Memory Allocation and Recycling

O(1) Addressing

- (Assume no "paging" nor "caching" for now).
- Linear Address Space:
  Memory is effectively like a big array.
- Each word is accessible in the same amount of time.
  - A **decoder tree** in logic permits this.
  - The time bound for decoding is actually O(log n).
  - However, the clock interval is designed to be long enough so that it **practically** is O(1).

How Memory is Used

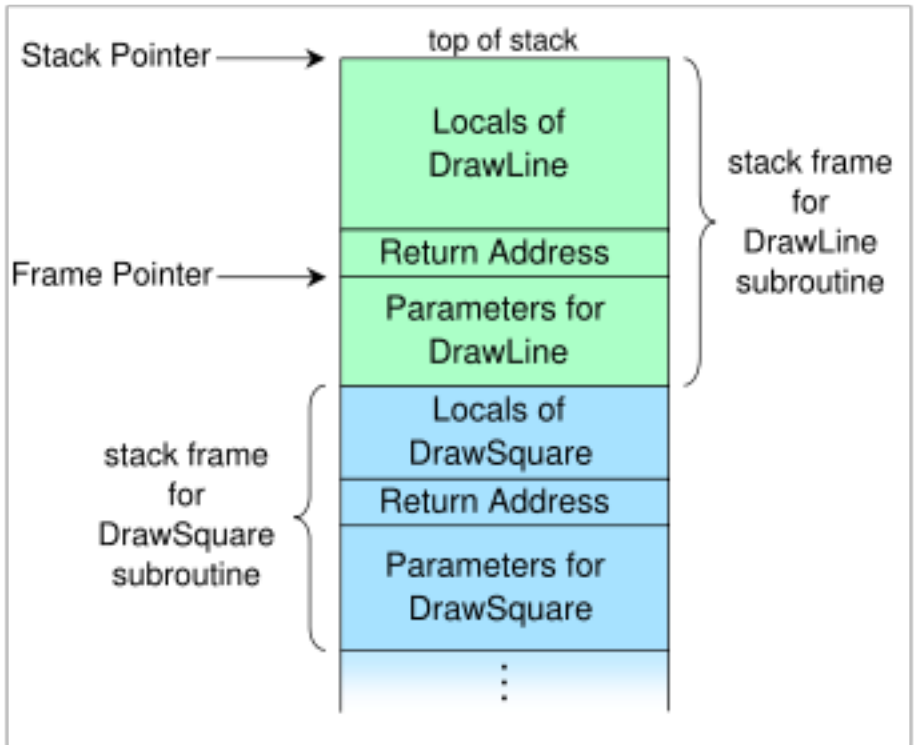
- Code
- Static variables:
  remain allocated throughout execution
- "Automatic" variables:
  e.g. arguments and local variables
  of nested functions
  These **cease to exist** after the
  function returns.
- Dynamic variables:
  instance variables of objects created
  during execution

Why "Automatic"?

- Automatic is not strictly necessary; dynamic could be used for it.
- However, due to **nested** calling discipline, reclamation of automatic is cheaper than dynamic in general.

Stack-Based Allocation

Low-overhead, but confining



From http://en.wikipedia.org/wiki/Call_stack

Heap-Based Allocation

More flexibility, but more overhead

Heap:

Space overheads:

Each block stores a size.

Free blocks also store a pointer to the "next" free block.

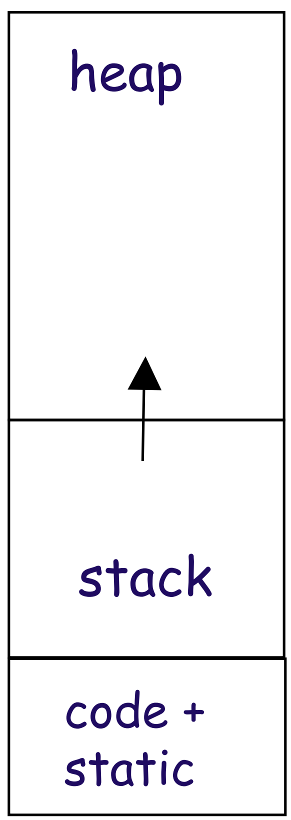
Time overheads:

Must *search* for an adequate free block.

Must *sub-divide* free blocks that are bigger than requirement.

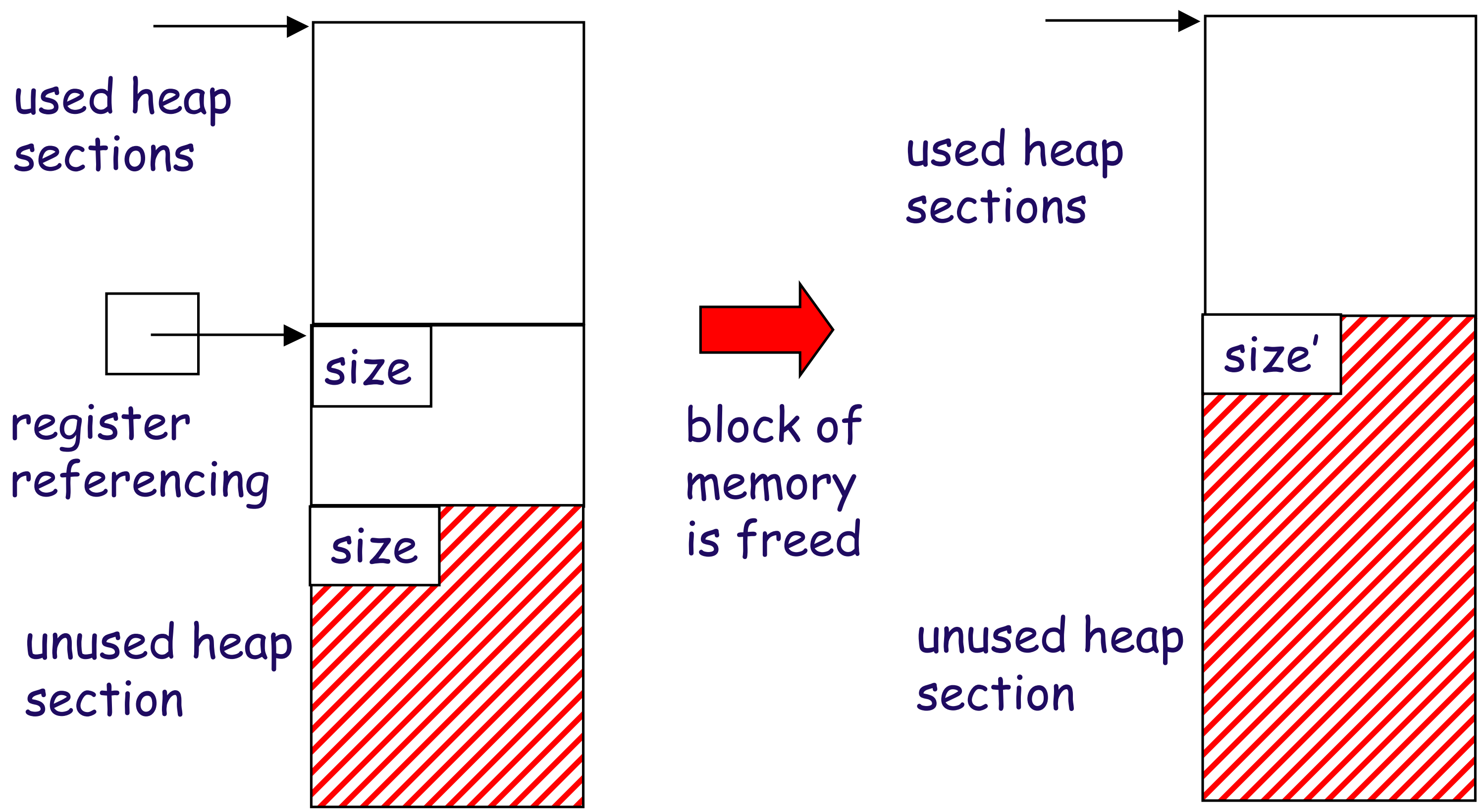
Must coalesce blocks as they become freed.

