

CSC 252/452: Computer Organization

Fall 2024: Lecture 23

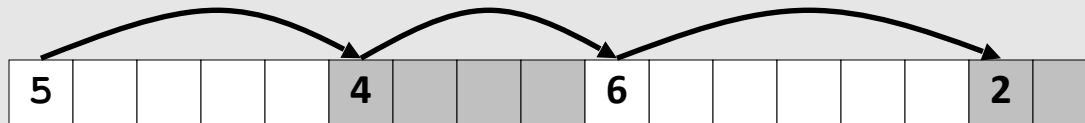
Instructor: Yanan Guo

Department of Computer Science
University of Rochester

Announcements

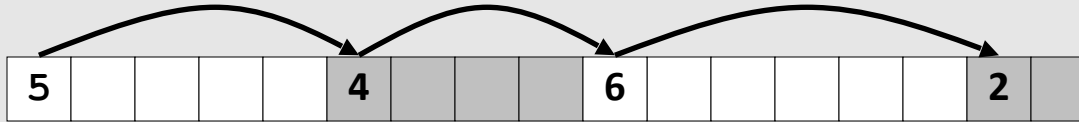
- Programming Assignment 5 has been released.
 - Due Dec. 4th (Wednesday)

Keeping Track of Free Blocks



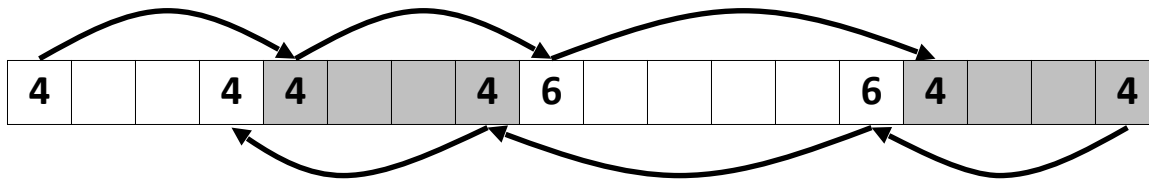
Keeping Track of Free Blocks

- Method 1: *Implicit list* using length—links all blocks



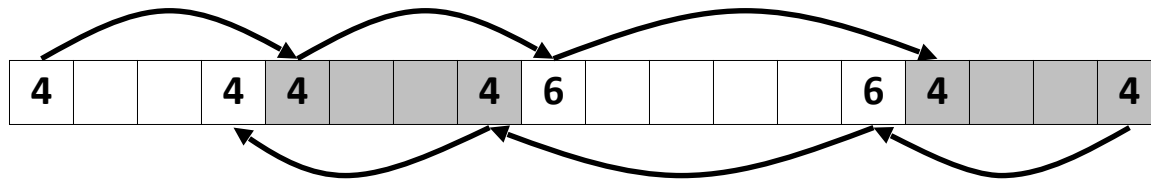
Implicit List

- For each block we need both size and allocation status

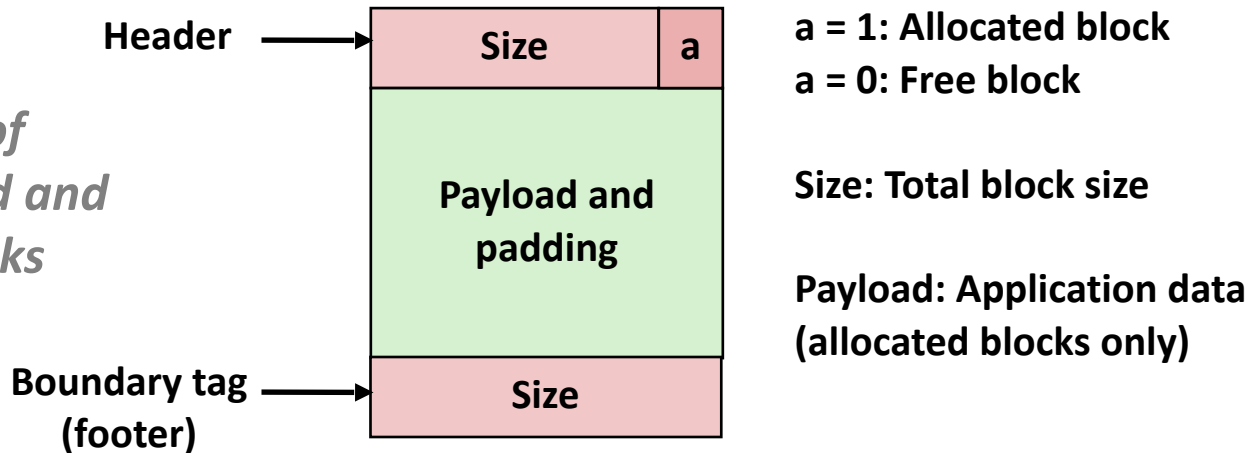


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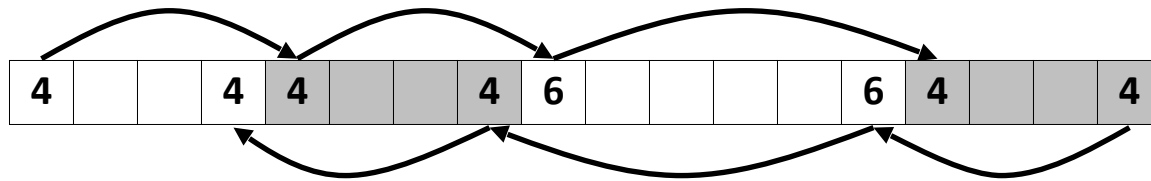


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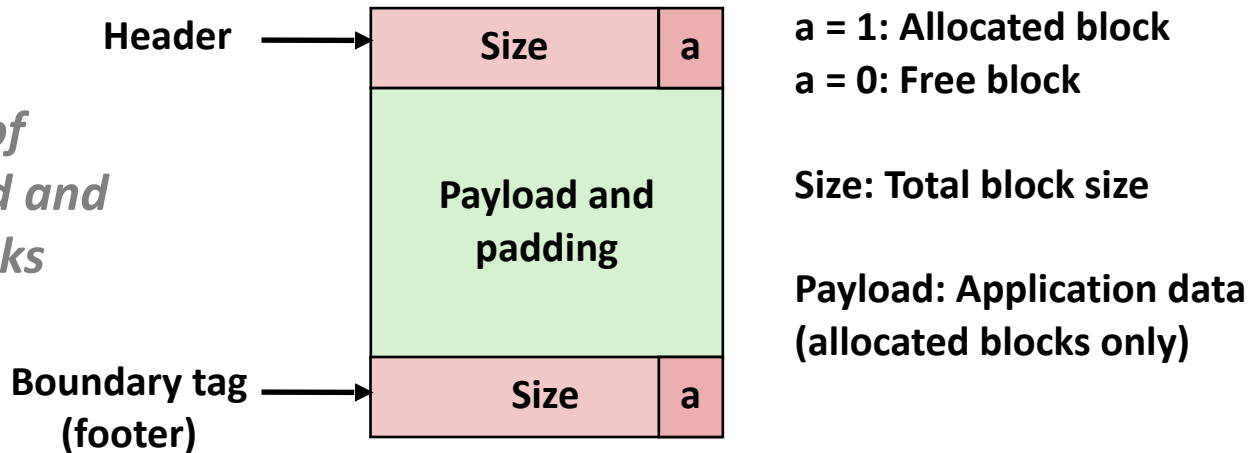


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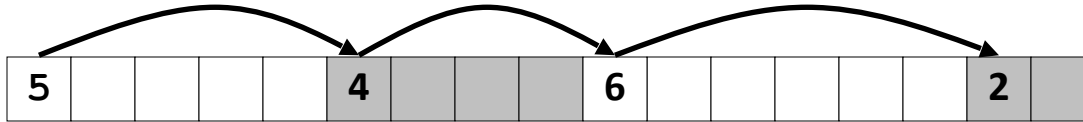


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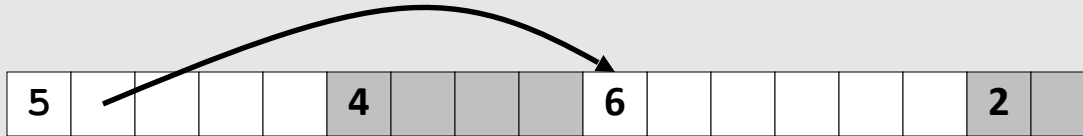


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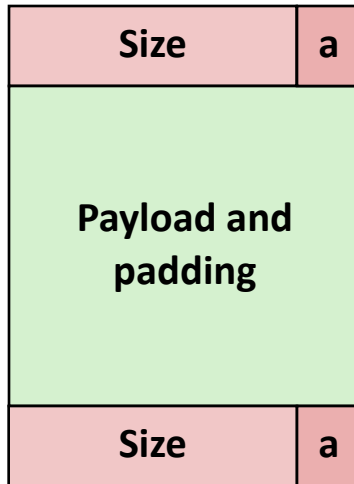
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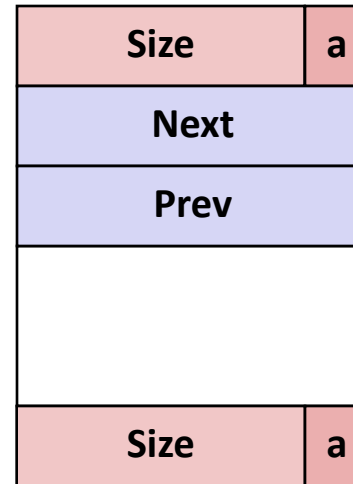
- Method 3: *Segregated free list*
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Explicit Free Lists

Allocated block
(same as before)



Free block



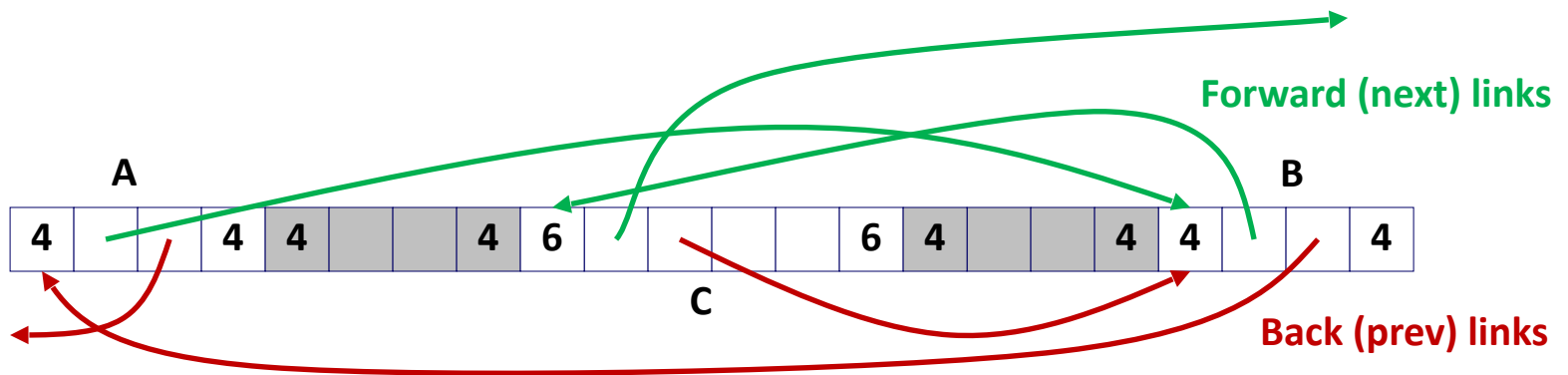
- Maintain list(s) of *free* blocks, not *all* blocks
 - The “next” free block could be anywhere
 - So we need to store forward/back pointers, not just sizes
 - These pointers exist only in free blocks, occupying the would-be payload area, so not really an overhead.
 - Still need boundary tags for coalescing.

Explicit Free Lists

- Logically:

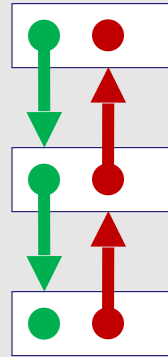


- Physically: blocks can be in any order



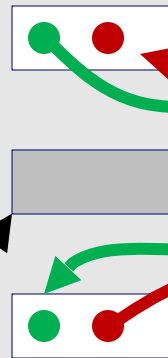
Allocating From Explicit Free Lists

Before



conceptual graphic

After



(with splitting)

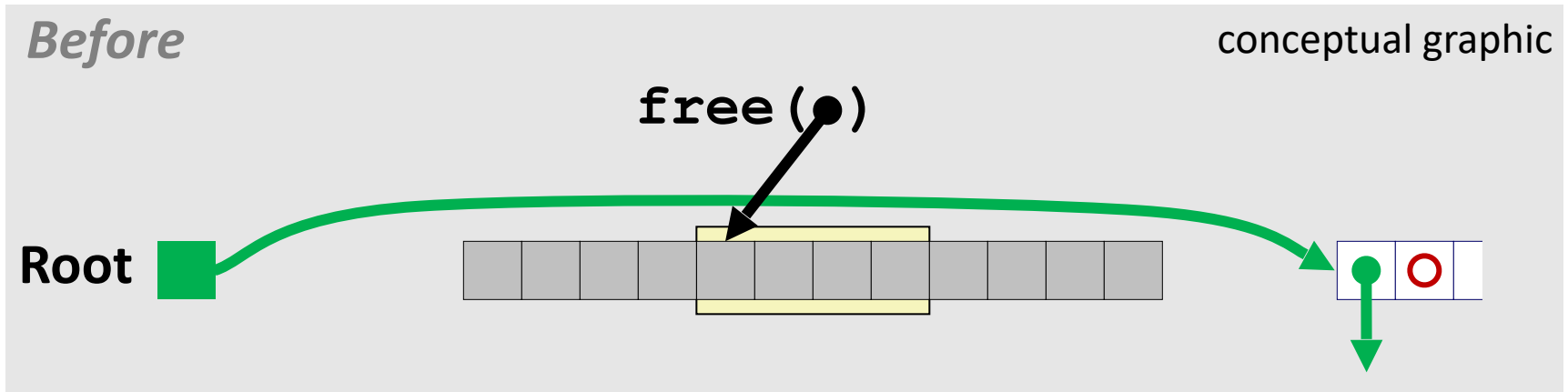
● = `malloc(...)`

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:
 $addr(prev) < addr(curr) < addr(next)$
 - *Con*: requires search
 - *Pro*: studies suggest fragmentation is lower than LIFO

