Dynamic Memory Allocation

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Some slides adapted from CMU 15.213 slides

Objectives

Be able to analyze a memory allocator's key characteristics

- **Memory usage efficiency (fragmentation)**
- **Speed of allocation and deallocation operations**
- **Locality of allocations**
- **Robustness**

Be able to implement your own efficient memory allocator (Malloc Project)

Be able to analyze the advantages and disadvantages of different garbage collector designs

Harsh Reality: Memory Matters

Memory is not unbounded

- It must be allocated and *freed*
- Many applications are memory dominated
  - E.g., applications based on complex graph algorithms

Memory referencing bugs especially pernicious

- Effects can be distant in both time and space

Memory performance is not uniform

- Cache and virtual memory effects can greatly affect program performance
- Adapting program to characteristics of memory system can lead to major speed improvements

Memory Allocation

Static size, static allocation

- Global and static variables
- Linker allocates final addresses
- Executable stores these allocated addresses

Static size, dynamic allocation

- Local variables
- Compiler directs stack allocation
- Frame pointer (%rbp) offsets stored in the code

Dynamic size, dynamic allocation

- Programmer controlled
- Allocated in the heap – how?

Dynamic Memory Allocation

Application
Dynamic Memory Allocator
Heap Memory

Explicit vs. implicit memory allocator

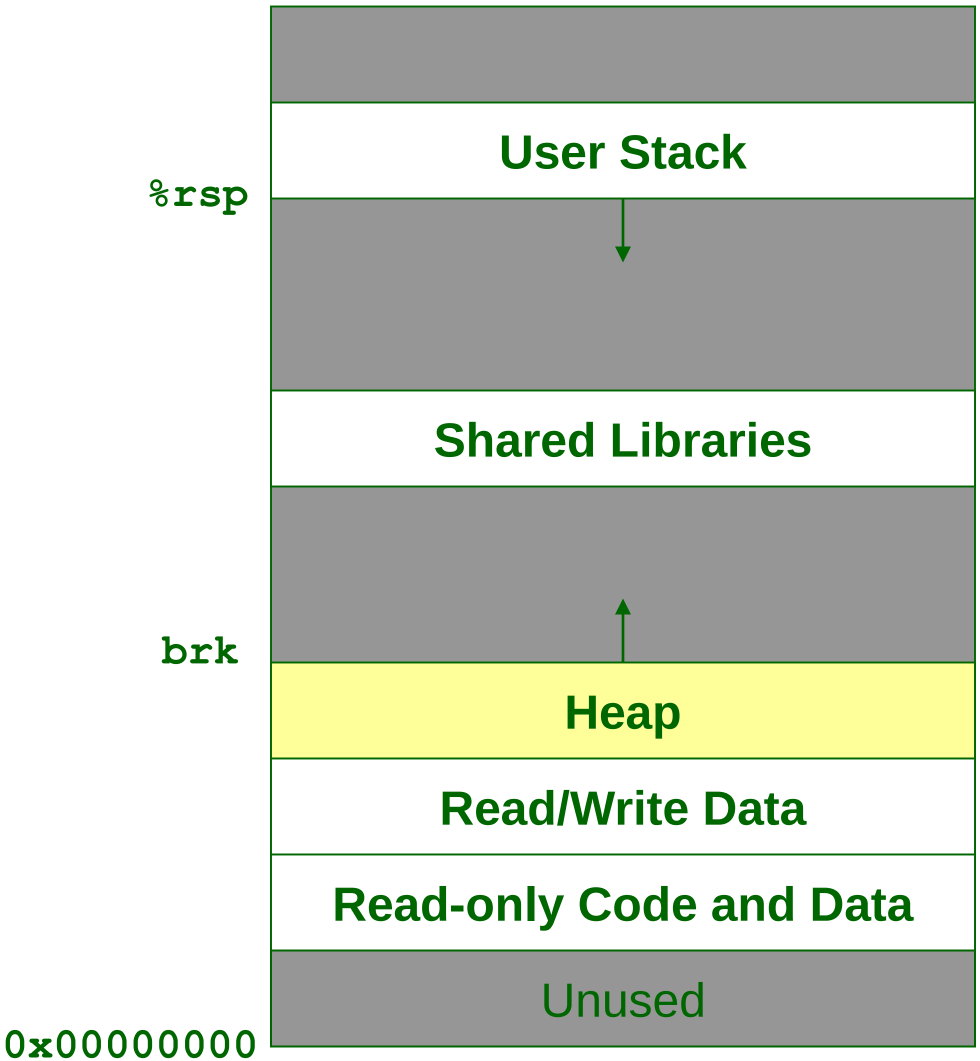
- **Explicit: application allocates and *frees* space**
  - e.g., malloc and free in C
- **Implicit: application allocates, but does not free space**
  - e.g., garbage collection in Java or Python

Allocation

- **In both cases the memory allocator provides an abstraction of memory as a set of blocks**
- **Doles out free memory blocks to application**

We will first discuss simple explicit memory allocation

Process Memory Image




```
void *sbrk(intptr_t incr)
```

- Used by allocators to request additional memory from the OS
- `brk` initially set to the end of the data section
- Calls to `sbrk` increment `brk` by `incr` bytes (new virtual memory pages are demand-zeroed)
- `incr` can be negative to reduce the heap size

Malloc Package

`#include <stdlib.h>`

`void *malloc(size_t size)`

- **If successful:**
  - **Returns a pointer to a memory block of at least `size` bytes, (typically) aligned to 8-byte boundary**
  - **If `size` == 0, returns NULL (or a unique pointer)**
- **If unsuccessful: returns NULL (0) and sets `errno`**

`void free(void *ptr)`

- **Returns the block pointed at by `ptr` to pool of available memory**
- **`ptr` must come from a previous call to `malloc` or `realloc`**

`void *realloc(void *ptr, size_t size)`

- **Changes size of block pointed at by `ptr` and returns pointer to new block**
- **Contents of new block unchanged up to the minimum of the old and new sizes**

Malloc/realloc/free Example

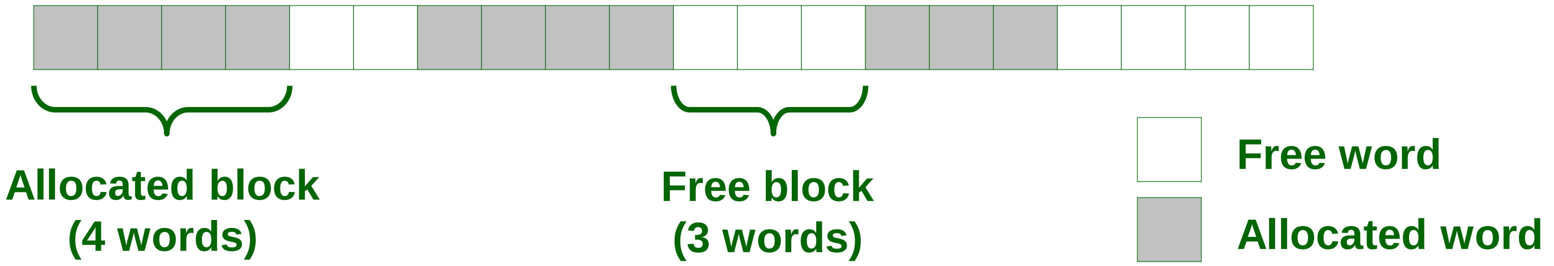
```
void foo(int n, int m)
{
  int i, *p;

  /* Allocate a block of n ints. */
  if ((p = malloc(n * sizeof(int))) == NULL) {
    perror("malloc");
    exit(1);
  }
  for (i = 0; i < n; i++)
    p[i] = i;
  /* Add m bytes to end of p block. */
  if ((p = realloc(p, (n + m) * sizeof(int))) == NULL) {
    perror("realloc");
    exit(1);
  }
  for (i = n; i < n + m; i++)
    p[i] = i;
  /* Print new array. */
  for (i = 0; i < n + m; i++)
    printf("%d\n", p[i]);
  /* Return p to available memory pool. */
  free(p);
}
```

Assumptions

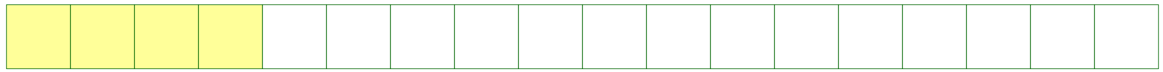
Conventions used in these lectures

- Memory is word addressed
- “Boxes” in figures represent a word
- Each word is 4 bytes in size and can hold an integer or a pointer

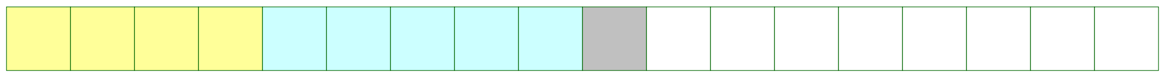


Allocation Examples

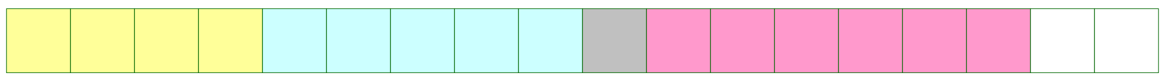
`p1 = malloc(4*sizeof(int))`



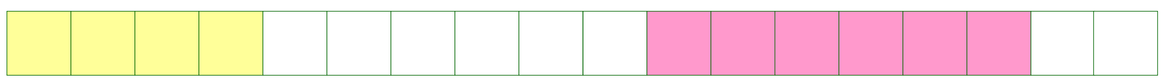
`p2 = malloc(5*sizeof(int))`



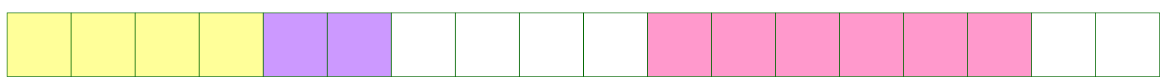
`p3 = malloc(6*sizeof(int))`



`free(p2)`



`p4 = malloc(2*sizeof(int))`



Governing Rules

Applications:

- Can issue arbitrary sequence of malloc and free requests
- Free requests must correspond to an allocated block

Allocators:

- Can't control number or size of allocated blocks
- Must respond immediately to all allocation requests
  - i.e., can't reorder or buffer requests
- Must allocate blocks from free memory
  - i.e., can only place allocated blocks in free memory
- Must align blocks so they satisfy all alignment requirements
  - 8-byte alignment for libc malloc on many systems
- Can only manipulate and modify free memory
- Can't move the allocated blocks once they are allocated
  - i.e., compaction is not allowed

Goals of Good `malloc/free`

Primary goals

- **Good time performance for malloc and free**
  - Ideally should take constant time (not always possible)
  - Should certainly not take linear time in the number of blocks
- **Good space utilization**
  - User allocated structures should use most of the heap
  - Want to minimize "fragmentation"

Some other goals

- **Good locality properties**
  - Structures allocated close in time should be close in space
  - "Similar" objects should be allocated close in space
- **Robust**
  - Can check that `free(p1)` is on a valid allocated object `p1`
  - Can check that memory references are to allocated space

Maximizing Throughput

- **Given some sequence of *n* malloc, realloc, and free requests:**
  - $R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$
- **Want to maximize throughput and peak memory utilization**
  - **These goals are often conflicting**
- **Throughput:**
  - **Number of completed requests per unit time**
  - **Example:**
    - **5,000 malloc calls and 5,000 free calls in 10 seconds**
    - **Throughput is 1,000 operations/second**

Maximizing Memory Utilization

Given some sequence of malloc and free requests:

- $R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$

Def: Aggregate payload P_k:

- `malloc(p)` results in a block with a payload of `p` bytes
- After request R_k has completed, the aggregate payload P_k is the sum of currently allocated payloads

Def: Current heap size is denoted by H_k

- Assume that H_k is monotonically increasing

Def: Peak memory utilization:

- After k requests, peak memory utilization is:
  - $U_k = (\max_{i<k} P_i) \ / \ H_k$

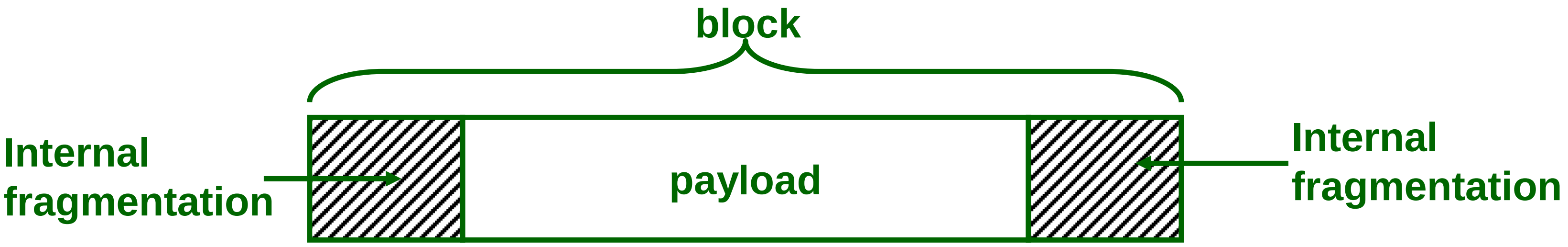
Internal Fragmentation

Poor memory utilization caused by fragmentation

- Comes in two forms: internal and external fragmentation

Internal fragmentation

- For some block, internal fragmentation is the difference between the block size and the payload size

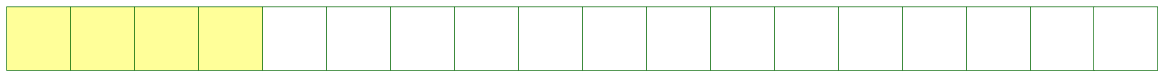


- Caused by overhead of maintaining heap data structures, padding for alignment purposes, or explicit policy decisions (e.g., not to split the block)
- Depends only on the pattern of *previous* requests, and thus is easy to measure

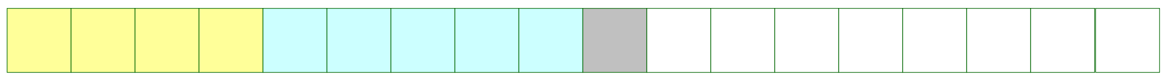
External Fragmentation

Occurs when there is enough aggregate heap memory, but no single free block is large enough

```
p1 = malloc(4*sizeof(int))
```



```
p2 = malloc(5*sizeof(int))
```



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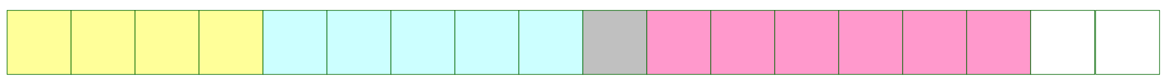
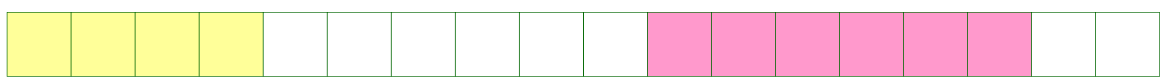


```
free(p2)
```



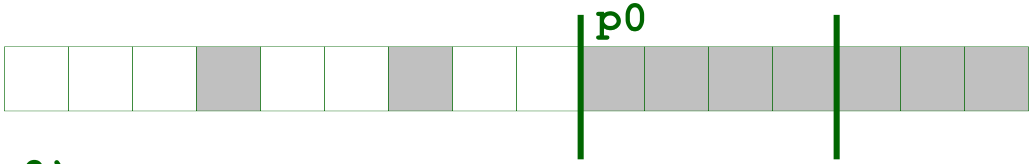
```
p4 = malloc(7*sizeof(int))
```

oops!

External fragmentation depends on the pattern of future requests, and thus is difficult to measure

Implementation Issues

- How do we know how much memory to free just given a pointer?
- How do we keep track of the free blocks?
- What do we do with the extra space when allocating a structure that is smaller than the free block it is placed in?
- How do we pick a block to use for allocation – many might fit?
- How do we reinsert a freed block?



