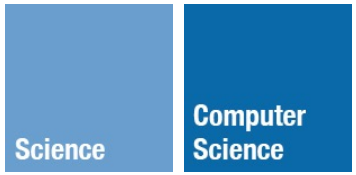
Garbage Collection



CS 351: Systems Programming

Michael Saelee <lee@iit.edu>

IIT College of Science
ILLINOIS INSTITUTE OF TECHNOLOGY

= “automatic” deallocation

i.e., malloc, but *no free*!

system must track status of *allocated* blocks

free (and potentially reuse) when *unneeded*

Two typical approaches:

1. *reference counting*
2. *tracing*

1. reference counting = maintain count of references to a given object; when refcount → 0, dealloc

(analogous to FD → OFD tracking; i.e., when 0 FDs refer to OFD, free it)

Two flavors of reference counting:

- *manual* reference counting
- *automatic* reference counting

manual/automatic pertain to who is in charge of tracking # refs (*user* vs. *runtime*)

case study: *ObjC*

refcount adjusting methods:

- `new`: create obj with refcount = 1
- `retain`: increment refcount
- `release`: decrement refcount

[note: ok to call methods on nil (no effect)]

e.g., manual reference counting (ObjC)

```
@implementation Foo {  // definition of class Foo
    Widget *_myWidget; // instance var declaration (inited to nil)
}
- (void)setWidget:(Widget *)w { // setter method
    [_myWidget release];        // no longer need old obj; refcount--
    _myWidget = [w retain];     // take ownership of new obj; refcount++
}
- (void)dealloc {               // called when Foo's refcount = 0
    [_myWidget release];        // release hold of obj in ivar; refcount--
}
@end
```

```
Widget *w = [Widget new]; // allocate Widget obj; refcount = 1
Foo *f = [Foo new];       // allocate Foo obj; refcount = 1
[f setWidget:w];          // f now (also) owns w; refcount on w = 2
[w release];              // don't need w anymore; refcount on w = 1
...

[f release];              // done with f; refcount on f = 0 (dealloc'd)
                          // refcount on w also -> 0 (dealloc'd)
```

how is this preferable to malloc/free?

much improved *granularity* of mem mgmt.

- a single free will not universally release an object (what if someone still needs it?)
- each object is responsible for its own data (instead of thinking for everyone)

and perhaps surprisingly, can also simplify mem mgmt. of nested/linked structures:

```
@implementation LinkedList {
    LLNode *_head;
}
- (void)add:(id)obj {
    LLNode *n = [LLNode new];
    [n setObj:obj];
    [n setNext:_head];
    [_head release];
    _head = n;
}

- (void)clear {
    [_head release];
    _head = nil;
}

- (void)dealloc {
    [_head release];
}
@end
```

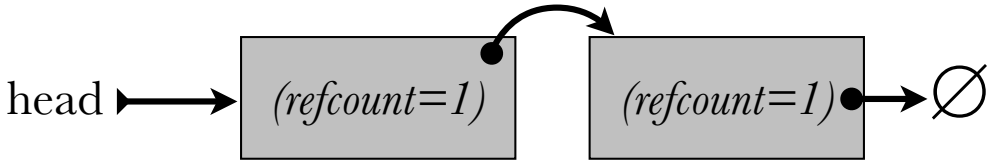
```
@implementation LLNode {
    id _obj;
    LLNode *_next;
}
- (void)setObj:(id)obj {
    [_obj release];
    _obj = [obj retain];
}

- (void)setNext:(LLNode *)next {
    [_next release];
    _next = [next retain];
}

- (void)dealloc {
    [_obj release];
    [_next release];
}
@end
```

```
@implementation LinkedList {
    LLNode *_head;
}
- (void)add:(id)obj {
    LLNode *n = [LLNode new];
    [n setObj:obj];
    [n setNext:_head];
    [_head release];
    _head = n;
}

- (void)clear {
    [_head release];
    _head = nil;
}

- (void)dealloc {
    [_head release];
}
@end
```

```
@implementation LLNode {
    id _obj;
    LLNode *_next;
}
- (void)setObj:(id)obj {
    [_obj release];
    _obj = [obj retain];
}

- (void)setNext:(LLNode *)next {
    [_next release];
    _next = [next retain];
}

- (void)dealloc {
    [_obj release];
    [_next release];
}
@end
```