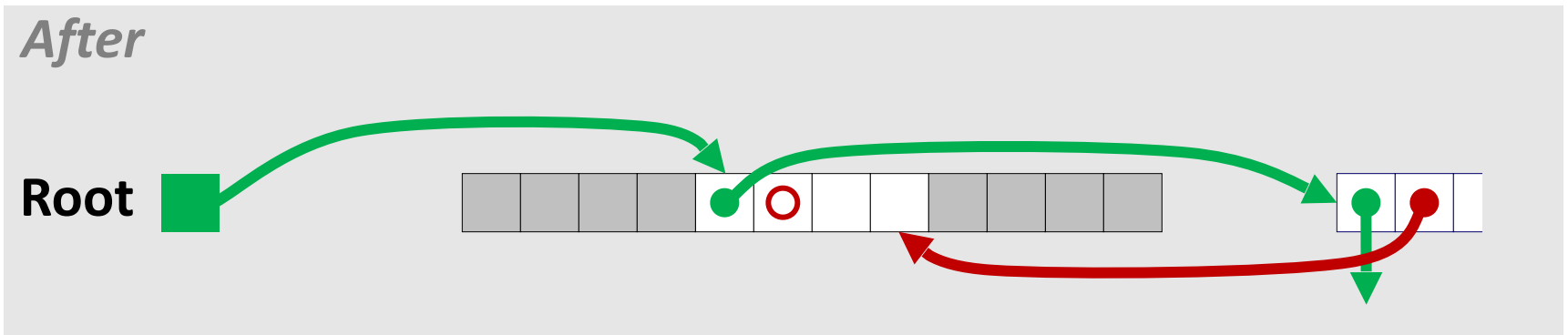
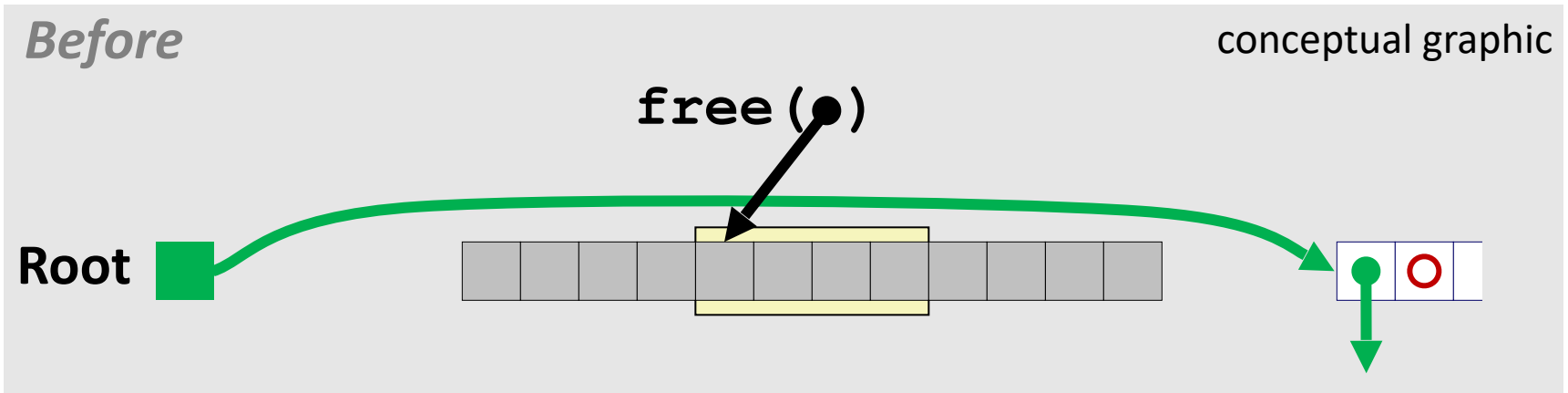
Freeing With a LIFO Policy (Case 1)

- Insert the freed block at the root of the list



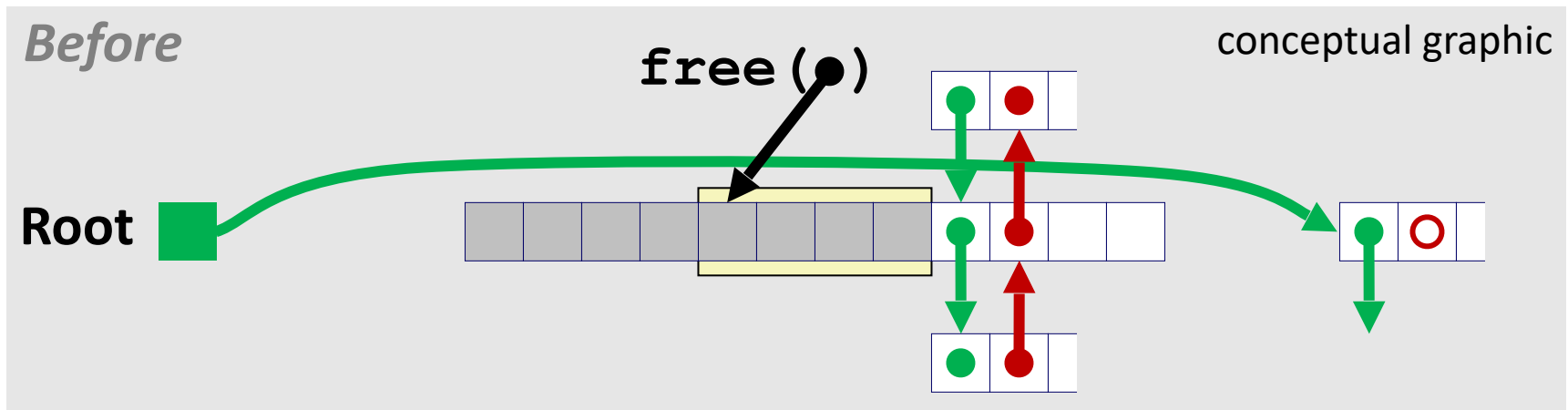
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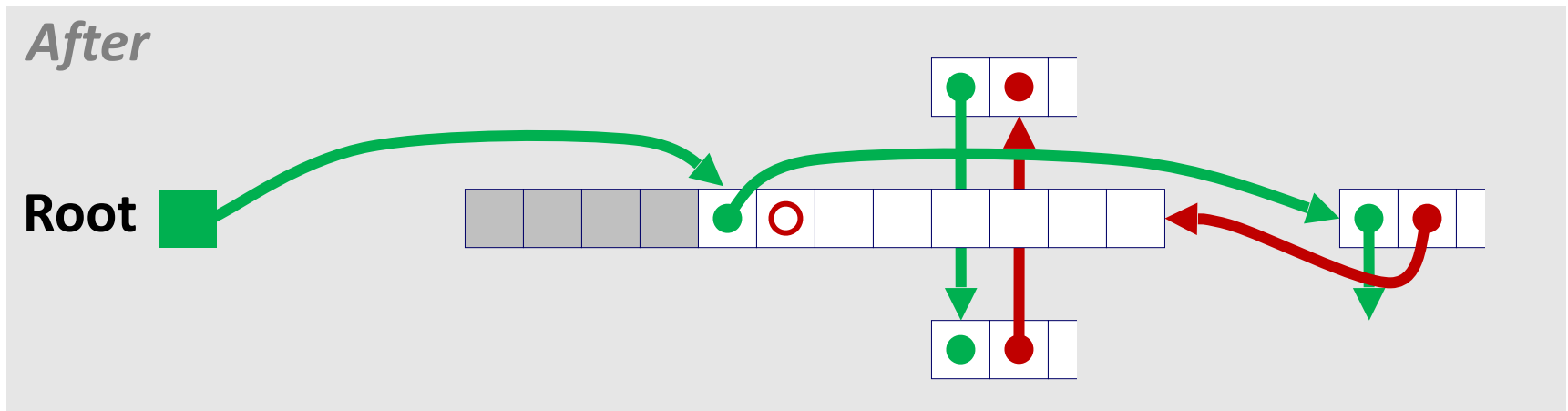
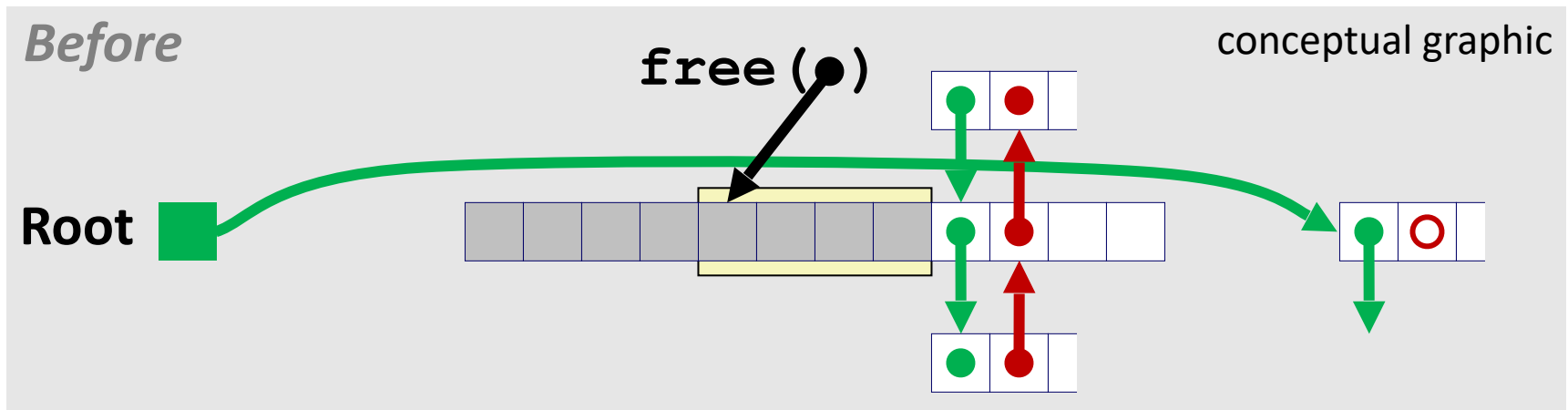
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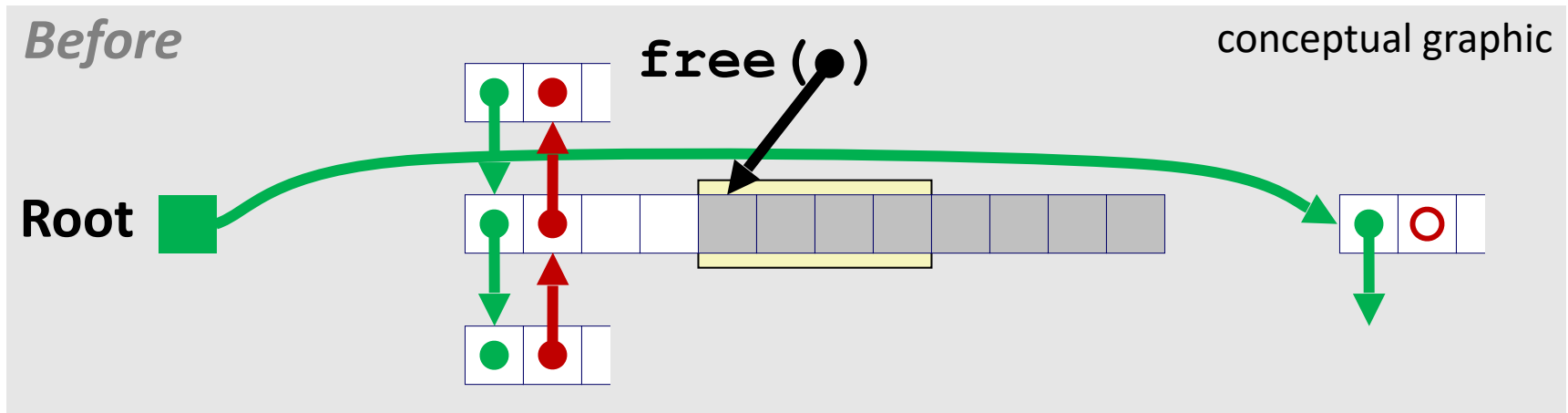
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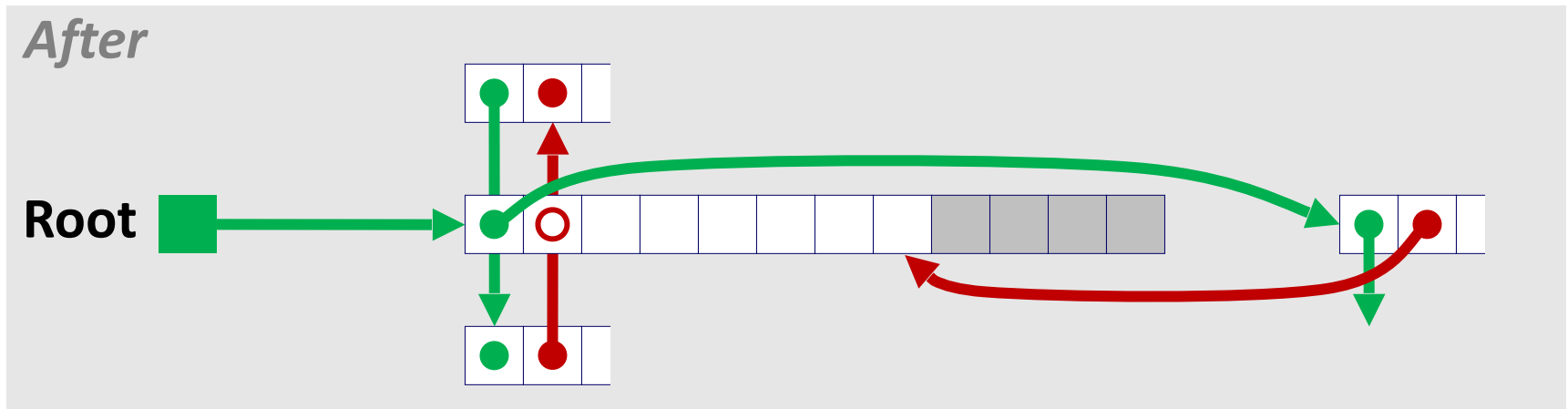
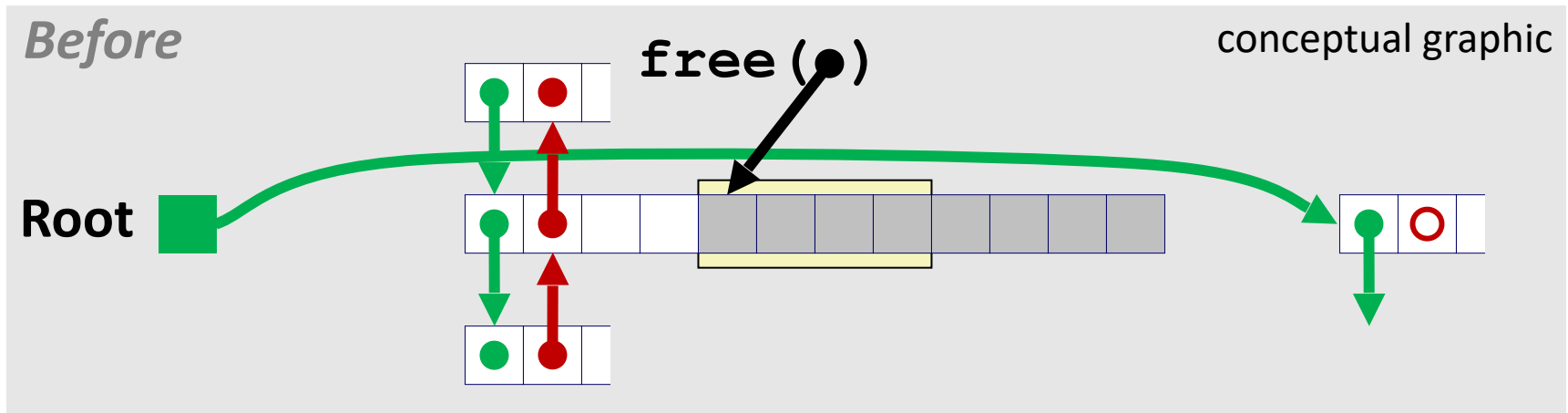
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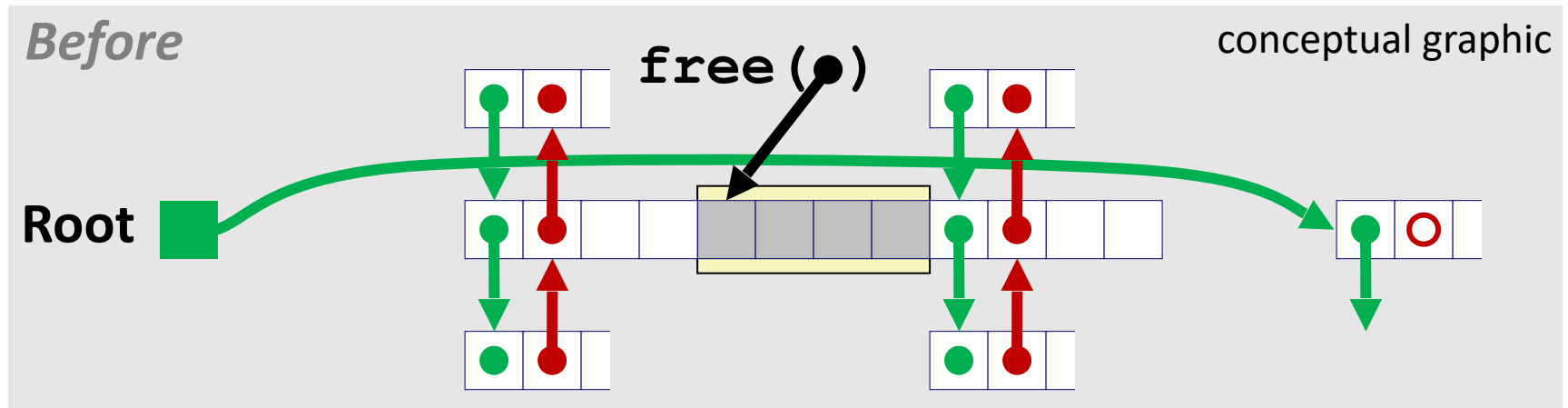
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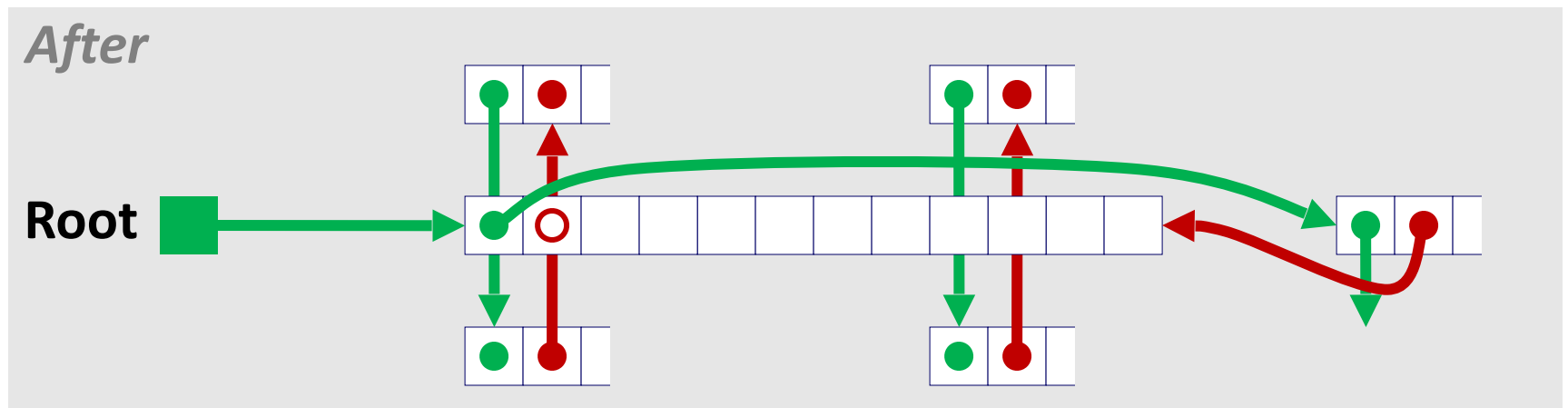
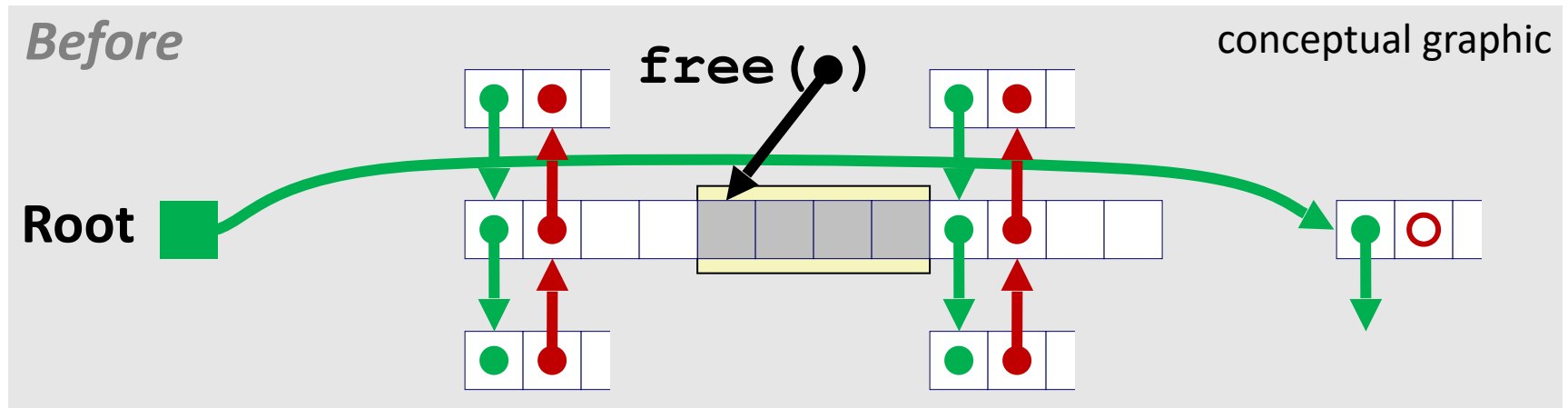
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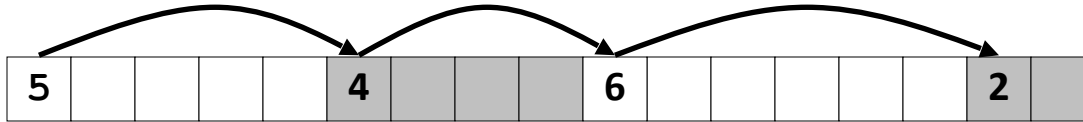