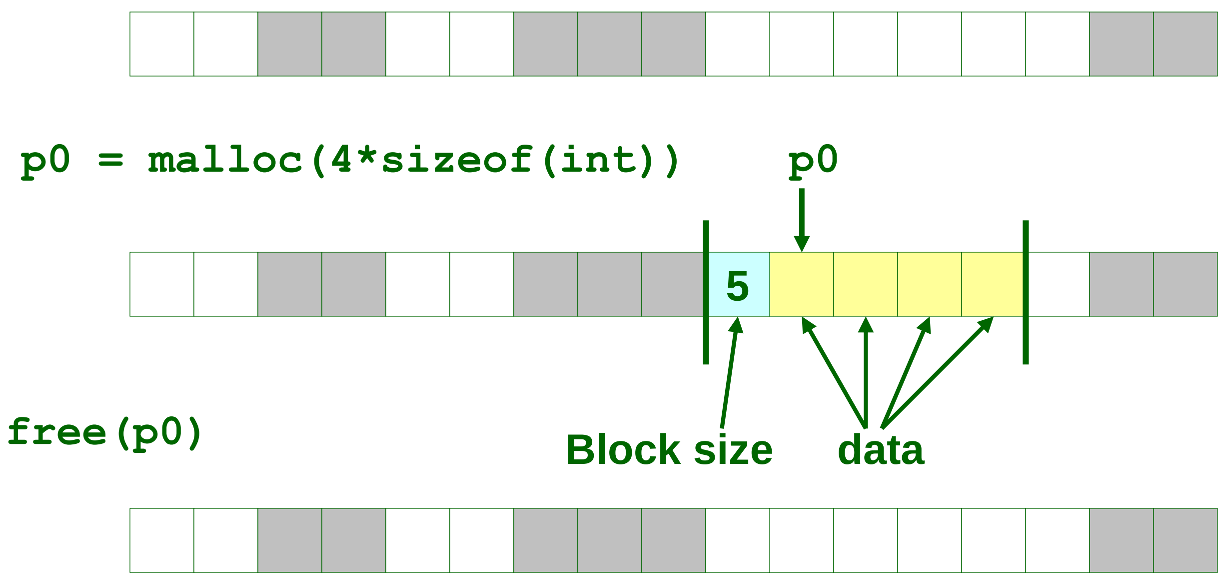

```
free(p0)

p1 = malloc(1)
```

Knowing How Much to Free

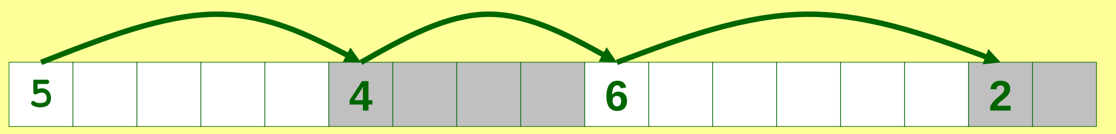
Standard method

- **Keep the length of a block in the word preceding the block.**
  - This word is often called the header field or header
- **Requires an extra word for every allocated block**



Keeping Track of Free Blocks

Method 1: Implicit list using lengths – links all blocks



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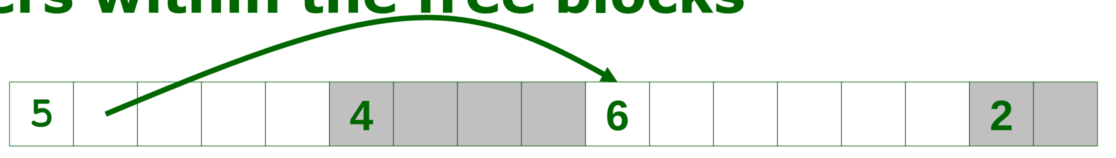


Method 3: Segregated free list

- Different free lists for different size classes

Method 4: Blocks sorted by size

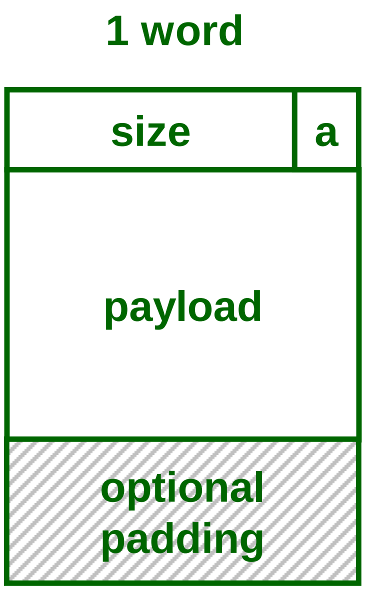
- Can use a balanced tree (e.g., Red-Black tree) with pointers within each free block, and the length used as a key

Method 1: Implicit List

Need to identify whether each block is free or allocated

- **Can use extra bit**
- **Bit can be put in the same word as the size if block sizes are always multiples of two (mask out low order bit when reading size)**

Format of allocated and free blocks



a = 1: allocated block
a = 0: free block

size: block size

payload: application data
(allocated blocks only)

Implicit List: Finding a Free Block

First fit:

- Search list from beginning, choose first free block that fits

```
p = start;
while ((p < end) &&     \\ not past end
       ((*p & 1) ||     \\ already allocated
        (*p <= len)))   \\ too small
  p = NEXT_BLKP(p);
```

- Can take linear time in total number of blocks (allocated/free)
- Can cause “splinters” (small free blocks) at beginning of list

Next fit:

- Like first-fit, but search list from end of previous search
- Research suggests that fragmentation is worse

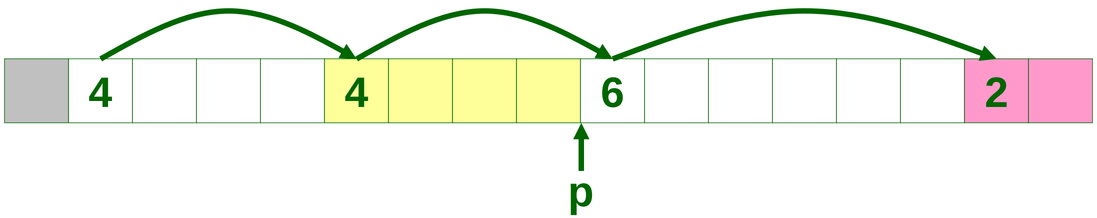
Best fit:

- Choose the free block with the closest size that fits (requires complete search of the list)
- Keeps fragments small – usually helps fragmentation
- Will typically run slower than first-fit

Implicit List: Allocating in Free Block

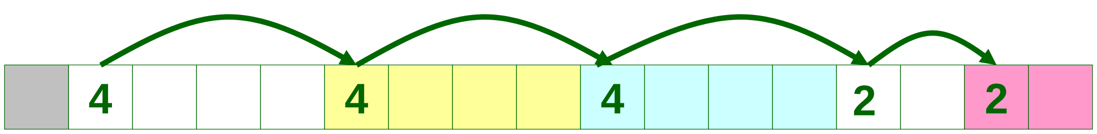
Allocating in a free block – splitting

- **Since allocated space might be smaller than free space, we might want to split the block**




```
void addblock(ptr p, int len) {
  int newsize = ((len + 1) >> 1) << 1;  // add 1 and round up
  int oldsize = *p & ~0x1;              // mask out low bit
  *p = newsize | 0x1;                   // set new length
  if (newsize < oldsize)
    *(p+newsize) = oldsize - newsize;   // set length in remaining
}                                       //   part of block
```

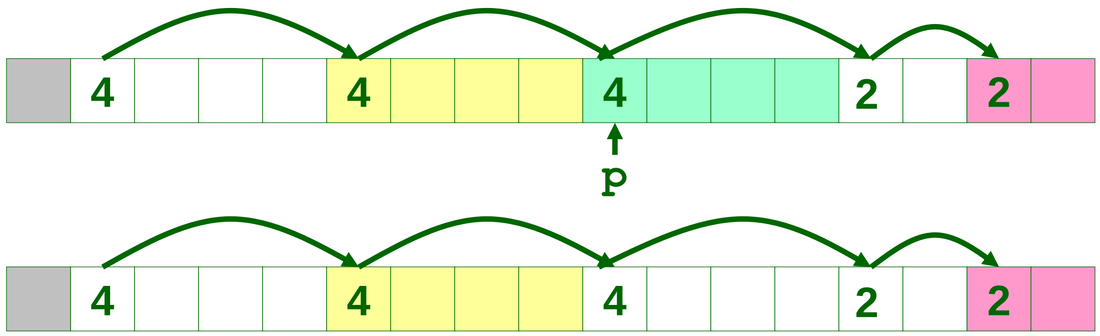
`addblock(p, 4)`



Implicit List: Freeing a Block

Simplest implementation:

- **Only need to clear allocated flag**
  - `void free_block(ptr p) { *p = *p & ~0x1}`
- **But can lead to "false fragmentation"**



`free(p)`

`malloc(5*sizeof(int))`

Oops!

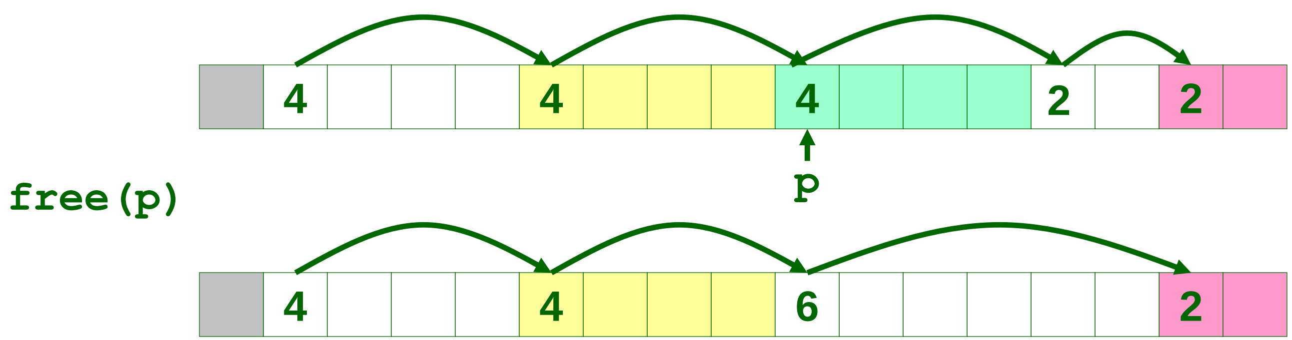
- **There is enough free space, but the allocator won't be able to find it!**

Implicit List: Coalescing

Join (coalesce) with next and/or previous block if they are free

- **Coalescing with next block**

```
void free_block(ptr p) {
     *p = *p & ~0x1;          // clear allocated flag
     next = p + *p;           // find next block
     if ((*next & 0x1) == 0)
       *p = *p + *next;       // add to this block if
}                             //    not allocated
```

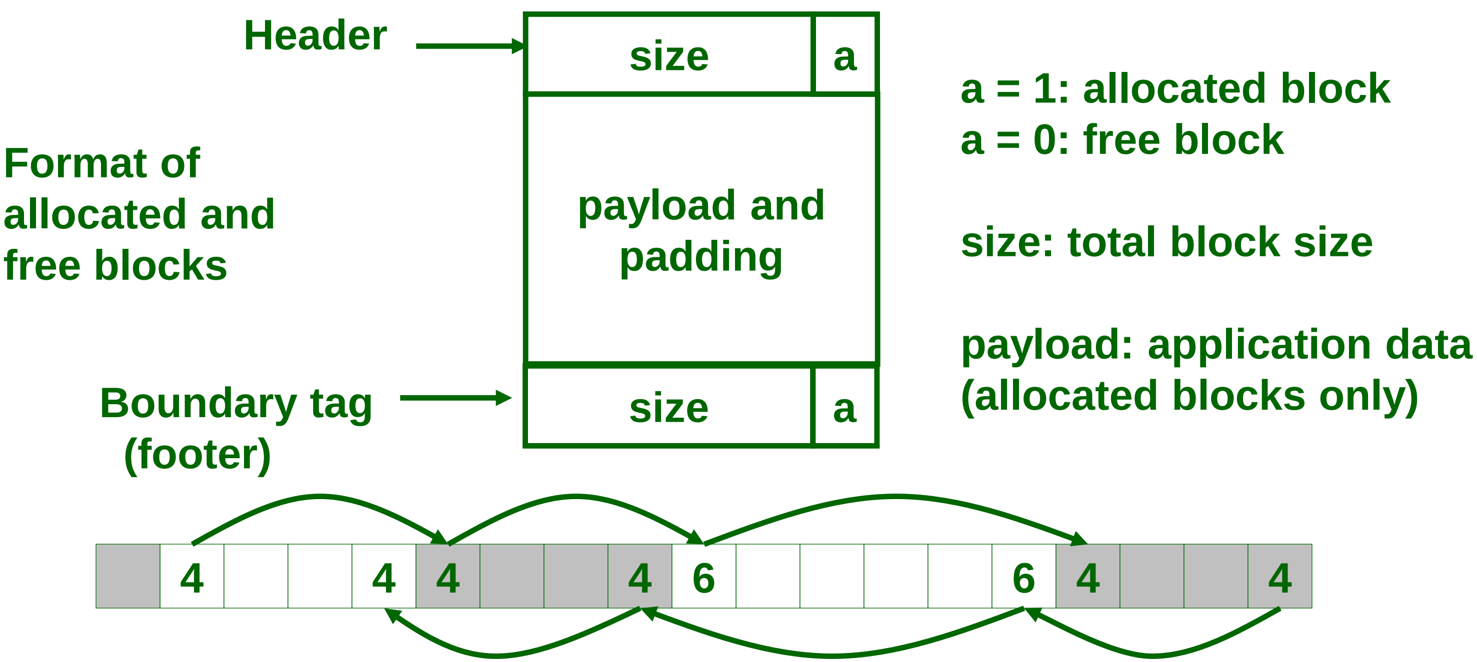


- **But how do we coalesce with previous block?**

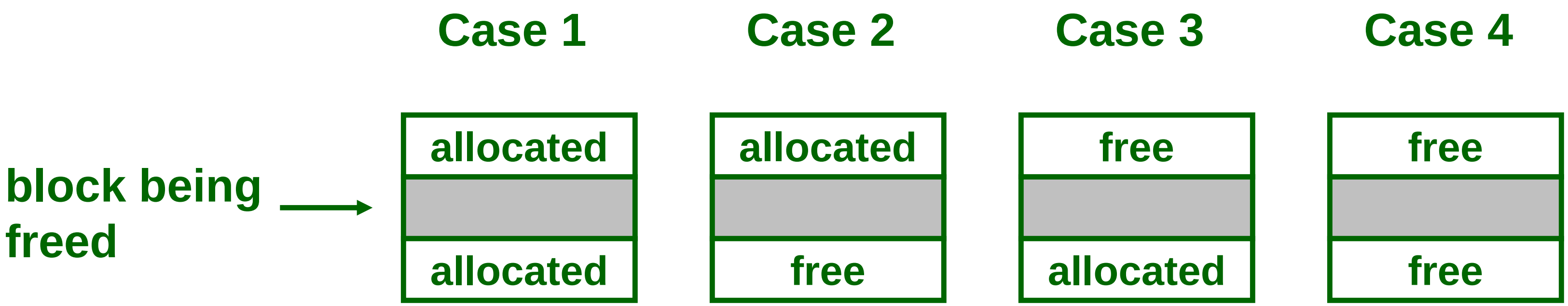
Implicit List: Bidirectional Coalescing

Boundary tags [Knuth73]

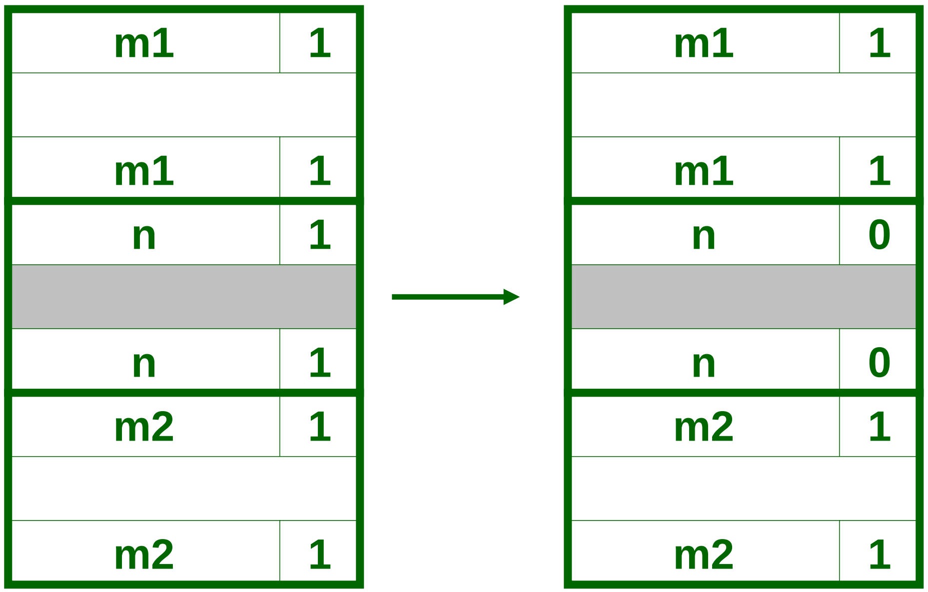
- Replicate header word at end of block
- Allows us to traverse the “list” backwards, but requires extra space
- Important and general technique!



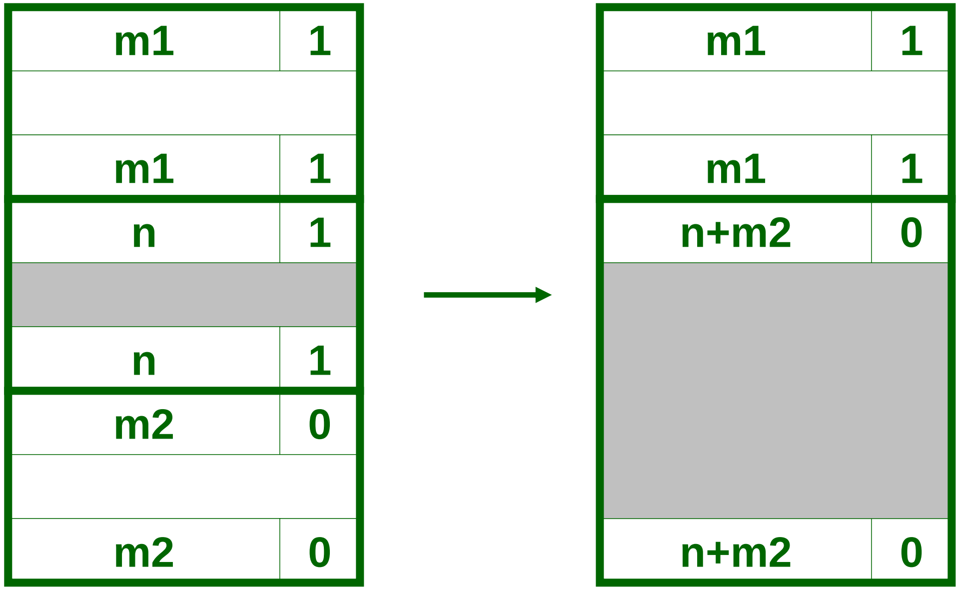
Constant Time Coalescing



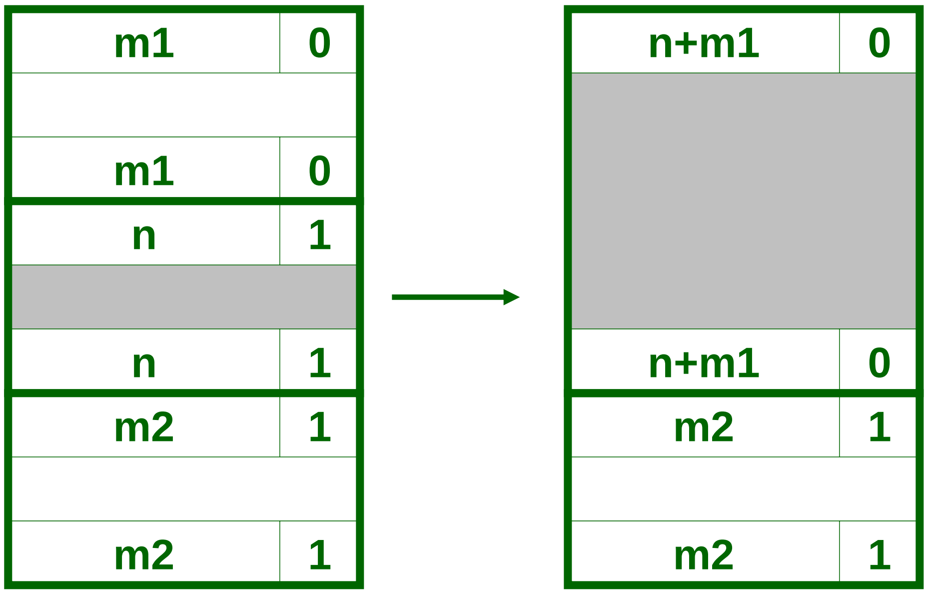
Constant Time Coalescing (Case 1)



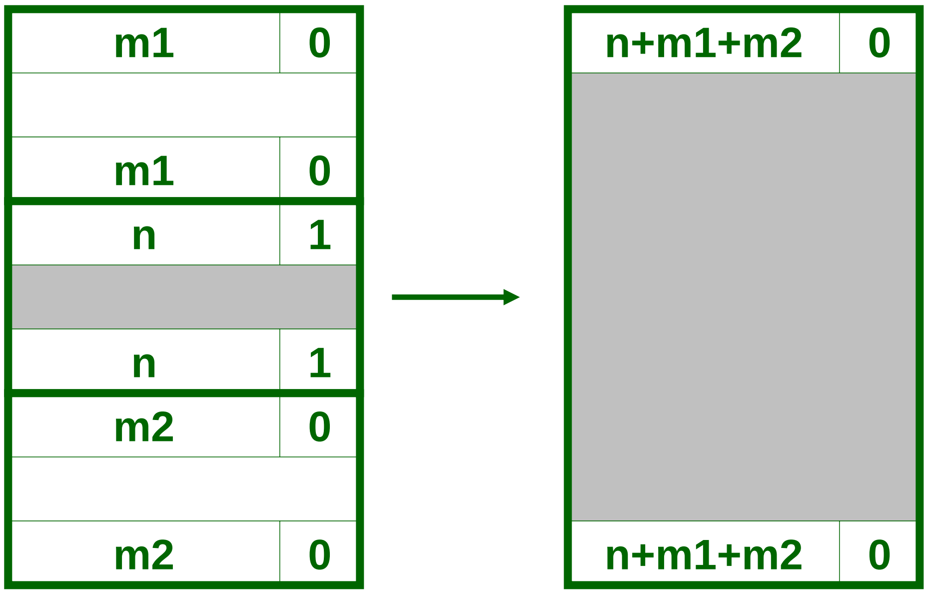
Constant Time Coalescing (Case 2)



Constant Time Coalescing (Case 3)



Constant Time Coalescing (Case 4)



Summary of Key Allocator Policies

Placement policy:

- First fit, next fit, best fit, etc.
- Trades off lower throughput for less fragmentation

Splitting policy:

- When do we go ahead and split free blocks?
- How much internal fragmentation are we willing to tolerate?

