Final Exam Review (Pt. 3)

Computer Operating Systems, Summer 2025

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Poll Everywhere

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- Any General questions on the course or PennOS before we begin?

Disclaimer

- **THIS REVIEW IS NOT EXHAUSTIVE**
- **Topics not in this review are still testable**

Disclaimer

- **THIS IS REVIEW**
- **DO THE OLD EXAMS FOR THE BEST PRACTICE YOU CAN GET**

New Problems Added

- New Cache Problem
- New Virtual Memory Problem
- New Memory Allocation Problem
- New File System Problem (Added now ☺)

Practice Problems

- Processes vs Threads
- Signal Handlers
- Memory Allocation
- Caches
- Scheduling (Same as extra practice at end of scheduling lecture)
- File System
- Virtual Memory
- Threads & Data Races
- Deadlock

Processes vs Threads

- Let’s say we had a program that did an expensive computation (like summing a 1,000,000 element array) that we wanted to parallelize, we could use either threads or processes. Which one would be faster and why?

Processes vs Threads

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- Probably threads. Threads and processes are both parallelizable, but processes have a larger overhead since they have separate address spaces that need to be switched between.
- Additionally, if we were using processes, how they would synchronize their sums would become a more involved issue.

Threads and Exec

- You spawn 10 threads and assign to each a random function to execute. Some seem harmless and others not so much.
- Specifically, one of the random functions they can call is the following.

```
int random_func_a(){
	char *argv[] = {"sleep", "0", NULL};
	execvp(argv[0], argv);
}
```

What happens if one of the threads is assigned this function and runs it?

Threads and Exec

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- Specifically, one of the random functions they can call is the following.

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int random_func_a(){
        char *argv[] = {"sleep", "0", NULL};
        execvp(argv[0], argv);
}
```

If a thread runs exec, the entire process is scrapped and thus, so are the other threads. It's all gone. Tada.

Processes vs Threads

- Let's say you've written a program that runs really well and does everything you need to, except that once every day it crashes. Fortunately for you, it's not doing anything critical - but it's not worth the development time to find and fix the cause of the crash.
- You decide to write a program that checks the status of another program and restarts it if it crashes. You are deciding whether your two programs (the one that crashes and the one that restarts) should be two threads in the same process or in two separate processes.
- Which do you choose? Briefly explain your answer

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- Which do you choose? Briefly explain your answer
- You need two separate processes because otherwise the two threads share a memory space and if one crashes they both will crash. If we have two processes there is some isolation and thus the program that “restarts” the failing program can keep running when the failing program

Processes vs Threads

- We have seen two concurrency models so far
  - Forking processes (fork)
    - Creates a new process, but each process will have 1 thread inside it
  - Kernel Level Threads (pthread_create)
    - User level library, but each thread we create is known by the kernel
    - 1:1 threading model

Processes vs Threads

- For each of the three concurrency models, state whether it is possible to do each of the following.
- In real exam, I would ask you to briefly explain why

	Processes	pthread
Can share files and concurrently access those files.		
Can communicate through pipes		
Run in parallel with one another (assuming multiple CPUs/Cores)		
Modify and read the same data structure that is stored in the heap		
Switch to another concurrent task when one makes a blocking system call.		

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Can communicate through pipes (can't redirect w/o affecting other threads though)	Yes	Yes
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Switch to another concurrent task when one makes a blocking system call.	Yes	Yes

Kernal Signal Handlers

- You're a TA in OS and you're overseeing a group. You notice they wrote functionality in their signal handlers (:/). PCBs are updated within the handler and also within their waitpid implementation. They leave all signals unblocked.

```
void update_pcb(ksignal __signal){
        //check for child updates
        //update pcb as necessary
}
```

This is ***exactly what the function does.***
It does nothing other than check for updates and update the PCB.

They tell you that sometimes the PCB updates correctly, but other times it becomes corrupted.

What could explain this behavior?

Kernal Signal Handlers

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They tell you that sometimes the PCB updates correctly, but other times it becomes corrupted.

What could explain this behavior?

If a section of your code must run to completion without being interrupted (meaning the current thread or process must finish executing it without being paused), you should disable interrupts to prevent preemption by another thread or interruption by a signal handler. In this case, there’s nothing stopping this code from being interrupted mid signal handler by something else or even within their waitpid implementation. Usually, all handler does is update a flag to indicate they need to update later, rather than doing the update within the handler. Gotta be fast to respond.

Memory Allocation

- Some memory allocators (like the internal memory allocator for the Linux kernel) allow for some options to be specified that can change the behavior of these allocators. For each of these can you explain why this feature may be useful to have as an option?
  - If there is no memory available, then the allocation call may wait for some memory to be freed up so that it can eventually succeed
  - If memory is not able to be immediately allocated, give up at once. Caller can retry later if they desire.

- Some allocators enforce a minimum size for each allocation. If you request less than the minimum size it is rounded up.
- Why may an allocator do this?
- What is a downside to doing this?

Memory Allocation

- Some memory allocators (like the internal memory allocator for the Linux kernel) allow for some options to be specified that can change the behavior of these allocators. For each of these can you explain why this feature may be useful to have as an option?
  - If there is no memory available, then the allocation call may wait for some memory to be freed up so that it can eventually succeed
    - In a multi-threaded environment we can try to avoid a catastrophic out of memory issue by just waiting till another thread releases memory. In the context of allocating kernel memory, this could also just be memory allocated to some other process's task that then gets deallocated at some point.
  - If memory is not able to be immediately allocated, give up at once. Caller can retry later if they desire.
    - Meeting tight timing requirements since doing memory allocation may take a while (especially if the heap needs to grow or a new page added to the virtual memory space). Try again later once more space is easily accessible.

Memory Allocation

- Some allocators enforce a minimum size for each allocation. If you request less than the minimum size it is rounded up.
- Why may an allocator do this?
  - For things like the buddy allocator, they do this since the larger allocation size (1 page) is core to how the system is designed. It makes it easier for the “math” to work out so that their allocation scheme is faster/easier to implement
  - Malloc may do something like this with a size of 8 as the minimum size to help make sure all allocations start at a multiple of 8 and/or to minimize external fragmentation.
- What is a downside to doing this?
  - Increased internal fragmentation, an allocation now takes up more space than it actually needs.

Memory Allocation

- Assume we have the following two pieces of code, which ones is likely faster than the other and why?

