Memory Allocation III

CSE 351 Autumn 2019

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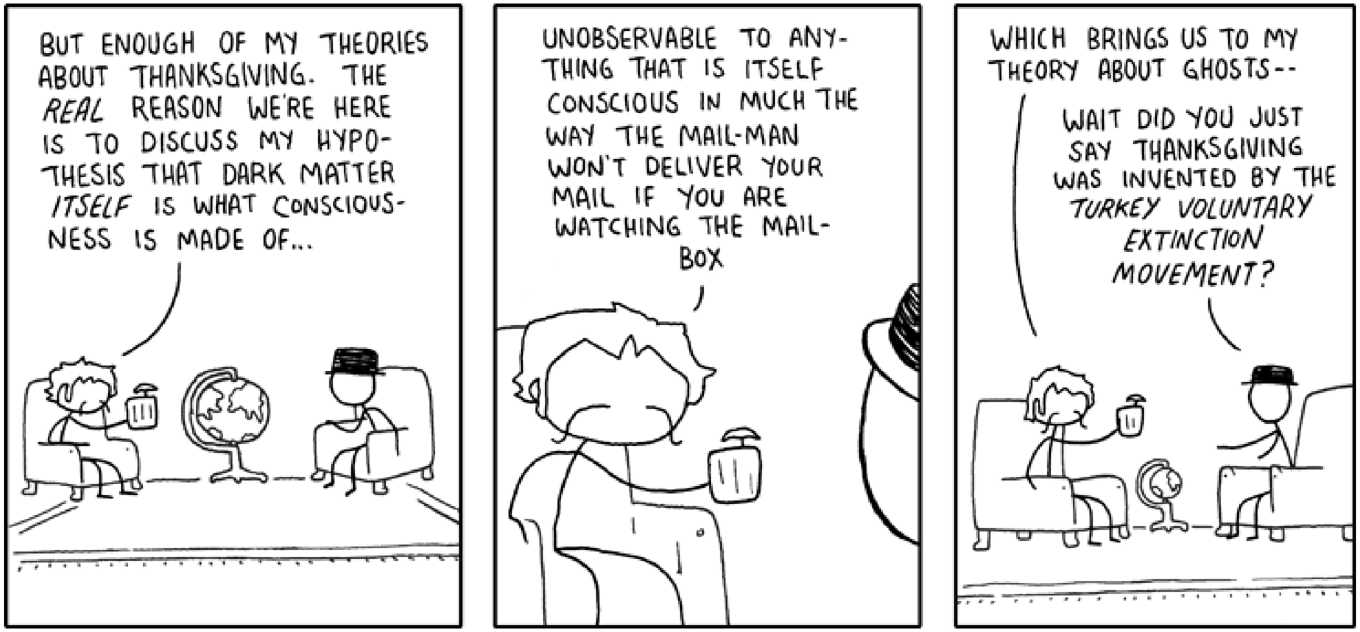

BUT ENOUGH OF MY THEORIES ABOUT THANKSGIVING. THE *REAL* REASON WE'RE HERE IS TO DISCUSS MY HYPOTHESIS THAT DARK MATTER *ITSELF* IS WHAT CONSCIOUSNESS IS MADE OF...
UNOBSERVABLE TO ANYTHING THAT IS ITSELF CONSCIOUS IN MUCH THE WAY THE MAIL-MAN WON'T DELIVER YOUR MAIL IF YOU ARE WATCHING THE MAILBOX
WHICH BRINGS US TO MY THEORY ABOUT GHOSTS--
WAIT DID YOU JUST SAY THANKSGIVING WAS INVENTED BY THE *TURKEY VOLUNTARY EXTINCTION MOVEMENT?*

https://xkcd.com/825/

Administrivia

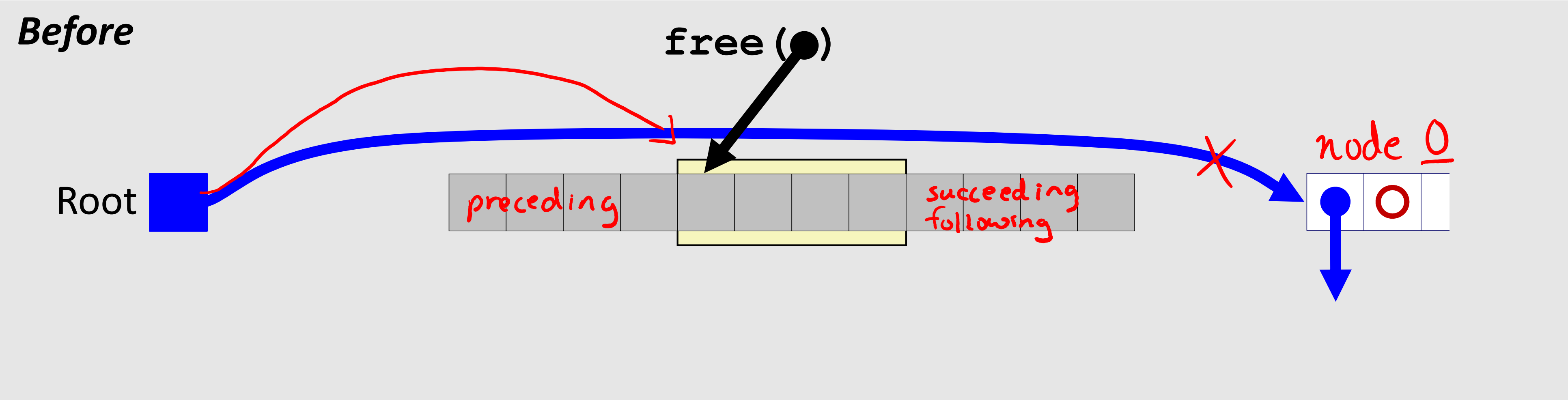
- hw22 due Monday (12/2)
- Lab 5 due next Friday (12/6)
  - Recommended that you watch the Lab 5 helper videos
  - "Virtual section" videos released over Thanksgiving

- **Final Exam:** Tue, Dec. 10 @ 12:30pm in KNE 120
  - Review Session: Sun, Dec. 8, 3:30 - 6 pm in SAV 260

