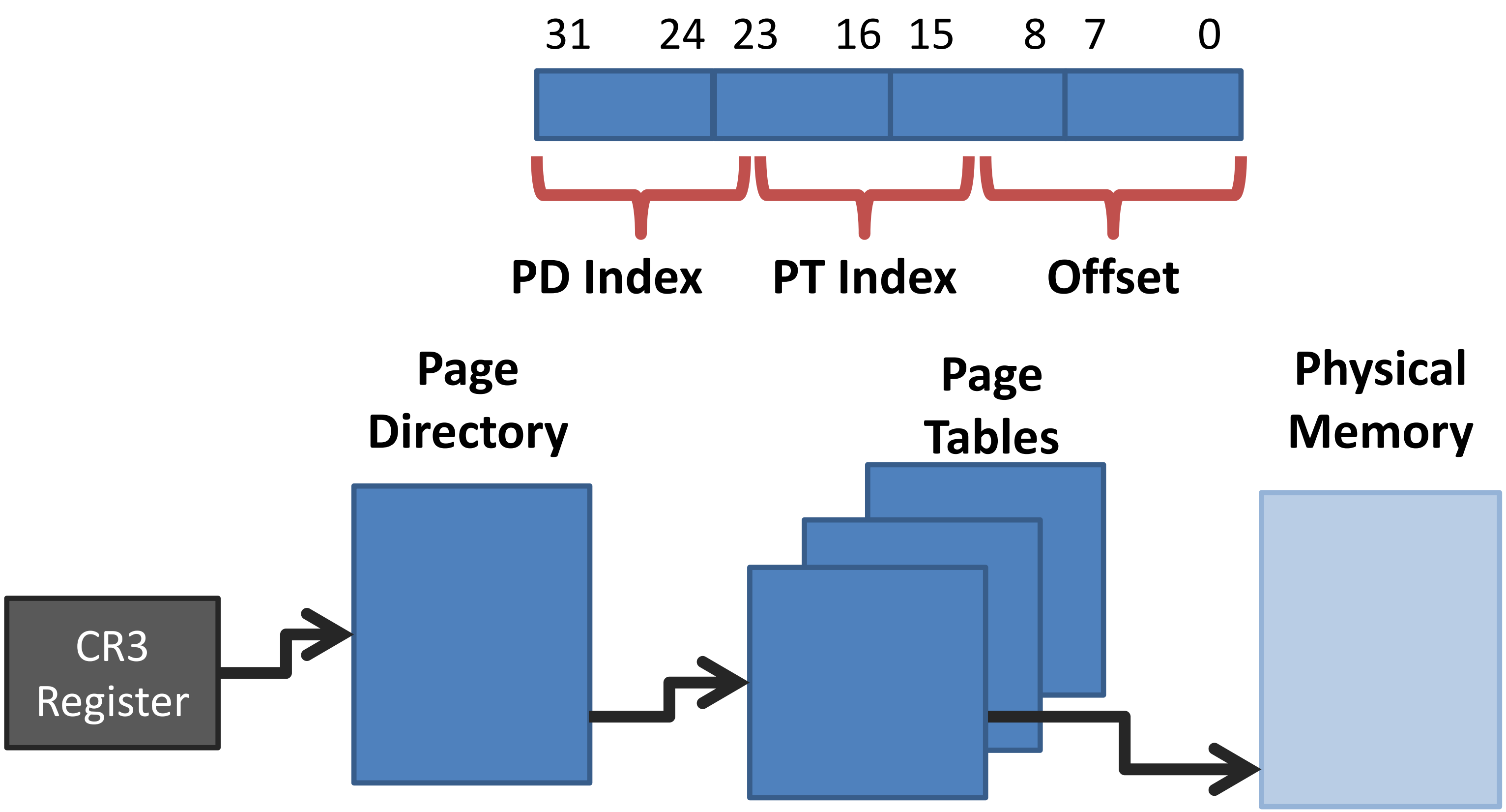
CS 5600
Computer Systems

Lecture 8: Free Memory Management

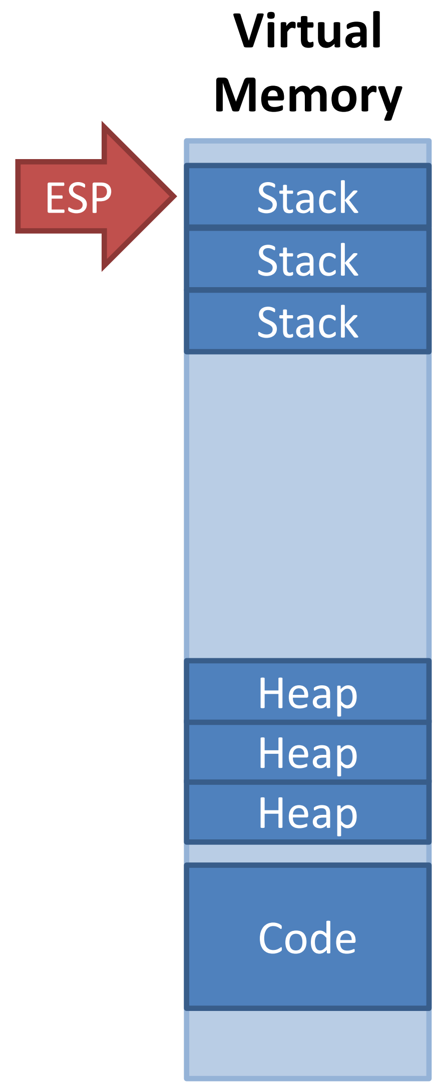
Recap of Last Week

- Last week focused on virtual memory
  - Gives each process the illusion of vast, empty memory
  - Offers protection and isolation



Dynamic Allocation of Pages

- Page tables allow the OS to dynamically assign physical frames to processes on-demand
  - E.g. if the stack grows, the OS can map in an additional page
- On Linux, processes use sbrk()/brk()/mmap() to request additional heap pages
  - But, these syscalls only allocates memory in multiples of 4KB pages



What About malloc() and free()?

- The OS only allocates and frees memory in units of 4KB pages
  - What if you want to allocate <4KB of memory?
  - E.g. char * string = (char *) malloc(100);
- Each process manages its own heap memory
  - On Linux, glibc implements *malloc()* and *free()*, manages objects on the heap
  - The JVM uses a garbage collector to manage the heap
- There are many different strategies for managing free memory

Free Space Management

- Todays topic: how do processes manage free memory?
  1. Explicit memory management
     - Languages like C, C++; programmers control memory allocation and deallocation
  2. Implicit memory management
     - Languages like Java, Javascript, Python; runtime takes care of freeing useless objects from memory
- In both cases, software must keep track of the memory that is in use or available

Why Should You Care?

- Regardless of language, all of our code uses dynamic memory
- However, there is a performance cost associated with using dynamic memory
- Understanding how the heap is managed leads to:
  - More performant applications
  - The ability to diagnose difficult memory related errors and performance bottlenecks

Key Challenges

- Maximizing CPU performance
  – Keeping track of memory usage requires effort
- Maximize parallelism
  – Heap memory is shared across threads
  – Thus, synchronization may be necessary
- Minimizing memory overhead
  – Metadata is needed to track memory usage
  – This metadata adds to the size of each object
- Minimize fragmentation
  – Over time, deallocations create useless gaps in memory

- Free Lists
  – Basics
  – Speeding Up *malloc()* and *free()*
  – Slab Allocation
  – Common Bugs
- Garbage Collectors
  – Reference Counting
  – Mark and Sweep
  – Generational/Ephemeral GC
  – Parallel Garbage Collection

Setting the Stage

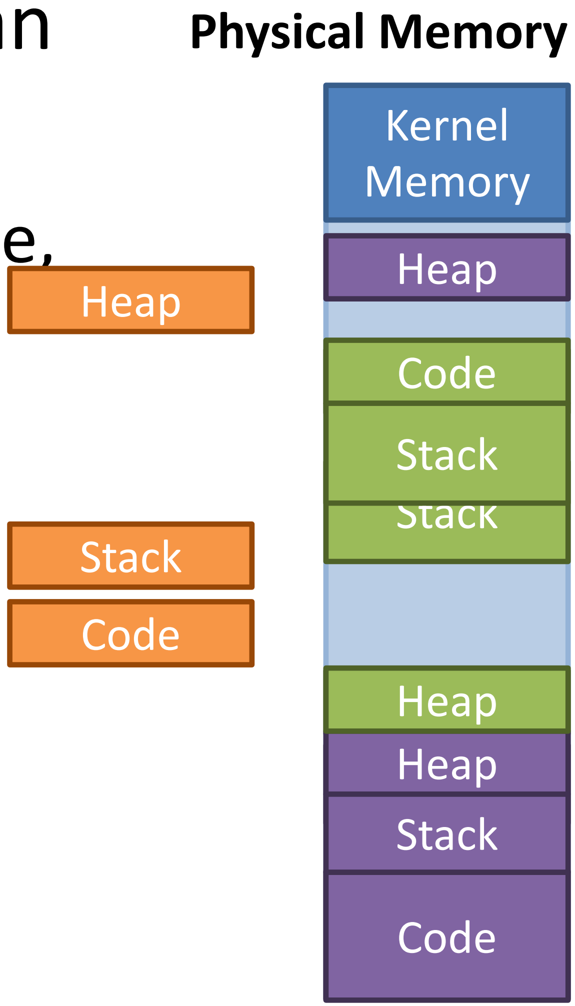
- Many languages allow programmers to explicitly allocate and deallocate memory
  - C, C++
  - *malloc()* and *free()*
- Programmers can *malloc()* any size of memory
  - Not limited to 4KB pages
- *free()* takes a pointer, but not a size
  - How does *free()* know how many bytes to deallocate?
- Pointers to allocated memory are returned to the programmer
  - As opposed to Java or C# where pointers are “managed”
  - Code may modify these pointers

Requirements and Goals

- Keep track of memory usage
  - What bytes of the heap are currently allocated/unallocated?
- Store the size of each allocation
  - So that *free()* will work with just a pointer
- Minimize fragmentation…
  - … without doing compaction or relocation
  - More on this later
- Maintain higher performance
  - O(1) operations are obviously faster than O(n), etc.