```c
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char** argv) {
  int* arr = malloc(sizeof(int) * 10);
  arr[0] = 1;
  arr[1] = 1;
  for(int i = 2; i < 10; i++) {
    arr[i] = arr[i-1] + arr[1-2];
  }

  printf("%d\n", arr[9]);
  free(arr);
}
```

```c
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char** argv) {
  int arr[10];
  arr[0] = 1;
  arr[1] = 1;
  for (int i = 2; i < 10; i++) {
    arr[i] = arr[i-1] + arr[1-2];
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  printf("%d\n", arr[9]);
}
```

Likely the one on the right. Instead of calling malloc, the array is a static size on the stack. The stack allocation is quicker to allocate and free.

Memory Allocation

- Lets say that in addition to malloc, we also had a custom slab allocator implemented that could allocate chunks of space that is 64 bytes (16 integers) large.
- What is one reason we may prefer the custom slab allocator to malloc?
- What is one reason we may prefer malloc?

Memory Allocation

- Lets say that in addition to malloc, we also had a custom slab allocator implemented that could allocate chunks of space that is 64 bytes (16 integers) large.

- What is one reason we may prefer the custom slab allocator to malloc?
  - One solution: It is probably faster and avoids the external fragmentation issues of malloc.

- What is one reason we may prefer malloc?
  - One Solution: If we need to allocate anything that is not 64-bytes big, we are either wasting space or not allocating enough space for what we want.

Memory Allocation

- How is the array in this snippet of code likely allocated at a low level (in assembly)?

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  }

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}
```

Just need to decrement the stack pointer by 10 * sizeof(int) and there is enough space to store the array on the stack now :P

Would also accept more vague answers like (grow the stack by 10 integers)

Slab Slob Slub ☺

- Sid is making a custom memory allocator that internally uses 4 different slab allocators with object sizes: 16 bytes, 64 bytes, 256 bytes, and 4096 bytes. Each of these allocators manage slabs that are 2 pages (8192 bytes) big.

- If a user makes these requests in this order, how much internal fragmentation do we get in total?
  - 18 bytes
  - 64 bytes
  - 1000 bytes
  - 2400 bytes
  - 152 bytes
  - 3990 bytes

- If we started with no slabs allocated, how many pages are being managed by the allocators after these allocations?

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- If a Slab allocator has multiple slabs that can fulfill an allocation request, it prefers to fill up slabs that are closest to being full. This is sort of the opposite of our "worst fit" algorithm. Why does the slab allocator do this?

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- If a user makes these requests in this order, how much internal fragmentation do we get in total?
  - 18 bytes -> 46 bytes
  - 64 bytes -> 0 bytes
  - 1000 bytes -> 3096 bytes
  - 2400 bytes -> 1696 bytes
  - 152 bytes -> 104 bytes
  - 3990 bytes ->106 bytes
  - Total: 5048 bytes

Slab Slob Slub ☺

- 18 bytes
- 64 bytes
- 1000 bytes
- 2400 bytes
- 152 bytes
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- If we started with no slabs allocated, how many pages are being managed by the allocators after these allocations
  - 16-byte slab allocator: 0 slabs
  - 64-byte allocator: 1 slab -> 2 pages
  - 256-byte allocator: 1 slab -> 2 pages
  - 4096-byte allocator: 2 slabs -> 4 pages

