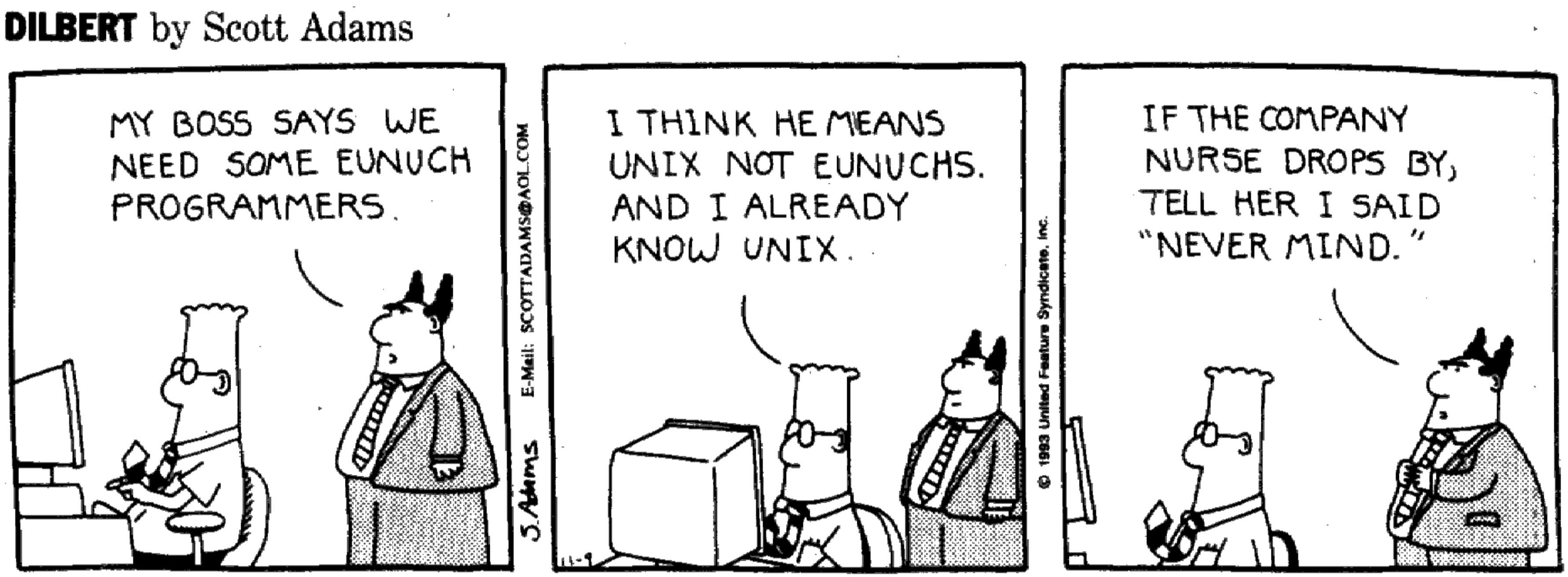
Virtual Machines & the OS Kernel



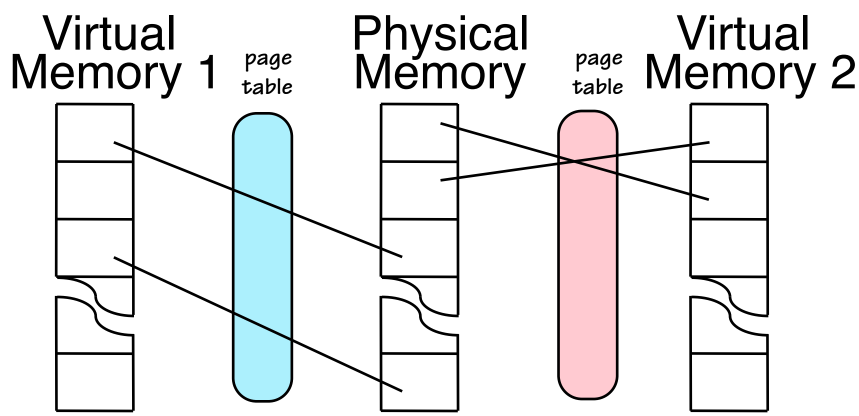
Study Session Tomorrow Night, 12/2 5:30-7:00pm in SN014

Final Exam on Saturday 12/5, 12:00pm-3:00pm in SN014

Final: ~50 questions,

~½ covering materials since 10/29, ~½ comprehensive

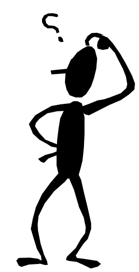
Power of Contexts: Sharing a CPU



Every application can be written as if it has access to all of memory, without considering where other applications reside.

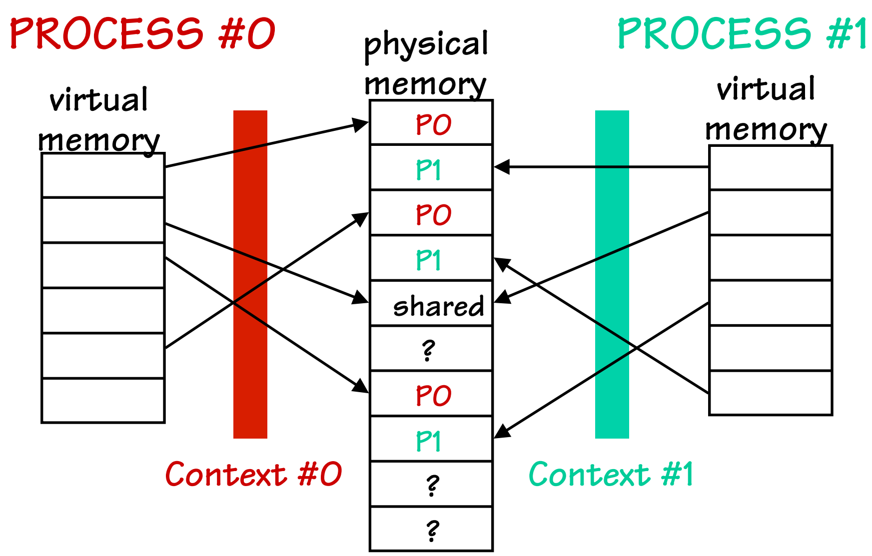
More than Virtual Memory
A VIRTUAL MACHINE

