NEU CS 3650 Computer Systems

Instructor: Dr. Ziming Zhao

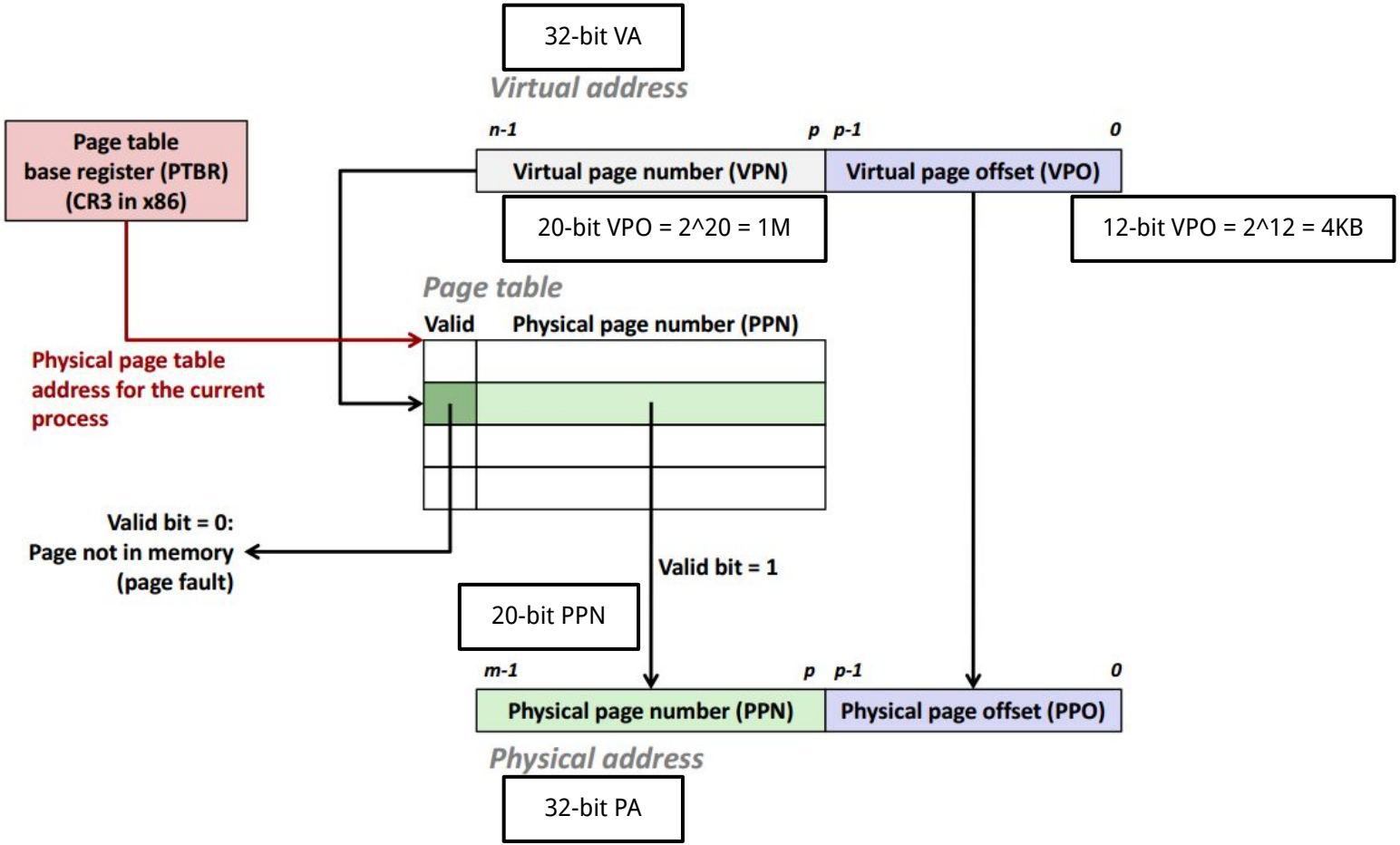
* Acknowledgements: created based on Christo Wilson, Ferdinand Vesely, Alden Jackson, Ben Weintraub, Gene Cooperman, Peter Desnoyers' lecture slides for the same course.

x86 32-bit as an Example

x86 32-bit as an Example: Goal

- Translate 32-bit virtual address to 32-bit physical address
- A page is 4096 (4KB).

How Big is the Page Table?



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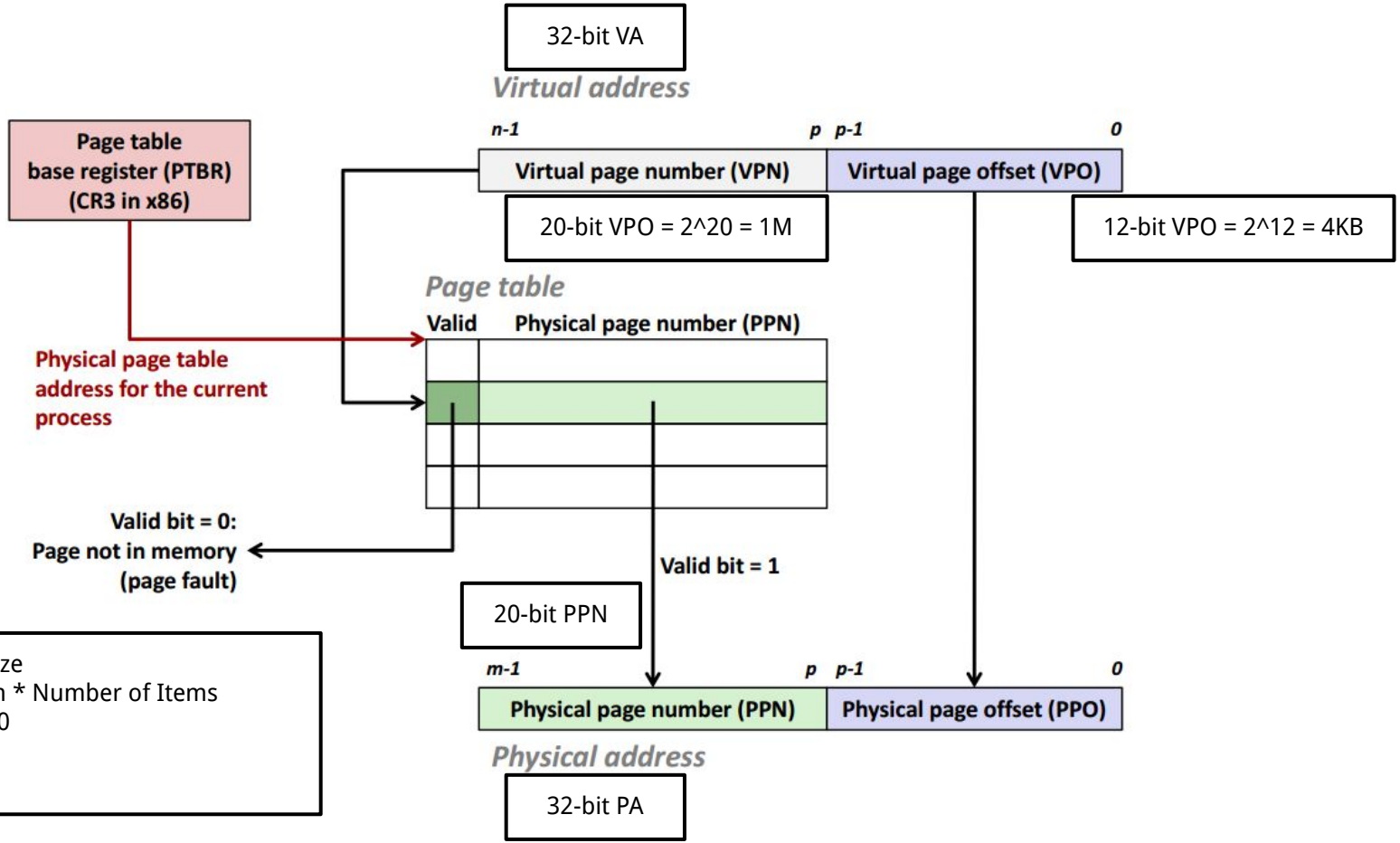


Page Table Size
= Size of Item * Number of Items
= 2^20 * 2^20
= 2^40
= 1TB

Observations

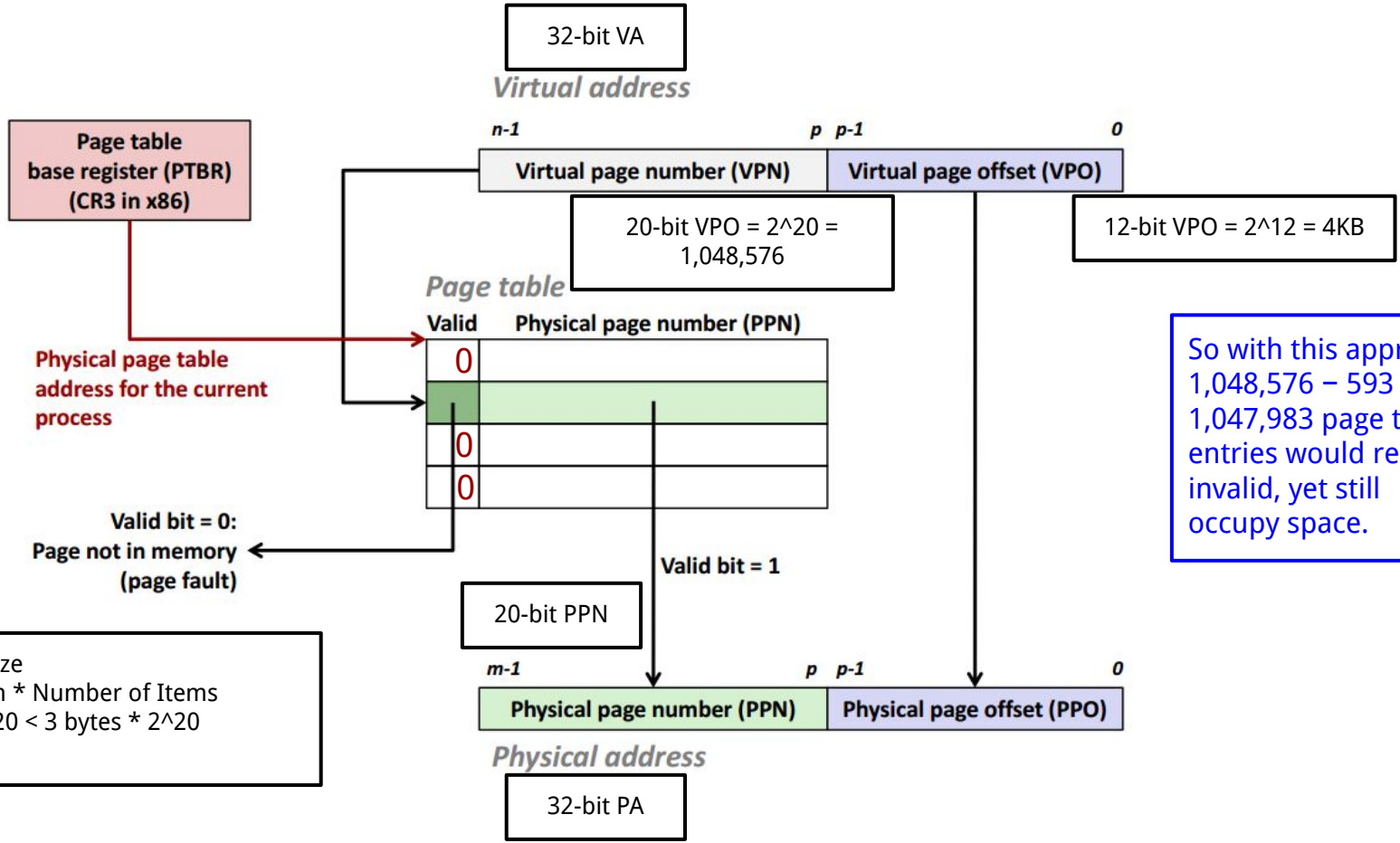
- A large portion of the Virtual Address Space is not used. So not every virtual page number (VPN) needs to be translated. (In the example below: only 2372/4 = 593 pages are used)

1 GB = 0x40000000

2 GB = 0x80000000

```
ziming@ziming-ThinkPad:~/Dropbox/myTeaching/System Security - Attack and Defense for Binaries UB 2020/code/processmap$ pmap -X 21732
21732:   ./pm
 Address Perm   Offset Device    Inode Size Rss Pss Referenced Anonymous LazyFree ShmemPmdMapped Shared_Hugetlb Private_Hugetlb Swap SwapPss Locked Mapping
56569000 r-xp 00000000 103:02 28575310    4   4   4          4         0        0             0              0               0    0       0      0 pm
5656a000 r--p 00000000 103:02 28575310    4   4   4          4         4        0             0              0               0    0       0      0 pm
5656b000 rw-p 00001000 103:02 28575310    4   4   4          4         4        0             0              0               0    0       0      0 pm
57cf2000 rw-p 00000000  00:00        0  136   4   4          4         4        0             0              0               0    0       0      0 [heap]
f7d73000 r-xp 00000000 103:02  2883591 1876 772 772        772         0        0             0              0               0    0       0      0 libc-2.27.so
f7f48000 ---p 001d5000 103:02  2883591    4   0   0          0         0        0             0              0               0    0       0      0 libc-2.27.so
f7f49000 r--p 001d5000 103:02  2883591    8   8   8          8         8        0             0              0               0    0       0      0 libc-2.27.so
f7f4b000 rw-p 001d7000 103:02  2883591    4   4   4          4         4        0             0              0               0    0       0      0 libc-2.27.so
f7f4c000 rw-p 00000000  00:00        0   12   8   8          8         8        0             0              0               0    0       0      0
f7f75000 rw-p 00000000  00:00        0    8   8   8          8         8        0             0              0               0    0       0      0
f7f77000 r--p 00000000  00:00        0   12   0   0          0         0        0             0              0               0    0       0      0 [vvar]
f7f7a000 r-xp 00000000  00:00        0    8   8   8          8         0        0             0              0               0    0       0      0 [vdso]
f7f7c000 r-xp 00000000 103:02  2883587  152 144 144        144         0        0             0              0               0    0       0      0 ld-2.27.so
f7fa2000 r--p 00025000 103:02  2883587    4   4   4          4         4        0             0              0               0    0       0      0 ld-2.27.so
f7fa3000 rw-p 00026000 103:02  2883587    4   4   4          4         4        0             0              0               0    0       0      0 ld-2.27.so
ffef3000 rw-p 00000000  00:00        0  132  12  12         12        12        0             0              0               0    0       0      0 [stack]
                                        ==== === === ========== ========= ======== ============= ============== =============== ==== ======= ======
                                        2372 988 988        988        60        0             0              0               0    0       0      0 KB
```

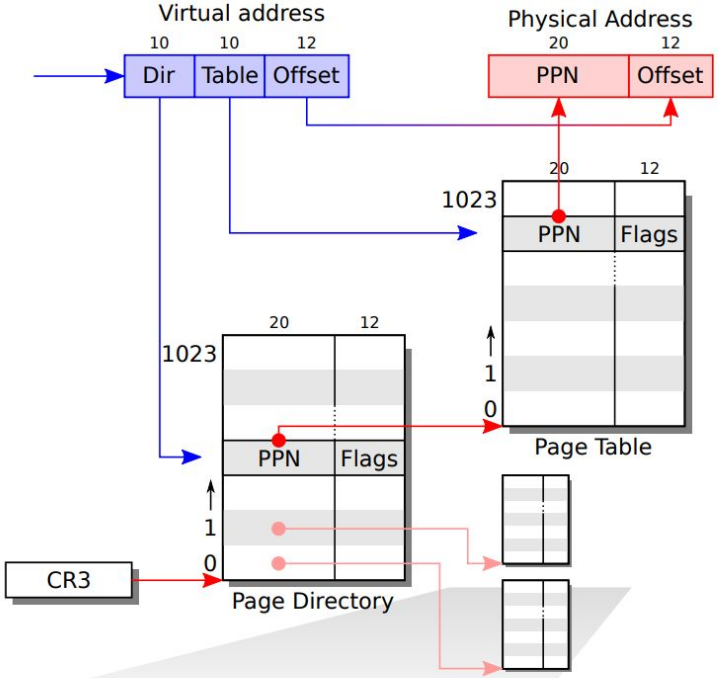
How Big is the Page Table?

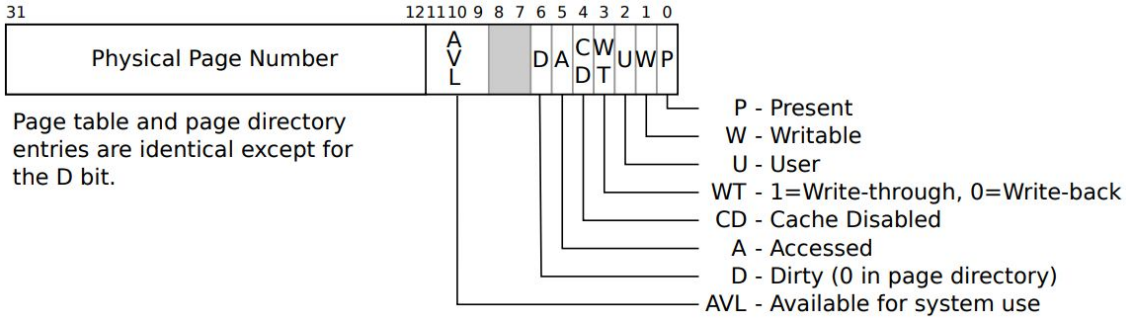


So with this approach, 1,048,576 − 593 = 1,047,983 page table entries would remain invalid, yet still occupy space.

