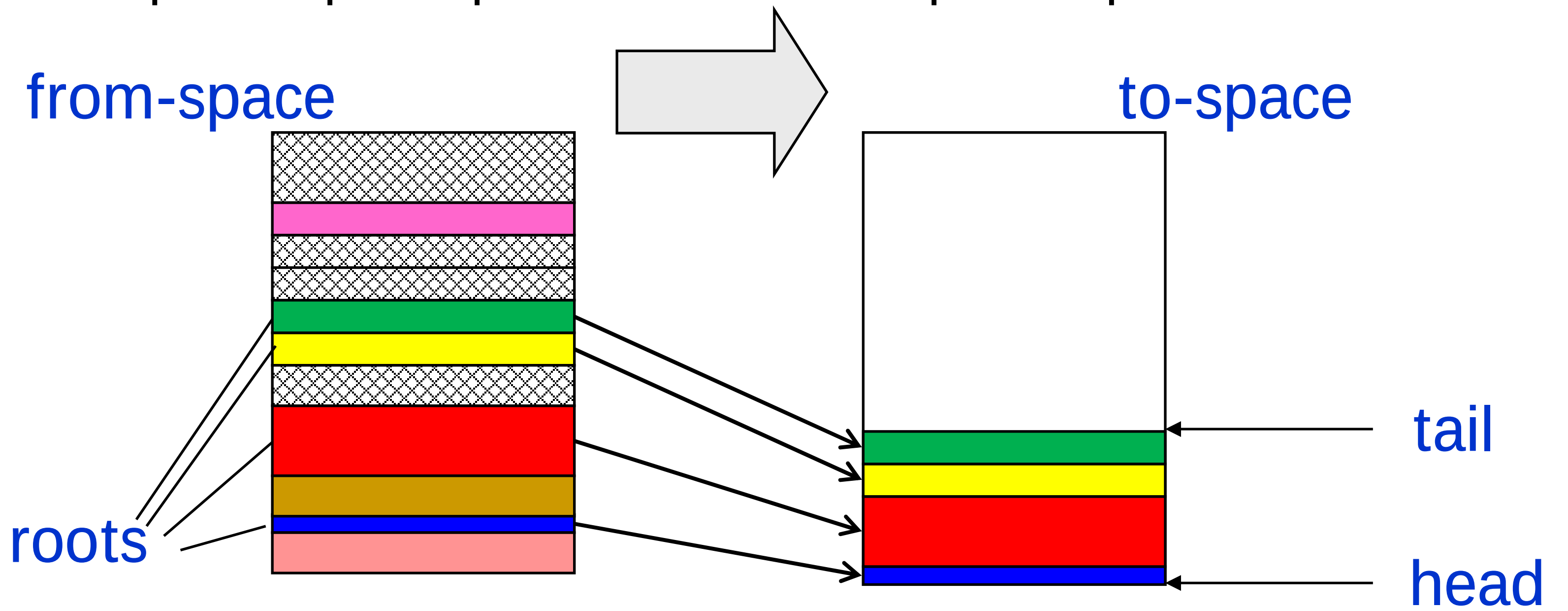

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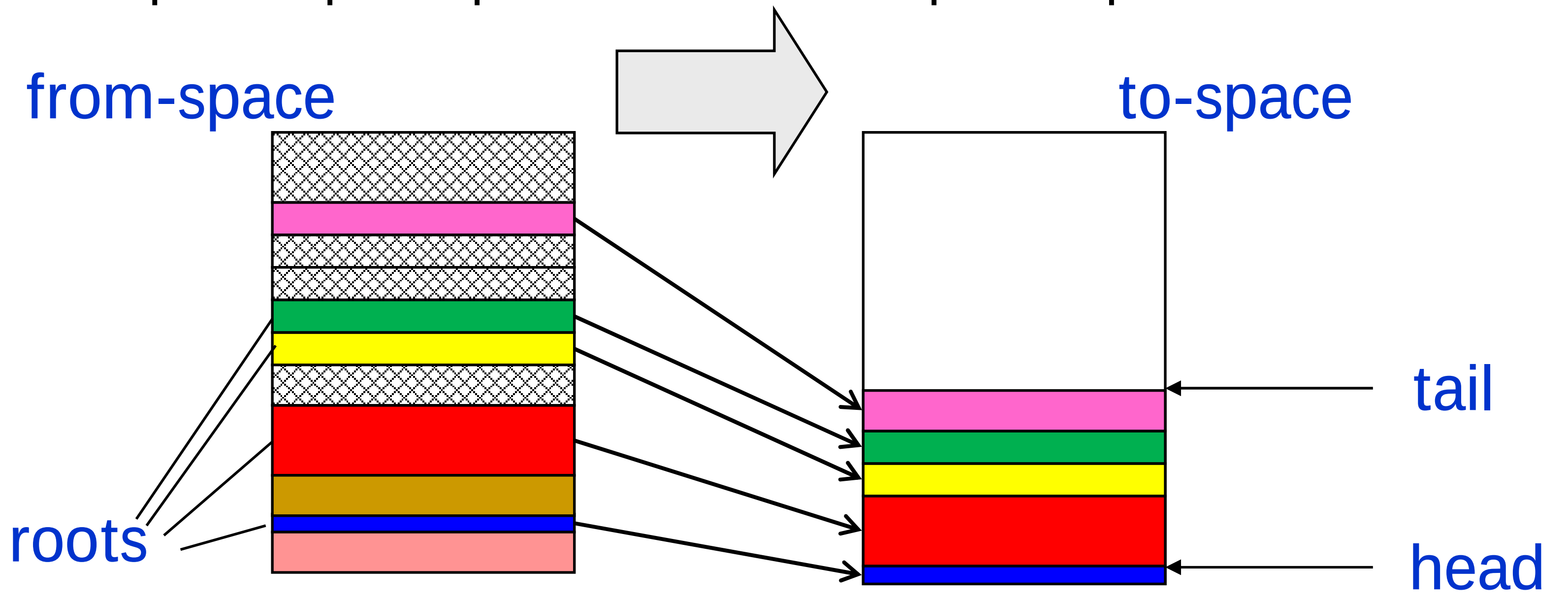