1. TIMESHARING among several programs --
   - Programs alternate running in time slices called "Quanta"
   - Separate context for each program
   - OS loads appropriate context into pagemap when switching among pgms
2. Separate context for OS "Kernel" (eg, interrupt handlers)...
   - "Kernel" vs "User" contexts
   - Switch to Kernel context on interrupt;
   - Switch back on interrupt return.



What is this OS KERNEL thingy?

Building a Virtual Machine

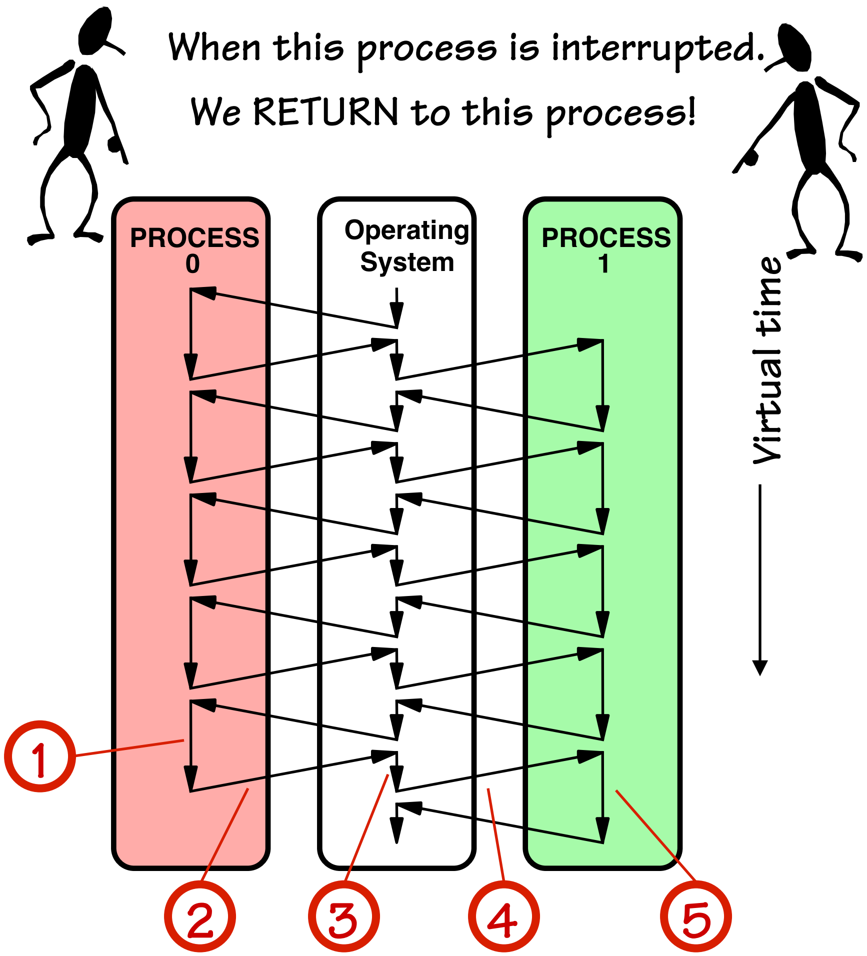


Goal: *give each program its own "VIRTUAL MACHINE"; programs don't "know" about each other…*

Abstraction: *create a* PROCESS, *with its own*

- machine state: $1, …, $31
- context (pagemap)
- stack
- program (w/ possibly shared code)
- virtual I/O devices (console…)

Multiplexing the CPU



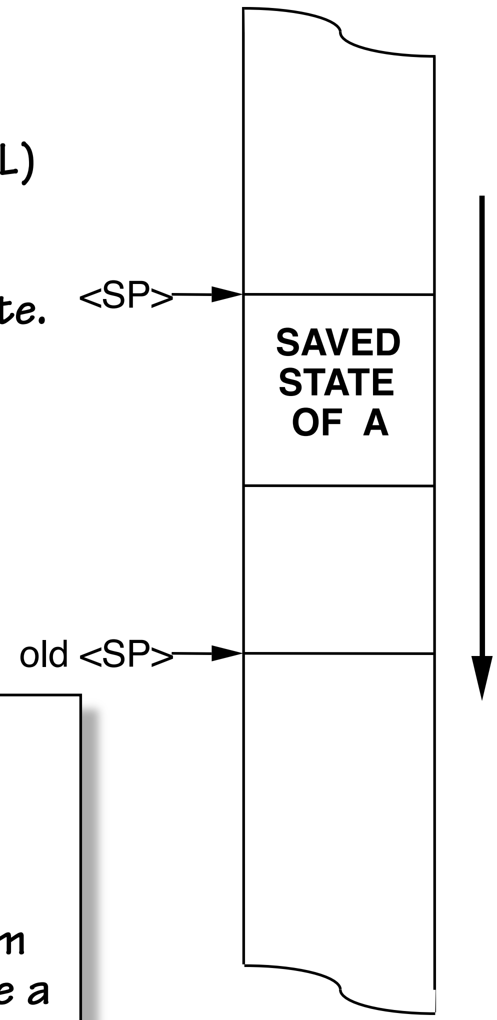
And, vice versa.
Result: Both processes get executed, and no one is the wiser

1. Running in process #0
2. Stop execution of process #0 either because of explicit *yield* or some sort of timer *interrupt*; trap to handler code, saving current PC in $27 ($k1)
3. First: save process #0 state (regs, context) Then: load process #1 state (regs, context)
4. "Return" to process #1: just like a return from other trap handlers (ex. jr $27) but we're returning from a *different* trap than happened in step 2!
5. Running in process #1

Stack-Based Interrupt Handling

BASIC SEQUENCE:

- Program A is running when some EVENT happens.
- PROCESSOR STATE saved on stack (like a procedure CALL)
- The HANDLER program to be run is selected.
- HANDLER state (PC, etc) installed as new processor state.
- HANDLER runs to completion
- State of interrupted program A popped from stack and re-installed, JMP returns control to A
- A continues, unaware of interruption.



