COMP310/ECSE427 Study guide

Francis Piché

December 6, 2018

Contents

Part I
Preliminaries

1 Disclaimer

These notes are curated from Professor Muthucumaru Maheswaran COMP310/ECSE427 lectures at McGill University, and *A. Tenenbaum and H. Bos, Modern Operating Systems, 4th Edition, Pearson, 2015.* They are for study purposes only. They are not to be used for monetary gain.

2 About This Guide

I make my notes freely available for other students as a way to stay accountable for taking good notes. If you spot anything incorrect or unclear, don't hesitate to contact me via Facebook or e-mail at `http://francispiche.ca/contact/`.

Part II
Overview of OS Concepts

3 Introduction

3.1 What is an OS?

An operating system is a trusted software which interfaces between the hardware and user applications to provide:

- Security
- Usability
- Efficiency
- Abstractions
- Resource management

They attempt to solve the problem of maximizing utilization, and minimizing idle time, to maximize throughput.

3.2 Design Concerns For Different OS's

For a personal/embedded system: response time should be minimal

For a time-sharing system: there should be *fair* time sharing

In batch-processing systems: goal is to maximize throughput.

3.3 Booting

First, the hardware is powered and the CPU is in "real-mode" which is essentially "trust everything mode". From here, the BIOS are loaded from ROM, and the CPU switches to "protected" or "user" mode. Finally the Kernel finishes initialization and the kernel services (OS) are started.

3.4 Processes

A process is a running program. Each process has an "address space" or "**core image**" in memory which it is allowed to use.

This address space contains the program's:

- executable code
- data (variables etc)
- call stack

The **process table** is an array of structures containing each process in existence. This includes all of the state information about each program, even if it is in a suspended or background state. (Some programs may run periodically or in the background).

A **child process** is a process that was created by another process.

Each person using a system is assigned a **UID**. Each process has the UID of the person who started it. Child processes have the UID of their parent.

Multiple processes allows for better utilization since while one process is idle (for example waiting for I/O) another process can work.

3.5 Memory Management

Processes need to be kept separate from other processes, and memory must also allow more than one process to exist in RAM at the same time.

We might also need to have these processes communicate.

Thanks to virtual memory, the address space can be larger than the actual amount of physical memory addresses. For more on virtual memory, see my COMP273 guide (or this guide in the later sections.) This also allows for better ”chunking” of memory to keep processes separate. We can also provide shared memory spaces for inter-process communcation. Virtual memory also allows for processes to not care where in memory they actually are, which is useful since they may be moved around when they get ”kicked out” by another process.

3.6 Storage

Need persistent storage, but it’s slow. A hard disk is broken up into blocks which contain binary data. So when you use files, for example, they are saved as a series of blocks of binary data on the secondary storage.

3.7 OS and Interrupts

There are two kinds of Interrupts, hardware and software. Hardware is when a device sends a signal to the CPU, for example, a mouse is moved and needs to be processed. Software is when a program (OS or otherwise) throws an exception (trap). This alters the regular flow of the CPU and is therefore an interrupt.

3.8 Dual-Mode OS

Dual mode is the idea of keeping Users (unprivileged) and the kernel (privileged) separate. This provides greater security since this ensures on the trusted OS can make potentially dangerous operations on the core of the computer.

When a program running in user mode sends a system call, the OS then switches to kernel mode to complete the operation, and back when complete.

3.9 Monolith vs Micro-Kernel

There are two main architectures for an OS, the Monolith (one big program that handles everything) and the Micro-kernel. The latter’s kernel is just the bare minimum inter-process communication, while the rest is a series of micro-services each capable of executing one OS task.

Part III
Scheduling

4 Processes

A process is an abstraction of a running program. (As stated previously). It is necessary because we need to be able to handle multi-programming. For example, a webserver handling many user requests at the same time.

This allows for better utilizaton (even if only 1 core CPU) since while one program needs to wait (IO or something) another can run. While there is overhead for context-switching, it is still generally faster to do this.

4.1 Process Representation

The process needs to contain:

- Program counter
- Stack
- Register state
- Memory state
- Stack etc.

A process is represented by a process control block. This is a table whose entries (indexed by process id's (PID)), are a sub-table containing (at least):

- CPU State
- Processor ID
- Memory
- Open files
- Status
- Parent and Child process'
- Priority

So to switch context, we would need to save all the things we need, load the new process, run it for a while, and repeat.

4.2 Lifecycle Management

We need to manage how process are handled through their whole lifecycle. This includes their creation, state changes and termination.

Processes are created using a system-call (can't just make processes willy-nilly, need to call the kernel).

There are two approaches to this, either we build the table from scratch, or we clone an existing process. The latter is the UNIX approach and the one we'll focus on. In this, we stop the current process and save it's state. We then make a copy of all the code, data, heap and PCB and give this new process a new PID. Then, we pass it to the dispatcher which will schedule the process.

4.2.1 fork()

This cloning method is done using the `fork()` system call, after which the parent and child run concurrently. Note that the `fork()` call returns the PID of the child process to the parent, and 0 to the child if successful, and -1 otherwise.

For example:

```
main() {
   int i;
   i = 10;
   if (fork() == 0) i+= 20;
   printf(" %d ", i);
}
ouput> 10, 30
```

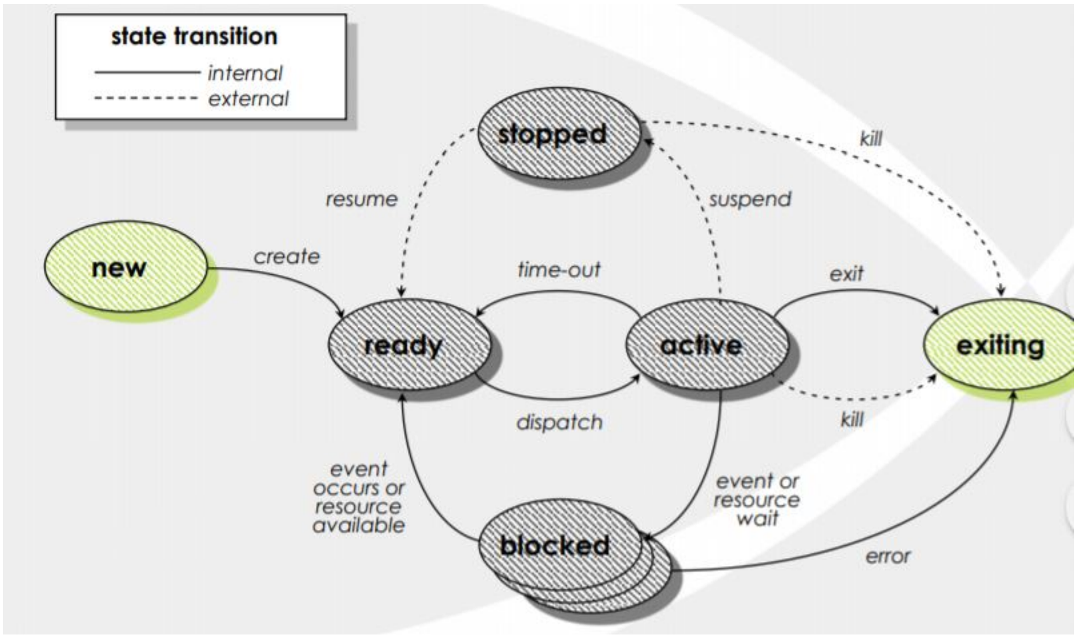
The parent outputs 10 (unchanged) and the child outputs 30 (was affected by the if statement).