Memory is Pre-Divided



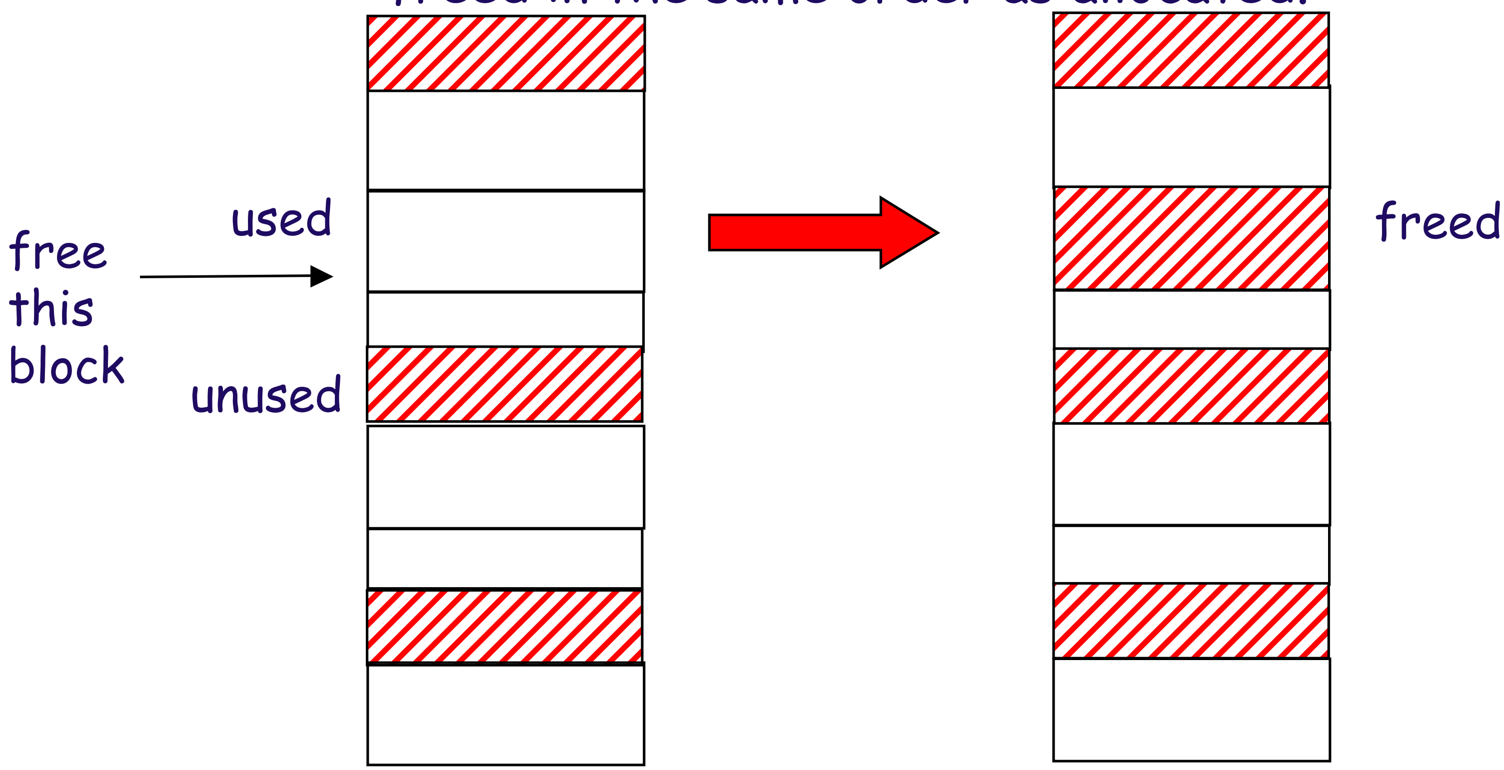
stack growth direction

The Recycling Aspect



The Bigger Picture

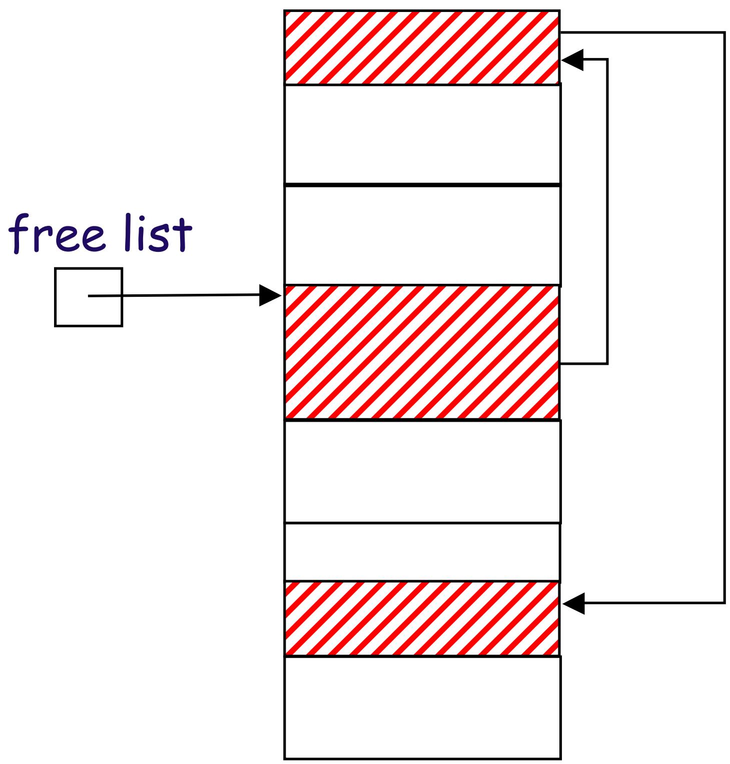
Memory becomes "fragmented" because blocks are not necessarily freed in the same order as allocated.



There are never **adjacent** unused blocks. They are always coalesced into one. (Why?)

Maintaining the "Free List"

Each unused block has a **size** field and a pointer to the **next** unused block.



Heap Issues

- Fragmentation ("checkerboarding")
  - Why is this an issue?
- Allocation Policy:
  - First-fit
  - Best-fit
  - . . .