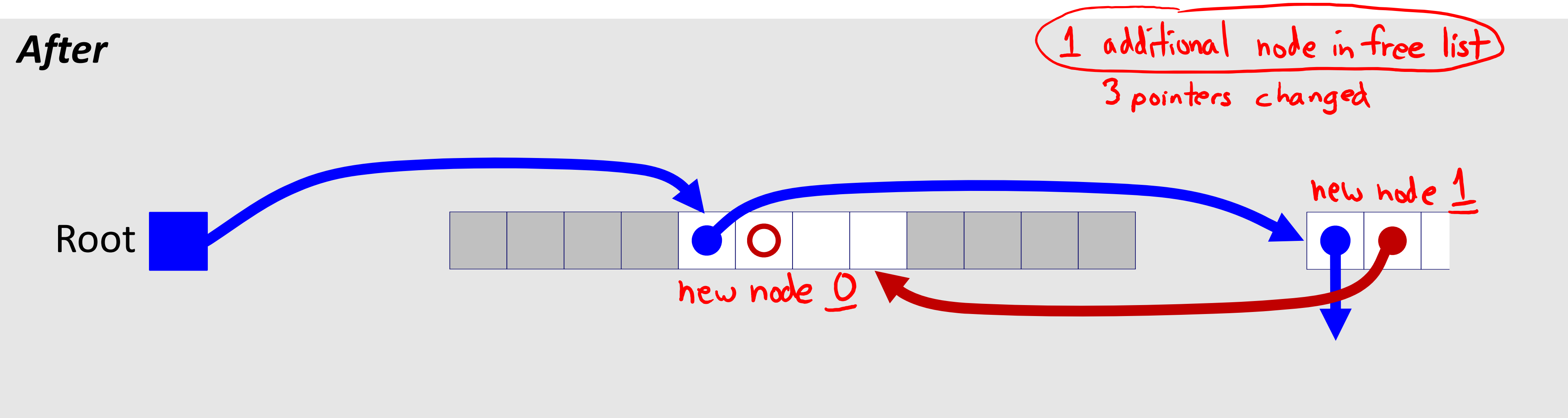
    Su18 Final
    - Take half of a practice exam in an exam environment, then go over problems (more info to be released on Piazza)
  - Cumulative (midterm clobber policy applies)
    - Midterm portion will be "harder" than the Midterm
  - TWO double-sided handwritten 8.5×11" cheat sheets

Freeing with LIFO Policy (Case 1)

Boundary tags not shown, but don't forget about them!

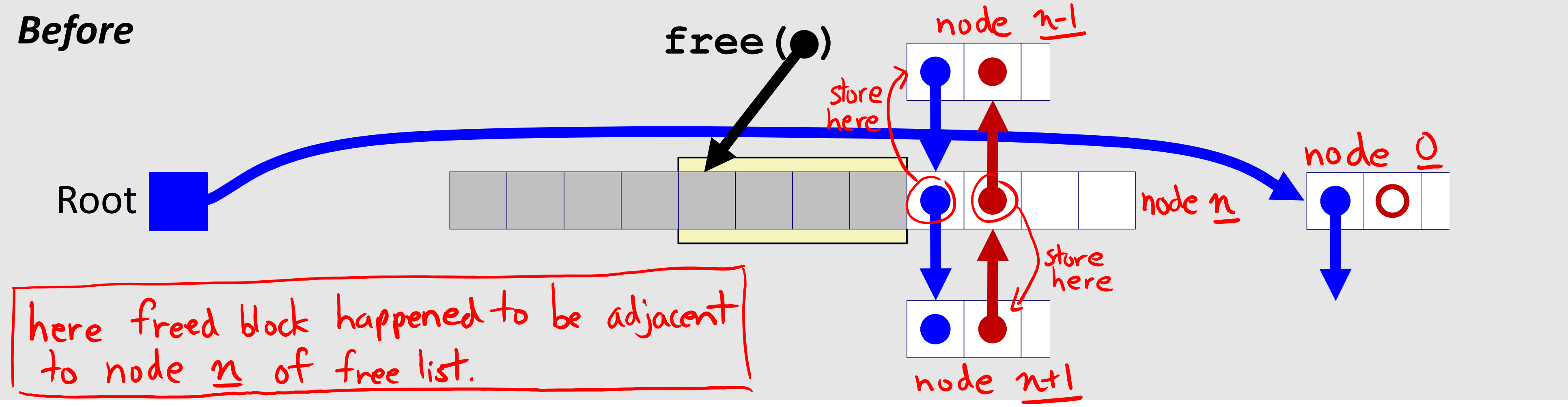


- Insert the freed block at the root of the list



Freeing with LIFO Policy (Case 2)

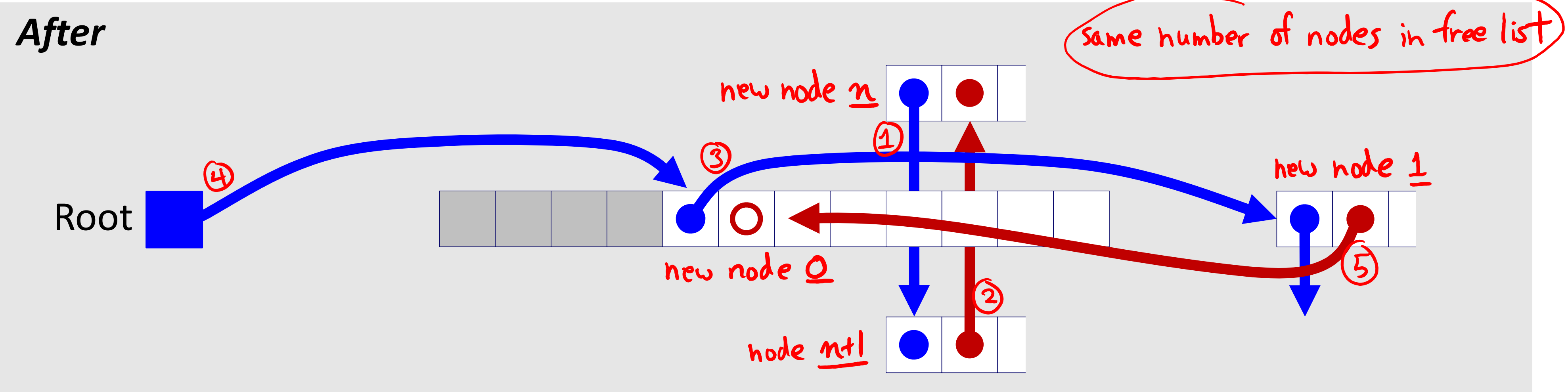
Boundary tags not shown, but don't forget about them!



here freed block happened to be adjacent to node n of free list.