4.2.2 State

A process can change state while it is executing. For example if theres no memory or processor available, waiting for some outside event, we finished the task and exit, etc. The possible states are:

- New (Process creation begins)
- Ready (Process has been created and is ready to be loaded and run.)
- Blocked (Waiting for some reason)
- Active (Running)

- Stopped (Suspended by the scheduler)
- Exiting (has been terminated (either normally or by killing))



A process enters the exiting state when either it finishes its task (uses an `exit()` call), caught an exception, or some user decided to kill it.

4.2.3 Tiny Shell

This is Prof Maheswaran's example of a shell.

```
while(1){
   printf("Prompt>")
   getline(line)
   if(strlen(line) > 1){
      if(fork() == 0){
         exec(line)
      }
      wait(child)
   }
}
```

In this, the parent creates a new child process for each command, and waits for the child to complete.

4.3 Dispatcher

There are two ways for the dispatcher to get control of the CPU (since it can only be used by one process at a time, and the dispatcher itself is a process), waiting (trust the other process) or by interrupts. The latter is preferred, since the other process may have an infinite loop, otherwise be bad.

When an interrupt is sent, the OS saves the state of the active process, and runs the interrupt routine. (This is the process of saving the PC, status, registers, file pointers, memory etc.) Note that while this process occurs, no other interrupts are allowed.

Also note that memory is not always saved to disk. Since we use isolated address spaces for each process, the memory of one process (even if idle) need not be overwritten by another.

5 Process I/O

How do processes deal with I/O?

They have an array of "handles" which are each hooked up to an external device. (Mouse, keyboard, file, etc) These handles allow for easy communication between the process and any external I/O devices.

This table exists in the Kernel memory. (Restricted block of RAM). So the only way for a process to access this table is through a system call.

5.1 File Descriptors

We call the slots of the array `file descriptors`. In code, this looks like:

```
main() {
   char buf[BUFFERSIZE];
   const char* note = "Write failed\n";

   while ((n = read(0, buf, sizeof(buf)) > 0))
      if(write(1, buf, n) != n){
         (void)) write(2, note, strlen(note));
         exit(EXIT_FAILURE);
      }
   return(EXIT_SUCCESS)
}
```

Where we are reading from 0, writing to 1 and 2. We call 0 `standard input`, 1 `standard output`, and 2 `standard error`.

We can then use the `read()` and `write()` methods to specify which file descriptor to use.

If we use `open()` to open a file. This returns a file descriptor of $n > 2$ (assuming close(0) or close(1) was not called before). We can then pass this number to a system call such as `read()` or `write()` to access the file.

It's worth noting that the operations are not being sent/recieved directly to/from disk, since that would be slow. We actually interface with a cached version of the file from kernel memory.

We can do: `close(1)` and `open("file")` to overwrite the 1 to point to the file. (Since open goes to the first available array slot)

Similarly we can do `close(0)` to do input redirection.

We can also implement piping. This is when we have one process' output be the input for another process. We need to pass through the kernel space. We use the `pipe()` system call. The pipe creates two file descriptors, one for each side of the pipe. This works since the pipe (a space in the kernel) is created by a parent process, and since the `fork()` system call clones everything from the parent to the child, the child will have access to the pipe.

Then, we rewire the file descriptors such that we set one end of the pipe to 1 (in the parent process), and the output end to 0. (in the child process) This is done using a close, and a `dup()`, which duplicates a file descriptor and puts it in the first open spot.

6 Threads

6.1 Concurrency vs Parallelism

Concurrency is running multiple, discrete tasks on a single-core system. Parallelism is running on completely separate cores (actually running at the same time). Concurrency is sort of "broader" and more conceptual than parallelism. It is not necessarily caring about performance, while parallelism is entirely concerned about performance.

6.2 Parallelism

We need parallelism to do things faster (duh).

Most applications are not completely parallel. They normally have a serial portion (non-parallel) and a parallel portion. But how much of a parallel portion can we make to make things go faster?

6.3 Amdhals Law

Performance improvement obtained by applying an enhancement on an application execution is limited by the fraction of time the enhancement can be applied.

Basically if your improvement only speeds up half of the application, the best you can do is speed up your application by one half, since the other half is unchanged.

So a speedup is given by:

$$speedup \leq \frac{1}{S + \frac{1-S}{N}}$$

where S is the serial portion, and N is the number of cores. So then $1 - S$ is the parallel portion.

6.3.1 Example of Ambhals Law

Suppose you have a problem that takes $500s$ to complete on a single core machine. How long would it take an 8 core machine if 60% of the problem can be run in parallel?

First, 40% that cannot be parallelized is $200s$. Next, we can divide the remaining $300s$ could be separated amongst 8 cores, so $300/8 = 37.5$. In total we have $200 + 37.5 = 237.5$

Now suppose we have 64 cores. Again we have $200s$ for the non-parallel part, then $300/64 = 4.6$ So in total $204.6s$. Not a big increase in speed for a massive increase in complexity (for managing 64 cores).

Now what if our process takes $5000s$? How does it run on 8 cores? 64 cores?

$$2000 + 365 = 2375s$$

$$2000 + 46 = 2046s$$

So again it doesn't scale all that great.

Now suppose further that we have 10 instances of the $500s$ application instead. On 8 cores, we can send 8 instances to individual cores to complete in $500s$, then divide the remaining two instances amongst the 8 cores (4 cores for each instance). So then we have

$$500 + 200 + 300/4 = 700.25s$$

Now what if we had 64 cores? We can break up the 64 cores into 9 groups of 6, and one group of 10. So we have 10 groups total. We can split each instance amongst a group. So the groups of 6 would take time:

$$200 + 300/6 = 250s$$

and the group of 10 would take time:

$$200 + 300/10 = 230s$$

All groups run at the same time, so the total time is the max of the group of 6, and the group of 10. So in total:

$$max(250, 230) = 250s$$

Obviously, all of these calculations don't include overhead.