Coalescing policy:

- Immediate coalescing: coalesce adjacent blocks each time free is called
- Deferred coalescing: try to improve performance of free by deferring coalescing until needed. e.g.,
  - Coalesce as you scan the free list for malloc
  - Coalesce when the amount of external fragmentation reaches some threshold

Implicit Lists: Summary

Implementation: very simple

Allocate: linear time worst case

Free: constant time worst case – even with coalescing

Memory usage: will depend on placement policy

- First fit, next fit or best fit

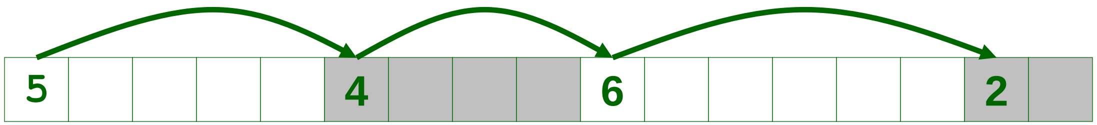
Not used in practice for `malloc/free` because of linear time allocate

- Used in many special purpose applications

However, the concepts of splitting and boundary tag coalescing are general to all allocators

Keeping Track of Free Blocks

Method 1: Implicit list using lengths – links all blocks



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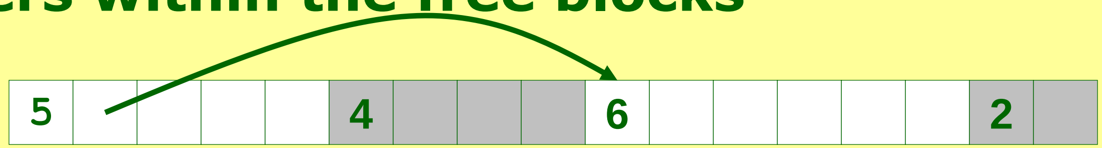


Method 3: Segregated free list

- Different free lists for different size classes

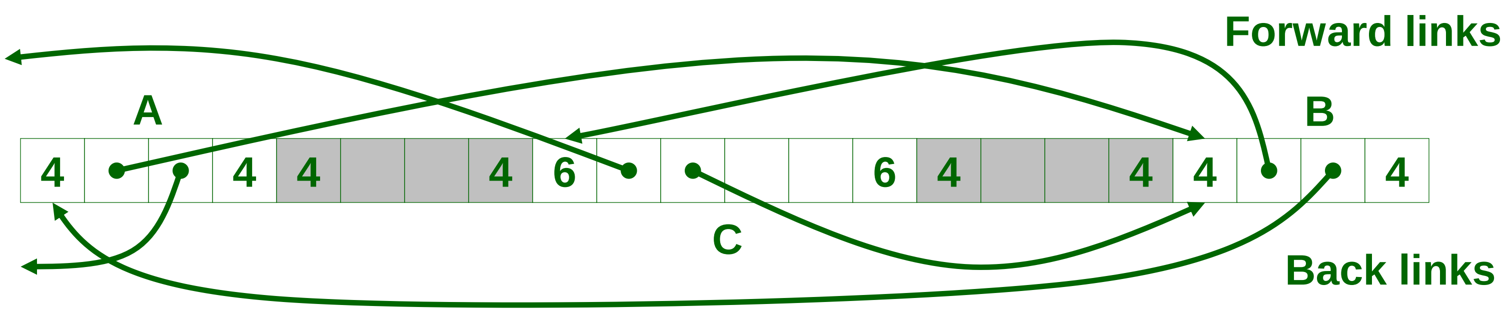
Method 4: Blocks sorted by size

- Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

Explicit Free Lists

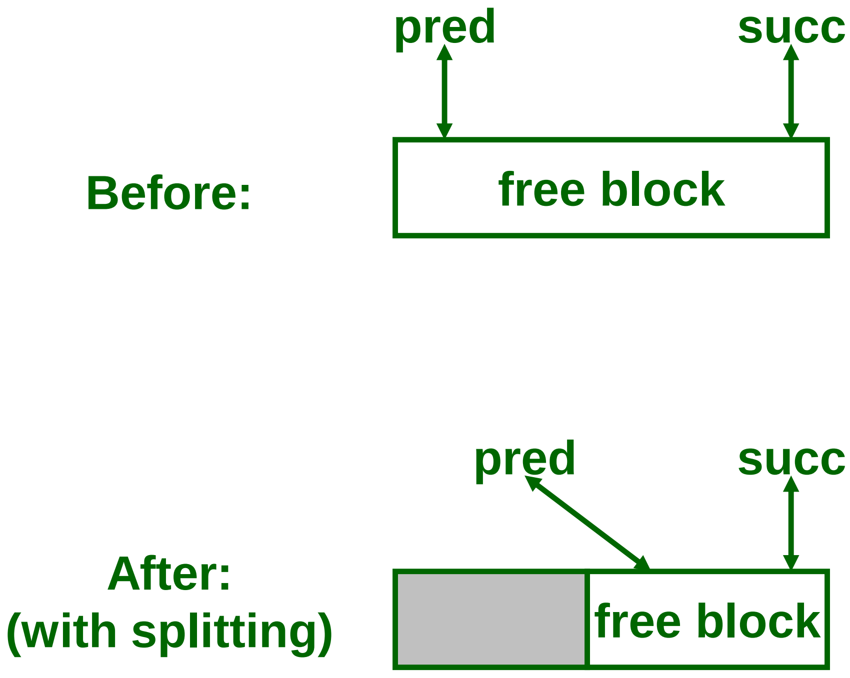
Use data space for link pointers

- Typically doubly linked
- Still need boundary tags for coalescing



- It is important to realize that links are not necessarily in the same order as the blocks

Allocating From Explicit Free Lists



Freeing With Explicit Free Lists

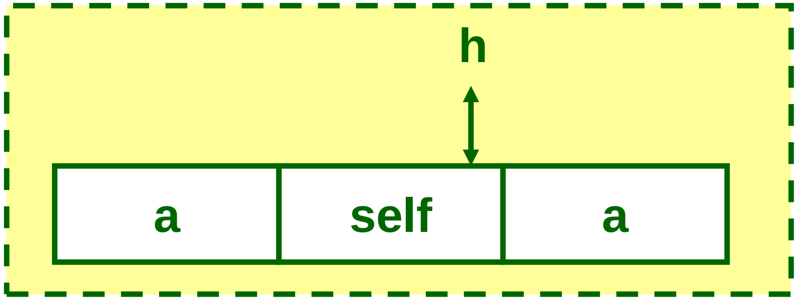
Insertion policy: Where in the free list do you put a newly freed block?

- **LIFO (last-in-first-out) policy**
  - Insert freed block at the beginning of the free list
  - Pro: simple and constant time
  - Con: studies suggest fragmentation is worse than address ordered
- **Address-ordered policy**
  - Insert freed blocks so that free list blocks are always in address order
    - i.e. addr(pred) < addr(curr) < addr(succ)
  - Con: requires search
  - Pro: studies suggest fragmentation is better than LIFO

Freeing With a LIFO Policy

Case 1: a-a-a

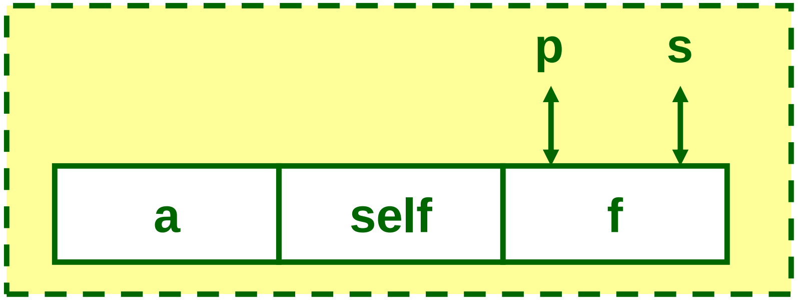
- Insert self at beginning of free list



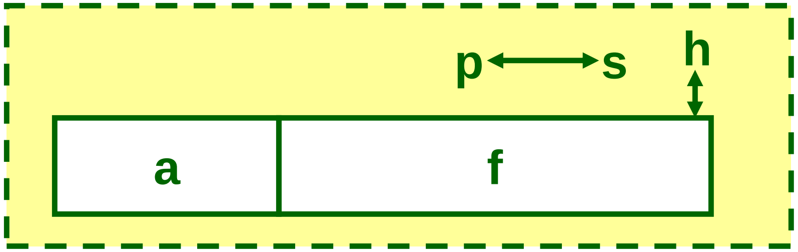
Case 2: a-a-f

- Splice out next, coalesce self and next, and add to beginning of free list

before:



after:

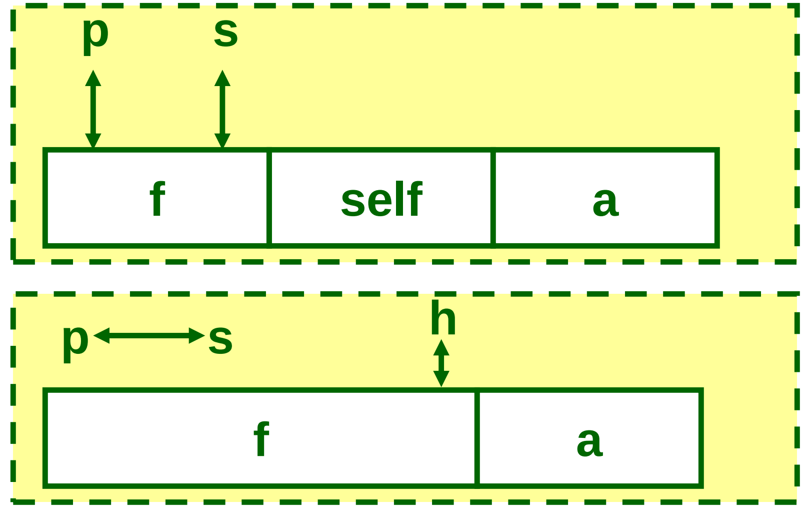


Freeing With a LIFO Policy (cont)

Case 3: f-a-a

- **Splice out prev, coalesce with self, and add to beginning of free list**

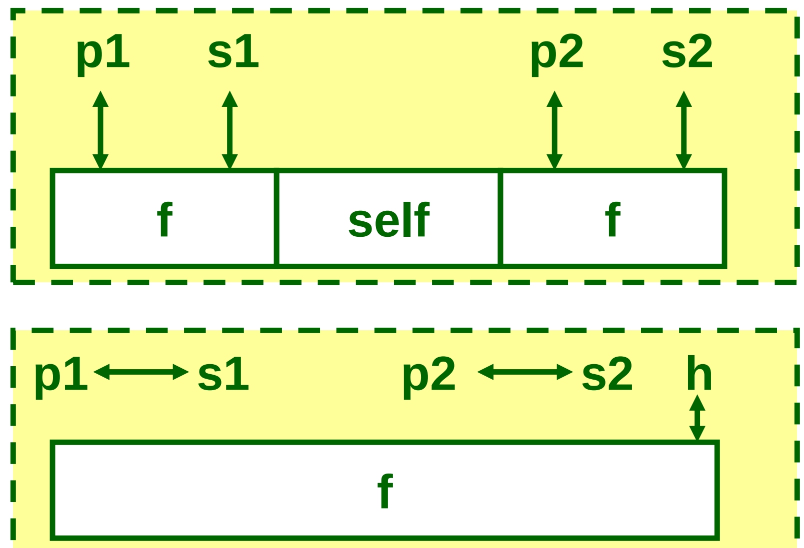
before:
after:



Case 4: f-a-f

- **Splice out prev and next, coalesce with self, and add to beginning of list**

before:
after:



Explicit List Summary

Comparison to implicit list:

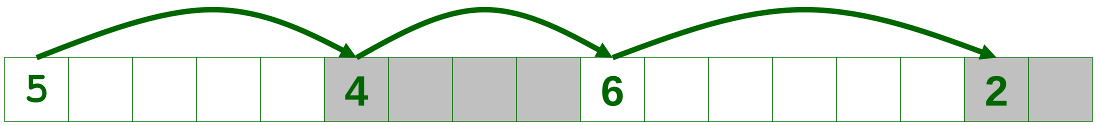
- Allocate is linear time in number of free blocks instead of total blocks – much faster allocates when most of the memory is full
- Slightly more complicated allocate and free since needs to splice blocks in and out of the list
- Some extra space for the links (2 extra words needed for each block)

Main use of linked lists is in conjunction with segregated free lists

- Keep multiple linked lists of different size classes, or possibly for different types of objects

Keeping Track of Free Blocks

Method 1: Implicit list using lengths – links all blocks



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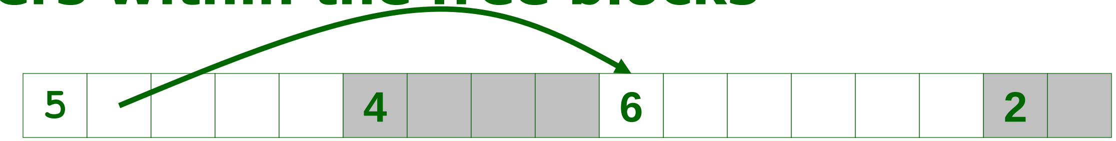


Method 3: Segregated free list

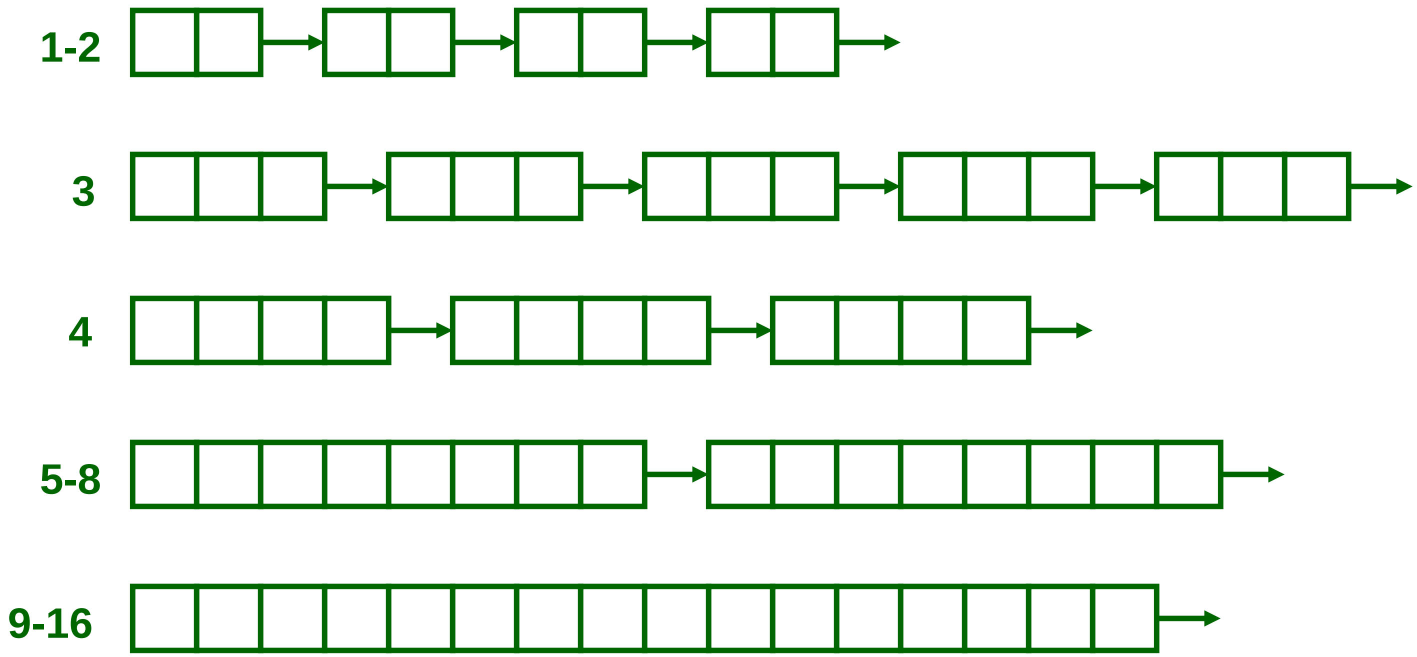
- Different free lists for different size classes

