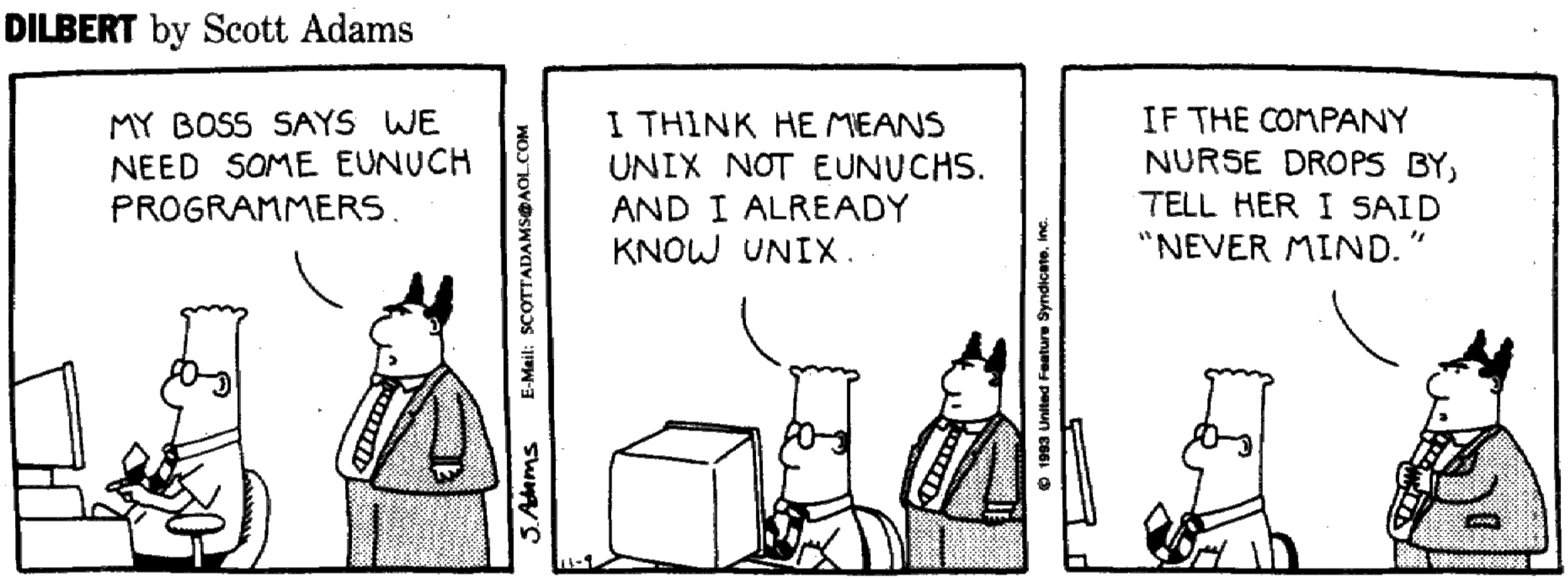
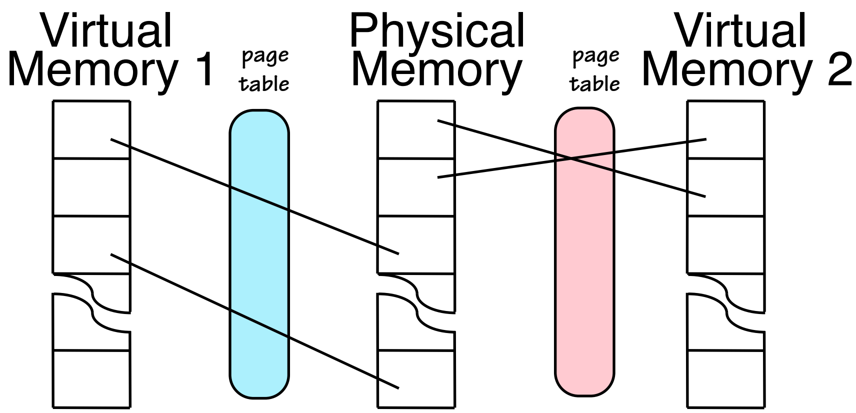
Virtual Machines & the OS Kernel



Not in the book!