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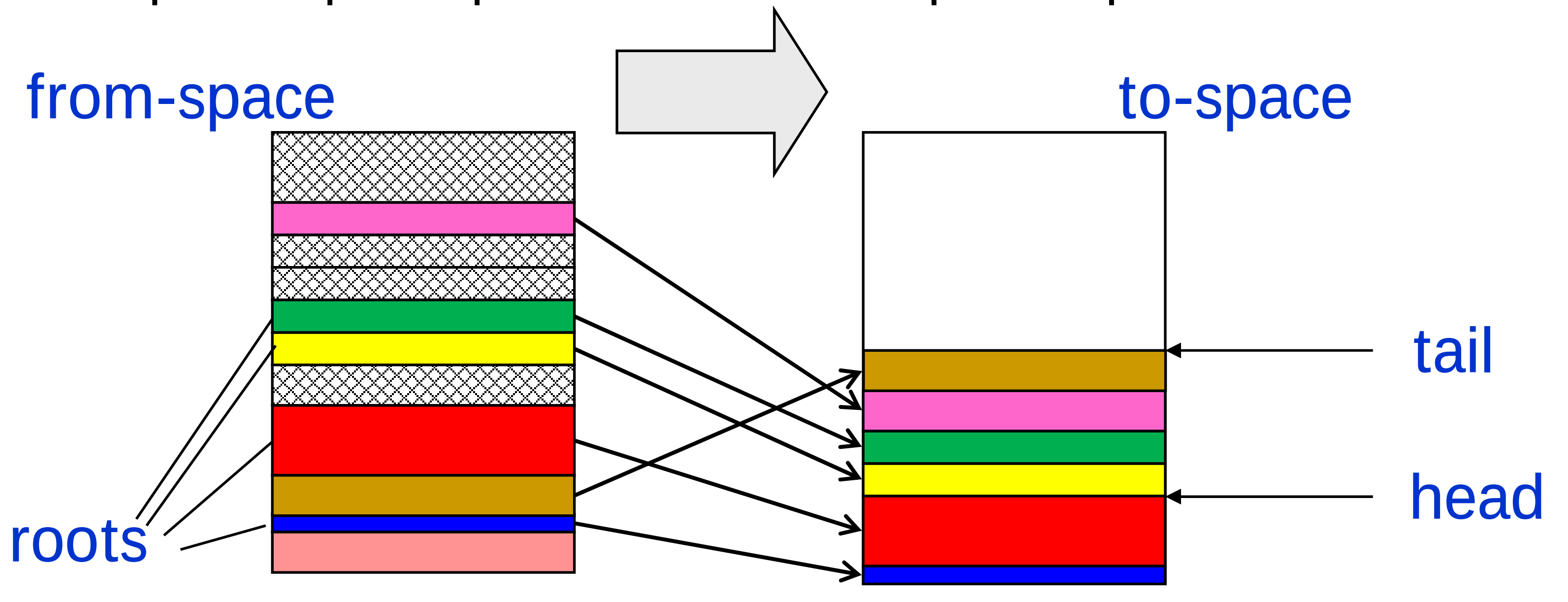