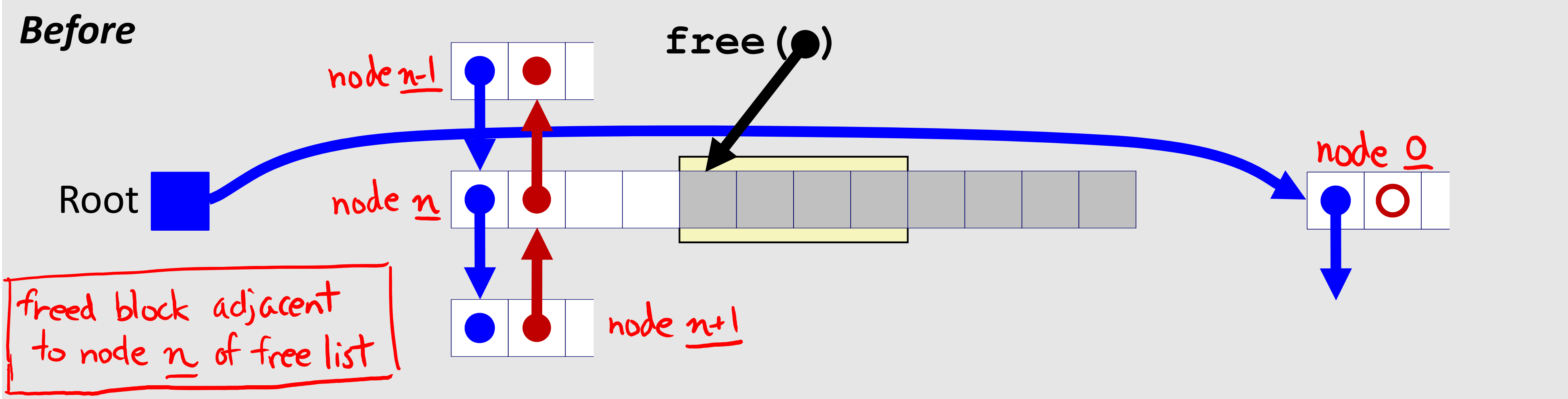
- Splice *successor* block out of list, coalesce both memory blocks, and insert the new block at the root of the list

5 pointers updated



Freeing with LIFO Policy (Case 3)

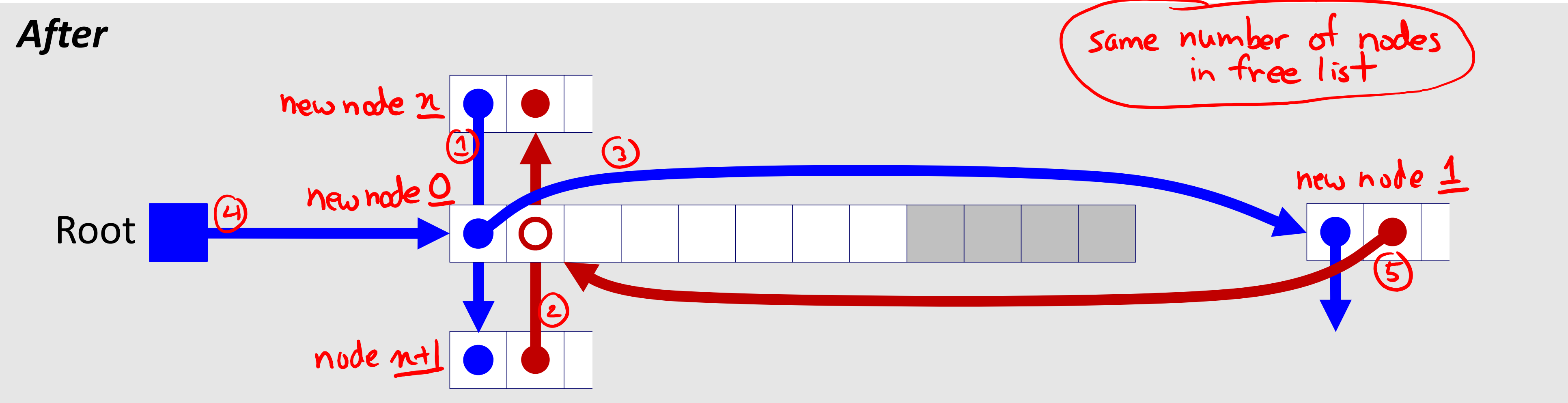
Boundary tags not shown, but don't forget about them!



freed block adjacent to node n of free list

- Splice *predecessor* block out of list, coalesce both memory blocks, and insert the new block at the root of the list