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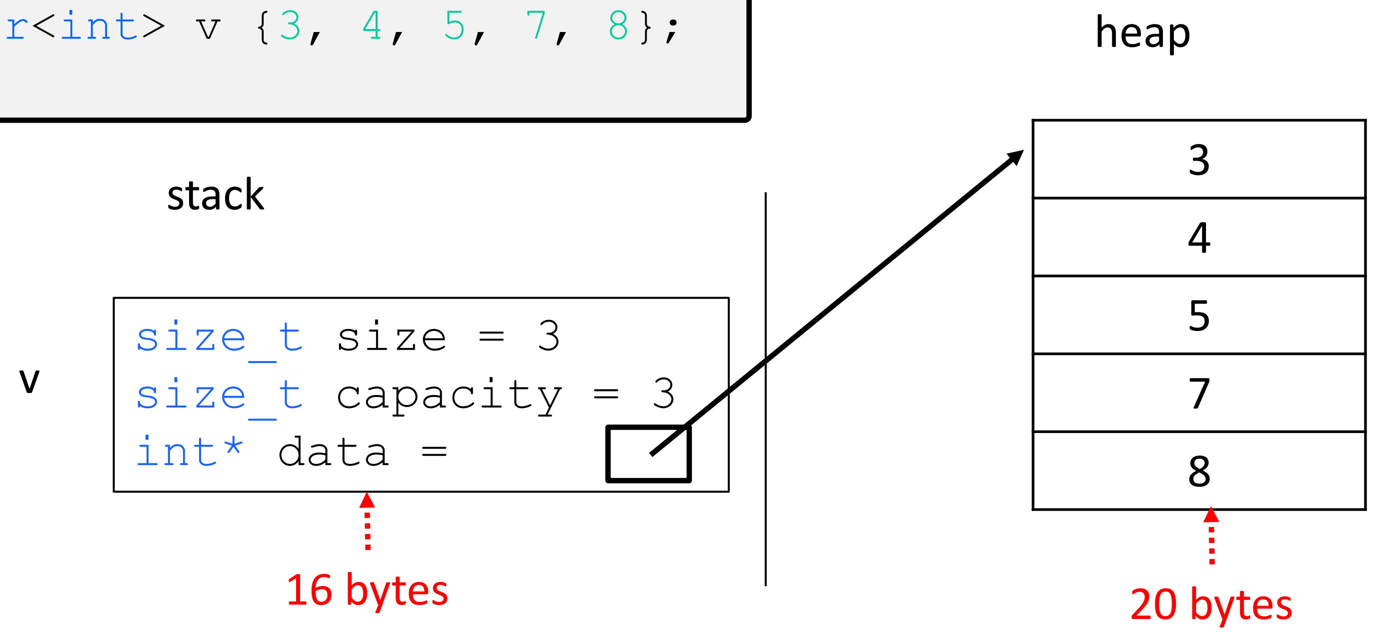
- If a Slab allocator has multiple slabs that can fulfill an allocation request, it prefers to fill up slabs that are closest to being full. This is sort of the opposite of our "worst fit" algorithm. Why does the slab allocator do this?
  - We don't have the same concern of "small chunks that can't be used" in a slab allocator since all allocations are of the same size. So the benefits of worst fit don't apply here.
  - This does benefit us though since if we can make some slabs empty, the slab allocator can give those page(s) back to the OS, thus decreasing the amount of memory it needs to take up.

Caches

- The most common way to store a sequence of elements in C++ and most languages is a dynamically resizable array (e.g. a vector).

  A vector of <int> looks something like this in memory:

```
int main(int argc, char** argv) {
  vector<int> v {3, 4, 5, 7, 8};
}
```



Caches

- Typically, a `bool` variable is 1 byte. How much space does a `bool` strictly ***need*** though?
  - 1 bit

- C++ goes against the standard implementation of a vector for the bool type, and instead has each bool stored as a bit instead of the type a stand-a-lone Boolean variable would be stored as.
  - Travis thinks this was a horrible design decision, but there is a reason why they did this. What are those reasons?

Caches

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  - Travis thinks this was a horrible design decision, but there is a reason why they did this. What are those reasons?
  - **A lot less space is taken up, and as a side effect of that, you probably don’t have to call malloc as often and will have better cache performance**

Caches

- If we stored a vector of 120 **`bool`**s, and wanted to iterate over all of them, roughly how many cache hits & misses would we have if we:
  - You can assume a cache line is 64 bytes.
  - If we used a **`vector<bool>`** that allocates the bools normally (1 byte per bool)
  - If we use a **`vector<bool>`** that represents each bool with a single bit

Caches

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  - You can assume a cache line is 64 bytes.
  - If we used a **`vector<bool>`** that allocates the bools normally (1 byte per bool)
    - 2 cache misses, 118 cache hits
  - If we use a **`vector<bool>`** that represents each bool with a single bit
    - 1 cache miss, 119 cache hits

Caches Q2

- Let's say we are making a program that simulates various particles interacting with each other. To do this we have the following structs to represent a color and a point

```c
struct color {
  int red, green, blue;
};
```

```c
struct point {
  double x, y;
  struct color c;
};
```

- If we were to store 100 point structs in an array, and iterate over all of them, accessing them in order, roughly how many cache hits and cache misses would we have?
  - Assume:
    - a cache line is 64 bytes
    - the cache starts empty
    - `sizeof(point)` is 32 bytes, `sizeof(color)` is 16 bytes

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  - Assume:
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    - the cache starts empty
    - `sizeof(point)` is 32 bytes, `sizeof(color)` is 16 bytes

Roughly every other time we access a point struct, it will already be in the cache. The other 50% of the time, it needs to be fetched from memory

Caches Q3

- Consider the previous problem with point and color structs.
- In our simulator, it turns out a VERY common operation is to iterate over all points and do calculations with their X and Y values.
- How else can we store/represent the point objects to make this operation faster while still maintaining the same data? Roughly how many cache hits would we get from this updated code?

Caches Q3

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- How else can we store/represent the point objects to make this operation faster while still maintaining the same data? Roughly how many cache hits would we get from this updated code?