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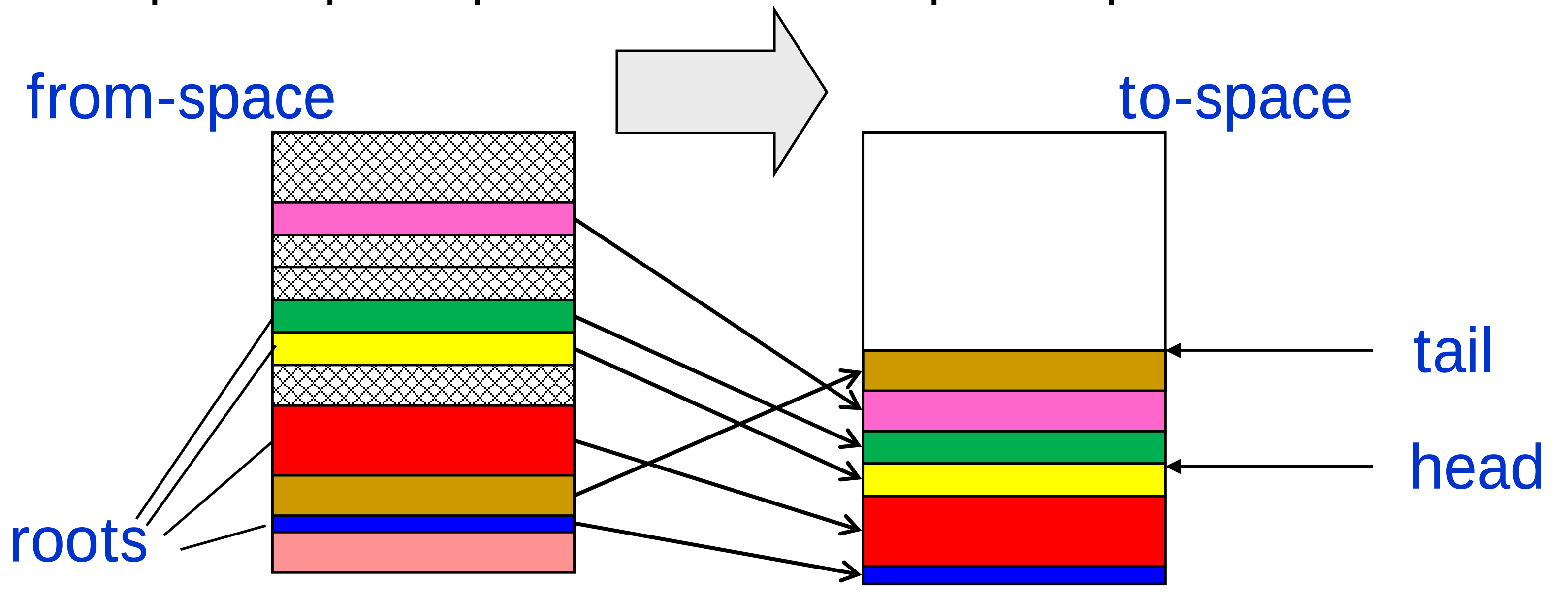

