Garbage Collection

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Major Areas of Memory

- Static area
  - Fixed size, fixed content, allocated at compile time
- Run-time stack
  - Variable size, variable content (activation records)
  - Used for managing function calls and returns
- Heap
  - Fixed size, variable content
  - Dynamically allocated objects and data structures
    - Examples: ML reference cells, malloc in C, new in Java

Cells and Liveness

- Cell = data item in the heap
  - Cells are “pointed to” by pointers held in registers, stack, global/static memory, or in other heap cells
- Roots: registers, stack locations, global/static variables
- A cell is live if its address is held in a root or held by another live cell in the heap

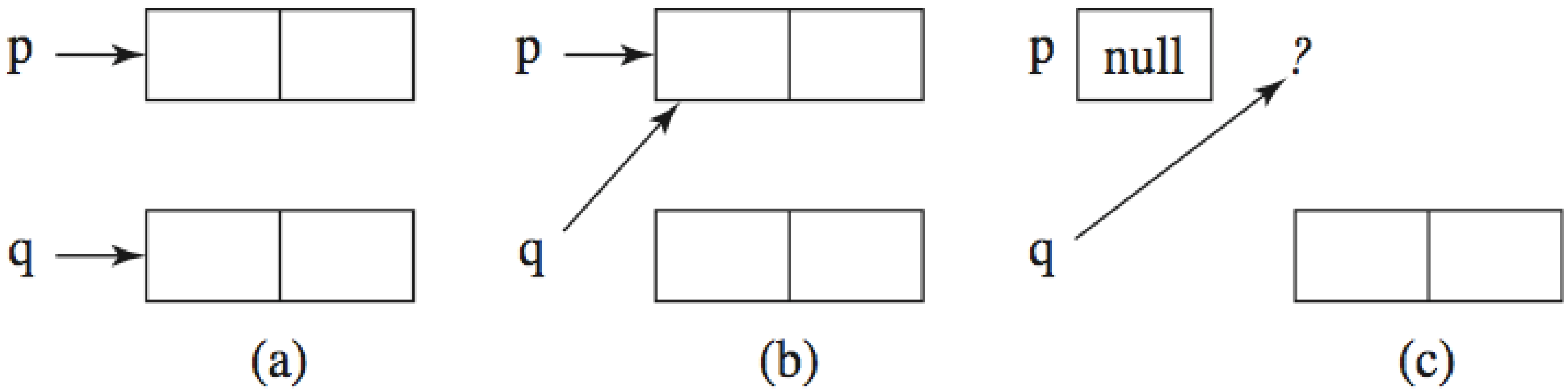
Garbage

- Garbage is a block of heap memory that cannot be accessed by the program
  - An allocated block of heap memory does not have a reference to it (cell is no longer "live")
  - Another kind of memory error: a reference exists to a block of memory that is no longer allocated
- Garbage collection (GC) - automatic management of dynamically allocated storage
  - Reclaim unused heap blocks for later use by program

Example of Garbage

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

```
p = new node();
q = new node();
q = p;
delete p;
```



Why Garbage Collection?

- Today's programs consume storage freely
  - 1GB laptops, 1-4GB deskops, 8-512GB servers
  - 64-bit address spaces (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
- 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 GC revival
  - Object-oriented languages: Modula-3, Java
    - 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