CHARACTERISTICS:

- *TRANSPARENT* to interrupted program!
- Handler runs to completion before returning
- Obeys stack discipline: handler can "borrow" stack from interrupted program (and return it unchanged) or use a special handler stack.

miniMIPS Interrupt Handling

Minimal Implementation:

- Check for EVENTS before each instruction fetch.
- On synchronous or asynchronous EVENT:
  - save PC into \$27, (\$k1);
  - INSTALL new PC: 0x80000000 + (0:RESET, 0x40:EXCEPTION, 0x80:INTERRUPT)

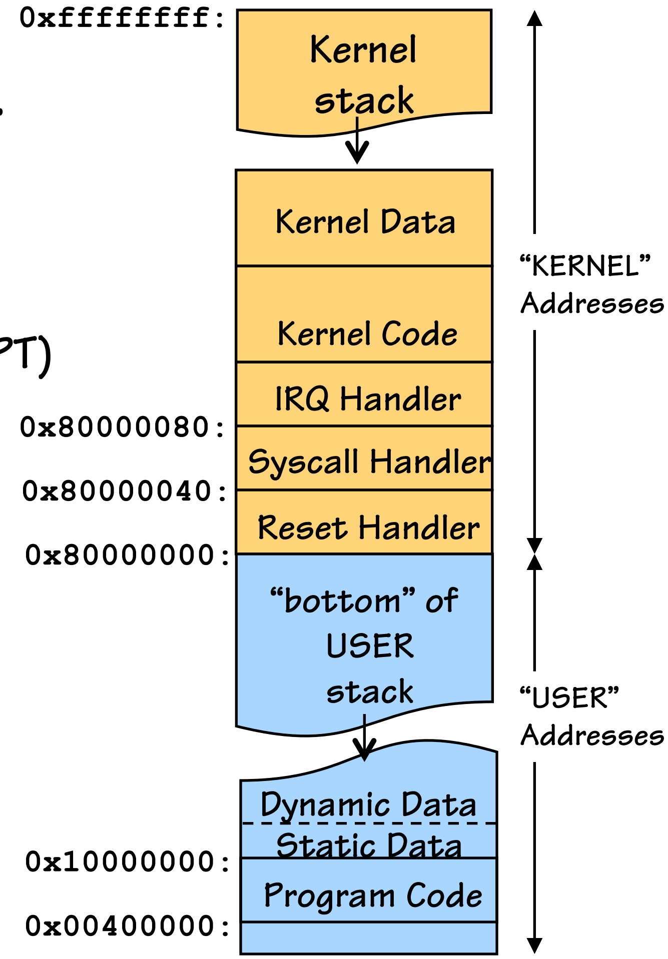
Handler Coding:

- Save state in "User" structure
- Call C procedure to handle the exception
- re-install saved state from "User"
- Return to \$27, (\$k1)

WHERE to find handlers?

miniMIPS Scheme: WIRE IN a high-memory address for each exception handler entry point

Real MIPS alternative: WIRE IN the address of a TABLE of handler addresses ("interrupt vectors")



External (Asynchronous) Interrupts

Example:

System maintains current time of day (TOD) count at a *well-known* memory location that can be accessed by programs. But…this value must be updated periodically in response to clock EVENTs, i.e. signal triggered by 60 Hz clock hardware.

Program A (Application)

- Executes instructions of the user program.
- Doesn't want to know about clock hardware, interrupts, etc!!
- Can access TOD programmatically by examining a well-known memory location.

Clock Handler

- GUTS: Sequence of instructions that increments TOD. Written in C.
- Entry/Exit sequences save & restore interrupted state, call the C handler. Written as assembler "stubs".

Interrupt Handler Coding

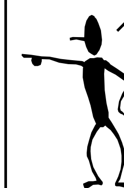
```
long TimeOfDay;
struct Mstate { int R1,R2,…,R31 } User;

/* Executed 60 times/sec */
Clock_Handler(){
   TimeOfDay = TimeOfDay + 1;
}
```

Handler
(written in C)

```
Clock_h:
    lui   $k0,(User>>16)        # make $k0 point to
    ori   $k0,$k0,User          # "User" struct
    sw    $1,0($k0)             # Save registers of
    sw    $2,4($k0)             # interrupted
    ...                         # application pgm...
    sw    $31,124($k0)          # program
    add   $sp,$0,KStack         # Use KERNEL stack
    jal   Clock_Handler         # call handler
    lw    $1,0($k0)             # Restore saved
    lw    $2,4($k0)             # registers
    ...
    lw    $31,124($k0)
    jr    $k1                   # Return to app.
```

Recall $k0 ($26) and $k1 ($27) are reserved for use by the kernel, and that the address of the next instruction before the exception is saved in $k1 ($27)



"Interrupt stub"
(written in assy.)