Since the max is take, we could have just divided 10 groups of 6, and left 4 cores idle. This would have less overhead and be more beneficial.

6.4 Threads

Threads can make things happen at the same time, and are much more lightweight than a process. For example, you may want a web server that can handle multiple threads at the same time, one for each request. If you were to use a new process, the application would be much heavier. This is why Chrome is so RAM heavy, since they use processes and not threads.

Threads can also share memory, which is easier for programming.

Threads however are much less fault tolerant, and can introduce a lot of synchronization issues if not implemented correctly.

Processes are heavy because we have the whole memory, resource allocation, table etc to worry about, while threads are light since they live within processes, and share resources with other threads in the process (minus the call-stack).

For this reason, you should be careful with the scope of your variables in threads, or else a change in one thread could affect another thread. Registers and the stack are the only things that are separate in threads.

6.5 User vs. Kernel Threads

User threads are when the management is done by the user-level libraries. This cannot use the scheduler, since it does not have access to the kernel. There is one kernel-level thread that all the user-level threads map into. If one of the threads block, all of the threads block. the advantage to this is that thread-switching would be faster since we wouldn't need to make system calls.

Meanwhile kernel threads are managed by the kernel scheduler and use kernel-level libraries.

Only kernel level threads are able to manage the multiple threads to run at the same time (or at least concurrently).

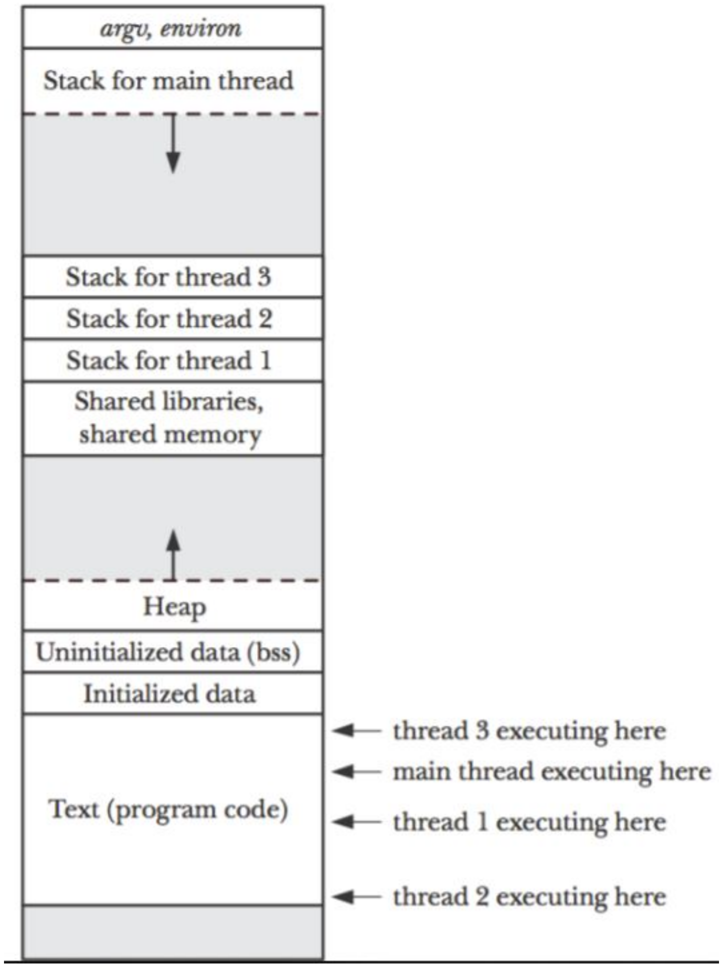
In this way, each user-level thread maps to one kernel-level thread.

6.5.1 Hybrid Threads

This is when there are multiple kernel threads, multiple kernel threads and they are mapped together (not necessarily 1 to 1). So this allows many user level threads to be mapped to a fewer number of kernel level threads. This is not often used.

6.6 Threads in Linux

Recall that threads share memory. However, they also have their own specific stacks. So in memory, it would look like:



We are therefore limited in the number of threads we can have.

6.7 Pthreads

Pthreads allow for portable threads. It is an interface (not implemented library) according to the POSIX standard so that we can develop for different operating systems.

To create one:

```
#include <pthread.h>
```

```
int pthread_create(pthread_t *thread, const pthread_attr_t *attr, void
    *(*start)(void*), void *arg);
```

Note that this signature is similar to clone(). This thread will be kernel level.

To then exit the thread, we can:

- The function we specified to `pthread_create` returns.
- Thread calls `pthread_exit()`
- Thread is canceled by `pthread_cancel()` (preferred).

Each thread is identified by an ID. We can get the thread ID with: `pthread_self()` or we can check if two threads are the same with `pthread_equal(pthread_t t1, pthread_t t2)`

One thread can wait for another thread using the `pthread_join(pthread_t thread, void **retval)` function.

7 Inter-Process Communication

Suppose we want to have synchronization between two processes. This is accomplished via either shared memory or message passing.

In shared memory, the kernel sets up a space in memory that multiple programs can access.

But how is this actually implemented? We can send messages directly, or indirectly (via a buffer obejct). How do we use buffering, and how do we deal with errors?

7.1 Direct Communication

This can be achieved either synchronously or asynchronously.

In the synchronous case, all send and receives are blocking operations.

In asynchronous case, send operations is usually non-blocking, but the receive may be blocking, or non-blocking.

We can also do symmetric or asymmetric addressing. This is when we either specify the name of the process we are talking with (symmetric) or we simply listen for anyone (asymmetric).

7.2 Indirect Communication

Here we use mailboxes. We simply write to the mailbox, or read from the mailbox. We don't care who the sender or receiver was.

A special case of this mailbox is ports. With ports many process can write, but only one can read. We need ports because if we just sent messages to the whole system, there would be no way of knowing which process the message is for.

7.3 Buffering

We can use `zero capacity` buffer for synchronous communication. This means that both processes must be ready to read/write to make the successful message.

`Bounded capacity` is when the buffer is full, the sender waits. `Infinite capacity` is when the sender never waits.

7.4 Error Handling

Messages can get messed up. They can get duplicated, delayed, or delivered out of order.

8 Synchronization

Concurrent processes can be of two main types: `competing` and `cooperating`. The OS manages competing processes through context switching and resource management. For this reason, competing processes are independent of eachother, and thus are deterministic and reproducible. So its the cooperating processes we need to worry about. These, by contrast, can influence each other, and in many cases are not deterministic. They are aware of each other, and pass messages (either directly or indirectly).