Explicit List Summary

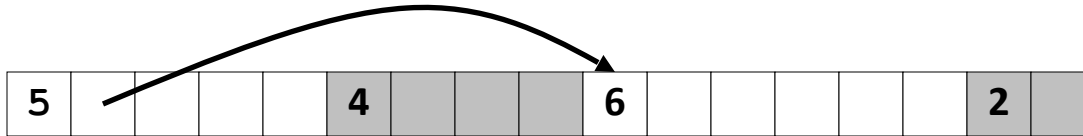
- Comparison to implicit list:
 - Allocate is linear time in number of **free** blocks instead of **all** blocks. Much faster when most of the memory is full.
 - Slightly more complicated allocate and free since needs to splice blocks in and out of the list
 - Some extra space for the links in free blocks (2 extra words needed for each block).

Keeping Track of Free Blocks

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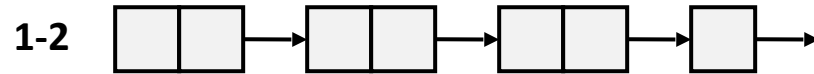


- Method 2: *Explicit list* among the free blocks using pointers



- Method 3: *Segregated free list*
 - Different free lists for different size classes

Segregated List (Seglist) Allocators



- Each *size class* of blocks has its own free list
- Organize the Seglist
 - Often have separate classes for each small size
 - For larger sizes: One class for each two-power size (why?)

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 - Remember heap is in VM, so request heap memory in pages
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- To free a block:
 - Coalesce and place on appropriate list

Advantages of Seglist allocators

- Higher throughput
 - Constant time allocation and free for requests that have a dedicated free list (most of the cases)
 - log time for power-of-two size classes (searching the lists)
- Better memory utilization
 - First-fit search of segregated free list approximates a best-fit search of entire heap.
 - Extreme case: Giving each block its own size class is equivalent to best-fit.

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- Common in many dynamic languages:
 - Python, Ruby, Java, JavaScript, Perl, ML, Lisp, Mathematica
- The key: **Garbage collection**
 - Automatic reclamation of heap-allocated storage—application never has to free

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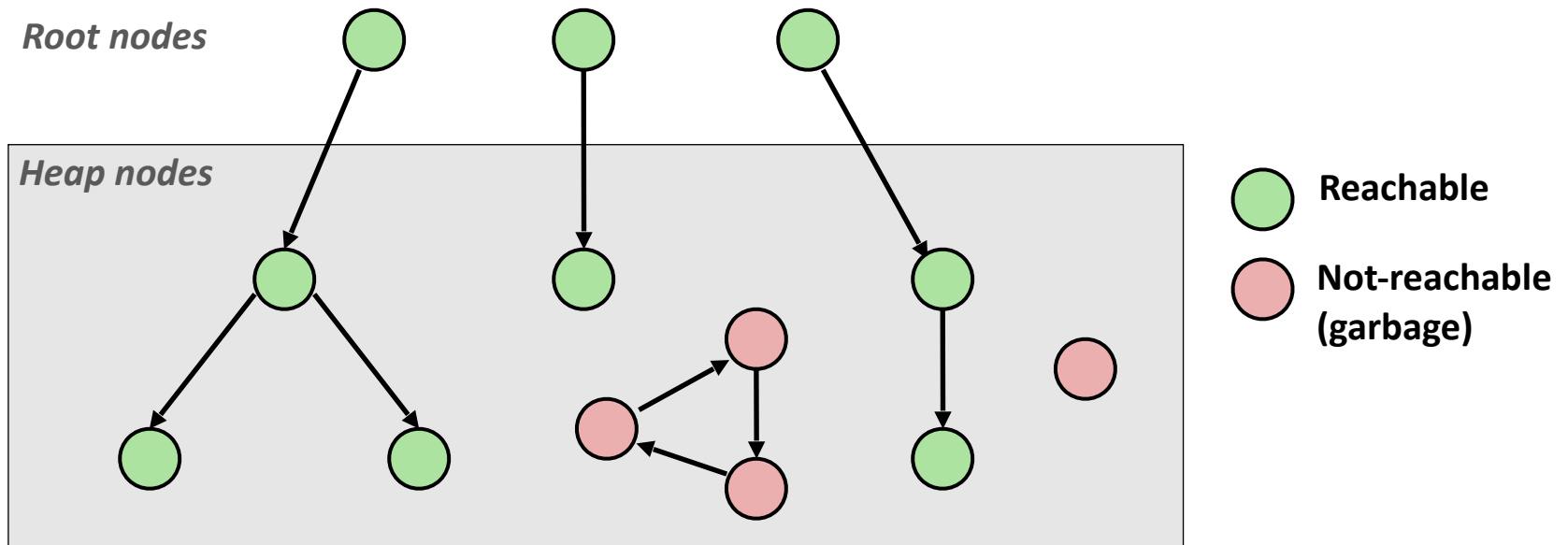
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 - But we can tell that certain blocks cannot possibly be used ***if there are no pointers to them***
 - Garbage collection is essentially to obtain all **reachable** blocks and discard unreachable blocks.