Method 4: Blocks sorted by size

- Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

Segregated Storage

Each size class has its own collection of blocks



- Often separate classes for every small size (2,3,4,…)
- Larger sizes typically grouped into powers of 2

Simple Segregated Storage

- Separate heap and free list for each size class
- No splitting
- To allocate a block of size n:
  - If free list for size n is not empty,
    - Allocate first block on list (list can be implicit or explicit)
  - If free list is empty,
    - Get a new page
    - Create new free list from all blocks in page
    - Allocate first block on list
  - Constant time
- To free a block:
  - Add to free list
  - If page is empty, could return the page for use by another size
- Tradeoffs:
  - Fast, but can fragment badly
  - Interesting observation: approximates a best fit placement policy without having the search entire free list

Segregated Fits

Array of free lists, each one for some size class

To allocate a block of size n:

- Search appropriate free list for block of size m > n
- If an appropriate block is found:
  - Split block and place fragment on appropriate list (optional)
- If no block is found, try next larger class
- Repeat until block is found

To free a block:

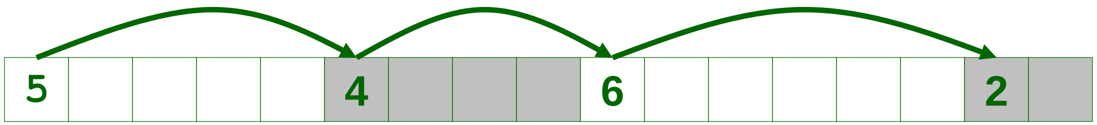
- Coalesce and place on appropriate list (optional)

Tradeoffs

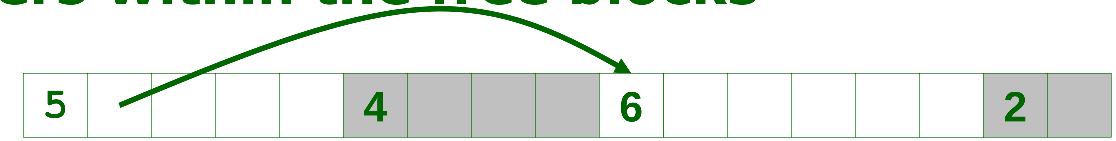
- Faster search than sequential fits (i.e., log time for power of two size classes)
- Controls fragmentation of simple segregated storage
- Coalescing can increase search times
  - Deferred coalescing can help

Keeping Track of Free Blocks

Method 1: Implicit list using lengths – links all blocks



Method 2: Explicit list among the free blocks using pointers within the free blocks



Method 3: Segregated free list

- Different free lists for different size classes

Method 4: Blocks sorted by size

- Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

Spatial Locality

Most techniques give little control over spatial locality

- **Sequentially-allocated blocks not necessarily adjacent**
- **Similarly-sized blocks (e.g., for same data type) not necessarily adjacent**

Would like a series of similar-sized allocations and deallocations to reuse same blocks

- **Splitting & coalescing tend to reduce locality**

? Of techniques seen, which best for spatial locality? ?

Simple segregated lists
Each page only has similar-sized blocks

Spatial Locality: Regions

One technique to improve spatial locality

Dynamically divide heap into mini-heaps

- Programmer-determined

Allocate data within appropriate region

- Data that is logically used together
- Increase locality
- Can quickly deallocate an entire region at once

Changes API
`malloc()` and `free()`
must take a region
as an argument

For More Info on Allocators

D. Knuth, "The Art of Computer Programming, Second 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)

Implementation Summary

Many options:

- Data structures for keeping track of free blocks
- Block choice policy
- Splitting & coalescing policies

No clear best option

- Many tradeoffs
- Some behaviors not well understood by anyone
- Depends on “typical” program’s pattern of allocation and deallocation

Explicit Memory Allocation/Deallocation

+ Usually low time- and space-overhead

- Challenging to use correctly by programmers
    - Lead to crashes, memory leaks, etc.

Implicit Memory Deallocation

+ Programmers don't need to free data explicitly, easy to use

+ Some implementations could achieve better spatial locality and less fragmentation in the hands of your average programmers

- Price to pay: depends on implementation

But HOW could a memory manager know when to deallocate data without instruction from programmer?

Implicit Memory Management: Garbage Collection

Garbage collection: automatic reclamation of heap-allocated storage – application never has to free

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

Common in functional languages and modern object oriented languages:

- C#, Go, Java, Lisp, Python, Scala, Swift

Variants (conservative garbage collectors) exist for C and C++

- Cannot collect all garbage

Garbage Collection

How does the memory manager 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 there are no pointers to them

Need to make certain assumptions about pointers

- Memory manager can distinguish pointers from non-pointers
- All pointers point to the start of a block
- Cannot hide pointers (e.g., by coercing them to an int, and then back again)

Classical GC algorithms

Reference counting (Collins, 1960)

- Does not move blocks

Mark and sweep collection (McCarthy, 1960)

- Does not move blocks (unless you also "compact")

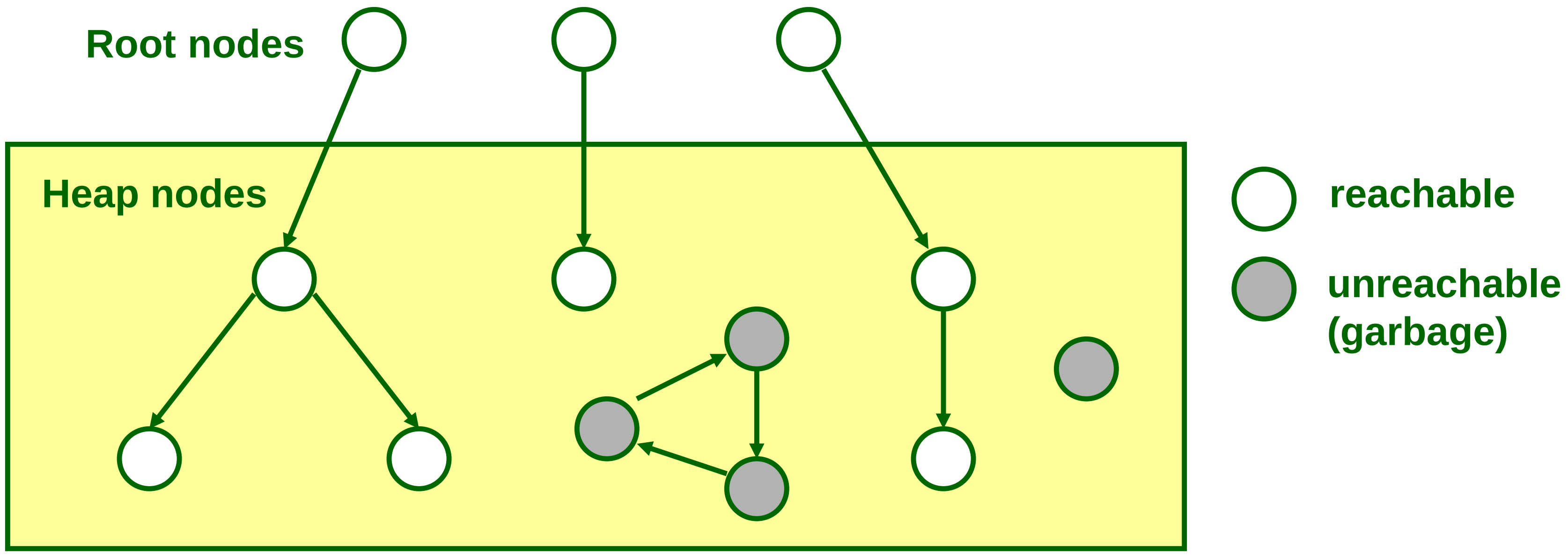
Copying collection (Minsky, 1963)

- Moves blocks (compacts memory)

For more information, see Jones and Lin, "Garbage Collection: Algorithms for Automatic Dynamic Memory", John Wiley & Sons, 1996.

Memory as a Graph

- Each data block is a node in the graph
- Each pointer is an edge in the graph
- Root nodes: locations not in the heap that contain pointers into the heap (e.g. registers, locations on the stack, global variables)



Reference Counting

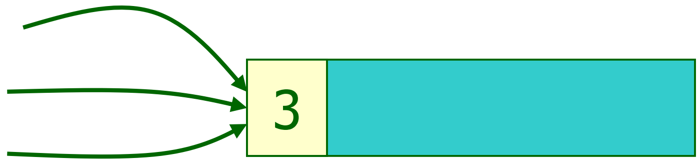
Overall idea

- Maintain a free list of unallocated blocks
- Maintain a count of the number of references to each allocated block
- To allocate, grab a sufficiently large block from the free list
- When a count goes to zero, deallocate it

Reference Counting: More Details

Each allocated block keeps a count of references to the block

- Reachable $\rightarrow$ count is positive
- Compiler inserts counter increments and decrements as necessary
- Deallocate when count goes to zero



Typically built on top of an explicit deallocation memory manager

- All the same implementation decisions as before
- E.g., splitting & coalescing

Reference Counting: Example

```
a = cons(10,empty)
b = cons(20,a)
a = b
b = …
a = …
```

Reference Counting: Example

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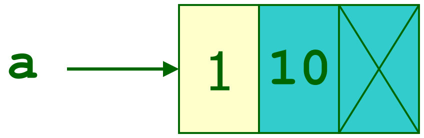

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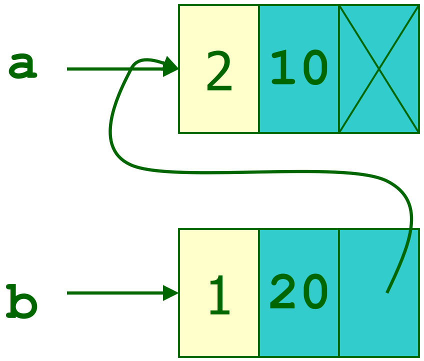

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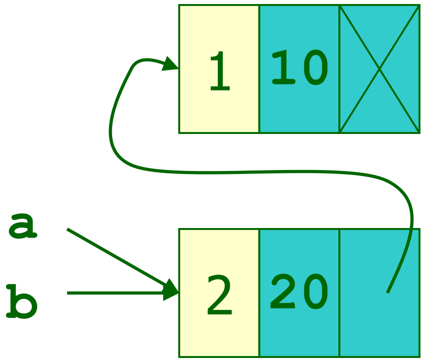

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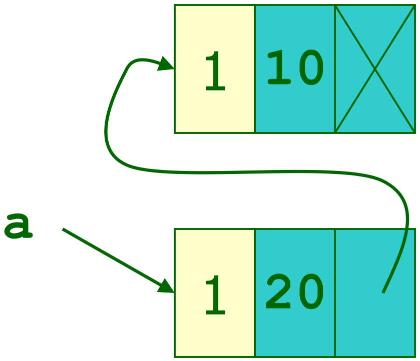

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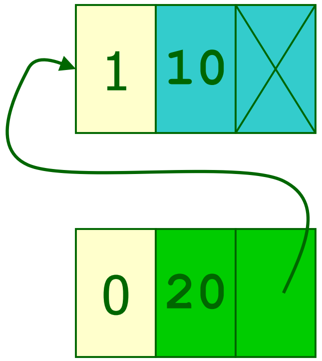

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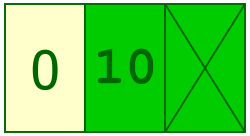