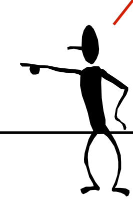
Time-Sharing the CPU

We can make a small modification to our clock handler implement time sharing.

```
long TimeOfDay;
struct Mstate { int R1,R2,…,R31 } User;

/* Executed 60 times/sec */
Clock_Handler(){
    TimeOfDay = TimeOfDay + 1;
    if (TimeOfDay % QUANTUM == 0) Scheduler();
}
```

Our clock handler calls another function



A Quantum is that smallest time-interval that we allocate to a process, typically this might be 50 to 100 mS. (Actually, most OS Kernels vary this number based on the processes priority).

Simple Timesharing Scheduler

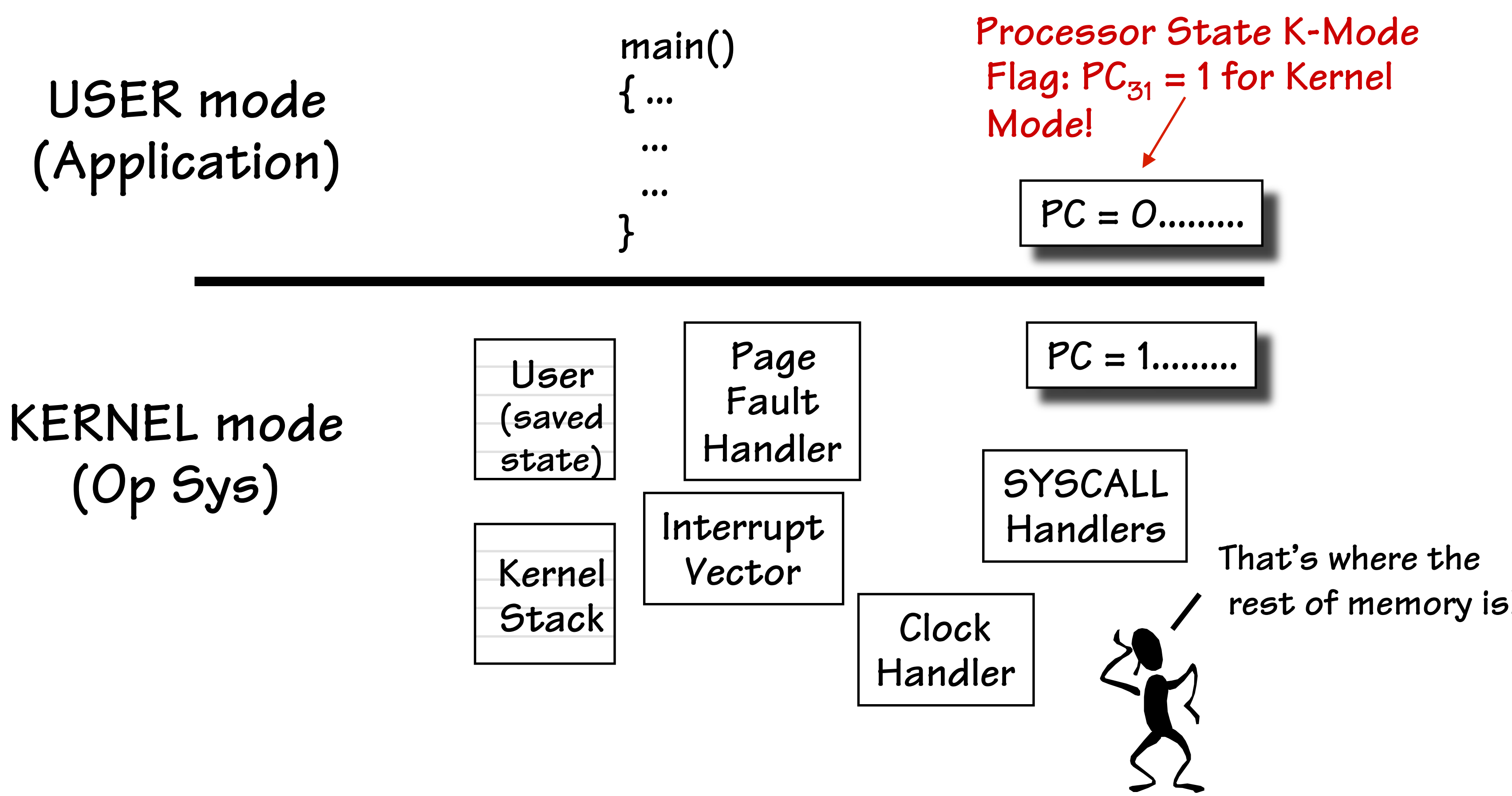
```
long TimeOfDay;
struct Mstate { int R1,R2,…,R31 } User;
.
.
.
struct PCB {                        /* A Process Control Block */
   struct MState State;                  /* Processor state   */
   Context PageMap;                      /* VM Map for proc   */
   int DPYNum;                           /* Console number    */
} ProcTbl[N];                            /* one per process   */

int Cur;                                 /* "Active" process  */

Scheduler() {
   ProcTbl[Cur].State = User;            /* Save Cur state */
   Cur = (Cur+1)%N;                      /* Incr mod N     */
   User = ProcTbl[Cur].State;            /* Install for next User */
}
```