Memory as a Graph

- We view memory as a directed graph
 - Each 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, locations on the stack, global variables)



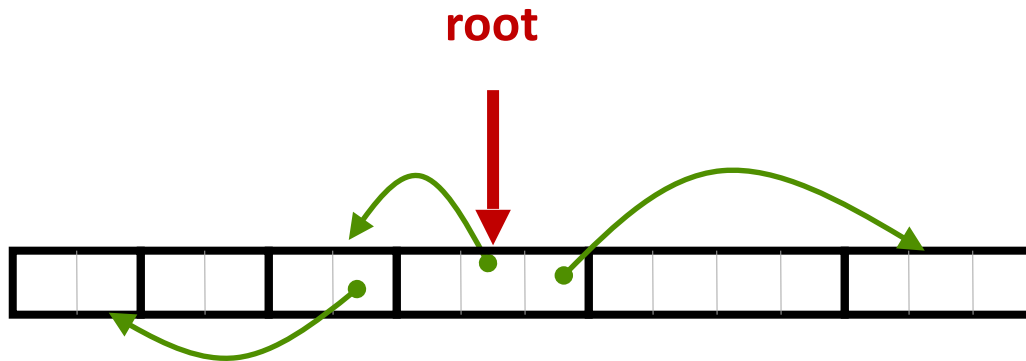
A node (block) is **reachable** if there is a path from any root to that node.

Non-reachable nodes are **garbage** (cannot be needed by the application)

Mark and Sweep Collecting

- Idea:

- Use extra **mark bit** in the header to indicate if a block is reachable
- **Mark**: Start at roots and set mark bit on each reachable block
- **Sweep**: Scan all blocks and free blocks that are not marked



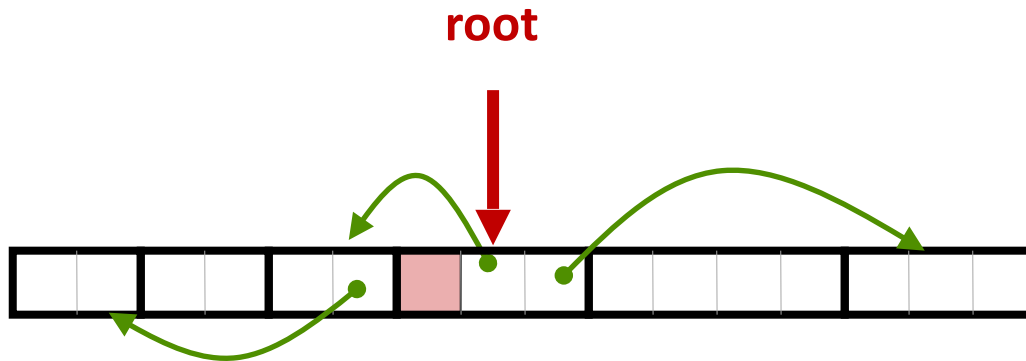
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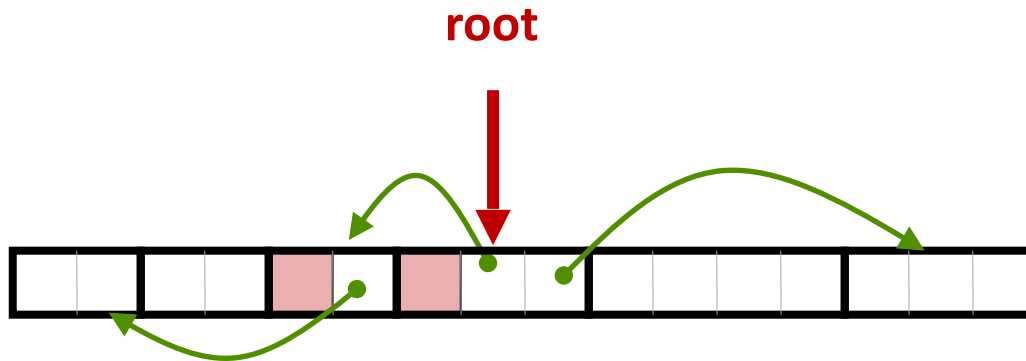
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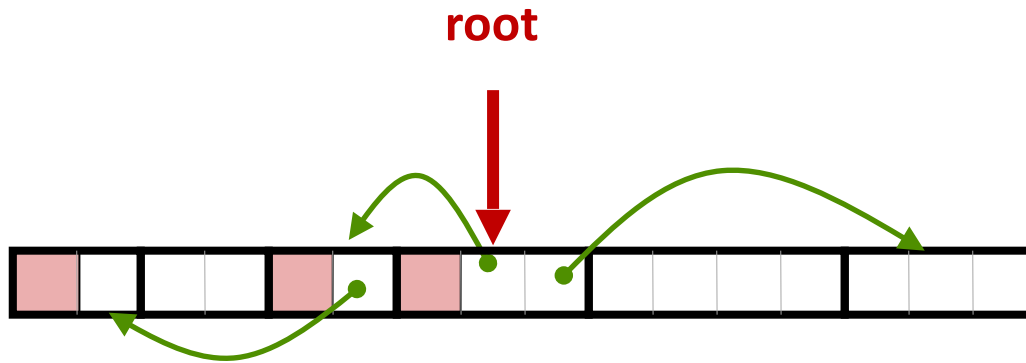
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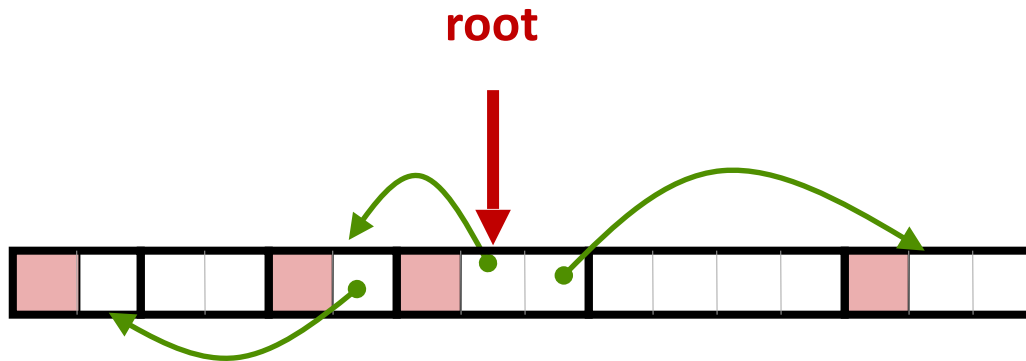
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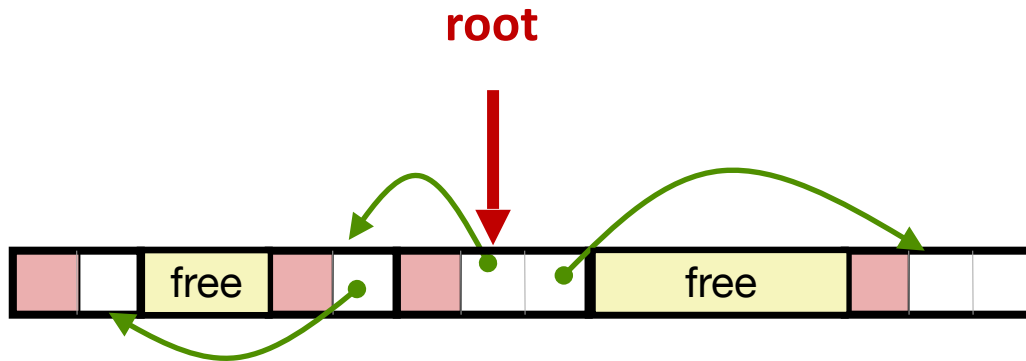
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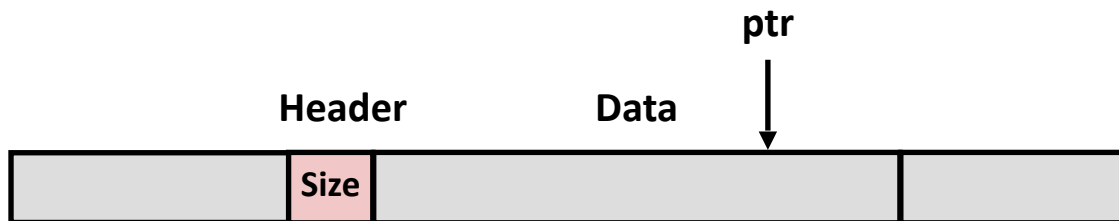
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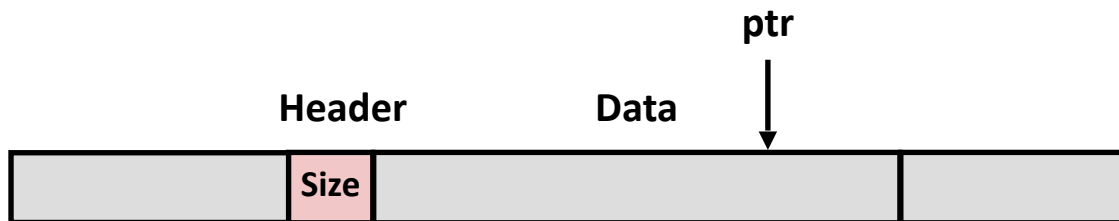
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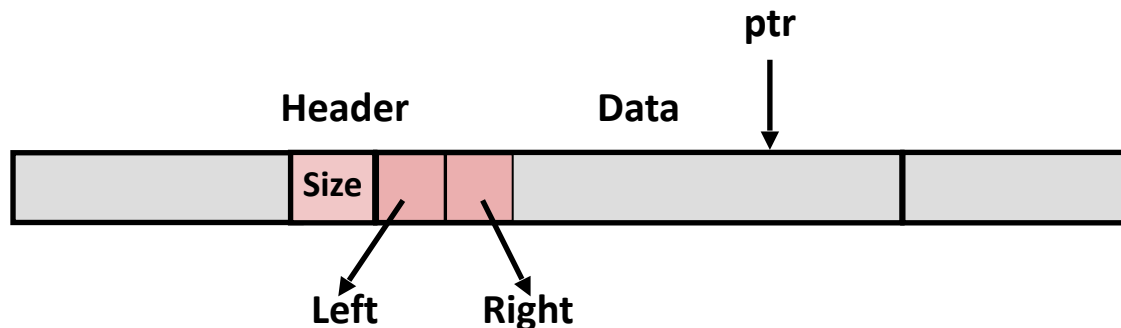
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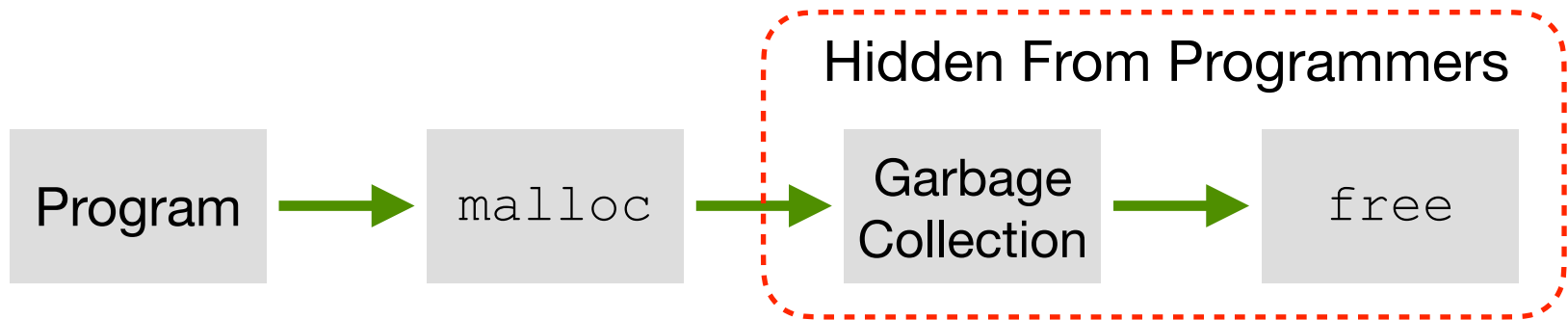
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Left: smaller addresses
Right: larger addresses

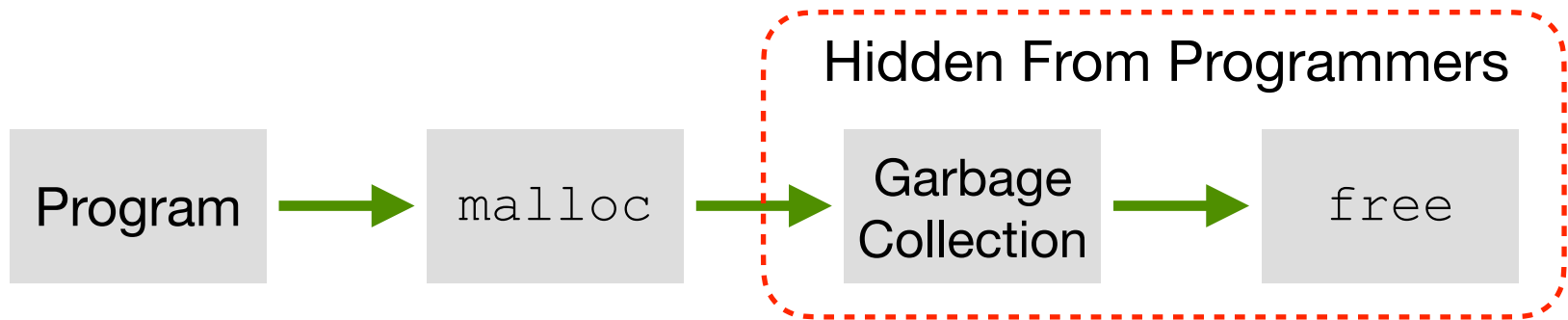
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 - Call `malloc` until you run out of space. Then `malloc` will call GC.