Page Table Size
= Size of Item * Number of Items
= 20 bit * 2^20 < 3 bytes * 2^20
= 3MB

The solution





- A page table is stored in physical memory as a two-level tree.
- The root of the tree is a 4096-byte page directory that contains 1024 PTE-like references to page table pages.
- Each page table page is an array of 1024 32-bit PTEs.
- This two-level structure allows a page table to omit entire page table pages.

xv6 definitions

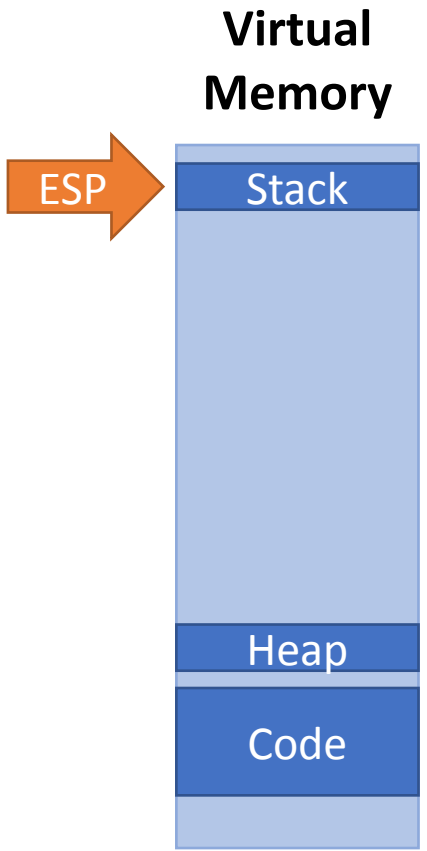
```
// page directory index
#define PDX(va)         (((uint)(va) >> PDXSHIFT) & 0x3FF)

// page table index
#define PTX(va)         (((uint)(va) >> PTXSHIFT) & 0x3FF)

// construct virtual address from indexes and offset
#define PGADDR(d, t, o) ((uint)((d) << PDXSHIFT | (t) << PTXSHIFT | (o)))

// Page directory and page table constants.
#define NPDENTRIES      1024    // # directory entries per page directory
#define NPTENTRIES      1024    // # PTEs per page table
#define PGSIZE          4096    // bytes mapped by a page

#define PTXSHIFT        12      // offset of PTX in a linear address
#define PDXSHIFT        22      // offset of PDX in a linear address

#define PGROUNDUP(sz)  (((sz)+PGSIZE-1) & ~(PGSIZE-1))
#define PGROUNDDOWN(a) (((a)) & ~(PGSIZE-1))

// Page table/directory entry flags.
#define PTE_P           0x001   // Present
#define PTE_W           0x002   // Writeable
#define PTE_U           0x004   // User
#define PTE_PS          0x080   // Page Size

// Address in page table or page directory entry
#define PTE_ADDR(pte)   ((uint)(pte) & ~0xFFF)
#define PTE_FLAGS(pte)  ((uint)(pte) &  0xFFF)
```

https://github.com/mit-pdos/xv6-public/blob/master/mmu.h

Memory allocators

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



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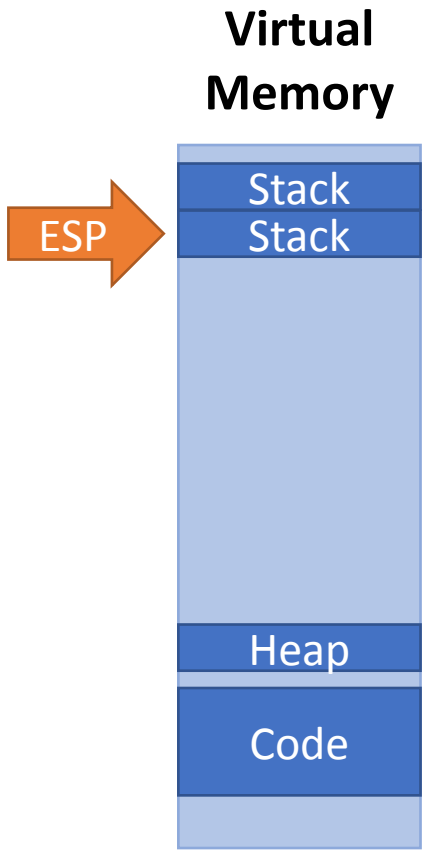

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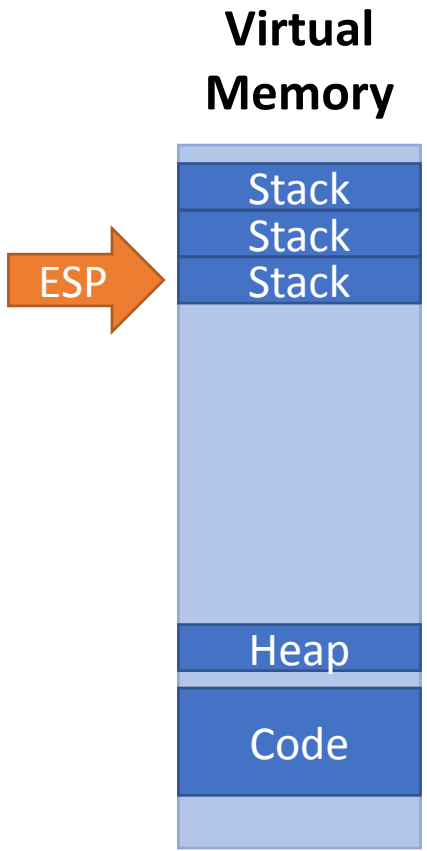

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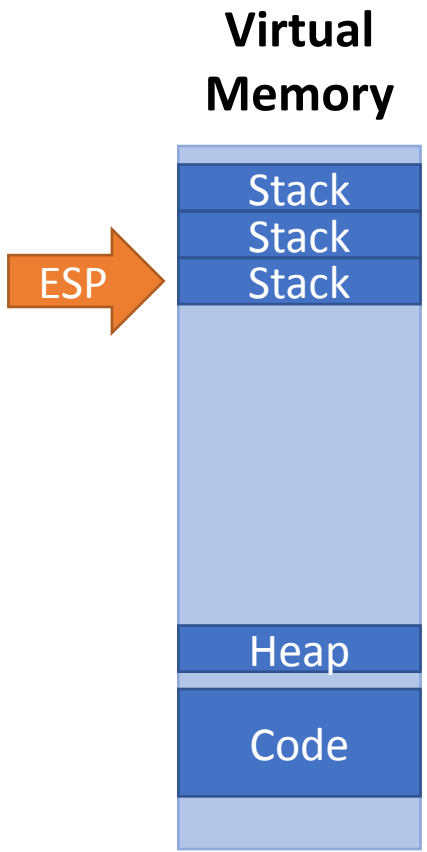
  - But these syscalls only allocates memory in multiples of 4KB

  - **Why 4KB?**



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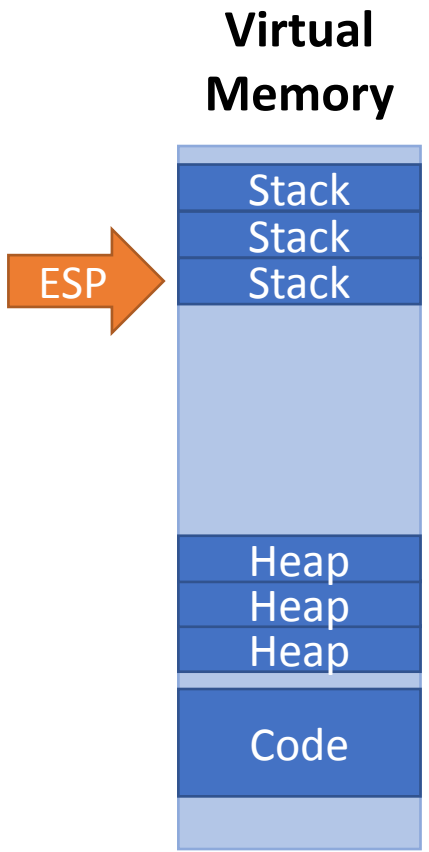

What About malloc() and free()?

- The OS only allocates and frees memory in units of 4KB pages
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- There are many different strategies for managing free memory

Free Space Management

- 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

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

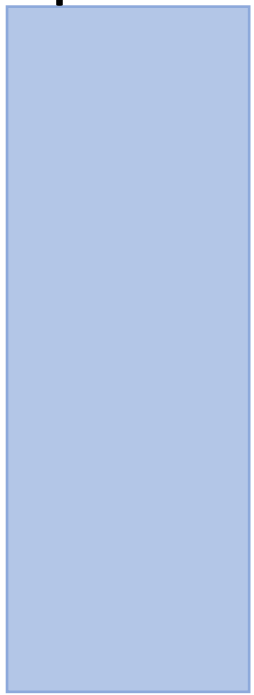
Requirements and Goals

- 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.
  - We won't cover this in class; you may refer to the textbook

Heap Fragmentation

```
obj * obj1, * obj2;
hash_tbl * ht;
int array[];
char * str1, * str2;
… // allocation of objects
```

Heap Memory



Heap Fragmentation

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… // allocation of objects
…
free(obj2);
free(array);
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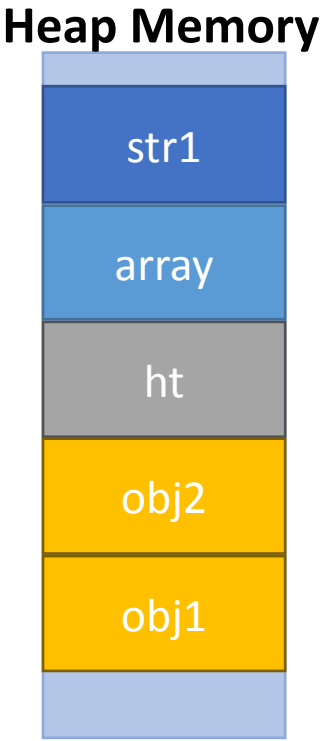

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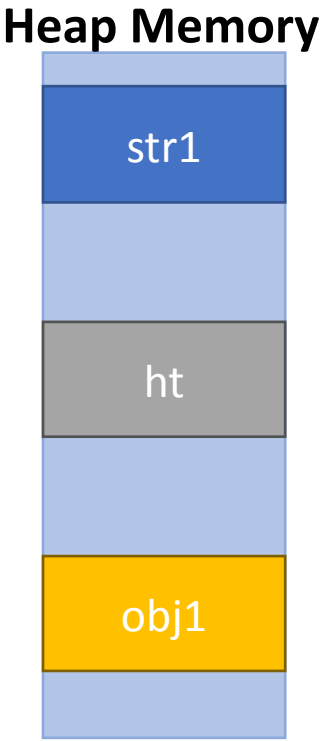
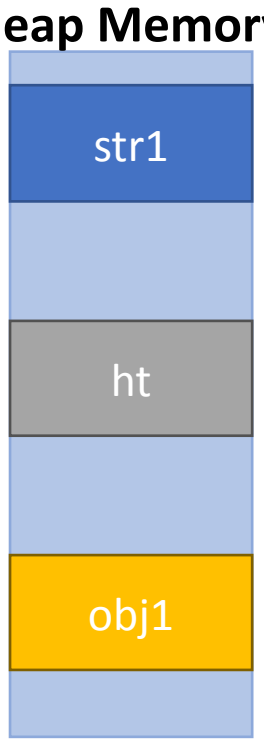