Change point to just be:

```
struct point {
  double x, y;
}
```

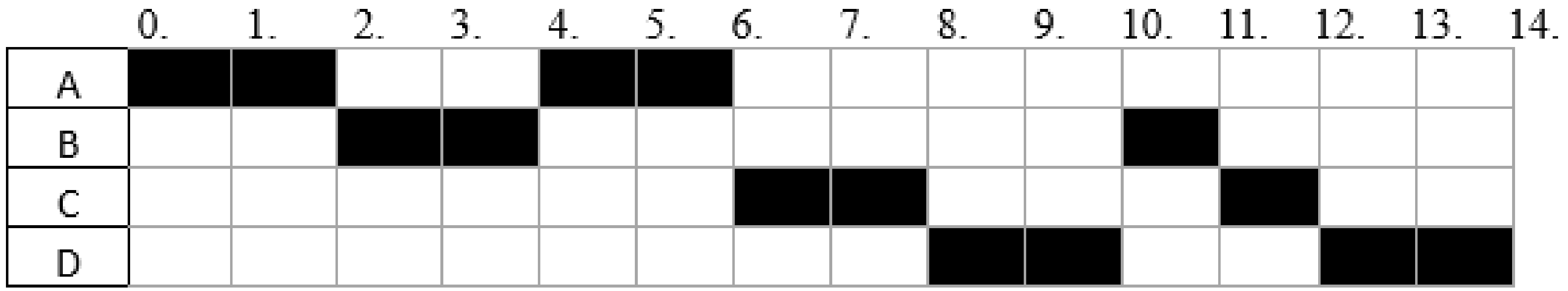
Then Store two arrays:

```
array<point, 100> arr1;
array<color, 100> arr2;
// point at index I
// has color arr2[i]
```

Each time we access a point, we can now load 4 points into the cache. We now get ~25 cache misses and 75 hits

Scheduling

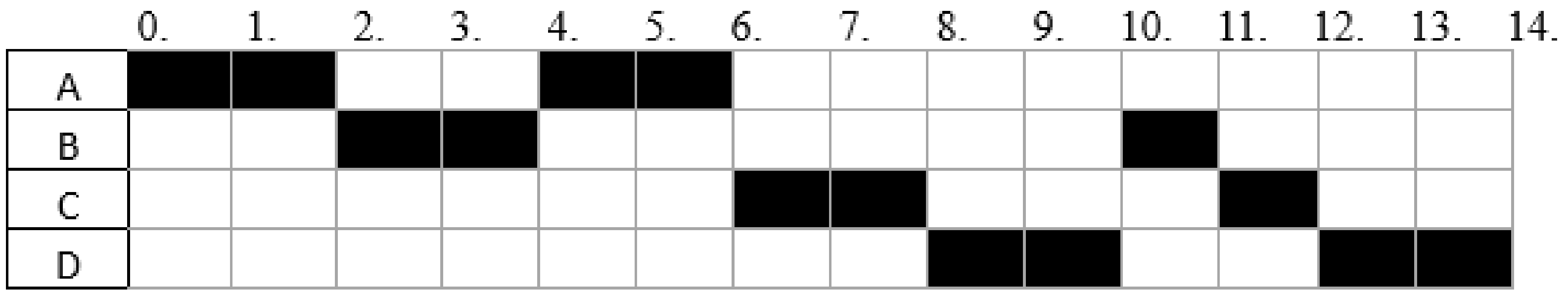
- Four processes are executing on one CPU following round robin scheduling:



	0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.
A	■	■			■	■									
B			■	■							■				
C							■	■				■			
D									■	■			■	■	

- You can assume:
  - All processes do not block for I/O or any resource.
  - Context switching and running the Scheduler are instantaneous.
  - If a process arrives at the same time as the running process' time slice finishes, the one that just arrived goes into the ready queue before the one that just finished its time slice.

Scheduling



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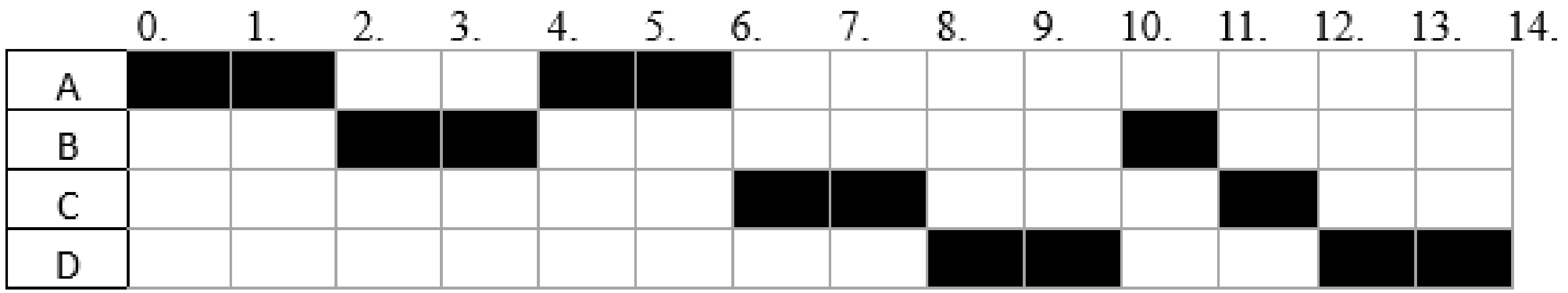
❖ What is the earliest time that process C could have arrived?

❖ Which processes are in the ready queue at time 9?

❖ If this algorithm used a quantum of 3 instead of 2, how many fewer context switches would there be?