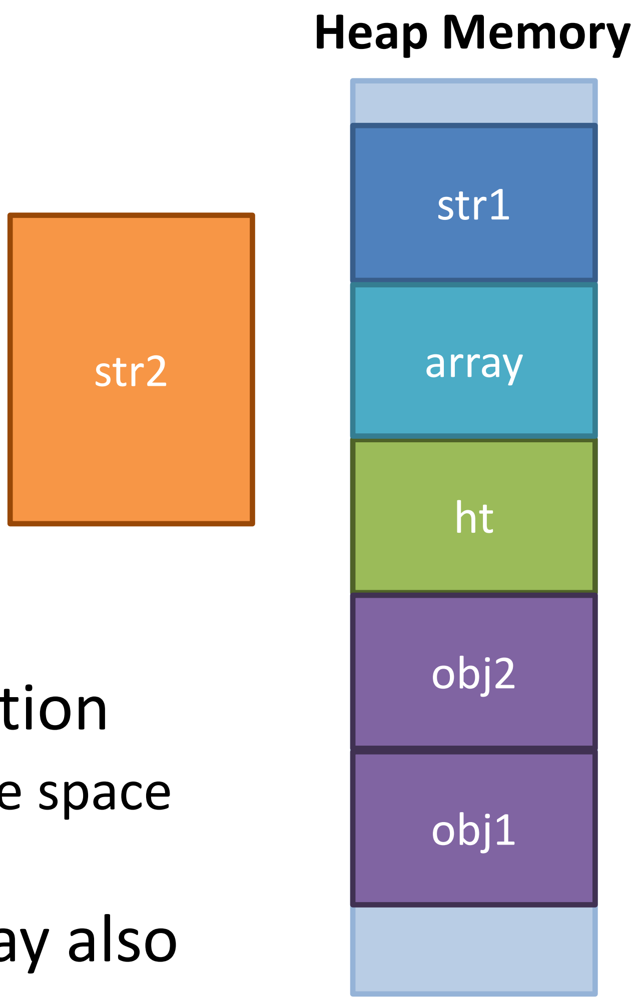
External Fragmentation, Revisited

- Problem: variable size segments can lead to external fragmentation
  - Memory gets broken into random size, non-contiguous pieces
- Example: there is enough free memory to start a new process
  - But the memory is fragmented :(
- Compaction can fix the problem
  - But it is extremely expensive



Heap Fragmentation

```
obj * obj1, * obj2;
hash_tbl * ht;
int array[];
char * str1, * str2;
…
free(obj2);
free(array);
…
str2 = (char *) malloc(300);
```



- This is an example of **external** fragmentation
  - There is enough empty space for str2, but the space isn’t usable
- As we will see, internal fragmentation may also be an issue

The Free List

- A free list is a simple data structure for managing heap memory
- Three key components
  1. A $\boxed{\text{linked-list}}$ that records free regions of memory
     - Free regions get split when memory is allocated
     - Free list is kept in sorted order by memory address
  2. Each allocated block of memory has a header that records the size of the block
  3. An algorithm that selects which free region of memory to use for each allocation request

Free List Data Structures

- The free list is a linked list
- Stored in heap memory, alongside other data
- For *malloc(n)*:

  num_bytes = *n* + sizeof(header)

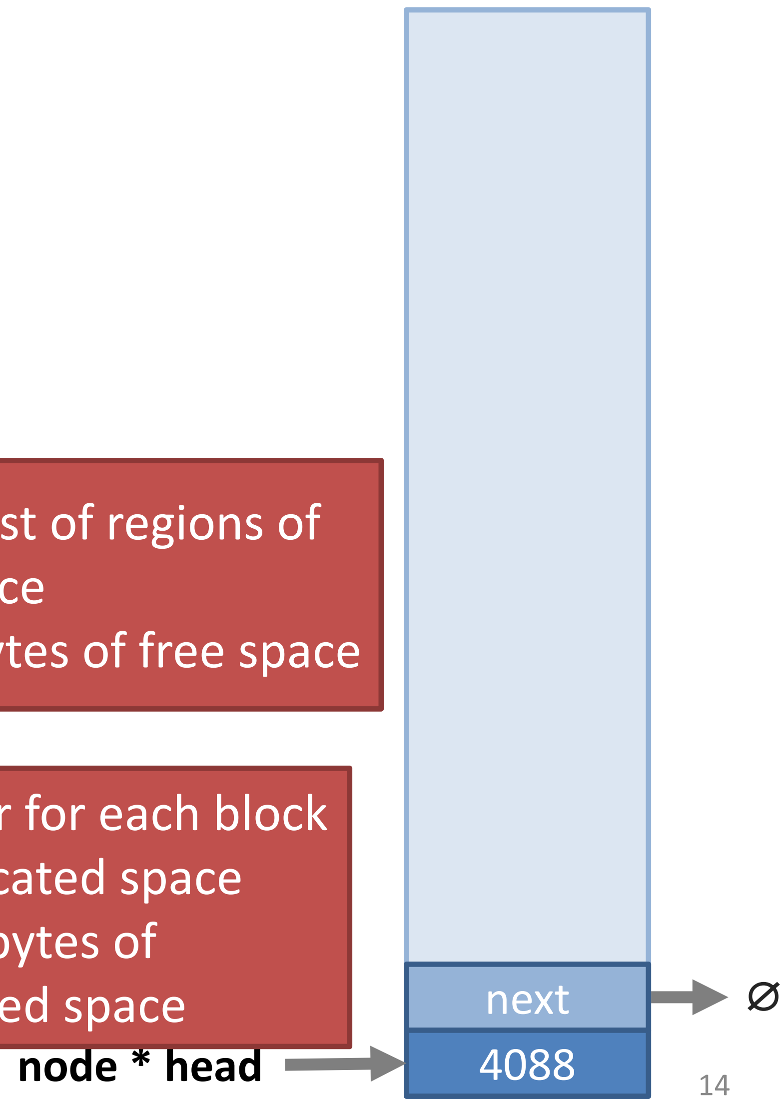
```
typedef struct node_t {
    int size;
    struct node_t * next;
} node;
```

- Linked list of regions of free space
- size = bytes of free space

```
typedef struct header_t {
    int size;
} header;
```

- Header for each block of allocated space
- size = bytes of allocated space

Heap Memory (4KB)



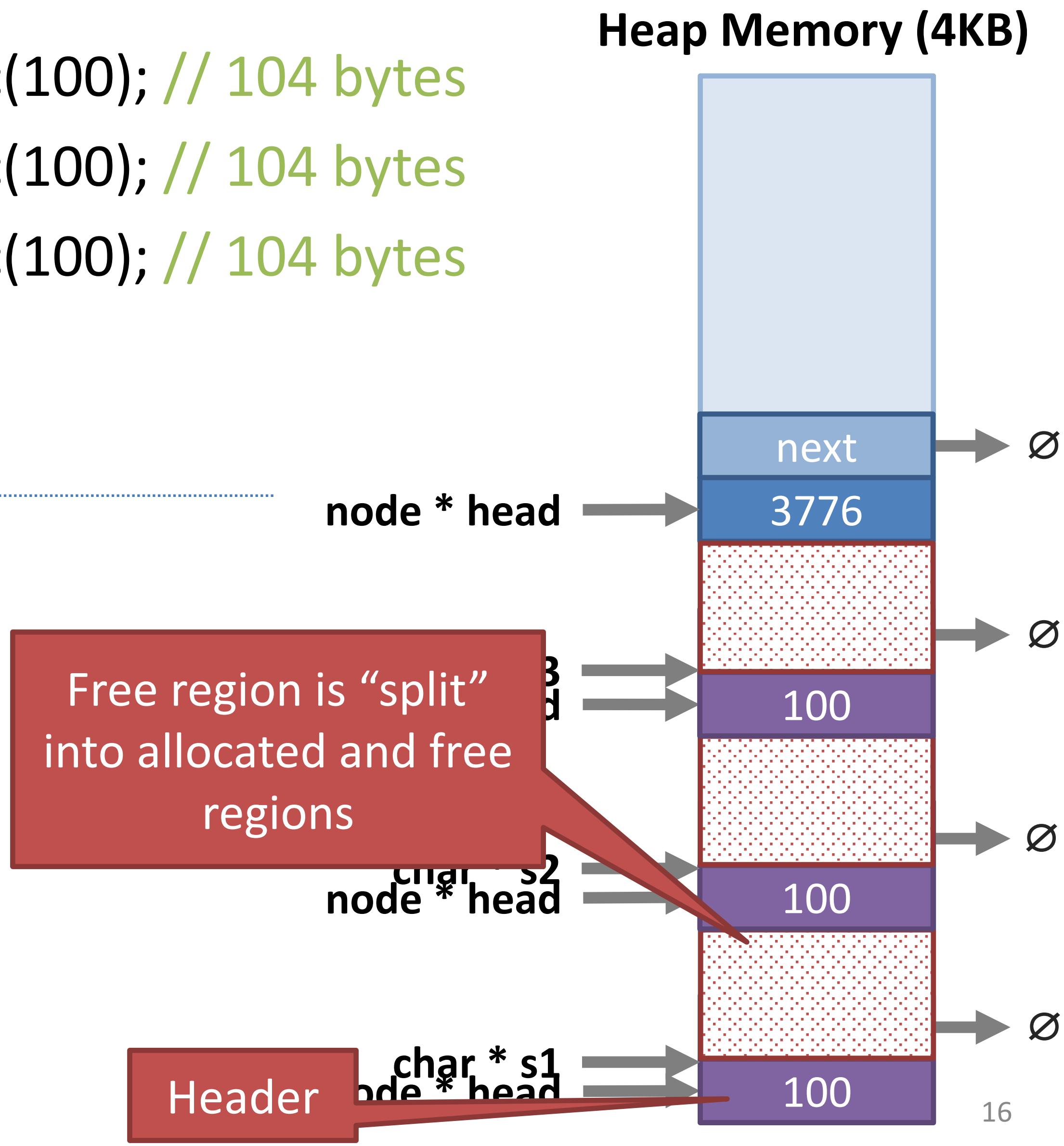
Code to Initialize a Heap

```
// mmap() returns a pointer to a chunk of free space
node * head = mmap(NULL, 4096,
        PROT_READ|PROT_WRITE,
        MAP_ANON|MAP_PRIVATE, -1, 0);
head->size = 4096 – sizeof(node);
head->next = NULL;
```

Allocating Memory (Splitting)

```
char * s1 = (char *) malloc(100); // 104 bytes
char * s2 = (char *) malloc(100); // 104 bytes
char * s3 = (char *) malloc(100); // 104 bytes
```

```
typedef struct node_t {
    int size;
    struct node_t * next;
} node;

typedef struct header_t {
    int size;
} header;
```



Freeing Memory

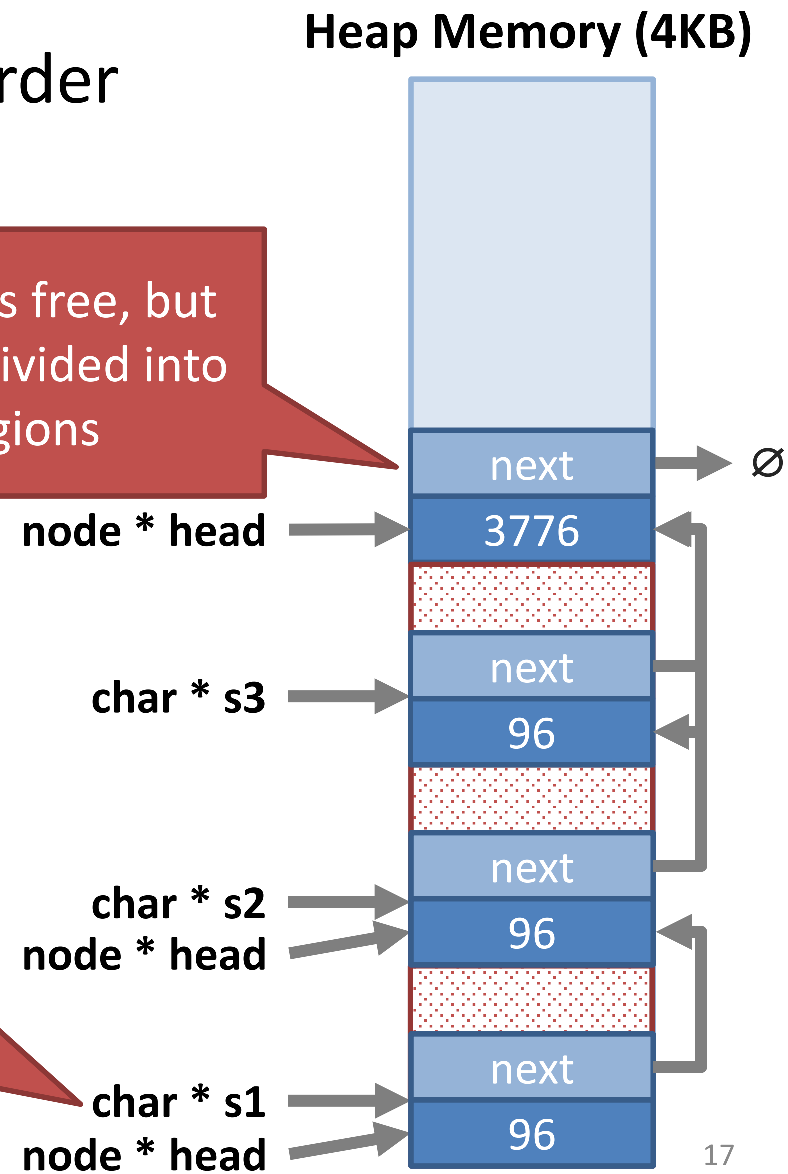
- The free list is kept in sorted order
  - free() is an O(n) operation

```
free(s2); // returns 100 +
free(s1); // returns 100 +
free(s3); // returns 100 +
```