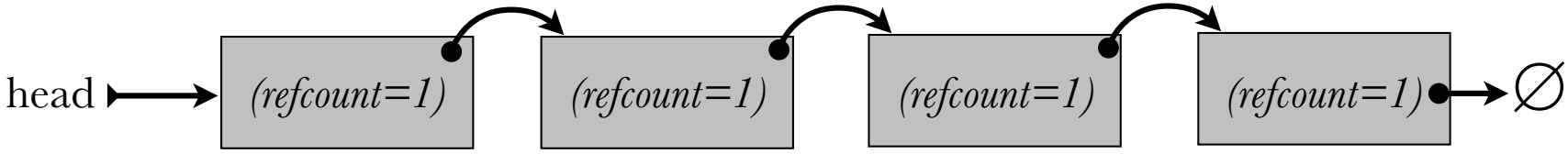
```objc
@implementation LinkedList {
    LLNode *_head;
}
- (void)add:(id)obj {
    LLNode *n = [LLNode new];
    [n setObj:obj];
    [n setNext:_head];
    [_head release];
    _head = n;
}

- (void)clear {
    [_head release];
    _head = nil;
}

- (void)dealloc {
    [_head release];
}
@end
```

```objc
@implementation LLNode {
    id _obj;
    LLNode *_next;
}
- (void)setObj:(id)obj {
    [_obj release];
    _obj = [obj retain];
}

- (void)setNext:(LLNode *)next {
    [_next release];
    _next = [next retain];
}

- (void)dealloc {
    [_obj release];
    [_next release];
}
@end
```



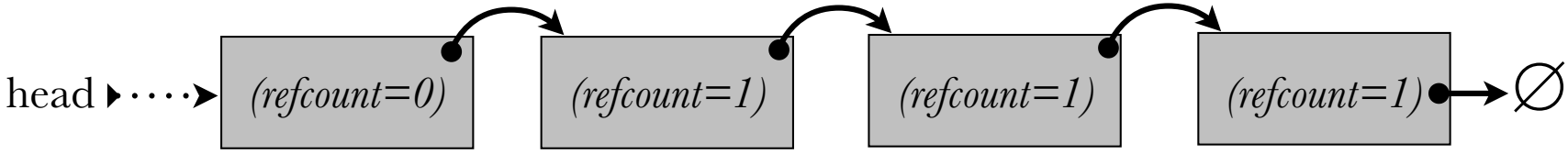
```
@implementation LinkedList {
    LLNode *_head;
}
- (void)add:(id)obj {
    LLNode *n = [LLNode new];
    [n setObj:obj];
    [n setNext:_head];
    [_head release];
    _head = n;
}

- (void)clear {
    [_head release];
    _head = nil;
}

- (void)dealloc {
    [_head release];
}
@end
```

```
@implementation LLNode {
    id _obj;
    LLNode *_next;
}
- (void)setObj:(id)obj {
    [_obj release];
    _obj = [obj retain];
}

- (void)setNext:(LLNode *)next {
    [_next release];
    _next = [next retain];
}

- (void)dealloc {
    [_obj release];
    [_next release];
}
@end
```