8.1 Race Conditions & Critical Sections

A race condition is when the order in which the steps of a procedure occur affects the outcome of the procedure.

We can avoid race conditions using mutual exclusion. This is when we declare sections of code in which a race condition occurs to be a critical section, and enforce the condition that only one process may be in the critical section at one time.

More formally, a critical section must meet these requirements:

- No two processes may be simultaneously in their critical sections
- No assumptions can be made about the speed or number of CPU's
- No process running outside its critical section may block other processes
- No process should have to wait forever to enter its critical section

Critical sections should always run to completion, and must never be interrupted in the middle.

For efficiency, we should try to minimize the lengths of the critical sections.

We could try to handle them by disabling all interrupts. This would work in a single processor case, since interrupts are generally the cause of out-of-order execution. However, this is not practical, since the OS would be frozen during the critical sections execution, and it doesn't work with multiple processors.

8.2 Locks

We only want one thread running through the critical section at a time, so how can we do this?

8.2.1 Attempts at Locks

: We could simply try to "take turns" by having a shared variable that is set after the critical section using a busy-wait. This is bad, because we violate the critical section conditions, namely, its possible that one process wait forever to enter.

We could also try to replace the turn variable with two flags. Process 0, waits for `flag[1]`, and sets `flag[0]` to true when entering, and then to false when exiting. Process 1 would do a symmetrical thing on it's side.

This doesn't work, since we would need a lock, for the lock! Imagine a scenario where the busy wait loop of process 0 completes, and it enters the block. Then, we have a context switch just before the flag can be set to true. Then, process 1 would be able to proceed into the critical section, ignoring the lock, and both processes would be executing the critical section.

But what if we set both flags to true *before* the busy wait. Well, in this case, both would be locked out of the critical section. This happens similarly to the last attempt, where if a context switch happens just after the flag is set, and before the busy wait, both flags would be true, and neither could enter. This is known as **deadlock**.

In yet another attempt, we can expand the while loop busy wait to include an unset of the flag, a delay, and then a reset of the flag. This allows time for the other process to ”unlock” itself. This works if the delays are truly random, and can never get synchronized in both processes. This is known as **livelock**

8.2.2 Petersons Algorithm

This algorithm uses a combination of the shared turn variable, and setting flags before a busy loop. The only difference is that the condition in the wait includes both the flag and the turn. This only works for 2 processes, but it’s good that it doesn’t use a system call or any OS involvement. It is a ”software only” solution.

8.3 Hardware Solutions

How can hardware help with mutual exclusion?

TSL, RX, LOCK are all CPU instructions that are often found on modern CPU’s. This works by setting a lock variable in memory, then, when a program calls `TSL R1 lockaddress`, it will pull the lock from the address, and place a 1 in the lock address. This is the same as the shared variable we were talking about, but not its in hardware so it works. It works, since hardware is completely atomic. A zero is only received from TSL when no other process is in the critical section. Whenever a 1 is received, a busy loop happens.

This has many advantages:

- works for n processes
- can be used by multiple processors (as long as they share memory)
- Simple
- works for n critical sections

But, it still uses busy waiting, and starvation is possible. The order in which processes enter is arbitrary.

8.4 Priority Inversion

This problem arises from mutual exclusion and busy waiting.

If there are two processes, one high priority and one low priority, where the scheduler always runs the high priority if it is ready, then say at some point the low priority is in it’s critical section. It’s possible that the low priority never leaves it’s critical section, since the high priority is constantly running, and is stuck in a busy wait.

8.5 Sleep/Wakeup

The alternative to busy waiting is to have a sleep wakeup using semaphores. This is better since it does not take up so much CPU time and is not as prone to priority inversion and deadlock.

However, this has some overhead, and so if there is a very few number of processes/context switches, busywaiting can still be better, since it has less overhead.

8.6 Assembly Level Instructions

As shown in the demo in class, even if something is a single instruction (in C) it does not necessarily mean it cannot be interrupted. One command, even as simple as a variable assignment, can be interrupted since it is broken down into multiple assembly instructions. This depends on the level of complexity of the instructions, and whether a 32-bit machine or 64-bit machine is being used. (If you use a 32-bit machine, more instructions are require to split up and manipulate numbers).

A lock instruction in Assembly will actually prevent any interrupts from entering the bus while it is executed so the lock instruction itself cannot be stopped as another instruction could.

8.7 Semaphores

Basically, processes can send messages to each other, and their execution can be altered (stopped, started etc.) by these messages. We can use this for more complex coordination of processes. A semaphore is a special variable that is used to accomplish this message passing. wait() and signal() are examples of sending a message through a semaphore.

Example:
`wait(sem)` will wait on the semaphore 'sem', by decrementing the value of `sem` if it is non-negative, it will proceed. Otherwise, the running process will go to sleep. So say the 'sem' is 1 initially. Some process can come through, change it to zero, and keep going. Then, some other process would come through, change it to -1, and go to sleep.

Semaphores are implemented inside the kernel, and so are only accessible through a system call.

8.7.1 Semaphore Structure

The semaphore is a struct made up of an integer to keep track of whether the lock is released or not (negative means no, 1 means yes), and a queue containing them. The wait() function would just be decrementing the count, and if the count is negative, add the process to the queue and block the process. The signal() function is the opposite, it increases the count, and if the count is not 1, remove a process from the queue and mark it as ”ready”.

8.7.2 Producer Consumer with Semaphores

The producer adds things to a buffer, the consumer removes them. Implemented with semaphores, there are 3 semaphores. The ”mutex”, which is the simple lock to protect the critical section, the ”empty” which is used to count how many slots in the buffer are empty (initialized to the size of the buffer, N), and the ”full” which is used to count how many slots are full (initialized to 0). So the producer needs to:

1.) produce an item
2.) wait() for the ”empty” semaphore to not add to the buffer if there is no empty slot available.
3.) wait() for the critical section
4.) Insert the item to the buffer
5.) signal() that it is done with it’s critical section
6.) signal() to the ”full” semaphore that it has added something to the buffer (increment it up)

The consumer then needs to

1.) wait() on the ”full” semaphore until there is something in the buffer
2.) wait() for the critical section
3.) remove an item from the buffer
4.) signal that it is done in the critical section
5.) siganl to the ”empty” semaphore that it has removed an item (decrement it)

The problem with the above implementation is that there are 4 system calls for each process (very heavy). It would be better if we could find a more lightweight version of this.

8.7.3 Types of Semaphores

A strong semaphore respects the FIFO queue, a weak semaphore does not.

