ECE 391 Lecture Notes

ECE 220 Review

- **Stack (main thing)**
    -
- **LC-3 to x86**
    - In LC-3, you only had a few things to worry about, in terms of instructions and registers. Follow along with the first few lectures and the transition shouldn't be bad.
- **Recursion**
    - Ignore this like the plague for this class.
- **Static Keyword**
    - You'll encounter this a lot throughout the class. Look at some examples right now:

```c
static void helper(int arg1);
```

    - `helper` will only be defined in the file that you put it in. You should not need to include any static functions in your header file, just declare them at the top of the C file if you use it in a function defined before it.
    - static variables are similar enough:

```c
static int global_in_file;
int func() {
	static int counter = 0;
	counter++;
	return counter;
}
```

    - `global_in_file` will be available for all functions in its specific C file to be used. `counter` though is only available to func( ). One thing to remember is that these variables are initialized once when the program starts, and keep their values throughout the lifespan of the program.

                - This means every time func( ) is called, counter increments by one.

- **Structs**
    - Example struct:

```
typedef struct dummy {
    uint32_t addr;
    int* ptr;
} dummy_t;
```

    -

1 - Class overview and big picture

Logistical lecture, quotes from past students, no material on class related topics. I thought class started at 2:30 and was 30 minutes late, good way to start the semester.

Discussion Week 1 - Overview of MPs and Environment

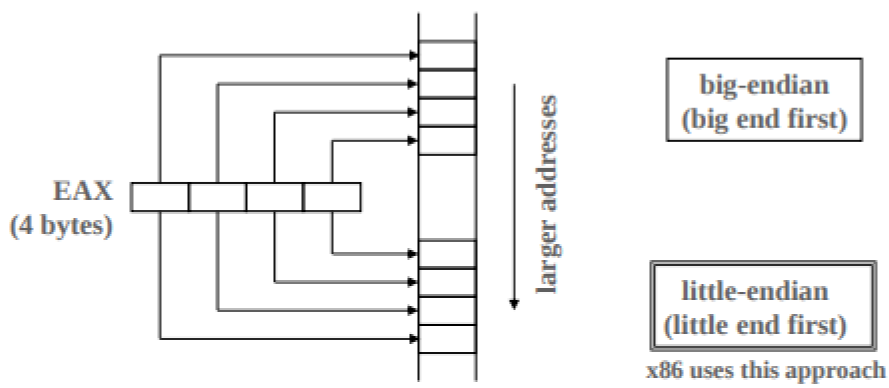
- Look at slides related to GDB, Git, Make, and other stuff. Here will talk about how to actually use QEMU (virtual machines you'll be using to test and debug MPs)
- After you have it all set up, either following MP0 directions or setting up on your own environment, focus on 3 shortcuts:
    - **test_nodebug** - Run your programs from here if you don't want to use GDB (useless when MP3 comes around, useful for MP2)
    - **test_debug** - When you're ready to debug your programs, use this VM in conjunction with **devel** to test.
    - **devel** - Launch your programs from here to debug. Start it up, go to your work directory with program you want to debug, and use gdb. For the simplest example, say you want to run a file called mp1 to debug. Following along:

      ```
      gdb mp1
      ...gdb stuff...
      (gdb) tar re 10.0.2.2:1234
      ...something pops up if test_debug is open…
      (gdb) start
      ```

    - tar re is shortened for target remote, in which you use it to access your test_debug VM (saves a lot of time in the long run, especially for MP3).
    - When you type tar re 10.0.2.2:1234, you can also click on VM, click and hold your cursor from tar to 1234, right click, and it should copy to clipboard and paste a copy onto the screen (should be fine to press enter here). Can right click to save time now until **devel** closed/bug.

2 - x86 instruction set architecture: introduction and instructions

- The six main registers you'll be using to manipulate data are **EAX, EBX, ECX, EDX, EDI, ESI,** which you can use just like LC-3 registers**.**
- Other registers are **ESP, EBP, EIP, EFLAGS, CS, DS, ES, SS, FS, GS** (more details on these registers)
    - **ESP, EBP** are the stack pointer and base pointer respectively
    - **EIP** is the instruction pointer, holding the current instruction address
    - **EFLAGS** holds all of the flag stuff (eg comparing values)
    - **CS (Code Segment), DS (Data Segment), ES (Extra Segment), SS (Stack Segment), FS, GS**. Will be important in MP3 but not now.
- The 'X' registers (like **EAX**) can be specified to access certain bits (**AX** is lower 16 bits, **AH** and **AL** hold upper and lower 8 bits of **AX** respecitively)
    - For the other 'X' registers, similar style (**BX, BH, BL** for example)
- Memory in x86 uses little-endian style (look at picture to make sense of it)



- Example x86 code

```
movl    $321, %eax
pushw   %ax
movb    %ah, 0xECE391(,1)
```

    - $321 - Signifies a constant (321) that can be up to 32 bits
    - %eax - Use % to access a register

- movl - Moves the first argument into the second argument. The **l** at the end signifies the type of data you're working with. Words from the professor: **Always include the data type**. The possible data types are **b (8 bits), w (16 bits), l (32 bits)**.
- pushw - Pushes onto the stack 16 bits (in this case, **AX**). It's the equivalent of doing

```
subl    $2, %esp
movw    %ax, %esp
```

- `movb    %ah, 0xECE391(,1)  -` Moving the 8 bits in **AH** into memory address **0xECE391** (will most likely crash or give an error without knowing specific details)

- **Important instructions to become acquainted with**
  - **CALL** - calls a function. **EIP** is pushed onto the stack to return to original function when the called function ends.
  - **RET** - Returns from a function, popping return address from the stack.
  - **LEAVE** - Don't use all the time, need to setup a stack frame for this (more on this later).
  - **MOV** - Main instruction when working with data, as you can do direct and indirect stuff if you know memory addresses.
  - **PUSH, POP** - Push and pop items onto/from the stack.
  - **JMP** - Mainly use for jump tables (more on that later).
  - **IRET** - Not right now, will explain later for MP3.
  - **INT** - Causes an interrupt based on **interrupt descriptor table** (**IDT**, more on this later).
- Use **CMP, TEST** to set flags such as **Sign Flag, Zero Flag, Carry Flag, Overflow Flag, and Parity Flag**.
  - One thing to note is that unsigned and signed comparisons are different. The following instructions jump to specified label if condition is met (eg `ja label_name` causes a program to move to label_name if a comparison happened, and val1 > val2)

unsigned	`jne`	`jb`	`jbe`	`je`	`jae`	`ja`
relationship	≠	<	≤	=	≥	>
signed	`jne`	`jl`	`jle`	`je`	`jge`	`jg`

- For memory accesses, the general syntax is something like this:

```
movl    (%eax, %ebx, 4), %ecx
```