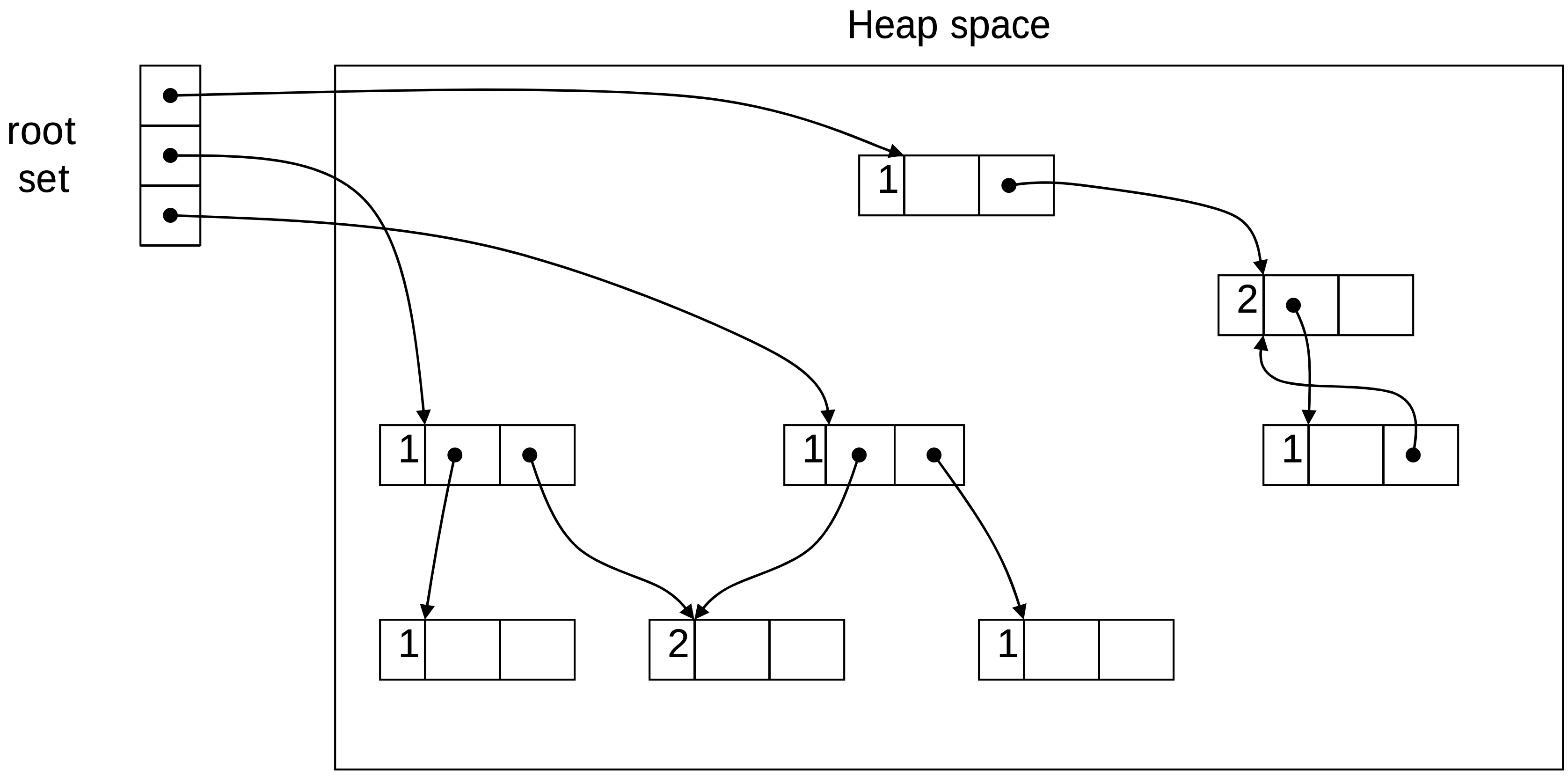
Summary of GC Techniques

- Reference counting
  - Directly keeps track of live cells
  - GC takes place whenever heap block is allocated
  - Doesn't detect all garbage
- Tracing
  - GC takes place and identifies live cells when a request for memory fails
  - Mark-sweep
  - Copy collection
- Modern techniques: generational GC

Reference Counting

- Simply count the number of references to a cell
- Requires space and time overhead to store the count and increment (decrement) each time a reference is added (removed)
  - Reference counts are maintained in real-time, so no “stop-and-gag” effect
  - Incremental garbage collection
- Unix file system uses a reference count for files
- C++ “smart pointer” (e.g., auto_ptr) use reference counts

Reference Counting: Example



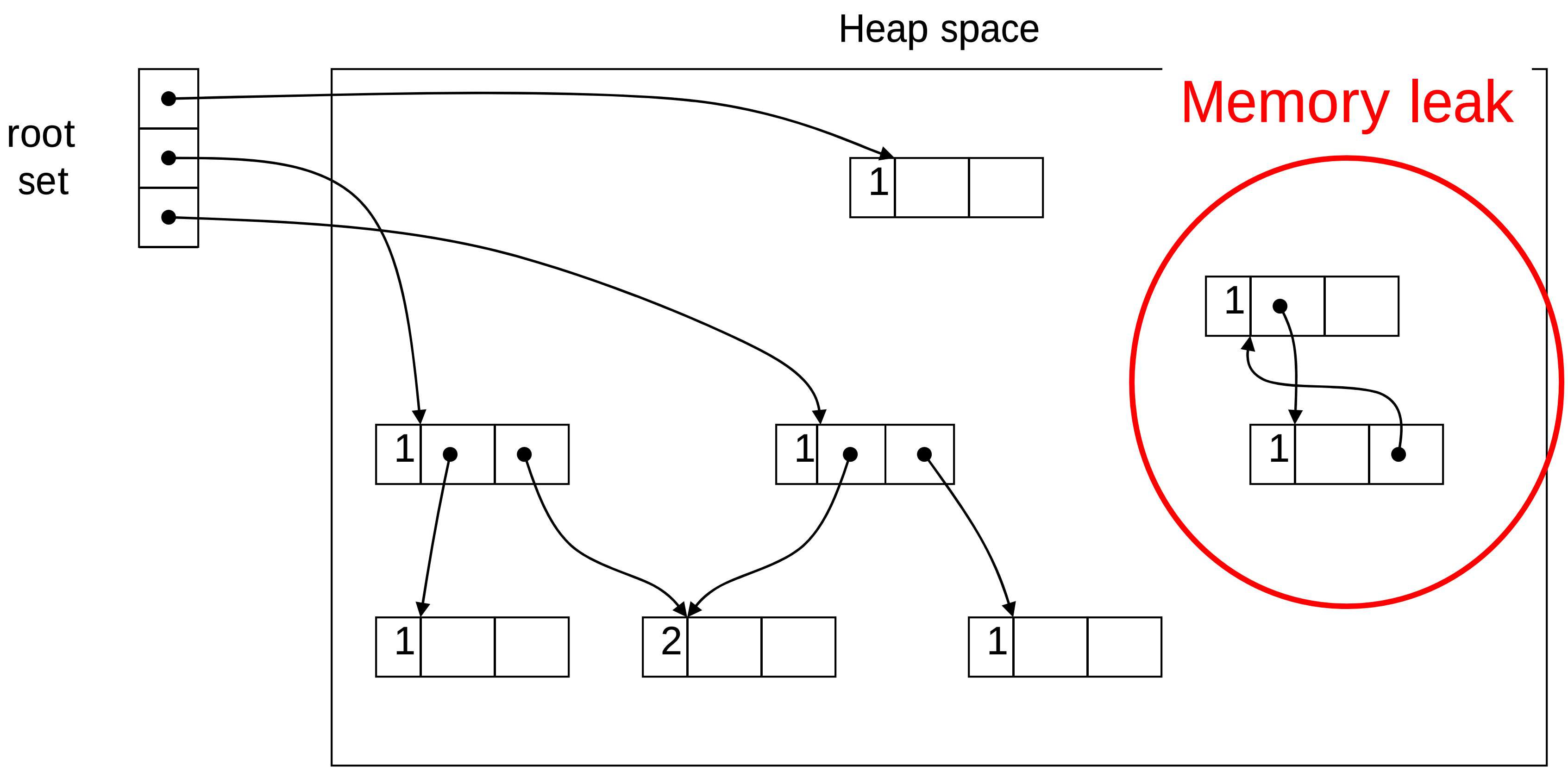
Reference Counting: Strengths

- Incremental overhead
  - Cell management interleaved with program execution
  - Good for interactive or real-time computation
- 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
- Can re-use freed cells immediately
  - If RC == 0, put back onto the free list