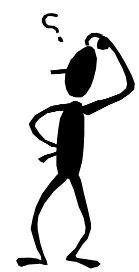
Power of Contexts: Sharing a CPU



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

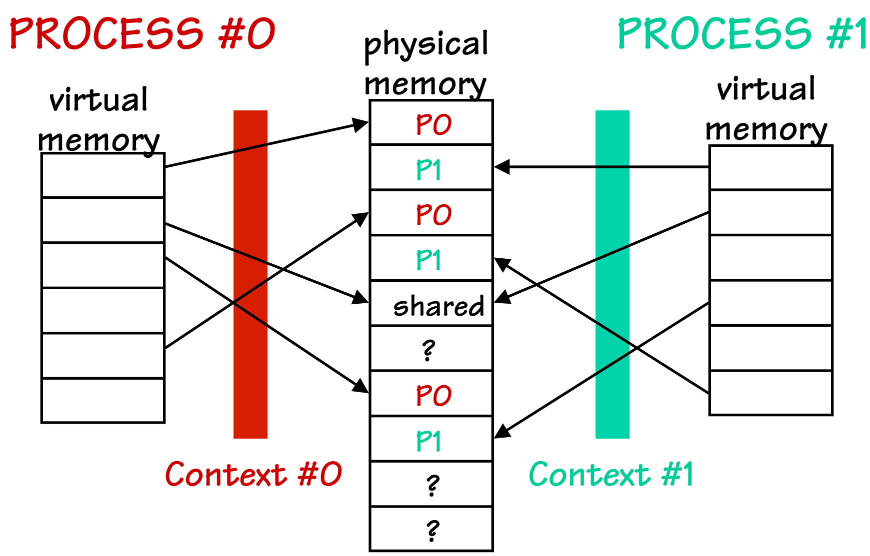
More than Virtual Memory
A VIRTUAL MACHINE

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

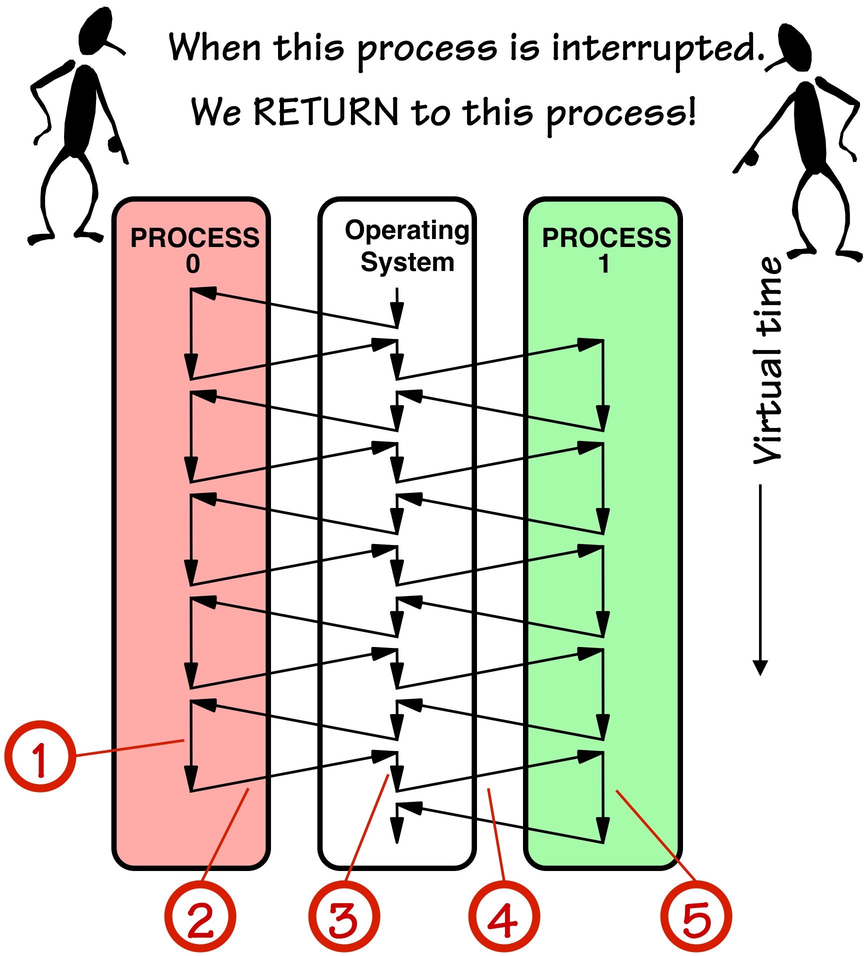


Goal: give each program its own "VIRTUAL MACHINE"; programs don't "know" about each other…