All memory is free, but the free list divided into four regions

```
typedef struct node_t {
    int size;
    struct node_t * next;
} node;

typedef struc
    int size;
} header;
```

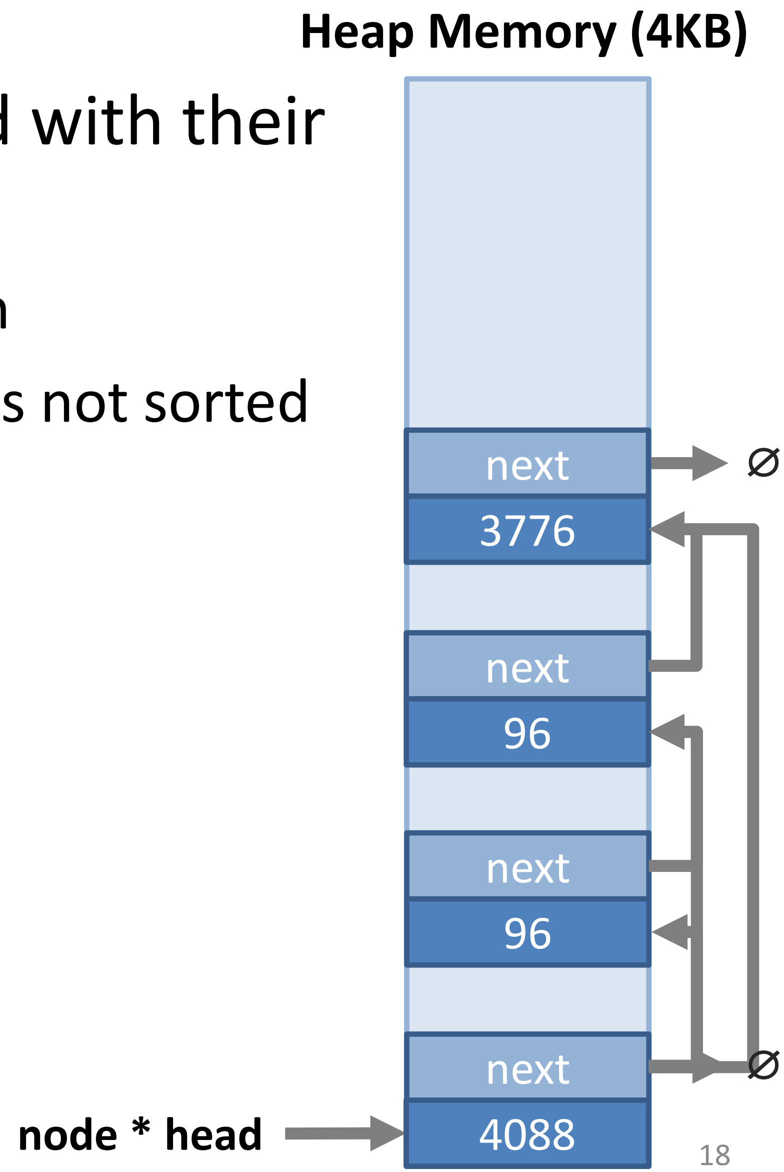
These pointers are “dangling”: they still point to heap memory, but the pointers are invalid



Coalescing

- Free regions should be merged with their neighbors
  - Helps to minimize fragmentation
  - This would be $O(n^2)$ if the list was not sorted

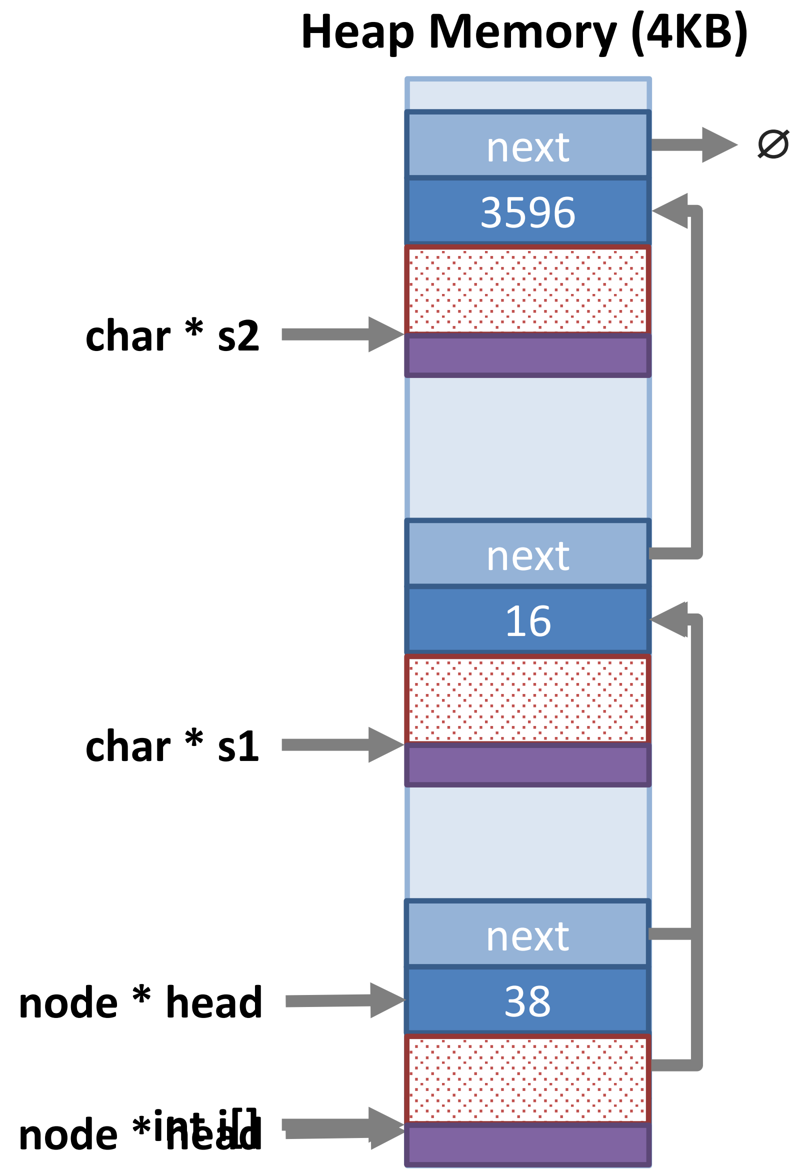
```
typedef struct node_t {
    int size;
    struct node_t * next;
} node;

typedef struct header_t {
    int size;
} header;
```



Choosing Free Regions (1)

```
int i[] = (int*) malloc(8);
// 8 + 4 = 12 total bytes
```

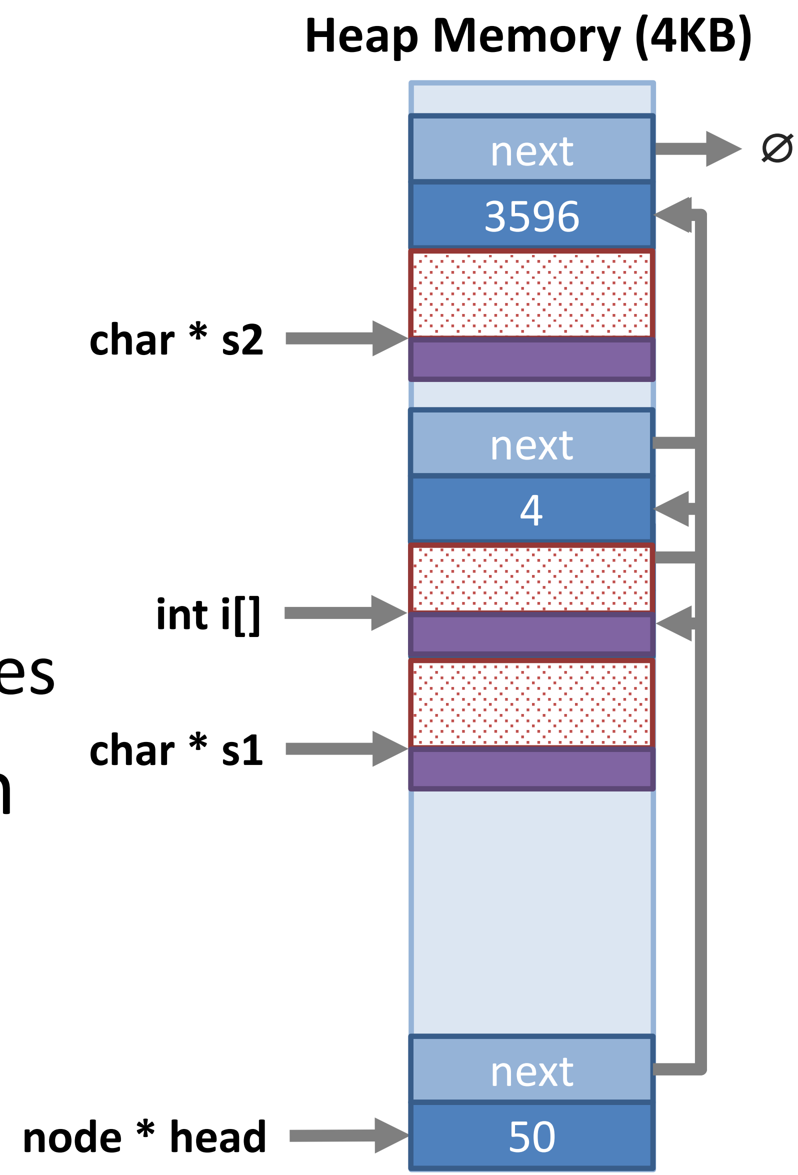
- Which free region should be chosen?
- Fastest option is **First-Fit**
  - Split the first free region with >=8 bytes available
- Problem with First-Fit?
  - Leads to external fragmentation



Choosing Free Regions (2)

```
int i[] = (int*) malloc(8);
// 8 + 4 = 12 total bytes
```

- Second option: **Best-Fit**
  - Locate the free region with size closest to (and >=) 8 bytes
- Less external fragmentation than First-fit
- Problem with Best-Fit?
  - Requires O(n) time