Reference Counting: Weaknesses

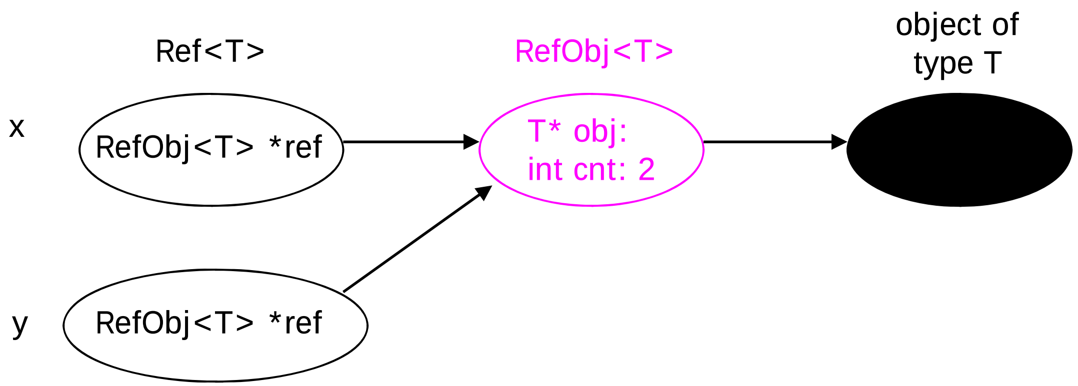
- Space overhead
  - 1 word for the count, 1 for an indirect pointer
- Time overhead
  - Updating a pointer to point to a new cell requires:
    - Check to ensure that it is not a self-reference
    - Decrement the count on the old cell, possibly deleting it
    - Update the pointer with the address of the new cell
    - Increment the count on the new cell
- One missed increment/decrement results in a dangling pointer / memory leak
- Cyclic data structures may cause leaks

Reference Counting: Cycles



“Smart Pointer” in C++

- Similar to std::auto_ptr<T> in ANSI C++



sizeof(RefObj<T>) = 8 bytes of overhead per reference-counted object

sizeof(Ref<T>) = 4 bytes

- Fits in a register
- Easily passed by value as an argument or result of a function
- Takes no more space than regular pointer, but much “safer” (why?)

Smart Pointer Implementation

```
template<class T> class Ref {
    RefObj<T>* ref;
    Ref<T>* operator&() {}
public:
    Ref() : ref(0) {}
    Ref(T* p) : ref(new RefObj<T>(p)) { ref->inc();}
    Ref(const Ref<T>& r) : ref(r.ref) { ref->inc(); }
    ~Ref() { if (ref->dec() == 0) delete ref; }

    Ref<T>& operator=(const Ref<T>& that) {
      if (this != &that) {
        if (ref->dec() == 0) delete ref;
          ref = that.ref;
          ref->inc(); }
       return *this; }
    T* operator->() { return *ref; }
    T& operator*() { return *ref; }
};
```

```
template<class T> class RefObj {
     T* obj;
     int cnt;
public:
    RefObj(T* t) : obj(t), cnt(0) {}
    ~RefObj() { delete obj; }

    int inc() { return ++cnt; }
    int dec() { return --cnt; }

    operator T*() { return obj; }
    operator T&() { return *obj; }
    T& operator *() { return *obj; }
};
```