Approaches to Recycling Heap Memory

- Don't-do-it approach
- Programmer-burden approach
- Automatic approaches
  - Reference-Counting
  - Garbage collection
    - Mark-Sweep
    - Copying
    - Generational
    - others

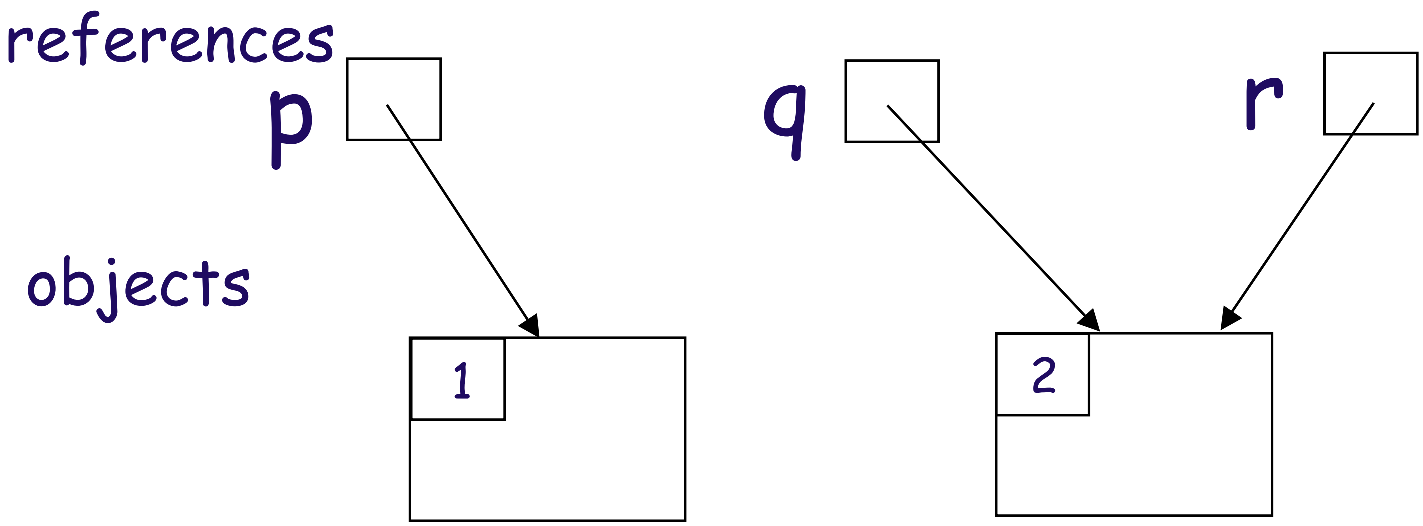
Reference Counting

- Each object has a reference count, not normally shown.
- An **invariant** is maintained:

  Reference count =

  # of references pointing to this object

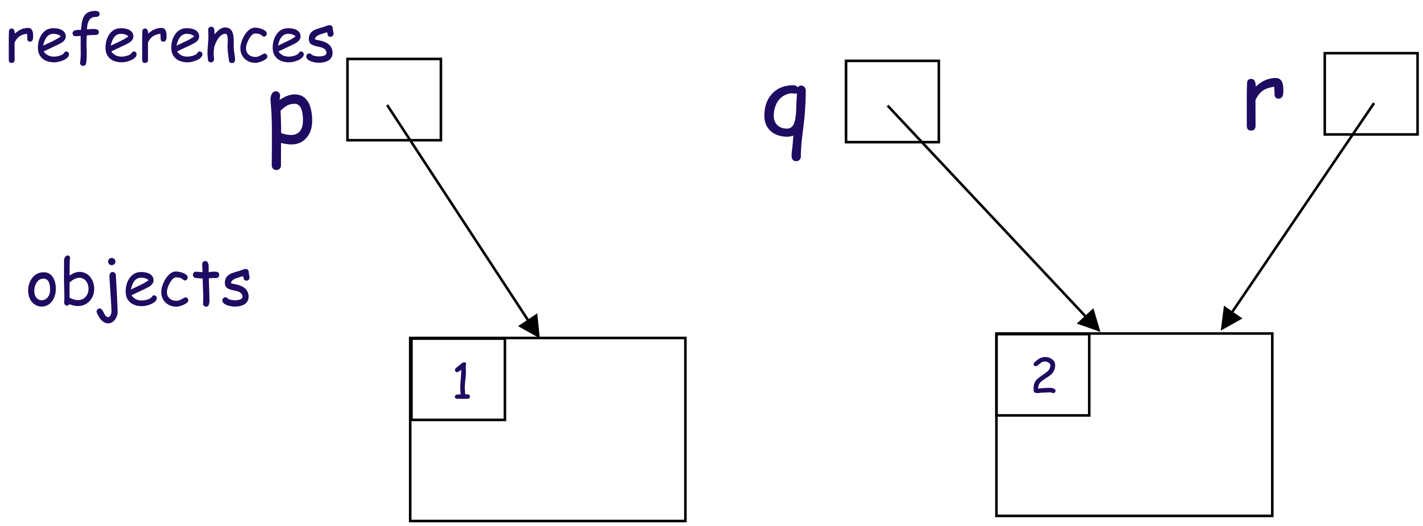
Reference Counting



What happens when we execute:

q = p;

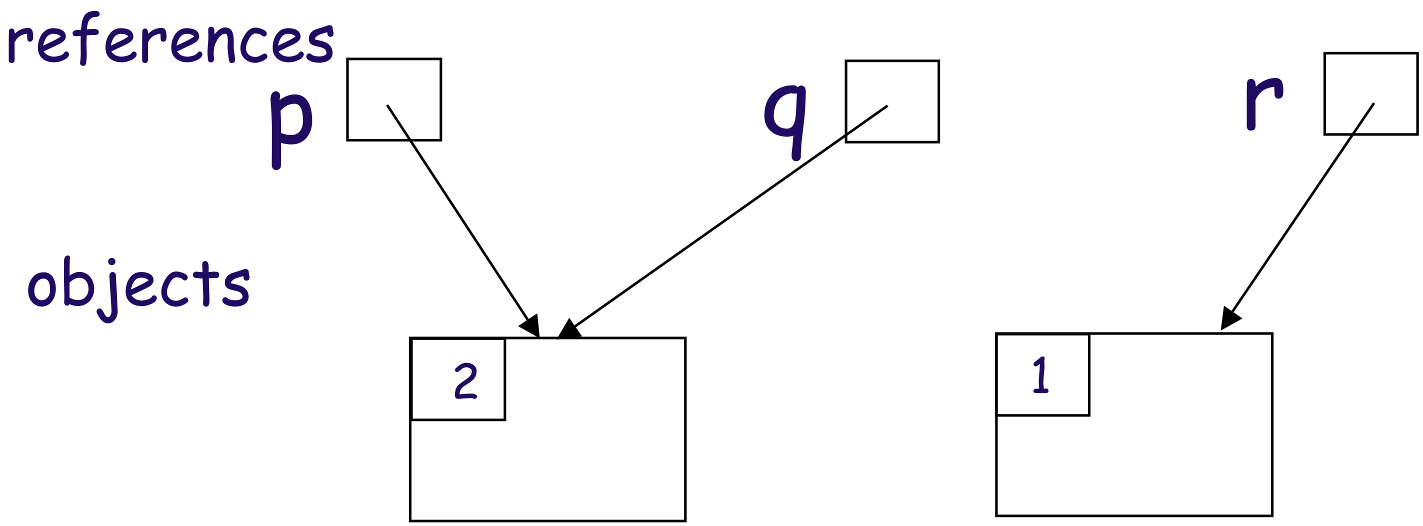
Reference Counting



What happens when we execute:

q = p; // “make q point to where p points”