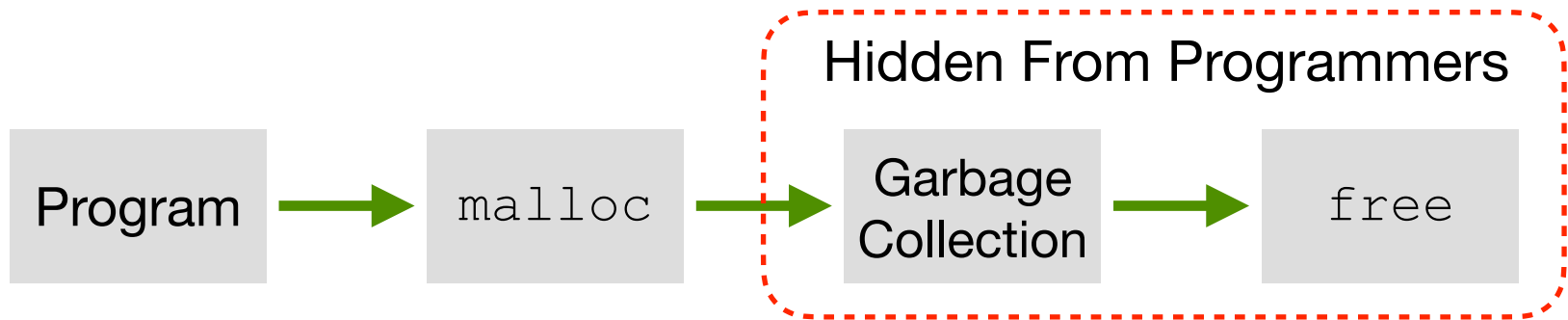
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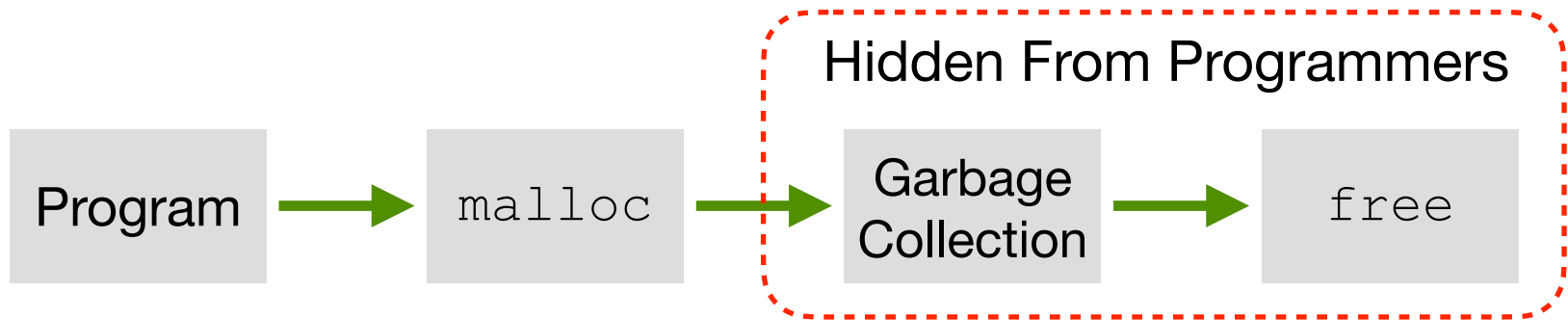
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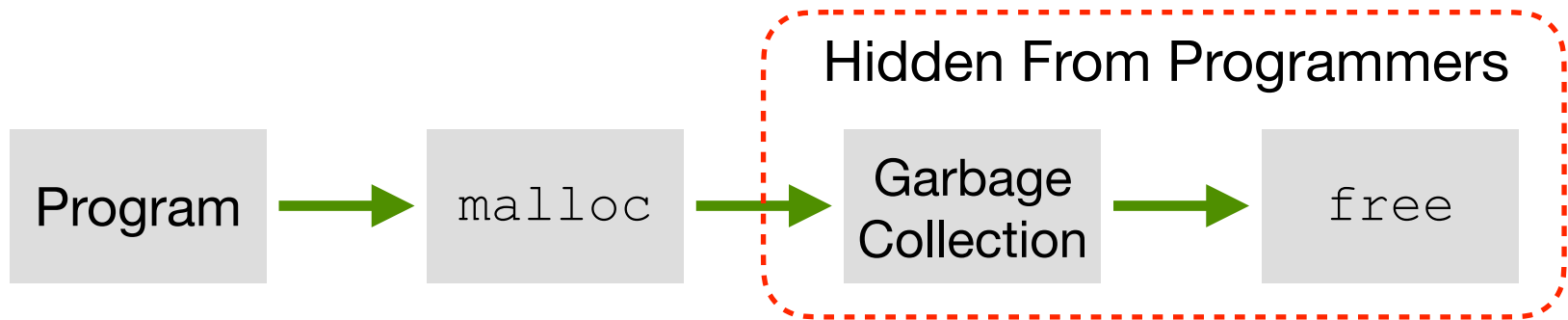
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 - **Concurrent GC**: Run GC service in a separate process/thread

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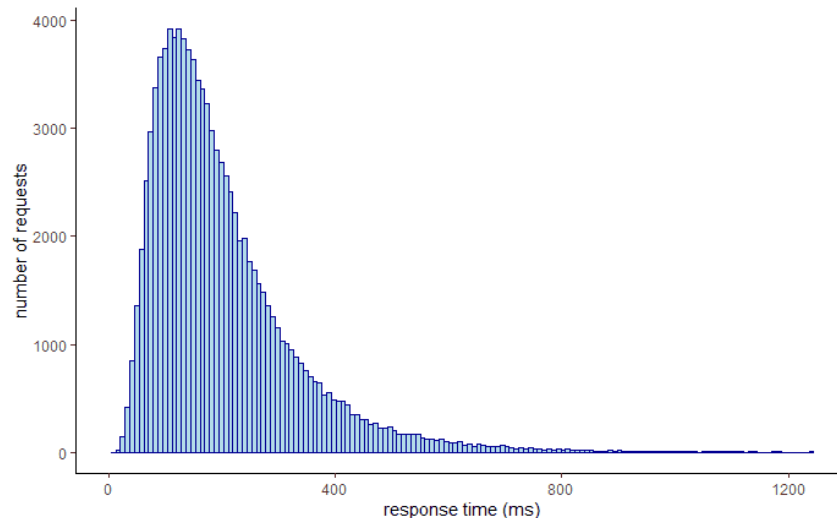
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 - Bad for server/cloud systems: GC is a great source of *tail latency*



Classical GC Algorithms

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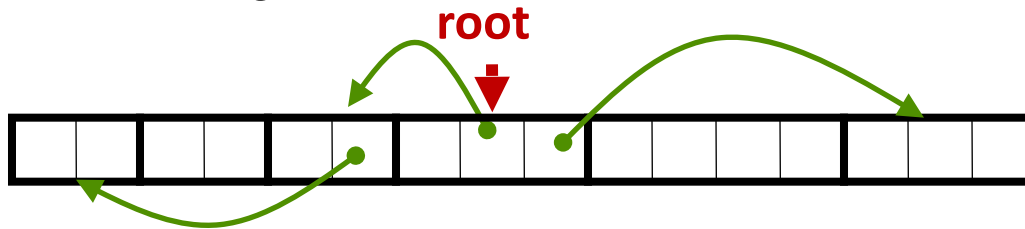
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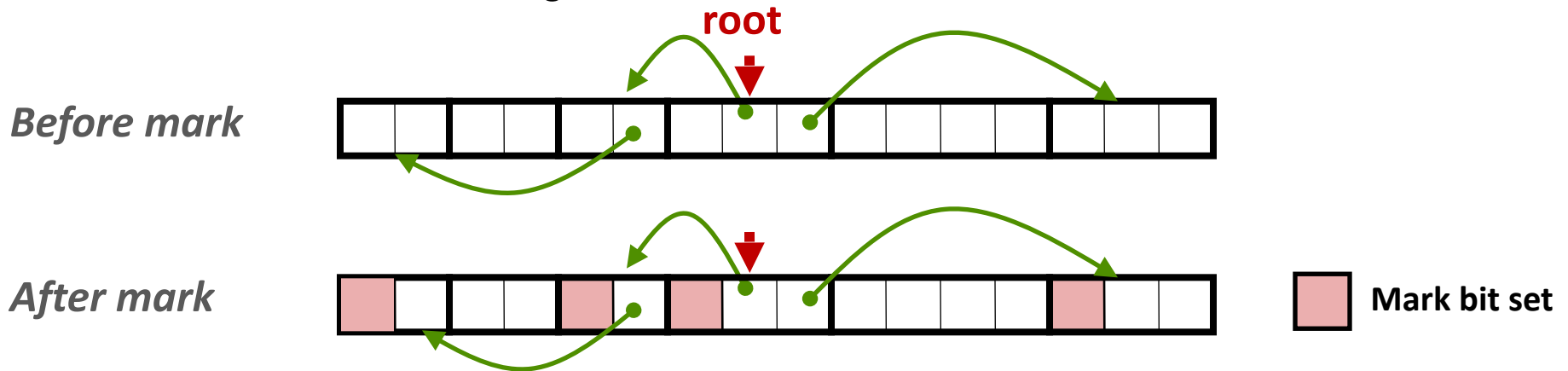
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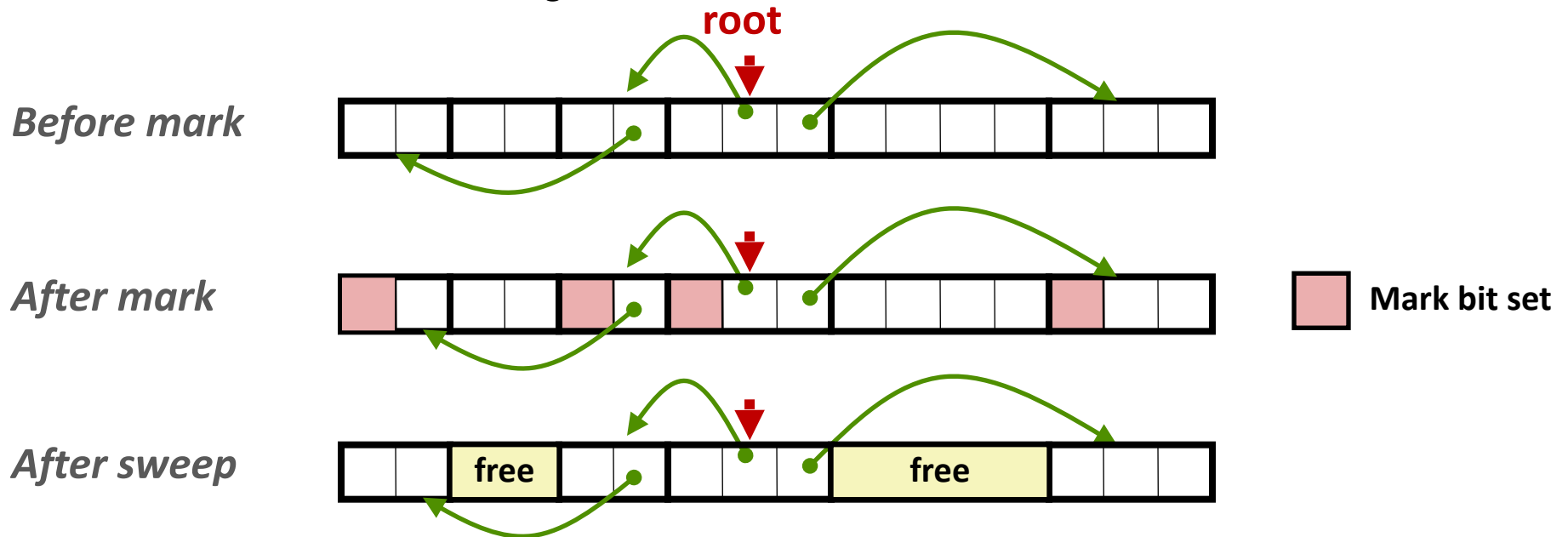
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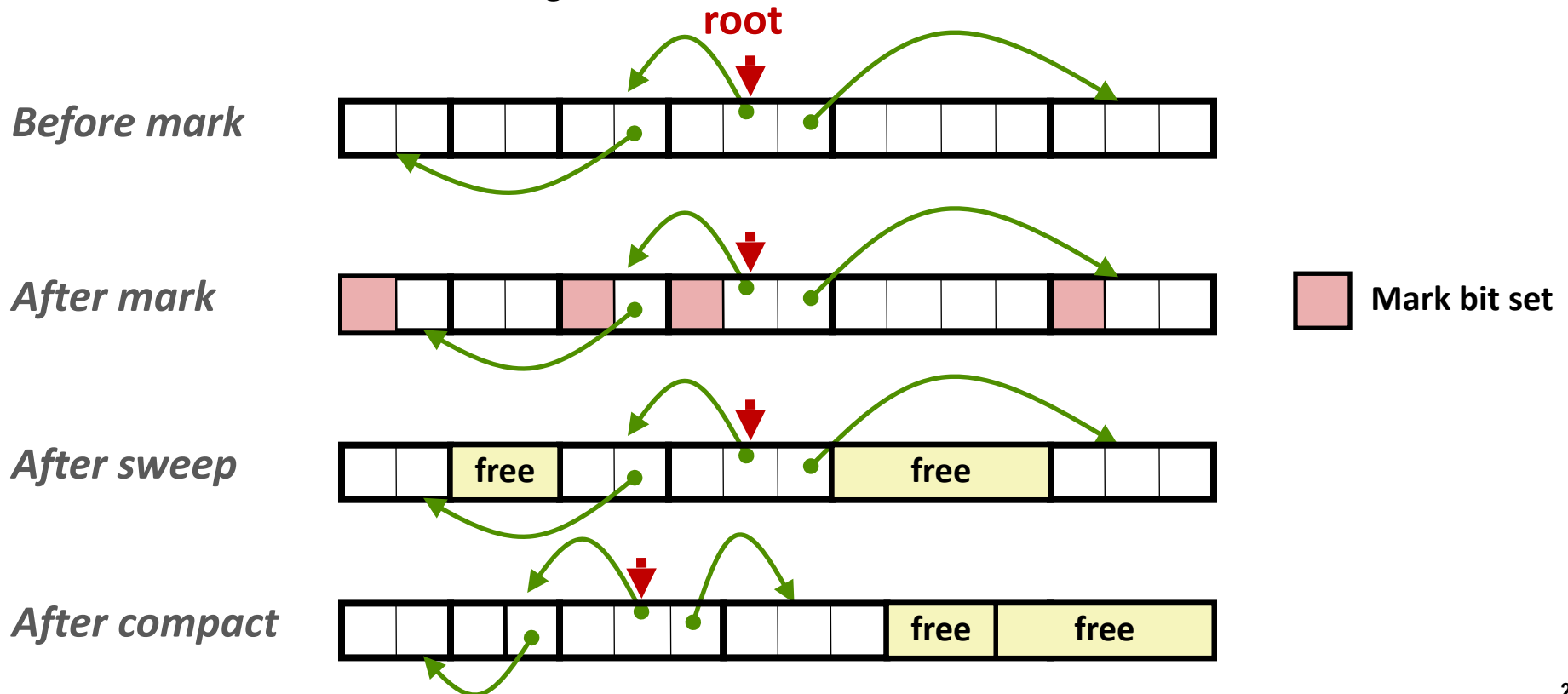
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- **Question: Can any of these algorithms be used for GC in C?**

Jones and Lin, “Garbage Collection: Algorithms for Automatic Dynamic Memory”, 1996.