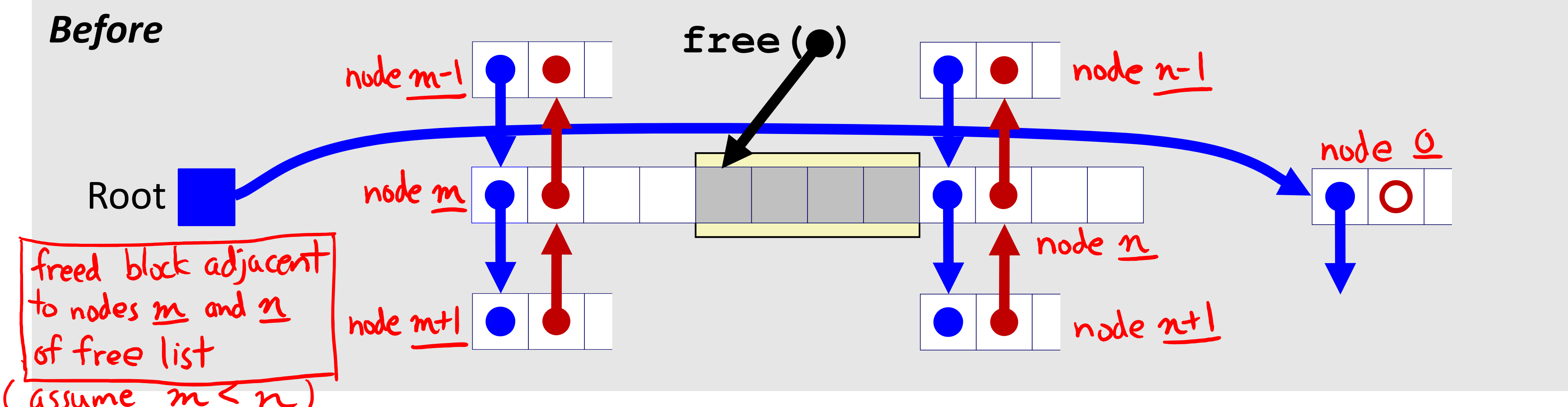
5 pointers updated



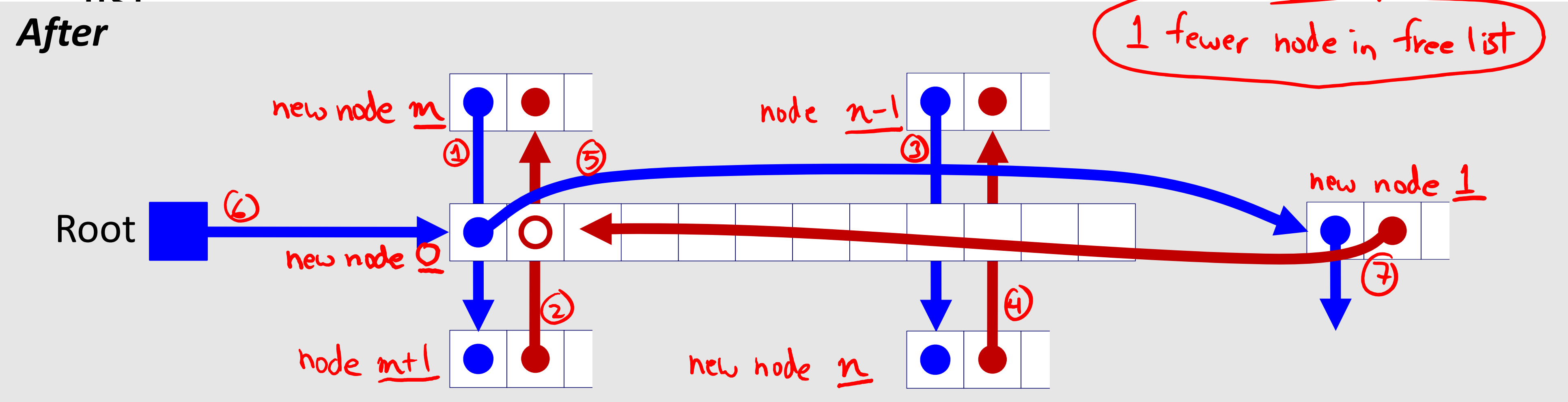
same number of nodes in free list

Freeing with LIFO Policy (Case 4)

Boundary tags not shown, but don't forget about them!



- Splice *predecessor* and *successor* blocks out of list, coalesce all 3 memory blocks, and insert the new block at the root of the list



Explicit List Summary

- Comparison with implicit list:
  - Block allocation is linear time in number of ***free*** blocks instead of ***all*** blocks
    - ***Much faster*** when most of the memory is full
  - Slightly more complicated allocate and free since we need to splice blocks in and out of the list
  - Some extra space for the links (2 extra pointers needed for each free block)
    - Increases minimum block size, leading to more internal fragmentation

- Most common use of explicit lists is in conjunction with *segregated free lists*
  - Keep multiple linked lists of different size classes, or possibly for different types of objects

Allocation Policy Tradeoffs

- Data structure of blocks on lists
  - Implicit (free/allocated), explicit (free), segregated (many free lists) – others possible!
- Placement policy: first-fit, next-fit, best-fit
  - Throughput vs. amount of fragmentation
- When do we split free blocks?
  - How much internal fragmentation are we willing to tolerate?
- When do we coalesce free blocks?
  - **Immediate coalescing:** Every time `free` is called

    we've assumed this up to now
  - **Deferred coalescing:** Defer coalescing until needed
    - e.g. when scanning free list for `malloc` or when external fragmentation reaches some threshold

More Info on Allocators

- D. Knuth, “*The Art of Computer Programming*”, 2nd edition, Addison Wesley, 1973
  - The classic reference on dynamic storage allocation

- Wilson et al, “*Dynamic Storage Allocation: A Survey and Critical Review*”, Proc. 1995 Int’l Workshop on Memory Management, Kinross, Scotland, Sept, 1995.
  - Comprehensive survey
  - Available from CS:APP student site (csapp.cs.cmu.edu)

Memory Allocation

- Dynamic memory allocation
  - Introduction and goals
  - Allocation and deallocation (free)
  - Fragmentation
- Explicit allocation implementation
  - Implicit free lists
  - Explicit free lists (Lab 5)
  - Segregated free lists
- **Implicit deallocation: garbage collection**
- **Common memory-related bugs in C**

Wouldn't it be nice…

- If we never had to free memory?
- Do you free objects in Java?
  - Reminder: *implicit* allocator

Garbage Collection (GC)
(Automatic Memory Management)