Heap Fragmentation

```
obj * obj1, * obj2;
hash_tbl * ht;
int array[];
char * str1, * str2;
… // allocation of objects
…
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 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

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- Design challenge: linked lists are dynamic data structures
- Dynamic data structures go on the heap
- But in this case, we are implementing the heap?!

Free List Data Structures

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

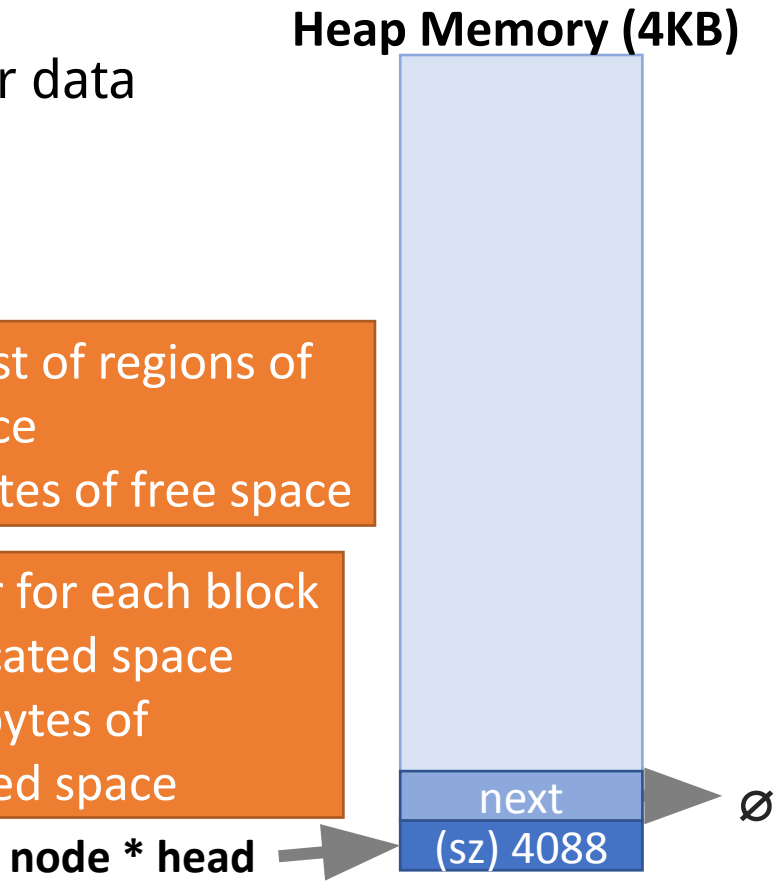
  num_bytes = *n* + sizeof(header)

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

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

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

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



Allocating Memory (Splitting)

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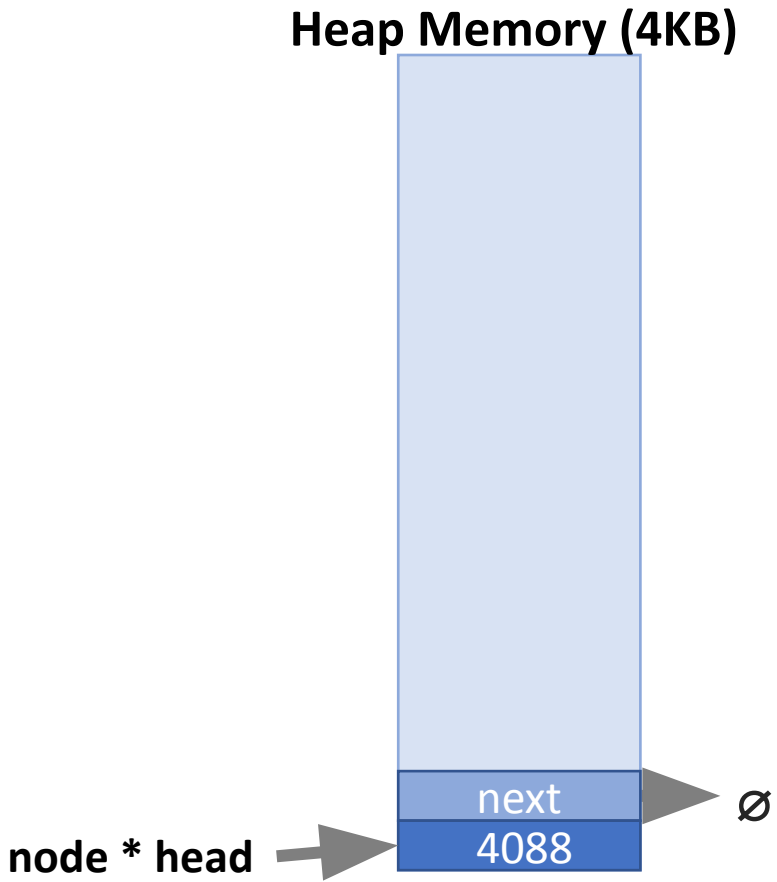

Allocating Memory (Splitting)

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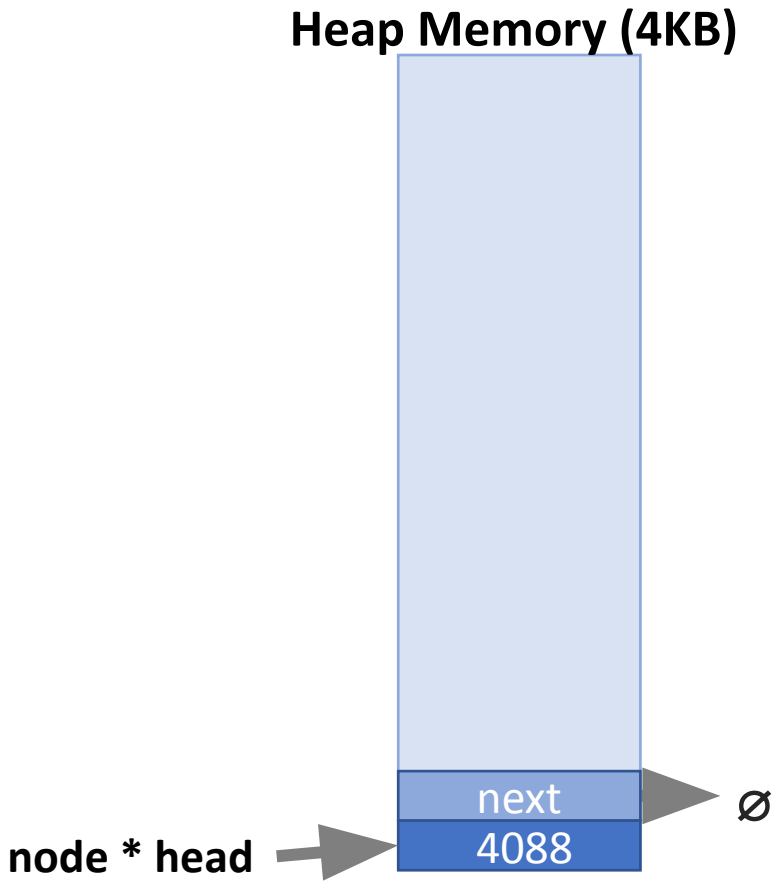

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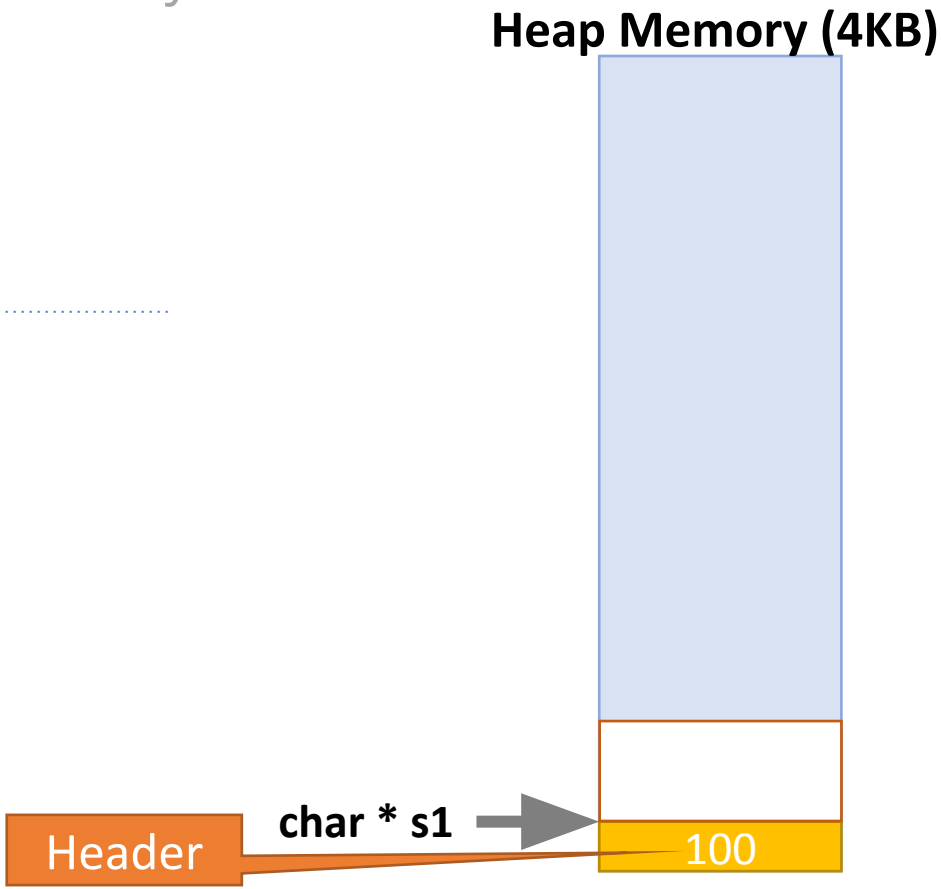

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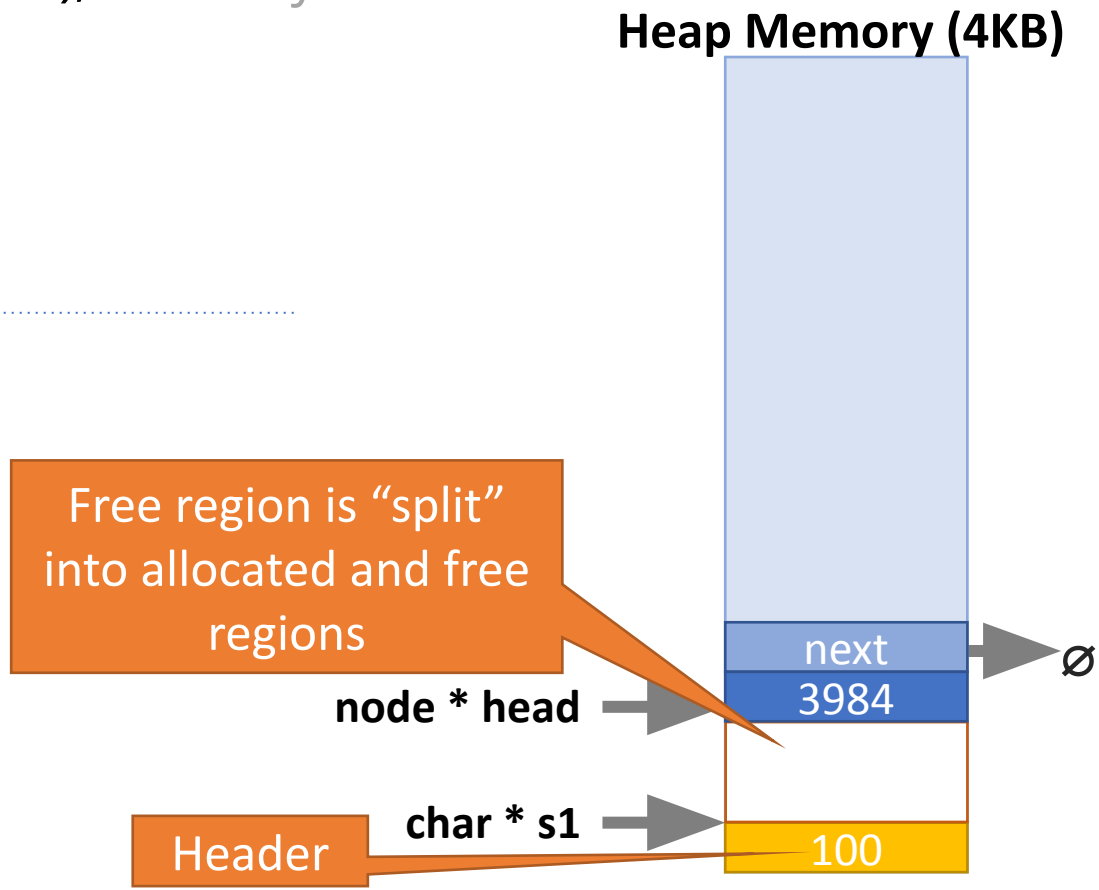

Allocating Memory (Splitting)

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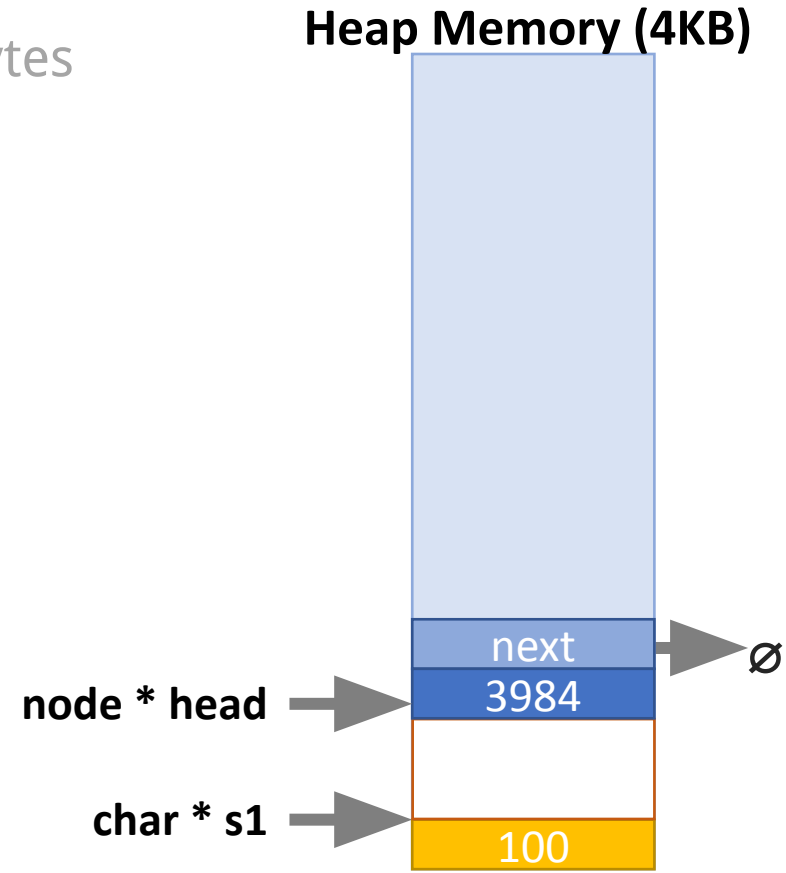

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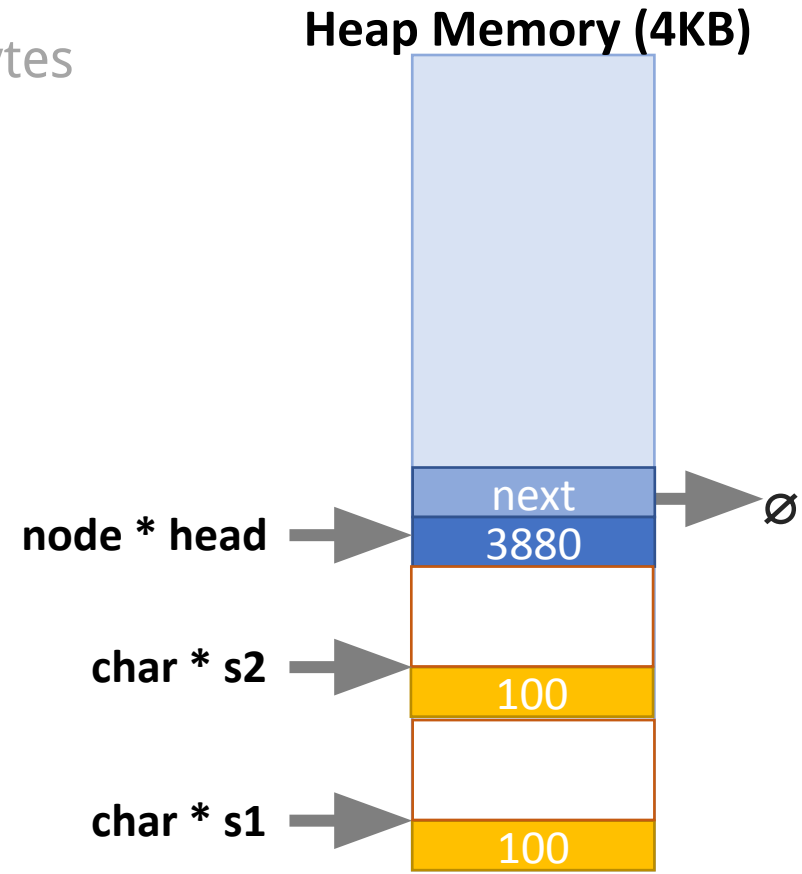

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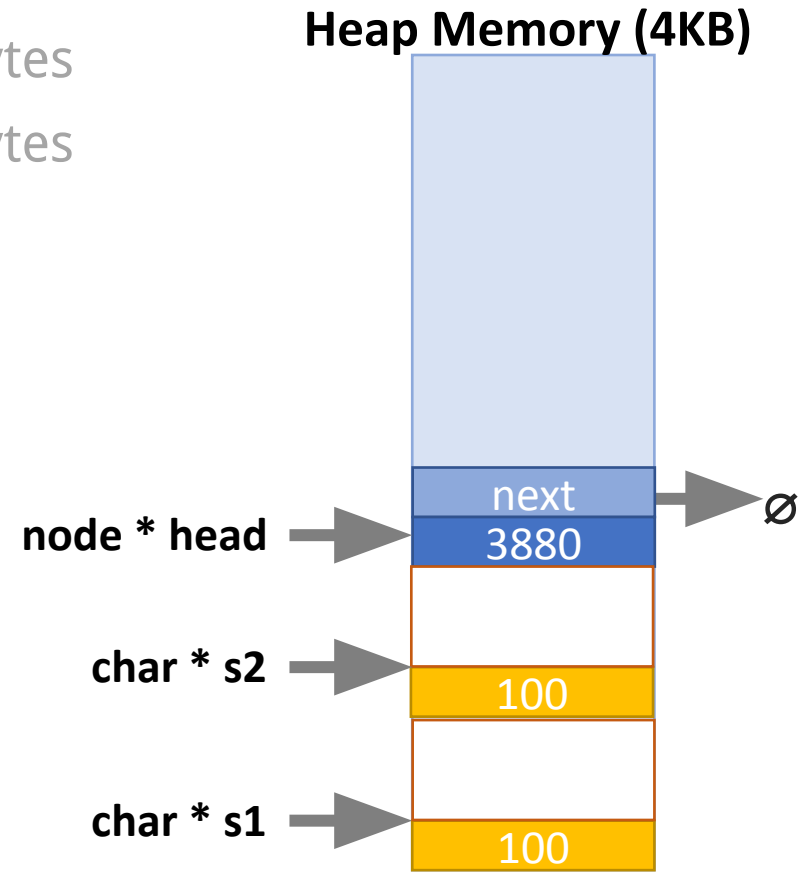

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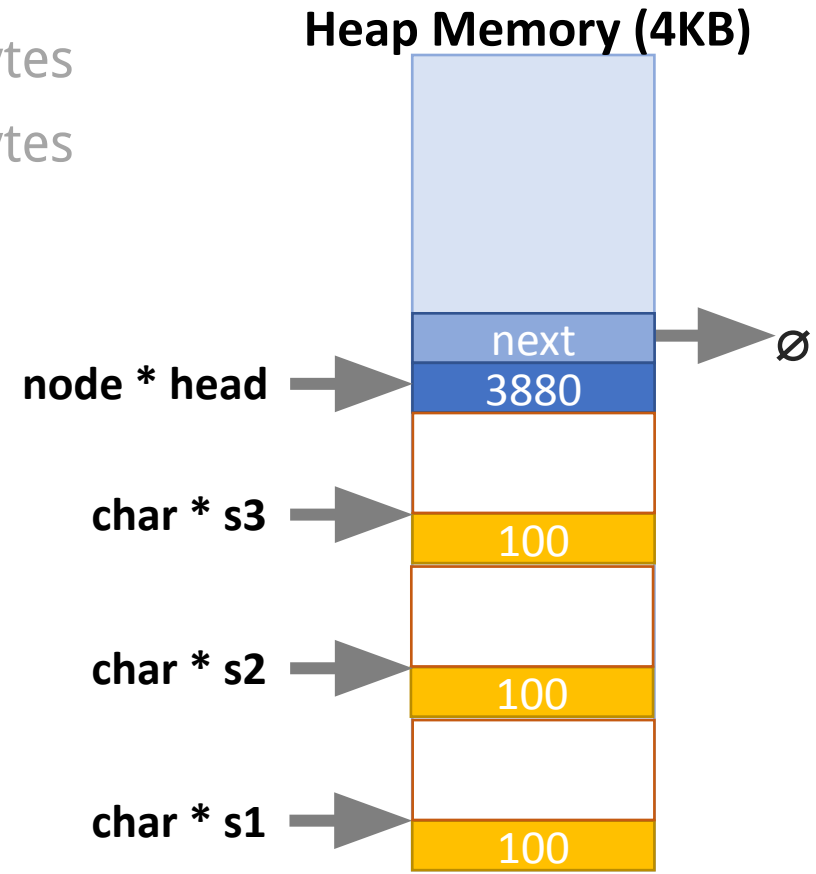

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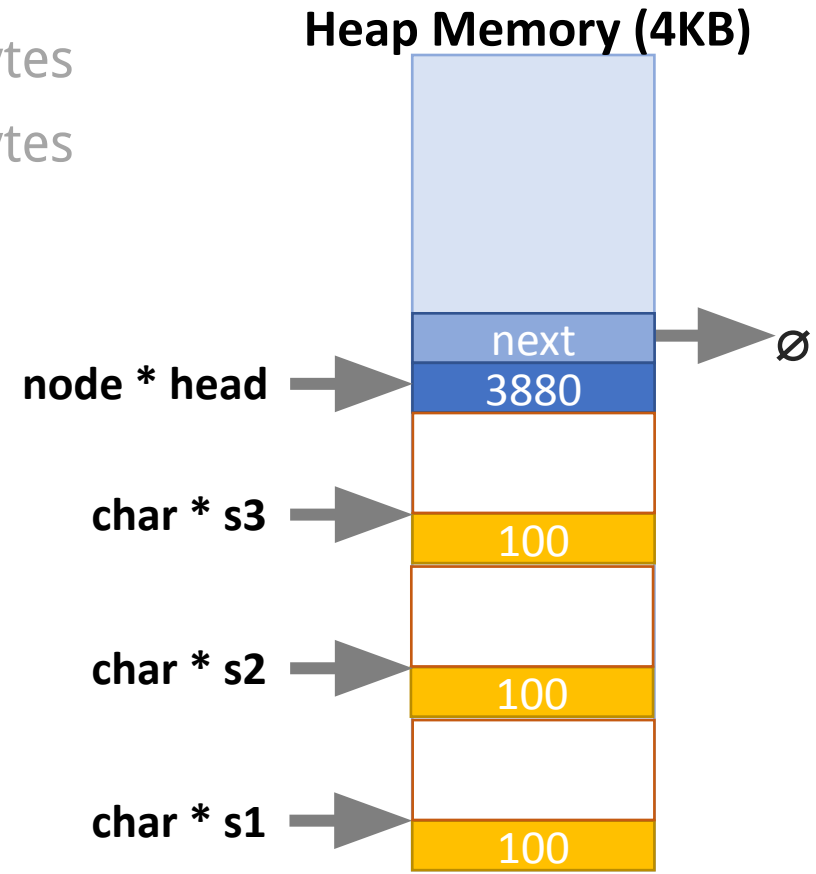

Freeing Memory

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  - free() is an O(n) operation