Reference Counting



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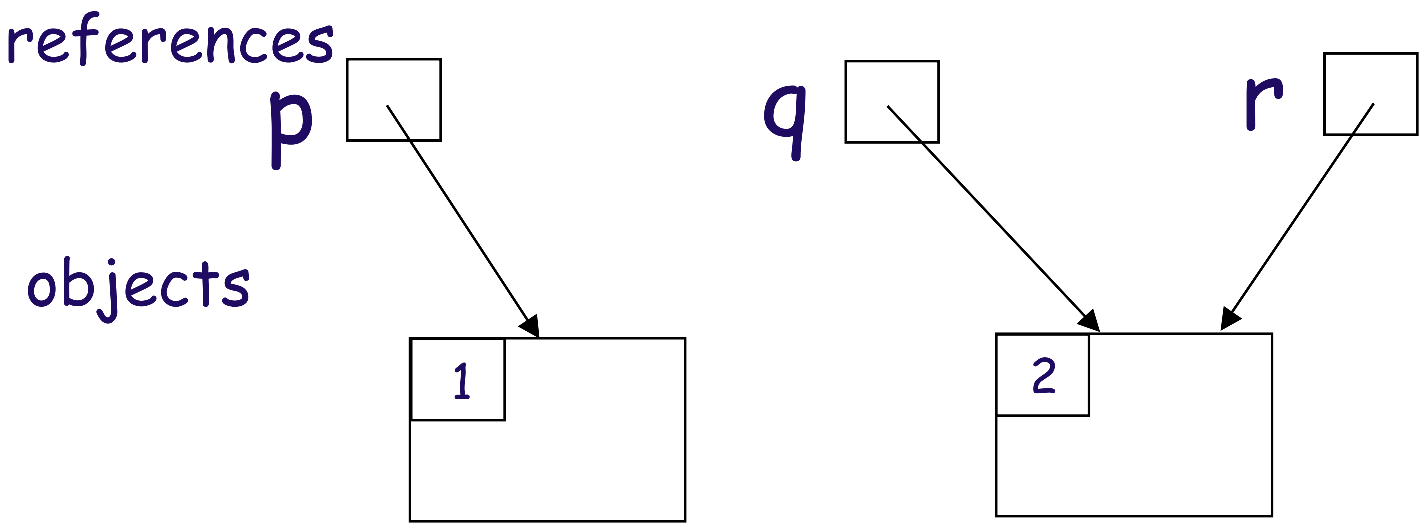

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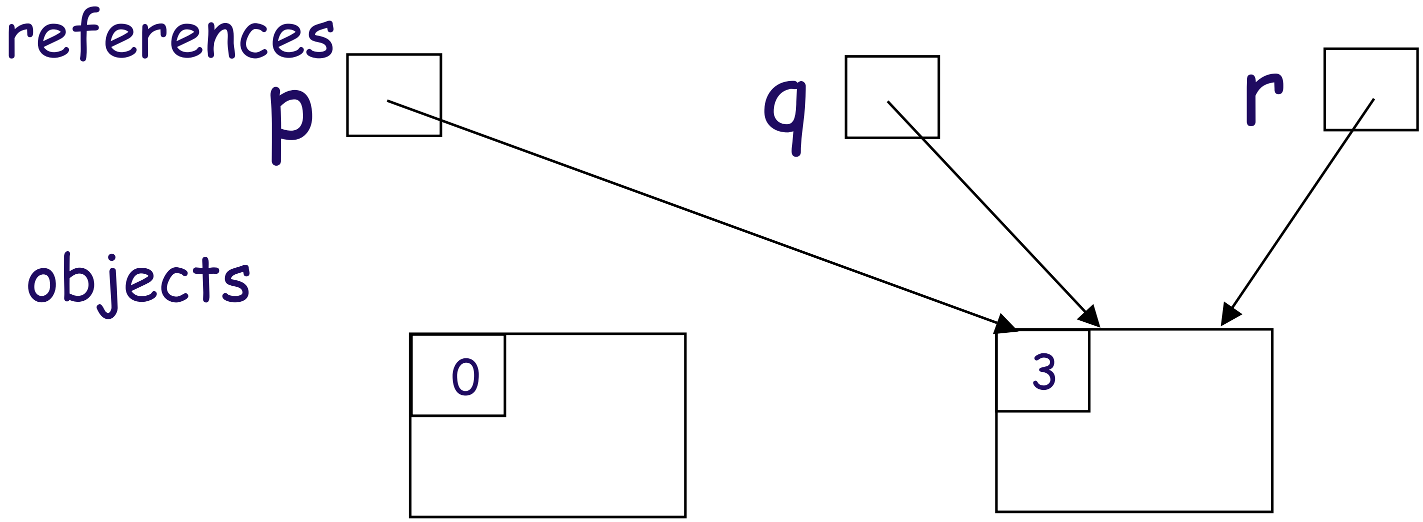
Reference Counting

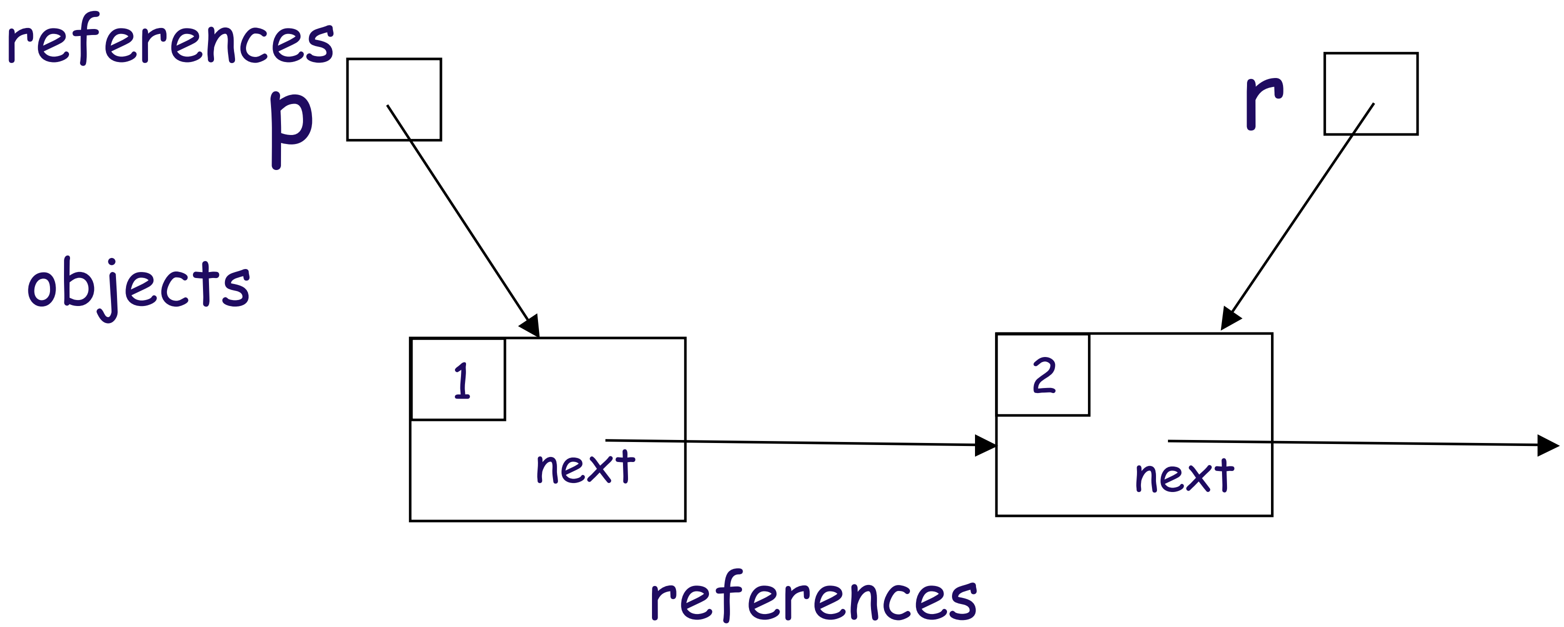


What happens when we execute:

$$p = q;$$

The block to which p formerly pointed is **reclaimable**.