- *Garbage collection:* automatic reclamation of heap-allocated storage – application never explicitly frees memory

```
void foo() {
    int* p = (int*) malloc(128);
    return;   /* p block is now garbage! */
}
```

stack

heap

p is deallocated

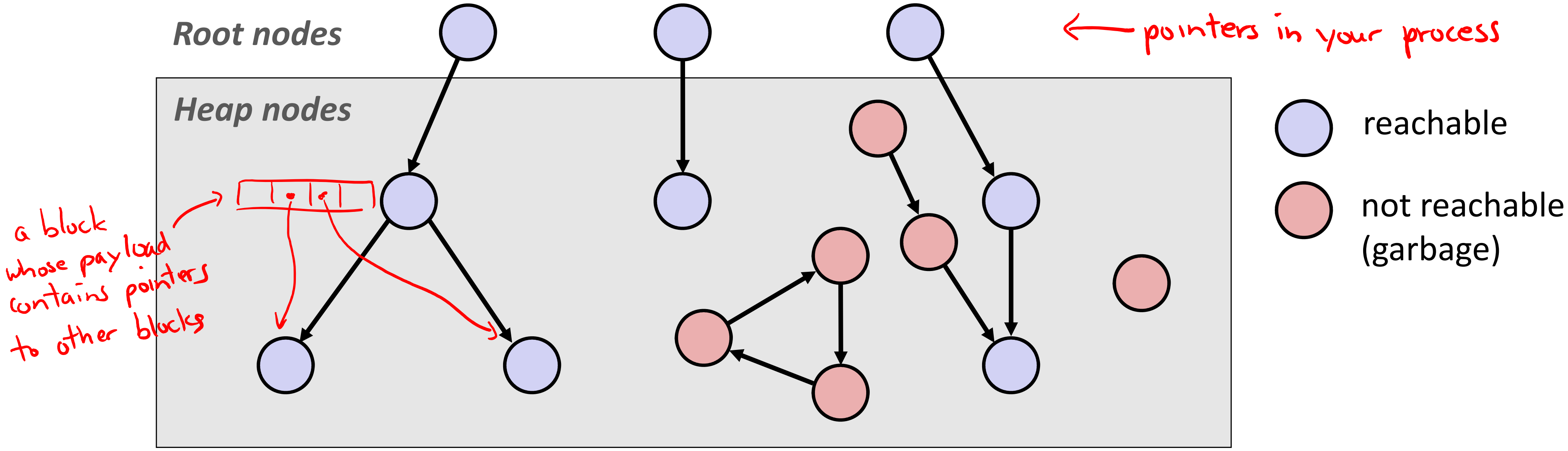
- Common in implementations of functional languages, scripting languages, and modern object oriented languages:
  - Lisp, Racket, Erlang, ML, Haskell, Scala, Java, C#, Perl, Ruby, Python, Lua, JavaScript, Dart, Mathematica, MATLAB, many more…
- Variants (“conservative” garbage collectors) exist for C and C++
  - However, cannot necessarily collect all garbage

Garbage Collection

- How does the memory allocator know when memory can be freed?
  - In general, we cannot know what is going to be used in the future since it depends on conditionals
  - But, we can tell that certain blocks cannot be used if they are *unreachable* (via pointers in registers/stack/globals)
- Memory allocator needs to know what is a pointer and what is not – how can it do this?
  - Sometimes with help from the compiler

Memory as a Graph

- We view memory as a directed graph
  - Each allocated heap block is a node in the graph
  - Each pointer is an edge in the graph
  - Locations not in the heap that contain pointers into the heap are called ***root*** nodes (e.g. registers, stack locations, global variables)


Root nodes
← pointers in your process
Heap nodes
a block whose payload contains pointers to other blocks
reachable
not reachable (garbage)

A node (block) is *reachable* if there is a path from any root to that node
Non-reachable nodes are *garbage* (cannot be needed by the application)

Garbage Collection

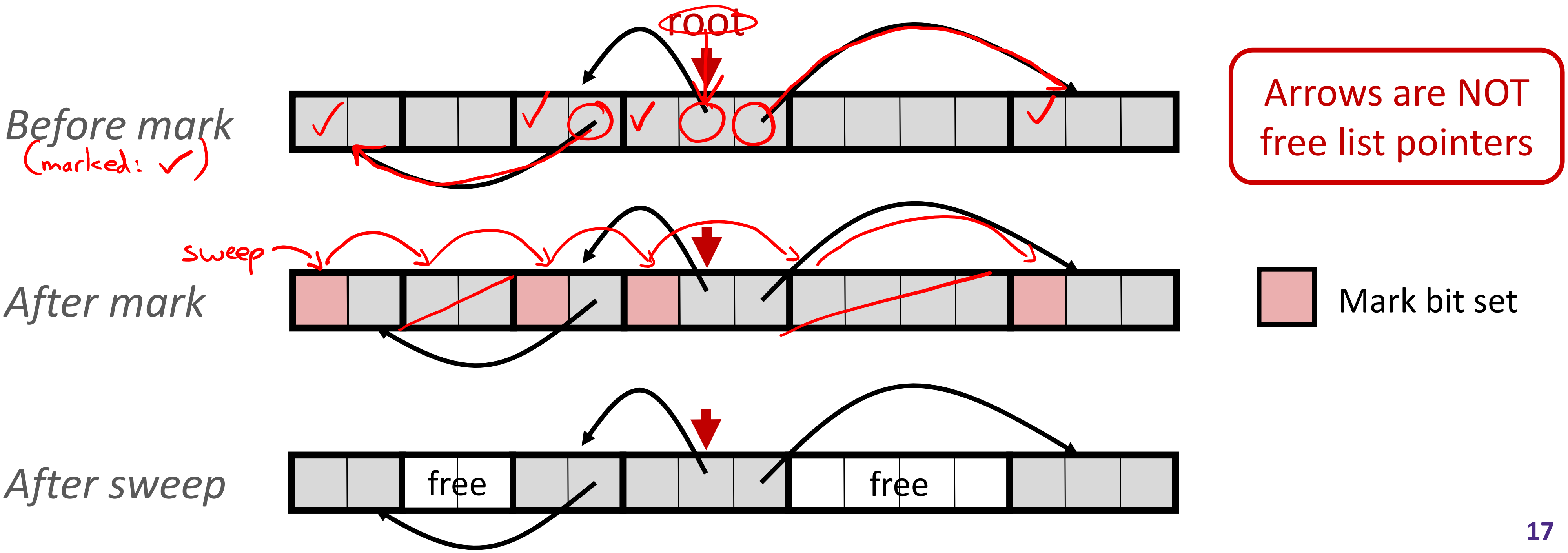
- Dynamic memory allocator can free blocks if there are no pointers to them
- How can it know what is a pointer and what is not?
- We'll make some *assumptions* about pointers:
  - Memory allocator can distinguish pointers from non-pointers ha!
  - All pointers point to the start of a block in the heap
  - Application cannot hide pointers (*e.g.* by coercing them to a `long`, and then back again)