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



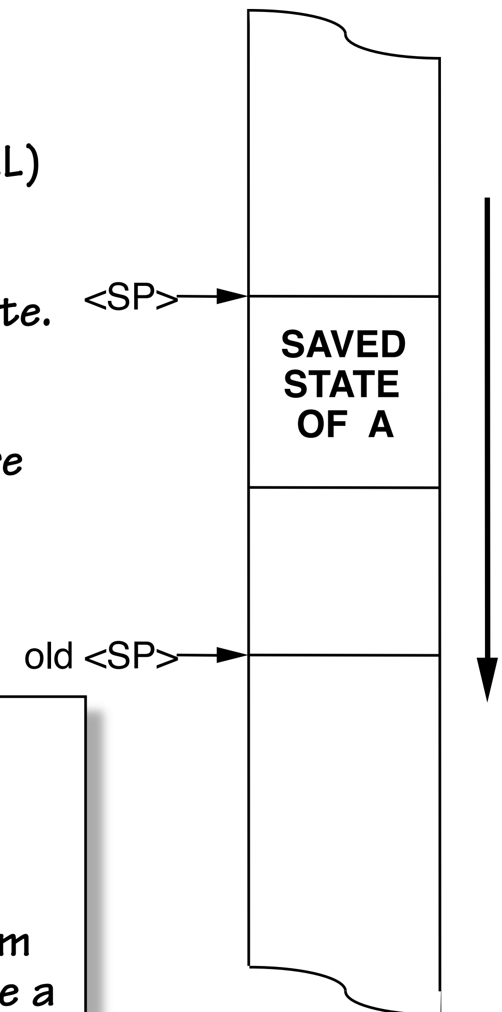
And, vice versa.
Result: Both processes get executed, and no one is the wiser

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 EVENT j:
  - save PC into $27, ($k1);
  - INSTALL 0x80000000 + j*40 as new PC.

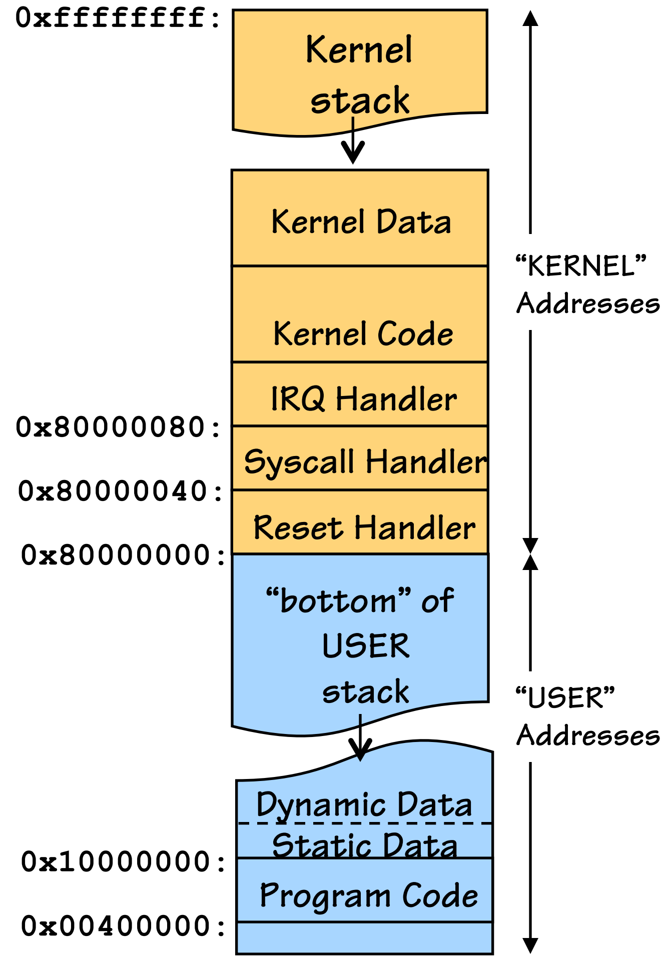
Handler Coding:

- 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 incorporate TOD into results by examining 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.
```

"Interrupt stub"
(written in assy.)

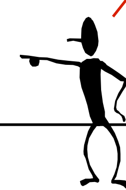
Time-Sharing the CPU

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;
.
.                        (PCB = Process Control Block)
.
struct PCB {
   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):

Processor State K-Mode Flag: PC_{31} = 1 for Kernel Mode!

USER mode (Application)