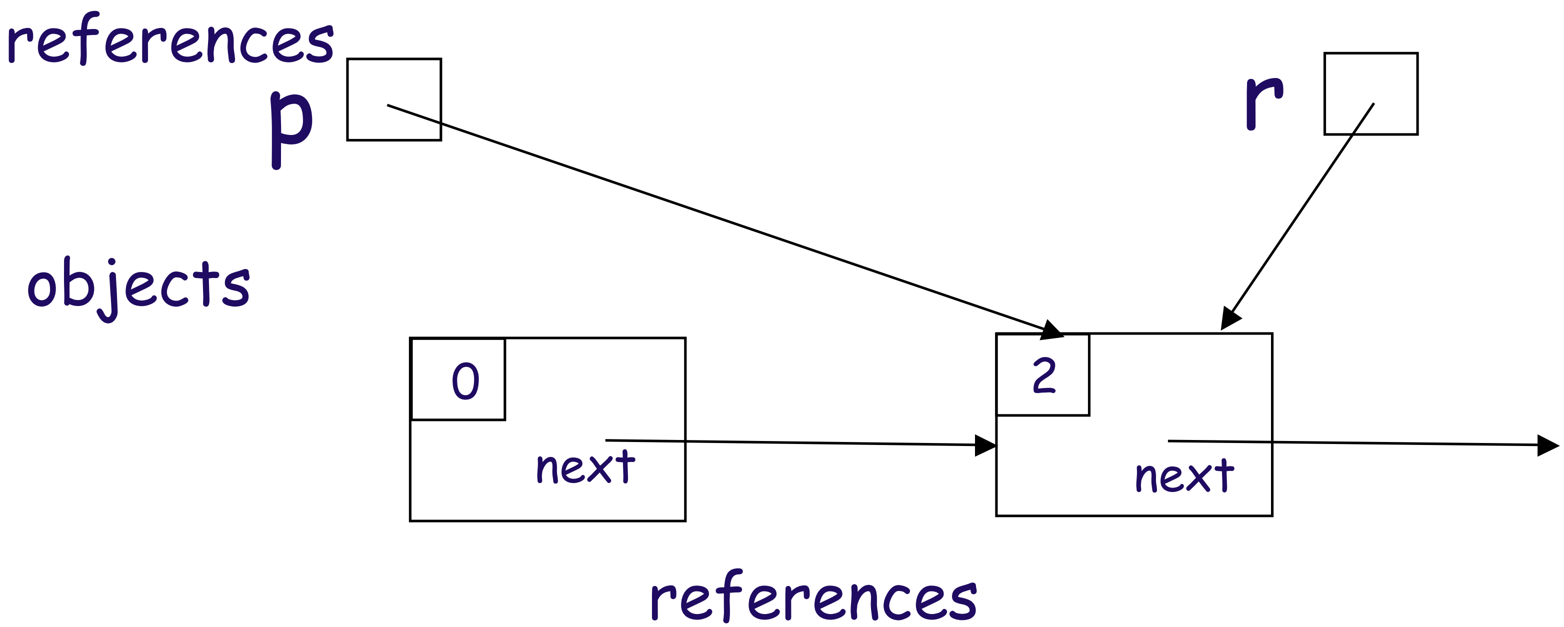
Linked List



What happens when we execute:

p = p.next;

Linked List



What happens when we execute:

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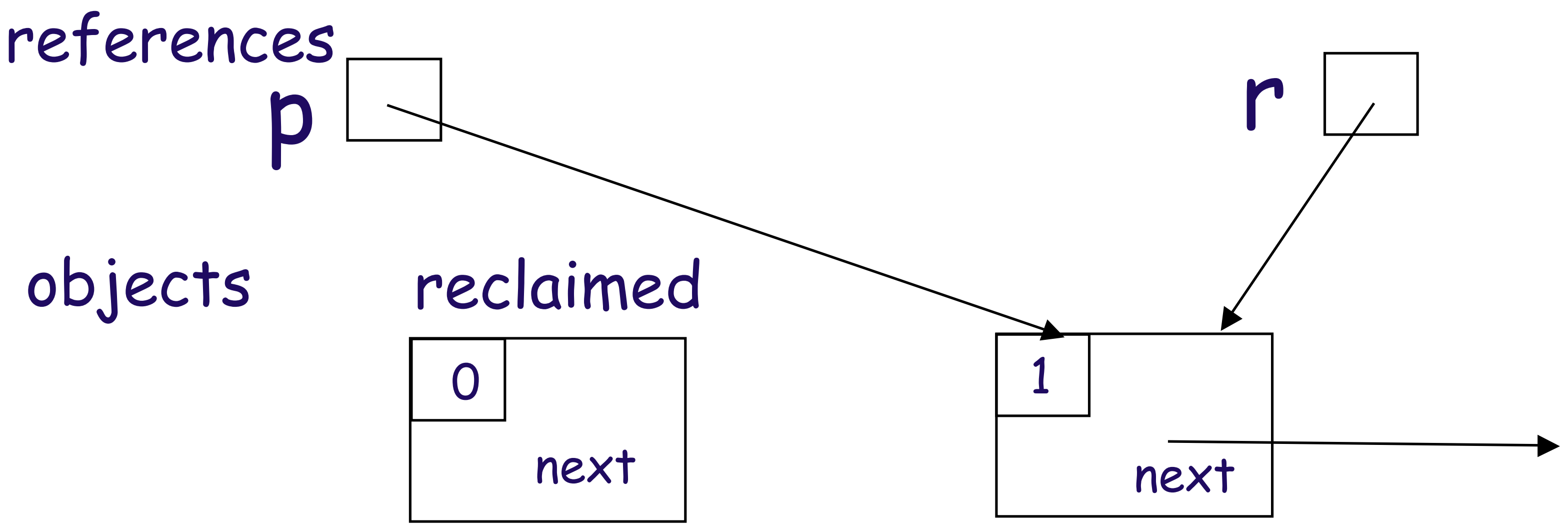
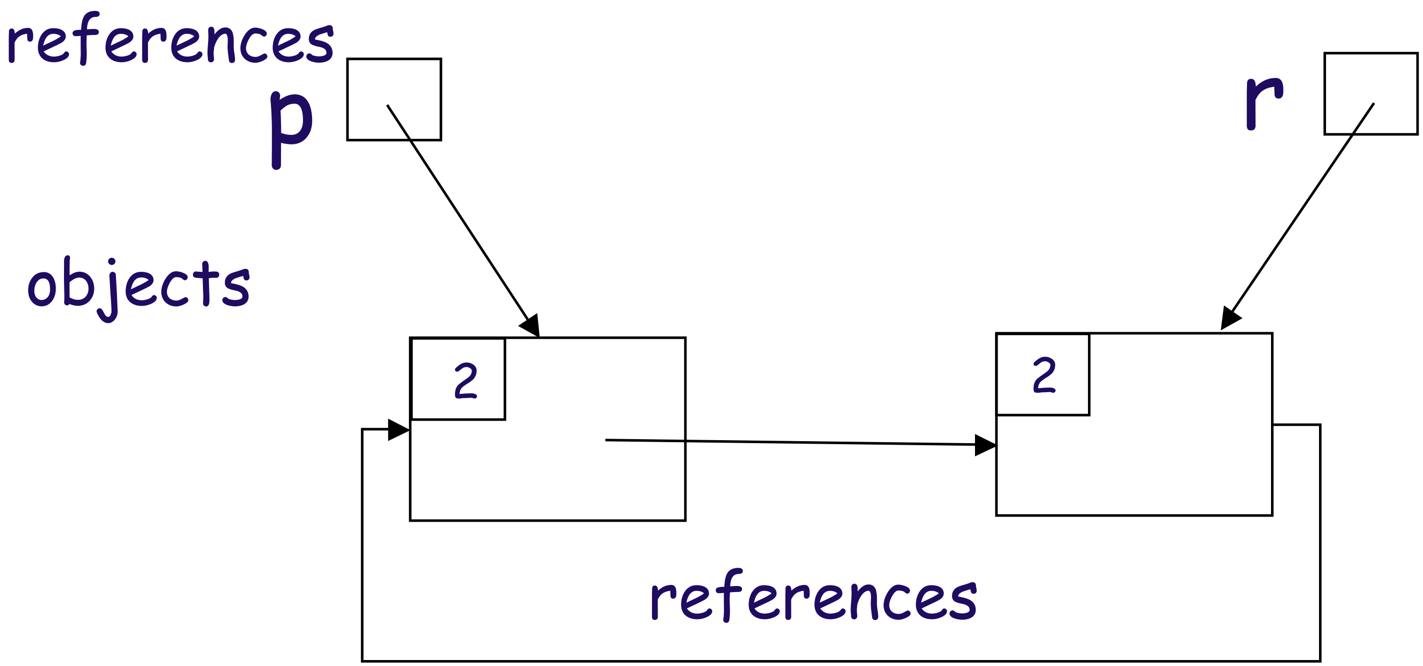
Linked List