Basic Free List Review

- Singly-linked free list
- List is kept in sorted order
  - *free()* is an O(n) operation
  - Adjacent free regions are coalesced
- Various strategies for selecting which free region to use for a given *malloc(n)*
  - First-fit: use the first free region with >=*n* bytes available
    - Worst-case is O(n), but typically much faster
    - Tends to lead to external fragmentation at the head of the list
  - Best-fit: use the region with size closest (and >=) to *n*
    - Less external fragments than first-fit, but O(n) time

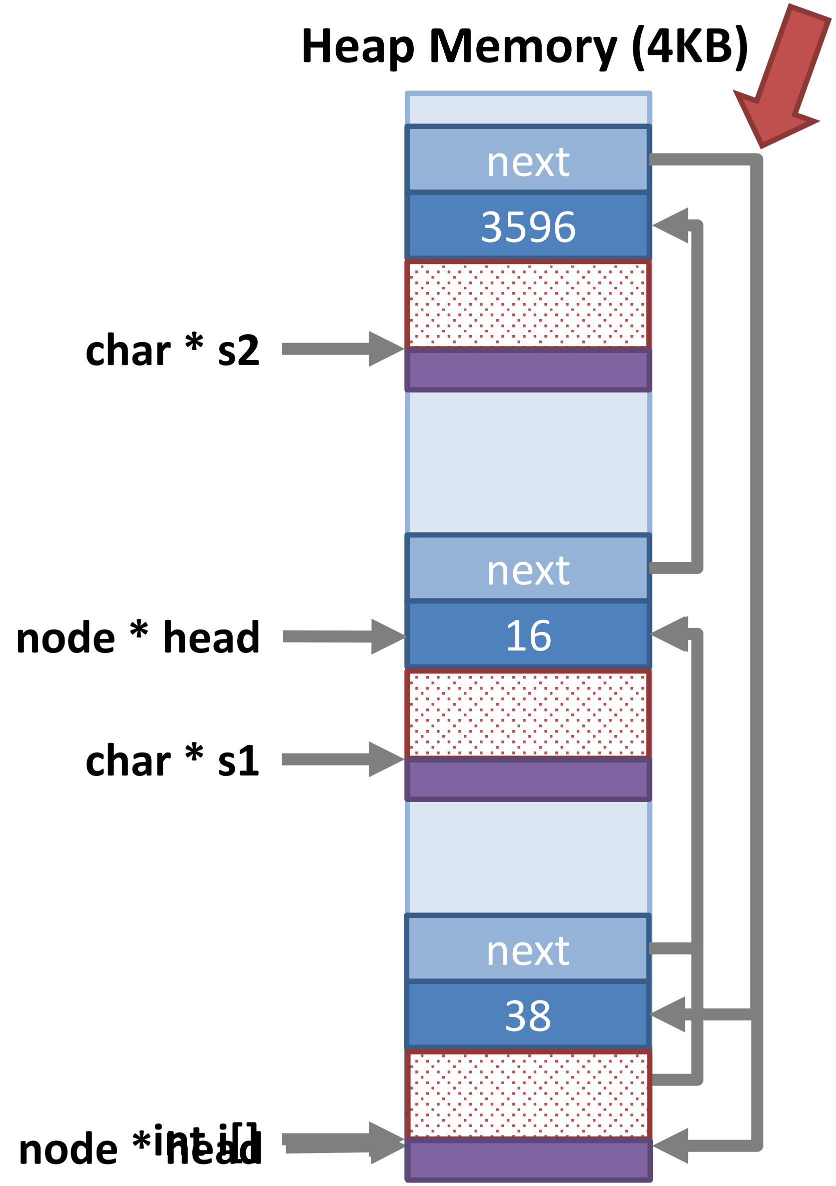
Improving Performance

1. Use a circular linked list and **Next-Fit**
   – Faster than Best-Fit, less fragmentation than First-fit
2. Use a doubly-linked free list with footers
   – Good: makes free() and coalesce O(1) time
   – Bad: small amount of memory wasted due to headers and footers
3. Use bins to quickly locate appropriately sized free regions
   – Good: much less external fragmentation, O(1) time
   – Bad: much more complicated implementation
   – Bad: some memory wasted due to internal fragmentation

Circular List and Next-Fit

```
int i[] = (int*) malloc(8);
```

1. Change a singly-linked, to circular linked list
2. Use First-Fit, but move head after each split
   - Known as **Next-Fit**
   - Helps spread allocations, reduce fragmentation
   - Faster allocations than Best-Fit



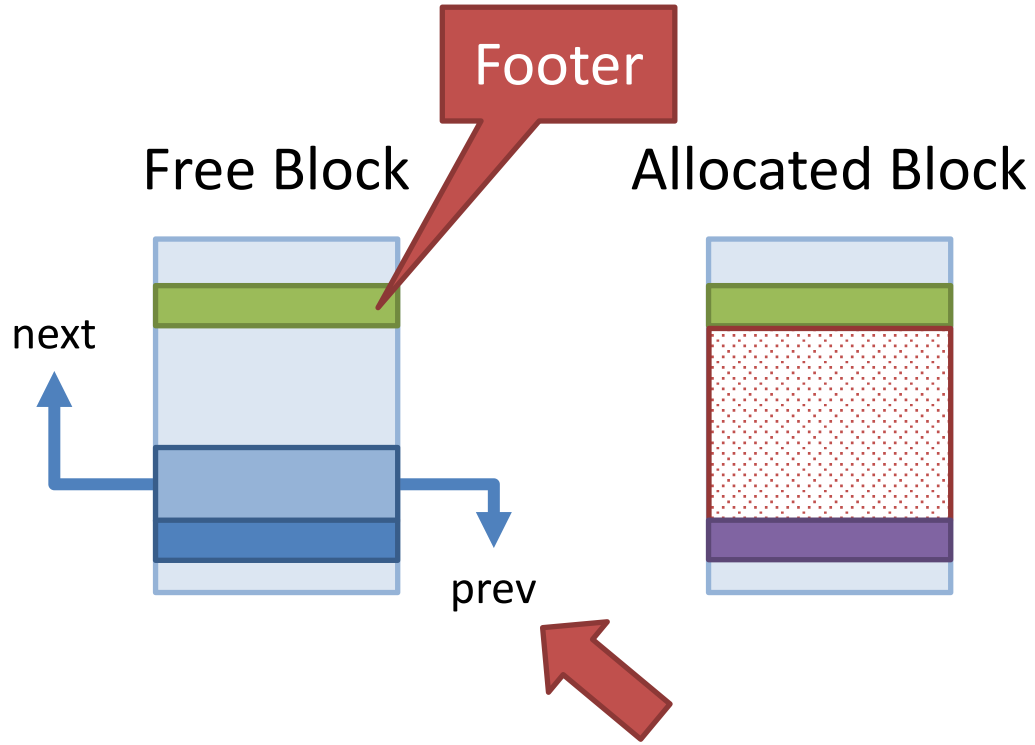
Towards O(1) *free()*

```
typedef struct node_t {
        bool free;
        int size;
        struct node_t * next;
        struct node_t * prev;
} node;

typedef struct header_t {
        bool free;
        int size;
} header;

typedef struct footer_t {
        int size;
} header;
```

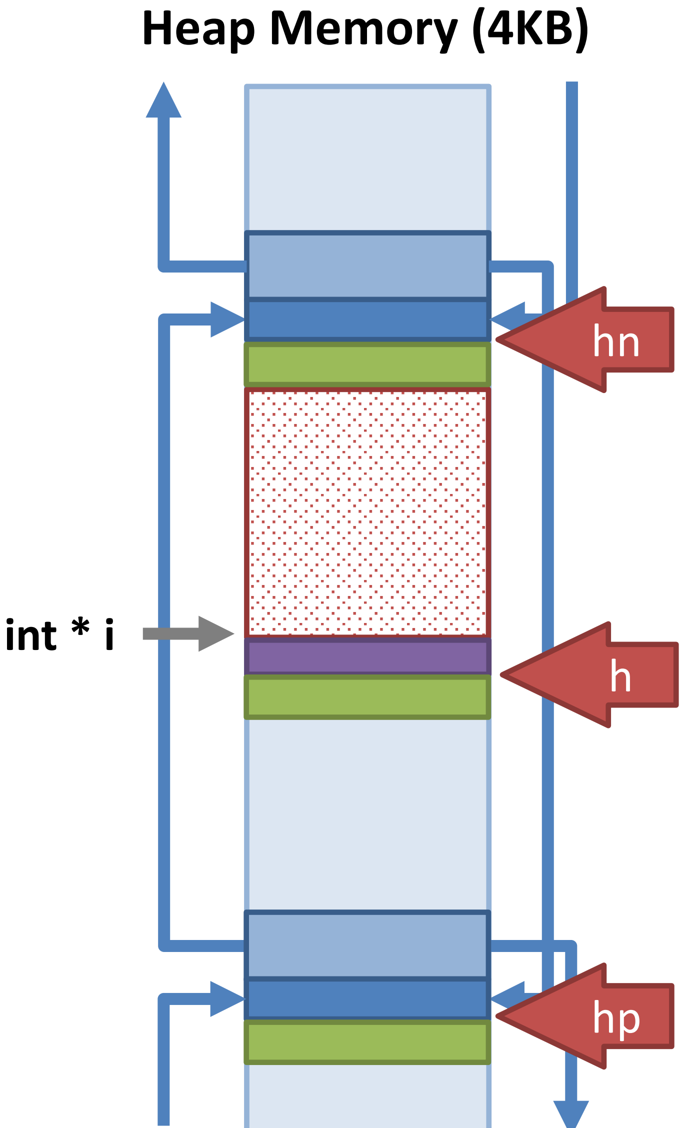
- *free()* is O(n) because the free list must be kept in sorted order
- Key ideas:
  - Move to a doubly linked list
  - Add footers to each block
- Enables coalescing without sorting the free list
  - Thus, *free()* becomes O(1)

Example Blocks

```
typedef struct node_t {
    bool free;
    int size;
    struct node_t * next;
    struct node_t * prev;
} node;

typedef struct header_t {
    bool free;
    int size;
} header;

typedef struct footer_t {
    int size;
} header;
```



Locating Adjacent Free Blocks



- Suppose we have *free(i)*
- Locate the next and previous free blocks

```
char * p = (char *) i; // for convenience
// header of the current block
header * h = (header *) (p – sizeof(header));
// header of the next block
header * hn = (header *) (p + h->size + sizeof(footer));
// previous footer
footer * f = (footer *) (p – sizeof(header) – sizeof(footer));
// previous header
header * hp = (header *)
    ((char *) f – f->size – sizeof(header));
```

Coalescing is O(1)

```
node * n = (node *) h, nn, np;
n->free = true;
if (hn->free) {  // combine with the next free
      nn = (node *) hn;
      n->next = nn->next;      n->prev = nn->prev;
      nn->next->prev = n;      nn->prev->next = n;
      n->size += nn->size + sizeof(header) + sizeof(footer);
      ((footer *) ((char *) n + n->size))->size = n->size;
}
if (hp->free) { // combine with the previous free block
      np = (node *) hp;
      np->size += n->size + sizeof(header) + sizeof(footer);
      ((footer *) ((char *) np + np->size))->size = np->size;
}
if (!hp->free && !hn->free) {
      // add the new free block to the head of the free list
}
```