```
main()
{ ...
  ...
  ...
}
```

PC = 0.........

KERNEL mode (Op Sys)

PC = 1.........

User (saved state)

Page Fault Handler

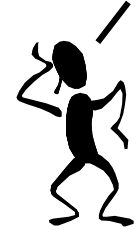
Kernel Stack

Interrupt Vector

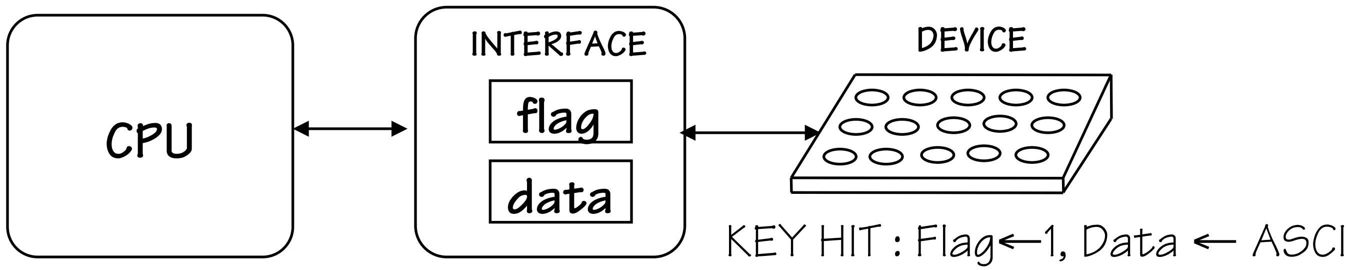
SYSCALL Handlers

Clock Handler

That's where the rest of memory is!



Polled I/O



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

```
loop: lw   $t0, flag($t1)  # $t1 points to
      beq  $t0,$0,loop     # device 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

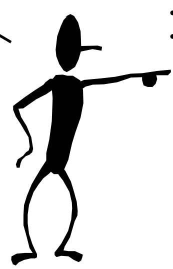
- on key strike: hardware asserts IRQ to request interrupt
- USER program interrupted, PC+4 saved in $k1
- state of USER program saved on KERNEL stack;
- KeyboardHandler (a "device driver") is invoked, runs to completion;
- state of USER program restored; program resumes.

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

TRANSPARENT to USER program.

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

Each keyboard has an associated buffer



```
struct Device {
  char flag, data;
} Keyboard;

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

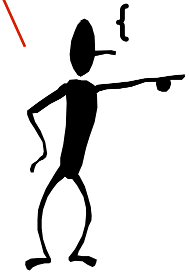
ReadKey SYSCALL: Attempt #1

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.

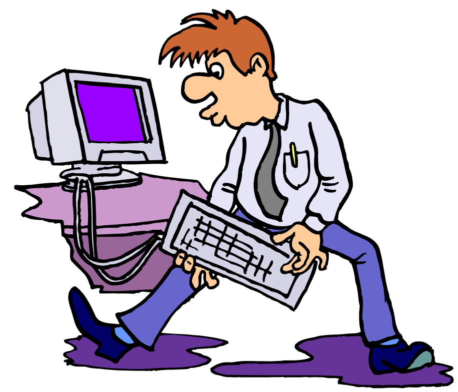
(Can be implemented as a "synchronous" interrupt, a.k.a. Illop)

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 binary value giving a condition for reactivation.
- wakeup(reason) - Makes active any process 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()
}
```