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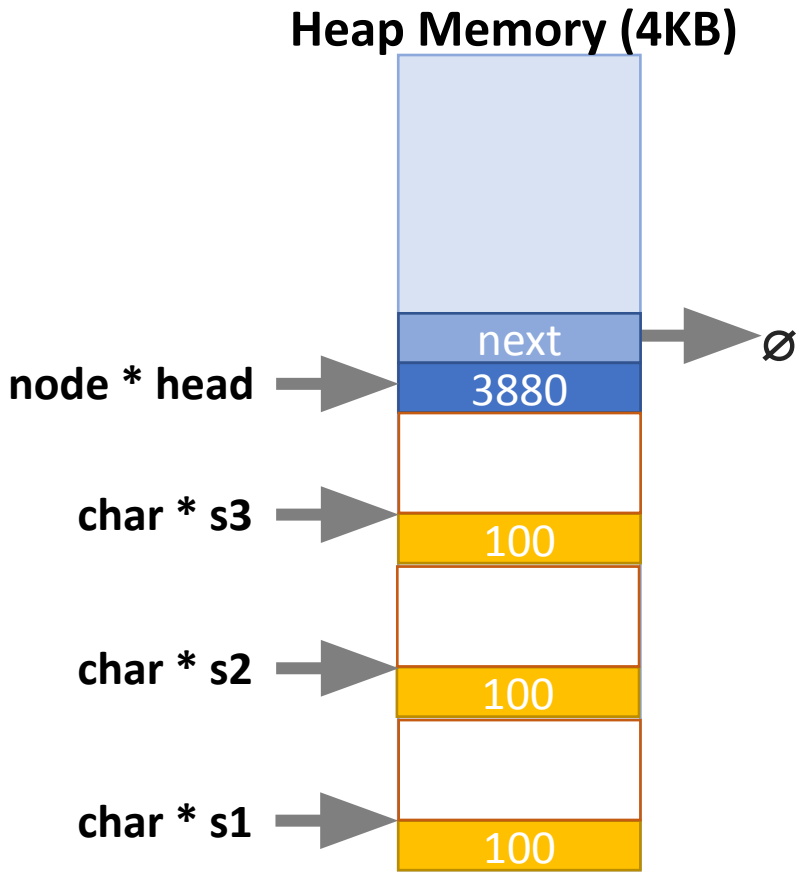

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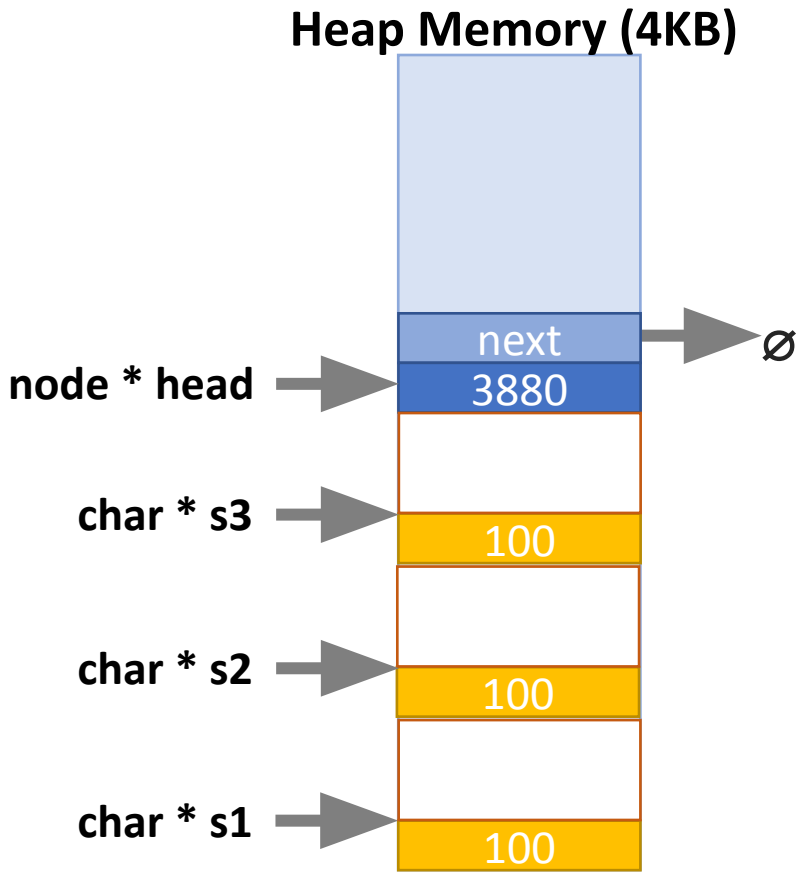

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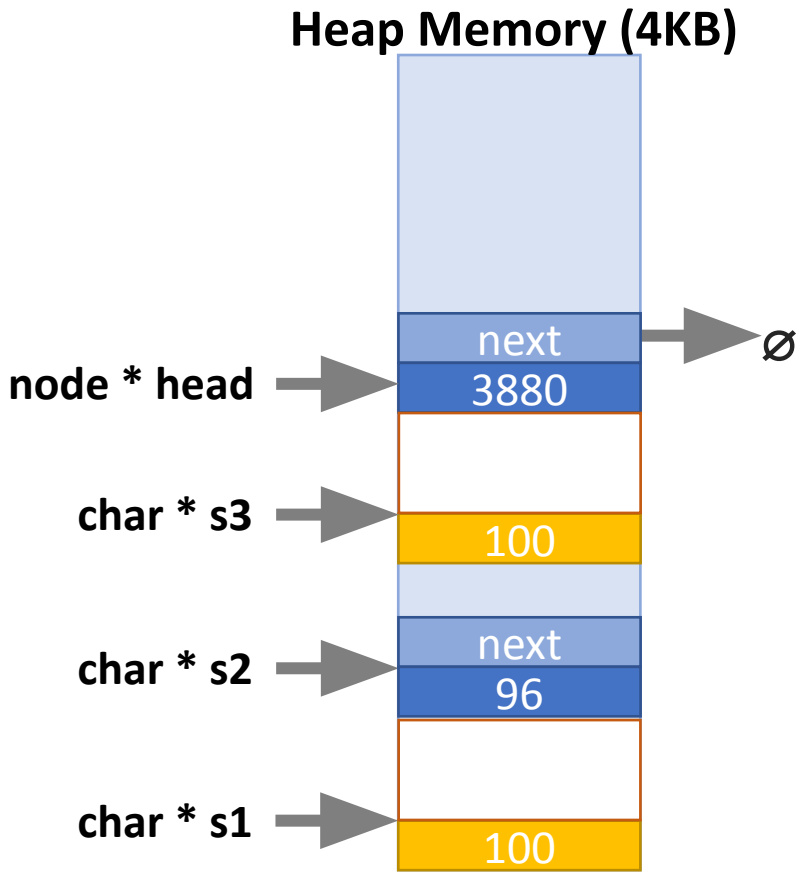

Freeing Memory

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

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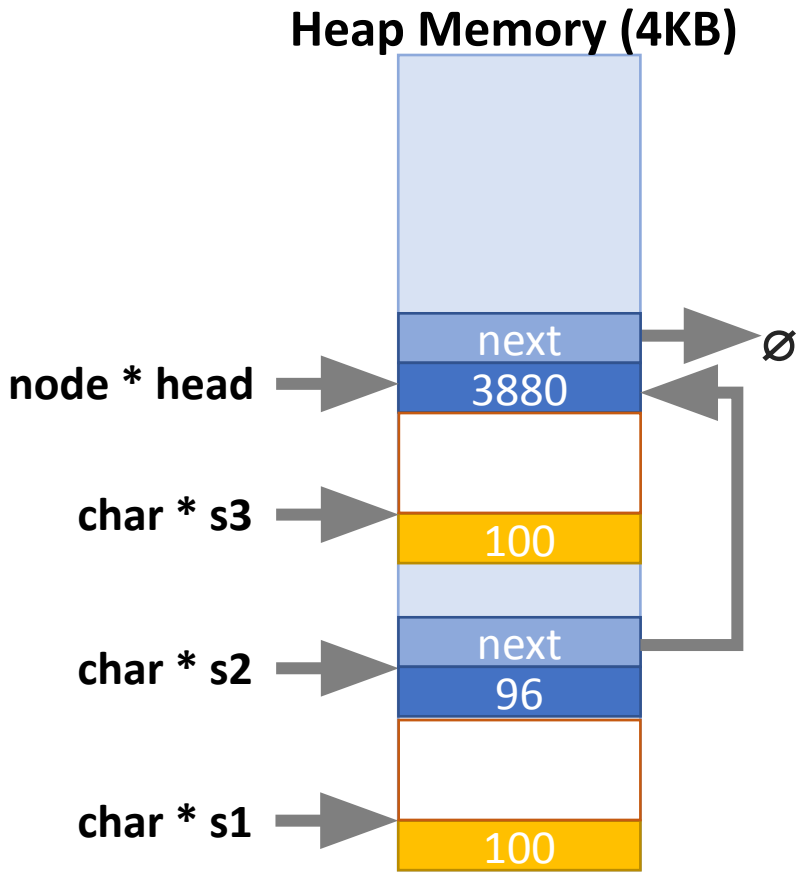

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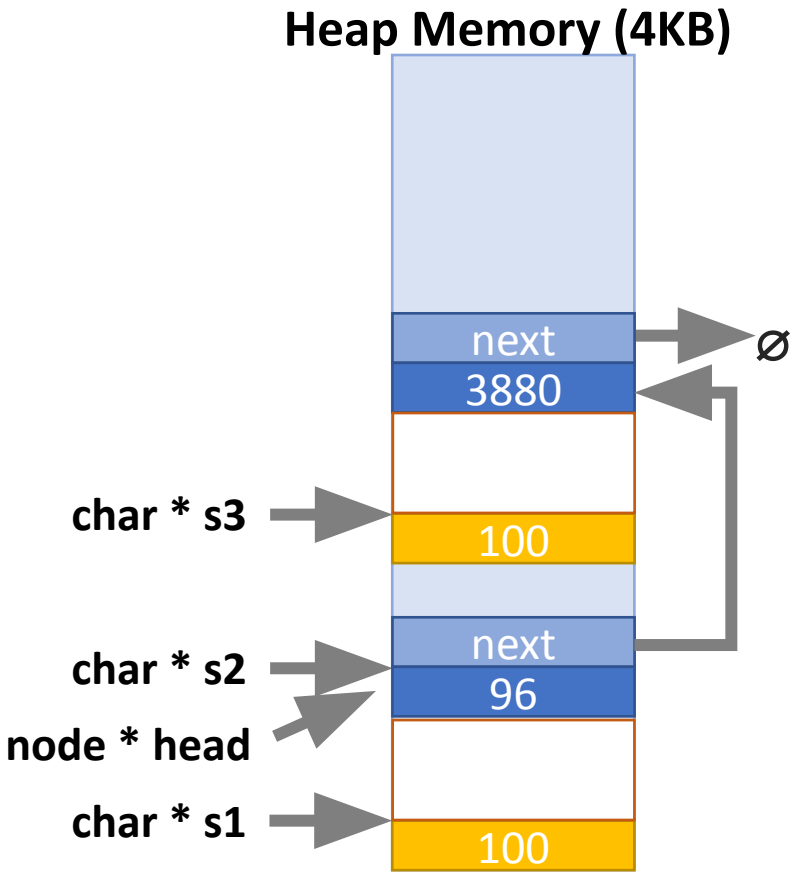

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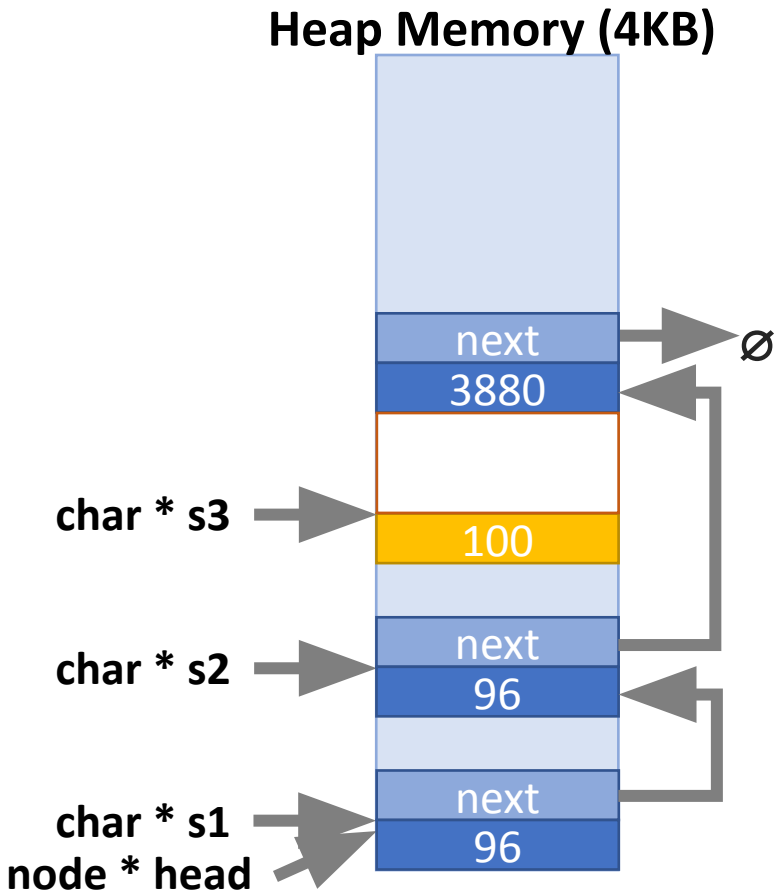

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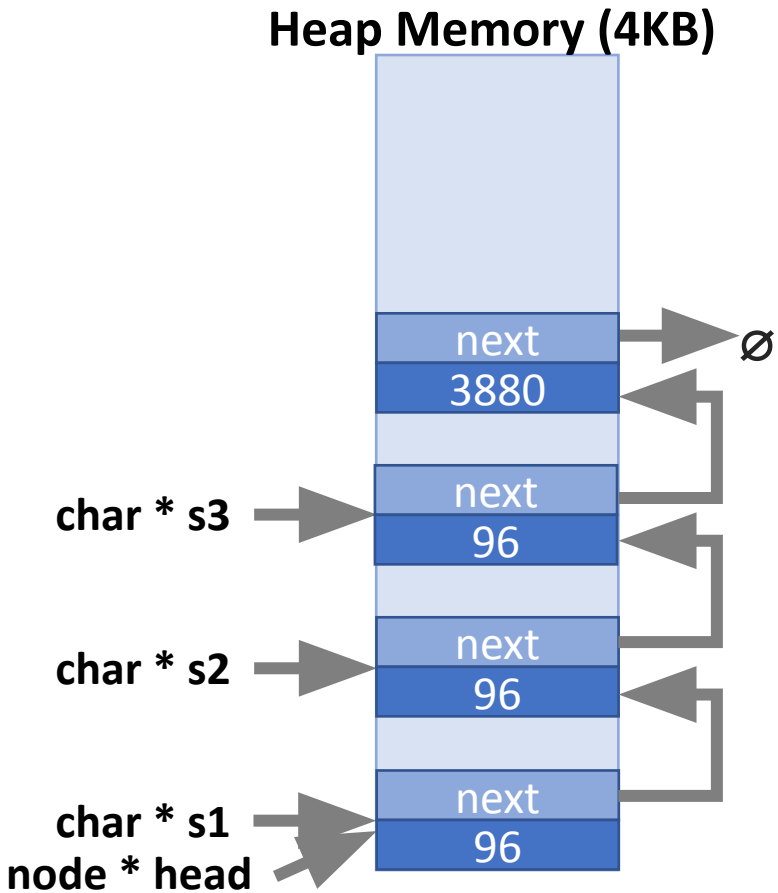

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```
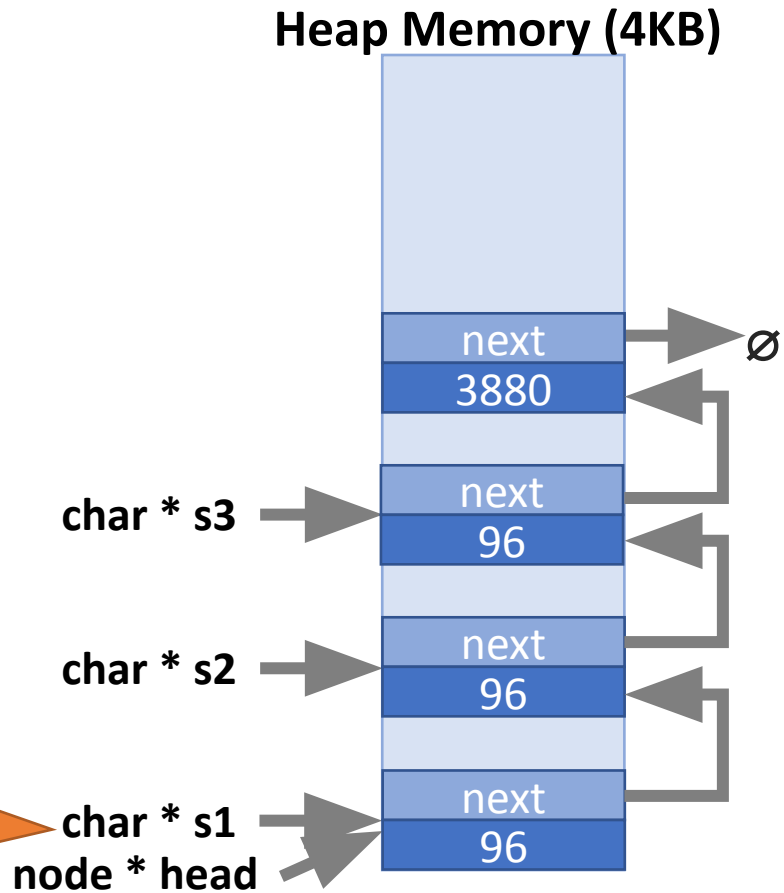

These pointers are “dangling”: they still point to heap memory, but the pointers are invalid



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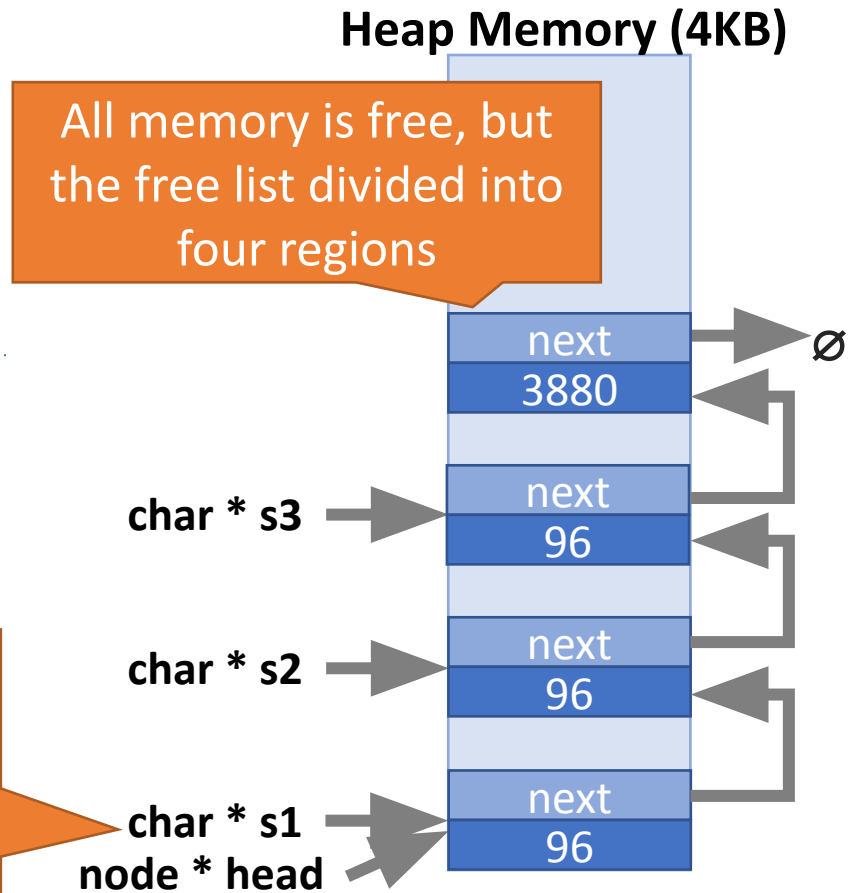

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If user calls malloc(4000) what would happen?

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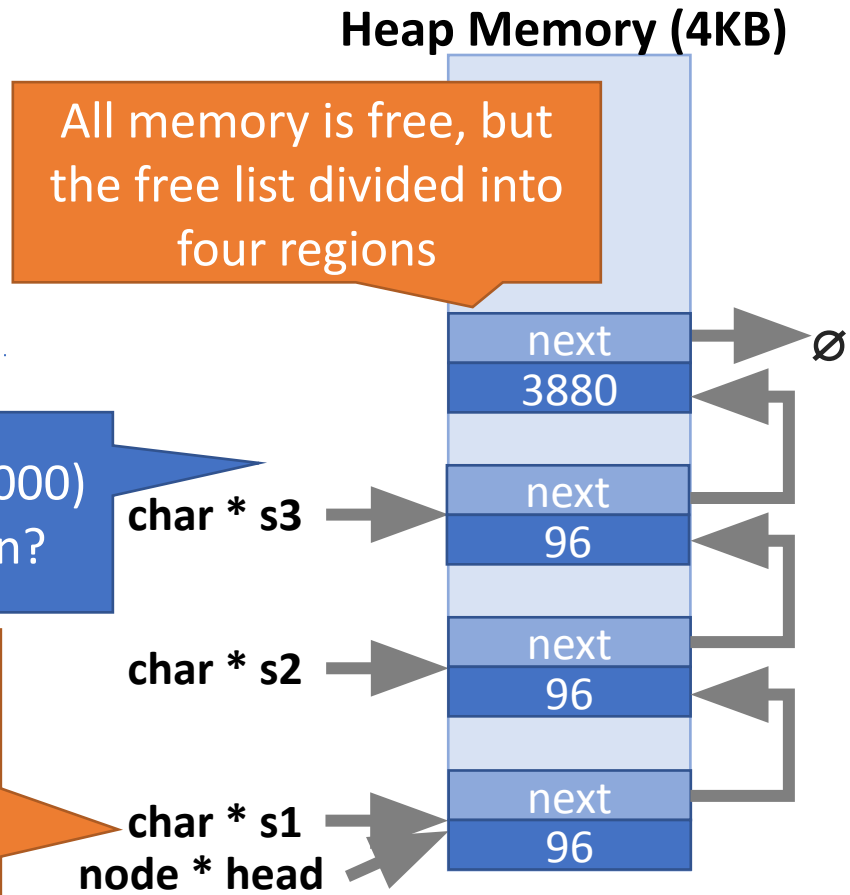

Coalescing

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

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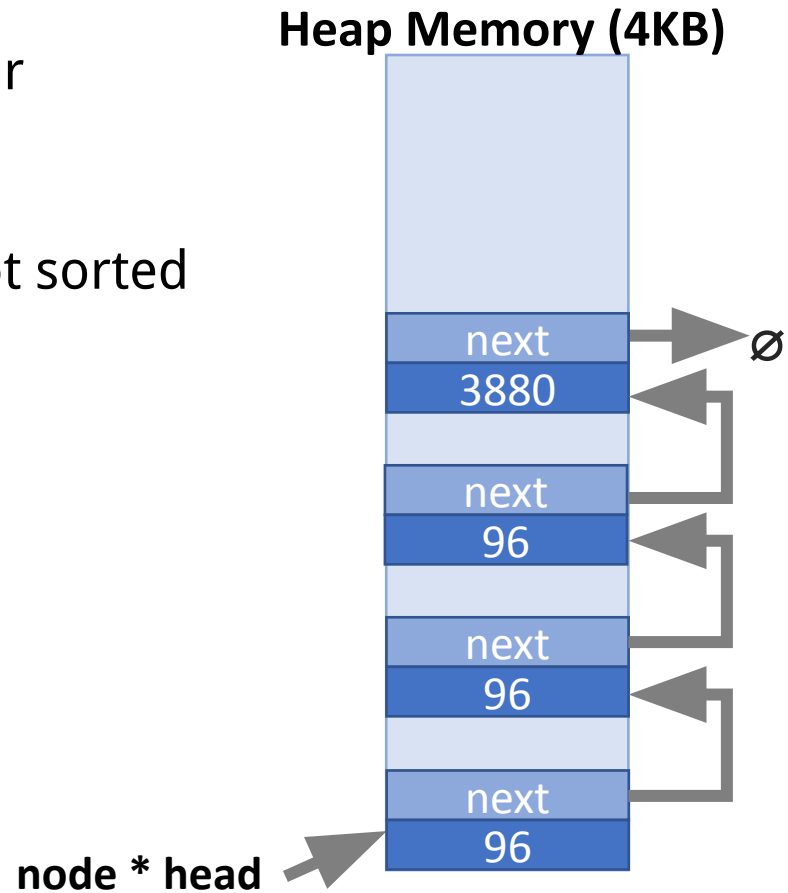

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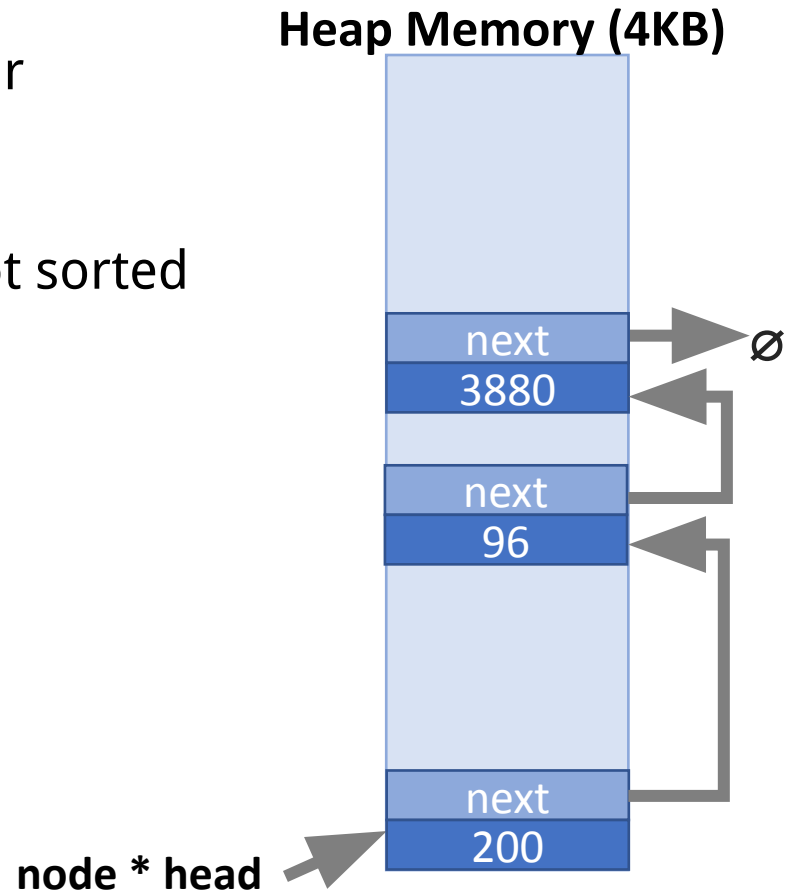

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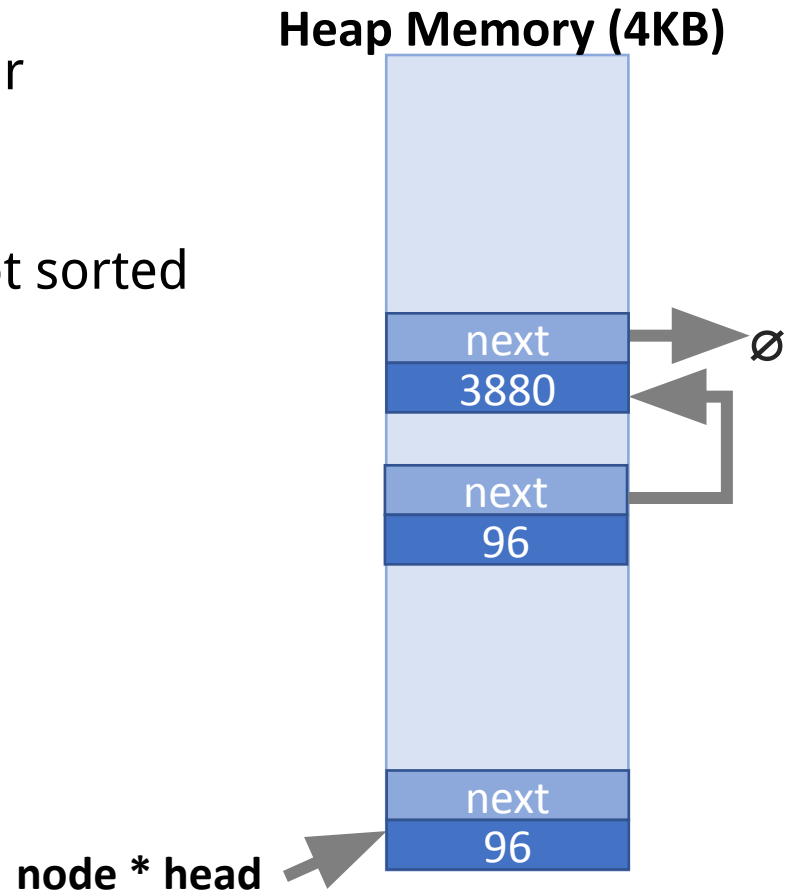

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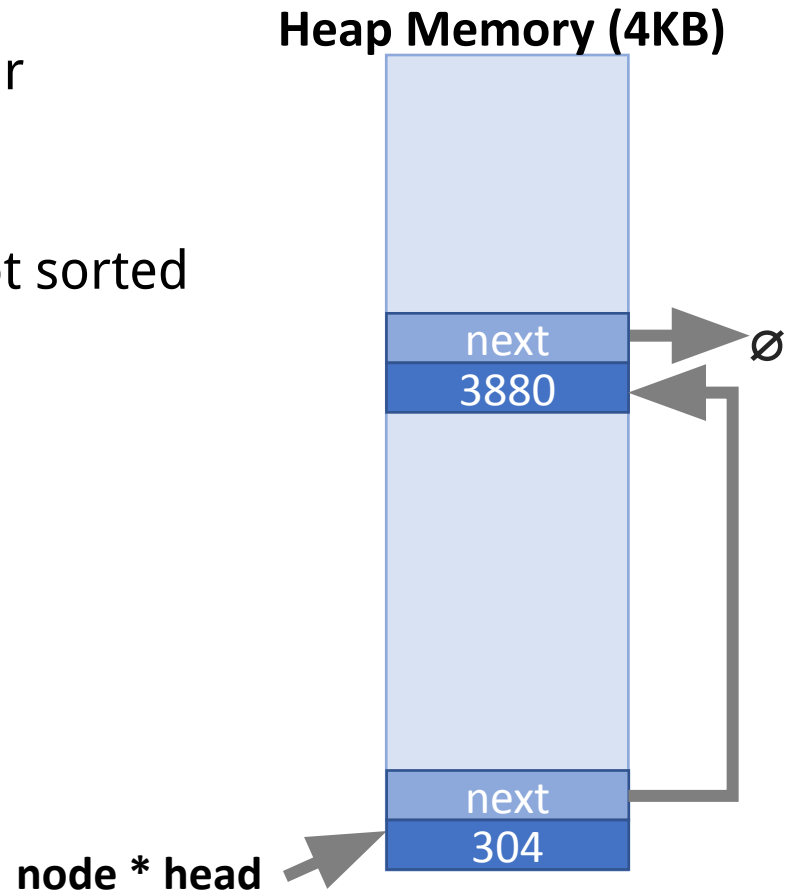

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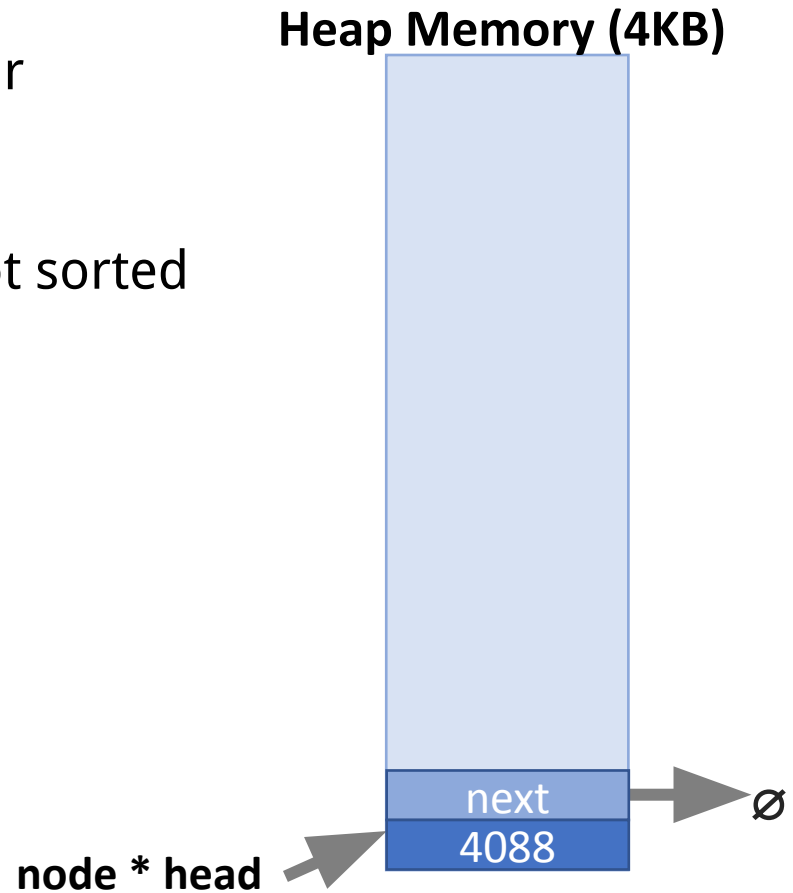

Choosing Free Regions (1)