  - Translation (with variables, assume eax is unsigned long type):
    `int32_t ecx = *(int32_t*)(eax + ebx*4);`
    - Note, eax is unsigned long in this example instead of int* to deal with the fact that pointer arithmetic will change what happens based on the type it points to
  - The value in **EAX** is offset by the value in **EBX*4**, which will then be dereferenced to store in **ECX**.
- For reference, use these two links when programming in x86:
  - http://flint.cs.yale.edu/cs421/papers/x86-asm/asm.html
  - https://drive.google.com/file/d/1Gvhio3cgXXQ6u8FrudeJ7c-ykXKkdkZW/view?usp=sharing (the x86 reference sheet from course site)

- The following slide is nice to know and left intact.

label: requires a colon, and is case-sensitive (unlike almost anything else in assembly)

```
# comment to end of line
/* C-style comment
     … (can consist of multiple lines)  */
;    command separator (NOT a comment as in LC-3)
.string "Hello, world!", "me"    # NUL-terminated
.byte   100, 0x30, 052           # integer constants of various sizes
.word …
.long …
.quad …
.single …                        # floating-point constants
.double …
```

If assembly file name ends in .S (case-sensitive!), file is first passed through C's preprocessor (#define and #include)

3 - x86 isa: assembler conventions, calling convention, examples

4 - C to x86 linkage, device I/O; role of system software, system calls

- **Calling convention (IMPORTANT TO KNOW)**
  - Say you call a function in x86 that's defined like this

    ```
    int c_func(int a, int b, int c);
    ```

  - Parameters are pushed from right to left, meaning you would do something like this (**EAX** = **a, EBX** = **b, ECX** = **c**, random regs picked):

    ```
    .globl   c_func

    random_label:
    ....some lines of code later....
          pushl    %ecx
          pushl    %ebx
          pushl    %eax
          call     c_func
          addl     $12, %esp          # args no longer needed
    ....rest of code....
    ```

  - Why push like this? Convention people agreed to. It allows functions to access variables in an easy way, knowing that the first variable is (ignoring the return address) the first on the stack, second variable is second, and so on.
  - `addl $12, %esp` restores stack back to state it was before **c_func** was called.
  - Registers **c_func** destroys if not saved properly:
    EAX, EDX (return value stored in EAX, EDX too if 64 bits), **ECX, EFLAGS** (shouldn't need to preserve this for the most part).
  - Registers **c_func** must preserve: **ESP, EBP, EBX, ESI, EDI**
  - Same goes for x86 functions, say you have a simple function defined like this

```c
int called_func(int argument);
```

that’s called from a C function (the function itself is useless):

```
1 called_func:
2     pushl    %ebp              # setup new stack frame
3     movl     %esp, %ebp        # by giving ebp esp val
4     pushl    %ebx              # using ebx, save prev val
5     movl     8(%ebp), %ebx     # get first argument
6     popl     %ebx              # restore ebx
7     leave                      # tear down stack frame
8     ret                        # return to prev function
```

- Go through it step by step
    - Lines 2-3 are setting up the stack frame for the function, you don’t always need this (as seen in MP1 by ioctl dispatcher)
    - Since this function is called, it should preserve any registers that it uses that need to be preserved (in this case line 4, **EBX**)
    - Line 5 gets the first argument off the stack, puts it into **EBX**
        - **ESP** points to return address at the start of the function
        - Since we pushed **EBP**, there’s an initial off by 4 to take into account
        - Offset needed to get the argument (not the return address) is then 8, meaning movl 8(%ebp) just gets the 4 bytes starting at memory (%ebp + 8) and puts into **EBX.**
        - If **EBX** wasn’t pushed and used a different register, first argument would be gotten like this.

          ```
          movl    4(%ebp), %eax
          ```

    - Once you’re done using the register, has to be popped in **reverse order** (if you pushed say **EBX, ESI,** you should pop **ESI, EBX,** in that order).

        - Line 7, leave, is the equivalent of doing:

```
addl    $4, %esp
movl    %esp, %ebp
```

        - Restores ebp if stack is back to how it was from pushing **EBP**, otherwise strange errors (and kernel panics) can occur. **Don't use leave if you don't set up a stack frame.**
        - ret goes back to function that called called_func, popping the return address off the stack.

- **Device I/O (Important for MP2, MP3)**
    - Ports are 16 bits, byte addressable and little-endian
    - **IN -** (port, dest_register) as arguments (reads data from port)
    - **OUT** - (source_register, port) as arguments (writes data to port)
        - When dealing with register/port stuff in MP2, refer back to here and the macros they have defined (I think arguments are reversed in the C macros). I was stuck for a while until I realized it was simple enough to use.
    - One thing to note is that the ports are in memory, so you have to know the memory address of whichever port you want to use to read/write data to it.

- **Data Type Alignment**
    - In C, structs may be padded to deal with how the processor accesses data. Say you have a struct like this:

```c
typedef struct dummy {
        int a;
        char b;
        int c;
} dummy_t;
```

    - If you were to use the sizeof( ) function and see that the size is 12 and not 9, padding was at play here to make it easier on the processor to access data faster.
        - Adding `__attribute__((__packed__))` between 'struct' and

    'dummy' will give you 9 (not recommended for x86).
    - No padding to worry about in MP1 though, use defined constants they give you.

- Let's compare two structs:

```c
typedef struct dummy1 {
      int a;
      short b;         // short is 2 bytes, int is 4
} dummy1_t;

typedef struct dummy2 {
      short a;
      short b;
      short c;
      short d;
} dummy2_t;
```

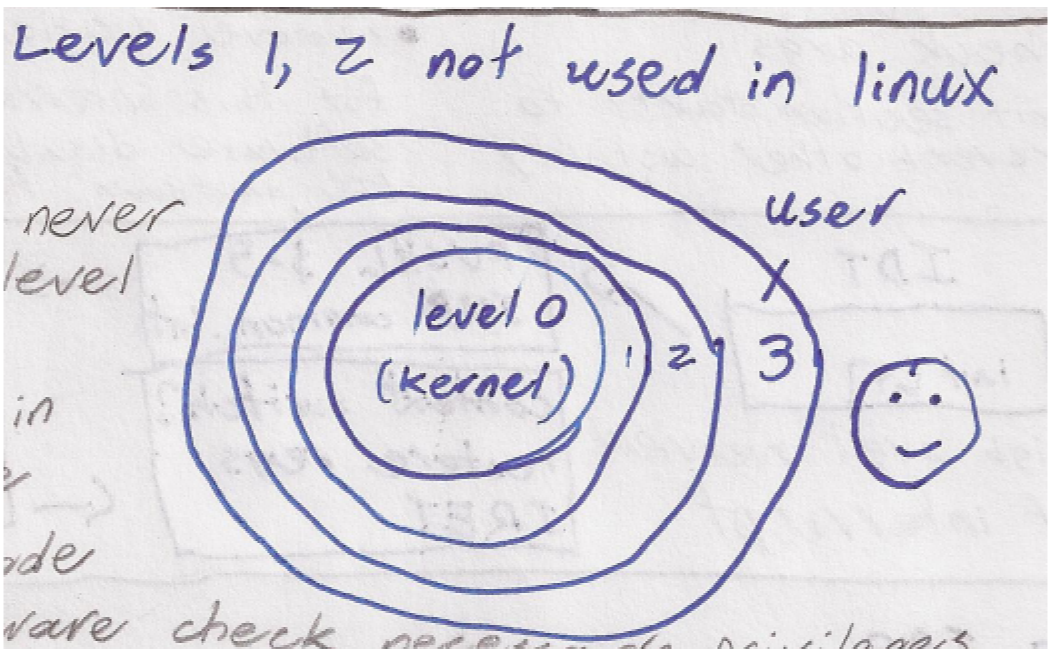
- Both structs will be 8 bytes in size, but `dummy2_t` seems to be able to hold more data if we distribute it as 4 shorts instead of an int and a short.
- In x86, use .align #, where # is the argument in however much you want to align certain things. For example:

```
random_label:
      .word    0
      .long    0
      .align   4
```