Scheduling



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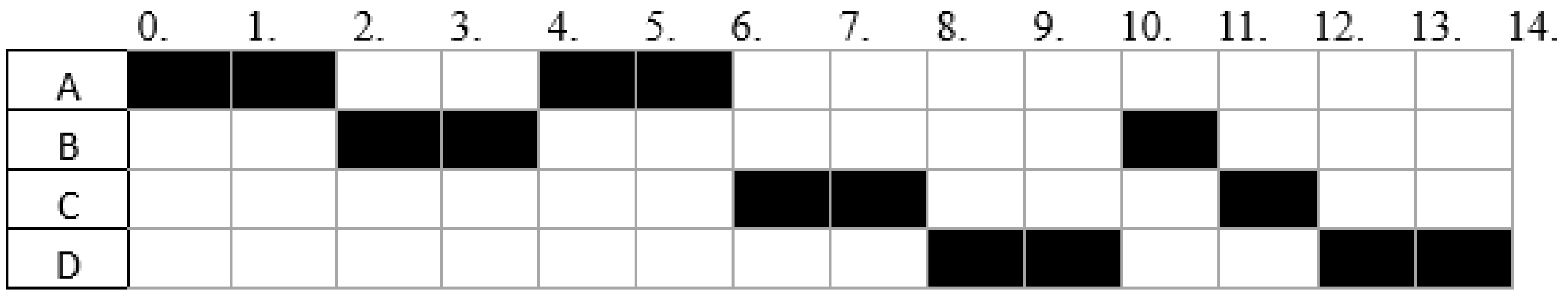
❖ What is the earliest time that process C could have arrived?

- If C arrived at time 0, 1, or 2, it would have run at time 4
- C could have shown up at time 3 and come after A in the queue
- C showed up at time 3 at earliest

Scheduling



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A	■	■			■	■								
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C							■	■				■		
D									■	■			■	■

14.

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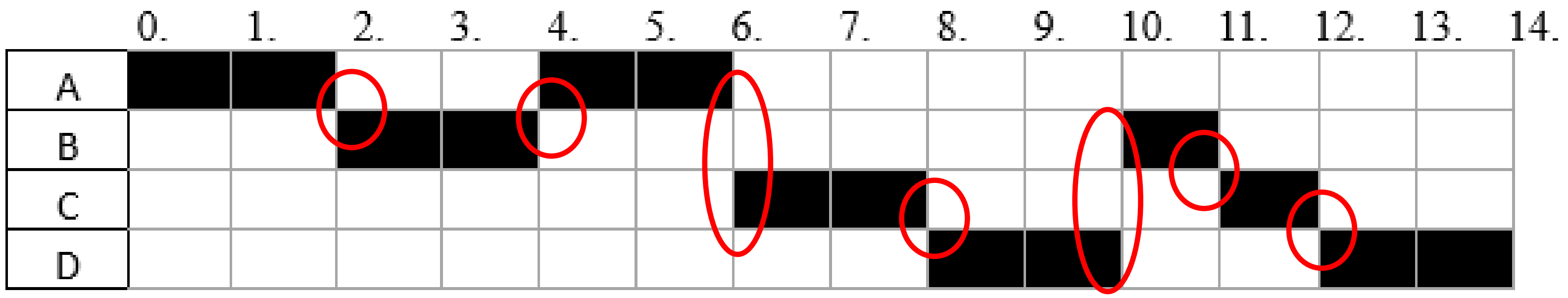
❖ Which processes are in the ready queue at time 9?

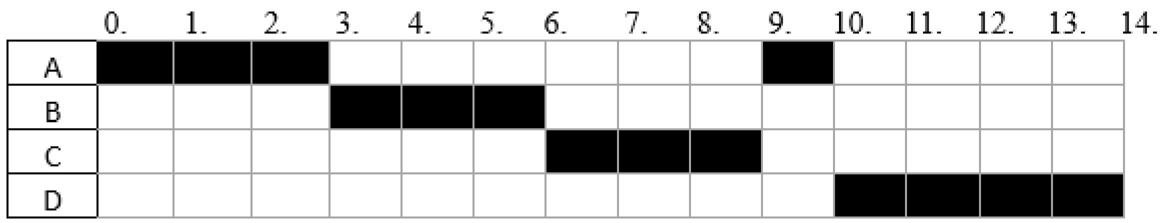
- D is running, so it is not in the queue
- A has finished
- B and C still have to finish, so they are in the queue.

Scheduling

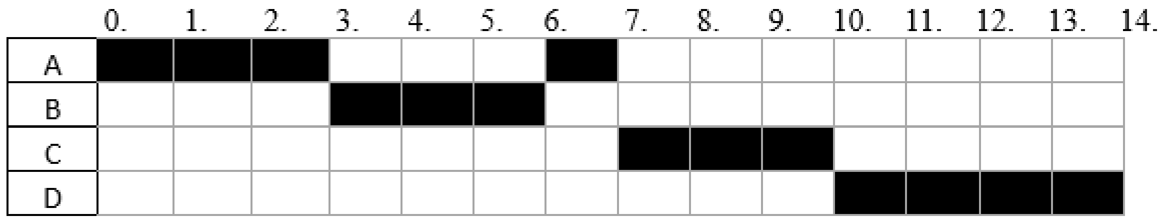


- If this algorithm used a quantum of 3 instead of 2, how many fewer context switches would there be?
  - Currently there are 7 context switches
  - If quantum was 3:

Depends on if C shows up at time 3 or 4



  - Or:



Either way, only 4 context switches, so 3 less than quantum = 2

File System Navigation

In a traditional Linux file system (like ext2), navigating a path like /dir1/dir2/file.txt involves multiple steps.

Describe what the file system must do to locate the inode for ***file.txt***, starting from the root directory.

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Describe what the file system must do to locate the inode for ***file.txt***, starting from the root directory.