Binary semaphores are simply an on/off switch, and can only take on two values, 0 and 1. Counting semaphores on the other hand can be used for any number, negative or positive. We saw this with the producer/consumer example.

8.7.4 Barrier() Synchronization Using Semaphores

A barrier is essentially a synchronization primitive.

Suppose we have two processes, P1 and P2, where P1 reaches a function $f()$ faster. How do make sure that P2 and P1 enter $f()$ at the same time? (not a critical section, just want them to go in the function at the same time).

Suppose we have a barrier, $b = 4$. (4 processes need to wait for eachother). Each process can call $b.bwait()$.

We use 1 binary semaphore *mutex*, and one counting semaphore *barrier*.

```
bwait(){
   wait(mutex)
   bcount--;
   if(bcount==0){
      signal(barrier) //trigger wakeup cascade
      signal(mutex)//release the mutex
   }else{
      signal(mutex) //release the mutex
      wait(barrier) //go to sleep
      signal(barrier) //wake up, this will cause a cascading effect when the
          bcount==0
   }
}
```

In the above, you can see that once the last process decrements count to 0, it causes a signal() which will wakeup a semaphore which will immediately wakeup and signal() again, which will wake up and signal() etc..

8.7.5 Light Mutex

How can we reduce the number of system calls?

First we need to assume an assembly instruction (atomic) is available to `fetch_and_add`. This will fetch whatever is add an address, and add the parameter given to it, and put it back. (Similar to TSL).

```
   lock(m){
      count = 0
      if (fetchandadd(count + 1)>0){ //increment count by one (atomically)
         wait(m) //if someone is in the lock, count is > 0
      }
   }
   unlock(m){
      count = 0
      if (fetchandadd(count - 1) > 1){
         signal(m)
      }
   }
```

By doing this, we can check if something is actually in the lock without needing to go to the kernel. Only when there is actually more than one process in the critical section do we need to invoke the kernel.

8.7.6 Light Semaphore

If we have a very short wait/signal we want to use busy waiting since there is less overhead. (Try as exercise).

8.8 Monitors

So far we have always looked at synchronization primitives of the form: enter -> do suff -> exit. But we have other options than semaphores (higher level). Semaphores are kind of like goto statements. They can be super fast in the right hands, but also can get very hairy.

Monitors are a high-level abstraction to allow for easy synchronization. It contains the sensitive data, and an API for safely accessing operations on the data. Monitors themselves are critical sections, but they already handle all mutual exclusion.

Monitors have condition variables to allow for flexibility in different types of synchronization. Each condition variable has only wait() and signal() operations. (These are different from the semaphore ones!)

How are monitors used for say adding to a global sum?

```
Monitor{
   int gsum
   add(s){
      gsum + s
   }
}m
```

The locking is handled by the monitor behind the scenes, so outside we can just all m.add(s) and not worry about locking.

Now how can we implement a semaphore?

```
Monitor {
   int count;
   condition waiting;

   init_sem(int i){
      count = i
   }

   sem_wait(){
      count--
      if (count <0){
         waiting.wait()
      }
   }

   sem_signal(){
      count++
      if (count <0){
         waiting.signal()
      }
   }
}m
```

Again we assume Monitor is a critical section for free :D

8.9 Lock-free Datastructures (NOT ON EXAM)

How can we implement something like a stack (which can be modified by many threads) without using locks? Locks are seemingly necessary since there is a global head pointer, and pointers to the next which can get messed up. But, killing the threads while one thread holds the lock, will cause the other to be locked out. (This is why you cannot kill threads, they must die on their own). But what if we do it without locks?

For this we will use a new atomic instruction: `compare_and_swap(new_value)` this takes a pointer, and checks if the value at that pointer is the same as the new value. It returns true or false. If true, it will swap in a new value. So, in the context of a stack, if one compare and swap passes, it will write, meanwhile the other process compare and swap will always fail, since the value it ”thinks” is inside the stack, is not the ”true” value.

8.10 Readers and Writers problem

Suppose you have a database, with several readers and writers. We want concurrent access to the database. How can we make sure that all readers can access at any time, but no two writers can access at the same time?

If we only allow writing when there are no readers, this can cause a problem, since there could be non-stop reads, which would starve the writer. Similarly, if we don't allow readers while writing, the readers could starve too.

This is the case that arises in the assignment. The solution is to have the writers have a simple lock, while the readers have something more involved.

```
READER:

wait(mutex)
readers_count ++;
if(readers_count == 1) wait(write_lock);
signal(mutex);

//DO READS

wait(mutex)
readers_count --;
if(readers_count == 0 ) signal(write_lock);
signal(mutex);
```

This has the problem of starvation, and gives readers priority. Starvation could be solved by having a maximum number of readers.

9 Deadlock

Deadlock is defined as the permanent blocking of a set of processes which compete for resources. In general, there is no efficient solution to this problem. They must involve conflicting resource needs, otherwise there is no possibility of a problem.

There are 4 conditions for a problem to be deadlock:

- Mutual exclusion: No two processes can use the resource at the same time
- Hold and wait: Process may wait for one resource while holding another resource.
- No preemption: Process cannot (or will not) give up the resource until it is done.
- Circular wait: each process in the chain holds a resource which another process is requesting.

If any of these conditions are not satisfied, no deadlock can occur. THis is useful when thinking of solutions. If we only allow shared resources (rather than competing), we can break mutual exclusion. If we abort the process when trying to request a resource in use, we break *hold and wait*. If we avoid/prevent deadlocks to begin with, we skip the cycle rule. If we allow to backout to a checkpoint, we break the irreversable process (no-preemption).

9.1 Resources

Resources can be grouped by:

Reusable: not depleted by a process using it. (cpu, memory etc)

Consumable: can be created and destroyed. (messages, signals etc)

Preemtable: Can be taken away by the process using it, with no consequences. (CPU, memory via context switches)

Non-preemptable: Cannot safely be removed from a running process (CD, printer etc)

Deadlocks mostly occur with reusable and non-preemtable resources.

9.2 Resource allocation Graphs

Processes are shown by circles, resources by squares. Arrow are interactions between processes and resources. If we have cycles in this graph, we may have deadlock but not always if there are multiple units per resource! A cycle is necessary for deadlock, but not sufficient. However, a *knot* is! A knot is when there is a cycle with no non-cycle path leaving the cycle.

9.3 Strategies for Deadlocks

- Ignore it: most of the time deadlocks are rare, so hope it doesn't happen.
- Prevent it: design the system in a way that deadlock can never happen. (Often inefficient)
- Avoid it: Add checks that will see if the next action will cause a deadlock
- Detection: Let the deadlock occur, and take action to recover.