- .align here will make sure you can access the .long data by offsetting `random_label`'s memory address by 4.

* **System Calls**
  - I don't see this anywhere on the slides but can give info (mostly midterm 2 material though).
  - **System calls** are the way to access kernel level functions through userspace.

- Let’s look at `malloc()` for a bit:
  - The user interface is `malloc()`, but underneath that is different system calls based on how it’s implemented (`sbrk()`, `mmap()`, etc.).
  - The memory allocation system calls are needed due to the privilege level needed to change how the OS views certain things (such as paging, discussed later).
- Two privilege levels/rings to worry about: **ring 3** (user space) and **ring 0** (kernel space).



  - Trying to do anything that requires **ring 0** privilege level in user space results in an exception occurring (for example, trying to access kernel memory).
  - System calls are done in **ring 0** since they are triggered by an interrupt (`int $0x80`).
  - To get back to ring 3, a **context switch** needs to happen, in which you set up a ‘fake’ stack and then use **IRET** (more on this later, may be misleading right now).

Discussion Week 2 - PS1, x86

- **Function Pointers and Jump Tables**
  - At first, it may seem weird to use, but there are some cases where function pointers are needed (mainly, MP3).
  - **Jump tables** are used to call a function knowing offset and an actual table.

```
/* void* = can be casted to different stuff */
void *jmp_table[3] = {func1, func2, func3}
```

  - A simple table like above could be used to lower amount of code used (for example, instead of if statements/a switch, can call a function knowing index you want based on conditions).
  - In x86, a jump table can be declared like this:

```
func1:....
func2:....
jump_table:
      .long func1, func2
```

  - In this table, func1 and func2 would be the x86 labels (or C function addresses in C). To actually jump to a function, the general syntax would be like this:

```
/* Calling func2 here */
movl    $1, %ecx
jmp     *jump_table(, %ecx, 4)
```

  - The * before jump_table means it will be based on that address as opposed to a relative jump. Using the 120 notation with memory addresses, it is doing

```
jmp M[jump_table + %ecx*4]
```

- **Typecasting (Very important later, PS1)**
  - C is a language that, if you mess up and it compiles, it’s going to be a bad time. But because it’s like this, you can do a lot of weird stuff. For example, say you have something like this:

```
// uint32_t = unsigned int (4 bytes).
// register lets C know to keep variable in register (in
// this case, ebp since it holds ebp already)
// The asm part just gets the value in ebp for the C func
register uint32_t ebp asm(“%ebp”);
uint32_t addr = *((uint32_t*) (ebp+4));
```

  - What this effectively does is get you the return address of the function that called the current function, and putting it into addr. For the problem set, if it doesn’t make sense, typecasting is what they want you to do probably.
  - Another silly example:

```
/* 0xECE391 holds a pointer to a string */
uint32_t x = 0xECE391;
char* string_391 = (char*) *((uint32_t*)x);
```

- **x86 to C**
  - Go to discussion and listen to TA

5 - Interrupts and exceptions, processor and ISA support (Note: A lot of this you won't see/apply until MP3, but will be on the midterm)

- System software serves 3 main purposes: **virtualization, protection, abstraction.**
  - **Virtualization** - Makes it look like there's unlimited resources available to use.
  - **Protection** - Stops the user from doing silly stuff or someone else from being hacker man.
  - **Abstraction** - Hides asynchronous nature by appearing to be running in parallel (in a single core processor).
- **System Calls and Exceptions**
  - Uses a jump table to go to correct function. More details:
    - To be able to use a **system call**, the following needs to happen:

      ```
      int $0x80
      ```

    - (FYI: This version of working with system calls is deprecated due to speed in newer versions of linux, but used in this class).
    - Similar to LC-3 **TRAP** instruction, **INT** goes to specific IDT table entry (in this case, IDT entry 0x80).
  - **Exceptions** happen when something goes wrong in a program/process.
    - Like system calls, map a table of exception handlers to deal with different exceptions.
    - Around 20 intel mapped exceptions.
- **Interrupts**
  - An **interrupt** interrupts the OS (wow). It can happen unexpectedly whenever any program is running.
    - **Maskable interrupt** can be stopped for a certain amount of time, either by clearing the interrupt enable flag (**IF**) (using **CLI** in x86) or not actually being set up properly in MP3 :(

            - **STI** restores **IF**, use after you use **CLI.**

```
cli
...some x86 stuff…
sti
```

        - **Non-maskable interrupt** can't be stopped.
    - Two interrupt types exist to deal with the fact that some are too important to stop.
- **Interrupt Descriptor Table (IDT)**
    - First, go through what each group entry represents.
        - **0x00 - 0x1F** - Defined by intel.
            - Entry groups for all exceptions that happen, there may be blank entries in here if not defined yet.
        - **0x20 - 0x27** - Master 8259 PIC (PIC introduced in lecture 9).
            - 8 interrupt request (IRQ) lines. Important ones are:
                - **IRQ0** = Timer chip, use this to schedule in MP3.
                - **IRQ1** = Keyboard handler (I hated this).
                - **IRQ2** = Cascade to slave PIC (more IRQ lines).
                - **IRQ4** = Serial port (KGDB).
        - **0x28 - 0x2F** - Slave 8259 PIC.
            - Another 8 IRQ lines. The important ones are:
                - **IRQ8** = Real time clock.
                - **/* Only IRQ8 from here worried about in MP3 */**
                - **IRQ11** = network stuff.
                - **IRQ12** = PS/2 mouse.
                - **IRQ14** = hard drive.
        - **0x30 - 0x7F** - Vectors available to device drivers.
        - **0x80** - System call vector.
        - **0x81 - 0xFF** - Idk other stuff.
    - The IDT has to be set up properly for all of the different interrupt