- Be careful of corner cases:
  - The first free block
  - The last free block

Speeding Up *malloc()*

- At this point, *free()* is O(1)
- But *malloc()* still has problems
  - Next-Fit: O(1) but more fragmentation
  - Best-Fit: O(n) but less fragmentation
- Two steps to speed up *malloc()*
  1. Round allocation requests to powers of 2
     - Less external fragmentation, some internal fragmentation
  2. Divide the free list into bins of similar size blocks
     - Locating a free block of size *round(x)* will be O(1)

Rounding Allocations

- *malloc(size)*

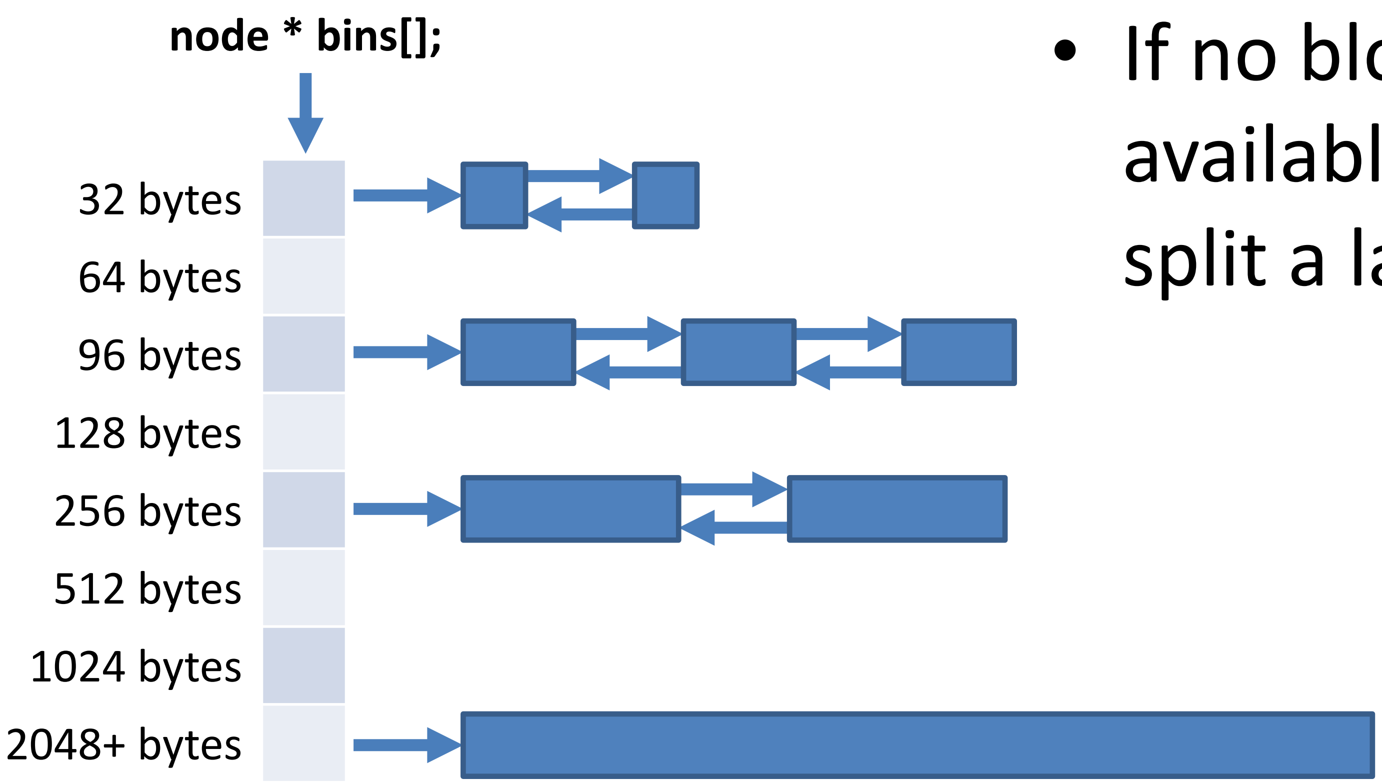
```
size += sizeof(header) + sizeof(footer); // will always be >16 bytes
if (size > 2048) size = 4096 * ((size + 4095) / 4096);
else if (size < 128) size = 32 * ((size + 31) / 32);
else size = round_to_next_power_of_two(size);
```

For large allocations, use full pages

- Examples:
  - *malloc(4)* → 32 bytes
  - *malloc(45)* → 64 bytes
  - *malloc(145)* → 256 bytes

Binning

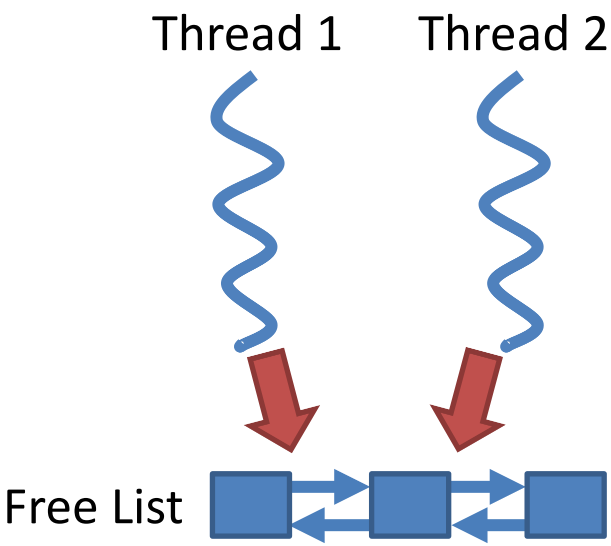
- Divided the free list into bins of exact size blocks
- Most allocations handled in O(1) time by pulling a free block from the appropriate list



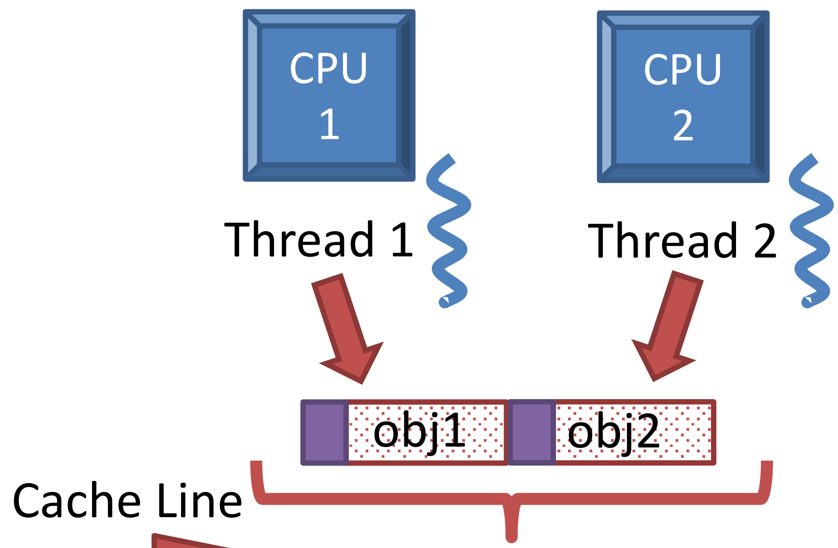
- If no block is available, locate and split a larger block

Next Problem: Parallelism

- Today's programs are often parallel
- However, our current memory manager has poor performance with >1 threads



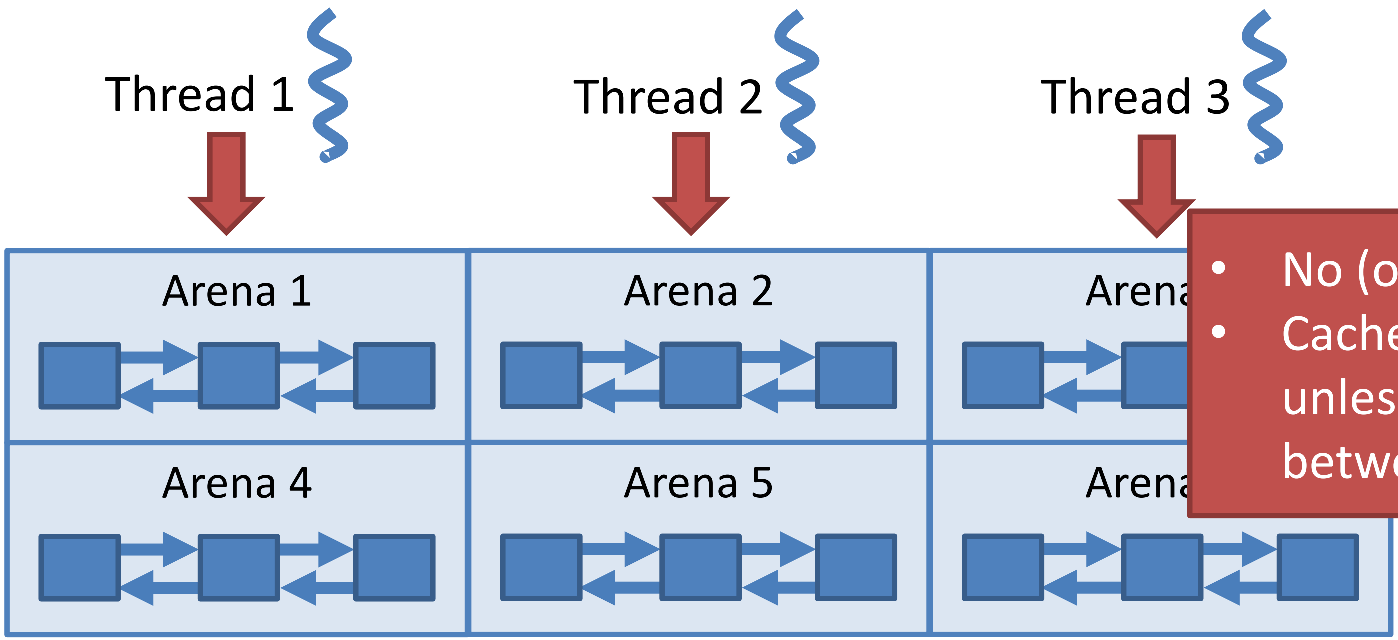
The free list is shared, thus it must be protected by a mutex



- Allocations are filled sequentially in memory
- Objects for different threads may share the same cache line
- This causes contention between CPU cores

Per-Thread Arenas

- To reduce lock and CPU cache contention, divide the heap into arenas
  - Each arena has its own free list
  - Each thread is assigned to several arenas



- No (or few) shared locks
- Cache affinity is high unless data is shared between threads

Two More Things

- How can you make your code manage memory more quickly?
  - Slab allocation
- Common memory bugs
  - Memory leaks
  - Dangling pointers
  - Double free

Speeding Up Your Code

- Typically, the memory allocation algorithm is not under your control
  - You don’t choose what library to use (e.g. glibc)
  - You don’t know the internal implementation
- How can your make your code faster?
  - Avoid the memory allocator altogether!
  - Use an object cache plus slab allocation

```
template<class T> class obj_cache {
    private:
        stack<T *> free_objs;

        void allocate_slab() {
            T * objs = (T *) malloc(sizeof(T) * 10);
            for (int x = 0; x < 10; ++x) free_objs.push(&objs[x]);
        }

    public:
        obj_cache() { allocate_slab(); } // start by pre-allocating some objects

        T * alloc() {
            if (free_objs.empty()) allocate_slab(); // allocate more if we run out
            T * obj = free_objs.top();
            free_objs.pop();
            return obj;  // return an available object
        }

        void free(T * obj) { free_objs.push(obj); } // return obj to the pool
};
```