What happens when we execute:

p = p.next;

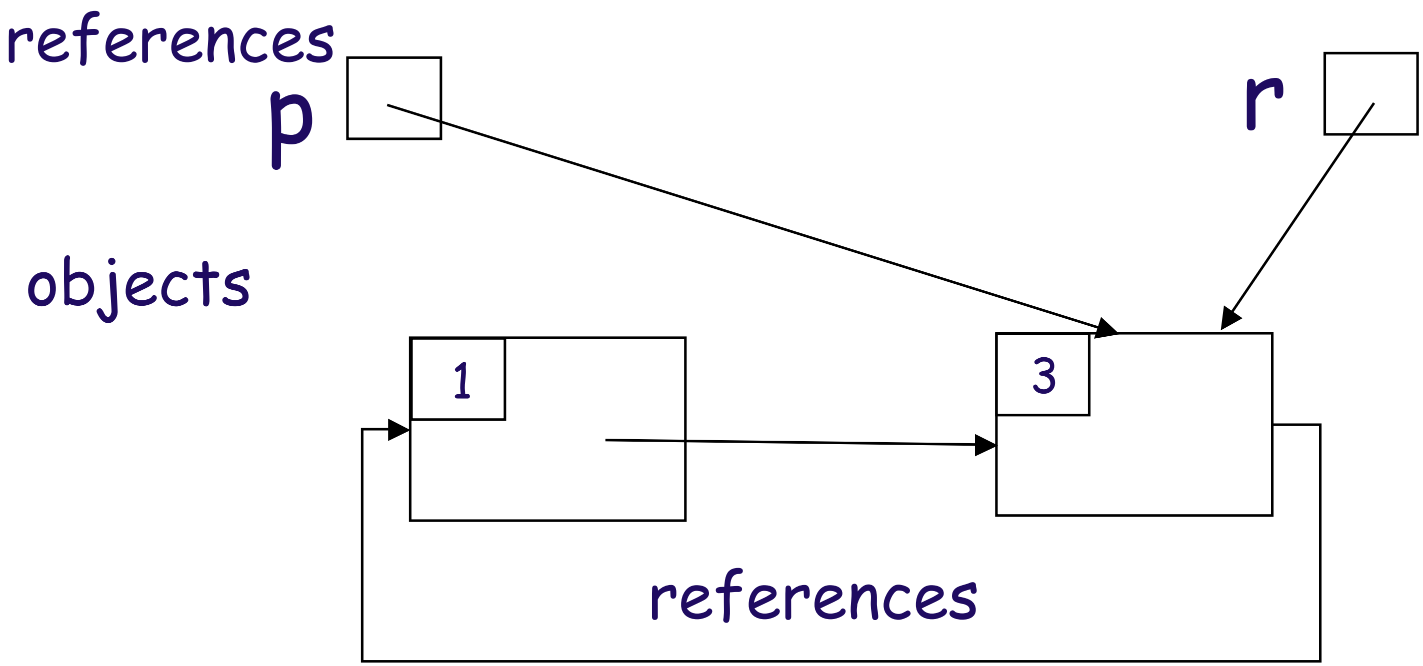
Circular Linked List



What happens when we execute:

p = r;

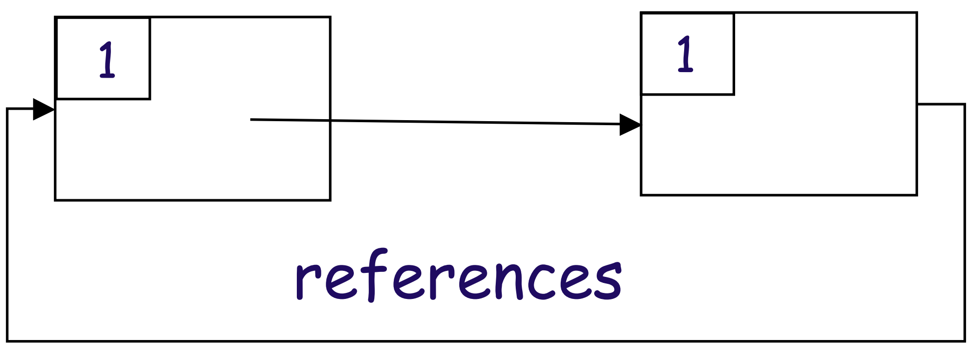
Circular Linked List



What happens when we execute:

```
p = null;
r = null;
```

Circular Linked List



Oops!

Garbage Collection (GC)

- Reference counting keeps track of what is accessible by modifying reference counts at each operation.
- Garbage collection does waits until memory is scarce, then determines what is accessible. The rest can become free memory.
- Garbage collection does not suffer from the cyclic problem of reference counting.
- GC was invented by John McCarthy in conjunction with early Lisp implementation.

Garbage Collection

- is essentially a graph-search problem.
- Determine what is accessible from one or more “roots” of a directed graph.
- The **complement** of accessible is inaccessible, i.e. garbage.

Graph Search?

- Depth-First Search
- Breadth-First Search
- Iterative Deepening

Some GC Techniques

- Mark/Sweep
- Copying
- Generational

Mark/Sweep Garbage Collection

- Do a search (say depth-first) from the roots of the “memory graph”.
- Mark any reachable nodes as you go.
- (By making a pass over *all* nodes linearly through memory) Sweep up any unmarked nodes into the free list.
- (This all supposes that node entities are clearly identifiable. It requires that memory be maintained appropriately.)