types, otherwise nothing will go through

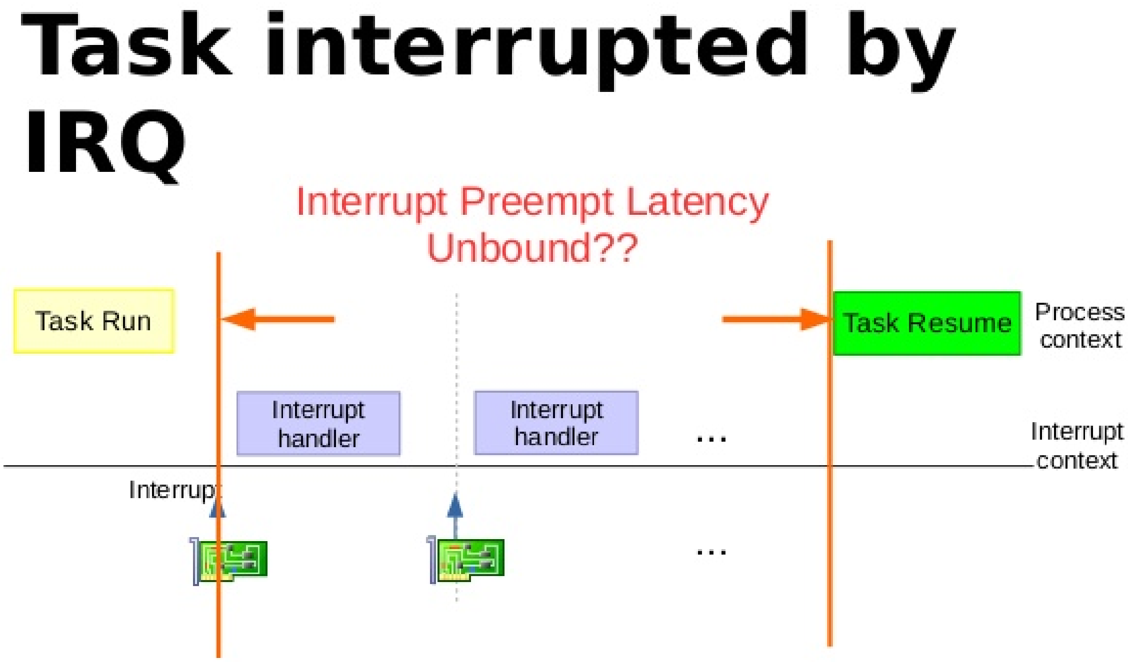
- Going along with this, the PIC has to also be setup for the 8 (16 w/slave) IRQ lines to handle those specific hardware interrupts.

- Why is this important? It is the main entryway for the operating system to actually do important things (keyboard input, launching programs, scheduling, etc.).
- An efficient way to deal with interrupts and exceptions, in that you can change them without messing up the operating system if you just have function pointers in your IDT.

Extra Notes on Lecture

- The point of this section is to understand certain concepts that may not be fully understood at the moment, so it touches a bit on later lecture material to try to help you understand.
- Interrupts are going to be a very important part of the course. They touch on it a bit in MP2, but MP3 deals with many interrupts.
- **PIC**
    - The PIC is a hardware device that lets your OS actually do stuff.
    - The IR lines on it are the IRQ lines talked about.
    - Certain data has to be sent to the PIC to actually initialize it using physical memory I/O.

- **Interrupts**



  - **Interrupt Handlers** are functions that deal with the interrupt that occurred.
    - For example, keyboard interrupts caused by clicking on a key needs a keyboard handler to deal with it.
    - After an interrupt has finished, at the end you need to send an end of interrupt (**EOI**) signal to the PIC to the correct IRQ line, otherwise the interrupt will most likely not happen again.
      - If your interrupt handler is on IRQ 2 for example, send **EOI** to IRQ 2.
      - For how to actually send **EOI**, refer to linux code handouts they give later on to get important information for MP3.
  - **Exception Handlers** are functions that deal with any exception that occurs in the system.

        - In MP3, your exception handlers have to halt the current process and return to the previous process.

- **High Level Overview of an Interrupt**
    - It can happen unexpectedly, or scheduled (**Real Time Clock (RTC)** and **Programmable Interval Timer (PIT) / Timer Chip** are examples of scheduled interrupts).
    - When a process is running, and the specific IRQ line isn't masked, an interrupt can occur at any given time.
        - Masking stops it from occurring until unmasked again.
    - Since it can happen unexpectedly, a few things have to happen
        - Save registers.
        - Context switch from user level to kernel level (if in userspace, more on this later).
        - Be able to return to previous process/function without having modified their stack/registers.
    - Synchronization constraints and other issues are worried about when dealing with interrupts, and designing how they will work in the system.

Discussion Week 3 - MP1, x86, calling convention

- **Demo Questions**
    - The questions they give aren't too bad, if you can give a semi decent answer your TA will probably guide you to what they wanted to get you those nice 10 points on the MP.
- **MP1 Overview**
    - The infamous 391 workload begins with MP1.
    - All in x86.
    - Fall MP (Missile Command) is harder than Spring one (Text-Mode Fish Animation).
    - Lots of lines of code incoming.
- **Tasklet**
    - Tasklets are a part of interrupt handlers, in that they are used to defer work from actual handler to this type of function.
        - Interrupt handlers need to be as short as possible due to them stopping the process they interrupted.
        - If work is deferred, can schedule another process while previous process is happening.
    - You're creating a tasklet in MP1 for your animation to happen, working with the **RTC** (only need to write tasklet, makefile/instructions help setup your tasklet).
- **Magic Numbers**
    - This will be pretty hard to keep track of; you're gonna have to comment a lot, define a lot of constants, and just try very hard to not have spaghetti code in your MPs.

```
movl    %eax, %ebx
addl    $23, %eax
pushl   %eax
call    some_func
```

- Why does the above code move a value into ebx, then push an updated eax value? You can infer that you're saving the previous eax value, but why add by 23?.
- Comment your code, and define as many constants as you can to lower the amount of magic number usage.

```
addl    $VIDEO_OFFSET, %eax
```

- With constants, you can make sense of stuff easier as you go through the MP and debug when bugs arise.
- You also don't need to go overboard with comments.

```
.data
     NULL    = 0
     SUCCESS = 0
     ERROR   = -1

.text

/* int some_func()
 *   Description: Sample function to show commenting, check
 *                if the memory addr passed in is null
 *   Inputs: %eax - Holds the previous func's memory addr
 *   Outputs: 0 on success, -1 on error
 *   Registers: %eax holds output, %ecx will then hold
 *              memory addr passed in (if not null)
 */
some_func:                 # no stack frame needed here
     cmpl    $NULL, %eax   # check if addr null, error if so
     je      null_addr
func_success:
     movl    %eax, %ecx    # saving output in eax, addr in ecx
     movl    $SUCCESS, %eax
     ret
null_addr:
     movl    $ERROR, %eax
     ret
```

    - One thing to note is that they really want you to write interfaces like the one above the actual function, so get in the habit of doing that.
    - You can lose a lot of points in your MPs over time because of magic numbers.