Reference Counting: Example

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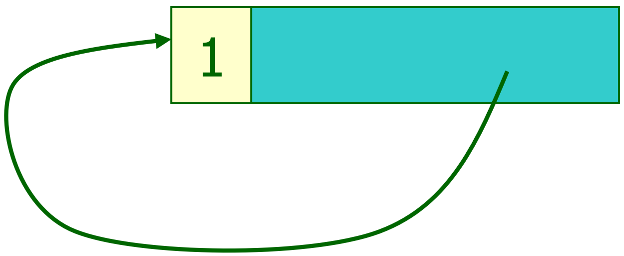
a = b
b = …
a = …
```

Reference Counting: Problem

? **What's the problem?** ?



- **No other pointer to this data, so can't refer to it**
  - **Count not zero, so never deallocated**
  - **Following does NOT hold: Count is positive → reachable**
- **Can occur with any cycle**

Reference Counting: Summary

Disadvantages:

- Managing & testing counts is generally expensive
  - Can optimize
- Doesn't work with cycles!
  - Approach can be modified to work, with difficulty

Advantage:

- Simple
  - Easily adapted, e.g., for parallel or distributed GC

Useful when cycles can't happen

- E.g., UNIX hard links

GC Without Reference Counts

If don't have counts, how to deallocate?

Determine reachability by traversing pointer graph directly

- **Stop user's computation periodically to compute reachability**
- **Deallocate anything unreachable**

Mark & Sweep

Overall idea

- Maintain a free list of unallocated blocks
- To allocate, grab a sufficiently large block from free list
- When no such block exists, GC
  - Should find blocks & put them on free list

Mark & Sweep: GC

Follow all pointers, marking all reachable data

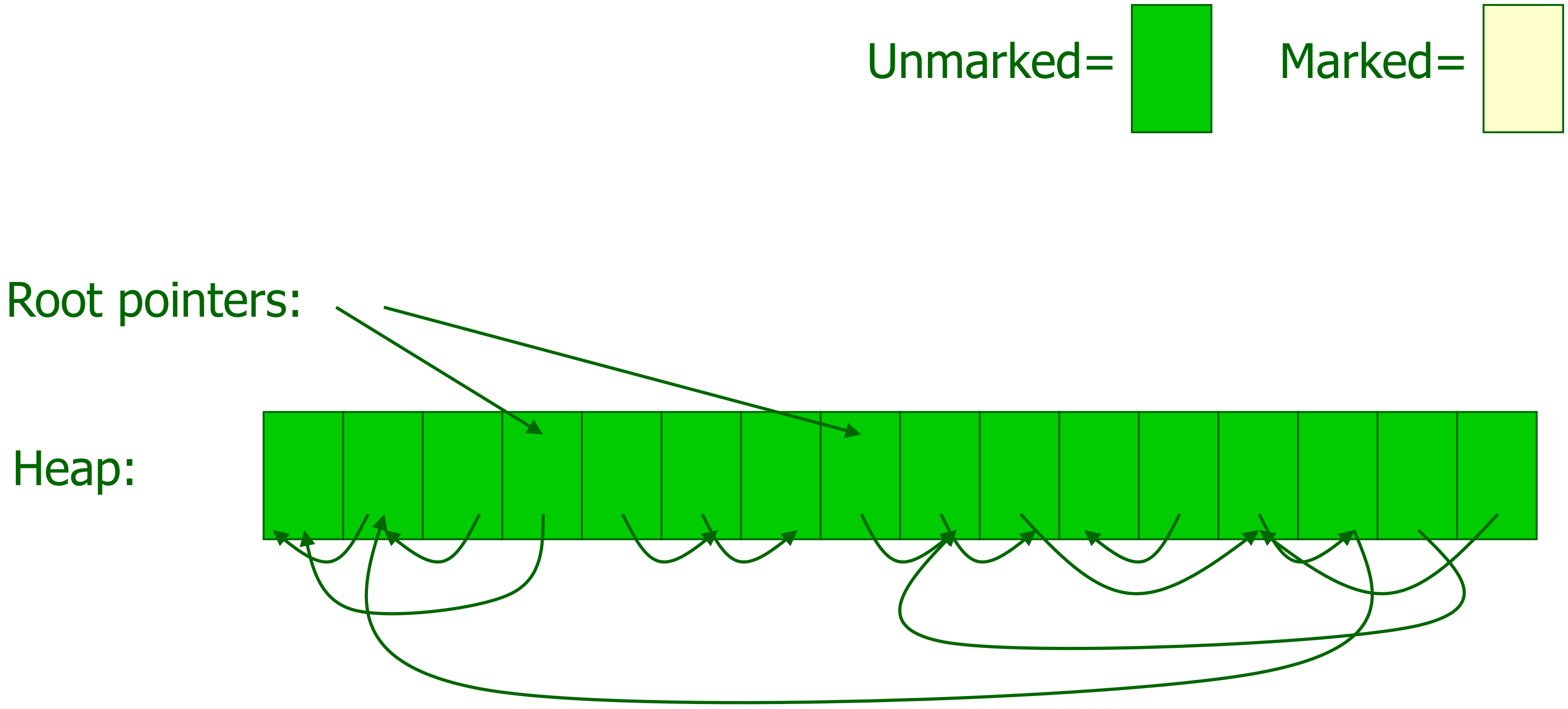
- Use depth-first search
- Data must be tagged with info about its type, so GC knows its size and can identify pointers