Using Smart Pointers

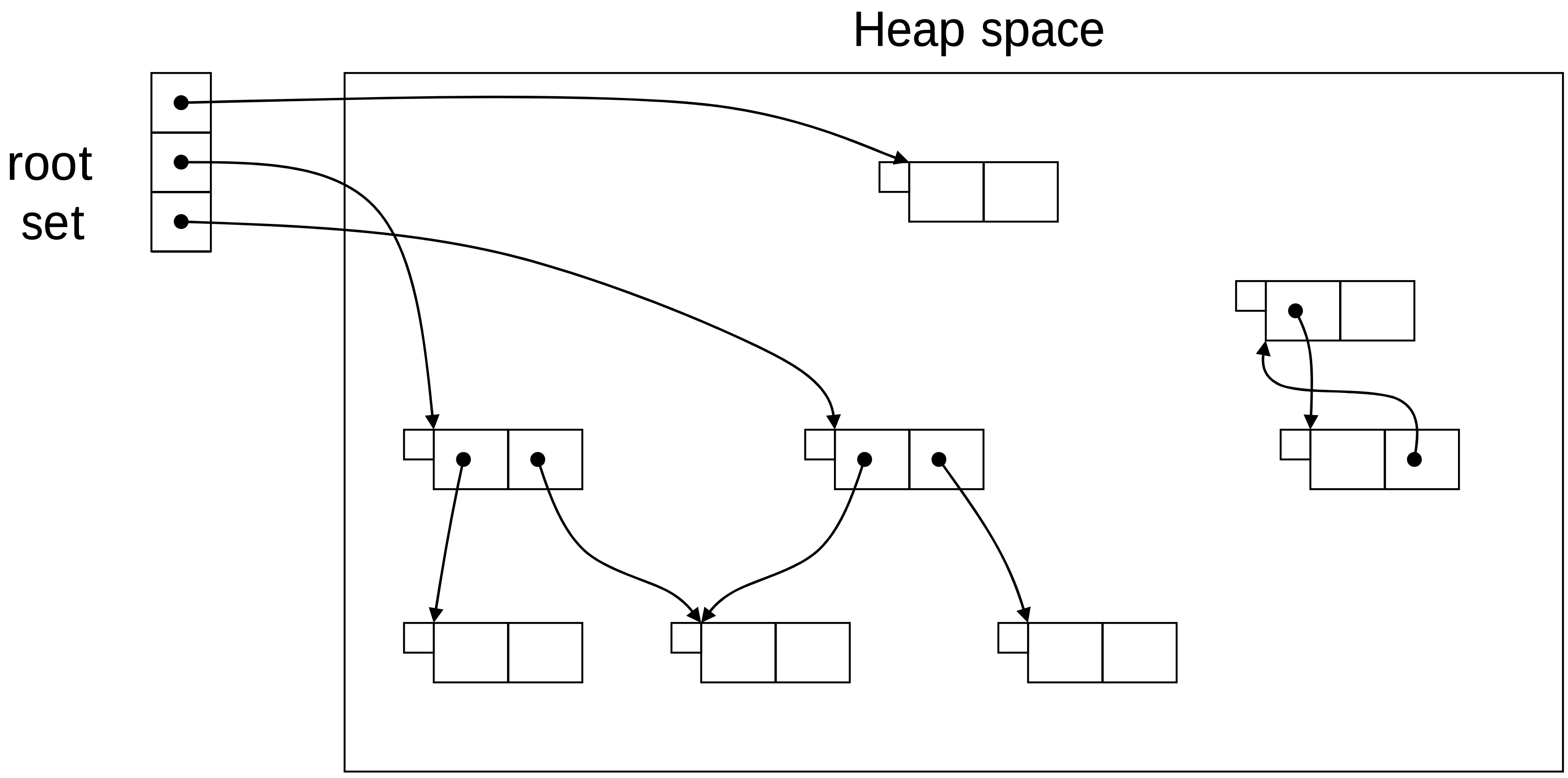
```
Ref<string> proc() {
    Ref<string> s = new string(“Hello, world”); // ref count set to 1
    ...
    int x = s->length();  // s.operator->() returns string object ptr
    ...
    return s;
} // ref count goes to 2 on copy out, then 1 when s is auto-destructed

int main()
{
    ...
    Ref<string> a = proc();  // ref count is 1 again
    ...
} // ref count goes to zero and string is destructed, along with Ref and RefObj objects
```