- **Virtual Memory**
    - One thing to note is that user-space addresses are different from kernel space ones.
        - Use provided functions like **mp1_copy_to_user** and **mp1_copy_from_user** when dealing with any user space address (or kernel to user space).
        - Also use to check for bad addresses instead of null checking since it does more checks.
    - Don’t worry too much for now about it.

- **Debugging**
    - Use gdb as much as you can when your program is messing up.
    - Working in user != working in kernel.
    - tar re 10.0.2.2:1234 is your friend.

6 - Shared resources, critical sections, examples

- **Shared Resources**
  - Due to the nature of operating systems, lots of resources may be shared by multiple parts.
    - This in turn leads to problems in dealing with how to share the resources.
  - What if something like a linked list is shared between two very different things?

```
list_head:
      .long 0

some_interrupt:
      ...uses list_head here...

1 update_head:
2     movl    list_head, %eax     # store previous head
3     movl    %ecx, list_head     # update list head
4     movl    %eax, 4(%ecx)       # update next ptr of head
5     ret
```

  - The problem with the above `update_head` function is that it doesn't properly update the head.
    - `list_head` is updated in line 3 without taking into account that the function can be interrupted at any given moment.
    - Since `some_interrupt` uses the list data, if it interrupts `update_head` at line 3, it will only have the new head's data, which could have garbage or NULL for the next ptr, making it the only item in the list or worse.
  - By taking the interrupt into account, can swap instructions:

```
1 update_head:
2     movl    list_head, %eax     # store previous head
3     movl    %eax, 4(%ecx)       # update next ptr of head
4     movl    %ecx, list_head     # update list head
5     ret
```

    - A simple switch in which instruction happens first can fix this problem.
    - There are more complex problems to worry about though, and so different measures will have to be taken into account.

- **Compiler Optimization**
    - When you're first introduced to this, you might think problems that may arise in MPs are due to this and start turning stuff into volatile.
        - Most likely not the problem but still a possibility.
    - **Volatile**
        - Any variables marked **volatile** will be constantly re-initialized/reloaded. (For this example, just know there can be multiple threads in a program, each one able to do its own thing and focus on a specific part/multiple parts).

```
volatile static int busy_variable = 0;

/* Thread 1 */
int func1() {
	while (busy_variable == 0) {
	...do stuff...
	}
}

/* Thread 2 */
int func() {
	...do stuff...
	busy_variable = 1;
	...do stuff...
}
```

        - In the example above if you didn't have the keyword, there's the off chance that the compiler would optimize your program and would make the while loop like this:

```
while (1)
```

        - To the compiler, it may look like `busy_variable` is never modified and may change your while loop to always occur since it's never modified in `func1()`.
        - Volatile variables come at a cost. Since you're always reloading the variable, a performance hit is taken every time you use it.

```
busy_variable = 1;
// busy_variable = old_value_in_memory
// busy_variable = 1
```

    - **Code reordering**
        - Another thing compilers may do is change how your code actually executes by switching which instructions happen first. It's not predictable and there's not much you can do about that when it happens (unless you know the inner workings of gcc).
        - If you have the unlucky fate of a bug happening because of this, you have some pretty bad luck on your side.
    - **Atomic Operations**
        - When code executes **atomically** it is happening as if it was one operation.

```
movl    %eax, %ebx
```

        - The above is atomic since it's only one instruction.
        - What else is atomic?

```
cli
...multiple instructions...
sti
```

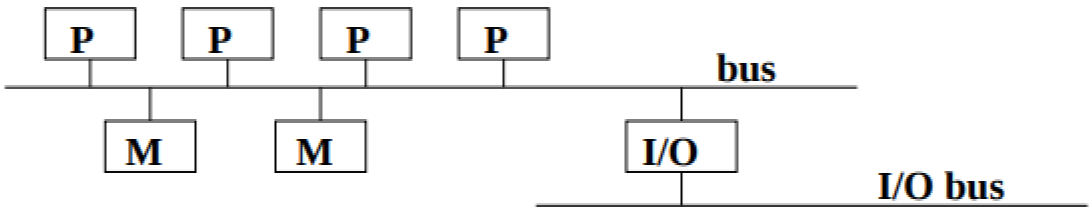
        - Since **CLI** clears **IF**, the only way this can be interrupted is through an exception or non-maskable interrupt, none of which should change anything that happens to data it uses.
            - **CLI** and **STI** can be made C macros to use these in C files, or even this may work but haven't tested it:

```
asm volatile ("cli");
...C stuff...
asm volatile ("sti");
```

- **Critical Sections**
  - Used when you need to make sure code executes in a specific order without being interrupted (and, even with code reordering, will work as intended).
  - Using **CLI** and **STI** is one way of creating critical sections, as interrupts that would affect/use certain data can't occur.
  - Drawbacks: Since it clears **IF**, no maskable interrupt handlers are going through, meaning that any interrupts that are happening at the time are delayed or not happening at all.
    - Can crash the system due to timeouts if certain handlers aren't handling important maskable interrupts.
    - Keep critical sections as short as possible, otherwise risk both performance losses and bad things happening with the system itself.
  - Critical sections by themselves are no longer enough due to how complex modern operating systems have become. Having multiple processors/cores makes things pretty complicated.
    - Solution(s)? Locks (next lecture).

7 - Multiprocessors and locks, conservative synchronization design

- **Multiprocessor**
    - **Symmetric Multiprocessor (SMP)**



        - All processors have equal latency to memory banks.
        - Different than multi-core processors but similar from our perspective.
    - **Non-uniform memory access (NUMA)**
        - Memory access depends on location relative to the processor.
        - Processor can access local memory faster than non-local memory.
        - Used for cluster multiprocessing systems, follow from SMP.
- **Locks**
    - If you clear **IF** on one processor, other processors still have their **IF**.
    - In terms of speed, clearing the interrupt flag for thousands of processors in a huge system is a heavy cost in performance.
    - **Locks** use shared memory between multiple processors to be able to synchronize properly. A simple explanation of how they work is down below:

        1. Wait until it's unlocked.
        2. Once unlocked, one processor/thread locks it.
        3. Do stuff with the data.
        4. Unlock it for others to use.

    - How are locks made, such that they happen atomically? That topic is beyond the scope of this class (highly optimized implementations that is, simple example next part).