- Each piece of data must have a mark bit
  - Can alternate meaning of mark bit on each GC to avoid erasing mark bits

Sweep over all heap, putting all unmarked data into a free list

- Again, same implementation issues for the free list

Mark & Sweep: GC Example

Assume fixed-sized, single-pointer data blocks, for simplicity.



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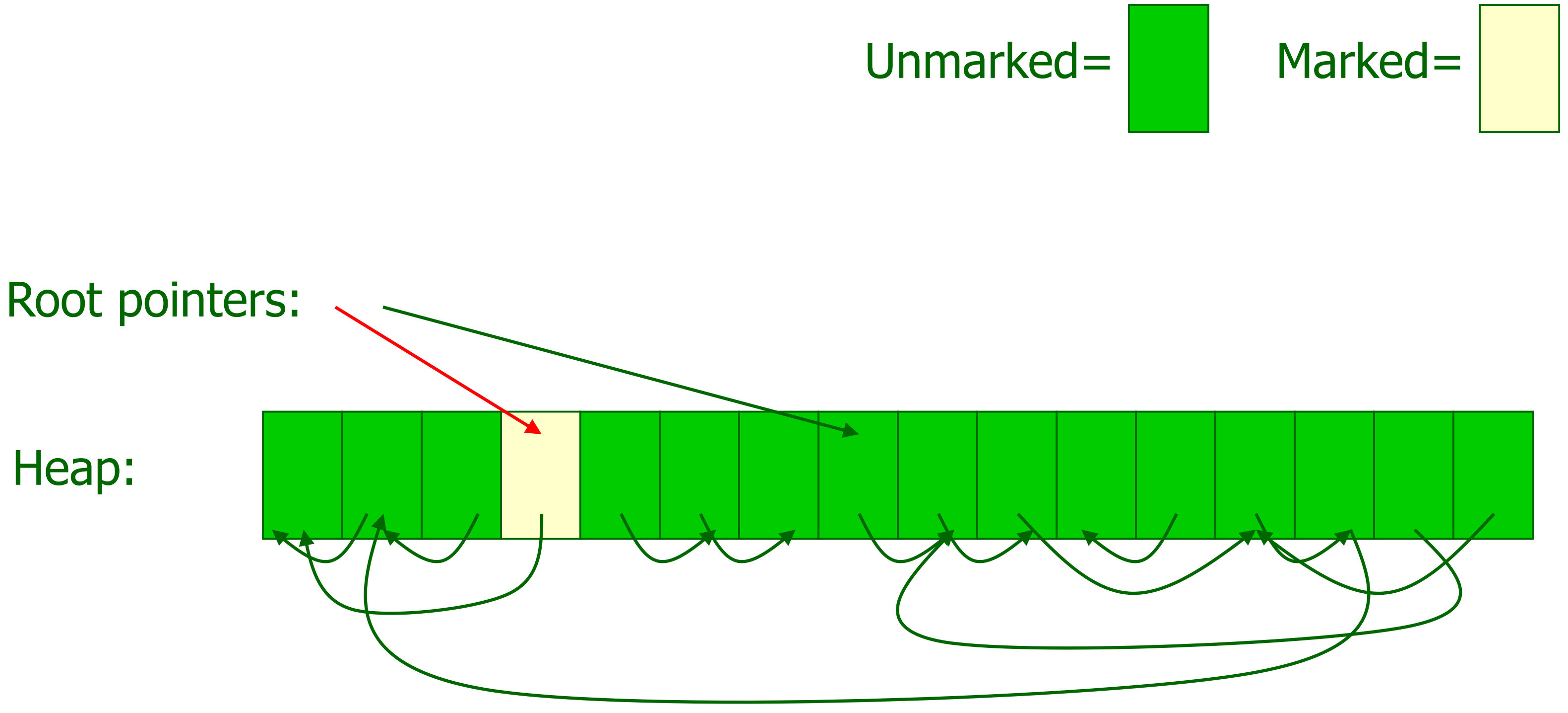

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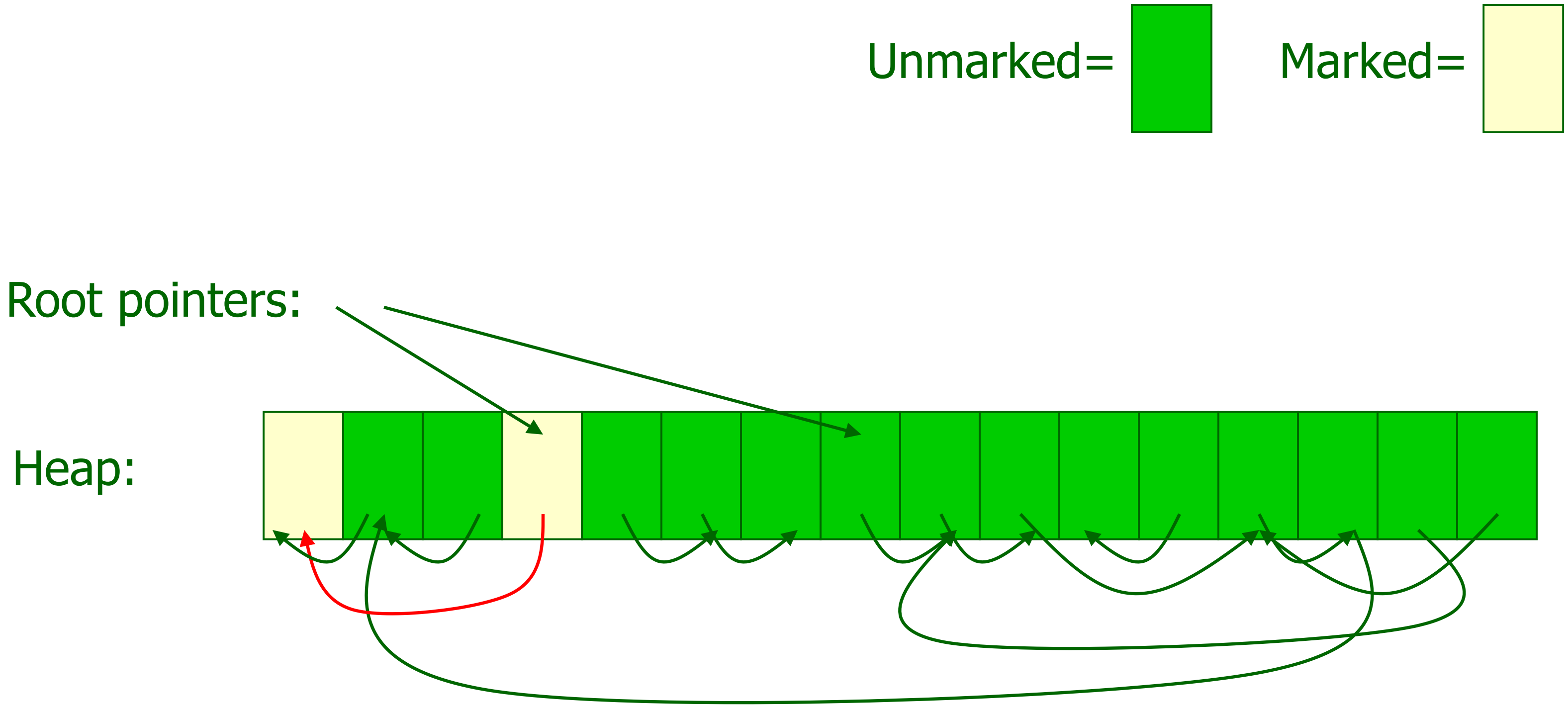

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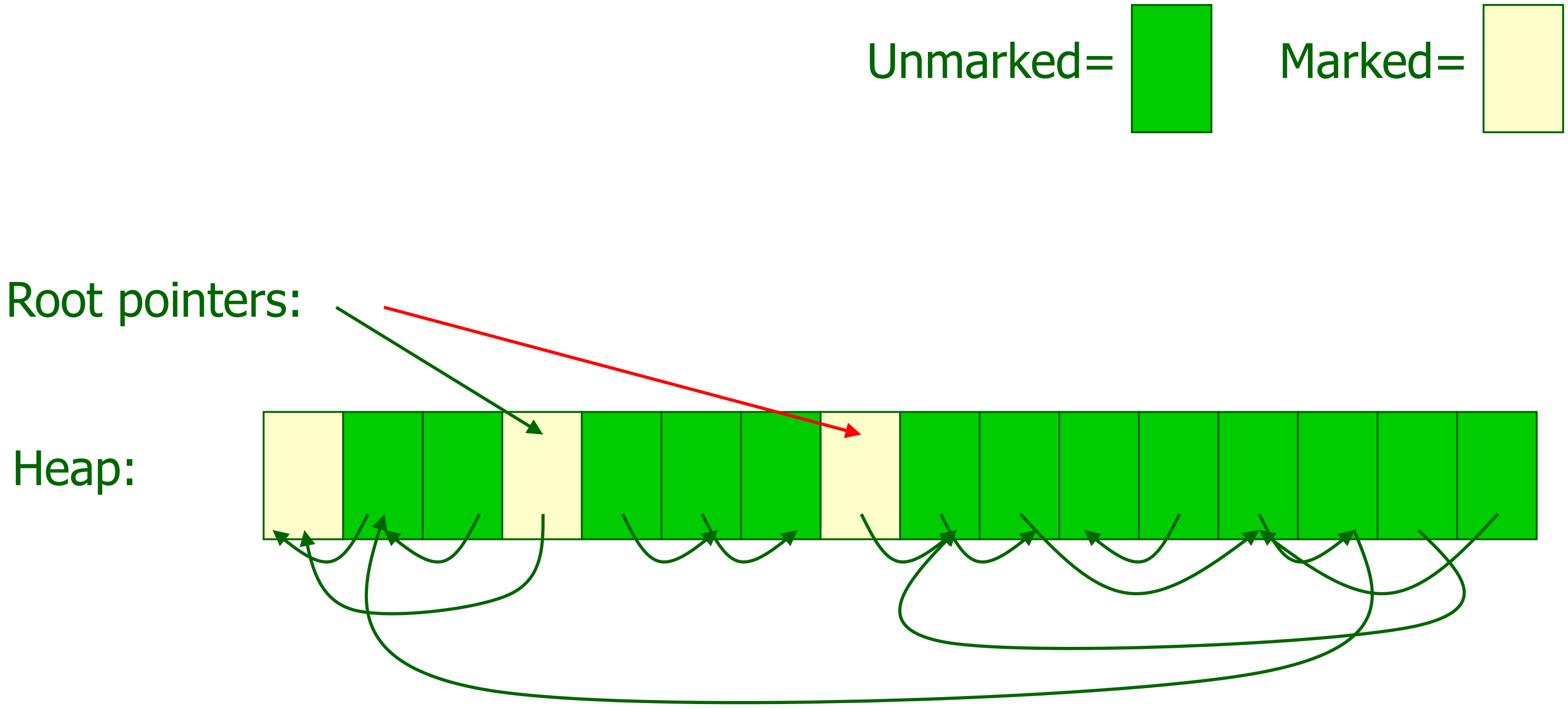

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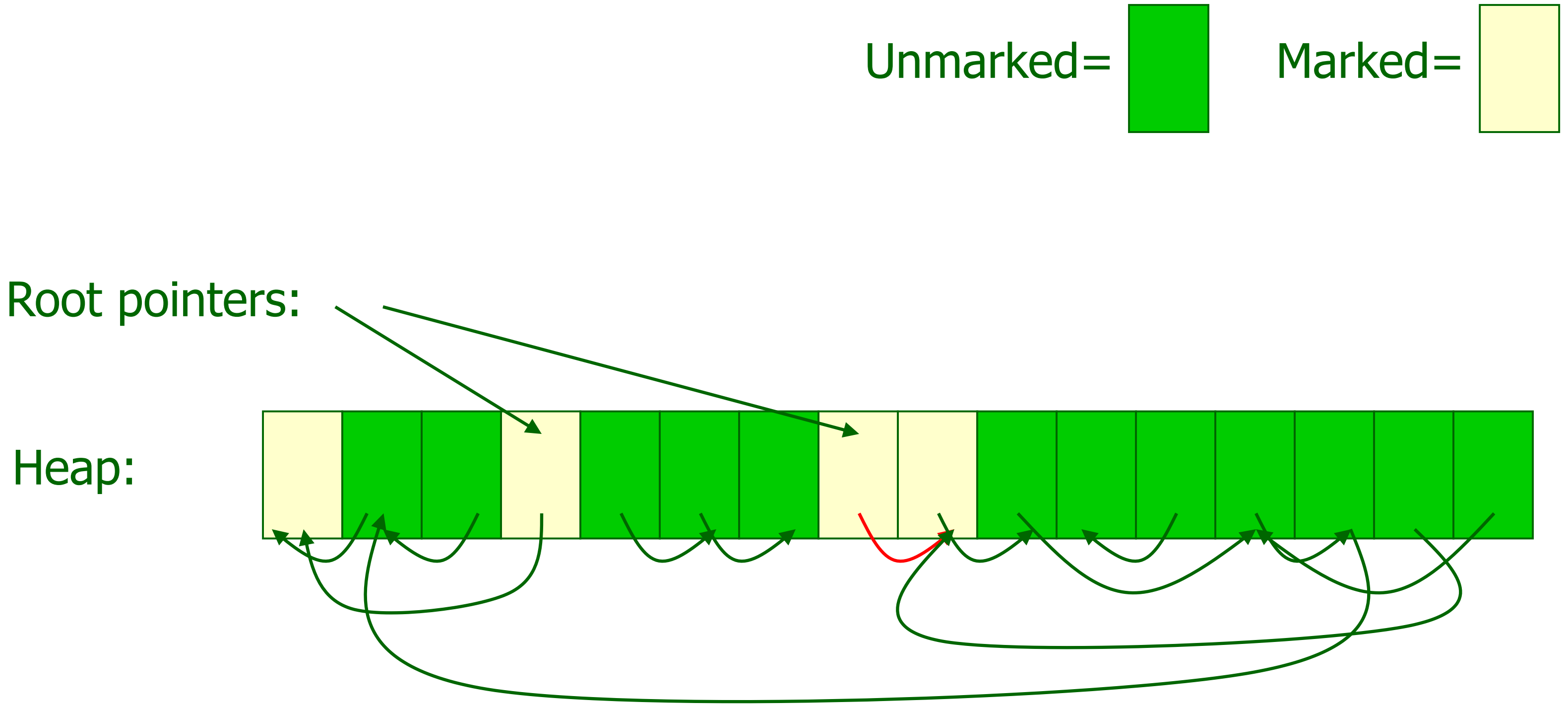

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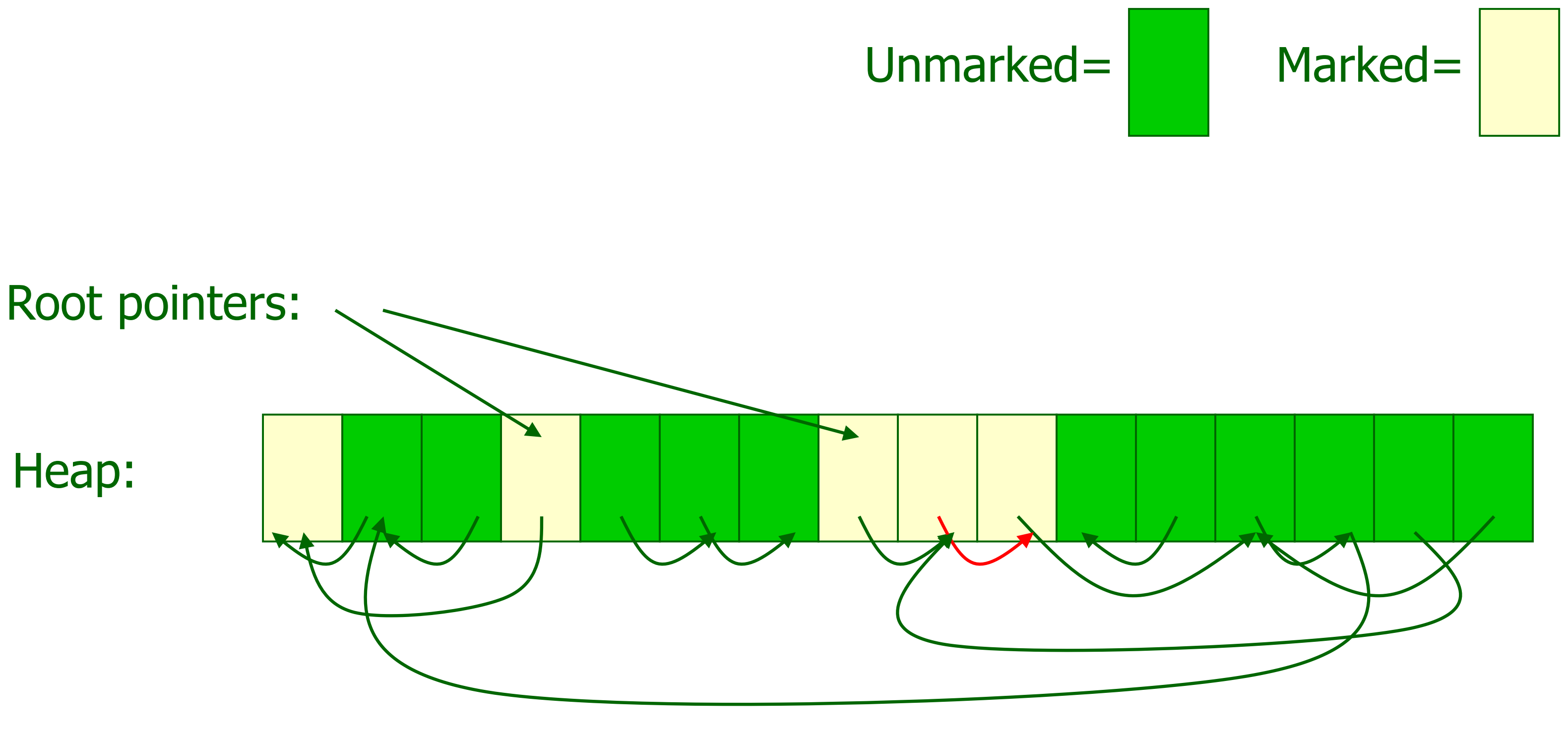

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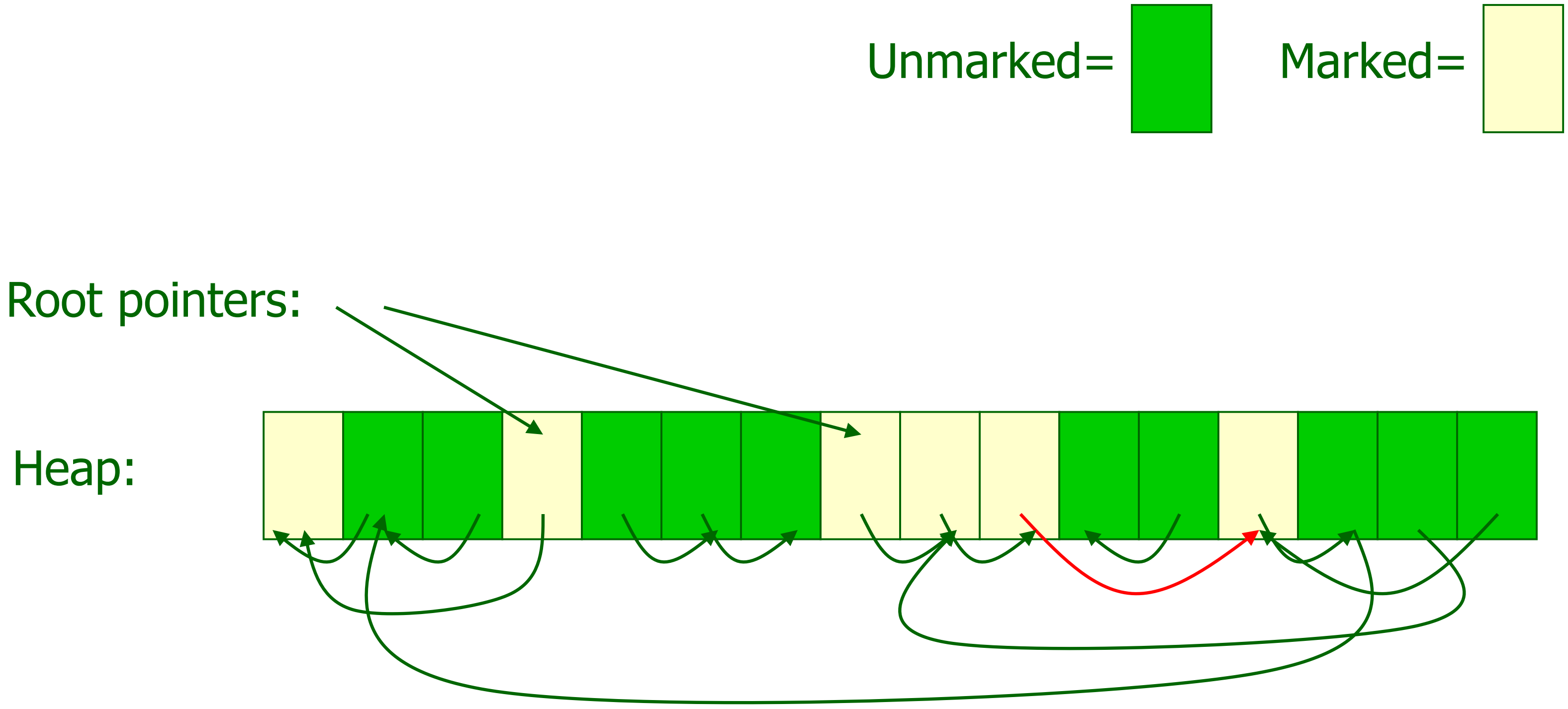

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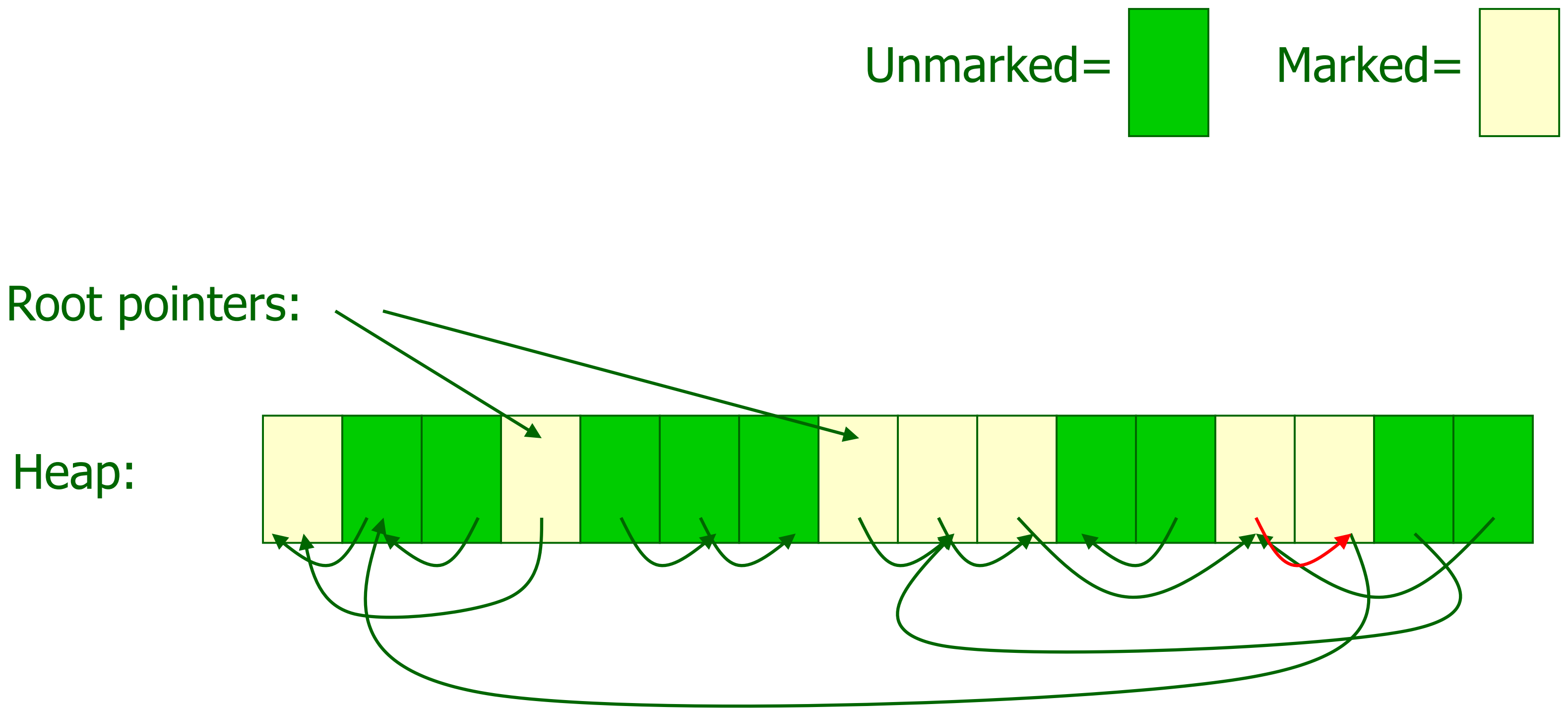

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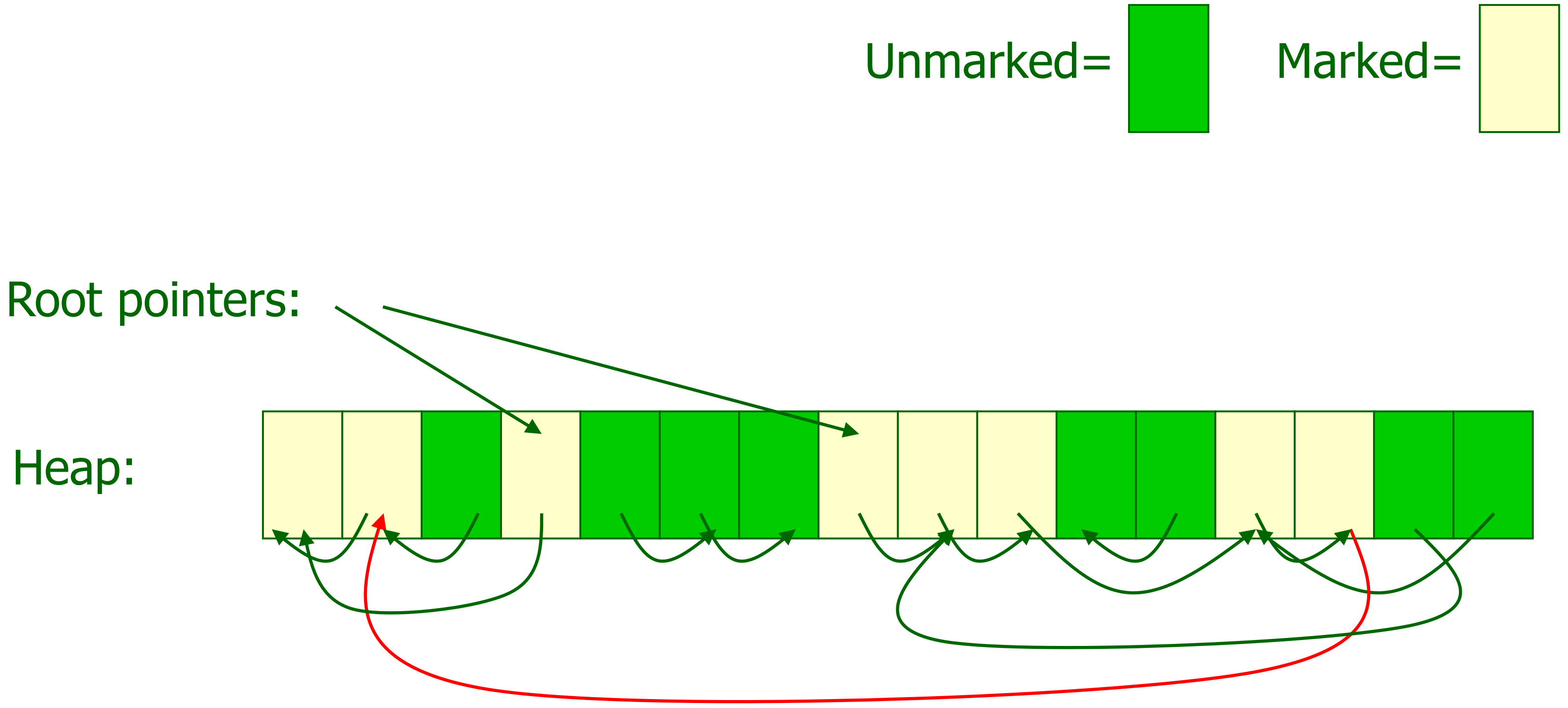

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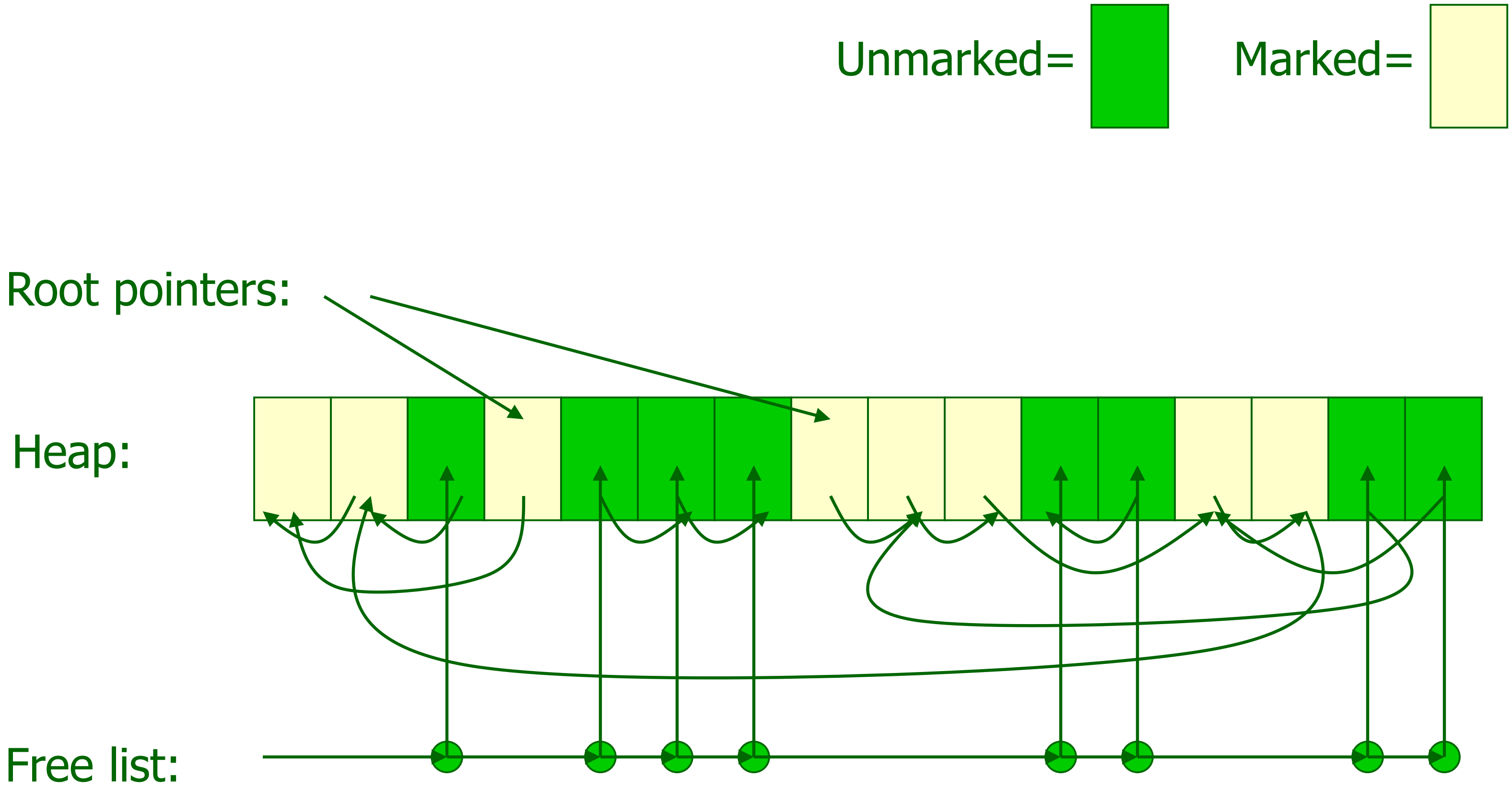

Mark & Sweep: Summary

Advantages:

- No space overhead for reference counts
- No time overhead for reference counts
- Handles cycles

Disadvantage:

- Noticeable pauses for GC

Stop & Copy

Overall idea:

- Maintain *From* and *To* spaces in heap