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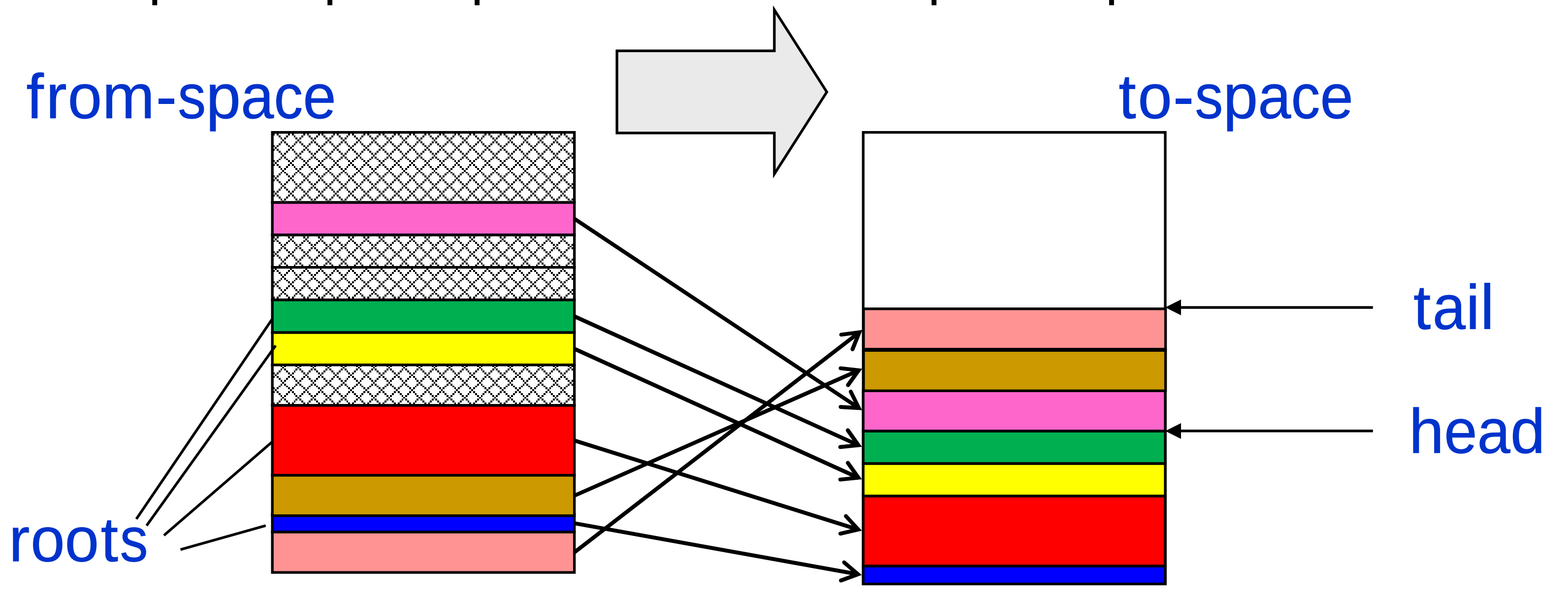