```
int i[] = (int*) malloc(8);
// 8 + 4 = 12 total bytes
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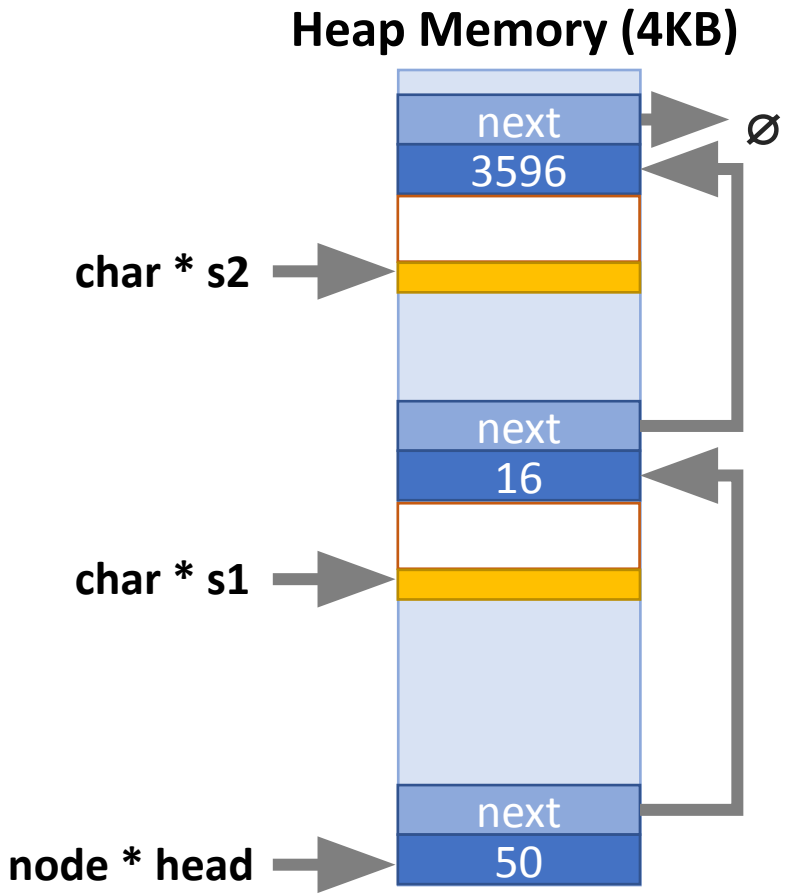
- Which free region should be chosen?