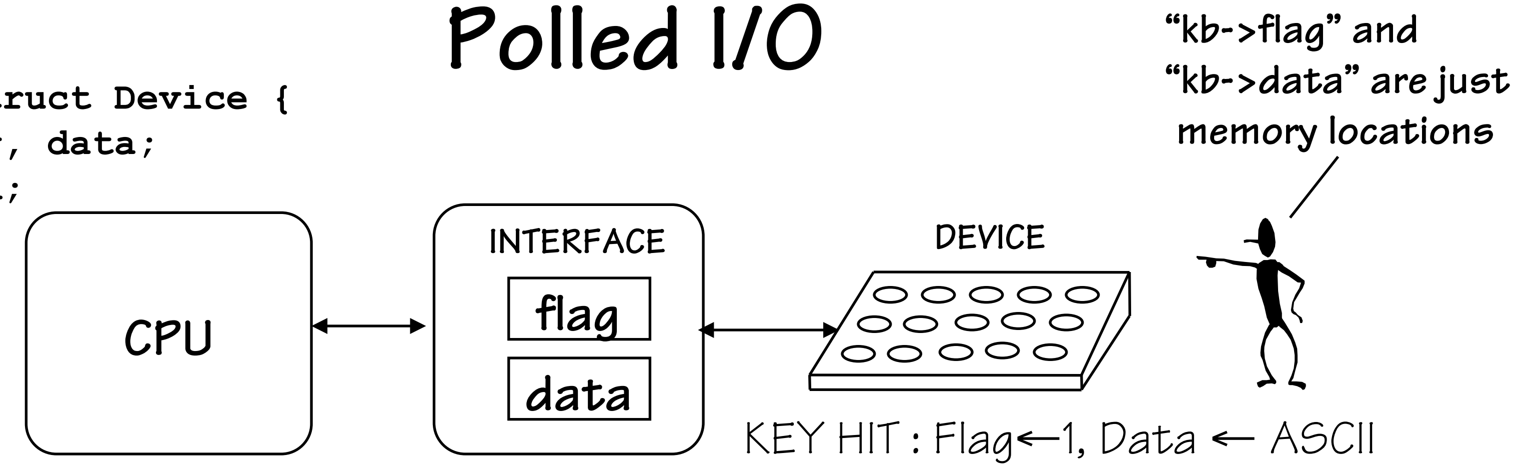
Avoiding Re-Entrance

Handlers which are interruptable are called *RE-ENTRANT*, and pose special problems... miniMIPs, like many systems, disallows reentrant interrupts! Mechanism: Interrupts are disabled in “Kernel Mode” (PC >= 0x80000000):



Polled I/O

```
Assumes:
  typedef struct Device {
    int flag, data;
  } Keyboard;
```



Application code deals directly with I/O (eg, by busy-waiting):

```
loop: lw   $t0, flag($t1)  # $t1 points to a
      beq  $t0,$0,loop     # keyboard structure
      lw   $t0, data($t1)  # process keystroke
      ...
```

PROBLEMS:

- Wastes (physical) CPU while busy-waiting

  (FIX: Multiprocessing, codestripping, etc)
- Poor system modularity: running pgm MUST know about ALL devices.
- Uses up CPU cycles even when device is idle!

Interrupt-driven I/O

OPERATION: NO attention to Keyboard during normal operation

- on key strike: hardware asserts IRQ to request interrupt
- USER program interrupted, PC+4 saved in $k1
- state of USER program saved on KERNEL stack;
- KeyboardHandler (a "device driver") is invoked, runs to completion;
- state of USER program restored; program resumes.

That's how data gets into the buffer. How does it get out?

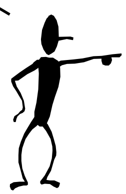
TRANSPARENT to USER program.

Keyboard Interrupt Handler (in O.S. KERNEL):

```
struct Device {
  int flag, data;
} Keyboard;
int inptr=0, outptr = 0;
int Buffer[100];

KeyboardHandler(struct Mstate *s) {
  Buffer[inptr] = Keyboard.data;
  inptr = (inptr + 1) % 100;
}
```

Each keyboard has an associated buffer



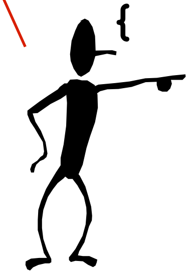
ReadKey SYSCALL: Attempt #1

A *system call* (syscall) is an instruction that transfers control to the kernel so it can satisfy some user request. Kernel returns to user program when request is complete.

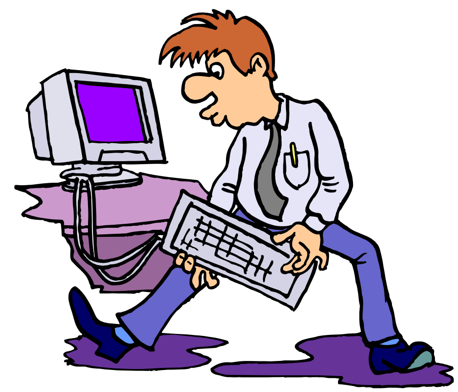
(Can be implemented as a "synchronous" interrupt, a.k.a. Illop)

First draft of a ReadKey syscall handler: returns next keystroke to user

Each process has an index to a keyboard



```
ReadKEY_h()
{
    int kbdnum = ProcTbl[Cur].DPYNum;
    while (BufferEmpty(kbdnum)) {
        /* busy wait loop */
    }
    User.R2 = ReadInputBuffer(kbdnum);
}
```



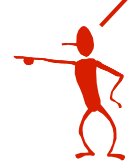
Problem: Can't interrupt code running in the supervisor mode… so the buffer never gets filled.

ReadKey SYSCALL: Attempt #2

A keyboard SYSCALL handler
(slightly modified, eg to support a Virtual Keyboard):

```
ReadKEY_h()
{
    int kbdnum = ProcTbl[Cur].DPYNum;
    if (BufferEmpty(kbdnum)) {
        User.R27 = User.R27 - 4;
    } else
        User.R2 = ReadInputBuffer(kbdnum);
}
```

That's a funny way to write a loop



> Problem: The process just wastes its time-slice waiting for some one to hit a key...

ReadKey SYSCALL: Attempt #3

BETTER: On I/O wait, YIELD remainder of time slot (quantum):

```
ReadKEY_h()
{
    int kbdnum = ProcTbl[Cur].DPYNum;
    if (BufferEmpty(kbdnum)) {
        User.R27 = User.R27 - 4;
        Scheduler( );
    } else
        User.R2 = ReadInputBuffer(kbdnum);
}
```

RESULT: Better CPU utilization!!