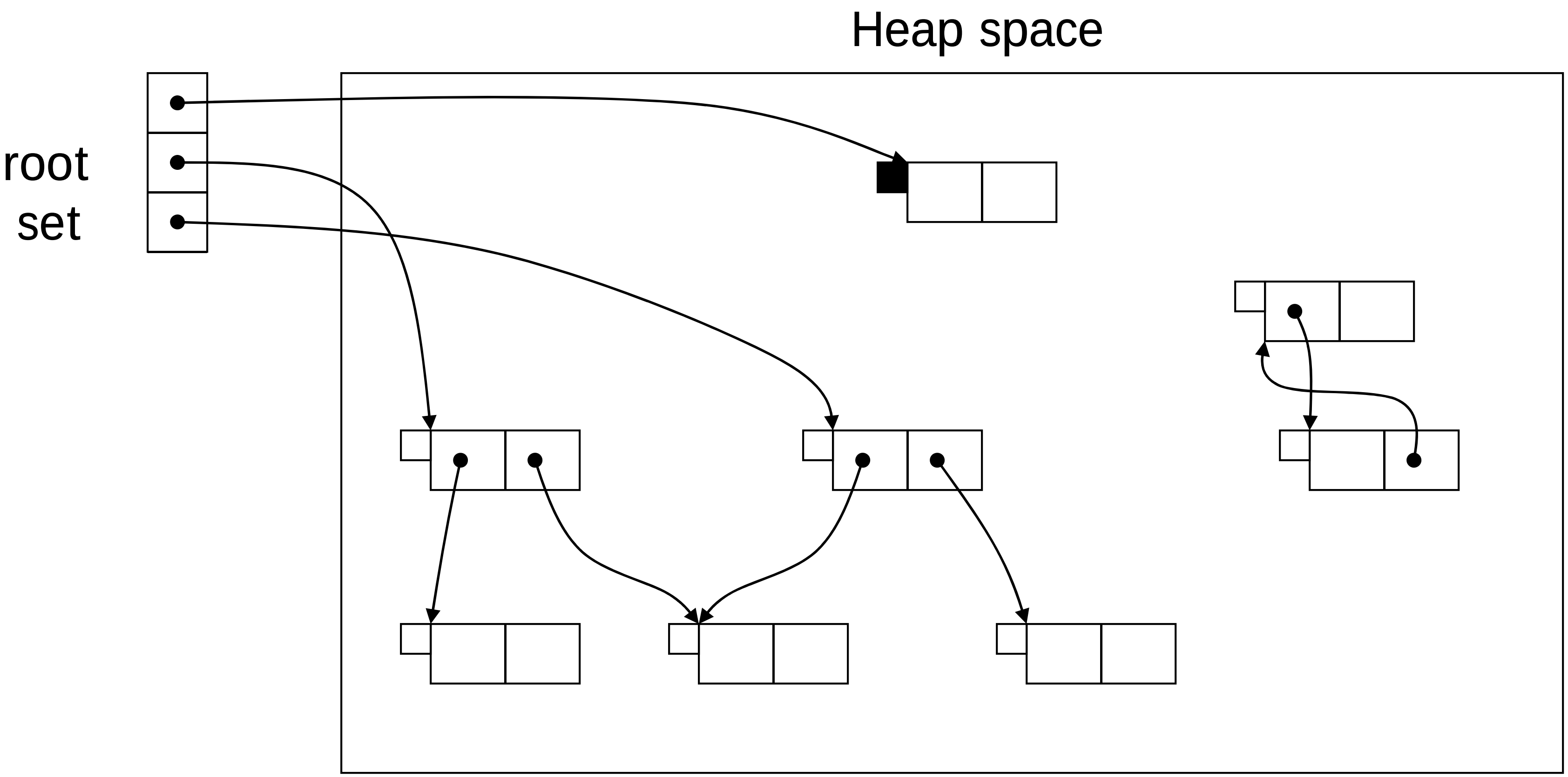
Mark-Sweep Garbage Collection

- Each cell has a mark bit
- Garbage remains unreachable and undetected until heap is used up; then GC goes to work, while program execution is suspended
- Marking phase
  - Starting from the roots, set the mark bit on all live cells
- Sweep phase
  - Return all unmarked cells to the free list
  - Reset the mark bit on all marked cells

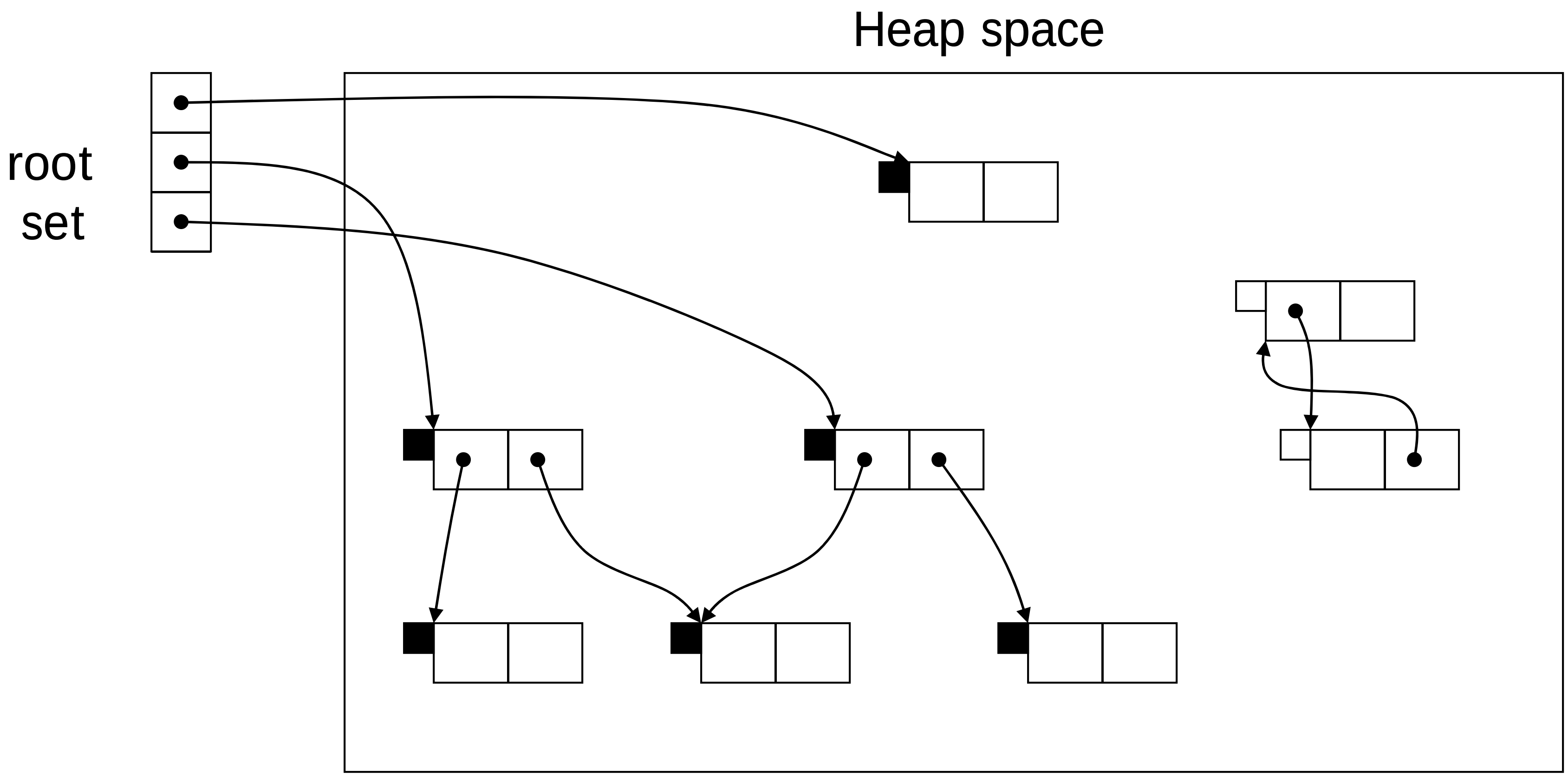
Mark-Sweep Example (1)