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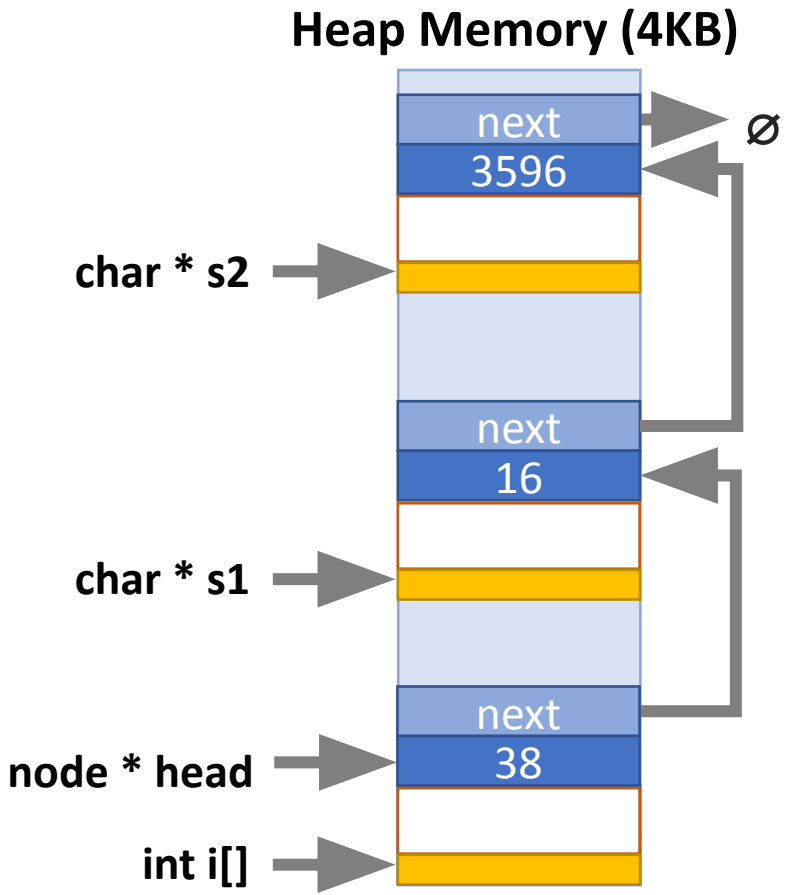

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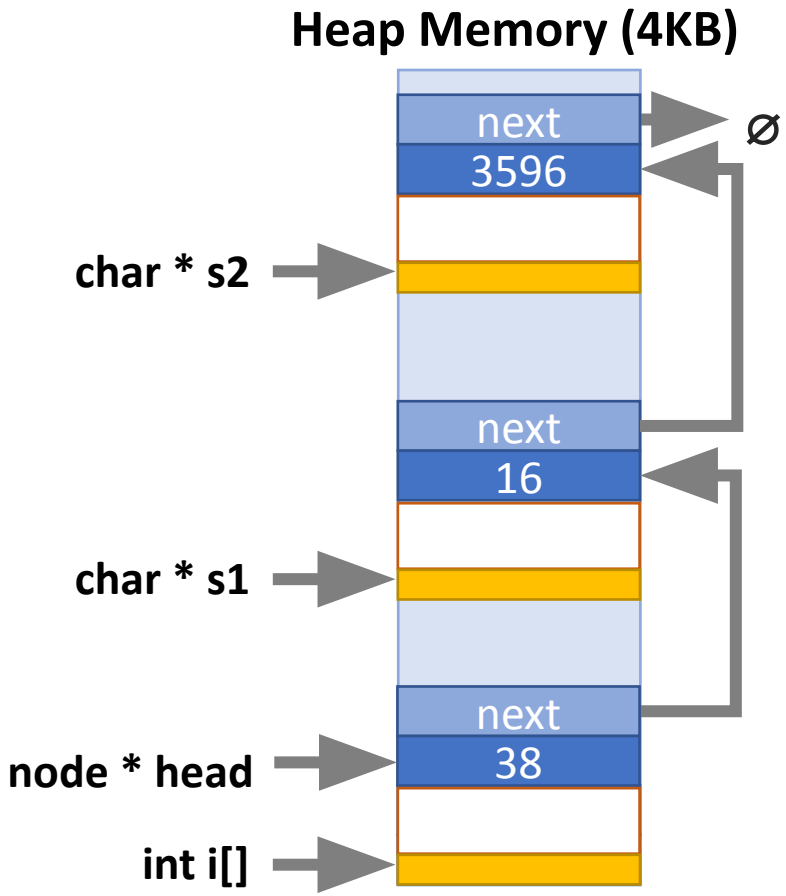

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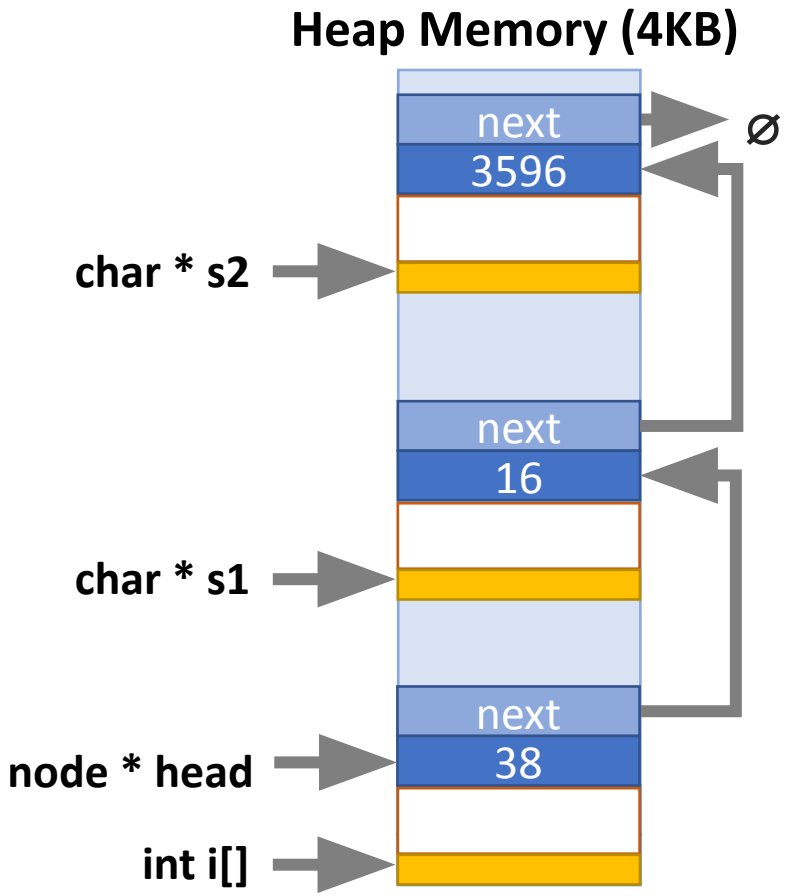

Choosing Free Regions (2)