- To allocate, get sequentially next block in *From* space
  - No free list!
- When From space full, GC into *To* space
  - Swap *From* & *To* names

Stop & Copy: GC

Follow all From-space pointers, copying all reachable data into To-space

- **Use depth-first search**
- **Data must be tagged with info about its type, so GC knows its size and can identify pointers**

Swap From-space and To-space names

Stop & Copy: GC Example

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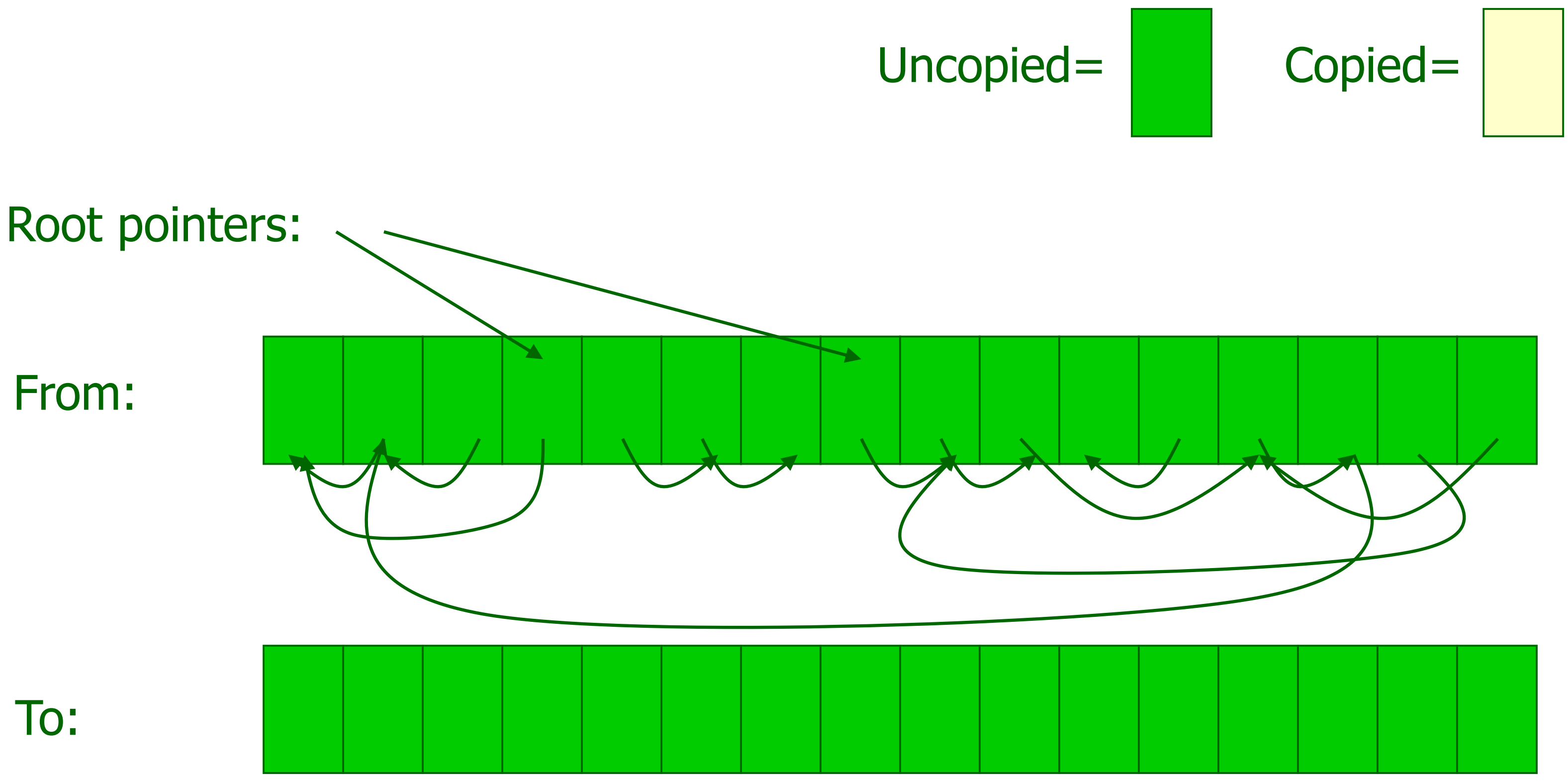

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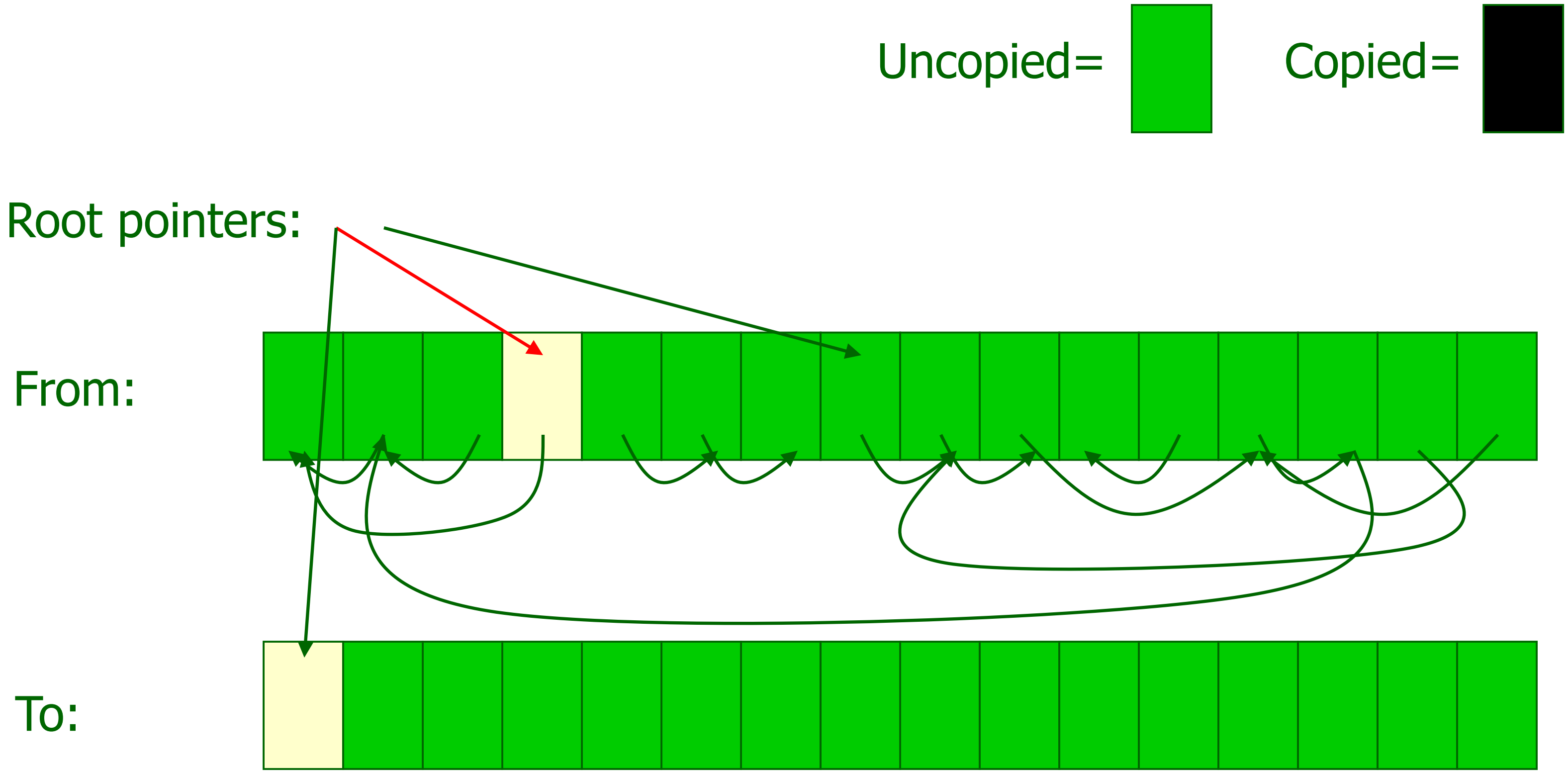

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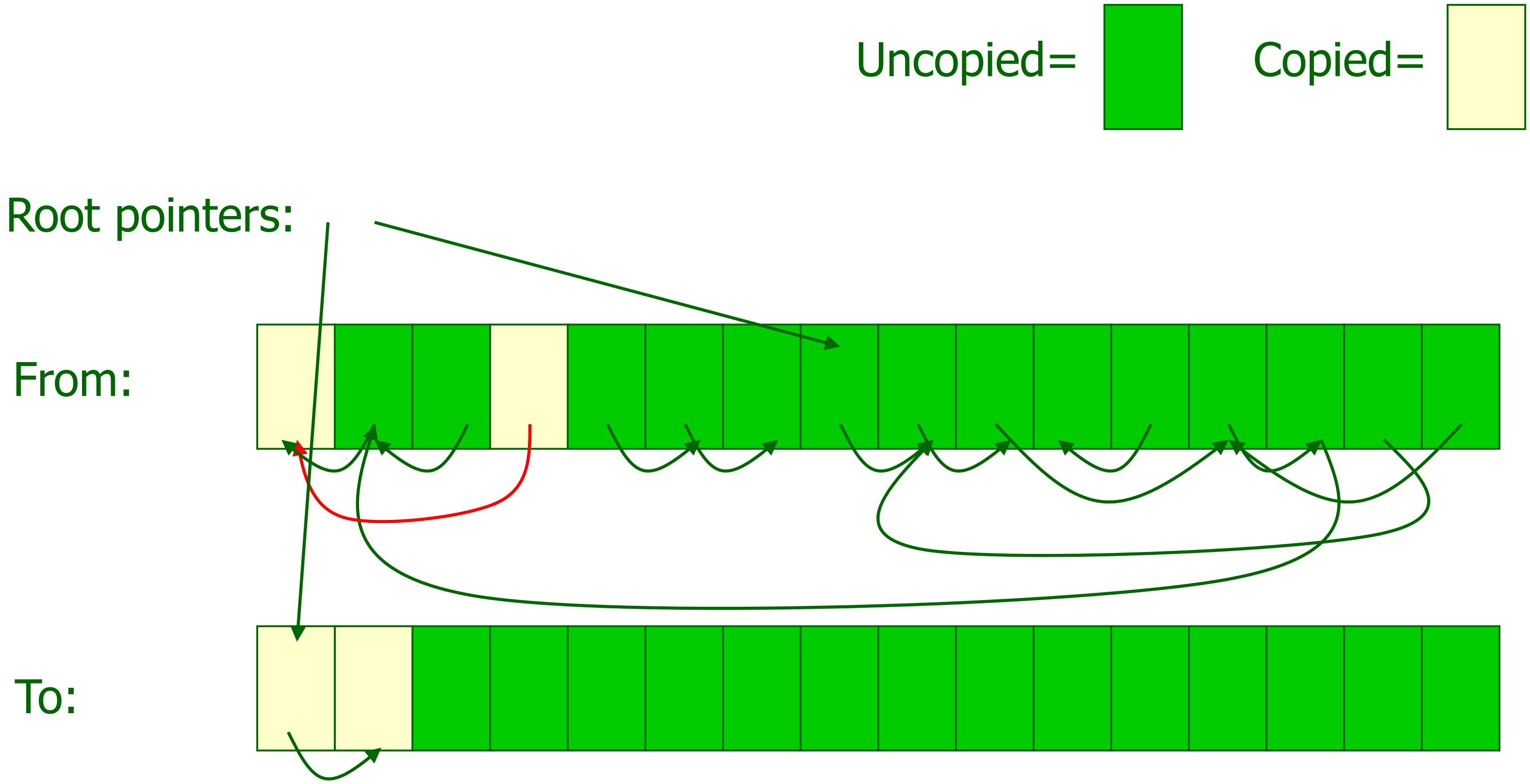

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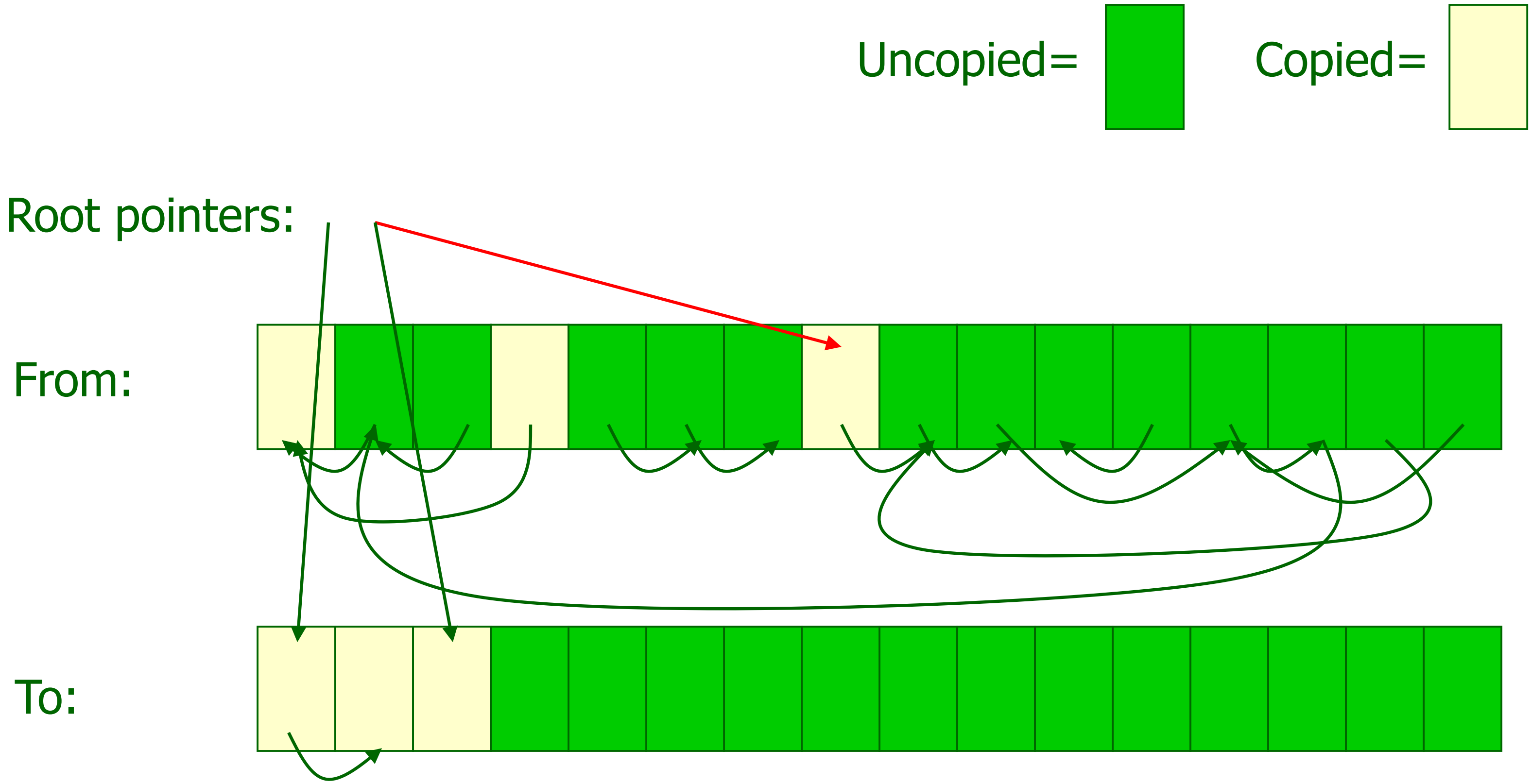

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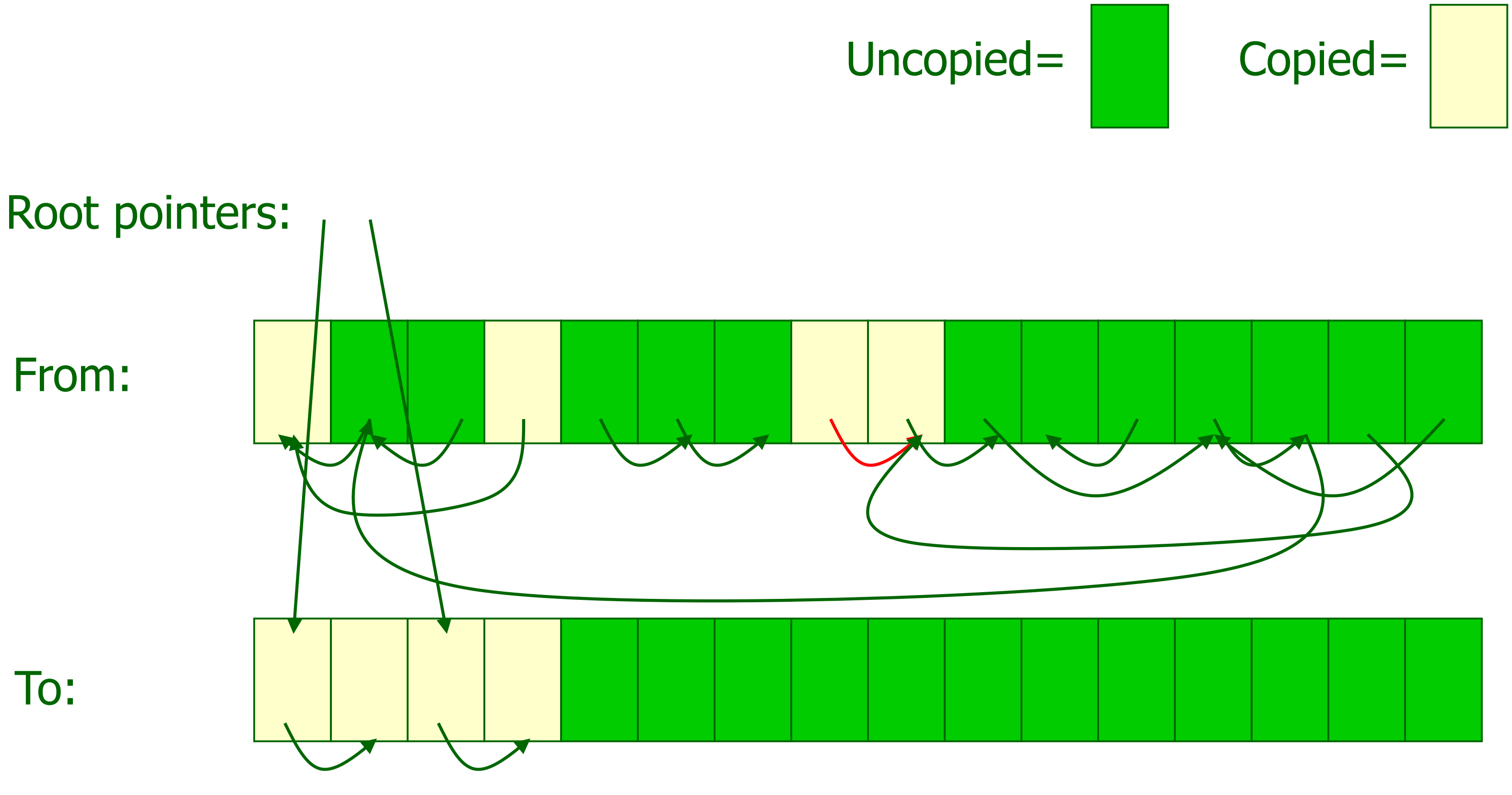

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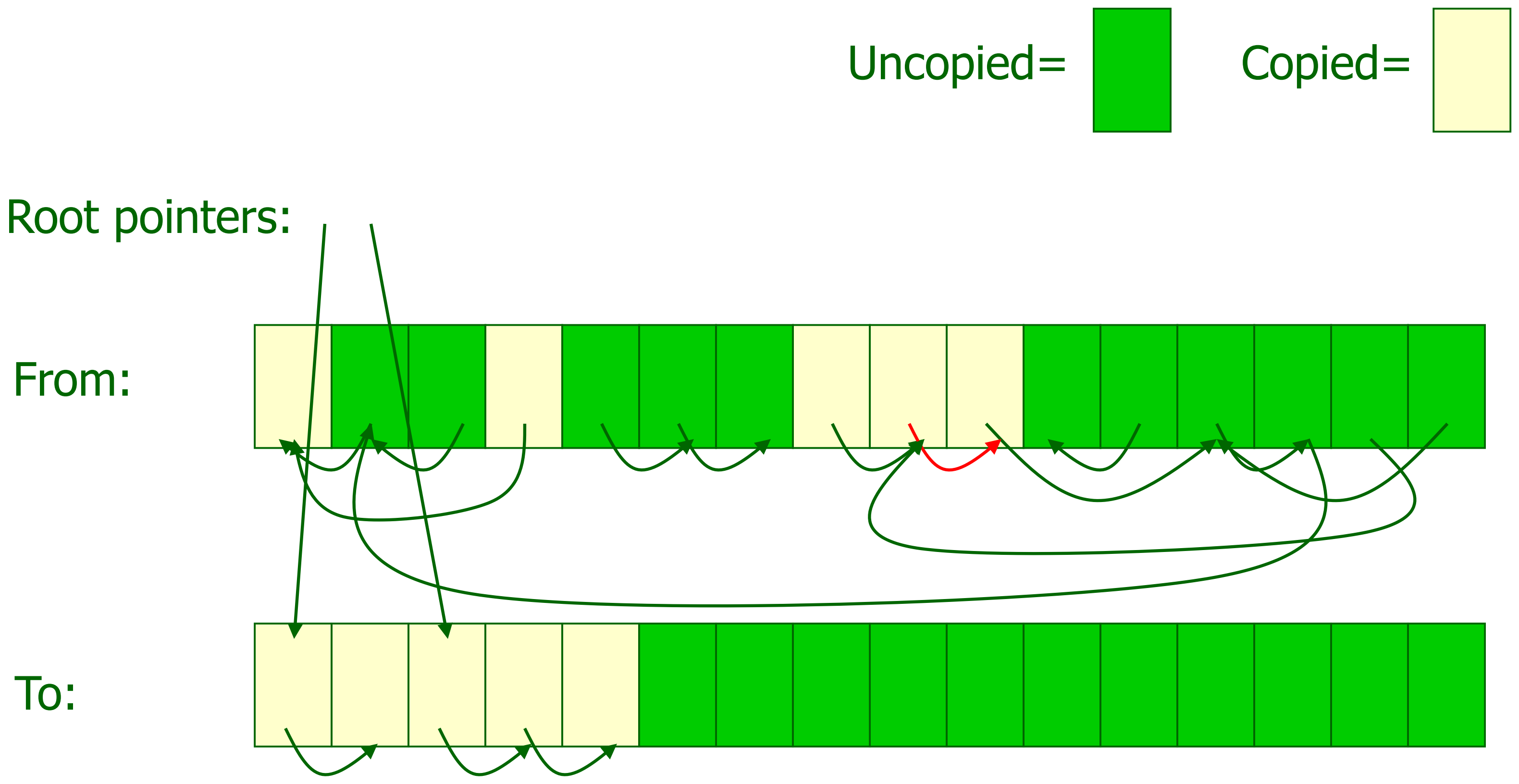

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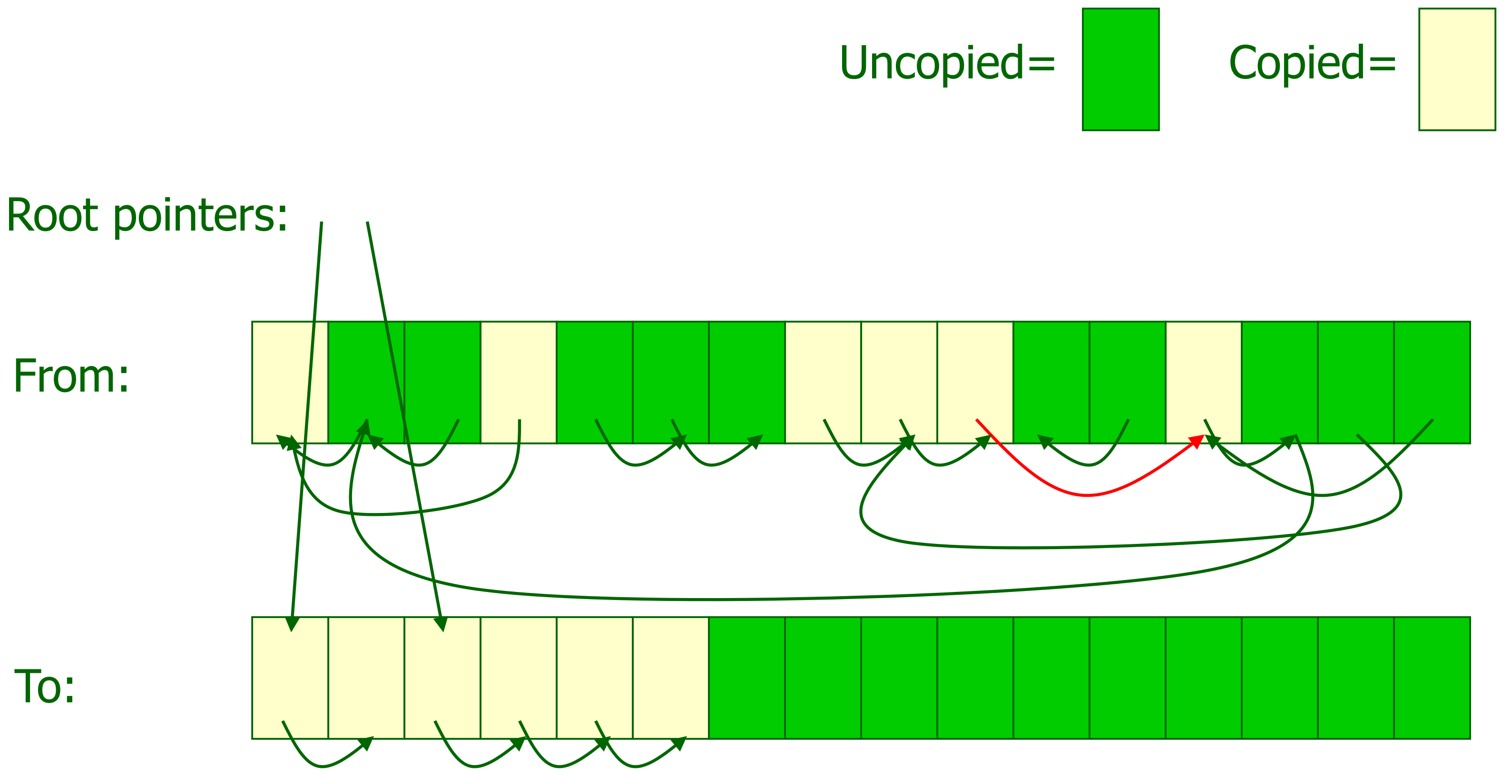

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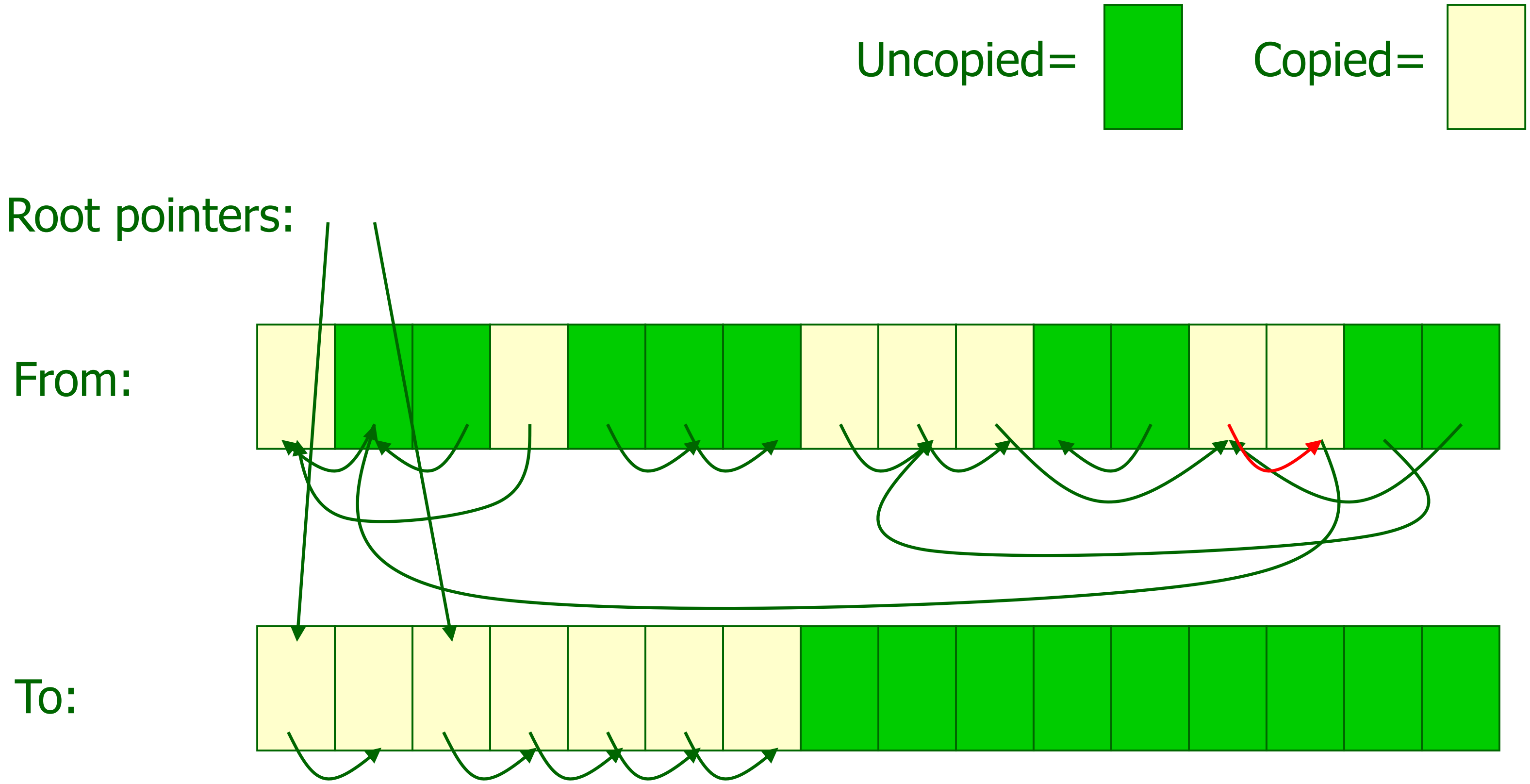

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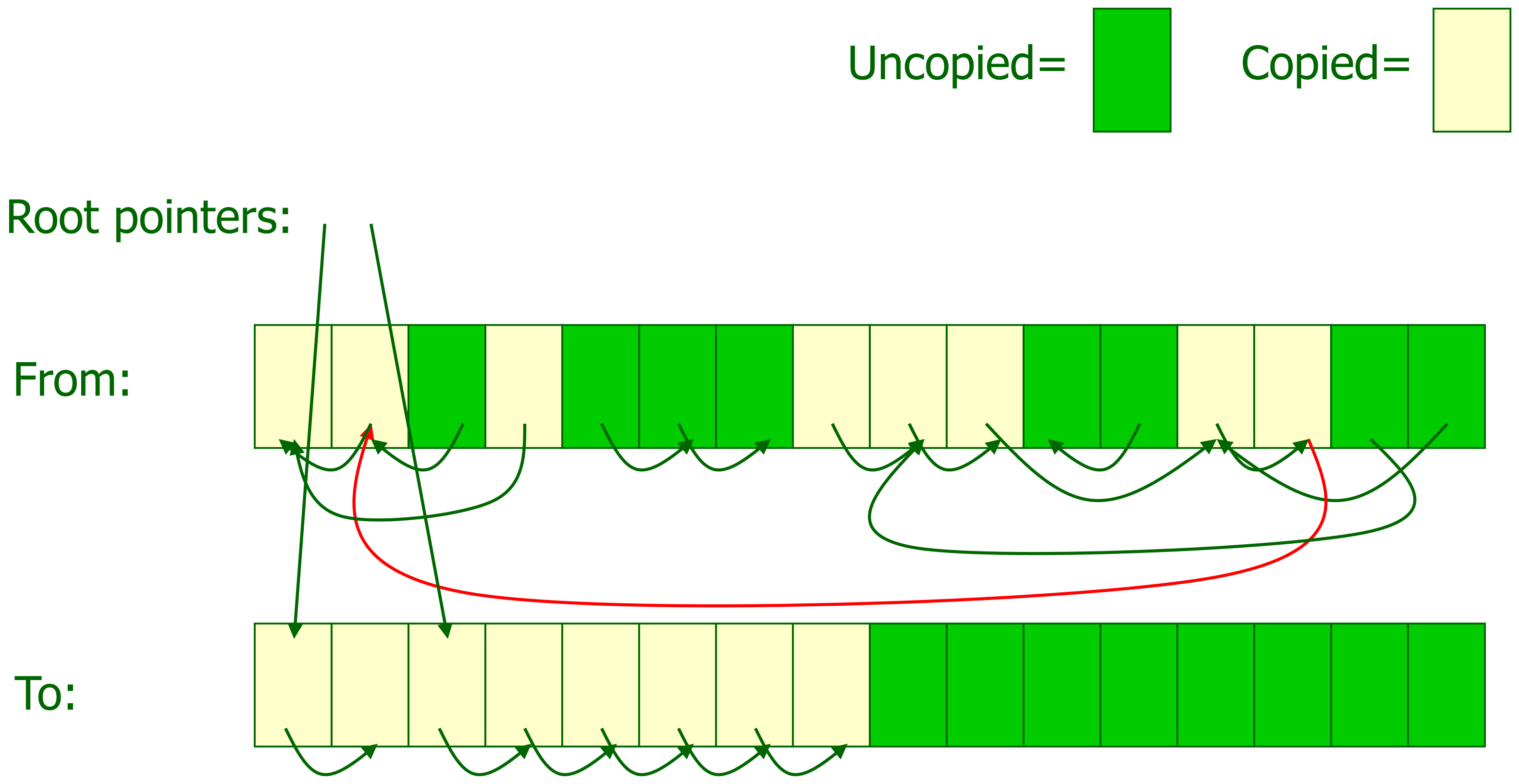

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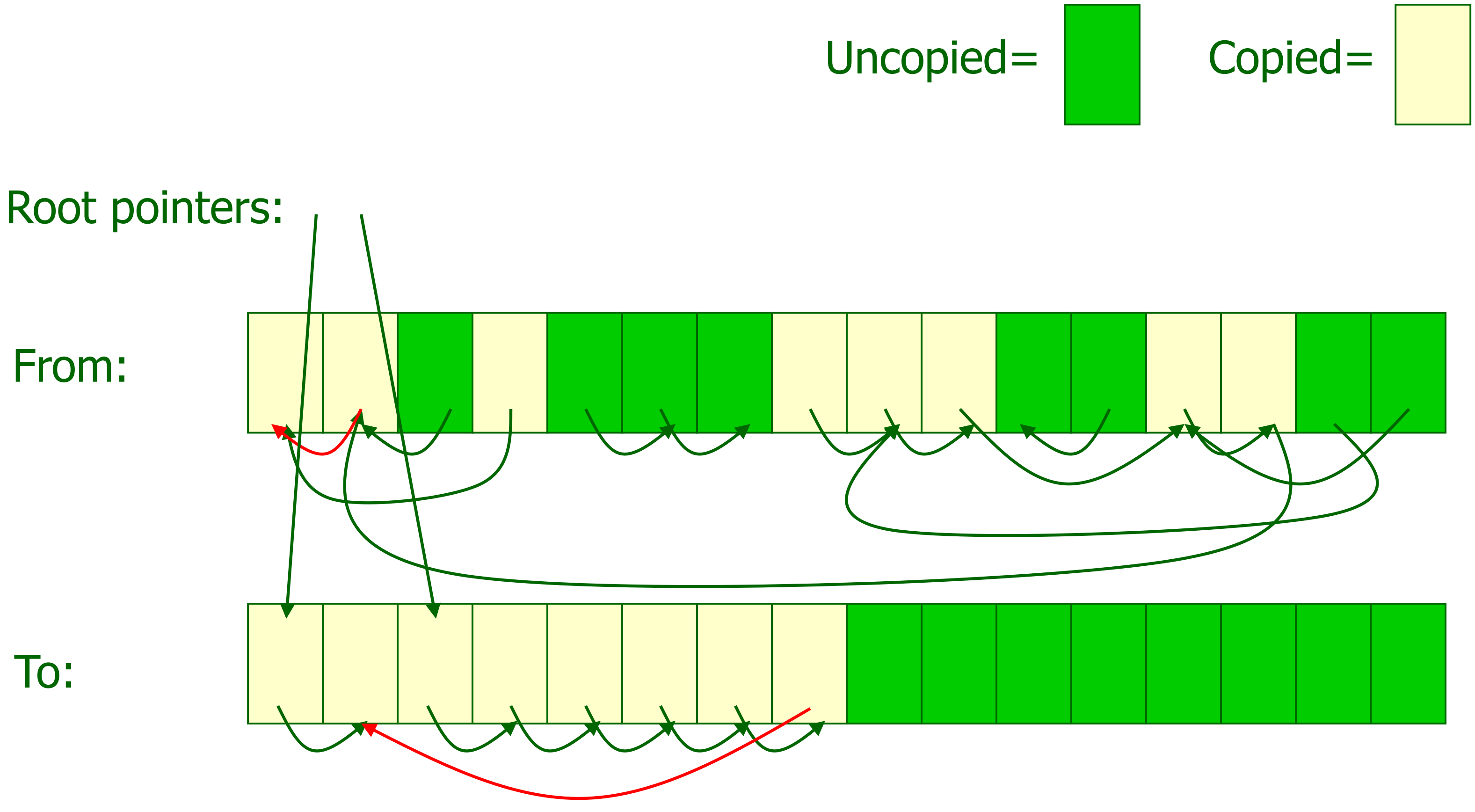