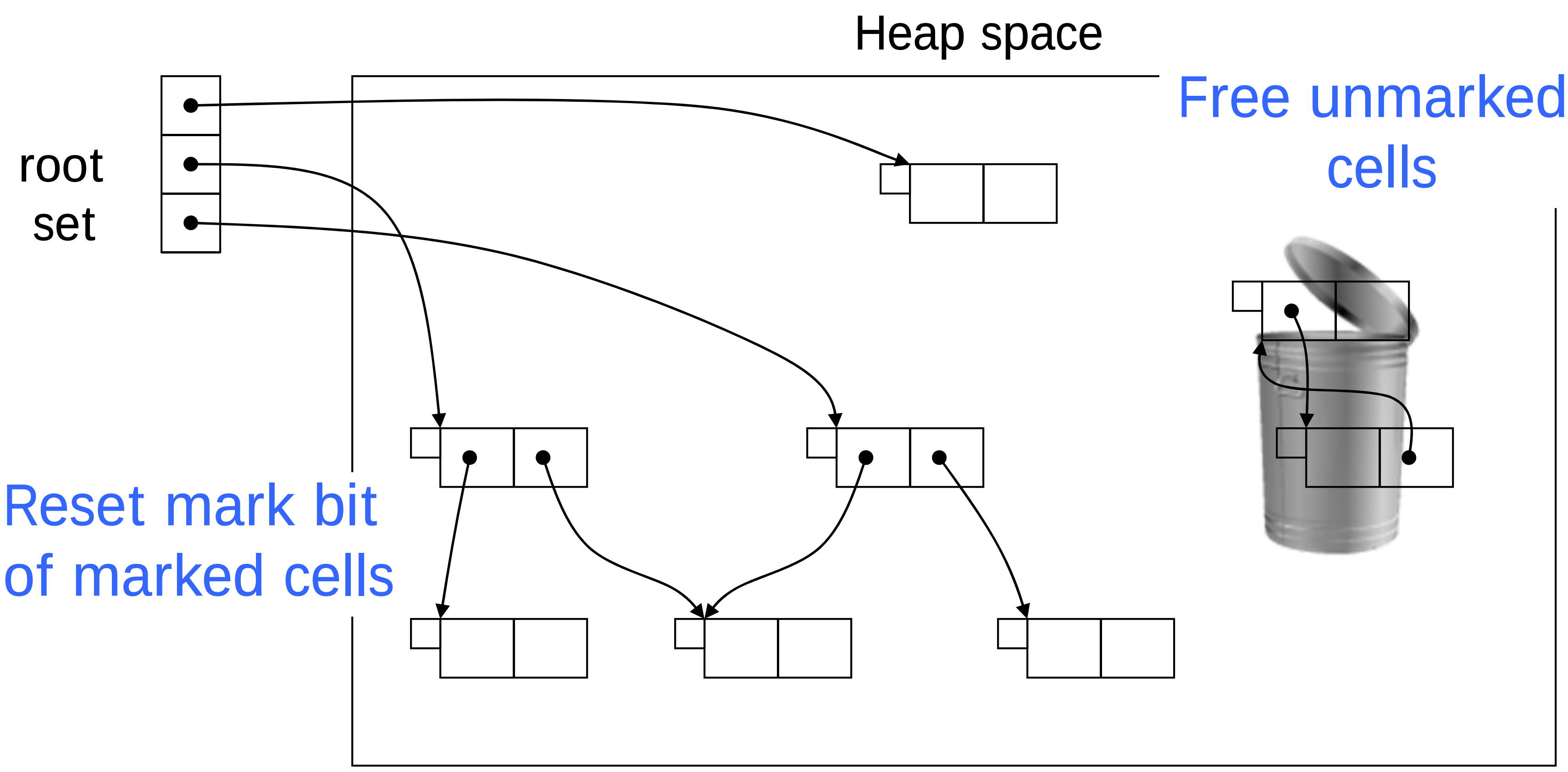
Mark-Sweep Example (2)



Mark-Sweep Example (3)



Mark-Sweep Example (4)



Mark-Sweep Costs and Benefits

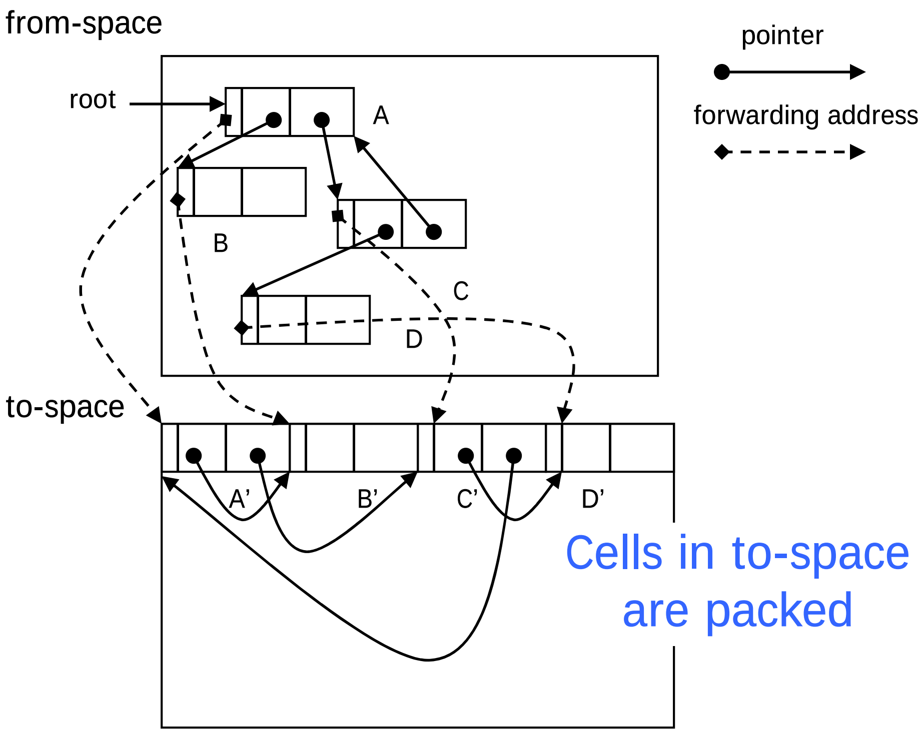
- Good: handles cycles correctly
- Good: no space overhead
  - 1 bit used for marking cells may limit max values that can be stored in a cell (e.g., for integer cells)
- Bad: normal execution must be suspended
- Bad: may touch all virtual memory pages
  - May lead to excessive paging if the working-set size is small and the heap is not all in physical memory
- Bad: heap may fragment
  - Cache misses, page thrashing; more complex allocation

