Managing Memory

Outline

- Memory Organization
- Garbage Collection
  - Reference counting
  - Mark-and-sweep
  - Copy collection

Memory organization

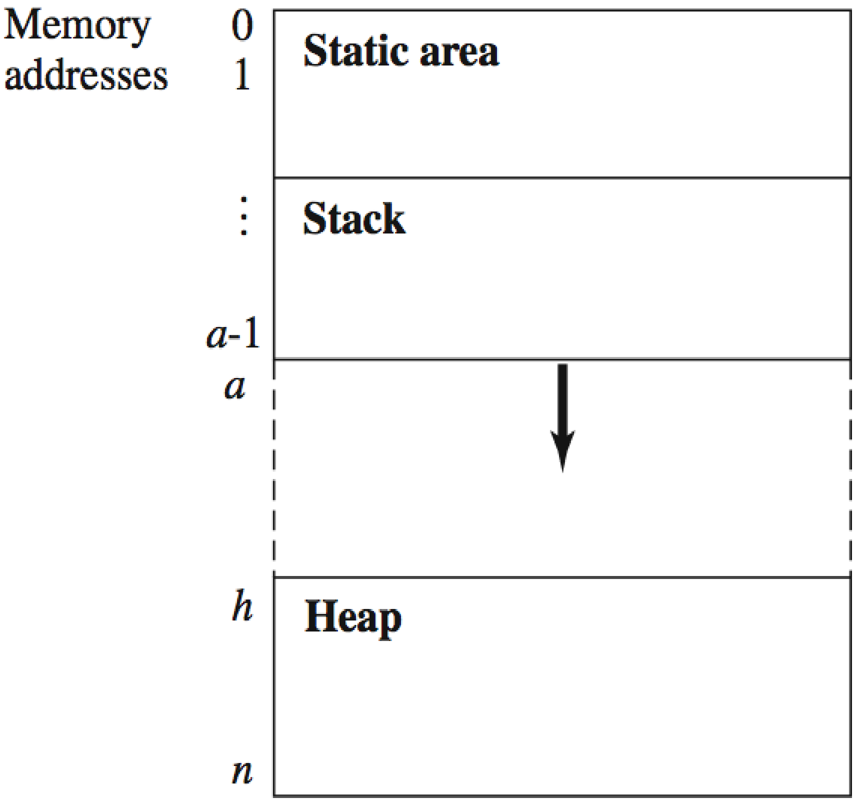
- *Memory management* is the process of *binding* values to memory locations.
- A *process* is a program in execution.
- All the memory used by a process must reside in the process's *address space*.
- How the address space is organized depends on the operating system and the programming language being used.
- We are primarily concerned with imperative languages (such as C/Lambda Calculus with references) in this lecture.
- Techniques developed here applies to all paradigms.

Major Areas of Memory

- *Static area*:
  - Storage requirements known in advance and remain constant
  - allocated at compile time (static or const)
- *Run-time stack*:
  - local variables that get allocated each time a function is called (a.k.a. call stack)
  - center of control for function call and return
- *Heap*:
  - dynamically allocated objects and data structures
  - recall the memory store M in last lecture
  - the least organized and most dynamic storage area
  - Easily fragmented – needs *garbage collection*

Structure of Runtime Memory

- $0 \le a \le h \le n$
- Each memory word can be:
  - Unused
  - Undef
  - An elementary value



Static Memory

- Global variables that can be statically allocated get placed in the *static area*.
- Constants may also be placed in the static area depending on their type.
- The static area may be split into different parts for variables and for constants.
  - Data segment: static and global variables/constants
  - text segment: executable instructions
- Values that can be statically bound (e.g. at compile time) can be placed here.
  - String literals: “hello world!”

Runtime Stack

- The stack is a contiguous region of memory that grows and shrinks as a process runs.
- It is used to hold *local environments (closures)* or *activation records* for functions and procedures. These are also called *stack frames*.
- When a function is called (activated), storage for its local variables, the calling parameters, and return linkage is allocated by growing the stack.
- When control is returned from the function, the stack frame is de-allocated and the stack shrinks.
- A function's stack frame exists as long as the function is active.