- Objects are allocated in bulk
- Less space wasted on headers and footers

Two More Things

- How can you make your code manage memory more quickly?
  - Slab allocation
- Common memory bugs
  - Memory leaks
  - Dangling pointers
  - Double free

Memory Management Bugs (1)

```c
int search_file(char * filename, char * search) {
    unsigned int size;
    char * data;
    FILE * fp = fopen(filename, "r");        // Open the file
    fseek(fp, 0, SEEK_END);                  // Seek to the end of the file
    size = ftell(fp);                        // Tell me the total length of the file
    data = (char *) malloc(size * sizeof(char));        // Allocate buffer
    fseek(fp, 0, SEEK_SET);                  // Seek back to the beginning of the file
    fread(data, 1, size, fp);                // Read
    return strstr(data, search) > 0;
}

void main(int argc, char ** argv) {
    if (search_file(argv[1], argv[2])) printf("String '%s' found in file '%s'\n", argv[2], argv[1]);
    else printf("String '%s' NOT found in file '%s'\n", argv[2], argv[1]);
}
```

- We forgot to free(data)!
- If this program ran for a long time, eventually it would exhaust all available virtual memory

Memory Management Bugs (2)

- Dangling pointer

```
char * s = (char *) malloc(100);
…
free(s);
…
puts(s);
```

> - Behavior is nondeterministic
> - If the memory has no been reused, may print s
> - If the memory has been recycled, may print garbage

- Double free

```
char * s = (char *) malloc(100);
…
free(s);
…
free(s);
```

> - Typically, this corrupts the free list
> - However, your program may not crash (nondeterminism)
> - In some cases, double free bugs are **exploitable**

- Free Lists
  - Basics
  - Speeding Up *malloc()* and *free()*
  - Slab Allocation
  - Common Bugs
- Garbage Collectors
  - Reference Counting
  - Mark and Sweep
  - Generational/Ephemeral GC
  - Parallel Garbage Collection

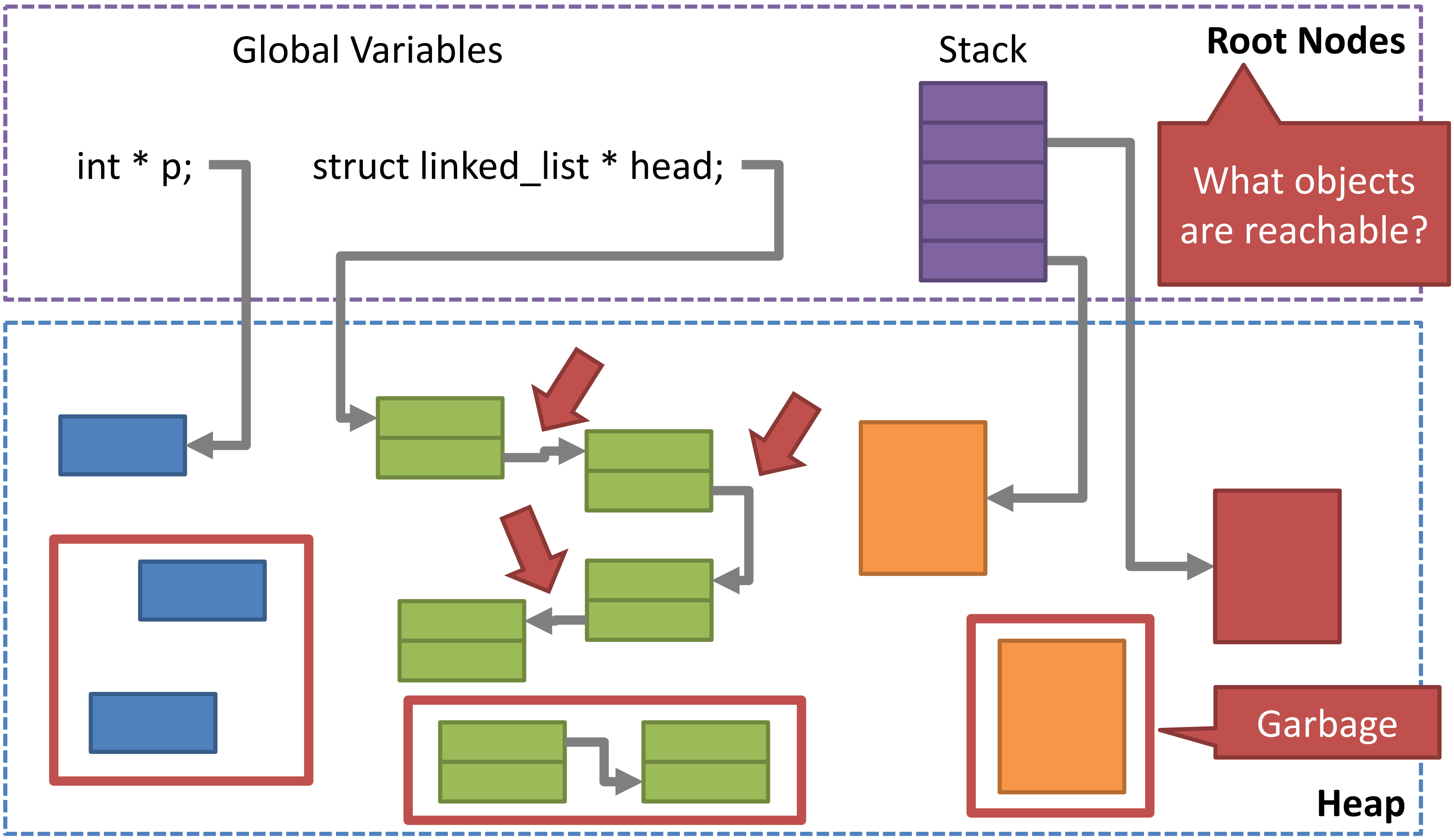
Brief Recap

- At this point, we have thoroughly covered how *malloc()* and *free()* can be implemented
  - Free lists of varying complexity
  - Modern implementations are optimized for low fragmentation, high parallelism
- What about languages that automatically manage memory?
  - Java, Javascript, C#, Perl, Python, PHP, Ruby, etc…

Garbage Collection

- Invented in 1959
- Automatic memory management
  - The GC reclaims memory occupied by objects that are no longer in use
  - Such objects are called garbage
- Conceptually simple
  1. Scan objects in memory, identify objects that cannot be accessed (now, or in the future)
  2. Reclaim these garbage objects
- In practice, very tricky to implement

Garbage Collection Concepts



Identifying Pointers

- At the assembly level, anything can be a pointer

```
int x = 0x80FCE42;
char * c = (char *) x;     // this is legal
```

- Challenge: how can the GC identify pointers?
  1. Conservative approach: assume any number that might be a pointer, is a pointer
     - Problem: may erroneously determine (due to false pointers) that some blocks of memory are in use
  2. Deterministic approach: use a type-safe language that does not allow the programmer to use unboxed values as pointers, or perform pointer arithmetic

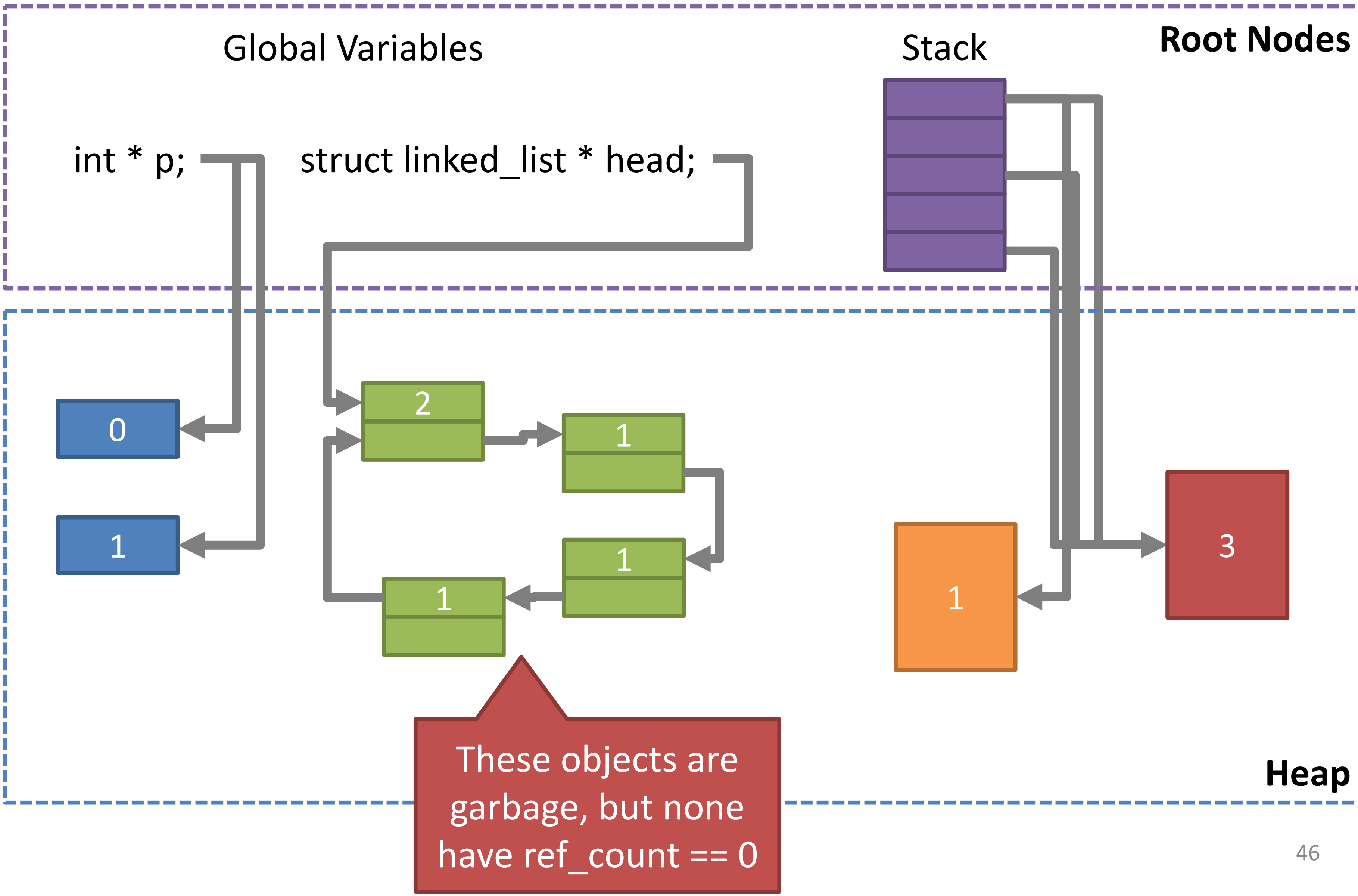
Approaches to GC

- Reference Counting
  - Each object keeps a count of references
  - If an objects count == 0, it is garbage
- Mark and Sweep
  - Starting at the roots, traverse objects and “mark” them
  - Free all unmarked objects on the heap
- Copy Collection
  - Extends mark & sweep with compaction
  - Addresses CPU and external fragmentation issues
- Generational Collection
  - Uses heuristics to improve the runtime of mark & sweep