Classical GC Algorithms

- Mark-and-sweep collection (McCarthy, 1960)
  - Does not move blocks (unless you also "compact")
- Reference counting (Collins, 1960)
  - Does not move blocks (not discussed)
- Copying collection (Minsky, 1963)
  - Moves blocks (not discussed)
- Generational Collectors (Lieberman and Hewitt, 1983)
  - Most allocations become garbage very soon, so focus reclamation work on zones of memory recently allocated.
- For more information:
  - Jones, Hosking, and Moss, *The Garbage Collection Handbook: The Art of Automatic Memory Management*, CRC Press, 2012.
  - Jones and Lin, *Garbage Collection: Algorithms for Automatic Dynamic Memory*, John Wiley & Sons, 1996.

Mark and Sweep Collecting

- Can build on top of `malloc`/`free` package
  - Allocate using `malloc` until you "run out of space"
- When out of space:
  - Use extra ***mark bit*** in the header of each block ← similar to is-allocated? bit
  - ***Mark:*** Start at roots and set mark bit on each reachable block
  - ***Sweep:*** Scan all blocks and free blocks that are not marked



Arrows are NOT free list pointers

🟥 Mark bit set

Assumptions For a Simple Implementation

Non-testable Material

- Application can use functions to allocate memory:
  - `b=new(n)` returns pointer, `b`, to new block with all locations cleared
  - `b[i]` read location `i` of block `b` into register
  - `b[i]=v` write `v` into location `i` of block `b`

- Each block will have a header word (accessed at `b[-1]`)

the magic that handles our assumptions!

- Functions used by the garbage collector:
  - `is_ptr(p)` determines whether `p` is a pointer to a block
  - `length(p)` returns length of block pointed to by `p`, not including header
  - `get_roots()` returns all the roots

Mark

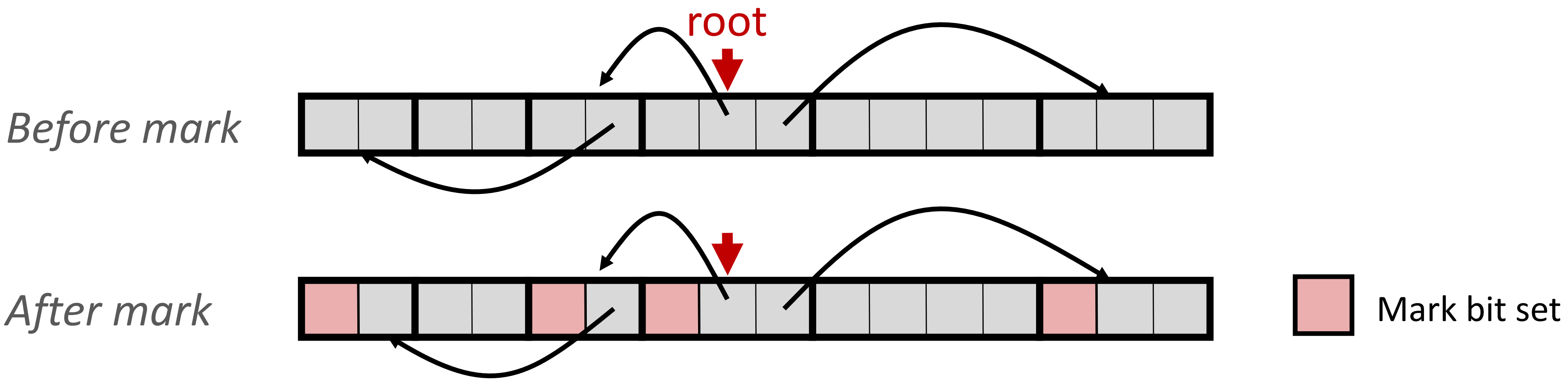
x = get_roots()
for p in x:
    mark(p)

Non-testable Material

- Mark using depth-first traversal of the memory graph

```
ptr mark(ptr p) {                    // p: some word in a heap block
   if (!is_ptr(p))     return;       // do nothing if not pointer
   if (markBitSet(p))  return;       // check if already marked
   setMarkBit(p);                    // set the mark bit
   for (i=0; i<length(p); i++)       // recursively call mark on
      mark(p[i]);                    //     all words in the block
   return;
}
```