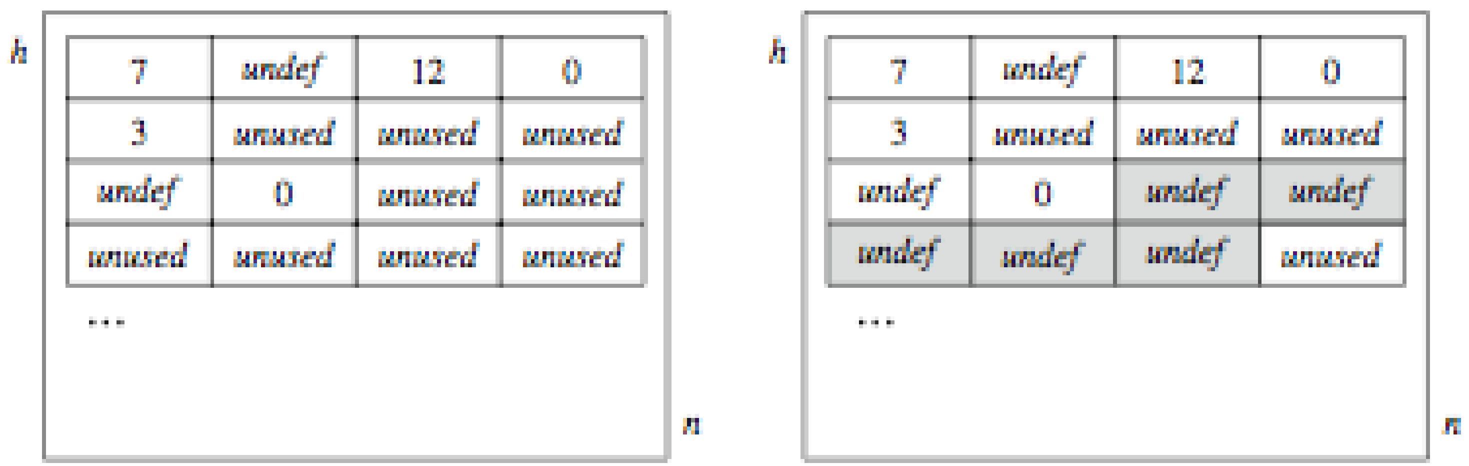
HEAP

- Variable storage that is dynamically allocate at run-time is placed in the heap.
- The heap is managed by dividing it into blocks.
  - In many real implementations, a tree structure (binary heap).
- As a process runs space is allocated to new variables from heap space (*malloc*, *new*).
- When a variable's lifetime expires its space may be returned to the heap (*deallocated*,). This can leave holes in the heap causing *fragmentation*.
- Some languages leave managing the heap in the hands of the programmer (C, C++, etc. using *free*, *delete*).
- Others do *heap management* (Java, Python, etc.).

Allocating Heap Blocks

- The function *new* allocates a *contiguous block* of heap space to the program.

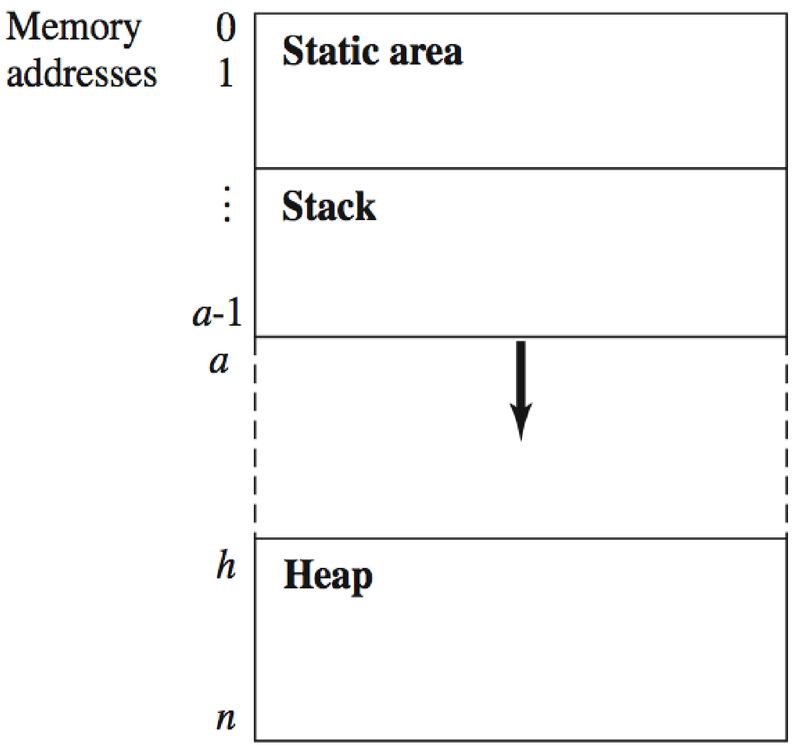
  E.g., new(5) returns the address of the next block of 5 words available in the heap:



Stack and Heap Overflow

- ***Stack overflow*** occurs when the top of stack, a, would exceed its (fixed) limit, h.
  - Stack can also go *underflow*.

- ***Heap overflow*** occurs when a call to *new* occurs and the heap does not have a large enough block available to satisfy the call.



Garbage Collection

- *Garbage* is a block of heap memory that cannot be accessed by the program.