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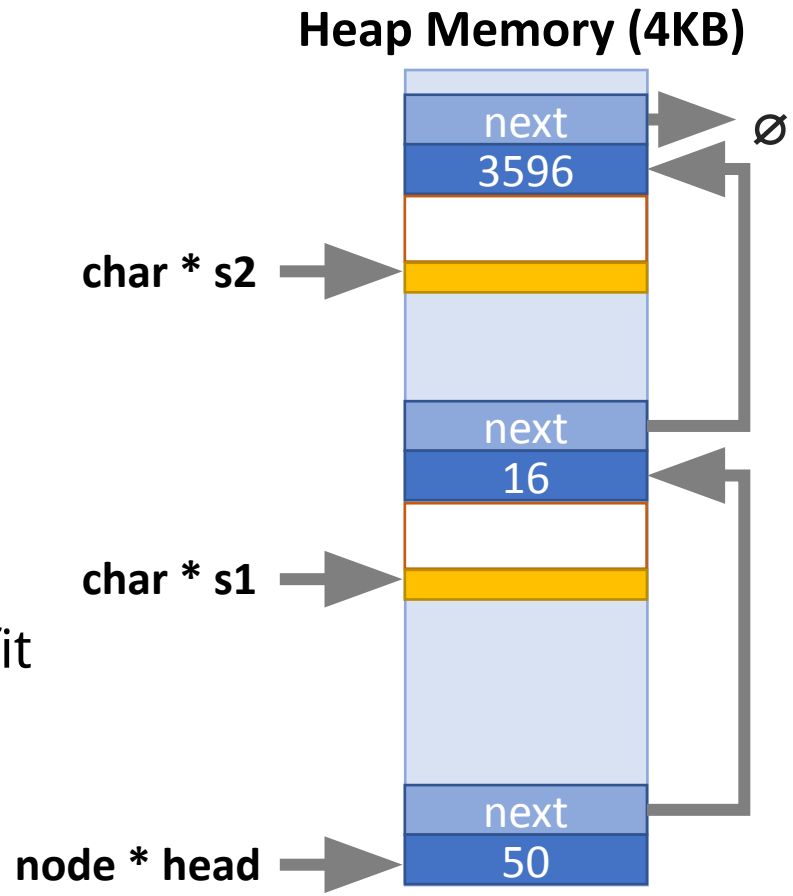
```

- Which free region should be chosen?
- Second option: **Best-Fit**
  - Locate the free region with size closest to (and >=) 8 bytes
- Less external fragmentation than First-fit



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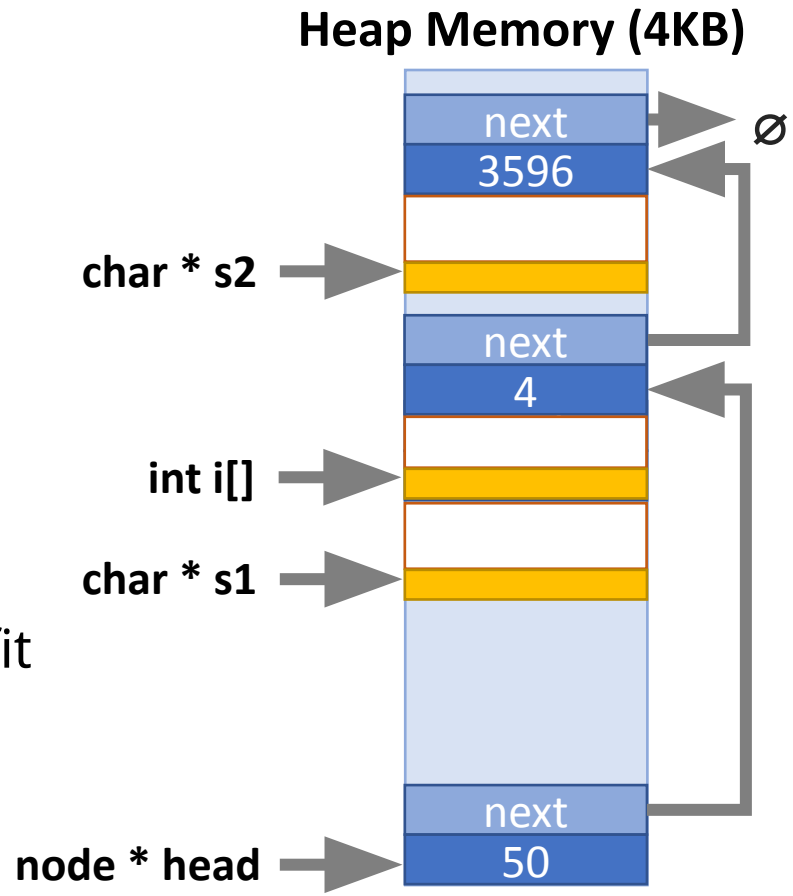

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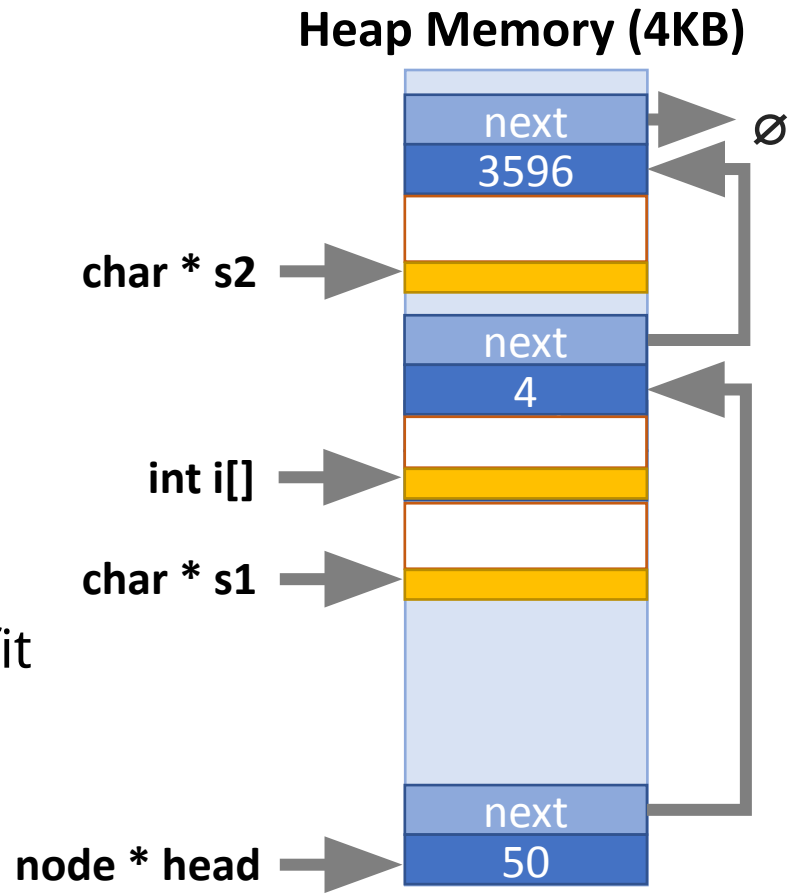

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- Second option: **Best-Fit**
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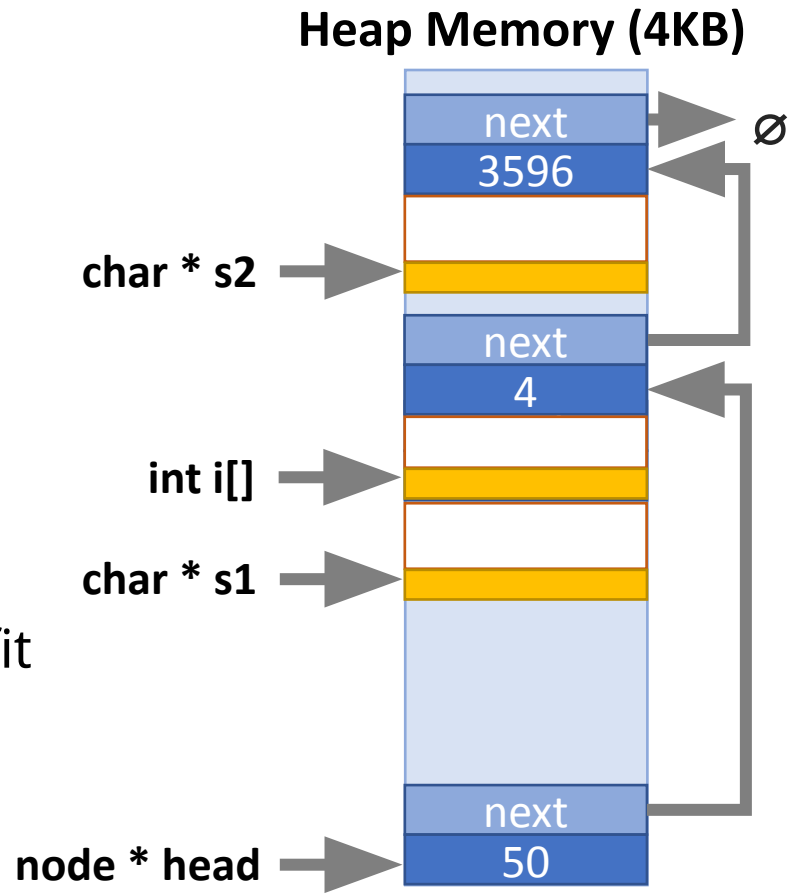
- Problem with Best-Fit?
  - Requires O(n) time



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
  - 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

Some clarification for the assignment

- You do not have to know about 4KB granularity allocation happening behind the scene
- You may treat as if sbrk(X) newly allocates X bytes of memory block
- You do not have to split the memory block when reusing it for allocation
- You do not have to merge the memory block during freeing
- You simply need to treat the allocated block from sbrk call as a single memory block and reuse the blocks as they are

Concurrency

Concurrent thinking

- Humans tend to think sequentially
- Thinking about all the potential sequences of events is difficult for humans.
  - https://www.psychologicalscience.org/news/why-humans-are-bad-at-multitasking.html
- Computers on the other hand, can multi-task quite well.

Parallelism vs Concurrency (programming context)

- What are parallelism and concurrency?
- What is the difference?

Parallelism vs Concurrency (programming context)

- Concurrency:

  Happening at at the same time, interleaving, sharing resources
  - Multiple tasks **in progress** at the same time
  - **Dealing** with multiple things at once

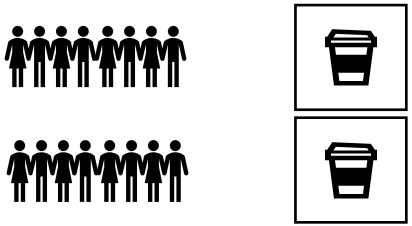
- Parallelism:

  Happening at the same time, progressing independently
  - Multiple tasks **executing** at the same time
  - **Doing** multiple things at once
  - Simultaneous execution

Parallelism vs Concurrency (programming context)

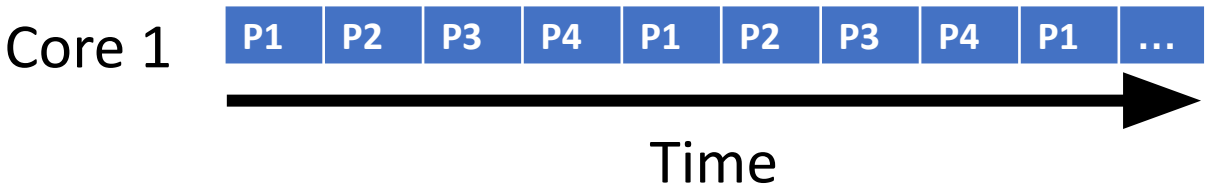
- Concurrency
  - Two queues for one vending machine

- Parallelism
  - Two queues for two vending machines



Parallelism vs Concurrency (programming context)

- Concurrent execution on a single-core system:



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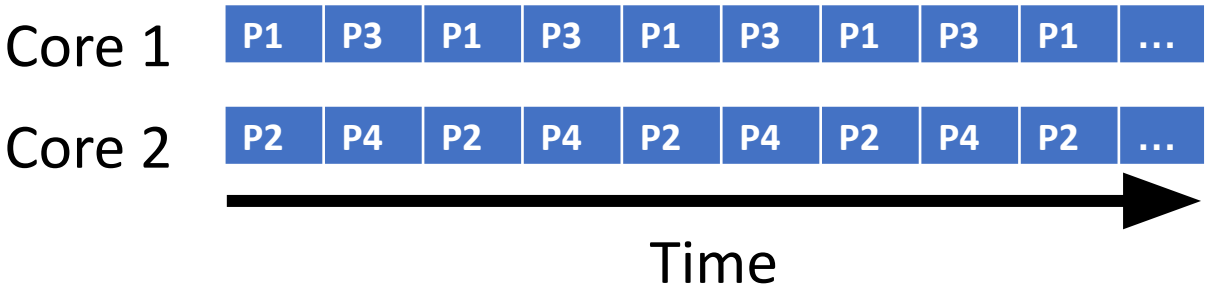
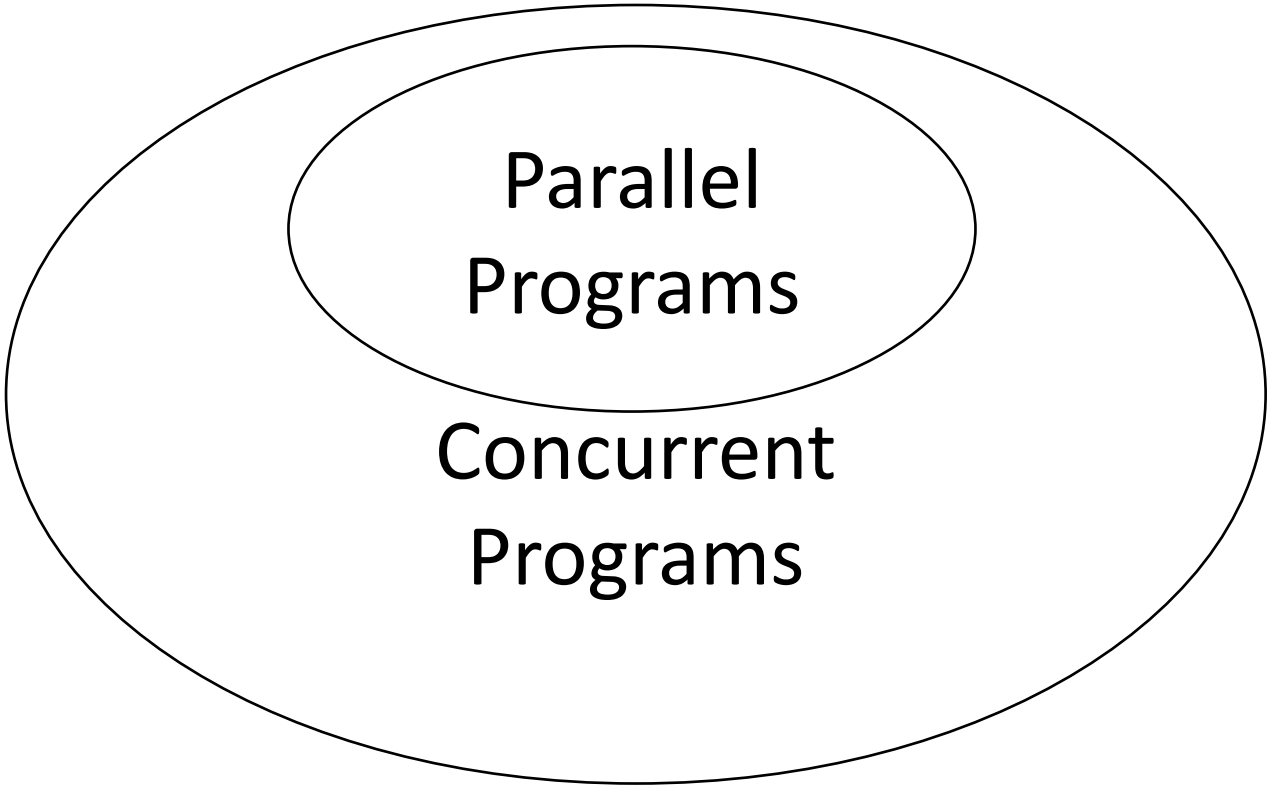


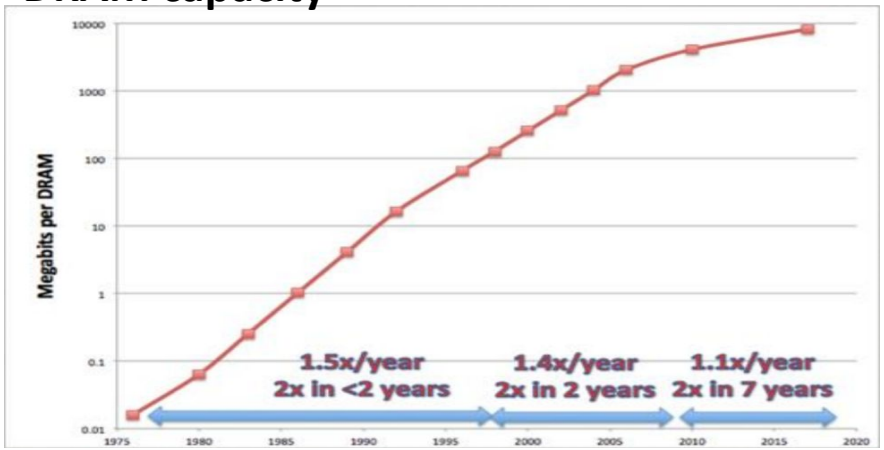

Parallel
Programs
Concurrent
Programs

Why is concurrency so important?

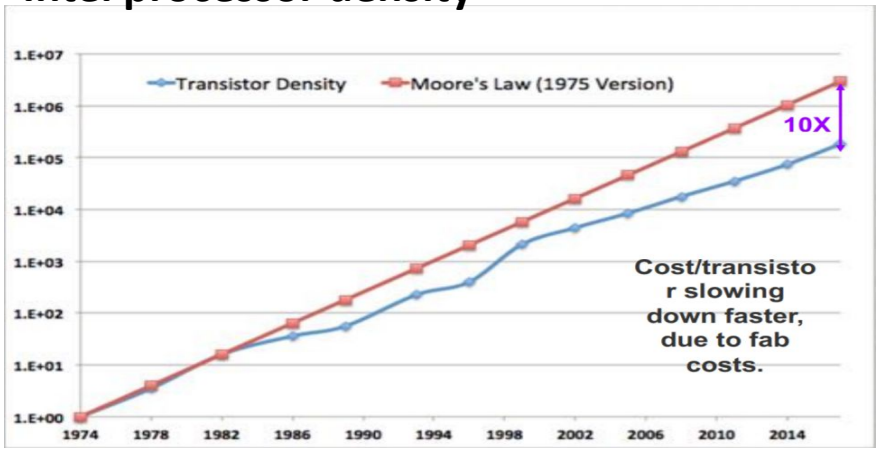
Moore's law is slowing down

- The number of transistors on IC chips doubles approx. every 2 years

DRAM capacity



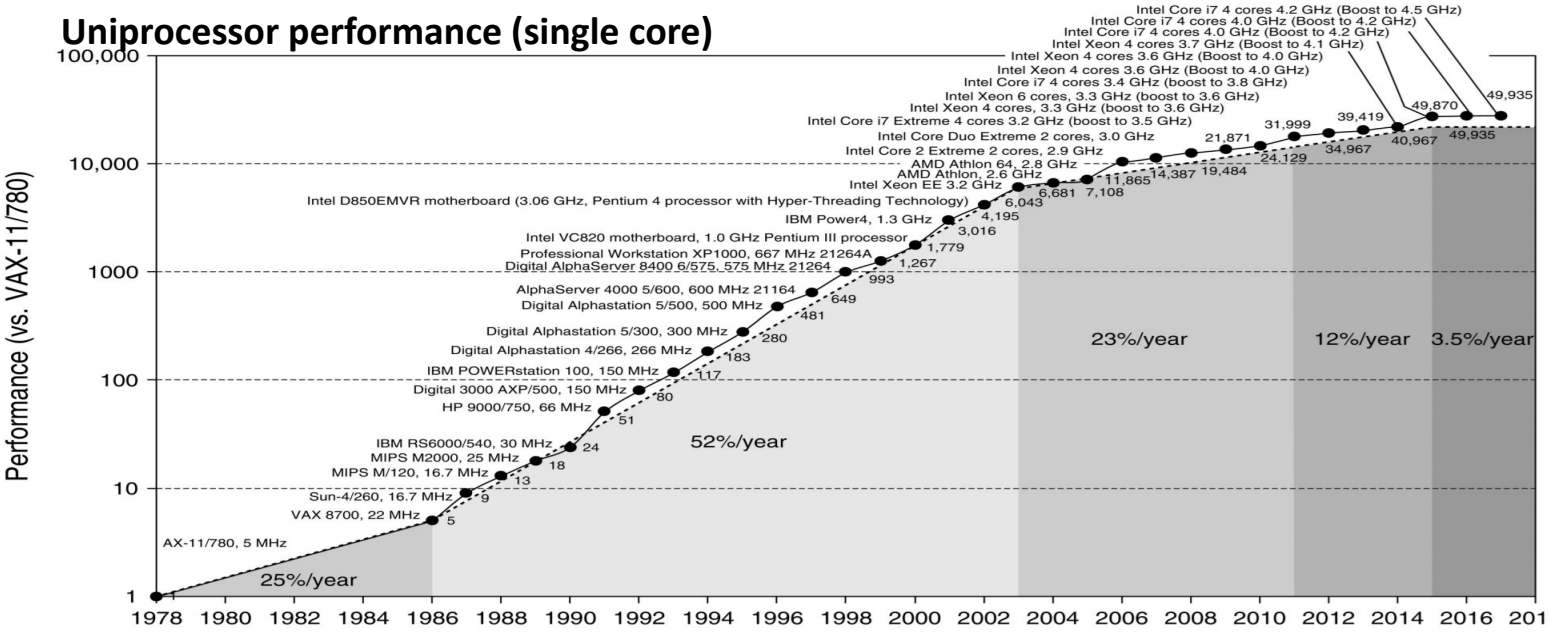
Intel processor density



Source:The end of moore's law & faster general purpose computing, and a road forward, John Hennessy. https://p4.org/assets/P4WS_2019/Speaker_Slides/9_2.05pm_John_Hennessey.pdf

End of Dennard scaling

- Processor frequency increased for free as transistors became smaller
- Transistors became so small that current leakage overheats the chip



Source:The end of moore's law & faster general purpose computing, and a road forward, John Hennessy. https://web.stanford.edu/~hennessy/Future%20of%20Computing.pdf

Implications of CPU Evolution

- Increasing transistor count/clock speed
  - Greater number of tasks can be executed concurrently

- Clock speed increases have almost stopped in the past few years
  - Instead, more transistors = more CPU cores
  - More cores = increased opportunity for parallelism

Amdahl's Law

- Speed up does not necessarily apply to the entire system
- Speed up indicates a relative performance improvement
  - Originally spent time to improved time ratio
- $\text{Speed up} = \frac{1}{(1-P)+P/S}$
  - (1 – P) = the part that was not enhanced
  - P = the part that was enhanced
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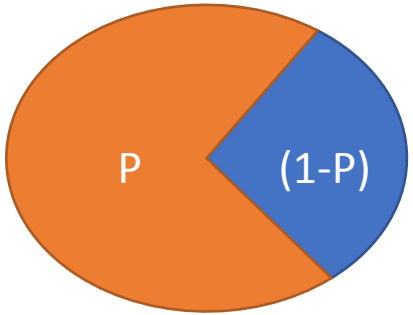

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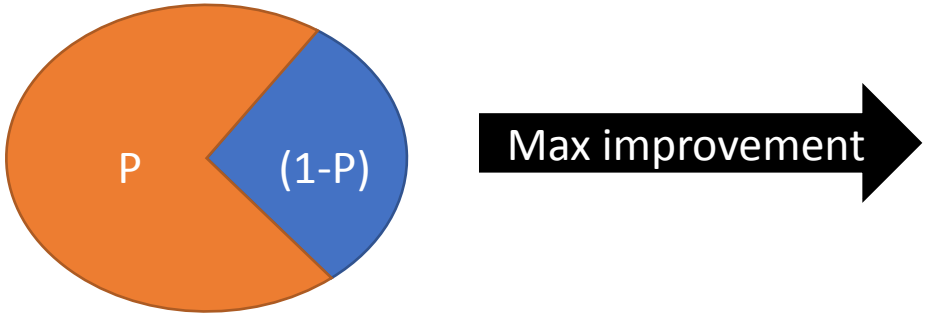

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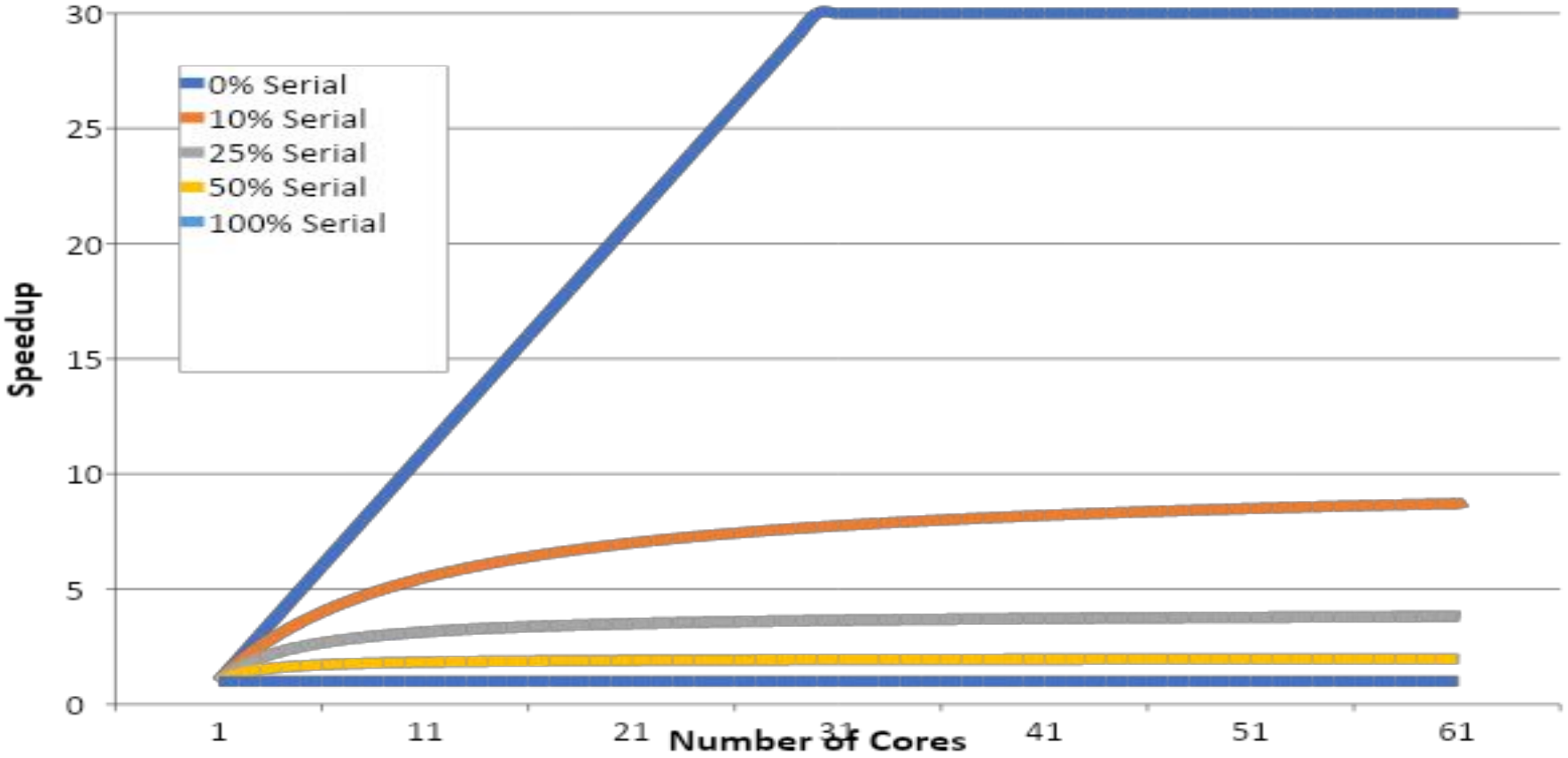
Amdahl's Law

- Upper bound on performance gains from parallelism
  - If I take a single-threaded task and parallelize it over *N* CPUs, how much more quickly will my task complete?

- Definition:
  - *seq* is the fraction of processing time that is processed sequentially
  - *par* is the fraction of processing time that can be parallelized
  - *seq+par = 1*
  - *N* is the number of CPU cores

$$\text{Speedup} = \frac{1}{seq + \frac{par}{N}}$$

Amdahl's Law


0% Serial
10% Serial
25% Serial
50% Serial
100% Serial
Speedup
30
25
20
15
10
5
0
1
11
21
31
41
51
61
Number of Cores

Concurrency

- In general, concurrency (like parallelism) is used because it is necessary for a system to function.

- It is also largely motivated by increased performance
  - The potential for more tasks to happen at once can thus increases performance (especially, if we have multiple cores on our machine)

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Concurrency comes with some caveats however (next slide!)

Bad Concurrency = Data Race

- When two (or more) processes contending for one shared resource.

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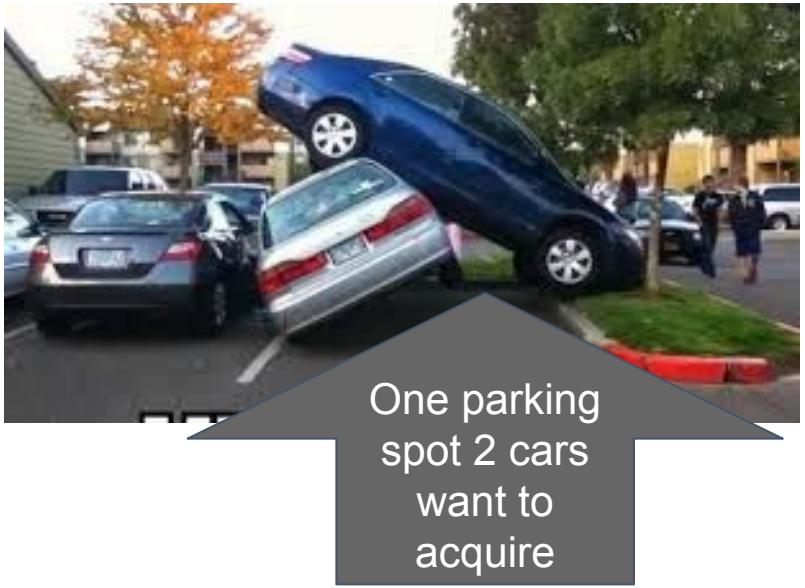

Data race is not always as obvious...(1/4)

- Imagine you check your fridge and find there is no milk
    - So you run to the store

Data race is not always as obvious...(2/4)

- Imagine you check your fridge and find there is no milk
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- Then moments later your roommate checks the fridge and finds it is empty
  - So they run to the store

Data race is not always as obvious...(3/4)

- Imagine you check your fridge and find there is no milk
  - So you run to the store
- Then moments later your roommate checks the fridge and finds it is empty
  - So they run to the store
- Roommate # 3 comes and notices the same
  - ....

Data race is not always as obvious...(4/4)

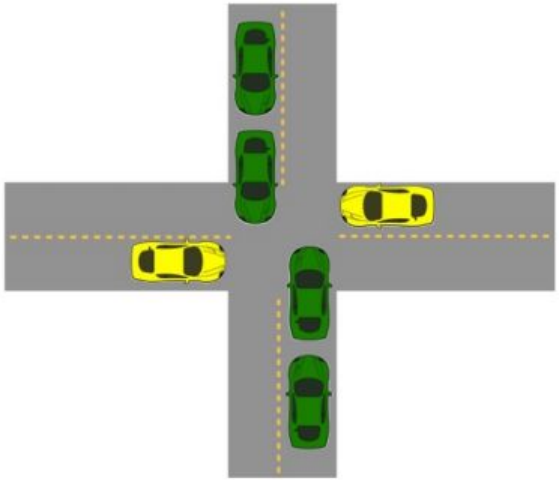
- You get the idea when you then find out you have 3 times as much milk as your house needs when everyone returns.

Bad Concurrency = Deadlock

- Grid lock in a traffic jam
- Each car prevents others from going through a shared resource (the intersection).
- (One car needs a piece of the intersection in order to move forward)

Bad Concurrency = Starvation

- Imagine a constant stream of green cars
- Progress is still being made by the green cars
- The yellow cars can never make progress to get across the street.
  - They are resource starved of a shared resource (again, they cannot cross the intersection)



Concurrent Programming needs some extra care

- Races
  - Outcome depends on the arbitrary scheduling decisions
  - e.g. Who gets the last seat on the airplane.
- Deadlock: Improper resource allocation prevents forward progress
  - e.g. traffic gridlock
- Starvation/Fairness: External events and/or scheduling decisions can prevent sub-task progress
  - e.g. Someone jumping in front of you in line

- But regardless, concurrent programming is important and necessary to get the most out of current processor architectures!

A Few Approaches to Concurrency

- Process-Based
  - Fork() different processes
  - Each process has its own private address space
- Event-Based
  - Programmer manually interleaves multiple logical flows and polls for events
  - All flows share the same address space
  - Uses technique called I/O multiplexing
- **Thread-based (Today's focus)**
  - **Kernel automatically interleaves multiple logical flows**
  - **Each flow shares the same address space**
  - **Hybrid of process-based and event-based.**

Threads

Problems with Processes

- Process creation is heavyweight (i.e. slow)

- IPC mechanisms are cumbersome

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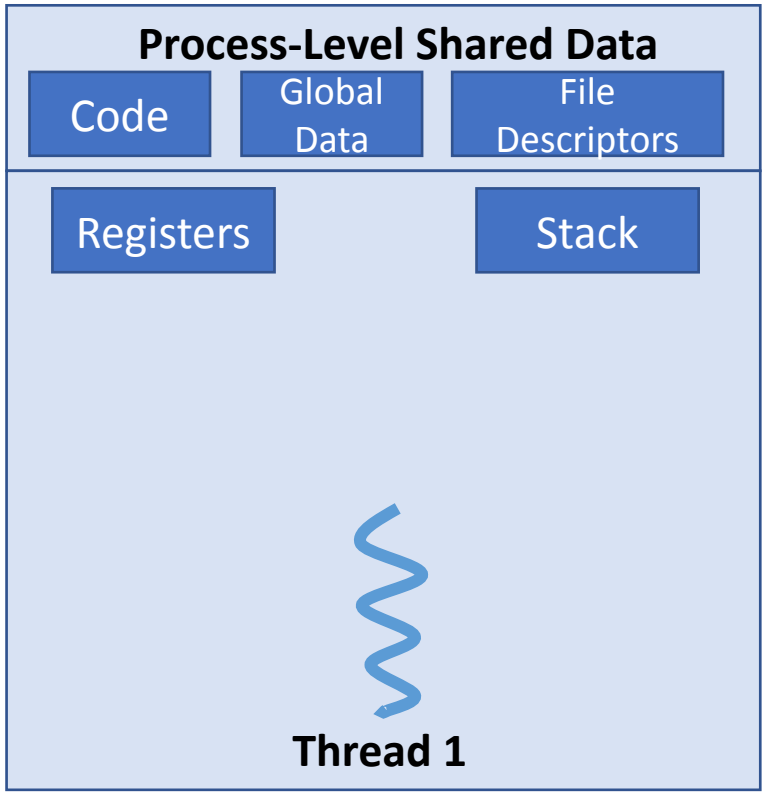
Problems with Processes

- Process creation is heavyweight (i.e. slow)
  - Space must be allocated for the new process
  - fork() copies all state of the parent to the child
- IPC mechanisms are cumbersome
  - Difficult to use fine-grained synchronization
  - Message passing is slow
    - Each message may have to go through the kernel

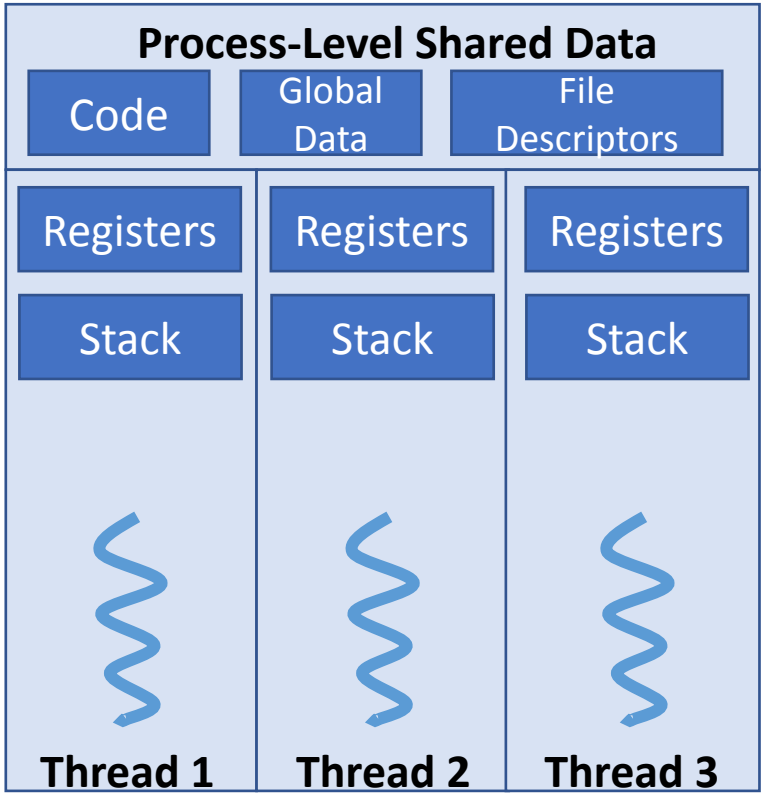
Threads

- Light-weight processes that share the same memory and state
- Every process has at least one thread
- Benefits:
  - Resource sharing, no need for IPC
  - Economy: faster to create, faster to context switch
  - Scalability: simple to take advantage of multi-core CPUs

Single-Threaded Process

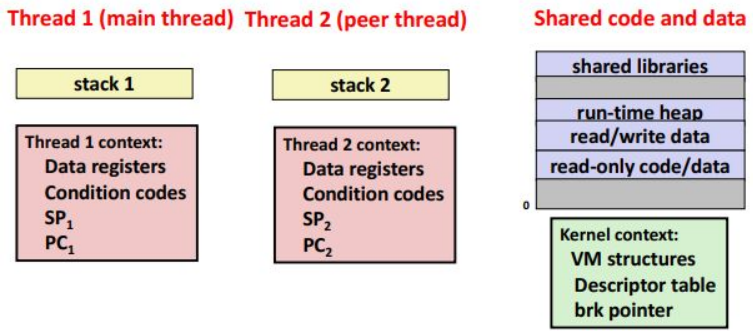


Multi-Threaded Process



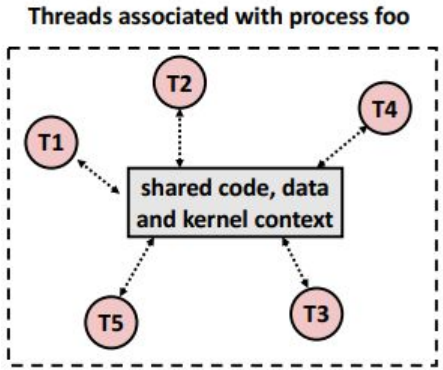
A Process can have Multiple Threads

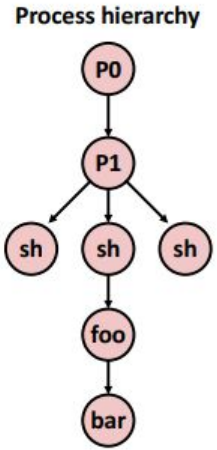
- Each thread shares the same code, data, and kernel context
- A thread has its own thread id (TID)
- A thread has its own logical control flow (no need to exec)
- A thread has its own stack for local variables



View of Threads

- Threads associated with a process form a “pool” of peers
  - Unlike processes (on the right) which form a tree hierarchy (i.e. parent/child relationship)

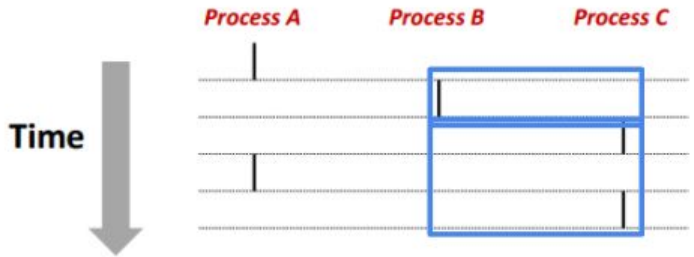




Remember this diagram on Concurrent Processes?

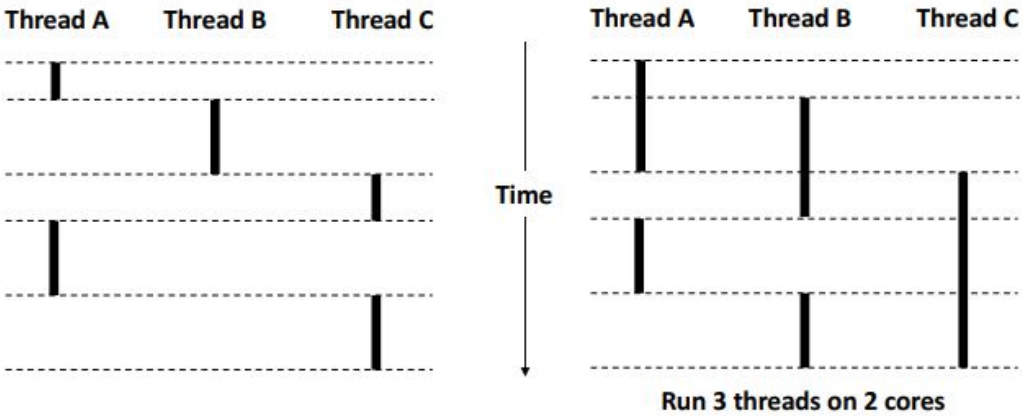
- We looked at multiple processes running on a single core (next slide for multiple cores)

  - On a single core, which processes here are concurrent relative to each other?
    - Concurrent: A&B, A&C
  - Which are sequential?
    - Sequential: B &C



Concurrent Thread (or Process) Execution

- Single Core Process
  - Simulate parallelism by time slicing
- Multi-Core Processor
  - Can have true parallelism



Threads vs Processes

- Similarities
  - Each has its own logical control flow
  - Each can run concurrently with others (possibly on different cores if available)
  - Each is context switched
- Differences
  - Threads share all code and data (except local stacks)
    - Processes (typically) do not (i.e. fork makes a copy)
  - Threads are usually less expensive than managing processes
    - Process control is twice as expensive as thread control
      - Linux estimates
        - ~20k cycles to create and reap a process
        - ~10k cycles to create and reap a thread

Pthreads
(POSIX Threads)

POSIX Pthreads

- POSIX
  - Portable Operating System Interface

- POSIX standard API for thread creation
  - IEEE 1003.1c
  - *Specification*, not *implementation*
    - Defines the API and the expected behavior
    - … but not how it should be implemented

- Implementation is system dependent
  - On some platforms, user-level threads
  - On others, maps to kernel-level threads

Posix Threads API (PThreads Interface)

- Sample functions
  - Creating and reaping threads
    - `pthread_create()`
    - `pthread_join()`
  - Determining 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` (mutual exclusion lock)
      - `pthread_mutex_lock` and `pthread_mutex_unlock`

Pthread examples

Hello Thread

- The thread that is “launched” is a function in the program
  - This is done when the thread is created
  - Different attributes can be sent to threads (in this case the first NULL)
  - Arguments can also be passed to the function (second NULL)