↑ avoids graph cycles and presumably already traversed



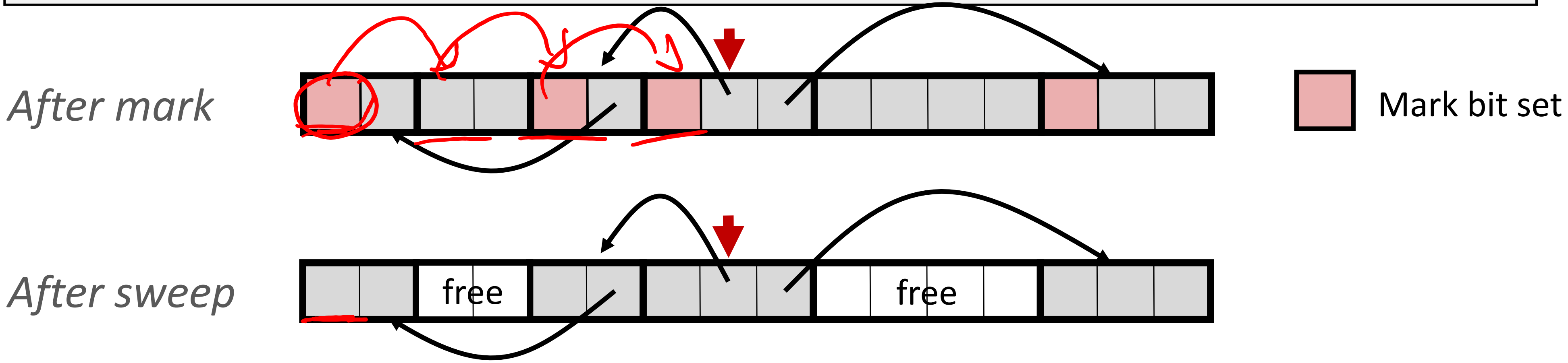
Sweep

Non-testable Material

- Sweep using sizes in headers

```
ptr sweep(ptr p, ptr end) {          // ptrs to start & end of heap
   while (p < end) {                 // while not at end of heap
      if (markBitSet(p))             // check if block is marked
         clearMarkBit(p);            // if so, reset mark bit
      else if (allocateBitSet(p))    // if not marked, but allocated
         free(p);                    // free the block
      p += length(p);                // adjust pointer to next block
   }
}
```

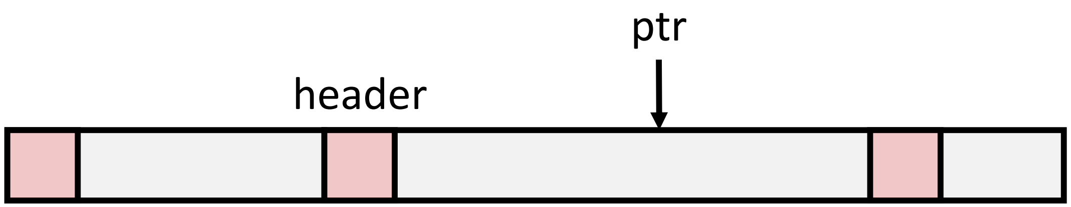
next block → p += length(p);



Conservative Mark & Sweep in C

Non-testable Material

- Would mark & sweep work in C?
  - `is_ptr` determines if a word is a pointer by checking if it points to an allocated block of memory
  - But in C, pointers can point into the middle of allocated blocks (not so in Java)
    - Makes it tricky to find all allocated blocks in mark phase



  - There are ways to solve/avoid this problem in C, but the resulting garbage collector is conservative:
    - Every reachable node correctly identified as reachable, but some unreachable nodes might be incorrectly marked as reachable
  - In Java, all pointers (*i.e.* references) point to the starting address of an object structure – the start of an allocated block

Memory-Related Perils and Pitfalls in C

		Slide	Program stop possible?	Fixes:
A)	Dereferencing a non-pointer	27	Y	scanf(..., &val)
B)	Freed block – access again	29	Y	free(x) later
C)	Freed block – free again	28	Y	free(y)
D)	Memory leak – failing to free memory	30	N	free all nodes
E)	No bounds checking	23	Y	fgets
F)	Reading uninitialized memory	26	N	calloc
G)	Referencing nonexistent variable	24	N	malloc
H)	Wrong allocation size	25	Y	sizeof (int *)

Find That Bug! (Slide 23)

```
char s[8];    // small buffer
int i;

gets(s);   /* reads "123456789" from stdin */
```

no bounds checking

buffer overflow!

Error Type: E

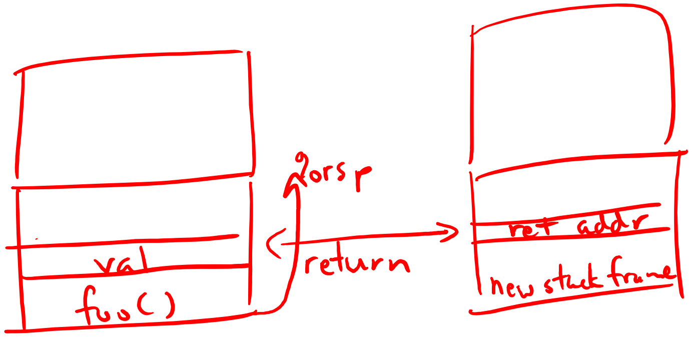
Prog stop Possible? Y

Fix: fgets(s, 8)

Find That Bug! (Slide 24)

```
int* foo() {
   int val = 0;

   return &val;
}
```

can't be in a register



referencing nonexistent variables

Error Type: G

valid address on the stack

Prog stop Possible? N

Fix: pass-by-reference to foo or use malloc instead

Find That Bug! (Slide 25)

```
int **p;

p = (int **)malloc( N * sizeof(int) );
                     ↑allocates N ints = 4*N bytes

for (int i = 0; i < N; i++) {
   p[i] = (int *)malloc( M * sizeof(int) );
}   ↑writes to N int* = 8*N bytes
```

- N and M defined elsewhere (#define)

wrong allocation size

Error Type: H

runs off end of allocated block

Prog stop Possible? Y

Fix: N * sizeof(int *)

Find That Bug! (Slide 26)

```
/* return y = Ax */
int *matvec(int **A, int *x) {
   int *y = (int *)malloc( N*sizeof(int) );
   int i, j;

   for (i = 0; i < N; i++)
      for (j = 0; j < N; j++)
         y[i] += A[i][j] * x[j];

   return y;
}
```

y[i] = y[i] + A[i][j] * x[j];

↑reads garbage!