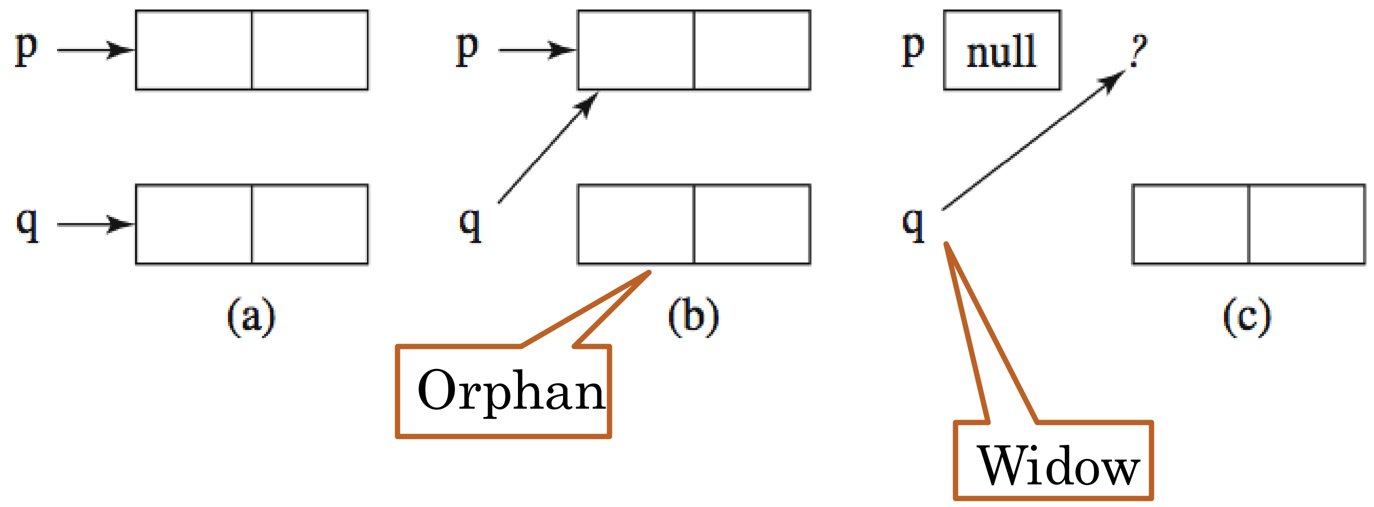
- Garbage can occur when either:

  1. An allocated block of heap memory has no reference to it (an "orphan"), or
  2. A reference exists to a block of memory that is no longer allocated (a "widow").

Garbage Example

```
class node {
    int value;
    node next;
}
node p, q;
```

```
p = new node(); /* Fig. (a) */
q = new node(); /* Fig. (a) */
q= p;           /* Fig. (b)  */
delete p;   /* Fig. (c)  */
```



Why Garbage Collection?

- Today's programs consume storage freely
  - 8GB laptops, 16-32 GB desktops, 512GB servers
  - 64-bit address spaces (x64, SPARC, Itanium, Opteron)
- … and mismanage it
  - Memory leaks, dangling references, double free, misaligned addresses, null pointer dereference, heap fragmentation
  - Poor use of reference locality, resulting in high cache miss rates and/or excessive demand paging
- Explicit memory management breaks high-level programming abstraction

GC and Programming Languages

- GC is <u>not</u> a language feature (it's a side effect)
- GC is a pragmatic concern for automatic and efficient heap management
  - Cooperative langs: Lisp, Scheme, Prolog, Smalltalk …
  - Uncooperative languages: C and C++
    - But garbage collection libraries have been built for C/C++
- Recent languages have GC built-in:
  - Object-oriented languages: Modula-3, Java, C#, Python
    - In Java, runs as a low-priority thread; System.gc may be called by the program
  - Functional languages: ML and Haskell

The Perfect Garbage Collector

- No visible impact on program execution
- Works with any program and its data structures
  - For example, handles cyclic data structures
- Collects garbage (and only garbage) cells quickly
  - Incremental; can meet real-time constraints
- Has excellent spatial locality of reference
  - No excessive paging, no negative cache effects
- Manages the heap efficiently
  - Always satisfies an allocation request and does not fragment