9.4 Deadlock Prevention

Two ways:

Indirect methods: prevent something other than the circular condition

Direct: break the cycle condition

We might not want to prevent deadlock, since it is almost always more inefficient. But if we did, we can do it by attacking any of the conditioned previously mentioned. However, mutual exclusion is often not-breakable.

9.5 Deadlock Avoidance

In this approach, we monitor the system, and ensure that no action will cause a deadlock. We will have a "Resource Manager" which will do all checks. So when processes ask for resources, they must ask the Resource Manager to do it for them.

For this we need to know in advance a maximum number of resources that a process needs. This can be declared by the process to the Resource Manager. Then the algorithm will need to dynamically figure out if the request will cause a cycle.

We break up the states into three categories: safe, unsafe and deadlock. Unsafe is when deadlock is possible, but has not yet occurred. Safe is when deadlock can never occur. Ie: there exists a sequence $P_1, P_2, ..., P_n$ of all processes in the system, such that for all P_i, the resources that P_i can request can be satisfied by the currently available resources and the resources held by P_j, for $j < i$. If there is not enough available resources, the P_i waits for enough P_j's to complete so that P_i can claim those resources. So, our Resource Manager will need to ensure that no process moves from the safe state to an unsafe state.

Using the graph we can easily check if allocating a resource will cause a cycle in the graph, and it it would, then don't allocate it.

9.5.1 Bankers Algorithm

Same idea as above, but the resources can have multiple units. We keep a *max* matrix of the processes as rows and resources as columns. The entries are how many units of a resource a process wants to use. We keep another matrix, *have*, similar to the other, which contains how many units the processes actually contain at this time. We keep a third matrix, *need* which has $max_{ij} - have_{ij}$. So when about to allocate a resource, we simply compare the resource vector to the *need* matrix. If there is a process that could run to completion given those resources, do it. Afterwards, update the *have* and *need* matricies accordingly.

For this to work, each resource must have multiple units, each process must pre-state its maximum usage of a resource, all processes must be able to wait for resources, and all processes must return its resources in a finite amount of time.

9.6 Deadlock avoidance example

Suppose you have a printer, and a disk. Two processes want to be able to send files from the disk to the printer.

```
program(){
   get_printer()
   get_disk()
      transfer_document()
   release_disk()
   release_printer()
}
```

suppose we have another version in which some orders are flipped, and suppose each process is using a different version.

```
program(){
   get_disk()
   get_printer()
      transfer_document()\end{document}
   release_printer()
   release_disk()
}
```

Assume only one process can access a resource at one time. If they were both using the same version everything would be fine. However, if they are using different versions, problems can arise. Suppose P_2 gets the disk, and P_1 gets the printer before the other process gets it. This results in a deadlock since both need both resources to

9.7 Deadlock Detection

Here we don't try to prevent deadlock, we instead try to detect it once it has occurred. Detect by running through the graph for cycles.

Can do on each resource request, or periodically. We can recover by either rolling back processes (keeping checkpoints), terminating processes, or trying to take the resource and give it to another process.

Part IV
Virtualization

In general, the goal of virtualization is to create a ”virtual cpu” as a thread to give the impression that it is its own CPU, independent of others. If implemented as processes, each process has its own memory view. However, the filesystem and kernel are still shared. Virtual machines is the idea of giving a process its own version of all of these things.

At the base level, a virtual machine monitor is placed on top of the hardware layer, which allows multiple virtual machines to run simultaneously. It does NOT run all of the instructions itself, it just takes care of housekeeping tasks and managing the VM's. The real hardware still takes care of instructions.

The **Host** is the underlying hardware system. The Virtual Memory Manager (VMM) creates an identical interface to the host. The Guest is a processes provided with a virtual copy of the host.

10 Types of VMMs

We also need to create logical partitions between multiple running VM's. This can be done by implementing the VMM in the actual hardware itself, some OS-like software, or run as an application on top of the OS.

- Paravirtualization: the guest OS is recompiled to be compatible with the VMM
- Programming-environment virtualization: VMMs that are entirely software-based.
- Emulators: Allow any machine to run things meant for a very specific hardware
- Application containment: Not actually virtualization, but segregates applications entirely from the OS.

11 Privilege Level In VMs

In a typical non-virtualized environment, we have the kernel between the user and hardware. In a virtualized environment, we have the VMM layer between the hardware and the guest kernel.

Suppose you have an instruction which can run in either user-mode or kernel mode, which sets a flag bit in the status register which disables interrupts. Obviously, we don't want this to be possible for user-level. So, if the CPU is in user-mode, the bit is ignored, and if in kernel mode, it is not.

In a virtualized environment, the guest kernel is running in user mode, so how can we disable interrupts only for the guest kernel?

First, we need to break sensitive instructions into:

- Control-sensitive instructions: Attempt to change configuration of resources
- Behavior-sensitive: Instructions who's behavior is determined by configuration of resources.

If you try to run a privileged instruction in user mode, this causes a fault, whereas if you're in privileged mode it should run fine. So with that in mind, consider this theorem:

For any third-generation computer, a virtual machine monitor may be constructed if the set of sensitive instructions for that computer is a subset of the set of privileged instructions.

The solution is to have sensitive instructions which cause a trap to go to the VMM. The VMM will then figure out which VM caused the trap, verifies and emulates the instruction in the guest OS. It does this by maintaining vCPU's which keep track of the mode of the real CPU.

11.1 Solutions to Privilege problem

11.1.1 Binary Translation

This translator sits between the program and the CPU, and makes sure that no instruction is going to cause problem. These bad instructions are those that are sensitive, but not privileged. Maintain a set of instructions ahead of current execution which are translated to run correctly, in a translation cache.

11.1.2 Improve hardware

This is done with VM extensions (actual hardware support for VM's). Here, we have a root mode, which runs the VMM.

11.1.3 ParaVirtualization

Part V
Scheduling

Suppose you have a bunch of jobs which need to run on a resource. Scheduling is the problem of finding the best sequence of jobs. This depends on what our priorities are (”goodness measure”)

Scheduling is not the same as allocation. Allocation is about which job will go to which CPU, not the order in which the jobs are executed.

The goal of scheduling could be to minimize response time, CPU utilization, total execution time (throughput), etc.

12 Required info

To properly tackle the problem, we need to know:

- Number of processes
- The rate of creation/termination
- How long each process takes
- How long the process is waiting for I/O
- The priorities

13 CPU Scheduler

The short term scheduler selects from a queue of ready processes whenever one changes from running to waiting, running to ready, waiting to ready or one terminates.

Running to waiting could occur when a semaphore is called, waiting for I/O, etc. This and termination are non-preemptive. (The OS doesn't have to influence it) Running to ready / waiting to ready can happen with a context switch / preemptive action.