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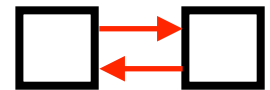
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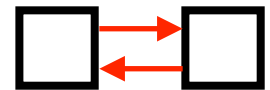
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- A heterogeneous approach (RC + tracing) is often used



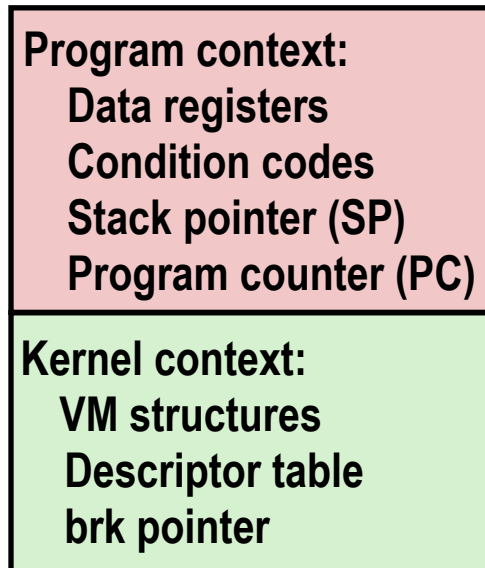
Today

- From process to threads
 - Basic thread execution model
- Multi-threading programming
- Hardware support of threads
 - Single core
 - Multi-core
 - Hyper-threading
 - Cache coherence

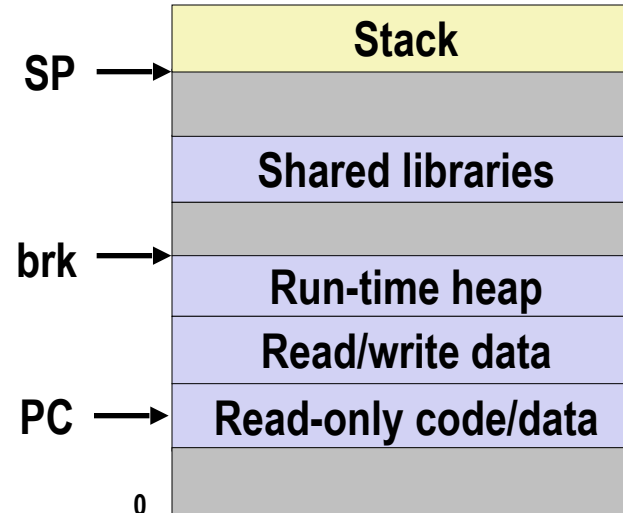
Programmers View of A Process

- Process = process context + code, data, and stack

Process context



Code, data, and stack



A Process With Multiple Threads

- Multiple threads can be associated with a process
 - Each thread has its own logical control flow
 - Each thread shares the same code, data, and kernel context
 - Each thread has its own stack for local variables
 - but not protected from other threads
 - Each thread has its own thread id (TID)

Thread 1 (main thread)

Thread 2 (peer thread)

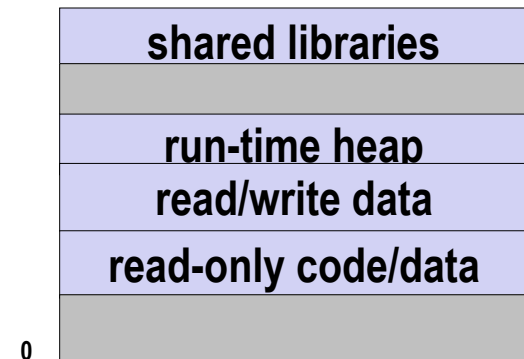
Shared code and data

stack 1

stack 2

Thread 1 context:
Data registers
Condition codes
SP1
PC1

Thread 2 context:
Data registers
Condition codes
SP2
PC2

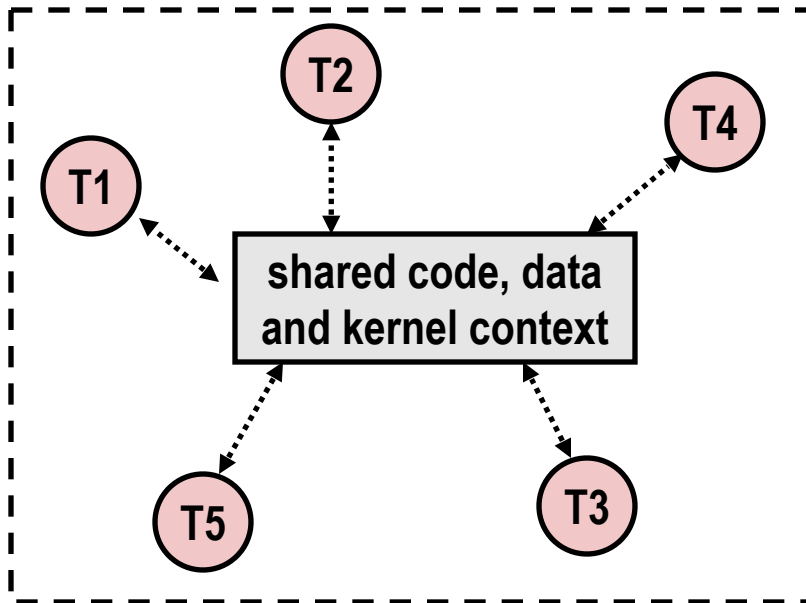


Kernel context:
VM structures
Descriptor table
brk pointer

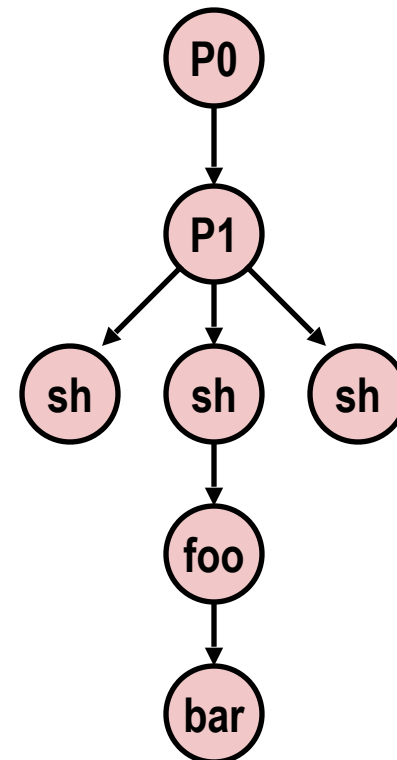
Logical View of Threads

- Threads associated with process form a pool of peers
 - Unlike processes which form a tree hierarchy

Threads associated with process foo

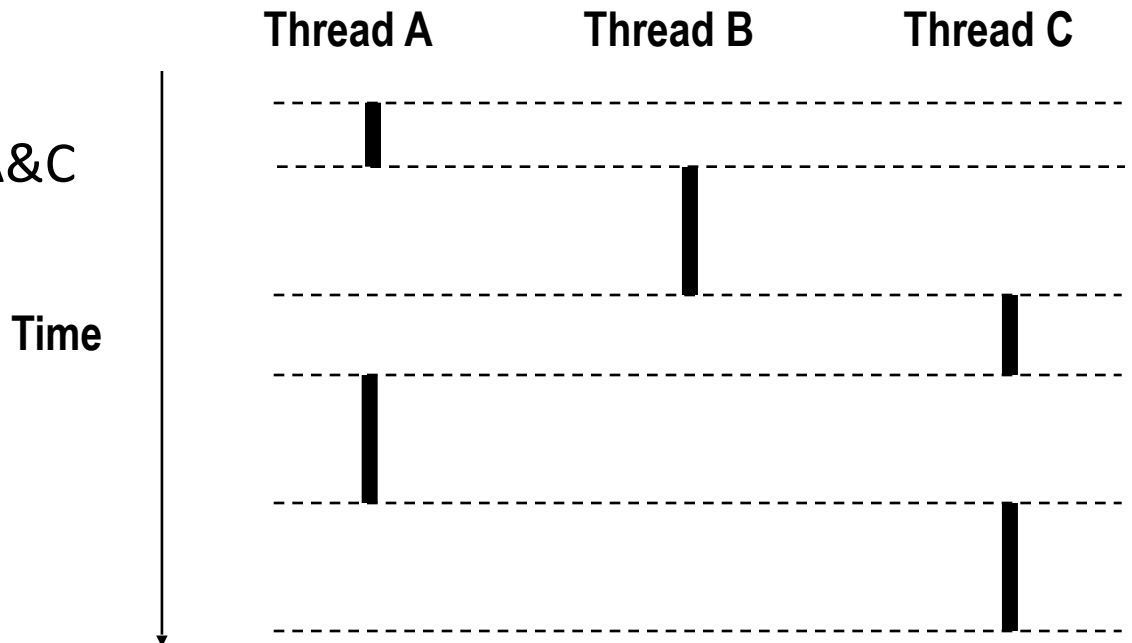


Process hierarchy



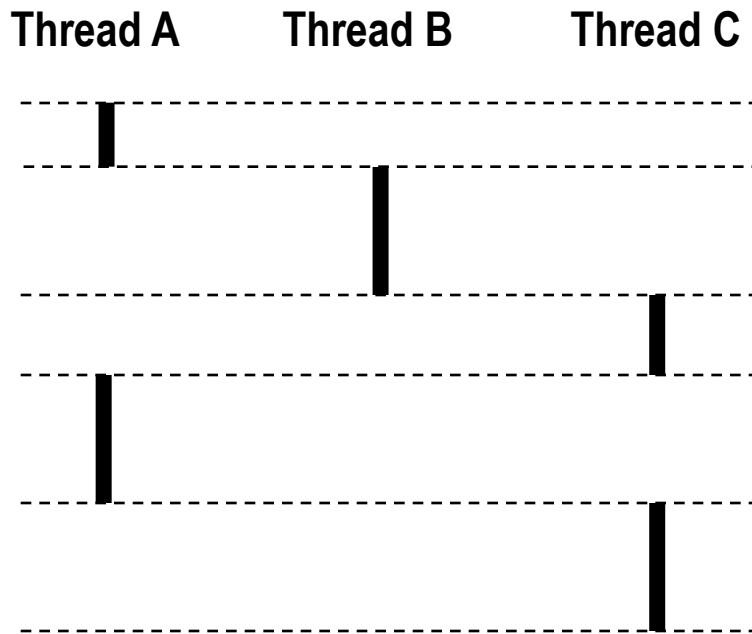
Concurrent Threads

- Two threads are *concurrent* if their flows overlap in time
- Otherwise, they are sequential
- Examples:
 - Concurrent: A & B, A&C
 - Sequential: B & C

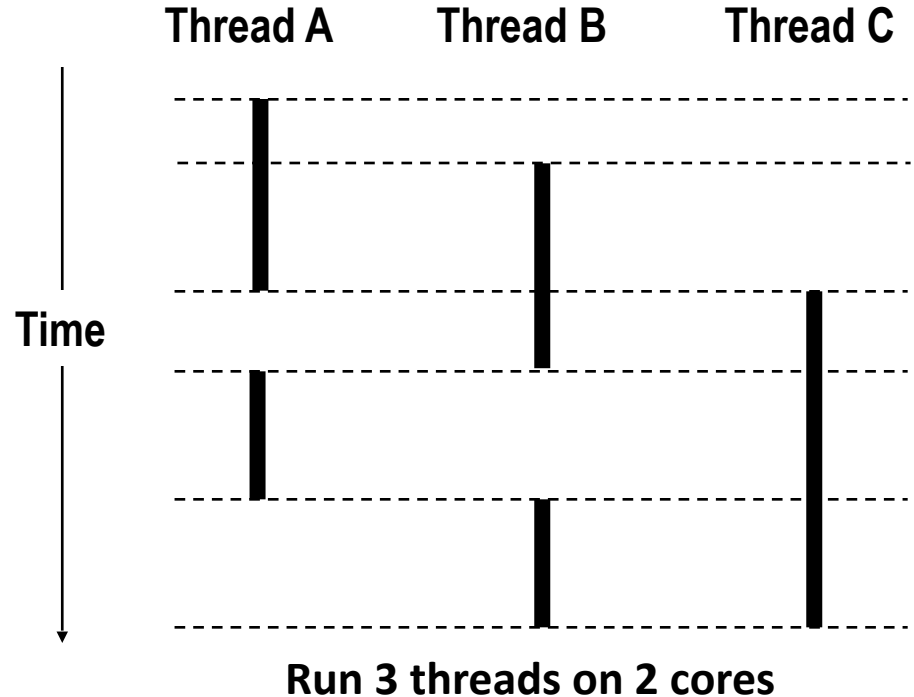


Concurrent Thread Execution

- Single Core Processor
 - Simulate parallelism by time slicing



- Multi Core Processor
 - Threads can have true parallelisms



Threads vs. Processes

- How threads and processes are similar
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- How threads and processes are similar
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 - Each is context switched, controlled by kernel
- How threads and processes are different
 - Threads share all code and data (except local stacks)
 - Processes (typically) do not
 - Threads are less expensive than processes
 - Space: threads share the same virtual address space except stacks, but processes have their own virtual address space
 - Process control (creating and reaping) twice as expensive
 - Typical Linux numbers:
 - ~20K cycles to create and reap a process
 - ~10K cycles (or less) to create and reap a thread

Posix Threads (Pthreads) Interface

- *Pthreads*: Standard interface for ~60 functions that manipulate threads from C programs
 - Creating and reaping threads
 - `pthread_create()`
 - `pthread_join()`
 - Determining your thread ID
 - `pthread_self()`
 - Terminating threads
 - `pthread_cancel()`
 - `pthread_exit()`
 - `exit()` [terminates all threads] , `return()` [terminates current thread]
 - Synchronizing access to shared variables
 - `pthread_mutex_init`
 - `pthread_mutex_[un]lock`