1. First, we need to load in the blocks containing the directory entries for the root directory, "/", in inode 2.
   - After looping through the blocks containing the dirents, we find the entry for "dir1" and its inode X.
2. We need to load in the blocks containing the directory entries for the directory, "dir1", in inode X.
   - After looping through the dirents, we find the associated entry for "dir2" and its inode Y.
3. Finally, we load in the blocks containing the directory entries for the directory, "dir2", in inode Y.
   - We can finally loop through the directory entries for "dir2" and find file.txt's entry and thus corresponding inode. And we are done!

Largest File Possible

You are tasked with designing **MinimalFS**, where each file is represented by an inode.

- Each inode can operate in one of two modes: **small** or **large** mode.
- In small mode, the inode directly stores up to **5 block numbers** that point to file data.
- Each block is **1024 bytes** in size.
- Assuming a file contains at least some data (i.e., it's not empty), what is the **smallest amount of space** that would be allocated for a file?

Largest File Possible

You are tasked with designing **MinimalFS**, where each file is represented by an inode.

- Each inode can operate in one of two modes: **small** or **large** mode.
- In small mode, the inode directly stores up to **5 block numbers** that point to file data.
- Each block is **1024 bytes** in size.
- Assuming a file contains at least some data (i.e., it's not empty), what is the **smallest amount of space** that would be allocated for a file?

THE SMALLEST AMOUNT OF SPACE ALLOCATED TO A FILE IS ONE BLOCK SO 1024 BYTES!

Largest File Possible

You are tasked with designing **MinimalFS**, where each file is represented by an inode.

- Each inode can operate in one of two modes: **small** or **large** mode.
- In large mode, the inode directly stores up to **10 block numbers. The 1st is singly indirect, the next 7 are double indirect, and the last 2 are triply indirect.**
- Each block is **1024 bytes** in size.
- And block numbers are 4 bytes large.
- Assuming a file contains at least some data (i.e., it's not empty), what is the **largest amount of space** that would be allocated for a file? Feel free to leave your answer as an expression.

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- In large mode, the inode directly stores up to **10 block numbers. The 1st is singly indirect, the next 7 are double indirect, and the last 2 are triply indirect.**
- Each block is **1024 bytes** in size And block numbers are **4 bytes**.
- What is the **largest amount of space** that would be allocated for a file? Feel free to leave your answer as an expression.

X = # of Block Nums for singly indirect = 1024/4

Y = # of Block Nums for doubly indirect = 7 * (1024/4 * 1024/4)

Z = # of Block Nums for triple indirect = 2 * (1024/4 * 1024/4 * 1024/4)

(X + Y + Z) * 1024 bytes or just x + y + x blocks would be fine to say or write on an exam

File System Block Allocation

- When you move (mv) a file from one directory to another **on the same Linux file system**, does the file’s inode number have to change?
  In other words, can the file keep the same inode number after the move?
  What needs to happen for this to work correctly?

```
$ mv myfile ./dir/
```

- Here, in this command, we are moving the file 'myfile' to directory './dir'.

File System Block Allocation

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  In other words, can the file keep the same inode number after the move?
  What needs to happen for this to work correctly?

```
$ mv myfile ./dir/
```

- Here, in this command, we are moving the file 'myfile' to directory './dir'.

Yes, the inode number can stay the same!

To move the file, the system only needs to **update the directory entries**: it adds an entry for 'myfile' in the target directory (./dir) that points to the same inode, and then **removes** the old entry from the original directory (.).

The inode itself, and all the information stored in the inode, do not change (other than last accessed/modified time stamps if so).

Processes and Virtual Memory

- Take a look at the following program:

```
int main(){
        pid_t child = fork();
        if(child == 0){
                printf("I'm the child!(:\n");
                return;
        }
        printf("Just exec'd a child!\n");
        waitpid(child, NULL, 0);
        return 0;
}
```

Suppose a kernel is unable to create new virtual memory mappings after a fork operation (you have an old computer what can I say). This means all address map to identical physical memory locations in each process here.

Could this program function correctly without requiring new mappings?

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Could this program function correctly without requiring new mappings?

REMEMBER: PRINTF MAINTAINS A BUFFER (GLOBAL STATE) AND IF THEY BOTH SHARE THE SAME BUFFER THEN NO BUENO! THEY NEED TO WRITE TO SEPARATE BUFFERS.
THERE IS ALSO pid_t child WHICH IS SHARED. THOUGH THIS COULD POSSIBLY BE KEPT IN SEPARATE REGISTERS.

Page Tables Q1

- One oddity is that page tables exist in memory themselves. However, the memory that is used to store *some (not all)* page tables are usually “pinned” in memory, meaning that those pages cannot be evicted/removed from physical memory even if we need more space.

- Why is it important that some of the pages containing these page tables remain “pinned”? Please explain your answer.

Page Tables Q1

- One oddity is that page tables exist in memory themselves. However, the memory that is used to store *some (not all)* page tables are usually “pinned” in memory, meaning that those pages cannot be evicted/removed from physical memory even if we need more space.

- Why is it important that some of the pages containing these page tables remain “pinned”? Please explain your answer.

A page table walk (resolving a physical address) might be required for **any** virtual address at **any** time — whether valid or invalid. To perform the walk, the system **must** be able to access the relevant page table entries. But if those entries themselves require translation (and we don’t know where the page tables are in physical memory), we’d be stuck in a loop.

That’s why some addresses — such as the ones containing the page tables — must be **pinned in physical memory** so the hardware can always find and use them without needing to translate further.