Part VI
File Systems

Secondary storage is non-volatile storage. It's managed by the File System part of the OS. File systems are accessed by both users and processes.

Each file is given these attributes:

- Name, owner, creator
- Type (code, data, binary)
- Location (i-node for UNIX, disk address)
- Organization (Random access, sequential, indexed)
- Access permissions
- Time and date info (last accessed, created etc)
- Size
- Other...

File systems provide:

- Keeping track of files (location)
- I/O support
- Management of secondary storage
- Sharing of I/O
- Protection for information in the system.

14 Directories

A directory is essentially a symbol table that can be used to lookup information about files, and is easily read by humans. Directories give a name space for the files to be stored.

A directory entry is the attributes of the file, and are updated when files are created, deleted or modified.

Directories can be **single level** (all users share the data, with no nesting of directories). **Two level** (one level for each user, (involves login)). **Tree** : each user has a sub-tree of the file system. (Commonly used today).

Unix uses a directed acyclic graph to manage directories. Basically a tree, but you can have two parent nodes pointing to the same child (using softlinks).

In UNIX, the filesystem also includes many "non-file" things such as processes, input devices, etc.

15 File System Layout

The disk is cut up into partitions. The MBR or (master boot record) holds all the information needed to boot the system (not the OS). This could contain some tool for switching to a different OS, since it contains the logic needed to "find" your OS partition on the disk.

Next, one of the disk partition will contain your filesystem. This is made up of blocks:

- The boot block is the chuck which loads the OS
- The super block contains all information about the partition think of it as an "address table" for the partition.
- A free space management block, containing information how to manage space
- I-nodes, which are the actual "file descriptor tables" containing data about files.
- The files and directories themselves.

16 File Sharing

When sharing files between users, we need to protect the files. We use the controlled access approach. This ensures that certain users only have restricted read, write, delete, list and append access.

We do not allow users to modify directly the block which stores this information.

17 File Operations

For this, we need to give users controlled access through operations. Users can:

- Create: Set all data/metadata for the file (name, permissions, creation date, size, owner etc). This creates an i-node, and stores it in the i-node block. Some need to be specified (name, permissions, type) and the rest is determined by the OS itself. `touch` is an example of this. It does not write any data to the actual file/directory.
- Write: Send data from a buffer to the file.

- Read: Get data from current position in file.
- Seek: Decide where to read/write in the file. Interesting thing: what if we seek to the end of the file, and write some data. How big is the file? In this case, it would be a sparse file. Sometimes we are interested in the size of the data in the file, not the actual length of the file block in memory.
- Delete: Storage is released
- Open: Fetch attributes of disk addresses into main memory so that it can be read-/written
- Close: Free internal table space. This can be automatically triggered by OS to limit number of open files at one time.

17.1 Open

A closer look at the open operation.

When we call open(), we want to associate the program to the file. The way this works is that the system call open(filename) will lookup the filename in an in-memory kernel-level data structure which will perform a lookup to find the i-node or data block containing the file.

Next, the disk blocks are loaded into memory, where file-descriptor tables are held. So essentially when we call open() we are opening a new entry in the file-descriptor table. This entry points to the **system-wide open-file table** which contains references to the actual data.

Calling close() will remove the entry from the per-process open-file table.

The last process associated to the file to call close() on that file will clear this entry in the system-wide open-file table.

18 File Allocation

How can we arrange files in the disk to optimize for space and time. Large blocks allow for fast access speed but lots of fragmentation (wasted space) due to small files using up large blocks. Small blocks allows for wasting less space but blocks are harder to search so longer access time. Note that one block can have data from only one file.

The sector 0 is always the Master Boot Record (MBR).

18.1 Contiguous

Keep a list of free spaces. So whenever we want to store data, we find a contiguous list of free blocks large enough to store all of the data.

Advantages:

- Easy to read and write, since the data is always sequential.
- Simplistic
- Don't need to search for the rest of the file after you've found the beginning

Disadvantages:

- Need to either know the file size ahead of time or copy the file into a new location once we don't have enough space.

External fragmentation is when we have not enough contiguous free space to place a file, even though we may have enough total free space.

18.2 Chained

Here we keep a linked list to the next blocks. Point to first block, then that block points to next block etc.

Advantages:

- No external fragmentation
- Files can easily grow

Disadvantages:

- Lots of seeking
- Random access is difficult since if we need to access only the nth block, we need to start from the first and run through all blocks to get to nth block.

This can be improved with a *FAT* table. This is a table which contains all information about the chain (which blocks come in which orders). This gets loaded into memory when we want to access the storage related to these blocks.

18.3 Indexed

During file creation, an array of pointers is allocated in storage. This block contains only the index of all the blocks which contain the actual data.

- Little internal fragmentation
- Easy access to files (both sequential and random access)

Disadvantages:

- There are still lots of seeks for large files
- Maximum file size is limited by how many indices the index block can hold (size of blocks).

UNIX uses this allocation system.

19 Free Space Management

Disk space is fixed, so we need to be able to reuse memory. To do this, we need to keep track of free space. Notice there are parallels between this and allocation, since the idea is very similar.

19.1 Bit Vectors

Bitmap is stored on disk at a known address, (often 0). This bitmap has a 0 if that index is free, or 1 if it is not.

19.2 Chains

Similar to allocation, simply link ALL the free blocks together in one giant chain (not necessarily in order).

19.3 Indexed

Similar to allocation, a table is stored at a known block (0). Each entry of the table is the index of a free block, and how many blocks are free after it. Likely ordered by the number of free blocks at the index.

19.4 Finding free space

There are several algorithms for finding free spaces. Bitmaps have machine instructions which can handle this.

For chained, we can try several methods:

- First fit: simply find the first block in the chain big enough for the request
- Best fit: find the region on the chain which has barely enough size to fit the request
- Worst fit: find the biggest portion of free space
- Next fit: First fit but starting from the previous allocation spot. The chain is circular in this case.

20 I-Nodes

An I-node is something that is pointed to by a directory entry in kernel memory. So every time we run open(), the filename is looked up in the file directory table, on a match it sends to the index of the inode. This inode contains information such as the mode of access to the file (read/write etc), link count (number of processes trying to access it), uid, gid, size etc.

The inode also contains 12 disk block pointers, one indirect pointer, one double indirect and one triple indirect pointer. To explain these pointers, consider the following:

Suppose you have all the above pointers in your inode, and suppose your block size is 1024bytes. Now say you have a 6000byte file. Then the file will need 6 blocks, with one being not completely filled. We could take 6 pointers and point them to the 6 blocks. Here the indirect do not need to be used.