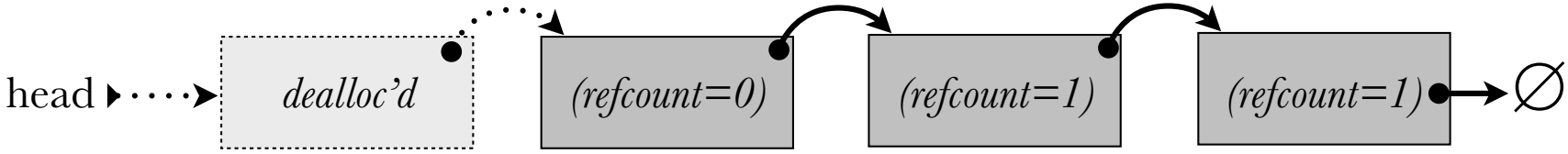
```
@implementation LinkedList {
    LLNode *_head;
}
- (void)add:(id)obj {
    LLNode *n = [LLNode new];
    [n setObj:obj];
    [n setNext:_head];
    [_head release];
    _head = n;
}

- (void)clear {
    [_head release];
    _head = nil;
}

- (void)dealloc {
    [_head release];
}
@end
```

```
@implementation LLNode {
    id _obj;
    LLNode *_next;
}
- (void)setObj:(id)obj {
    [_obj release];
    _obj = [obj retain];
}

- (void)setNext:(LLNode *)next {
    [_next release];
    _next = [next retain];
}

- (void)dealloc {
    [_obj release];
    [_next release];
}
@end
```



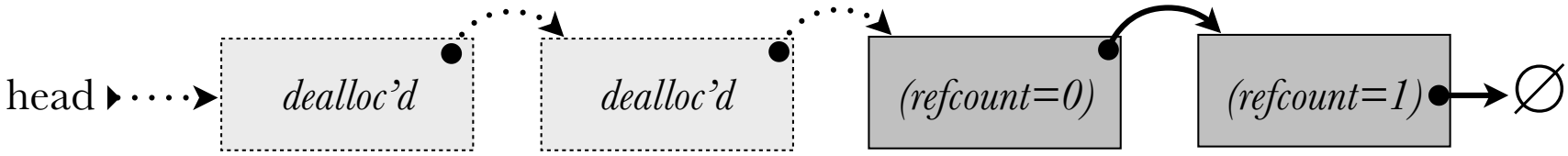
```
@implementation LinkedList {
    LLNode *_head;
}
- (void)add:(id)obj {
    LLNode *n = [LLNode new];
    [n setObj:obj];
    [n setNext:_head];
    [_head release];
    _head = n;
}

- (void)clear {
    [_head release];
    _head = nil;
}

- (void)dealloc {
    [_head release];
}
@end
```

```
@implementation LLNode {
    id _obj;
    LLNode *_next;
}
- (void)setObj:(id)obj {
    [_obj release];
    _obj = [obj retain];
}

- (void)setNext:(LLNode *)next {
    [_next release];
    _next = [next retain];
}

- (void)dealloc {
    [_obj release];
    [_next release];
}
@end
```



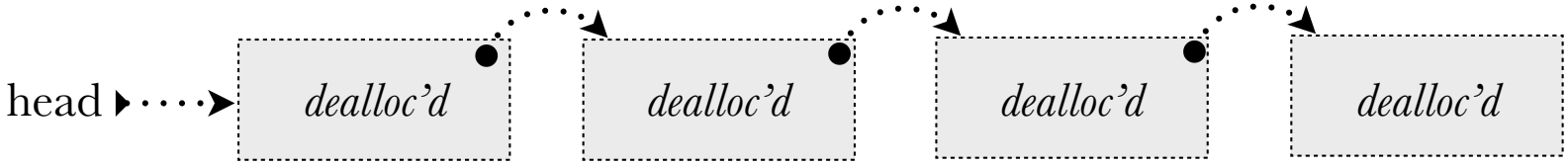
```objc
@implementation LinkedList {
    LLNode *_head;
}
- (void)add:(id)obj {
    LLNode *n = [LLNode new];
    [n setObj:obj];
    [n setNext:_head];
    [_head release];
    _head = n;
}

- (void)clear {
    [_head release];
    _head = nil;
}

- (void)dealloc {
    [_head release];
}
@end
```

```objc
@implementation LLNode {
    id _obj;
    LLNode *_next;
}
- (void)setObj:(id)obj {
    [_obj release];
    _obj = [obj retain];
}

- (void)setNext:(LLNode *)next {
    [_next release];
    _next = [next retain];
}

- (void)dealloc {
    [_obj release];
    [_next release];
}
@end
```