Page Tables Q2

- At the beginning, we imagined the page table as one giant array containing one page table entry for each page (where the page number was the index into the table). However, we saw that this design is pretty wasteful (do you remember why?)
- Let’s say we had a virtual page number that we wanted to translate to a physical page number. What would the look up speed be of the “big array” page table be? What about one with 4 page table levels?

Page Tables Q2

- At the beginning, we imagined the page table as one giant array containing one page table entry for each page (where the page number was the index into the table). However, we saw that this design is pretty wasteful (do you remember why?)

We would then need one PTE for every virtual page, but most virtual pages won’t have a mapping (or “exist”) .

In multilevel we can allocate PTE’s & create mappings later (when the page gets accessed for the first time and thus the mapping is needed)

Page Tables Q2

- Let’s say we had a virtual page number that we wanted to translate to a physical page number. What would the look up speed be of the “big array” page table be? What about one with 4 page table levels?

The large array model provides **constant-time lookup** with just **one memory access**, since the specific section of the table we need can be **directly indexed** using the virtual page number (VPN). Once we have the VPN, we index into the page table, and the translation is complete. Tada.
In contrast, a 4-level page table requires us to **traverse 4 separate memory locations**, one for each level of the hierarchy. Although this may seem like a minor increase, the overhead can quickly add up — especially if any of those accesses trigger a **page fault**, causing the system to load different page table levels from disk…no bueno (but we hope this doesn’t happen. ;))

Page Replacement Policy

- Eric and Akash are debating the best page replacement policy. One of them says that LRU is strictly better (e.g. better in all cases) than FIFO page replacement and always leads to less page faults.

- Is this true or false? Please explain your answer. If it is not true, provide an example of page accesses that counters this claim.

Page Replacement Policy

- Eric and Akash are debating the best page replacement policy. One of them says that LRU is strictly better (e.g. better in all cases) than FIFO page replacement and always leads to less page faults.

- Is this true or false? Please explain your answer. If it is not true, provide an example of page accesses that counters this claim.

False: consider we have 4 physical pages and have the reference string:
0 1 2 3 0 4 1 2 3
In LRU we get 8 page faults
In FIFO we get 5 page faults

Inverted Page Table

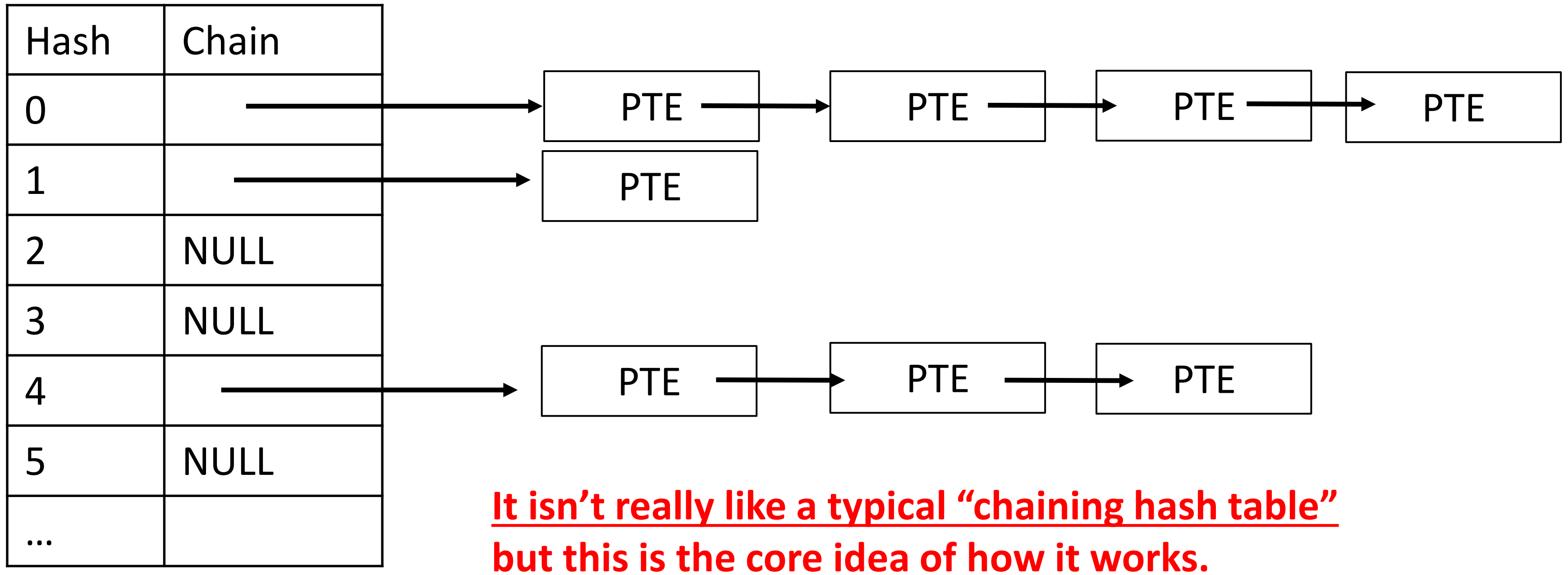
- Some systems used something different than a multi-level page table. They realized that there are a lot more virtual pages than there are physical pages… So why not just have one entry per physical page?

- Would be one global page table since it is based on physical memory

- Implemented essentially as a chaining hash table

Inverted Page Table

- Chaining Hash Table
  - Hash: If a process wants to lookup to see if a page is in physical memory, it hashes the virtual page number and iterates through that chain



It isn’t really like a typical “chaining hash table” but this is the core idea of how it works.