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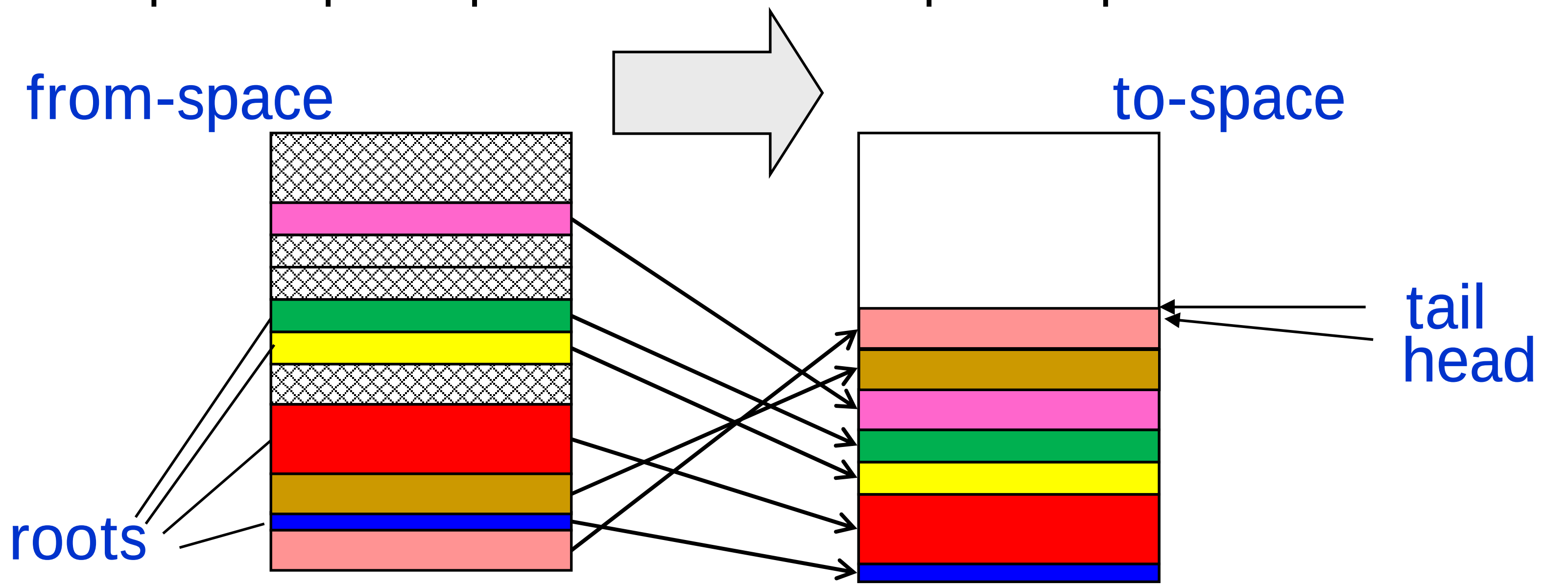