Memory Overhead Comparison

- Reference counting:
  - One integer per node
- Mark/sweep:
  - One bit per node

Time Overhead Comparison

- Reference counting:
  - A small tax on every operation
- Mark/sweep:
  - A big tax when memory runs out

Copying Garbage Collection

- Divide the memory into two **half-spaces**, say A and B.
- Work within one half-space (A or B) at any given time.
- Assuming using A now. When it comes time to collect garbage, perform a depth-first search, **copying** each used record from A to B. Then switch to using B.

Copying Advantages

- Trivial to **compact** as you copy. Relative locations do not get maintained.
- Caution: Cannot rely on any absolute addresses, because memory is generally **relocated**.
- This results in a single large unused chunk of memory on each collection.
- **Real-time** versions of copying have been devised (cf. Henry Baker article).

Copying GC Disadvantages?

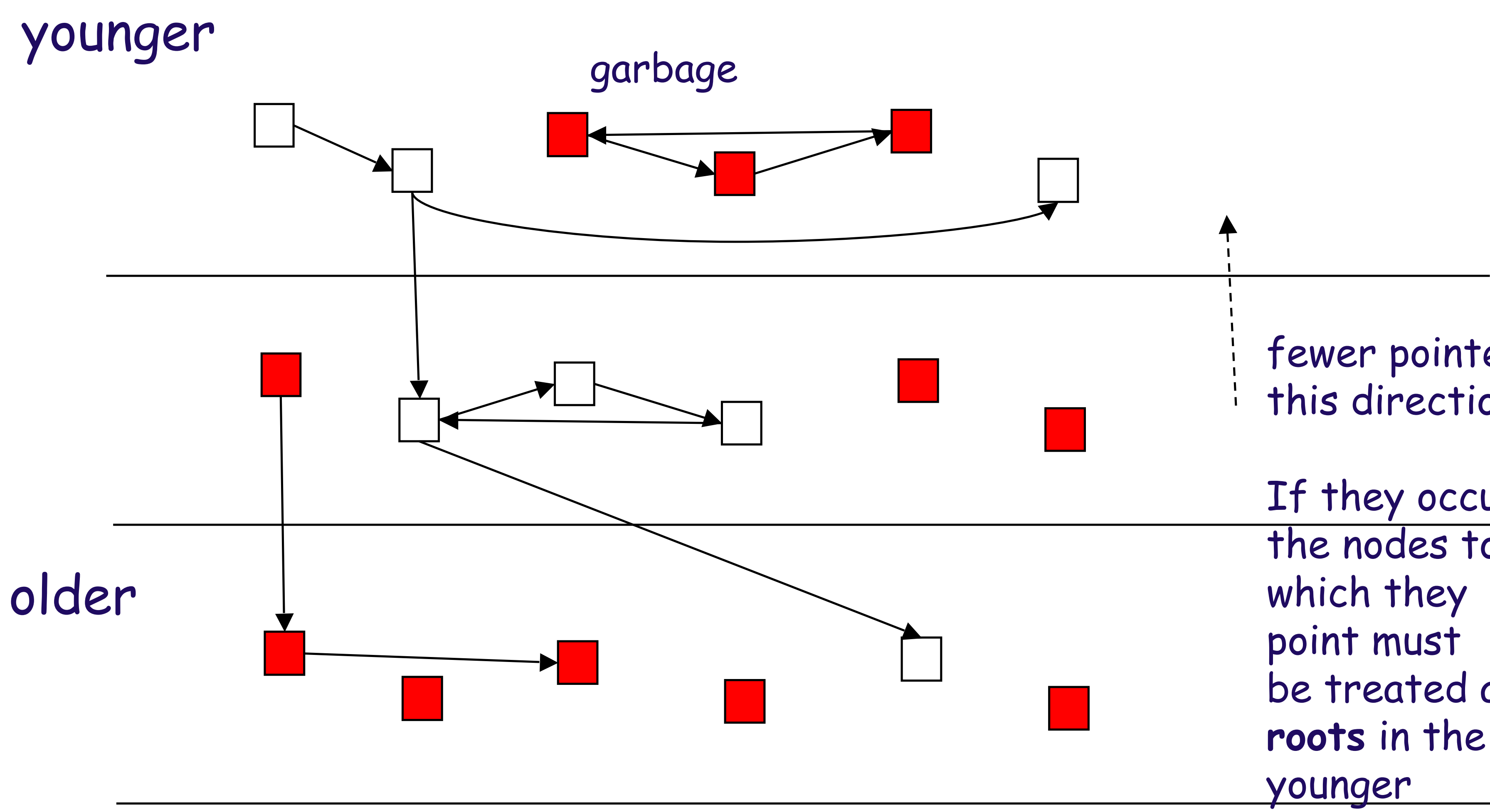
Generational Garbage Collection

- This is one of many heuristics used to reduce overhead in GC.
- It can be observed that some nodes are **ephemeral** (temporary and quickly become garbage), while others have great **longevity**.
- Thus devise a way to do a **quick partial** collection to pick up the ephemeral nodes, reserving a full GC until more desperate.

Generational Garbage Collection

- The extension of the dichotomy ephemeral vs. long-lived is achieved by assigning nodes to **generations**.
- A node in the **youngest** generation is usually the more likely to become garbage.
- References generally point from a younger to an older generation, but not so much vice-versa.
- If a node survives collection at one generation, it is **promoted** to the next older generation.
- A generation is collected only if there is not enough memory freed by collecting younger generations.

Generational Garbage Collection



fewer pointers this direction

If they occur, the nodes to which they point must be treated as **roots** in the younger generation.

Food for Thought
(or indigestion?)

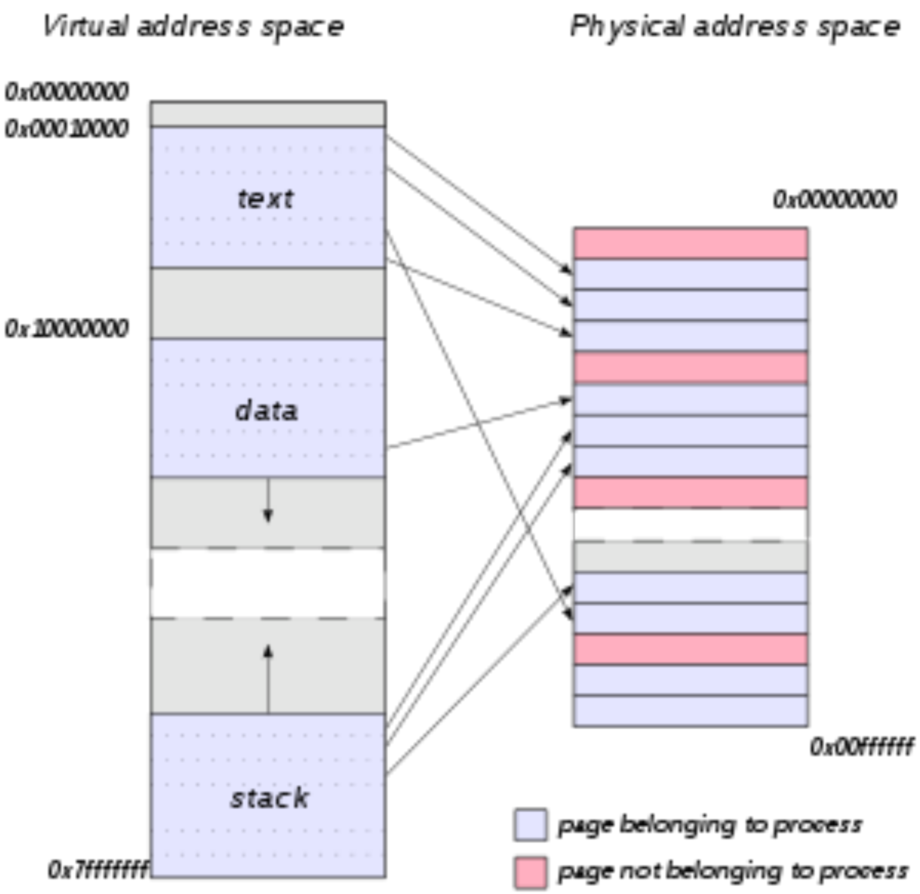
- How does the need for memory recycling impact the desire to use **threads**?