- A is NxN matrix, x is N-sized vector (so product is vector of size N)
- N defined elsewhere (#define)

reading uninitialized memory

just using garbage values
- runs fine but get weird results

Error Type: F

Prog stop Possible? N

Fix: calloc(N, sizeof(int))

Find That Bug! (Slide 27)

- The classic `scanf` bug
  - `int scanf(const char *format)`

```
int val;
...
scanf("%d", val);
```

← reads input, parses int, stores into location val

dereferencing a non-pointer

Error Type: A

segfault if val does not contain a valid address

Prog stop Possible? Y

Fix: scanf("%d", &val);

Find That Bug! (Slide 28)

```
x = (int*)malloc( N * sizeof(int) );
   // manipulate x
free(x);

   ...

y = (int*)malloc( M * sizeof(int) );
   // manipulate y
free(x);
```

free again

undefined behavior
(some systems will segfault)

Error Type: C

Prog stop Possible? Y

Fix: free(y)

↑ probably a typo

Find That Bug! (Slide 29)

```
x = (int*)malloc( N * sizeof(int) );
   // manipulate x
free(x);

   ...

y = (int*)malloc( M * sizeof(int) );
for (i=0; i<M; i++)
   y[i] = x[i]++;
```

access freed memory

undefined behavior

Error Type: B

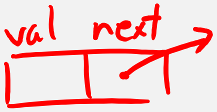
Prog stop Possible? Y

Fix: free(x) later (at bottom)

Find That Bug! (Slide 30)

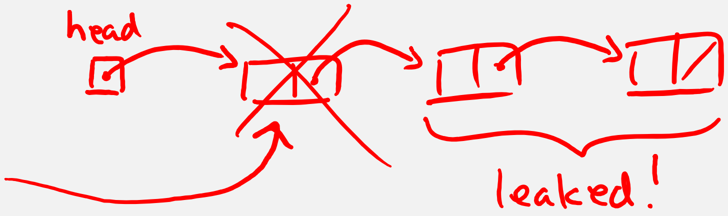
```
typedef struct L {
    int val;
    struct L *next;
} list;

void foo() {
    list *head = (list *) malloc( sizeof(list) );
    head->val = 0;
    head->next = NULL;
        // create and manipulate the rest of the list
        ...
    free(head);
    return;
}
```

node:



↑ mallocs here

↑ only frees first node!



memory leak

Error Type: D

how do you detect?

Prog stop Possible? N

Fix: recursive/iterative free over list

Dealing With Memory Bugs

Non-testable Material

- Conventional debugger (`gdb`)
  - Good for finding bad pointer dereferences
  - Hard to detect the other memory bugs
- Debugging `malloc` (UToronto CSRI `malloc`)
  - Wrapper around conventional `malloc`
  - Detects memory bugs at `malloc` and `free` boundaries
    - Memory overwrites that corrupt heap structures
    - Some instances of freeing blocks multiple times
    - Memory leaks
  - Cannot detect all memory bugs
    - Overwrites into the middle of allocated blocks
    - Freeing block twice that has been reallocated in the interim
    - Referencing freed blocks

Dealing With Memory Bugs (cont.)

Non-testable Material

- Some `malloc` implementations contain checking code
  - Linux glibc malloc: **`setenv MALLOC_CHECK_ 2`**
  - FreeBSD: **`setenv MALLOC_OPTIONS AJR`**
- Binary translator: valgrind (Linux), Purify
  - Powerful debugging and analysis technique
  - Rewrites text section of executable object file
  - Can detect all errors as debugging **`malloc`**
  - Can also check each individual reference at runtime
    - Bad pointers
    - Overwriting
    - Referencing outside of allocated block

What about Java or ML or Python or …?

Non-testable Material

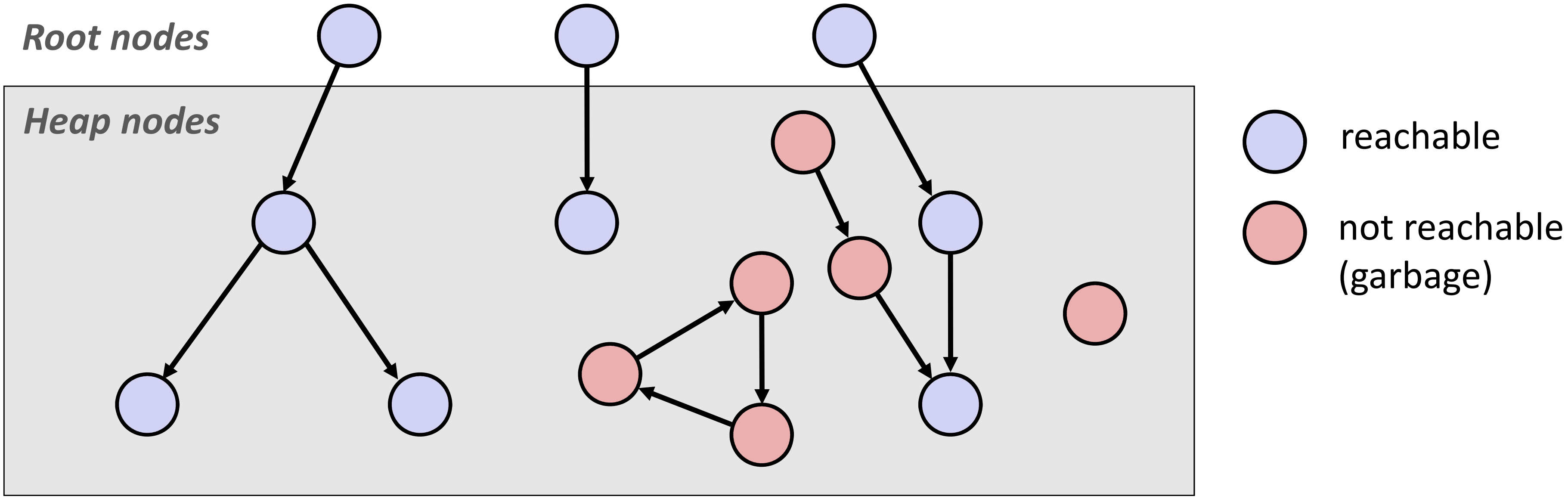
- In *memory-safe languages*, most of these bugs are impossible
  - Cannot perform arbitrary pointer manipulation
  - Cannot get around the type system
  - Array bounds checking, null pointer checking
  - Automatic memory management
- But one of the bugs we saw earlier is possible. Which one?

Memory Leaks with GC

- Not because of forgotten `free` — we have GC!
- Unneeded "leftover" roots keep objects reachable
- *Sometimes* nullifying a variable is not needed for correctness but is for performance

free(p);
p = NULL;

- Example: Don't leave big data structures you're done with in a static field


Root nodes
Heap nodes
reachable
not reachable
(garbage)