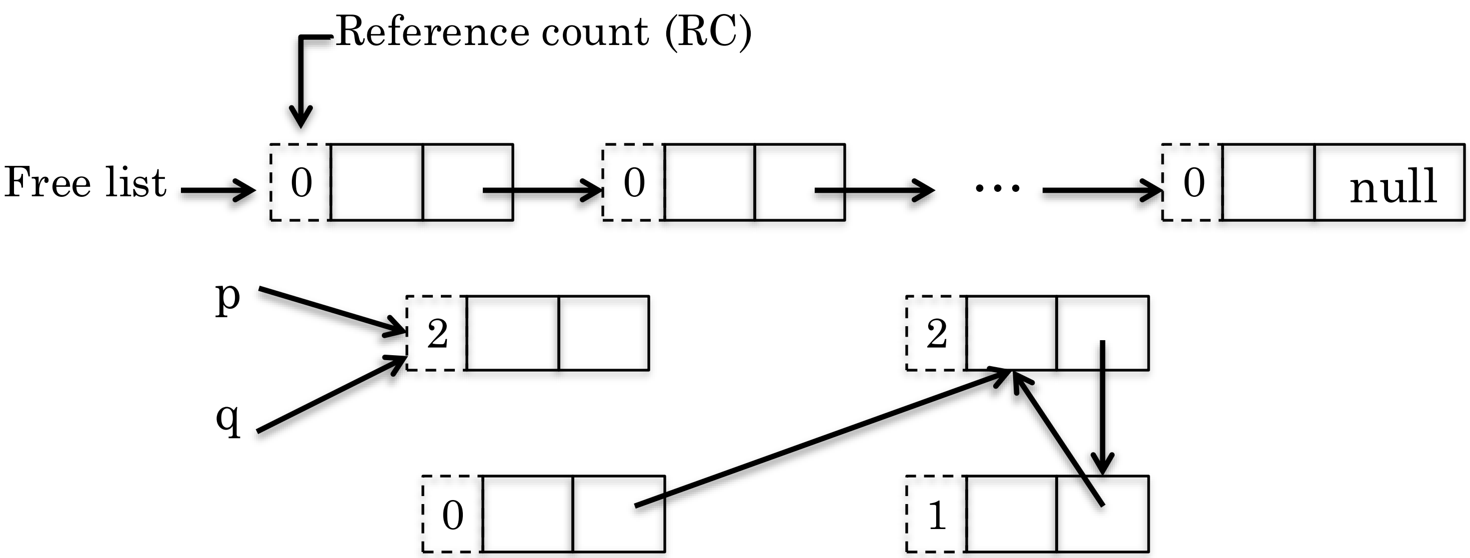
Garbage Collection Algorithms

- *Garbage collection* is any strategy that reclaims unused heap blocks for later use by the program.

- Three classical garbage collection strategies:
  - Reference Counting
    - occurs whenever a heap block is allocated, but doesn't detect all garbage.
  - Mark-and-Sweep
    - Occurs only on heap overflow, detects all garbage, but makes two passes on the heap.
  - Copy Collection
    - Faster than mark-sweep, but reduces the size of the heap space.

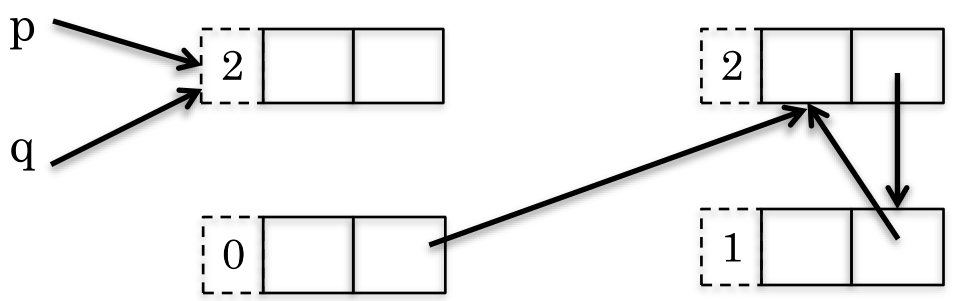
Reference Counting

- The heap is a chain of nodes (the *free_list*).
- Each node has a reference count (RC).
- For an assignment, like q = p, garbage can occur:



BUT NOT ALL GARBAGE IS COLLECTED…

- Since q's node has RC = 0, the RC for each of its children is reduced by 1, it is returned to the free list, and this process repeats for its descendents, leaving:



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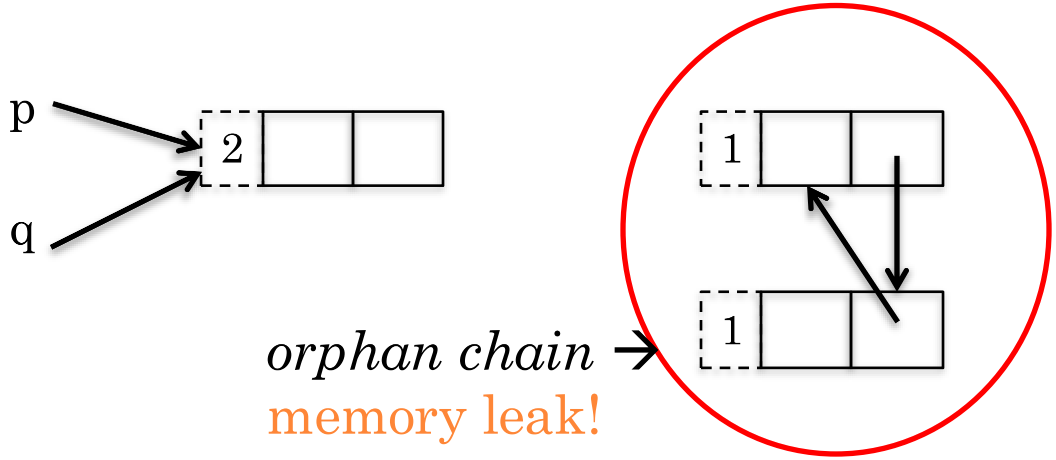


Advantages of Reference Counting

- Occurs dynamically, overhead of garbage collection is spread over time
- Relatively easy to implement
- Can coexist with manual memory management
- Spatial locality of reference is good
  - Access pattern to virtual memory pages no worse than the program, so no excessive paging
  - No long jumps.
- Can re-use freed cells immediately
  - If RC == 0, put back onto the free list

Disadvantages of Reference Counting

- Failure to detect inaccessible circular structure and hence the GC is incomplete
- Space overhead by appending an integer number to every node in the heap
- Performance overhead created by the book-keeping done during pointer assignment or when a heap block is allocated/de-allocated:
  - Check to ensure that it is not a self-reference
  - Decrement the count on the old cell, possibly deleting it
  - Update the pointer with the address of the new cell
  - Increment the count on the new cell

Mark-and-Sweep

- Each node in the *free_list* has a mark bit (MB) initially 0.