Reference Counting

- Key idea: each object includes a ref_count
  - Assume obj * p = NULL;
  - p = obj1; // obj1->ref_count++
  - p = obj2; // obj1->ref_count--, obj2->ref_count++
- If an object's ref_count == 0, it is garbage
  - No pointers target that object
  - Thus, it can be safely freed

Reference Counting Example



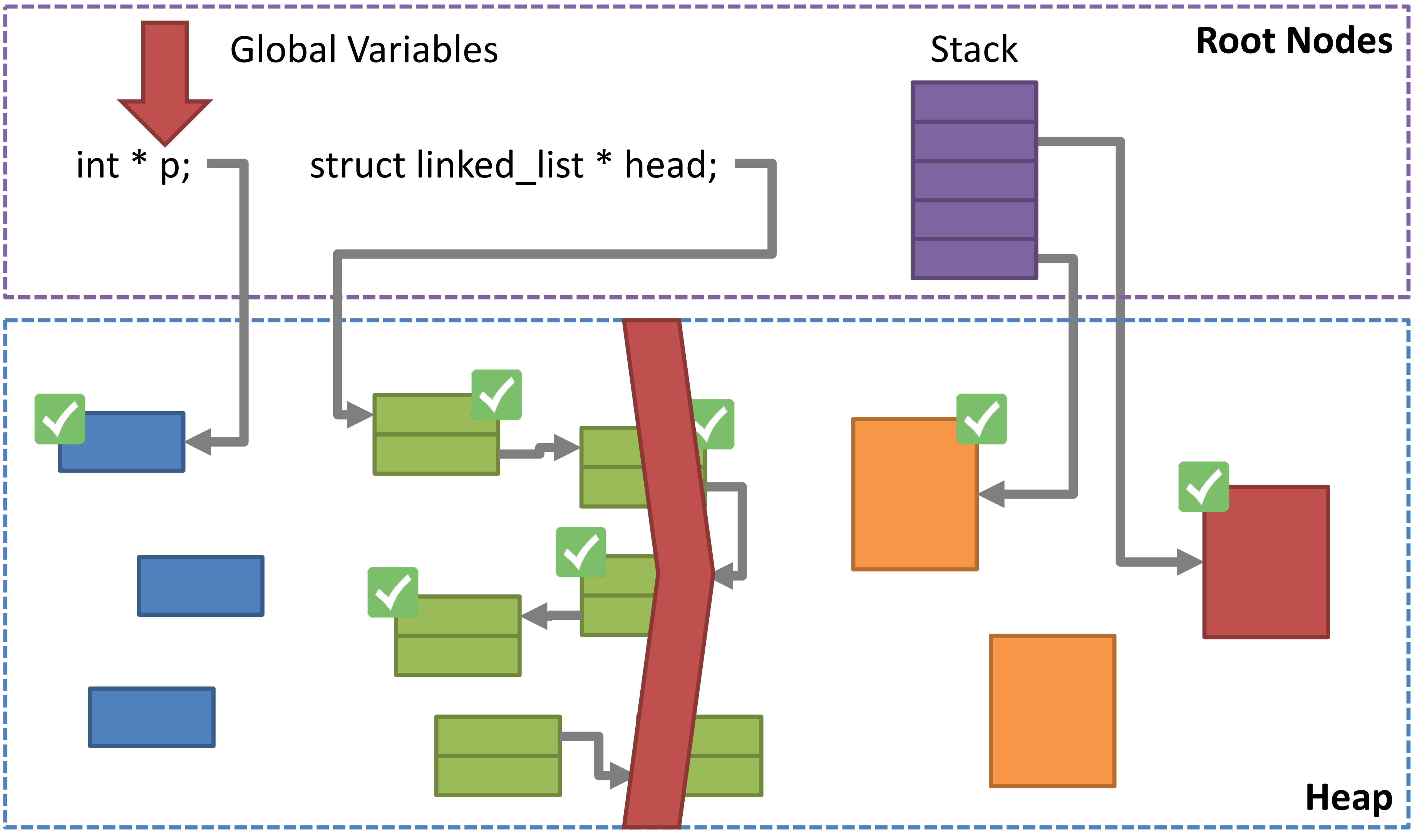
Pros and Cons of Reference Counting

The Good	The Bad
• Relatively easy to implement • Easy to conceptualize	• Not guaranteed to free all garbage objects • Additional overhead (int ref_count) on all objects • Access to obj->ref_count must be synchronized

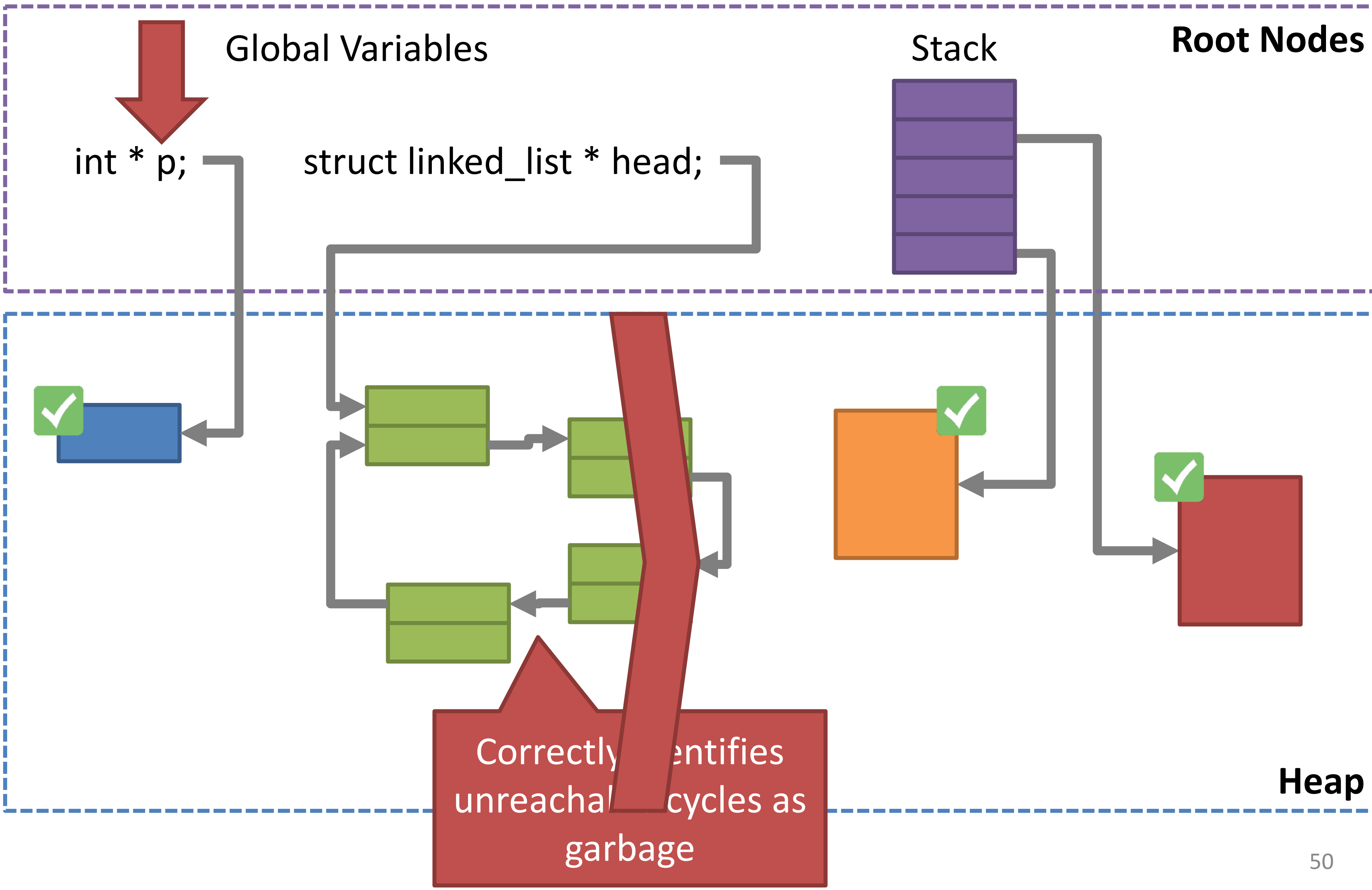
Mark and Sweep

- Key idea: periodically scan all objects for reachability
  - Start at the roots
  - Traverse all reachable objects, mark them
  - All unmarked objects are garbage

Mark and Sweep Example



Mark and Sweep Example



Pros and Cons of Mark and Sweep

The Good

- Overcomes the weakness of reference counting
- Fairly easy to implement and conceptualize
- Guaranteed to free all garbage objects

Be careful: if you forget to set a reference to NULL, it will never be collected (i.e. Java can leak memory)

The Bad

- Mark and sweep is CPU intensive
  - Traverses all objects reachable from the root
  - Scans all objects in memory freeing unmarked objects
- Naïve implementations “stop the world” before collecting
  - Threads cannot run in parallel with the GC
  - All threads get stopped while the GC runs

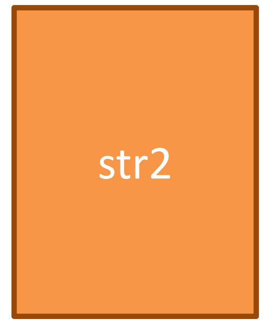
Copy Collection

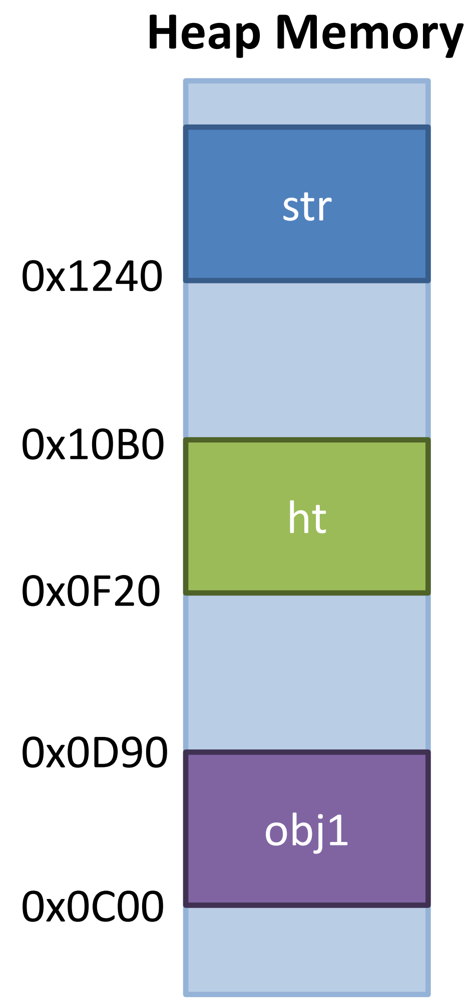
- Problem with mark and sweep:
  - After marking, all objects on the heap must be scanned to identify and free unmarked objects
- Key idea: use compaction (aka relocation)
  - Divide the heap into *start space* and *end space*
  - Objects are allocated in *start space*
  - During GC, instead of marking, copy live object from *start space* into *end space*
  - Switch the *space* labels and continue

Compaction/Relocation

String str2 = new String();