Suppose you have a larger file, of size 15000bytes. This is more than 12 blocks! Since we only have 12 block pointers, we can only cover 12288bytes with 1024 blocksize and 12 direct pointers. To deal with this, we assign the 12 direct pointers, and the indirect pointer will point to a data block, which will contain even more disk block pointers. Then, *those* blocks will contain the data. So, if each pointer is 4bytes, we could potentially point to $\frac{1024}{4} = 256$ blocks, so $256 * 1024$ bytes total from just one indirect pointer. Similarly, for doubly and triply indirect pointers, we can handle much much larger files. With those, you point to a block which contains pointers to other blocks, which then contain pointers to other blocks.

20.1 Example

Suppose we have a UNIX file system, 1024 byte block sizes. We seek to 956876, and read 1 byte. How many disk accesses are needed?

First, the block number is:

$$\frac{956876}{1024} = 934$$

which corresponds to a double indirect pointer, which means we need 3 accesses (2 index blocks, and 1 data block). Here we assumed that the i-node already exists and this is the first time we access this block. If this was the 2nd or later access to this block, they would already be loaded and we wouldn't need to access them.

20.2 I-node caching

Whenever a file is opened, it's i-node is added to the open-file descriptor table, and it's i-node is loaded into memory. The open-file descriptor table has one entry per process (and it's children). What's important is that the transfer from disk to memory is always done in terms of blocks. We never write bytes. So the I-nodes in memory have entire blocks loaded, once they have accessed and cached them.

21 Disk Memory Basics

The disk is some magnetic media platter which rotates. You may have many of these plates stacked on top of eachother, each with several tracks. For each platter, we can separate it into sectors. For our purposes, we call these blocks.

The drawback to this, is that access time is very slow. The disk must rotate the full sector while under the head, and then the head must move from the current position to the desired cylinder.

21.1 Disk Scheduling

Suppose we want to maximize the throughput for concurrent I/O requests. These requests will all be handled by the disk driver. The strategy is to minimize the time spend by the disk seeking for data, and maximize the time spent reading/writing data. (Minimize movement of the head).

Strategies:

- Random: (slow, sometimes used as benchmark)
- First come first served: fair, no starvation, not good for response time.
- Priority
- Last in first out
- Shortest service time first: shortest seek time, no guarentee of better average seek time but better than FIFO in general.

Advanced Strategies:

- SCAN: move head back and forth over disk, when head reaches the section that needs to be serviced, do it
- CSCAN: can only one direction then quickly go back to the beginning. Reduces delay for new arrivals compared to SCAN.
- LOOK: look for a request in a given direction, move in that direction untill no more requests in that direction, then change direction.
- CLOOK: similar to CSCAN, but for LOOK

The request queue is batched into small groups since we don't want to change the algorithm every time a new request comes in.

Part VII
Memory Management

Multiprogramming systems need memory management to be able to coexist in memory. We must keep in mind transparency (keeping process unaware of the others), safety, efficiency, and relocation.

22 Absolute Loading and Overlays

Absolute loading is when a program requires to be loaded into the same memory location all the time. If there is another program in that location, then your program could not load, even if you have extra space.

Overlays, by contrast, are the idea of having your program broken up into a tree in which different paths can be loaded into memory at one time, and not need the rest of the tree. Thus, we can have portions of the program in memory at one time, instead of the whole thing. The root is always roaded into the memory, and the subtrees are loaded / reloaded as needed.

23 Partitioning

Static partitioning is when your ram is split into fixed blocks. These blocks are for small, average and large jobs. (With one space for the operating system). We have absolute loading for this type of partitioning.

Dynamic partitioning is when we create partitions just large enough to fit the next program. This requires the addresses to be relative addresses, not absolute.

- First Fit: allocate the first hole thats big enough
- Next Fit: first fit using a circular free list.
- Best Fit: allocate the smallest hole that is big enough
- Worst Fit: Allocate the largest hole

Here we deal with the problem of external fragmentation rather than internal fragmentation. External since the wasted space will always be "outside" the partition.

24 Swapping

Swapping treats the main memory as a "preemptable" resource. This allows for flexibility to systems with even fixed partitions, since then the system can make room for high priority programs on the CPU no matter what. We swap out memory to a high-speed storage if the process needs to be kicked out. This can work together with the CPU scheduler to have high flexibility.

25 Memory Protection

We must be able to protect programs from eachother. This applies to the OS itself too. This can be provided at both the hardware and software level.

Address translation is the idea of using both partitioning and a hardware capability called memory address mapping. All jumps, loads etc are with relative addresses, not absolute, so each program believes it is in a certain set of addresses. We then place a limit on the address range, and throw an error when the address goes outside the range.

25.1 Dynamic relocation

With dynamic relocation, each program-generated (logical) address is translated to a true hardware address at runtime by the MMU. (memory management unit in the CPU). With this, the programs need not even be in a contiguous block of memory! (segmentation).

Suppose we take a program, and split it into segments. One for the code, one for the stack, one for the heap, and one for the shared memory. We then have a base and bound for each of the segments. This is kept as a mapping table for the process. We need to be able to lookup the logical address. To do this, each logical address has a portion call the segment selector, and segment offset. The selector is usually the leftmost digit(s). This tells us which row to look up in the mapping table. The rest is the segment offset. We add this to the base and compare this with the bound. If the bound is higher, then it is a valid access.

26 Paging

Physical memory is divided into fixed sized frames. Logical memory divided into equally sized chunks called pages. So, logical addresses are made up of the page # (like the segment number) and the page offset. Then, we lookup in the page table to get to the frame and frame offset (real address). This is very analagous to the segmentation mentioned before.

The page table is managed by the OS and kept in OS memory. The MMU looks at this table. Note that in the assignment, we had a memory hog program that would be killed once it uses more than the cgroup allows. However, if we only malloc, the program would never get killed, since the program never actually used the memory it requested. Only when you actually use up that memory can it be killed.

The problem is that, say we have more logical addresses than real ones, how can we hold a table if the table cannot be held in one page?

26.1 Multi Level paging

Similar to the idea of I-nodes, we keep tables which map to other pages. So the logical addresses are actually split into 3. The first part is the page in the top-level page table, then next part is the page in the second-level page table, and the last is the offset in actual ram. However, this is slow. We now have to do many memory accesses.

27 TLB

The translation lookaside buffer is a cache that remembers the mappings that we find, kept in the CPU. See my comp 273 guide for more on the TLB.

28 Virtual Memory

This is the idea of keeping pages in the disk to keep more memory in the storage, and swapping out processes from memory that are not being run. However, disk access is slow, so we need to look in the past, and approximate which processes wont be run in the near future, in order to kick out the best one.