- **Spinlock**
    - From the wikipedia page, a simple implementation could be something like this (converted to our syntax from intel):

```
locked:
      .long   0             # 1 = locked, 0 unlocked

spin_lock:
      movl    $1, %eax
      xchg    locked, %eax  # atomically swaps values
      cmpl    $1, %eax      # stop when locked changes value
      je      spin_lock
      ret

spin_unlock:
      xorl    %eax, %eax    # clear eax, and unlock locked
      xchg    %eax, locked
      ret
```

    - For a uniprocessor/single core processor, spinlocks are replaceable.
        - Since you can clear the **IF**, that's all you need.
    - Used a lot in modern operating systems due to reliability (but only when it's for a short period).
    - Why not long periods? It's essentially doing this:

```
while (locked) {
      // spin, in other words do nothing
}
```

    - The thread trying to access the lock essentially becomes useless until it acquires it, ignoring doing anything else (besides handling interrupts) while waiting for the lock to be unlocked.
        - You can also clear interrupts along with the spinlock if you need to.
    - Simple example of how to utilize spinlock API:

```c
#include <linux/spinlock.h>
// Usually want lock initialized at start, not dynamically
// but there are cases when it needs to be dynamic
static spinlock_t lock = SPIN_LOCK_UNLOCKED;

// Two threads, only one will do work at a time based on
// this inefficient example. Other locks introduced later.
int thread_1() {
    // Activates in middle of program once only
    spin_lock(&lock);
    ...thread 1 stuff...
    spin_unlock(&lock);
    return 0;
}

int thread_2() {
    // Active thread, do stuff until breaks
    while (1) {
        spin_lock(&lock);
        ...thread 2 stuff...
        if (some_condition) {
            spin_unlock(&lock);
            break;
        }
        // Unlock after every loop cycle in case thread 1
        // is started and uses it
        spin_unlock(&lock);
    }
    return 0;
}
```

- **Remember: Keep lock as short as possible.**
- With respect to operating systems, there are different spinlock functions you should use based on the situation, such as if you have an interrupt happening that shares data with a system call (this is where it gets interesting).

- **Race Conditions**

- Say you have two race cars trying as fast as they can to reach a pit stop that only takes in one car at a time.
    - Race car 1 reaches it before race car 2.
    - Race car 1 is in such bad condition that race car 2 has to wait for a very long time.
- **Race conditions** are programming conditions that can lead to programs acting differently based on which process/thread reached a certain point first.
    - One of the outcomes is a **deadlock** (similar to race car example, except waiting forever instead).
-

Discussion Week 4 - PS2, Synchronization

8 - Linux synchronization interface, synchronization hazards

9 - Programmable interrupt controller motivation and design

Discussion Week 5 - MP2.1, Synchronization

10 - Linux abstraction of PIC; Interrupt support in Linux: data structures, installation and removal

12 - Interrupt support in Linux: initialization and assembly linkage

Discussion Week 7 - MP2.2, Tux Synchronization

13 - Interrupt support in Linux: invocation; summary of the interrupt support

14 - Soft interrupts/tasklets; Virtual memory: rationale, segmentation

Discussion Week 8 - MP3 overview, MP3.1

15 - Virtual memory: paging

16 - Filesystem: philosophy, ext2 as example (file system in MP3)

Discussion Week 9 - MP3.2

17 - Programs to processes: rationale, terminology, and structures (task structure, kernel stack, TSS)

18 - Programs to processes: creating processes; job types and basics of scheduling; scheduler design and implementation

- **Types of Jobs**
  - Depending on the job time, scheduler can focus on other processes/give them more priority based on what is needed from the different types of jobs.
  - **Interactive**
    - Although there's not much work for this type of job, since the user is interacting with it, a quick response time is needed.
    - Wake up quick when inactive, otherwise can appear funky.
  - **Batch**
    - Data processed at regular intervals.
    - Run in background mainly.
    - Since it uses a fair amount of CPU, best to schedule when there are not other main processes that need good speed/not much activity.
  - **Real-time**
    - Work should be done quick based on requirements needed for the specific job.
    - Shouldn't be blocked by processes with lower priority, as they should have a short guaranteed response time.
      - Given highest priority, but priority for separate ones decided among themselves.
  - There are 2 other ways to classify, namely **I/O-bound** and **CPU-bound**.
    - **I/O-bound -** Uses a lot of I/O devices and operations (database server is one).
    - **CPU-bound -** Requires heavy CPU usage to complete (image-rendering program is one).
- The linux scheduler has certain algorithms in play to be able to dynamically change priority of a given process based on many different factors.

- **Scheduling**
    - Rule of thumb is to keep quantum duration as long as possible, while also as responsive as possible (interrupts, interactions, etc).
    - **Preemptive**
        - Involuntarily suspend running process to work on another (used in Linux).
        - **Timeslice** / **Quantum** - time a process has before another one is then worked on (aim for milliseconds).
            - If it's too short, overhead from constantly switching processes becomes high, slowing down applications.
            - If it's too long, concurrent illusion is no longer true (say it's 5 seconds, your program will stop for 5 * number of current tasks).
            - If you have preemptive scheduling and priority in place, having long quantums shouldn't have too much of a bad effect since you can change the task whenever (along with decent enough CPU).
        - Interactive jobs can preempt when something like a keyboard interrupt occurs.
    - **Cooperative**
        - Process does not stop running until voluntarily does so.
        - Not used much as processes that hogs CPU / becomes stuck never finishes, effectively killing OS.
    - There are five states any task can be in at a given moment.
        - **TASK_RUNNING**
            - Process is executing / in run-queue.
        - **TASK_INTERRUPTIBLE**
            - Suspended until a condition becomes true.
        - **TASK_UNINTERRUPTIBLE**
            - Same as above, except signals can't wake up this process.
        - **TASK_STOPPED**

            - Execution has stopped.
                - SIGSTOP, SIGSTP, SIGTTIN, SIGTTOU signals can cause process to be in this state.
                - SIGSTOP cannot be ignored or caught.
                - SIGCONT lets process continue.
        - **TASK_ZOMBIE**
            - Execution is terminated, but has to wait until parent receives info about child process.
    - **Run-queue**
        - Array like data structure to place active processes in.
        - Quantum stops, put back into run-queue, and start next process with highest priority.
        - Removed from run-queue when sleep, waiting for a resource, or are terminated.
    - **Priority Array**
        - Two in each run-queue (and 1 run-queue for each CPU), active and expired.
        - Provide O(1) scheduling using bitmaps to find highest priority task in system.
    - **Rescheduling**
        - Task can be rescheduled due to a signal, interrupt, or user calls sched_yield to go to next task.
        - Use timer ticks (each one = 10ms) to be able to change task when given time for it is up.
- **First in first out (FIFO)**
    - Process starts. ends when finished.
- **Round robin scheduling**
    - Each task gets equal quantum, meaning inactive tasks are also given same time as others.
    - Implemented in MP3, simple enough, can optimize it a bit though to ignore inactive tasks.