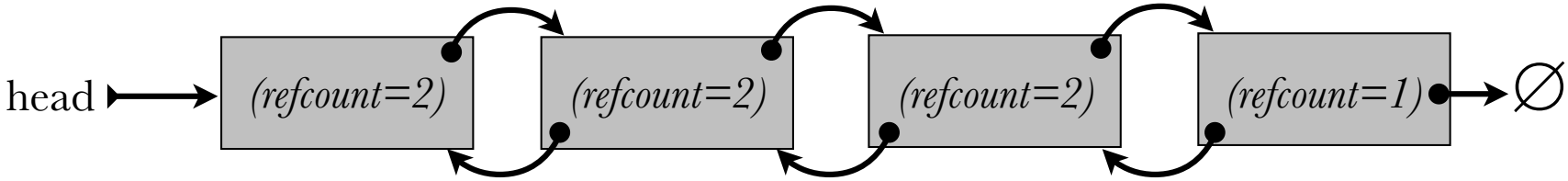


```objc
@implementation LinkedList {
    LLNode *_head;
}
- (void)add:(id)obj {
    LLNode *n = [LLNode new];
    [n setObj:obj];
    [n setNext:_head];
    [_head release];
    _head = n;
}

- (void)clear {
    [_head release];
    _head = nil;
}

- (void)dealloc {
    [_head release];
}
@end
```

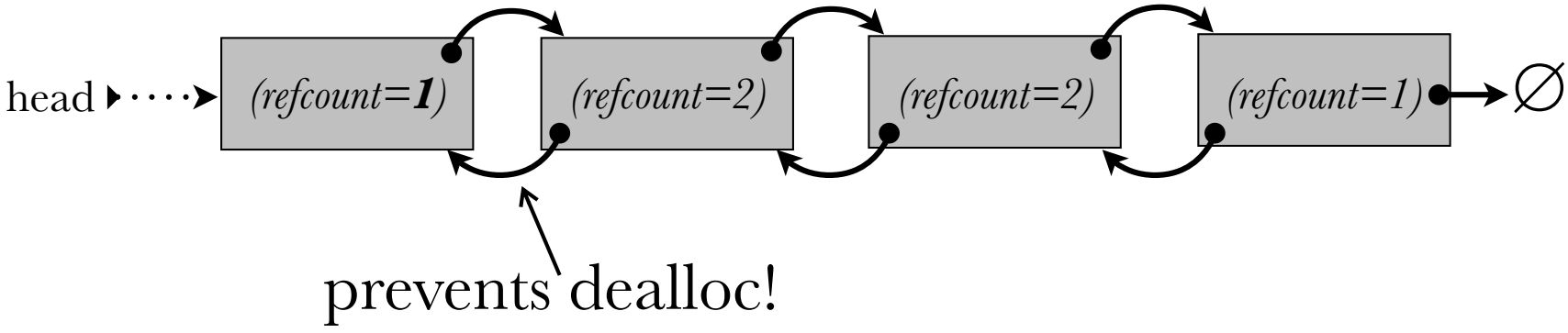
```objc
@implementation LLNode {
    id _obj;
    LLNode *_next;
}
- (void)setObj:(id)obj {
    [_obj release];
    _obj = [obj retain];
}

- (void)setNext:(LLNode *)next {
    [_next release];
    _next = [next retain];
}

- (void)dealloc {
    [_obj release];
    [_next release];
}
@end
```



but, a catch: beware *circular* references!



but, a catch: beware *circular* references!



typically establish conventions for non-retaining references; aka. *weak* references

e.g., list:prior & tree:child links

rules for ref-counting are quite simple:

- for “strong” pointers, on assignment must release old obj & retain new one
  - also release if pointer goes out of scope
- for “weak” pointers, never retain; obj refcount is unaffected

automatic reference counting requires that we designate strong & weak pointers

- retains & releases are automatic
- dealloc on refcount = 0 is automatic

```
@implementation LLNode {
    __strong id _obj;
    __strong LLNode *_next;
}
@end

@implementation LinkedList {
    __strong LLNode *_head;
}
- (void)add:(id)obj {
    LLNode *node = [LLNode new];
    node.obj  = obj;    // obj is retained by node
    node.next = _head;  // _head is retained by node
    _head     = node;   // node is retained; old _head value is released
}

- (void)clear {
    _head = nil; // releases (previous) _head, causing chain of deallocs
}
@end
```

```
@implementation LLNode {
    __strong id _obj;
    __strong LLNode *_next;
    __weak LLNode *_prior; // note weak pointer; will not auto-retain
}
@end

@implementation LinkedList {
    __strong LLNode *_head;
}
- (void)add:(id)obj { // creates a circular doubly-linked list
    LLNode *node = [LLNode new];
    node.obj  = obj;
    if (_head == nil) {
        node.next = node.prior = node; // only next retains (not prior)
        _head = node;
    } else {
        node.next = _head;
        node.prior = _head.prior;
        _head.prior.next = _head.prior = node;
        _head = node;
    }
}

- (void)clear {
    _head.prior.next = nil; // take care that head is not in retain cycle
    _head = nil;            // so that this deallocs list (prior refs ok)
}
@end
```

important: ref-counting provides *predictable* deallocation — i.e., when refcount → 0 for an obj, it *will* be deallocated

(contrast this with the next approach)

2. *tracing* = periodically determine what memory has become *unreachable*, and deallocate it

general approach:

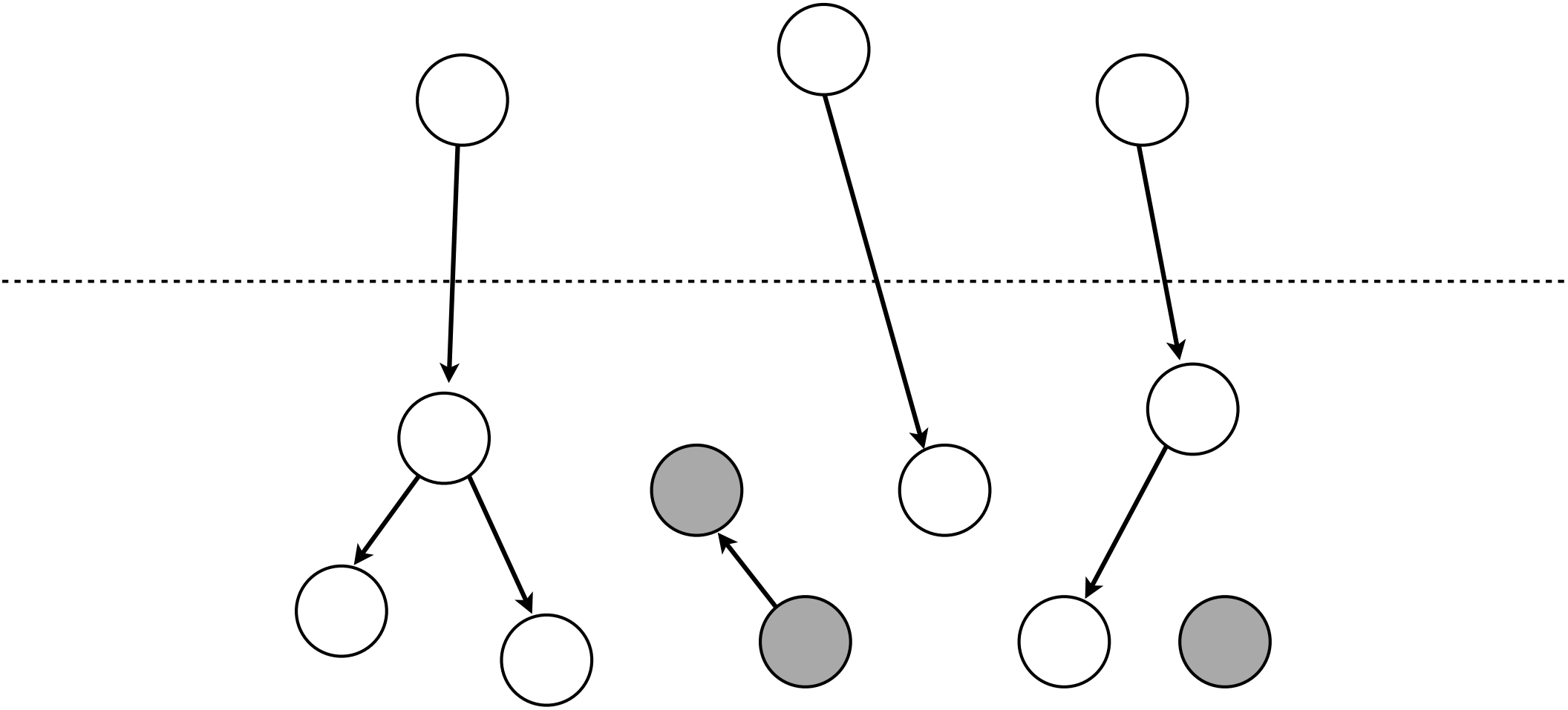
- treat memory as a *graph*
- identify *root nodes / pointers*
- (recursively) find all *reachable* memory