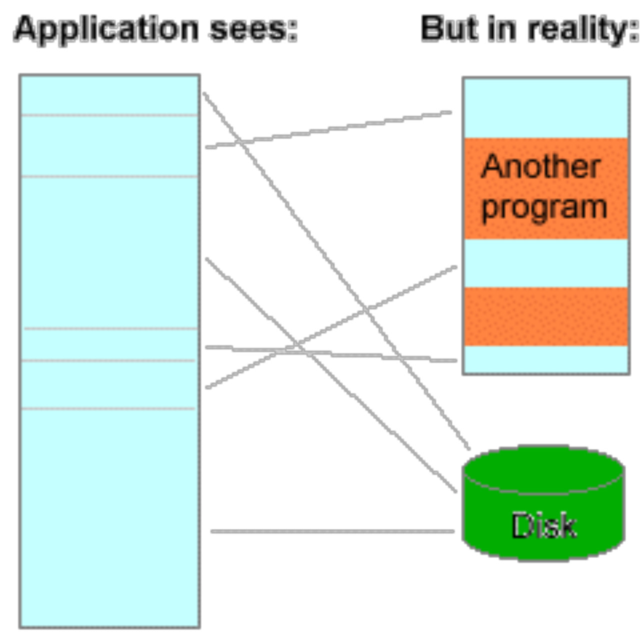
More Considerations

- Approaches to making memory larger/faster:
  - Paging, Virtual Memory
  - Caching
  - Each comes with its own set of issues

Paging

Purpose: Virtual memory, Sharing physical memory

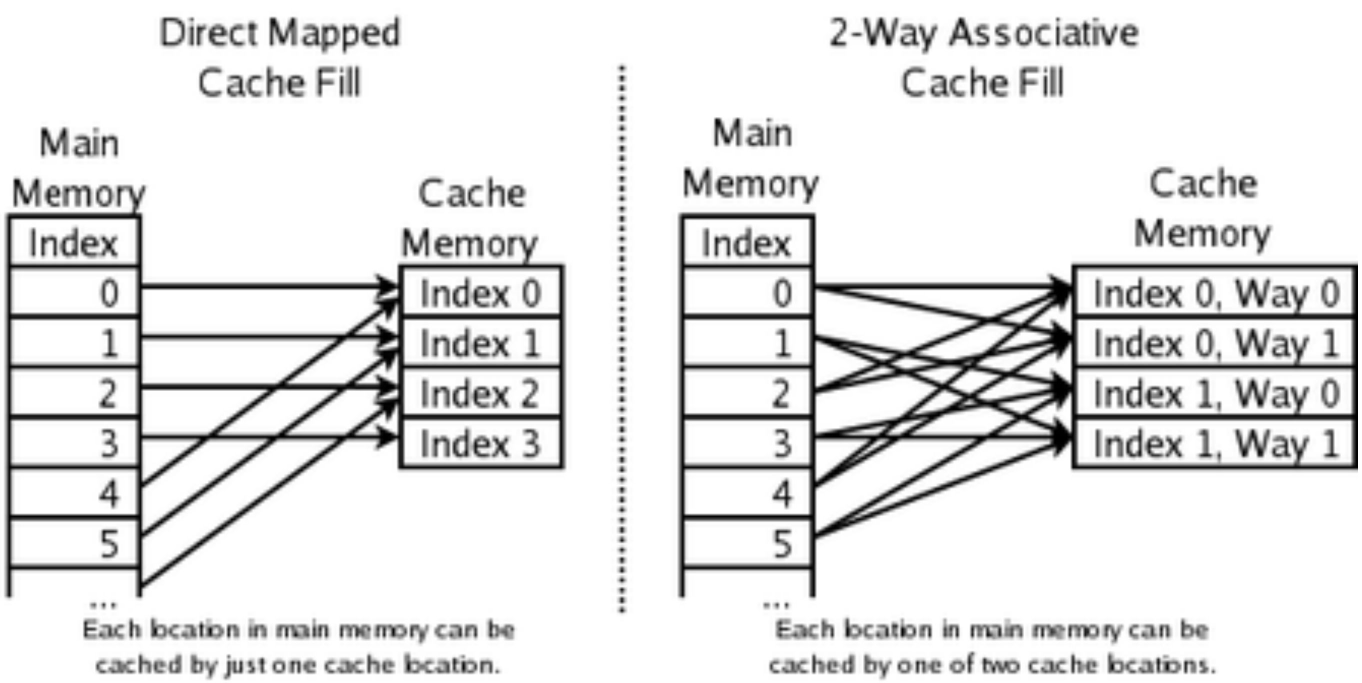




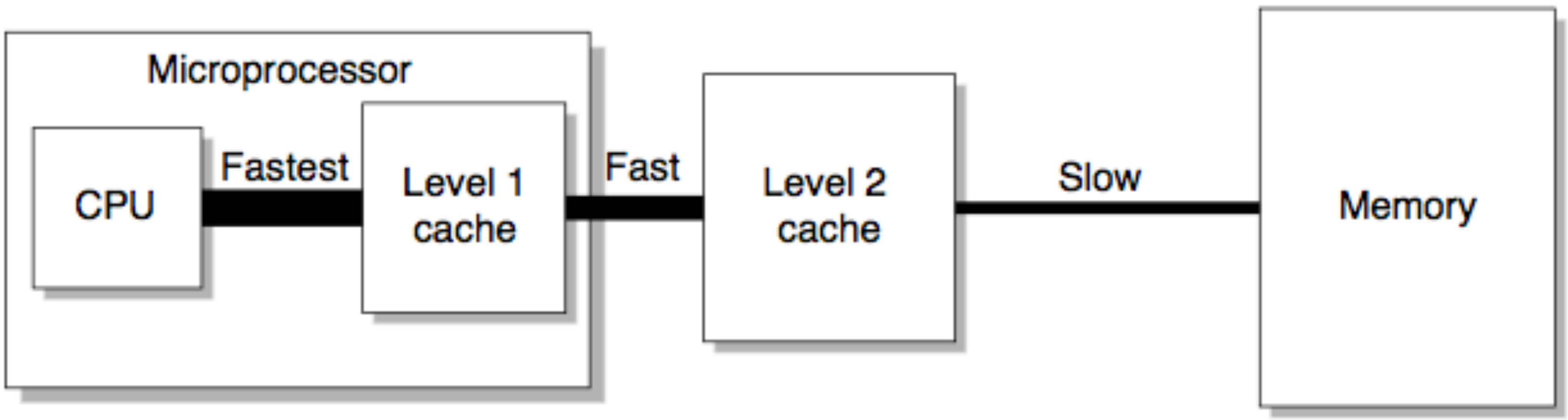
Caching

Purpose: Faster memory for faster execution

Analogous to paging and to hashing in some ways, but done in hardware.



Multi-Level Cache



Computer Memory Hierarchy

by Dan Lash (.com)