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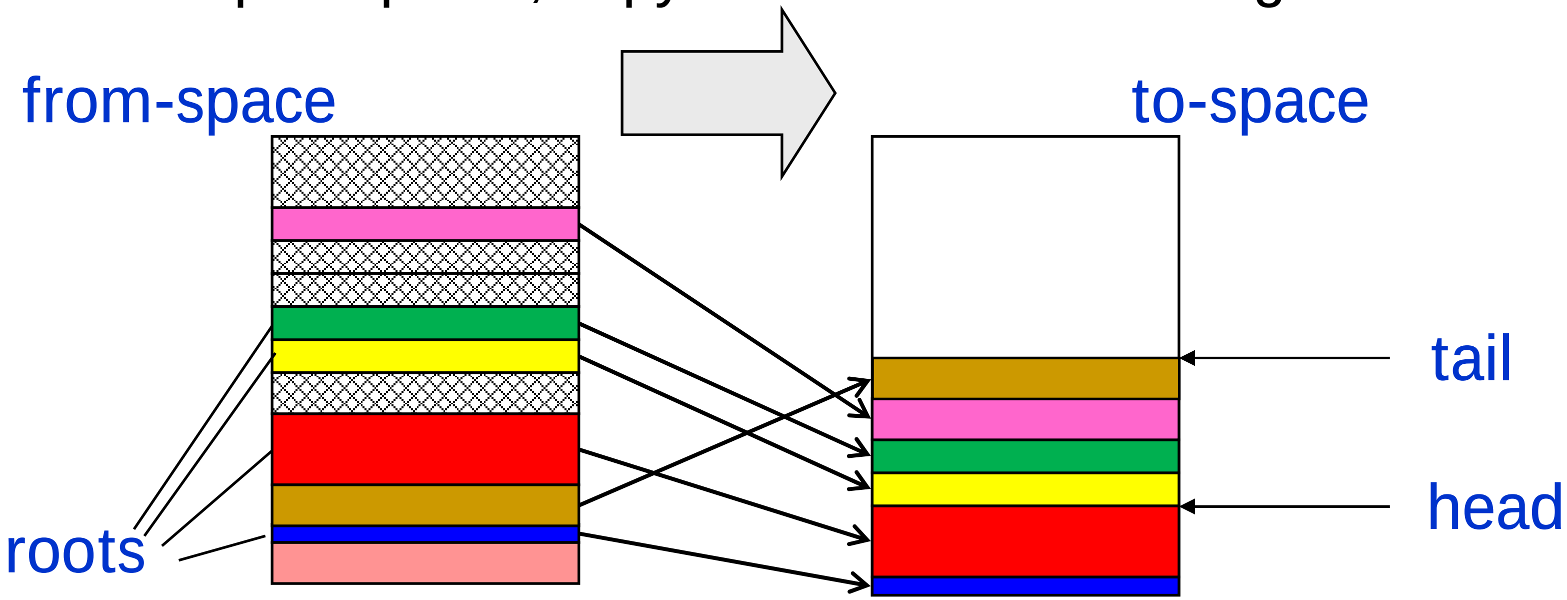
Benefits of Copying Collection

- Once head=tail, all uncopied objects are garbage. Root pointers (registers, stack) are swung to point into to-space, making it active
- Good:
  - Simple, no stack space needed
  - Run time proportional to # live objects
  - Automatically eliminates fragmentation by compacting memory
  - malloc(n) implemented as (tail= tail+ n)
- Bad:
  - Precise pointer information required
  - Twice as much memory used

Incremental and Concurrent GC

- GC pauses avoided by doing GC incrementally; collector & program run at same time
- Program only holds pointers to to-space
- On field fetch, if pointer to from-space, copy object and update pointer to to-space copy.
- On swap of spaces, copy roots and fix stack/registers



Generational GC

- Observation: if an object has been reachable for a long time, it is likely to remain so
- In long-running system, mark & sweep, copying collection waste time, scanning/copying older objects

- Approach: assign heap objects to different generations G_0, G_1, G_2,...
- Generation G_0 contains newest objects, most likely to become garbage (<10% live)

Generations

- Consider a two-generation system. G_0 = new objects, G_1 = tenured objects
- New generation is scanned for garbage much more often than tenured objects
- New objects eventually given tenure if they last long enough
- Roots of garbage collection for collecting G_0 include all objects in G_1 (as well as stack, registers)

Remembered Set

- How to avoid scanning all tenured objects?
- In practice, few tenured objects will point to new objects; unusual for an object to point to a newer object
- Can only happen if older object is modified long after creation to point to new object
- Compiler inserts extra code on object field pointer writes to catch modifications to older objects—older objects are remembered set for scanning during GC, tiny fraction of G_1

Summary

- Garbage collection is an aspect of the program environment with implications for compilation
- Important language feature for writing modular code

- IC: Boehm/Demers/Weiser collector

  http://www.hpl.hp.com/personal/Hans_Boehm/gc/

  - conservative: no compiler support needed
  - generational: avoids touching lots of memory
  - incremental: avoids long pauses
  - true concurrent (multi-processor) extension exist