```
1  // Compile with:
2  //
3  // clang -lpthread thread1.c -o thread1
4  //
5  #include <stdio.h>
6  #include <stdlib.h>
7  #include <pthread.h>
8
9  // Thread with variable arguments
10 void *thread(void *vargp){
11         printf("Hello from thread\n");
12         return NULL;
13 }
14
15 int main(){
16         // Store our Pthread ID
17         pthread_t tid;
18         // Create and execute the thread
19         pthread_create(&tid, NULL, thread, NULL);
20         // Wait in 'main' thread until thread executes
21         pthread_join(tid,NULL);
22         // end program
23         return 0;
24 }
```

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- `pthread_join` is the equivalent to “`wait`” for threads

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24 }
```

Hello Thread

- The thread that is “launched” is a function in the program
  - This is done when the thread is created
  - Different attributes can be sent to threads (in this case the first NULL)
  - Arguments can also be passed to the function (second NULL)
- `pthread_join` is the equivalent to “`wait`” for threads
- What if we don’t call join?

```
1  // Compile with:
2  //
3  // clang -lpthread thread1.c -o thread1
4  //
5  #include <stdio.h>
6  #include <stdlib.h>
7  #include <pthread.h>
8
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15 int main(){
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19         pthread_create(&tid, NULL, thread, NULL);
20         // Wait in 'main' thread until thread executes
21         pthread_join(tid,NULL);
22         // end program
23         return 0;
24 }
```
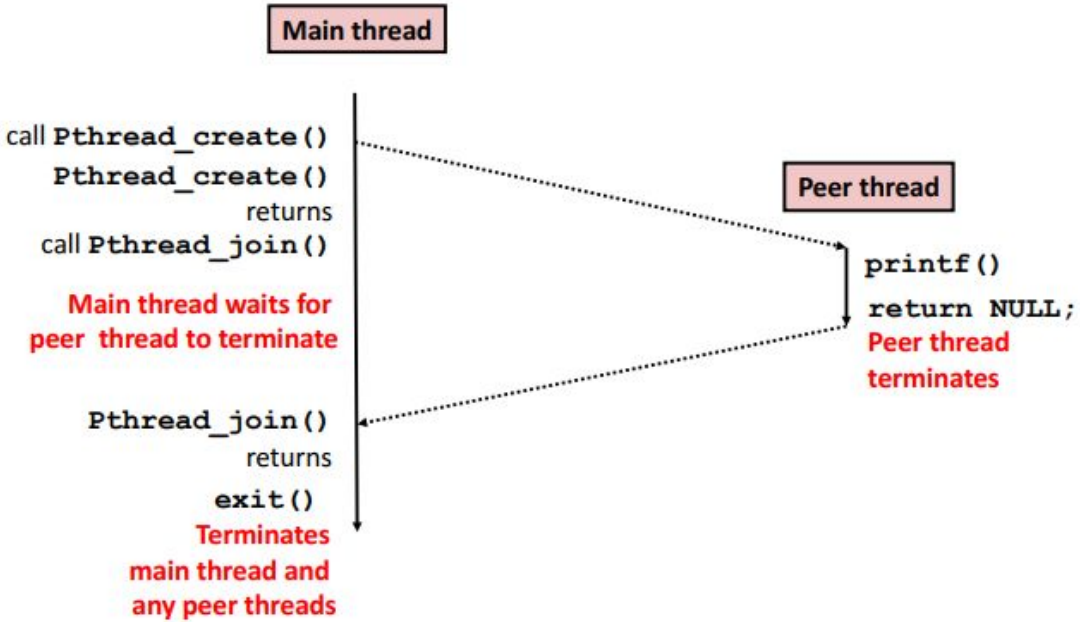

Visual execution of “Hello Thread”



Launching multiple threads

- Store 10 thread ids.

```c
// Compile with:
//
// clang -lpthread thread2.c -o thread2
//
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

#define NTHREADS 10

// Thread with variable arguments
void *thread(void *vargp){
        printf("Hello from thread %ld\n", pthread_self());
        return NULL;
}

int main(){
        // Store our Pthread ID
        pthread_t tids[NTHREADS];
        printf("Main thread id: %ld\n",pthread_self());
        // Create and execute multiple threads
        for(int i=0; i < NTHREADS; ++i){
                pthread_create(&tids[i], NULL, thread, NULL);
        }
        // Make main wait for each thread
        for(int i=0; i < NTHREADS; ++i){
                pthread_join(tids[i], NULL);
        }

        printf("Main thread returns: %ld\n",pthread_self());
        // end program
        return 0;
}
```

Launching multiple threads

- Store 10 thread ids.
- Launch 10 threads

```c
// Compile with:
//
// clang -lpthread thread2.c -o thread2
//
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

#define NTHREADS 10

// Thread with variable arguments
void *thread(void *vargp){
        printf("Hello from thread %ld\n", pthread_self());
        return NULL;
}

int main(){
        // Store our Pthread ID
        pthread_t tids[NTHREADS];
        printf("Main thread id: %ld\n",pthread_self());
        // Create and execute multiple threads
        for(int i=0; i < NTHREADS; ++i){
                pthread_create(&tids[i], NULL, thread, NULL);
        }
        // Make main wait for each thread
        for(int i=0; i < NTHREADS; ++i){
                pthread_join(tids[i], NULL);
        }

        printf("Main thread returns: %ld\n",pthread_self());
        // end program
        return 0;
}
```

Launching multiple threads

- Store 10 thread ids.
- Launch 10 threads
- Print out their thread ids to show which thread is executing.

```
1  // Compile with:
2  //
3  // clang -lpthread thread2.c -o thread2
4  //
5  #include <stdio.h>
6  #include <stdlib.h>
7  #include <pthread.h>
8
9  #define NTHREADS 10
10
11 // Thread with variable arguments
12 void *thread(void *vargp){
13         printf("Hello from thread %ld\n", pthread_self());
14         return NULL;
15 }
16
17 int main(){
18         // Store our Pthread ID
19         pthread_t tids[NTHREADS];
20         printf("Main thread id: %ld\n",pthread_self());
21         // Create and execute multiple threads
22         for(int i=0; i < NTHREADS; ++i){
23                 pthread_create(&tids[i], NULL, thread, NULL);
24         }
25         // Make main wait for each thread
26         for(int i=0; i < NTHREADS; ++i){
27                 pthread_join(tids[i], NULL);
28         }
29
30         printf("Main thread returns: %ld\n",pthread_self());
31         // end program
32         return 0;
33 }
```

Launching multiple threads

- Store 10 thread ids.
- Launch 10 threads
- Print out their thread ids to show which thread is executing.
- Join all of our threads with the main thread
  - (i.e. make the main thread wait until all 10 threads have executed.)

```c
// Compile with:
//
// clang -lpthread thread2.c -o thread2
//
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

#define NTHREADS 10

// Thread with variable arguments
void *thread(void *vargp){
        printf("Hello from thread %ld\n", pthread_self());
        return NULL;
}

int main(){
        // Store our Pthread ID
        pthread_t tids[NTHREADS];
        printf("Main thread id: %ld\n",pthread_self());
        // Create and execute multiple threads
        for(int i=0; i < NTHREADS; ++i){
                pthread_create(&tids[i], NULL, thread, NULL);
        }
        // Make main wait for each thread
        for(int i=0; i < NTHREADS; ++i){
                pthread_join(tids[i], NULL);
        }

        printf("Main thread returns: %ld\n",pthread_self());
        // end program
        return 0;
}
```

Launching multiple threads

- *New Program*

```
1  // Compile with:
2  //
3  // clang -lpthread thread3.c -o thread3
4  //
5  #include <stdio.h>
6  #include <stdlib.h>
7  #include <pthread.h>
8
9  #define NTHREADS 10000
10
11 int counter = 0;
12
13 // Thread with variable arguments
14 void *thread(void *vargp){
15         counter = counter +1;
16         return NULL;
17 }
18
19 int main(){
20         // Store our Pthread ID
21         pthread_t tids[NTHREADS];
22         printf("Counter starts at: %d\n",counter);
23         // Create and execute multiple threads
24         for(int i=0; i < NTHREADS; ++i){
25                 pthread_create(&tids[i], NULL, thread, NULL);
26         }
27         // Create and execute multiple threads
28         for(int i=0; i < NTHREADS; ++i){
29                 pthread_join(tids[i], NULL);
30         }
31
32         printf("Final Counter value: %d\n",counter);
33         // end program
34         return 0;
35 }
```

Launching multiple threads

- *New Program*
- This time launch 10000 threads

```c
// Compile with:
//
// clang -lpthread thread3.c -o thread3
//
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

#define NTHREADS 10000

int counter = 0;

// Thread with variable arguments
void *thread(void *vargp){
        counter = counter +1;
        return NULL;
}

int main(){
        // Store our Pthread ID
        pthread_t tids[NTHREADS];
        printf("Counter starts at: %d\n",counter);
        // Create and execute multiple threads
        for(int i=0; i < NTHREADS; ++i){
                pthread_create(&tids[i], NULL, thread, NULL);
        }
        // Create and execute multiple threads
        for(int i=0; i < NTHREADS; ++i){
                pthread_join(tids[i], NULL);
        }

        printf("Final Counter value: %d\n",counter);
        // end program
        return 0;
}
```

Launching multiple threads

- This time launch 10000 threads
- counter is shared between threads
- What is wrong with this program?

```
1 // Compile with:
2 //
3 // clang -lpthread thread3.c -o thread3
4 //
5 #include <stdio.h>
6 #include <stdlib.h>
7 #include <pthread.h>
8
9 #define NTHREADS 10000
10
11 int counter = 0;
12
13 // Thread with variable arguments
14 void *thread(void *vargp){
15         counter = counter +1;
16         return NULL;
17 }
18
19 int main(){
20         // Store our Pthread ID
21         pthread_t tids[NTHREADS];
22         printf("Counter starts at: %d\n",counter);
23         // Create and execute multiple threads
24         for(int i=0; i < NTHREADS; ++i){
25                 pthread_create(&tids[i], NULL, thread, NULL);
26         }
27         // Create and execute multiple threads
28         for(int i=0; i < NTHREADS; ++i){
29                 pthread_join(tids[i], NULL);
30         }
31
32         printf("Final Counter value: %d\n",counter);
33         // end program
34         return 0;
35 }
```

Launching multiple threads

- This time launch 10000 threads
- counter is shared between threads
- What is wrong with this program?
- What is the final output?

```c
// Compile with:
//
// clang -lpthread thread3.c -o thread3
//
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

#define NTHREADS 10000

int counter = 0;

// Thread with variable arguments
void *thread(void *vargp){
        counter = counter +1;
        return NULL;
}

int main(){
        // Store our Pthread ID
        pthread_t tids[NTHREADS];
        printf("Counter starts at: %d\n",counter);
        // Create and execute multiple threads
        for(int i=0; i < NTHREADS; ++i){
                pthread_create(&tids[i], NULL, thread, NULL);
        }
        // Create and execute multiple threads
        for(int i=0; i < NTHREADS; ++i){
                pthread_join(tids[i], NULL);
        }

        printf("Final Counter value: %d\n",counter);
        // end program
        return 0;
}
```

Launching multiple threads

- This time launch 10000 threads
- counter is shared between threads
- What is wrong with this program?
- What is the final output?

```
Counter starts at: 0
Final Counter value: 9998
-bash-4.2$ ./thread3
Counter starts at: 0
Final Counter value: 9998
-bash-4.2$ ./thread3
Counter starts at: 0
Final Counter value: 9997
-bash-4.2$ ./thread3
Counter starts at: 0
Final Counter value: 9999
-bash-4.2$ ./thread3
Counter starts at: 0
Final Counter value: 9997
```

```c
// Compile with:
//
// clang -lpthread thread3.c -o thread3
//
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

#define NTHREADS 10000

int counter = 0;

// Thread with variable arguments
void *thread(void *vargp){
        counter = counter +1;
        return NULL;
}

int main(){
        // Store our Pthread ID
        pthread_t tids[NTHREADS];
        printf("Counter starts at: %d\n",counter);
        // Create and execute multiple threads
        for(int i=0; i < NTHREADS; ++i){
                pthread_create(&tids[i], NULL, thread, NULL);
        }
        // Create and execute multiple threads
        for(int i=0; i < NTHREADS; ++i){
                pthread_join(tids[i], NULL);
        }

        printf("Final Counter value: %d\n",counter);
        // end program
        return 0;
}
```

What was happening?

Thread 1 (counter = counter + 1)	Thread 2 (counter = counter + 1)
Read “counter”: 10	Read “counter”: 10
Add 1 to “counter”: 11	Add 1 to “counter”: 11
Write to “counter”: 11	Write to “counter”: 11

What was happening?

Thread 1 (counter = counter + 1)

Read “counter”: 11

Add 1 to “counter”: 12

Write to “counter”: 12

Thread 3 (counter = counter + 1)

Read “counter”: 12

Add 1 to “counter”: 13

Write to “counter”: 13

Thread 2 (counter = counter + 1)

Read “counter”: 11

Add 1 to “counter”: 12

Write to “counter”: 12

Synchronization of Threads

- Shared variables are thus handy for moving around data
- If we do not share properly, we can have synchronization errors!
  - There is a solution however!
  - (recap below)

=

```
Counter starts at: 0
Final Counter value: 9998
-bash-4.2$ ./thread3
Counter starts at: 0
Final Counter value: 9998
-bash-4.2$ ./thread3
Counter starts at: 0
Final Counter value: 9997
-bash-4.2$ ./thread3
Counter starts at: 0
Final Counter value: 9999
-bash-4.2$ ./thread3
Counter starts at: 0
Final Counter value: 9997
```

Locks

- If multiple entities tries to acquire the lock, only one will succeed
  - Lock cannot be shared
- If someone is holding the lock others have to wait until the lock holder unlocks

- Lock can project shared variables or code regions that should not be executed concurrently

Example with lock

- Included a pthread_mutex_lock

```c
// Compile with:
// clang -lpthread thread4.c -o thread4
// This program fixes a problem with thread3.c
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

#define NTHREADS 10000

int counter = 0;
pthread_mutex_t mutex1 = PTHREAD_MUTEX_INITIALIZER;

// Thread with variable arguments
void *thread(void *vargp){
        pthread_mutex_lock(&mutex1);
                counter = counter +1;
        pthread_mutex_unlock(&mutex1);
        return NULL;
}

int main(){
        // Store our Pthread ID
        pthread_t tids[NTHREADS];
        printf("Counter starts at: %d\n",counter);
        // Create and execute multiple threads
        for(int i=0; i < NTHREADS; ++i){
                pthread_create(&tids[i], NULL, thread, NULL);
        }

        // Create and execute multiple threads
        for(int i=0; i < NTHREADS; ++i){
                pthread_join(tids[i], NULL);
        }
        printf("Final Counter value: %d\n",counter);
        // end program
        return 0;
}
```

Example with lock

- Included a pthread_mutex_lock
- lock and unlock protects
- Locks in other words enforce, that we have exclusive access to a region of code.

```
1  // Compile with:
2  // clang -lpthread thread4.c -o thread4
3  // This program fixes a problem with thread3.c
4  #include <stdio.h>
5  #include <stdlib.h>
6  #include <pthread.h>
7
8  #define NTHREADS 10000
9
10 int counter = 0;
11 pthread_mutex_t mutex1 = PTHREAD_MUTEX_INITIALIZER;
12
13 // Thread with variable arguments
14 void *thread(void *vargp){
15         pthread_mutex_lock(&mutex1);
16                 counter = counter +1;
17         pthread_mutex_unlock(&mutex1);
18         return NULL;
19 }
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32                 pthread_join(tids[i], NULL);
33         }
34         printf("Final Counter value: %d\n",counter);
35         // end program
36         return 0;
37 }
```

What was happening?

Thread 1 (counter = counter + 1)	Thread 2 (counter = counter + 1)
pthread_mutex_lock	pthread_mutex_lock

Read “counter”: 10	// Lock is held by thread 1 so
	// thread 2 has to wait until
	// thread 1 unlocks
	BLOCKS EXECUTION

Add 1 to “counter”: 11	// Now acquires the lock and runs
Write to “counter”: 11	Read “counter”: 10
pthread_mutex_unlock	Add 1 to “counter”: 11
	Write to “counter”: 11
	pthred_mutex_unlock

Example with lock

- Included a pthread_mutex_lock
- lock and unlock protect
- Locks in other words enforce, that we have exclusive access to a region of code.

```
mike:8$ gcc thread4.c -o thread4 -lpthread
mike:8$ ./thread4
Counter starts at: 0
Final Counter value: 10000
mike:8$ ./thread4
Counter starts at: 0
Final Counter value: 10000
mike:8$ ./thread4
Counter starts at: 0
Final Counter value: 10000
mike:8$ ./thread4
Counter starts at: 0
^[[AFinal Counter value: 10000
```

```c
// Compile with:
// clang -lpthread thread4.c -o thread4
// This program fixes a problem with thread3.c
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

#define NTHREADS 10000

int counter = 0;
pthread_mutex_t mutex1 = PTHREAD_MUTEX_INITIALIZER;

// Thread with variable arguments
void *thread(void *vargp){
        pthread_mutex_lock(&mutex1);
                counter = counter +1;
        pthread_mutex_unlock(&mutex1);
        return NULL;
}

int main(){
        // Store our Pthread ID
        pthread_t tids[NTHREADS];
        printf("Counter starts at: %d\n",counter);
        // Create and execute multiple threads
        for(int i=0; i < NTHREADS; ++i){
                pthread_create(&tids[i], NULL, thread, NULL);
        }

        // Create and execute multiple threads
        for(int i=0; i < NTHREADS; ++i){
                pthread_join(tids[i], NULL);
        }
        printf("Final Counter value: %d\n",counter);
        // end program
        return 0;
}
```

Posix Threads API (PThreads Interface)

- Sample functions
  - Creating and reaping threads
    - `pthread_create()`
    - `pthread_join()`
  - Determining 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_lock` and `pthread_mutex_unlock`