- Called only when heap overflow occurs:

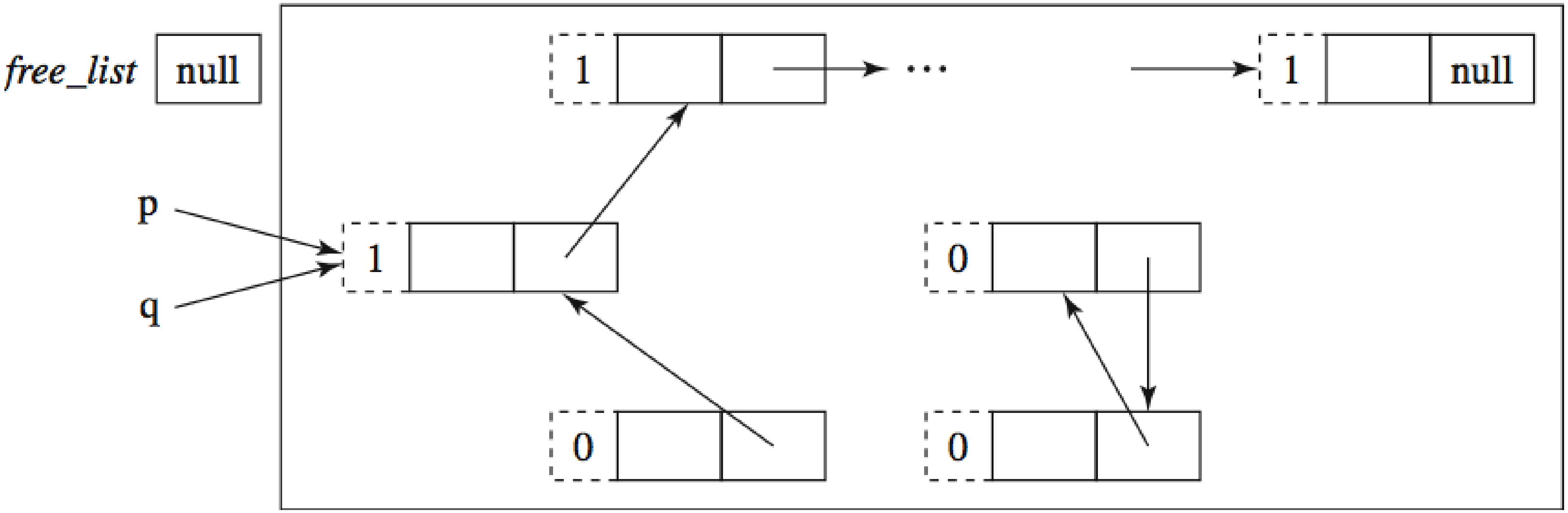
  Pass I: Mark all nodes that are (directly or indirectly) accessible from the stack by setting their MB=1.

  Pass II: Sweep through the entire heap and return all unmarked (MB=0) nodes to the free list.