root nodes?

- pointers in static memory
- pointers in active stack frames

Static & Local

"Root" space



Heap space

simple algorithm: “mark & sweep”

1. mark all reachable blocks in heap
2. find all allocated, non-reachable blocks in heap & free (sweep) them; also unmark all blocks traversed

```
#define IS_ALLOCATED(p) (*(size_t *)(p) & 1)   // bit 0 = allocated?
#define IS_MARKED(p)    (*(size_t *)(p) & 2)   // bit 1 = marked?
#define BLK_SIZE(p)     (*(size_t *)(p) & ~3L)

void sweep () {
    char *bp = heap_start();
    while (bp < heap_end()) {
        if (IS_MARKED(bp))
            *bp &= ~2L; // clear out mark bit
        else if (IS_ALLOCATED(bp))
            free(bp + SIZE_T_SIZE); // free unmarked, allocated block
        bp += BLK_SIZE(bp);
    }
}

void mark(void *p) {
    char *bp = find_block_header(p); // expensive, but doable (how?)
    if (bp == NULL || !IS_ALLOCATED(bp) || IS_MARKED(bp)) {
        return;
    }
    *(size_t *)bp |= 2; // mark block

    // next, must recurse and mark all blocks reachable from this one

}
```

```
#define IS_ALLOCATED(p) (*(size_t *)(p) & 1)   // bit 0 = allocated?
#define IS_MARKED(p)    (*(size_t *)(p) & 2)   // bit 1 = marked?
#define BLK_SIZE(p)     (*(size_t *)(p) & ~3L)

void sweep () {
    char *bp = heap_start();
    while (bp < heap_end()) {
        if (IS_MARKED(bp))
            *bp &= ~2L; // clear out mark bit
        else if (IS_ALLOCATED(bp))
            free(bp + SIZE_T_SIZE); // free unmarked, allocated block
        bp += BLK_SIZE(bp);
    }
}

void mark(void *p) {
    char *bp = find_block_header(p); // expensive, but doable (how?)
    if (bp == NULL || !IS_ALLOCATED(bp) || IS_MARKED(bp)) {
        return;
    }
    *(size_t *)bp |= 2; // mark block
    for (int i=SIZE_T_SIZE; i<=BLK_SIZE(bp)-sizeof(void *); i++) {
        mark(*(void **)(bp + i)); // all words in payload can be pointers!
    }
}
```

```
for (int i=SIZE_T_SIZE; i<=BLK_SIZE(bp)-sizeof(void *); i++) {
    mark(*(void **)(bp + i)); // all words in payload can be pointers!
}
```

need to do this because the user can store a pointer just about *anywhere* using C

- but may encounter a lot of *false positives*
  - i.e., not a real pointer, but results in an allocated block being marked

this is a *conservative* GC implementation

```
for (int i=SIZE_T_SIZE; i<=BLK_SIZE(bp)-sizeof(void *); i++) {
    mark(*(void **)(bp + i)); // all words in payload can be pointers!
}
```

note: this may still not be good enough!