The Pthreads "hello, world" Program

```
/*
 * hello.c - Pthreads "hello, world" program
 */
#include "csapp.h"
void *thread(void *vargp);

int main()
{
    pthread_t tid;
    Pthread_create(&tid, NULL, thread, NULL);
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hello.c

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void *thread(void *vargp) /* thread routine */
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A diagram consisting of a light blue rectangular box with a black border containing the text "Thread ID". A black arrow originates from the bottom-left corner of this box and points diagonally down and to the left, terminating at the variable "tid" in the second argument of the `Pthread_create` function call within the `main` function.

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Return value
(void **p)

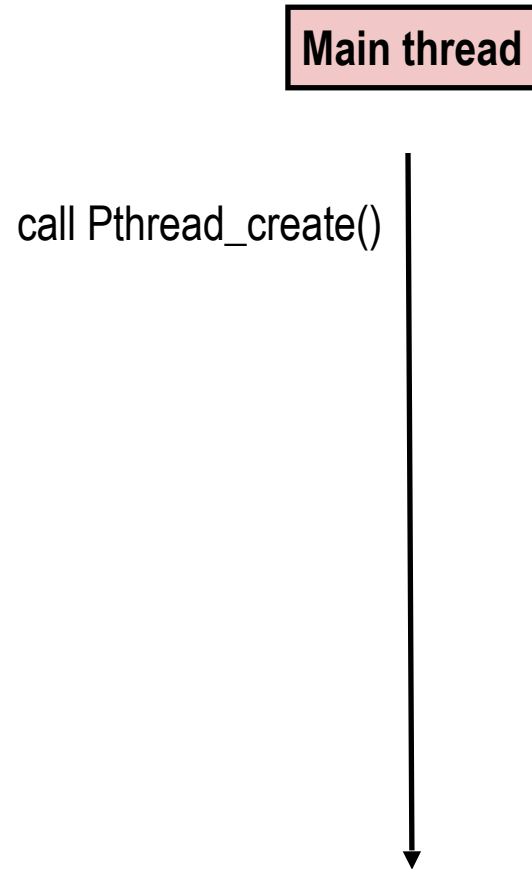
hello.c

Execution of Threaded “hello, world”

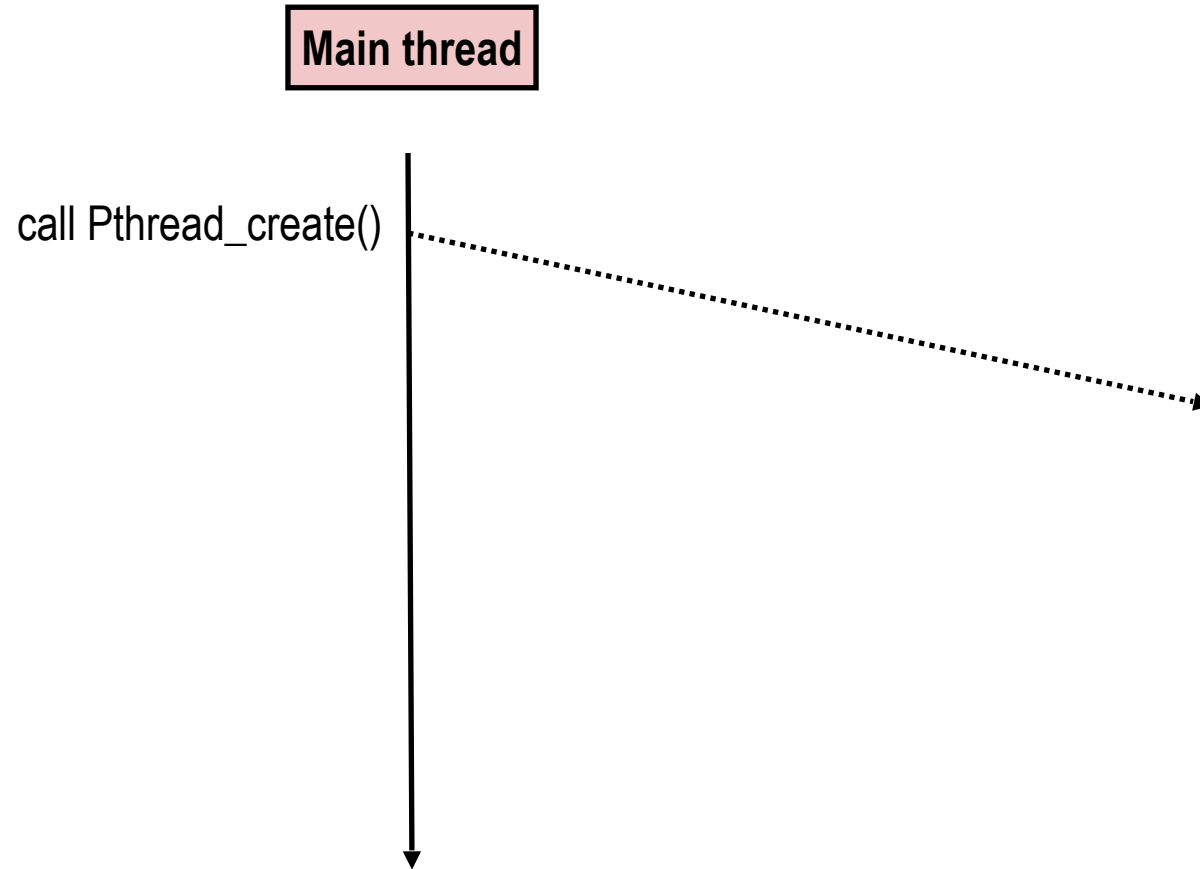
Main thread



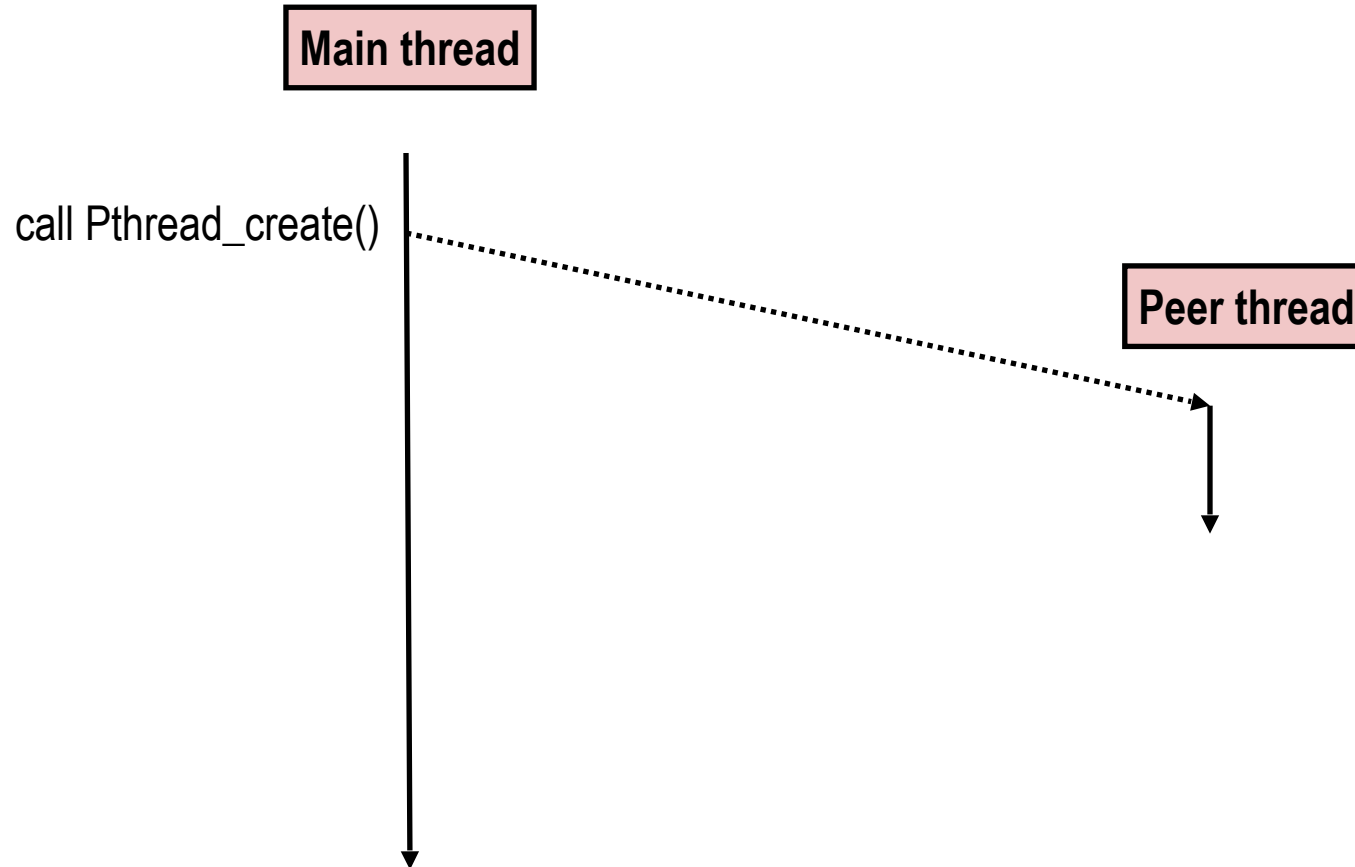
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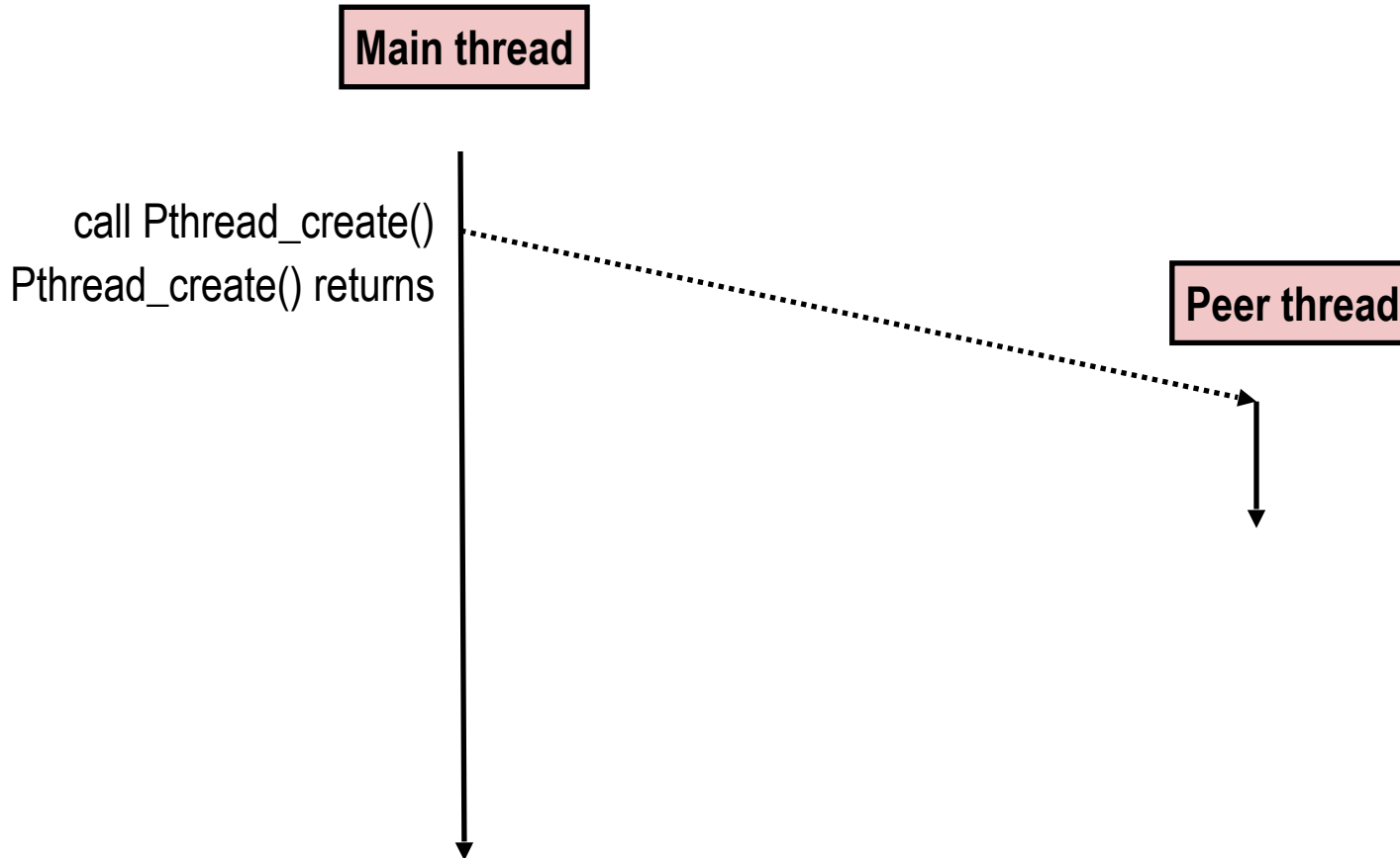
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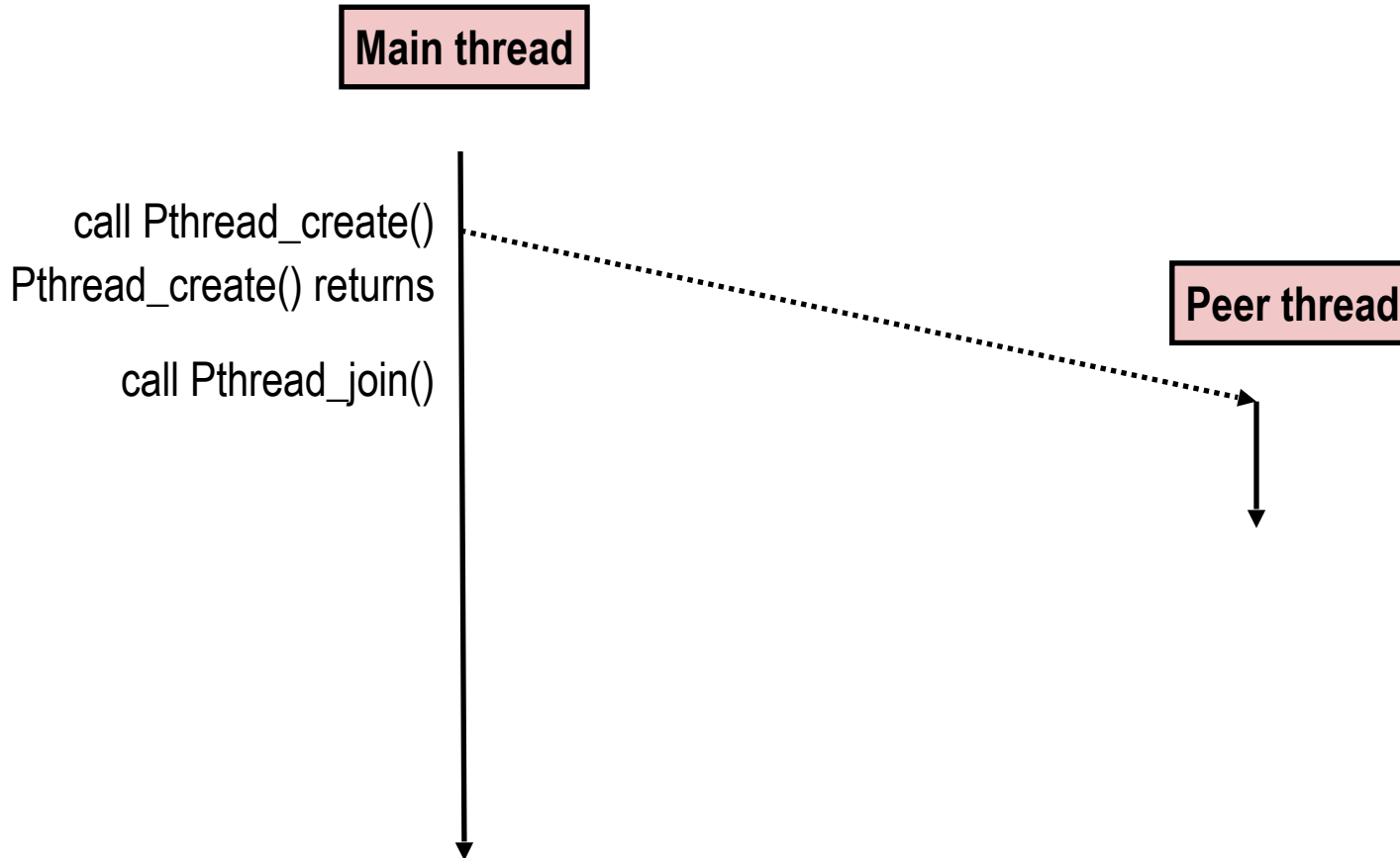
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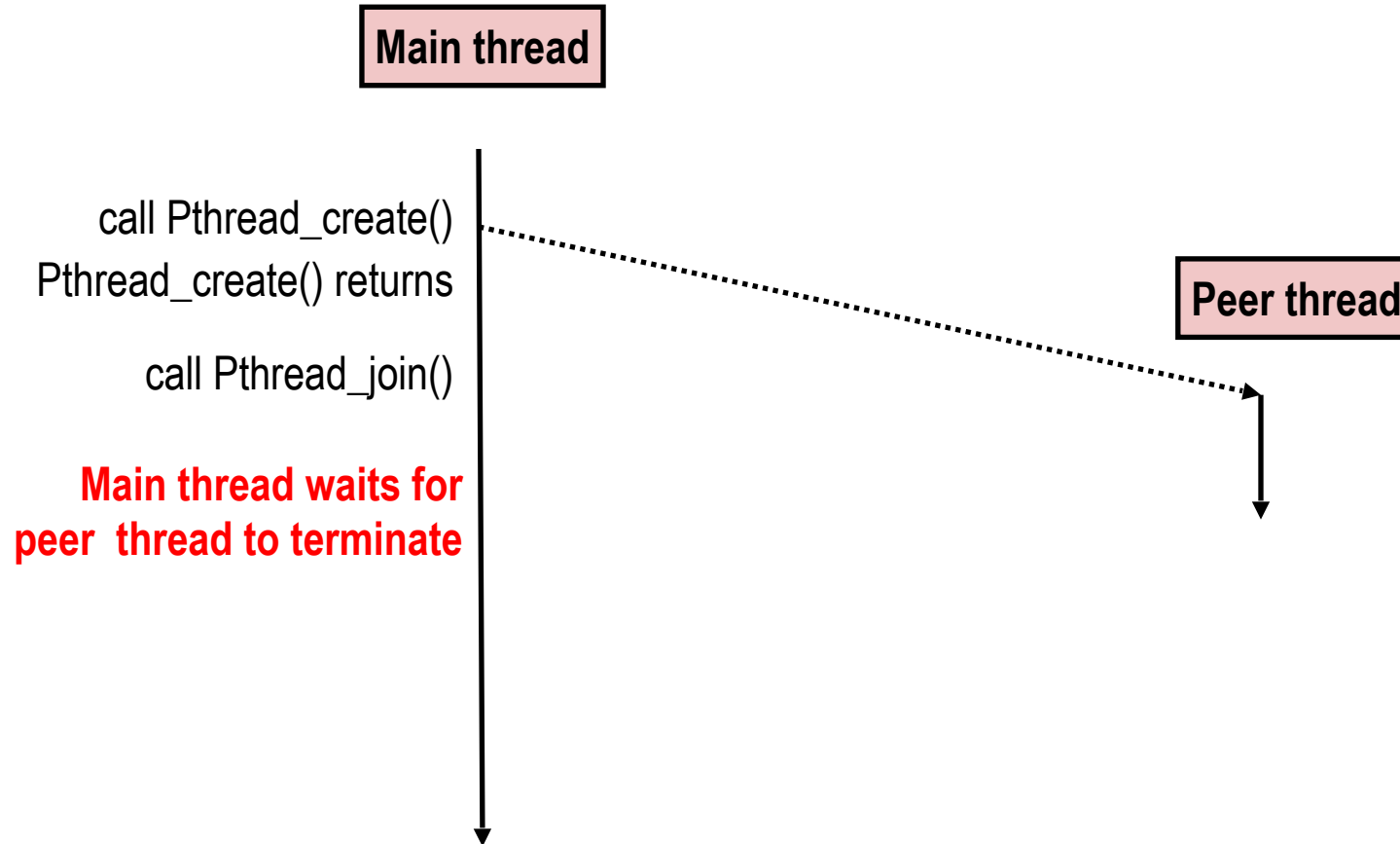
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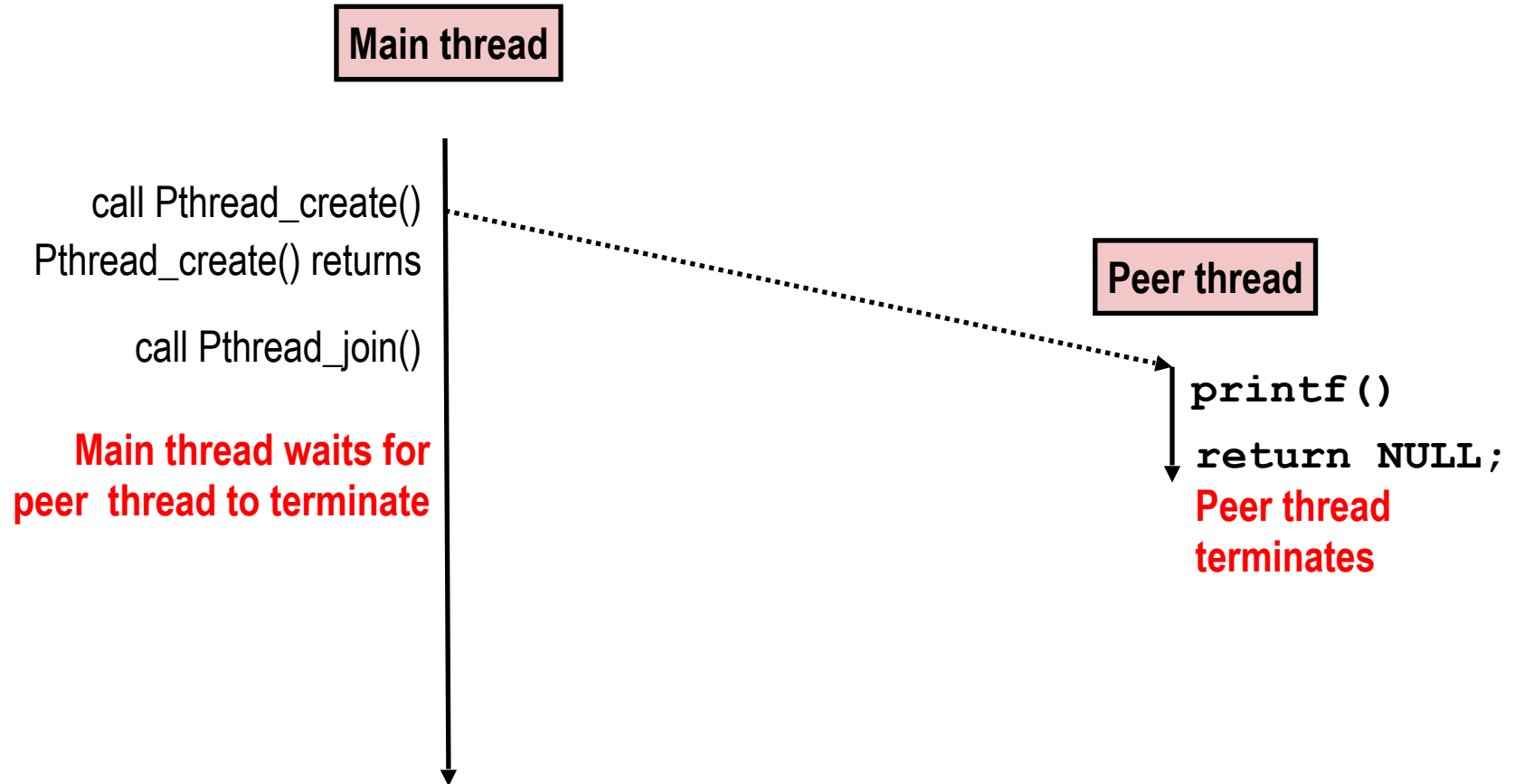
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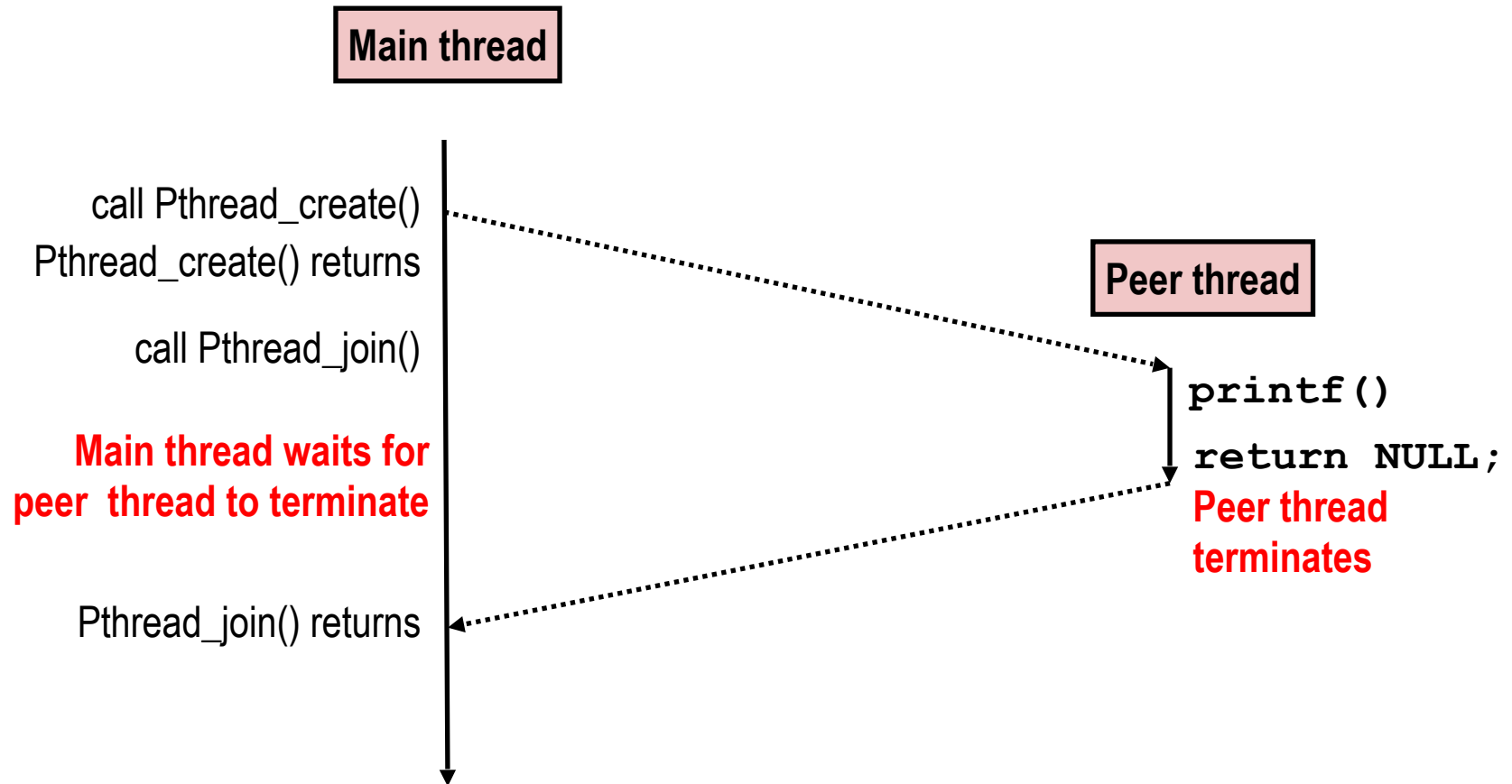
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