- *Note: all orphans are detected and returned to the free list.*

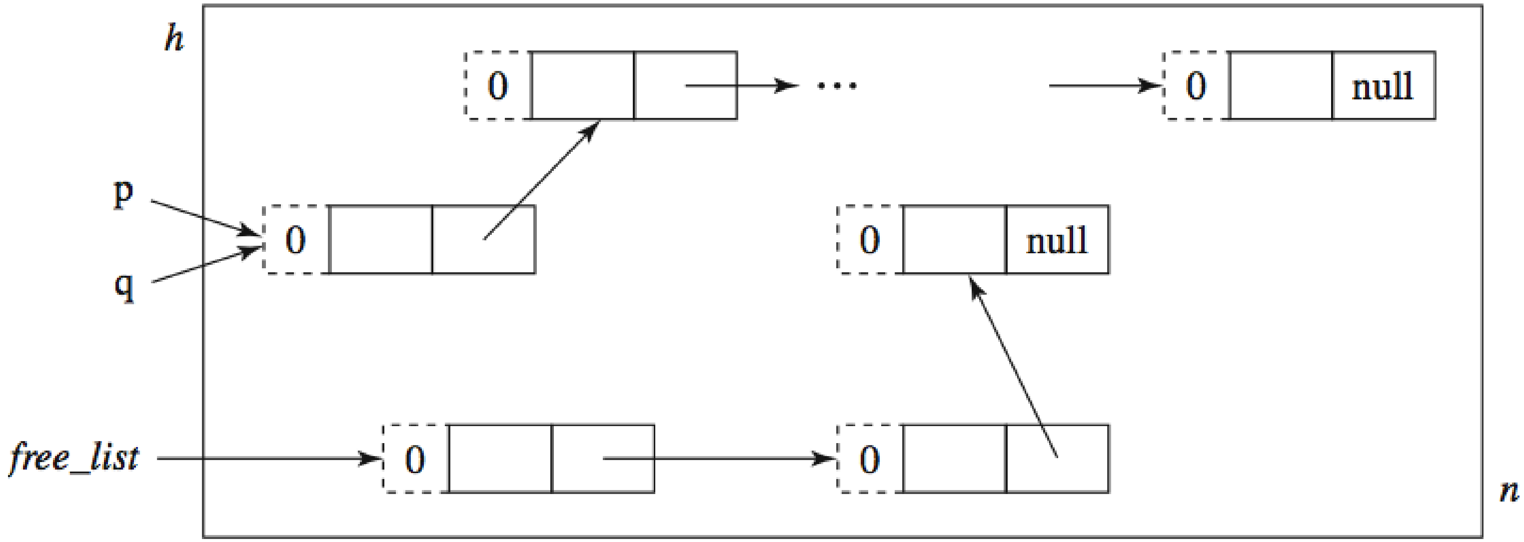
HEAP AFTER PASS I OF MARK-AND-SWEEP

- Triggered by q=new node() and *free_list* = null.
- All accessible nodes are marked 1.



Heap after Pass II of Mark-and-Sweep

- Now *free_list* is restored and
- the assignment `q=new node()` can proceed.

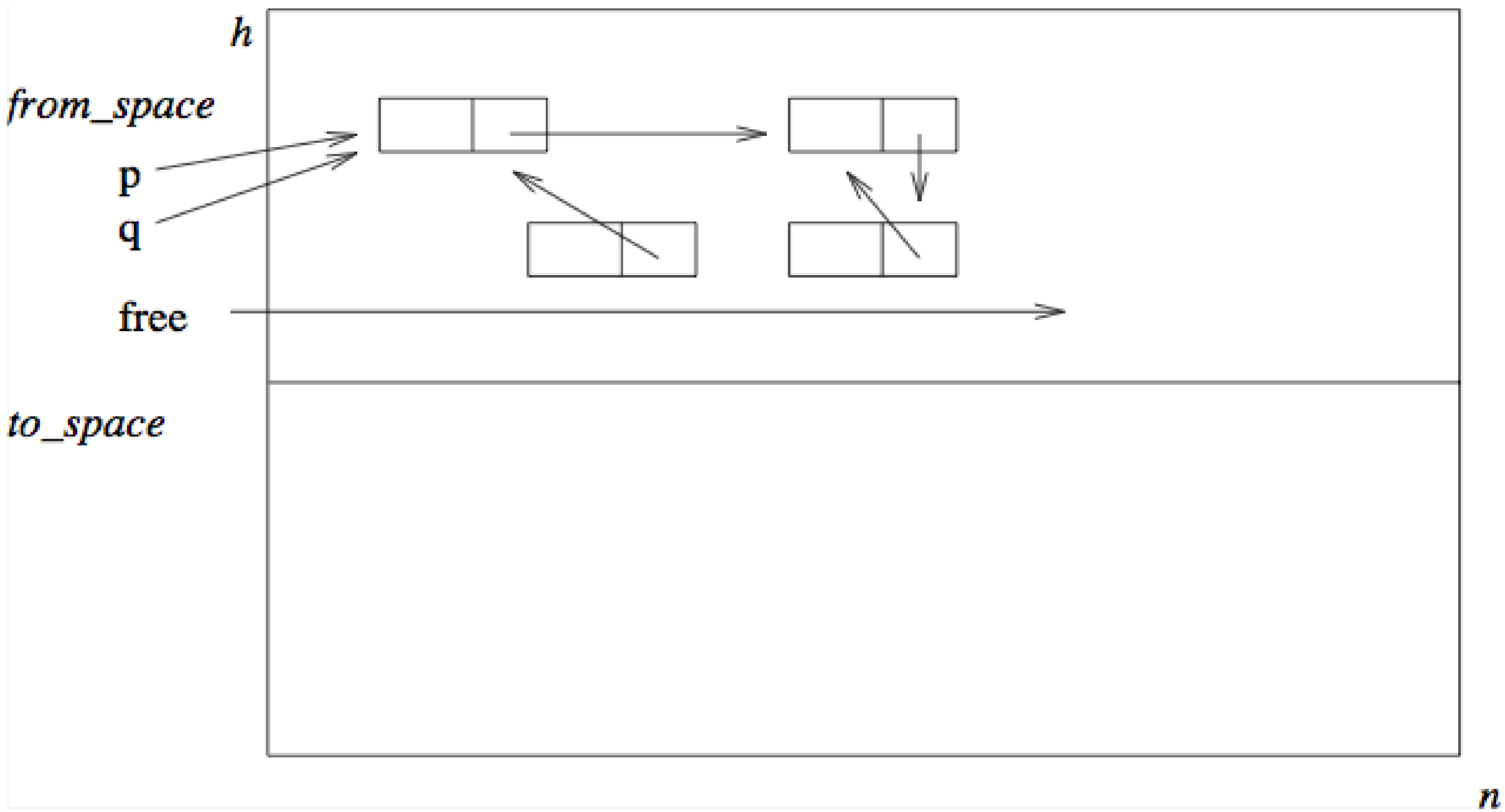


Pros and Cons of Mark-and-Sweep

- Pros:
  - handles cycles correctly
  - very little space overhead
    - 1 bit used for marking cells may limit max values that can be stored in a cell (e.g., for integer cells)
- Cons:
  - normal execution must be suspended (noticeable pause)
  - may touch all virtual memory pages
    - May lead to excessive paging if the working-set size is small and the heap is not all in physical memory
  - heap may fragment
    - Cache misses, page thrashing; more complex allocation