FALLACY:

Timesharing causes a CPUs to be less efficient

Sophisticated Scheduling

To improve efficiency further, we can avoid scheduling processes in prolonged I/O wait:

- Processes can be in ACTIVE or WAITING ("sleeping") states;
- Scheduler cycles among ACTIVE PROCESSES only;
- Active process moves to WAITING status when it tries to read a character and buffer is empty;
- Waiting processes each contain a code (eg, in PCB) designating what they are waiting for (eg, keyboard N);
- Device interrupts (eg, on keyboard N) move any processes waiting on that device to ACTIVE state.

UNIX kernel utilities:

- sleep(reason) - Puts CurProc to sleep. "reason" is an arbitrary value providing a condition for reactivation.
- wakeup(reason) - Makes active any and all processes in sleep(reason).

ReadKey SYSCALL: Attempt #4

```
ReadKEY_h() {
  ...
  if (BufferEmpty(kbdnum)) {
    User.R27 = User.R27 - 4;
    sleep(kbdnum);
  ...
}
```

SYSCALL from application

```
sleep(status s) {
  ProcTbl[Cur].status = s;
  Scheduler()
}
```

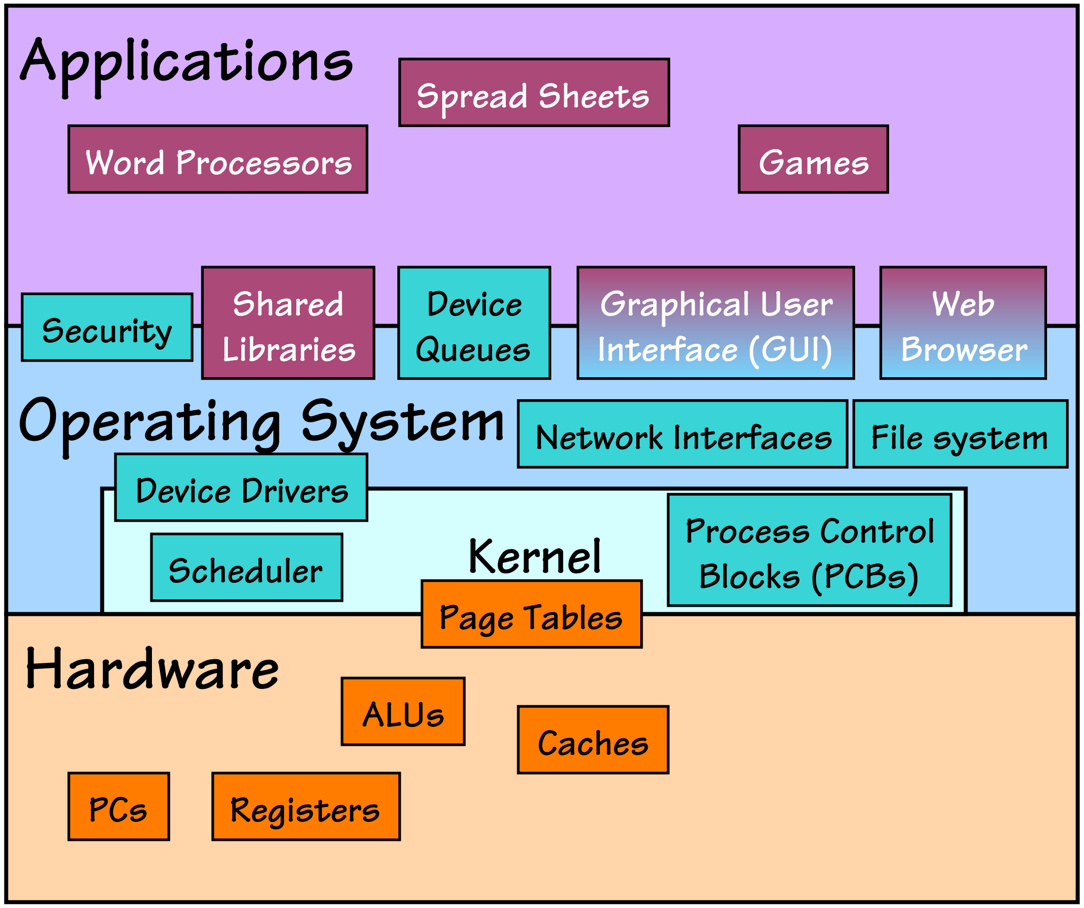
```
Scheduler() {
  ...
  while (ProcTbl[i].status != 0) {
    i = (i+1)%N;
  }
  ...
}
```

```
wakeup(status s) {
  for (i = 0; i < N; i += 1) {
    if (ProcTbl[i].status == s)
      PCB[i].status = 0;
  }
}
```

```
KEYhit_h() {
  ...
    WriteBuffer(kbdnum, key)
    wakeup(kbdnum);
  ...
}
```