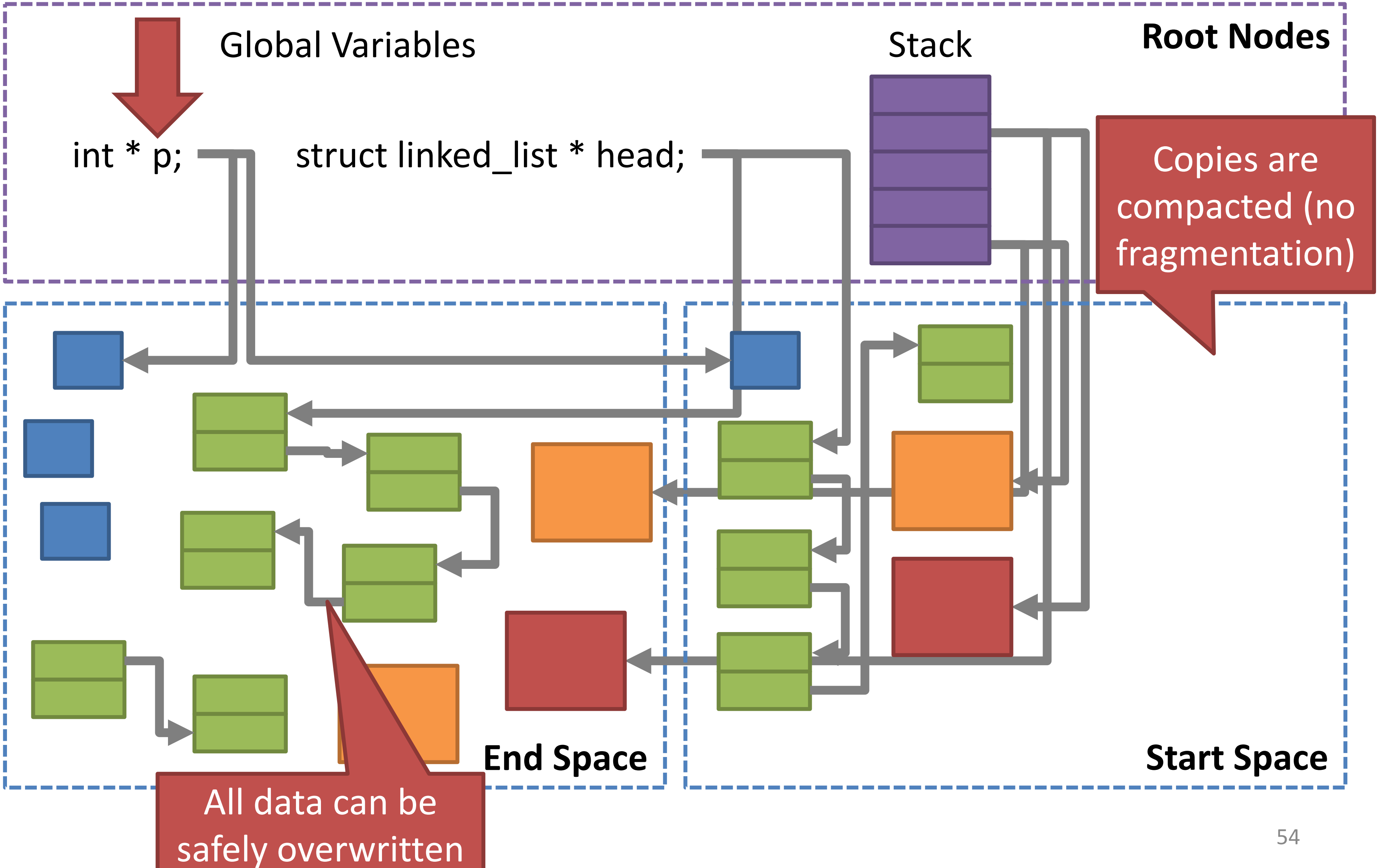
Pointer	Value	Location
obj1	0x0C00	0x0C00
ht	**0x0D90**	**0x0D90**
str	**0x0F20**	**0x0F20**
str2	0x10B0	0x10B0





- One way to deal with fragmentation is compaction
  - Copy allocated blocks of memory into a contiguous region of memory
  - Repeat this process periodically
- This only works if pointers are boxed, i.e. managed by the runtime

Copy Collection Example



Pros and Cons of Copy Collection

The Good	The Bad
• Improves on mark and sweep • No need to scan memory for garbage to free • After compaction, there is no fragmentation	• Copy collection is slow – Data must be copied – Pointers must be updated • Naïve implementations are not parallelizable – “Stop the world” collector

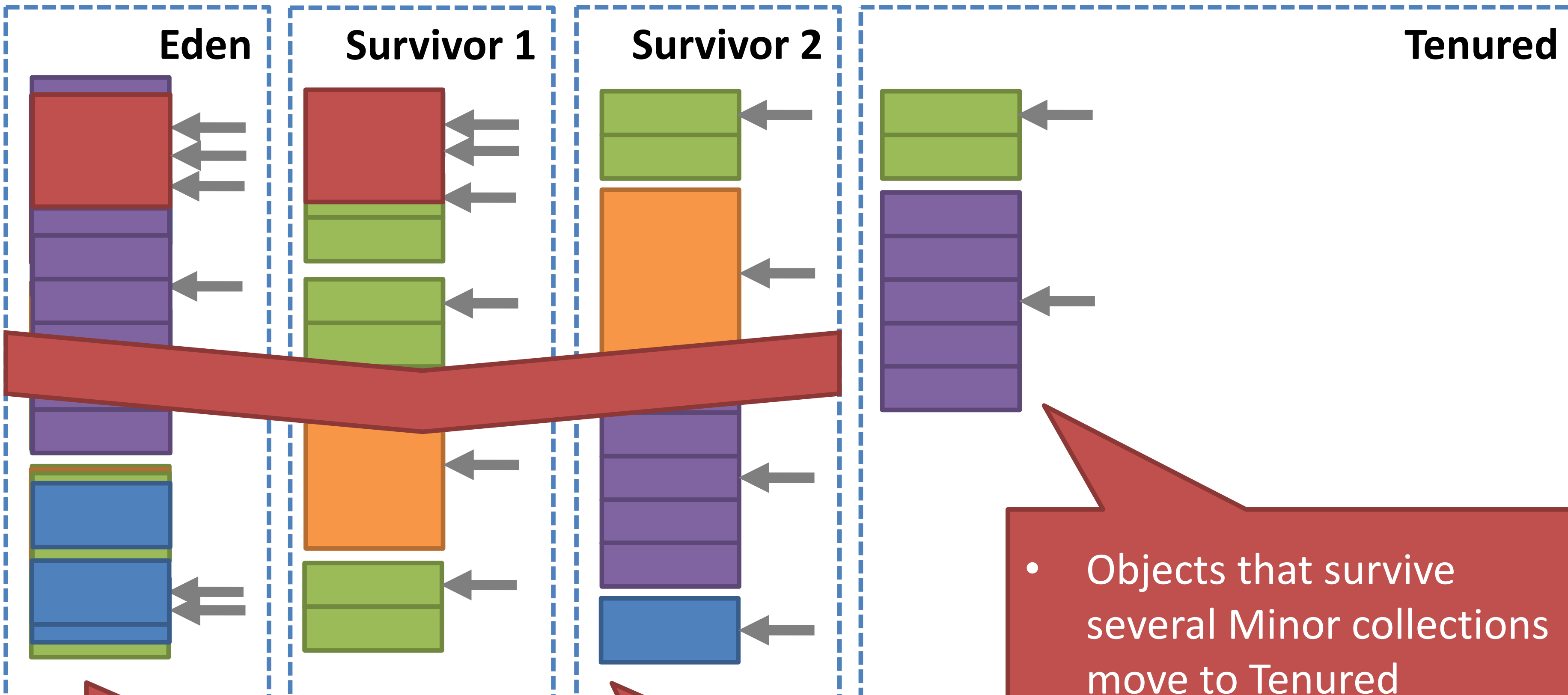
Generational Collection

- Problem: mark and sweep is slow
  - Expensive full traversals of live objects
  - Expensive scan of heap memory
- Problem: copy collection is also slow
  - Expensive full traversals of live objects
  - Periodically, all live objects get copied
- Solution: leverage knowledge about object creation patterns
  - Object lifetime tends to be inversely correlated with likelihood of becoming garbage (generational hypothesis)
  - Young objects die quickly – old objects continue to live

Garbage Collection in Java

- By default, most JVMs use a generational collector
- GC periodically runs two different collections:
  1. Minor collection – occurs frequently
  2. Major collection – occurs infrequently
- Divides heap into 4 regions
  - Eden: newly allocated objects
  - Survivor 1 and 2: objects from Eden that survive minor collection
  - Tenured: objects from Survivor that survive several minor collections

Generational Collection Example



- Minor collection occurs whenever Eden gets full
- Live objects are copied to Survivor

- Survivor 1 and 2 rotate as destinations for a copy collector

- Objects that survive several Minor collections move to Tenured
- Tenured objects are only scanned during Major collection
- Major collections occur infrequently

More on Generational GC

- Separating young and old objects improves performance
  - Perform frequent, minor collections on young objects
  - No need to scan old objects frequently
- Copy collection reduces fragmentation
  - Eden and Survivor areas are relatively small, but they are frequently erased

Parallel and Concurrent GC

- Modern JVMs ship with multiple generational GC implementations, including:
  - The Parallel Collector
    - Runs several GC threads in parallel with user threads
    - Multiple GC threads take part in each minor/major collection
    - Best choice if your app is intolerant of pauses
  - The Concurrent Mark and Sweep Collector
    - Also implements multi-threaded GC
    - Pauses the app, uses all CPU cores for GC
    - Overall fastest GC, if your app can tolerate pauses
- Selecting and tuning Java GCs is an art

malloc()/free() vs. GC

Explicit Alloc/Dealloc

- Advantages:
  - Typically faster than GC
  - No GC “pauses” in execution
  - More efficient use of memory
- Disadvantages:
  - More complex for programmers
  - Tricky memory bugs
    - Dangling pointers
    - Double-free
    - Memory leaks
  - Bugs may lead to security vulnerabilities

Garbage Collection

- Advantages:
  - Much easier for programmers
- Disadvantages
  - Typically slower than explicit alloc/dealloc
  - Good performance requires careful tuning of the GC
  - Less efficient use of memory
  - Complex runtimes may have security vulnerabilities
    - JVM gets exploited all the time

Other Considerations

- Garbage collectors are available for C/C++
  - Boehm Garbage Collector
  - Beware: this GC is conservative
    - It tries to identify pointers using heuristics
    - Since it can't identify pointers with 100% accuracy, it must conservatively free memory
- You can replace the default *malloc()* implementation if you want to
  - Example: Google's high-performance tcmalloc library
  - http://goog-perftools.sourceforge.net/doc/tcmalloc.html

Sources

- Slides by Jennifer Rexford
  - http://www.cs.princeton.edu/~jrex
- Operating Systems: Three Easy Pieces, Chapter 17 by Remzi and Andrea Arpaci-Dusseau
  - http://pages.cs.wisc.edu/~remzi/OSTEP/vm-freespace.pdf
- Java Platform, Standard Edition HotSpot Virtual Machine Garbage Collection Tuning Guide by Oracle (Java SE v. 8)
  - http://docs.oracle.com/javase/8/docs/technotes/guides/vm/gctuning/toc.html