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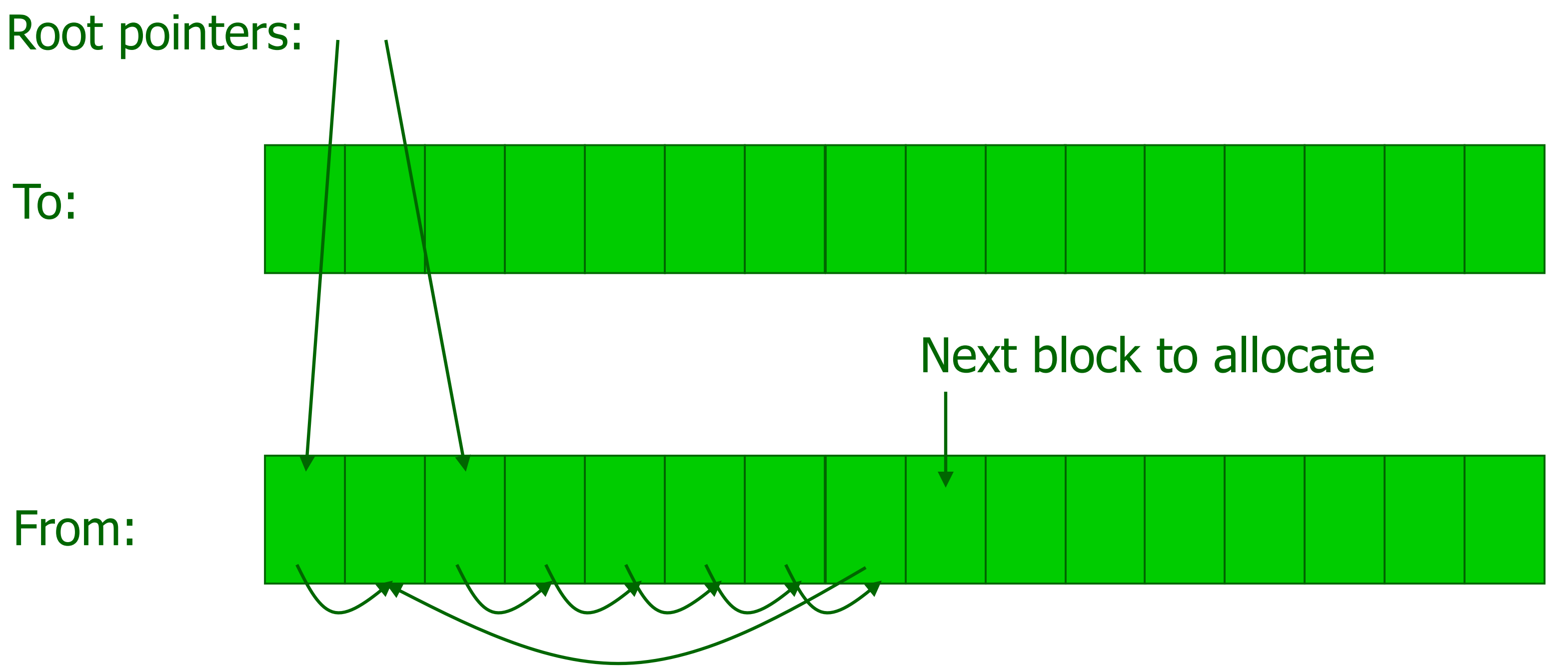

Stop & Copy

Advantages:

- Only one pass over data
- Only touches reachable data
- Little space overhead per data item
- Very simple allocation
- “Compacts” data
- Handles cycles

Disadvantages:

- Noticeable pauses for GC
- Double the basic heap size

Compaction

Moving allocated data into contiguous memory

Eliminates fragmentation

Tends to increase spatial locality

Must be able to reassociate data & locations

- Not possible if C-like pointers in source language

GC Variations

Many variations on these three main themes

- **Concurrent GC, which does not stop the computation during GC**
- **Generational GC, which exploits the observation that most objects have a short lifetime**
- **Conservative GC**

Combinations of these three main themes are common

- **Java uses both Copying and Mark-and-Sweep within a Generational GC**

Conservative GC

Goal

- Allow GC in C-like languages

Usually a variation on Mark & Sweep

Must conservatively assume that integers and other data can be cast to pointers

- Compile-time analysis to see when this is definitely not the case
- Code style heavily influences effectiveness

GC vs. `malloc/free` Summary

Safety is not programmer-dependent

Compaction generally improves locality

Higher or lower time overhead

- Generally less predictable time overhead

Generally higher space overhead

Next Time

Virtual Memory