Discussion Week 10 - MP3.3

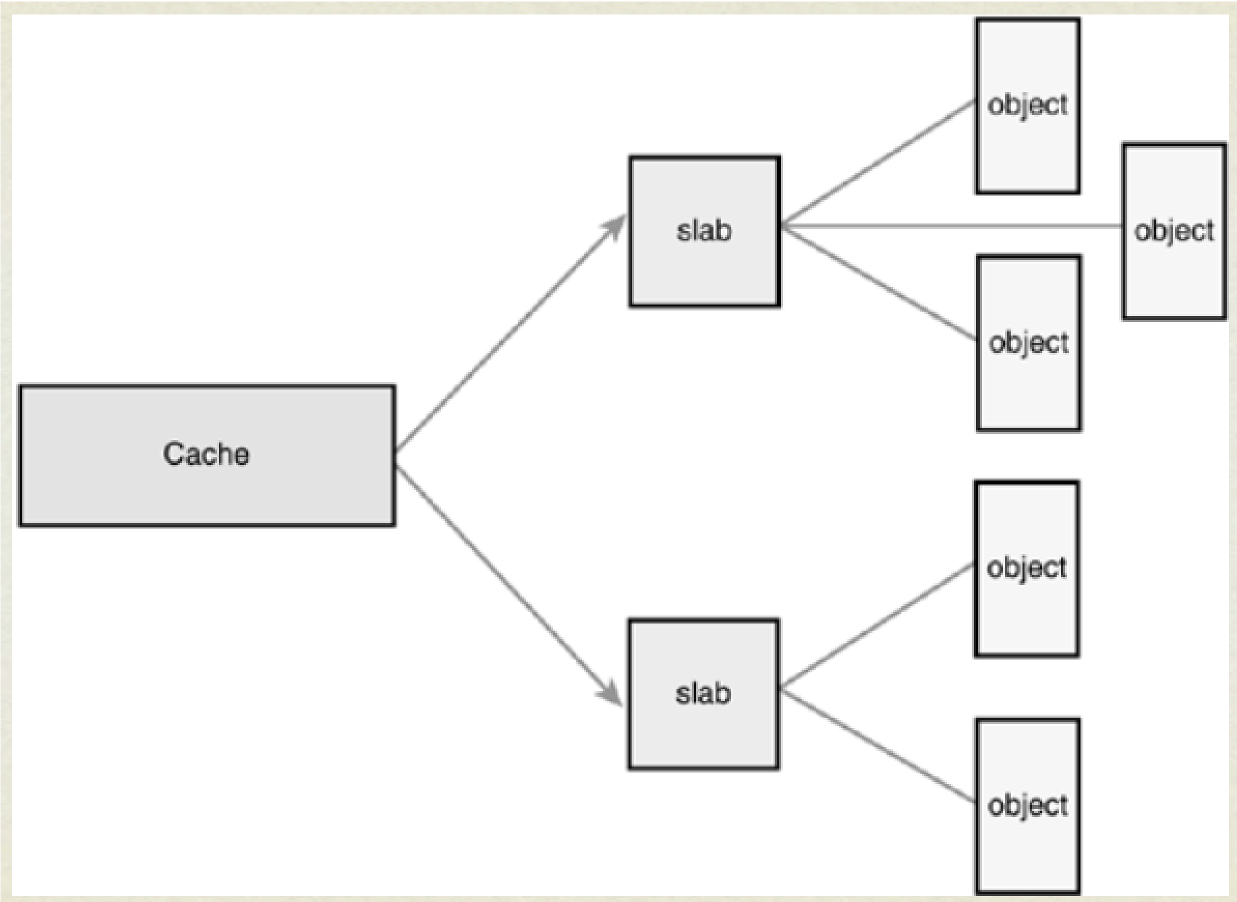
19 - System call linkage

21 - Memory allocation

- **Overview**
  - This lecture focused a lot on how linux handles memory allocation, and introduces the buddy system that can bring your exam grade down (this one's gonna be big).

- **kmalloc** - Used for a few small items (less than a page size type of stuff).
  - `void* kmalloc(size_t size, gfp_t flags);`
    - There are too many flags to list/remember, just know that the flags are to specify types of allocations/memory to allocate, conditions, etc. Can have multiple at same time by ORing.
    - Normal method of allocating memory in kernel
  - **gfp_t** is just unsigned int/long (depending on system).
  - Exponentially-sized slab caches used, contiguous in physical memory

- **slab cache -** Lots of items, and for reusing.
  - Frequent allocations/deallocations.
  - One cache per item type, w/ physical contiguous memory.
  - Constant initialization can slow down performance, instead of re-initializing constantly used objects, slab caches were made.
  - Helps alleviate memory fragmentation by being able to re-allocate certain caches when an object no longer in use.
  - **Constructor function**
    - Only called when new slab needed for an object type
    - `void* kmem_cache_alloc(kmem_cache*, gfp_t flags)`
    - `void* kmem_cache_zalloc(kmem_cache*, gfp_t flags)` (zeroes memory in object).
    - Flags passed to kmalloc iff (if and only if) new slab is allocated.

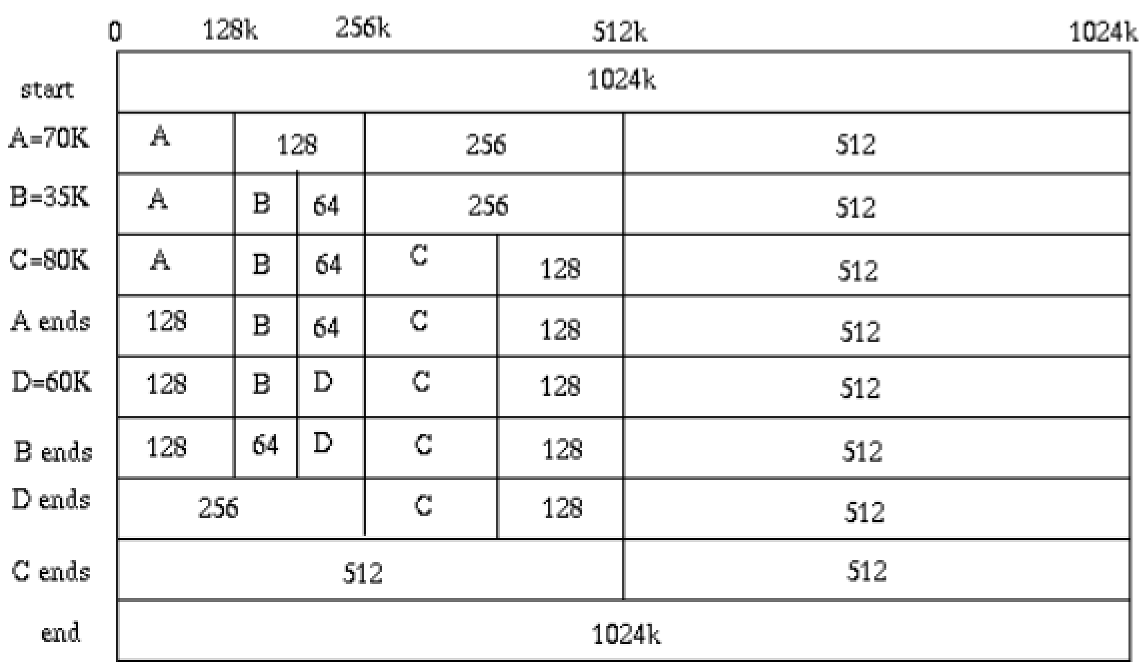


- **free pages** - Big contiguous region of memory.
  - `unsigned long ...page(gfp_t flags) (3 versions).`
  - Multiple of page size (4kB x86), contiguous, same flags as kmalloc.
  - Pages requested are log (base 2) of number of pages requested (3rd version, `__get_free_pages(gfp_t flags, unsigned int order)`.
  - `void free_page(unsigned long)`
  - `void free_pages(unsigned long, int order)`
    - Only free pages you allocate, otherwise corruption can occur since the function doesn't check for you.
- **vmalloc** - Lots of virtual memory (doesn't have to be contiguous though).
  - `void* vmalloc(unsigned long size) (size is in bytes).`
  - If you don't need contiguous memory and need a lot of memory, use vmalloc.
    - Drawback to using this is performance, kmalloc is faster but