Copying Collector

- Divide the heap into “from-space” and “to-space”
- Cells in from-space are traced and live cells are copied (“scavenged”) into to-space
  - To keep data structures linked, must update pointers for roots and cells that point into from-space
    - This is why references in Java and other languages are not pointers, but indirect abstractions for pointers
  - Only garbage is left in from-space
- When to-space fills up, the roles flip
  - Old to-space becomes from-space, and vice versa

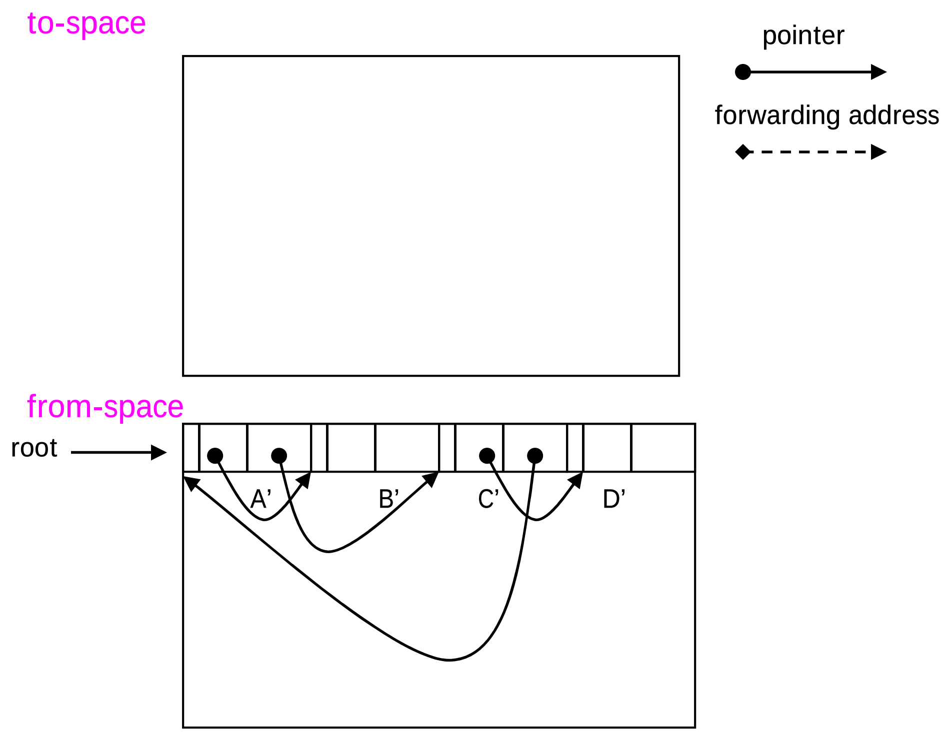
Copying a Linked List

[Cheney's algorithm]



Cells in to-space are packed

Flipping Spaces



Copying Collector Tradeoffs

- Good: very low cell allocation overhead
  - Out-of-space check requires just an addr comparison
  - Can efficiently allocate variable-sized cells
- Good: compacting
  - Eliminates fragmentation, good locality of reference
- Bad: 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