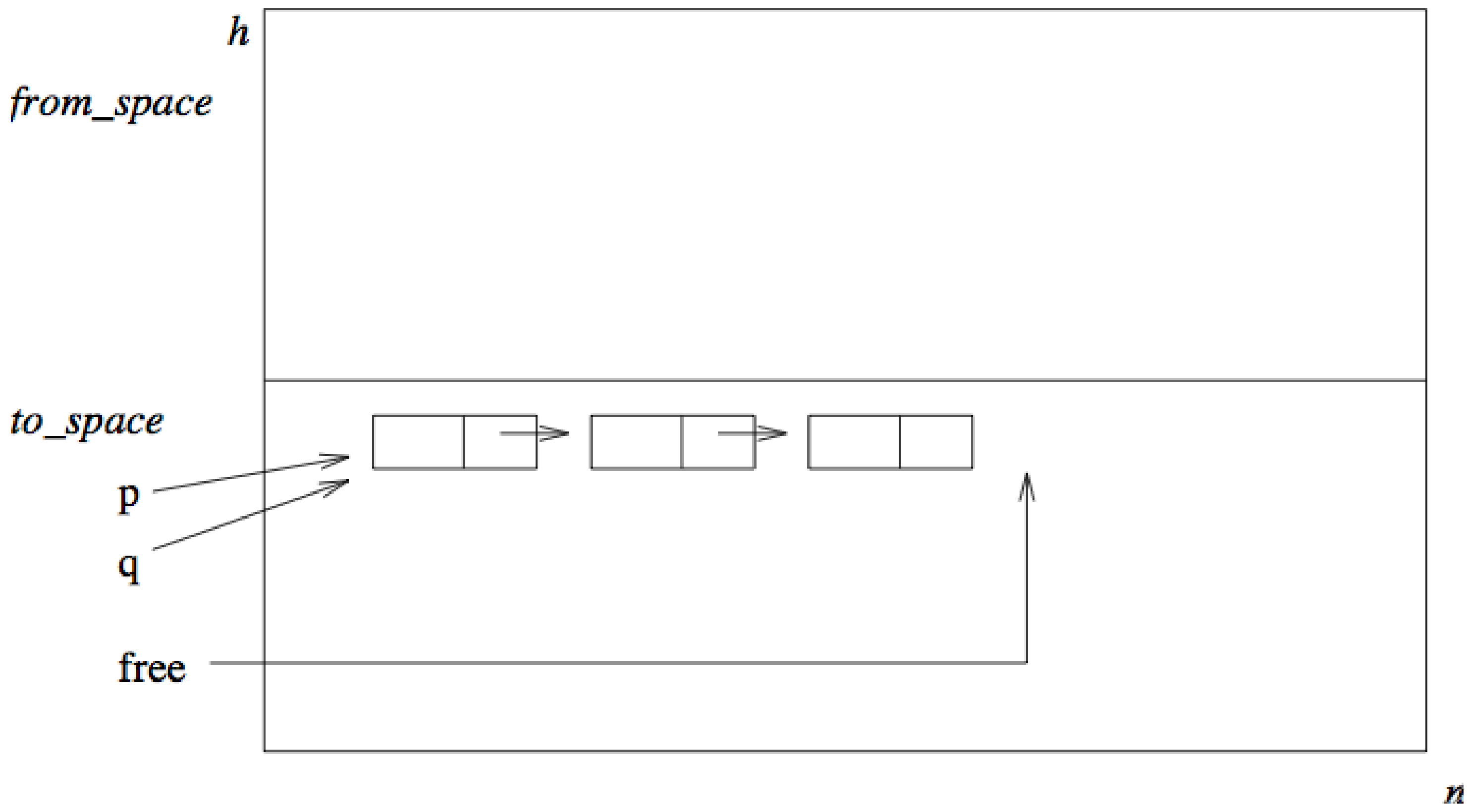
COPY COLLECTION

- Heap partitioned into two halves; only one is active.
- Triggered by q=new node() and *free_list* outside the active half:

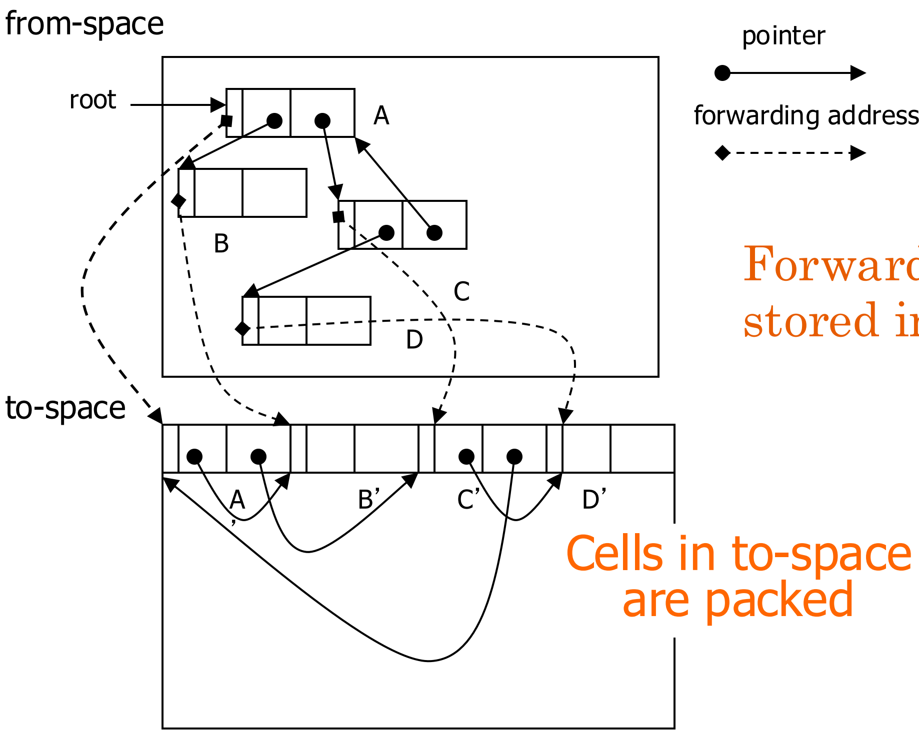


ACCESSIBLE NODES COPIED TO OTHER HALF

- Note: The accessible nodes are packed, orphans are returned to the free_list, and the two halves reverse roles.



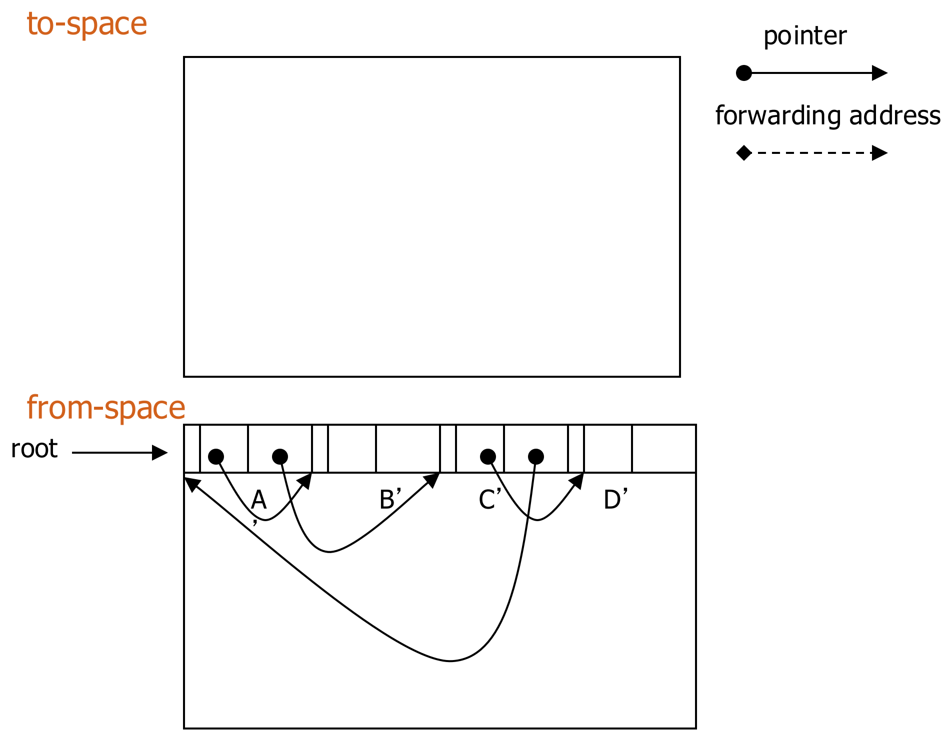
Cheney's Algorithm



Forwarding addresses stored in from-space

Cells in to-space are packed

CHENEY'S ALGORITHM



Pros and Cons of Copy Collection

- Pros:
  - very low cell allocation overhead
    - Out-of-space check requires just an addr comparison
    - Can efficiently allocate variable-sized cells
  - compacting
    - Eliminates fragmentation, good locality of reference
- Cons:
  - Twice the memory footprint
    - Probably Ok for 64-bit architectures (except for paging)
    - When copying, pages of both spaces need to be swapped in. For programs with large memory footprints, this could lead to lots of page faults for very little garbage collected
    - Large physical memory helps

Garbage Collection Summary

- Modern algorithms are more elaborate.
  - Most are hybrids/refinements of the above three.
  - E.g., generational garbage collection
    - Nodes that die, die young
    - Divide the heap into generations, and GC younger generations more often
    - Doesn't reclaim all free space – may need mark & sweep or copy collection occasionally
    - Java/.NET: GC a few recent generations only
- In Java, garbage collection is built-in.
  - runs as a low-priority thread.
  - Also, System.gc may be called by the program.
- Functional languages have garbage collection built-in.
- C/C++ default garbage collection to the programmer.