Inverted Page Table

- How can we enforce process isolation in the table if it is shared across all processes?
- What is at least one advantage this has over the multi-level page tables?
- What is at least one disadvantage? (Other than the one in the question below)
- It turns out there is a benefit to having an entry for mappings that still exist, but point to the swap file and not physical memory. Why do you think this is?

Inverted Page Table

- How can we enforce process isolation in the table if it is shared across all processes?
  - The hash and "key" into the table should not just include the virtual page number, but also the process ID.

- What is at least one advantage this has over the multi-level page tables?
  - Uses up a LOT less space, only 1 PTE per frame that is being used.

Inverted Page Table

- What is at least one disadvantage? (Other than the one in the question below)
  - Doesn’t benefit from locality as much. In multi-level the PTE’s of nearby addresses are next to each other, here they aren’t
  - Could be more difficult to manage as it is shared across all processes as opposed to one process having it’s own. If one process needs to change the table, it could “lock” it and bottleneck other processes from using the table.

- It turns out there is a benefit to having an entry for mappings that still exist but point to the swap file and not physical memory. Why do you think this is?
  - It makes it easier to know that the page is in swap, and where to fine it in the swap file

Threads & Data Races

- Consider the following pseudocode that uses threads. Assume that file.txt is large file containing the contents of a book. Assume that there is a **main()** that creates one thread running **first_thread()** and one thread for **second_thread()**

- There is a data race. How do we fix it using just a mutex? (where do we add calls to lock and unlock?)

```
string data = "";  // global

void* first_thread(void* arg) {
  f = open("file.txt", O_RDONLY);
  while (!f.eof()) {
     string data_read = f.read(10 chars);
     data = data_read;
  }
}
void* second_thread(void* arg) {
  while (true) {
    if (data.size() != 0) {
      print(data);
    }
    data = "";
  }
}
```

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string data = "";   // global
pthread_mutex_t mutex;

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  f = open("file.txt", O_RDONLY);
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      pthread_mutex_lock(&mutex);
      data = data_read;
      pthread_mutex_unlock(&mutex);
  }
}
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    pthread_mutex_lock(&mutex);
    if (data.size() != 0) {
      print(data);
    }
    data = "";
    pthread_mutex_unlock(&mutex);
  }
}
```

Threads & Data Races

- After we remove the data race on the global string, do we have deterministic output? (Assuming the contents of the file stays the same).

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string data = "";   // global

void* first_thread(void* arg) {
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      print(data);
    }
    data = "";
  }
}
```

Threads & Data Races

- After we remove the data race on the global string, do we have deterministic output? (Assuming the contents of the file stays the same).
  - No, we could still have a difference in output depending on when threads are run. It is possible a the first thread overwrites the global before second thread reads it

    This is the distinction between a data race and a race condition

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void* first_thread(void* arg) {
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Threads & Data Races

- There is an issue of inefficient CPU utilization going on in this code. What is it and how can we fix it?

- (You can describe the fix at a high level, no need to write code)

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```

Threads & Data Races

- There is an issue of inefficient CPU utilization going on in this code. What is it and how can we fix it?

- (You can describe the fix at a high level, no need to write code)
  - Busy waiting possible in second_thread. We could have the threads use a condition variable to wait for data to be updated and thread1 to signal thread2 once ready

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Deadlock

- Consider we are working with a data base that has N numbered blocks. Multiple threads can access the data base and before they perform an operation, the thread first acquires the lock for the blocks it needs.
  - Example: Thread1 accesses B3, B5 and B1. Thread2 may want to access B3, B9, B6. Here is some example pseudo code:

```
void transaction(list<int> block_numbers) {
  for (every block_num in block_numbers) {
    acquire_lock(block_num)
  }

  operation(block_numbers);

  for (every block_num in block_numbers) {
    release_lock(block_num);
  }
}
```

Deadlock

- This code has the possibility to deadlock. Give an example of this happening. You can assume no thread tries to acquire the same lock twice

- Someone proposes we fix this by locking the whole database instead of locking at the block level. What downsides does this have? Does it even avoid deadlocks?

- How can we fix this (without locking the whole database if that even works)?

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void transaction(list<int> block_numbers) {
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```

Deadlock

- This code has the possibility to deadlock. Give an example of this happening. You can assume no thread tries to acquire the same lock twice
  - **Thread 1 wants B2 and B4. Thread 2 also wants B2 and B4, but lists them in a different order. Thread 1 gets B2, Thread 2 get B4, and we deadlock.**

```
void transaction(list<int> block_numbers) {
  for (every block_num in block_numbers) {
    acquire_lock(block_num)
  }

  operation(block_numbers);

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    release_lock(block_num);
  }
}
```

Deadlock

- Someone proposes we fix this by locking the whole database instead of locking at the block level. What downsides does this have? Does it even avoid deadlocks?
  - **This works, but now our data base is run entirely sequentially for these transactions even if two thread have completely separate blocks they operate on, they cannot run in parallel.**

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  }

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  for (every block_num in block_numbers) {
    release_lock(block_num);
  }
}
```

Deadlock

- How can we fix this (without locking the whole database if that even works)?
- **Have each thread acquire the locks in a strict increasing numerical order. This prevents any cycles from happening**

```
void transaction(list<int> block_numbers) {
  for (every block_num in block_numbers) {
    acquire_lock(block_num)
  }

  operation(block_numbers);

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