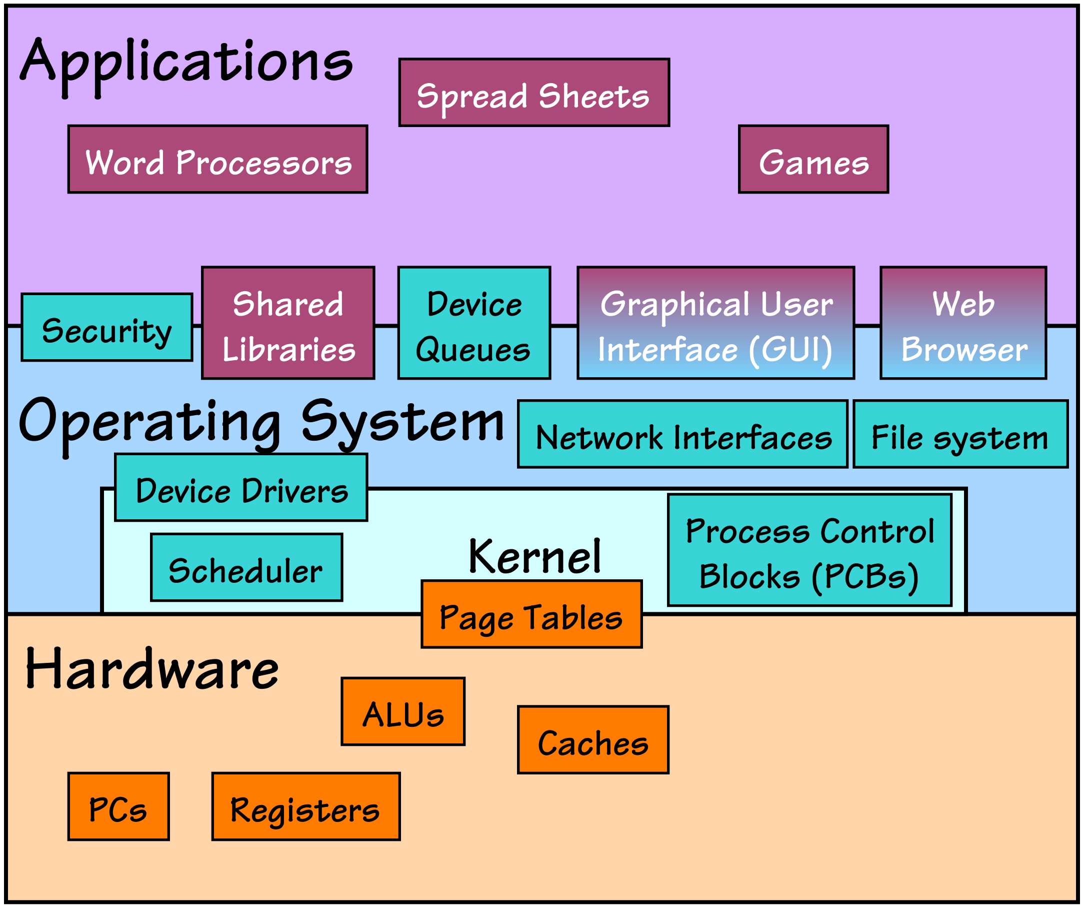
```
Scheduler() {
  ...
  while (ProcTbl[i].status != 0) {
    i = (i+1)%N;
  }
  ...
}
```

```
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

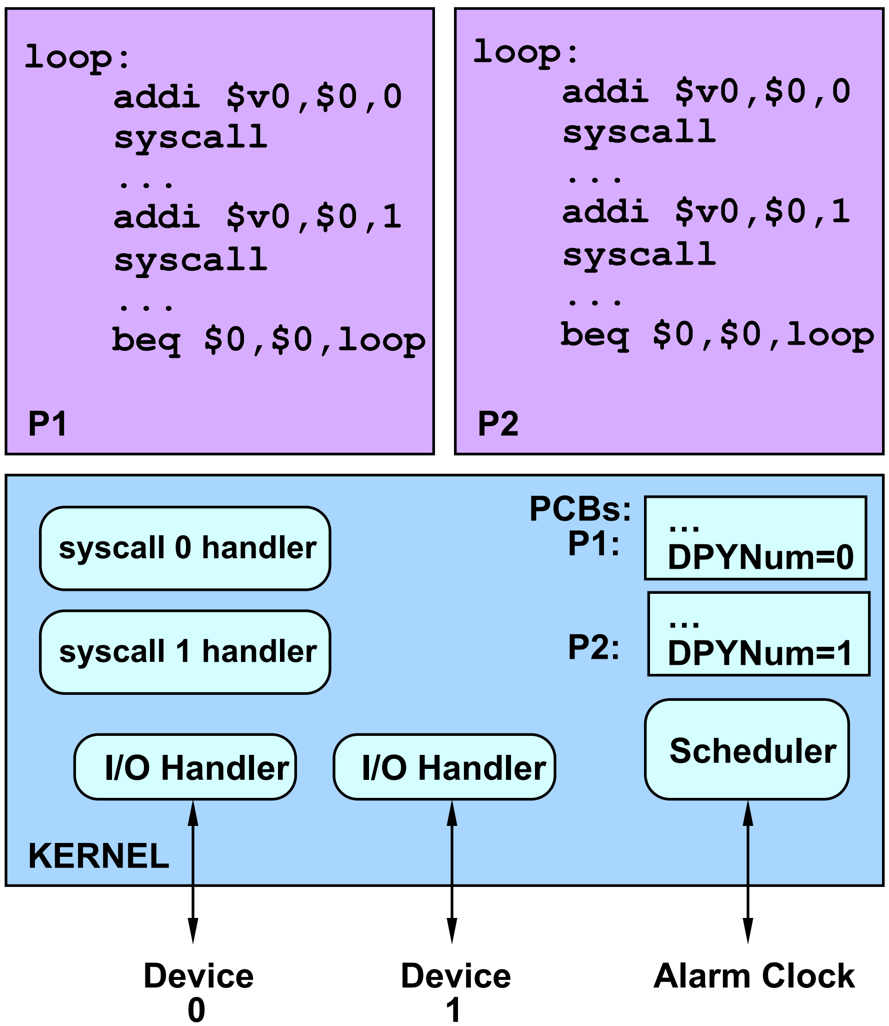


An OS is the Glue that holds a computer together.

- 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