… if the user chooses to *derive* pointer values (e.g., via arithmetic)

GC typically needs to be able to make some assumptions for efficiency

in a system with *run time type information*,
can reliably detect if a value is a pointer

enables *precise* garbage collection

(moving onto other issues)

typically want GC to run periodically in the background so that memory is freed without interrupting the user program

but may lead to concurrent access of heap data structures …

```
void sweep () {
    char *bp = heap_start();
    while (bp < heap_end()) {
        if (IS_MARKED(bp))
            *bp &= ~2L; // clear out mark bit
        else if (IS_ALLOCATED(bp))
            free(bp + SIZE_T_SIZE); // free unmarked, allocated block
        bp += BLK_SIZE(bp);
    }
}
```

and, if unlucky, race conditions! (e.g., what if free leads to coalescing of block currently being allocated?)

also, in mark & sweep, manipulating the heap during a GC cycle *invalidates* marks

mark & sweep requires that the heap be *frozen* while being carried out

aka “stop-the-world” GC

horrible performance implications!

other algorithms permit *on-the-fly* marking

e.g., *tri-color* marking

partition allocated blocks into 3 sets:

- white: unscanned
- black: reachable nodes that don't refer to white nodes
- grey: reachable nodes (but may refer to black/white nodes)

at outset:

- directly reachable blocks are grey
- all other nodes are white

periodically:

- scan all children of a grey object (making them black)
- move white blocks found to grey set

i.e., always white → grey → black

when grey set is empty; i.e., when we've scanned all reachable blocks, free any remaining white blocks