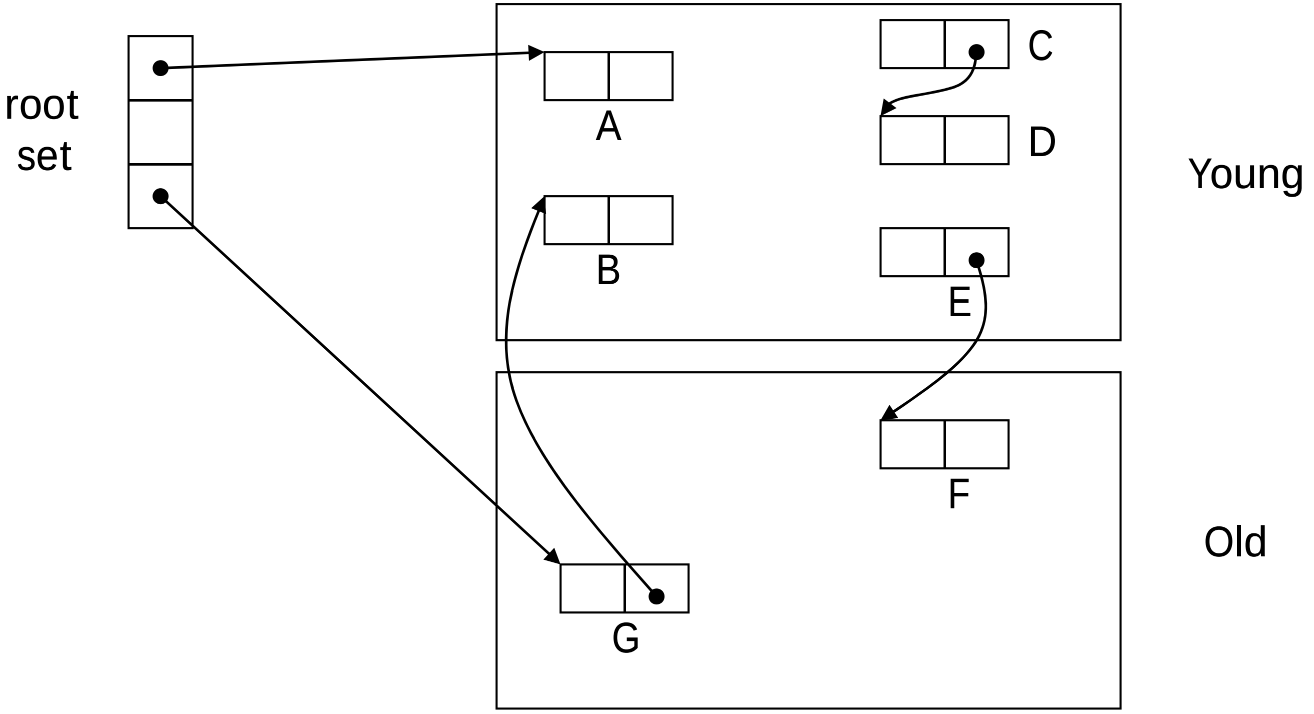
Generational Garbage Collection

- Observation: most cells that die, die young
  - Nested scopes are entered and exited more frequently, so temporary objects in a nested scope are born and die close together in time
  - Inner expressions in Scheme are younger than outer expressions, so they become garbage sooner
- Divide the heap into generations, and GC the younger cells more frequently
  - Don't have to trace all cells during a GC cycle
  - Periodically reap the "older generations"
  - Amortize the cost across generations

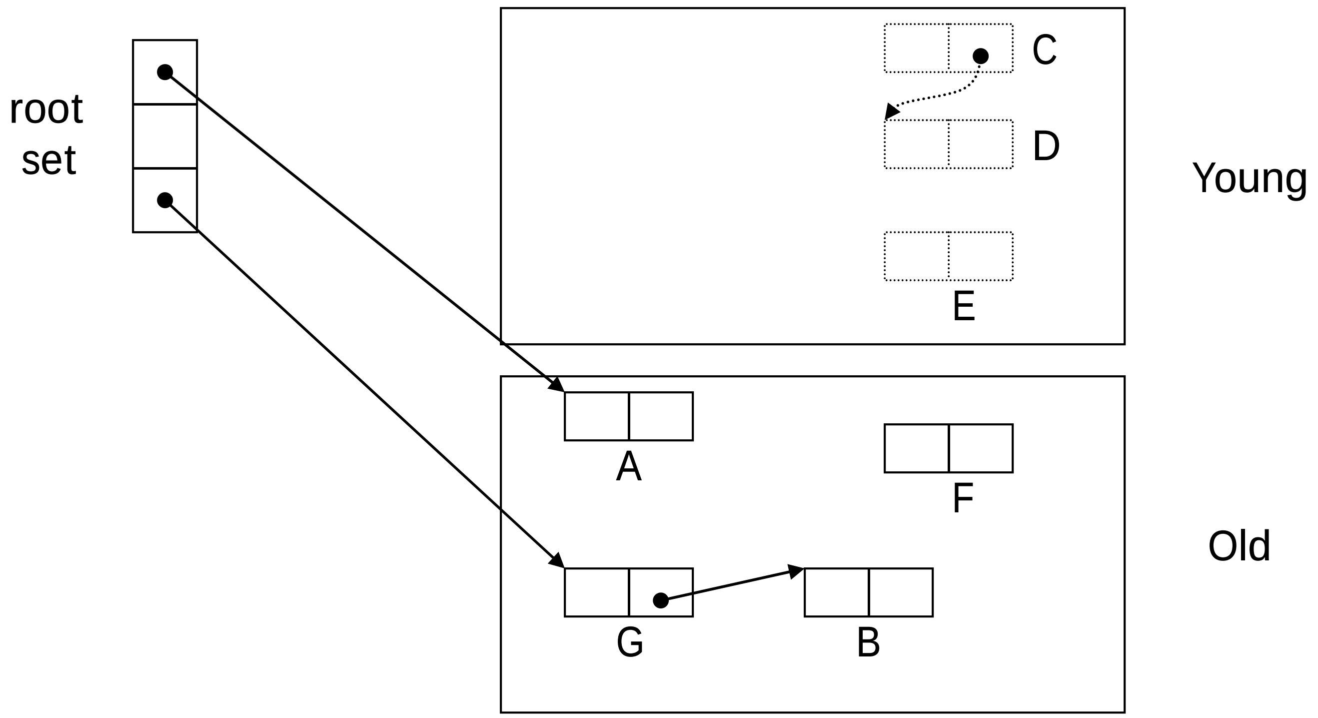
Generational Observations

- Can measure "youth" by time or by growth rate
- Common Lisp: 50-90% of objects die before they are 10KB old
- Glasgow Haskell: 75-95% die within 10KB
  - No more than 5% survive beyond 1MB
- Standard ML of NJ reclaims over 98% of objects of any given generation during a collection
- C: one study showed that over 1/2 of the heap was garbage within 10KB and less than 10% lived for longer than 32KB

Example with Immediate “Aging” (1)



Example with Immediate “Aging” (2)



Generations with Semi-Spaces