INTERRUPT from Keyboard n

A "Typical" OS layer cake

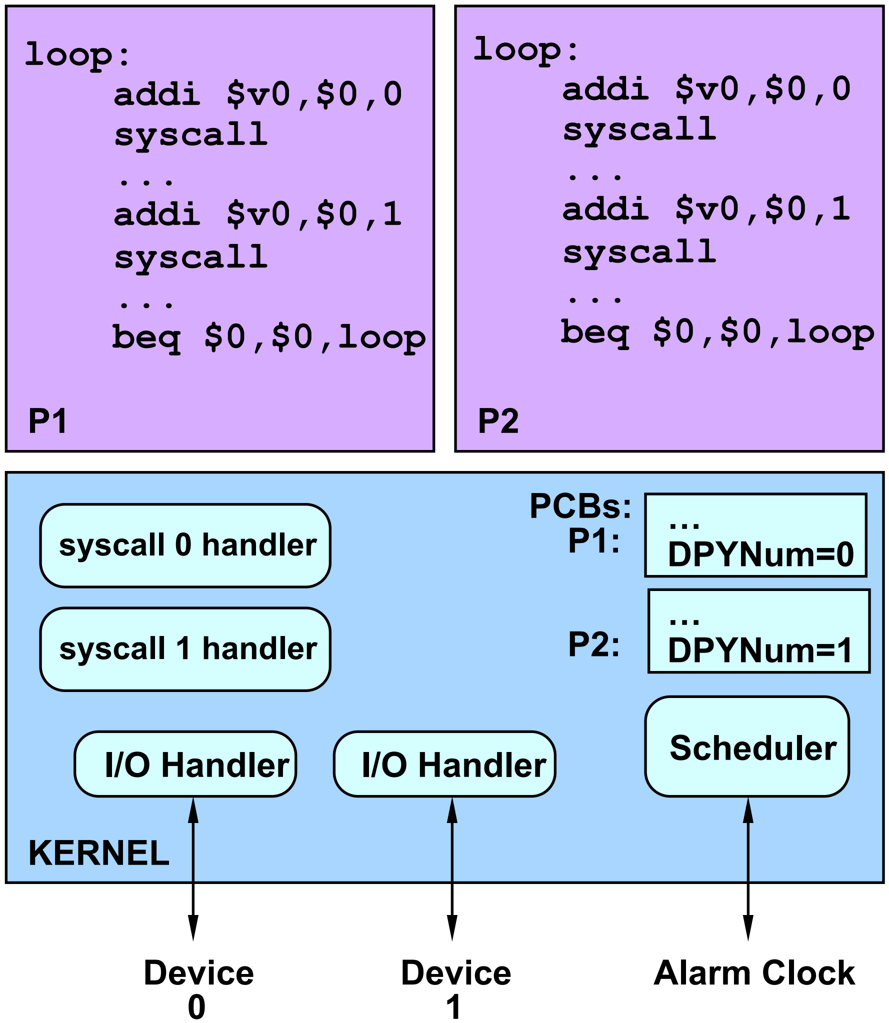


An OS is the Glue that holds a computer together.

- Mediates between competing requests
- Resolves names/bindings
- Maintains order/fairness

KERNEL - a RESIDENT portion of the O/S that handles the most common and fundamental service requests.

A "Thin Slice" of OS organization



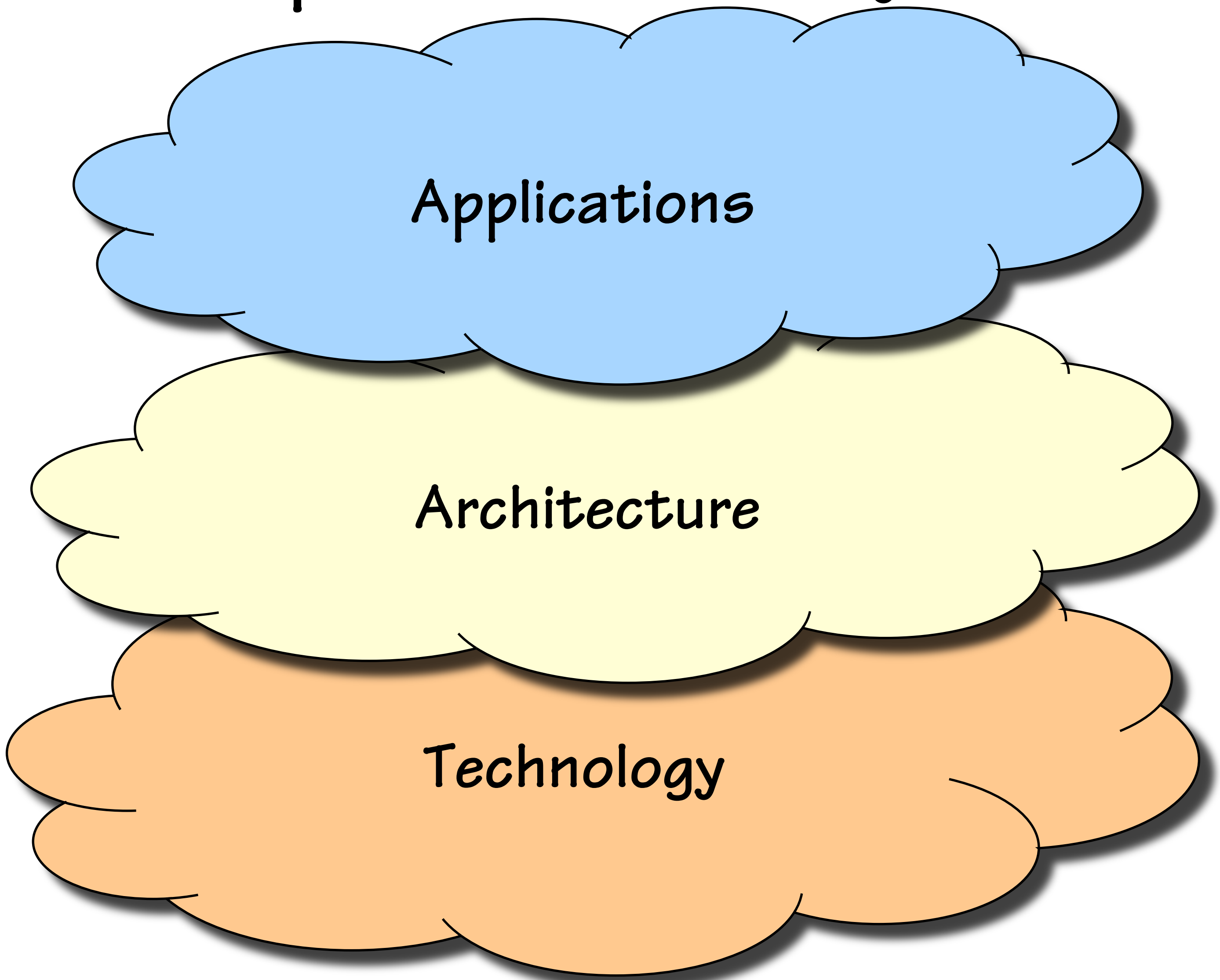
"Applications" are quasi-parallel "PROCESSES" on "VIRTUAL MACHINES", each with:

- CONTEXT (virtual address space)
- Virtual I/O devices

O.S. KERNEL has:

- Interrupt handlers
- SYSCALL (trap) handlers
- Scheduler
- PCB structures containing the state of inactive processes

411 was an introduction to Computer Science "Systems"



Systems: 2015

Tablet computing, Client computing (Chrome, HTML 5), Cloud computing, E-commerce, Android, Arduino, Video Games, Wireless, Streaming Media, …

Von Neumann Architectures, Multi-Core
Procedures, Objects, Processes
(hidden: pipelining, superscalar, SIMD, …)

CMOS: 4.3 billion transistors/chip
(2014 15-core Xeon Ivy Bridge-EX)
10x transistors every 5 years
1% performance/week!

Systems 2025?

Natural language/speech interfaces, Virtual Assistants, Computer vision, systems that "learn" rather than require programming, field-programmable microbes, direct brain interfaces, human augmentation …

Von Neumann Architecture???
1024-way multicore?
Neural Nets?
How will we program them?

CMOS:
450 billion transistors
20 GHz clock

Computer Science is the fastest changing field in the history of mankind!

To predict his stuff, follow the news and think creatively

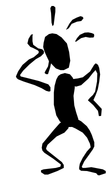
This is the hard part.

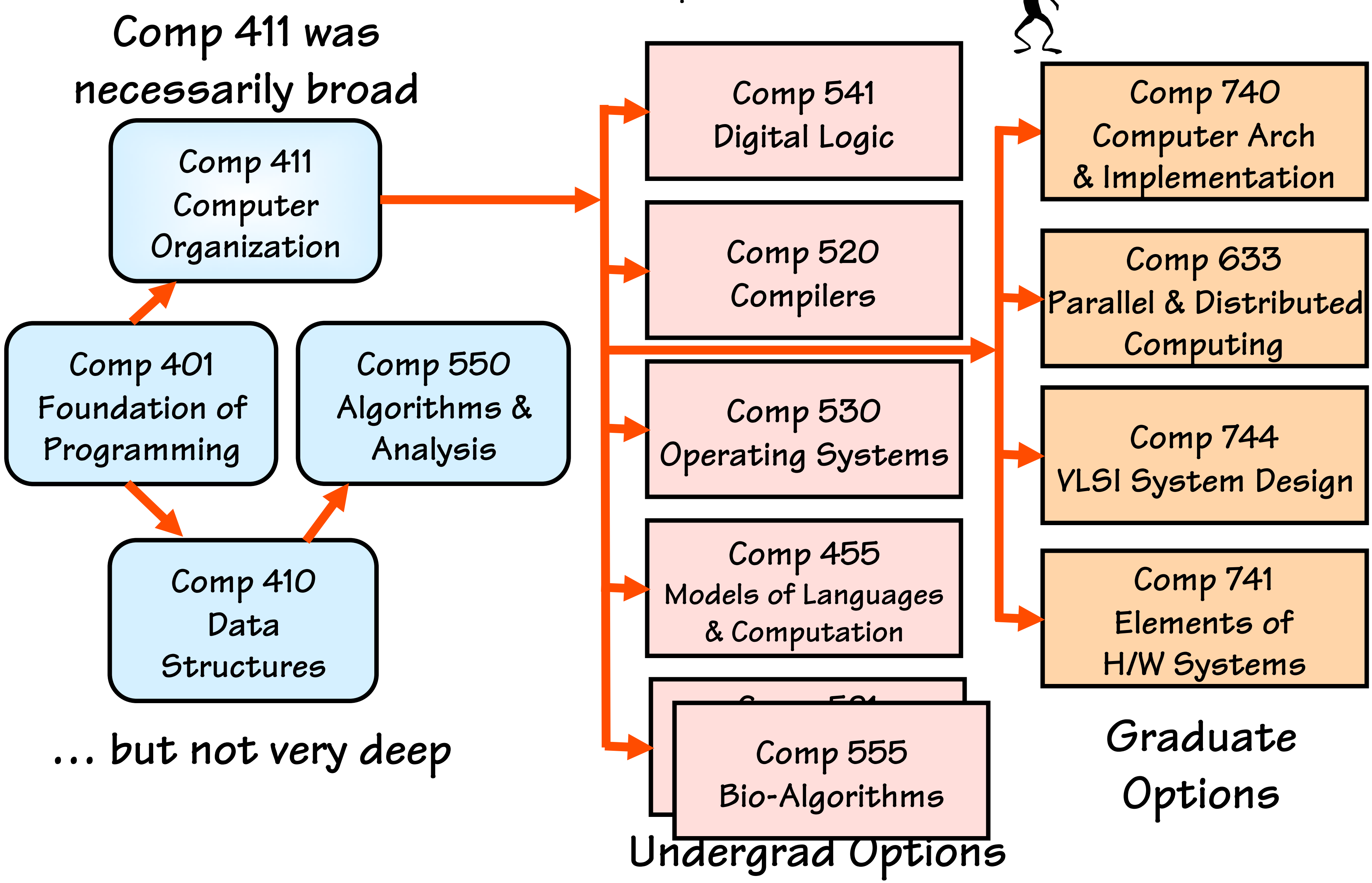
This stuff is relatively easy to predict.

What's next?

Some options…

Should I take or avoid these?





THE END!

Computers are tools
that are designed to realize
a programmer's dreams.

The only problem
with Haiku is that you just
get started and then…