many other *heuristics* exist to optimize GC

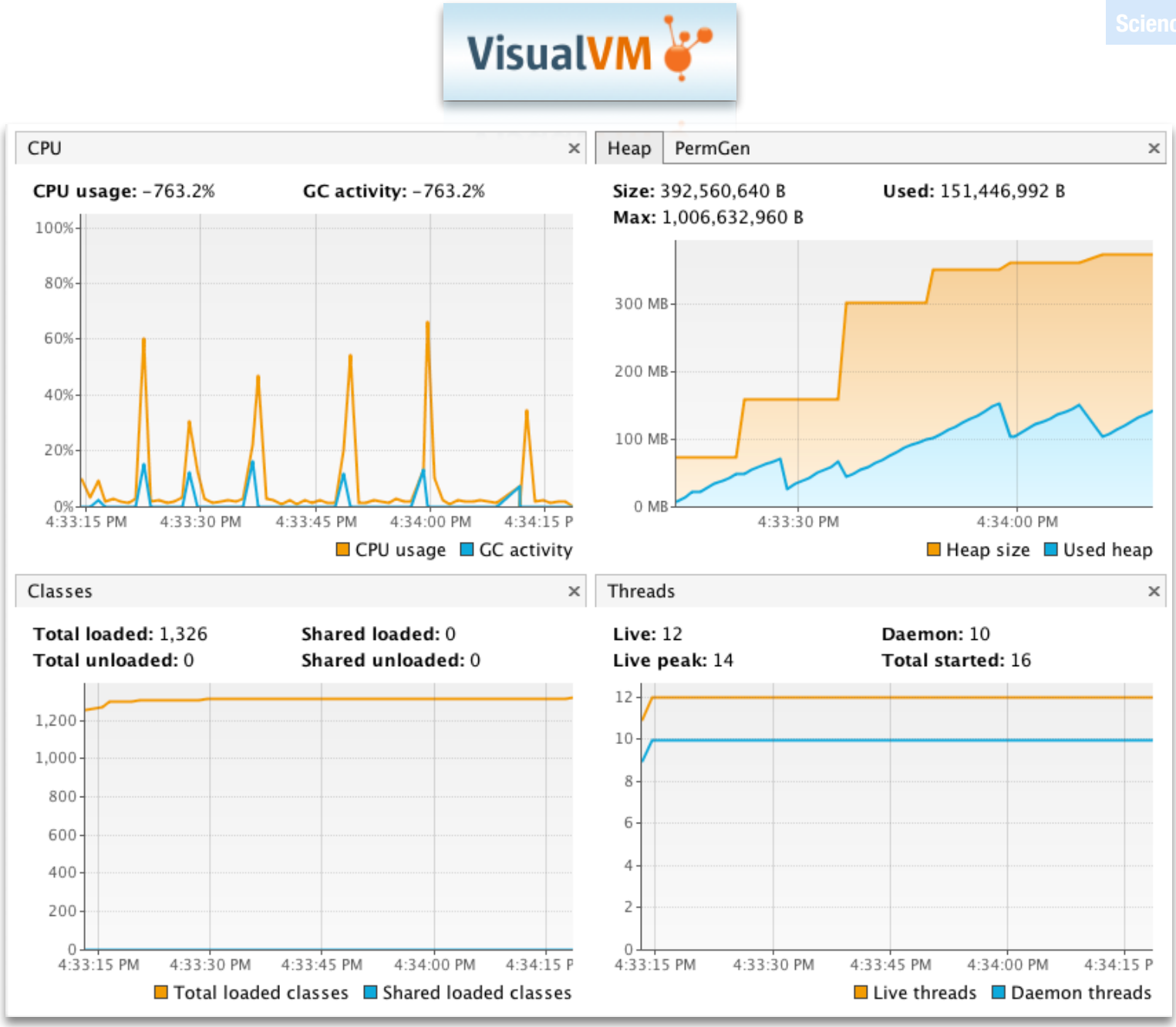
- *generational* GCs classify blocks by age and prioritize searching recent ones
- *copying* GCs allow for memory compaction (require opaque pointers)

but question remains: *when* & *how frequently* to perform G.C.?

- invariably incurs overhead
- worse, results in *unpredictable* performance!

Demo: Java GC behavior

```
// Test bench for GC
public class TestGCThread extends Thread {
    public void run(){
        while(true){
            try {
                int delay = (int)Math.round(100 * Math.random());
                Thread.sleep(delay); // random sleep
            } catch(InterruptedException e){ }

            // create random number of objects
            int count = (int)Math.round(10000 * Math.random());
            for (int i=0; i < count; i++){
                new TestObject(); // immediately unreachable!
            }
        }
    }

    public static void main(String[] args){
        new TestGCThread().start();
    }
}

class TestObject {
    static long alloced = 0;
    static long freed   = 0;
    public TestObject () { alloced++; }
    public void finalize () { freed++; }
}
```


VisualVM
CPU
CPU usage: -763.2%
GC activity: -763.2%
100%
80%
60%
40%
20%
0%
4:33:15 PM
4:33:30 PM
4:33:45 PM
4:34:00 PM
4:34:15 P
CPU usage
GC activity
Heap
PermGen
Size: 392,560,640 B
Used: 151,446,992 B
Max: 1,006,632,960 B
300 MB
200 MB
100 MB
0 MB
4:33:30 PM
4:34:00 PM
Heap size
Used heap
Classes
Total loaded: 1,326
Shared loaded: 0
Total unloaded: 0
Shared unloaded: 0
1,200
1,000
800
600
400
200
0
4:33:15 PM
4:33:30 PM
4:33:45 PM
4:34:00 PM
4:34:15 P
Total loaded classes
Shared loaded classes
Threads
Live: 12
Daemon: 10
Live peak: 14
Total started: 16
12
10
8
6
4
2
0
4:33:15 PM
4:33:30 PM
4:33:45 PM
4:34:00 PM
4:34:15 P
Live threads
Daemon threads