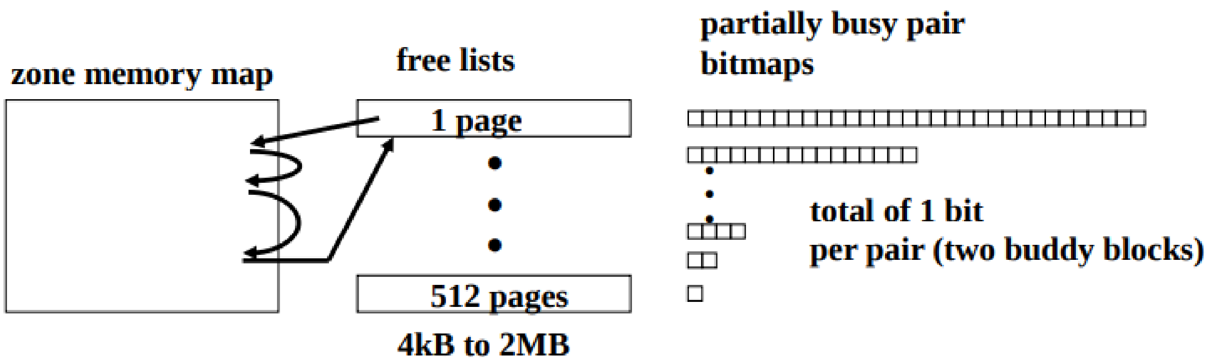
can’t be used for everything.

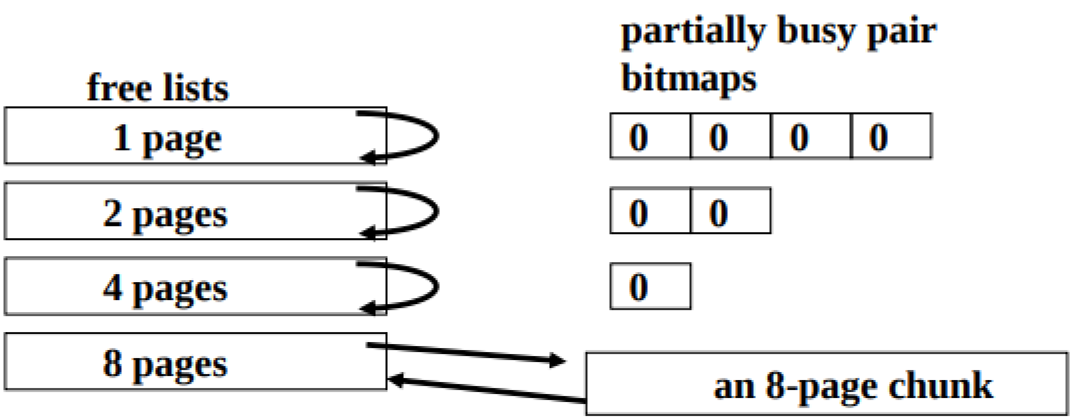
- If you don’t know whether it will go through something that needs physical contiguous memory, don’t use this.

- **Buddy System**
  - **granularity** - Smallest possible size something can be.
  - The many design problems that come with memory allocation (page alignment, contiguous or not, allocation granularity size, rewriting page tables, how to add information to allocated memory) bring the **Buddy System** into play.
  - **High Level Overview**
    - Entire memory space available for allocation treated as a single block, size = power of 2.
      - If requested size > half of initial block, entire block allocated.
      - Else, block is split into two equal ‘buddies’.
        - If requested size > half of new block, new block is allocated.
        - Else, repeat until smallest block >= request size is found and allocated



- Let's look at the slide pictures





- Each buddy system has own set of bitmaps to keep track of blocks that have been allocated.
  - If bit of bitmap is 0, both buddy blocks of pair are free or busy.
  - If bit is 1, one of the blocks is busy.
  - If both blocks are free, just a giant block of combined size.
- Two blocks are considered buddies if:
  - Located in contiguous physical memory.
  - Physical address of first page frame
- Reference: https://www.halolinux.us/kernel-reference/the-buddy-system-algorithm.html

- **Memory Zones**
    - Location of zone memory maps, having information about each type of memory (Note that zones are different depending on architecture, the following is based on x86 32 bit machines).

Zone	Description	Physical Memory
`ZONE_DMA`	DMA-able pages	< 16MB
`ZONE_NORMAL`	Normally addressable pages	16–896MB
`ZONE_HIGHMEM`	Dynamically mapped pages	> 896MB

    - Each zone struct has an array of free area structs.
        - Indexed by page order (0 to 10; 4kB to 4MB)
        - Keeps track of page usage statistics, free area, locks, etc.
    - Each free area struct includes a doubly-linked list of chunks of memory, and a count of chunks in it.

Discussion Week 12 - MP3.4, system calls

- Not much to this discussion actually, just read the slides.

22 - Memory management data structures - process address space

- **Overview**
    - Just going more in depth into material from lecture 21
- **Sharing (is caring)**
    - Task structs may share data with other tasks, including:
        - File pointer array
        - Filesystem info
        - Signal Delivery and handlers
        - Memory map
    - Having shared memory makes passing data from one program to another more efficient.
        - Memory is also shared between multiple threads for programs with multi-threading.
    - `do_fork` has clone flags for different tasks to share certain things like the ones mentioned in the first bullet points.
        - Threading is different from fork since fork creates a copy of the process, while threads in 1 program are all in 1 process.
        - Switching between threads > Switching between tasks made from fork/original due to having to do a full context reload (like TLB flushing) with fork.
- **Memory Maps**
    -

23 - Abstracting devices: block and character devices; device drivers

- **Overview**
  - Focuses on Linux abstraction on device drivers, along with an example driver made be Lumetta (crazy guy)
-

Discussion Week 13 - MP3.5, Scheduling

24 - Driver development process and detailed example

25 - Detailed example of driver development, continued

Discussion Week 14 - MP3.5

26 - Signals: user-level analogue of interrupts, controlling behavior

Glossary - Terms and Definitions