CS162
Operating Systems and Systems Programming
Lecture 3

Processes (con't), Fork, System Calls

January 28th, 2020

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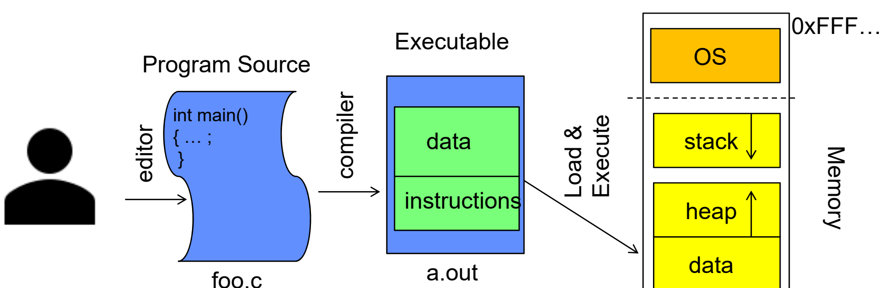
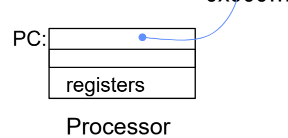
Recall: Four Fundamental OS Concepts

- **Thread: Execution Context**
  - Fully describes program state
  - Program Counter, Registers, Execution Flags, Stack
- **Address space** (with or w/o **translation**)
  - Set of memory addresses accessible to program (for read or write)
  - May be distinct from memory space of the physical machine (in which case programs operate in a virtual address space)
- **Process: an instance of a running program**
  - Protected Address Space + One or more Threads
- **Dual mode operation / Protection**
  - Only the "system" has the ability to access certain resources
  - Combined with translation, isolates programs from each other and the OS from programs

Recall: OS Bottom Line: Run Programs

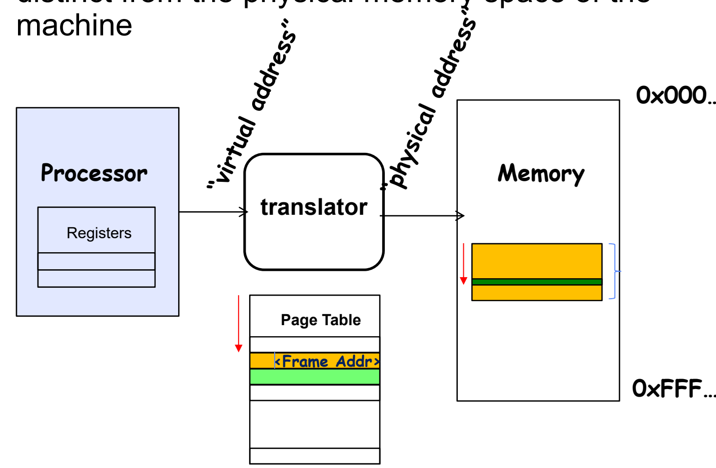




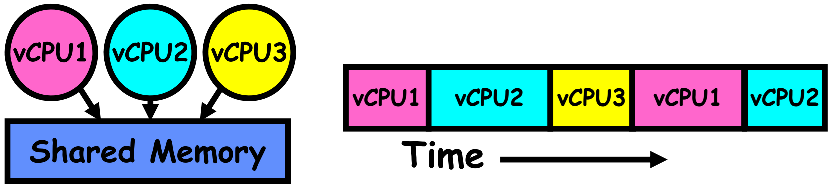
- Create OS "PCB", address space, stack and heap
- Load instruction and data segments of executable file into memory
- "Transfer control to program"
- Provide services to program
- While protecting OS and program

Recall: Protected Address Space

- Program operates in an address space that is distinct from the physical memory space of the machine



Recall: give the illusion of multiple processors?

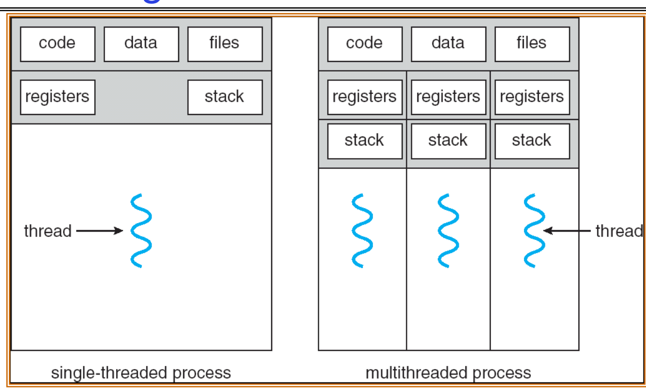


- Assume a single processor. How do we provide the *illusion* of multiple processors?
  - Multiplex in time!
  - Multiple "virtual CPUs"
- Each virtual "CPU" needs a structure to hold:
  - Program Counter (PC), Stack Pointer (SP)
  - Registers (Integer, Floating point, others…?)
- How switch from one virtual CPU to the next?
  - Save PC, SP, and registers in current state block
  - Load PC, SP, and registers from new state block
- What triggers switch?
  - Timer, voluntary yield, I/O, other things

Recall: The Process

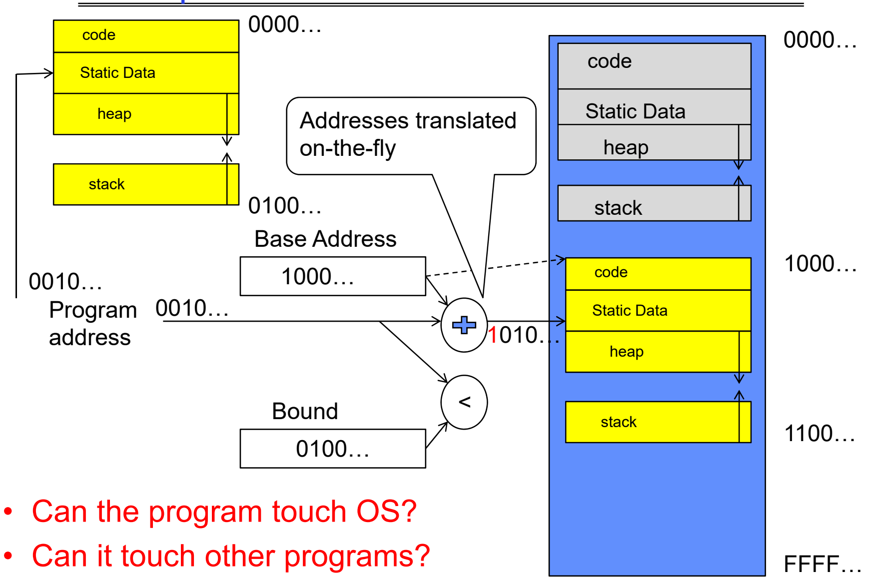
- Definition: **execution environment with restricted rights**
  - Address Space with One or More Threads
    - » *Page table per process!*
  - Owns memory (mapped pages)
  - Owns file descriptors, file system context, …
  - Encapsulates one or more threads sharing process resources
- Application program executes as a process
  - Complex applications can fork/exec child processes [later]
- Why processes?
  - Protected from each other. OS Protected from them.
  - Execute concurrently [trade-offs with threads? later]
  - Basic unit OS deals with

Recall: Single and Multithreaded Processes



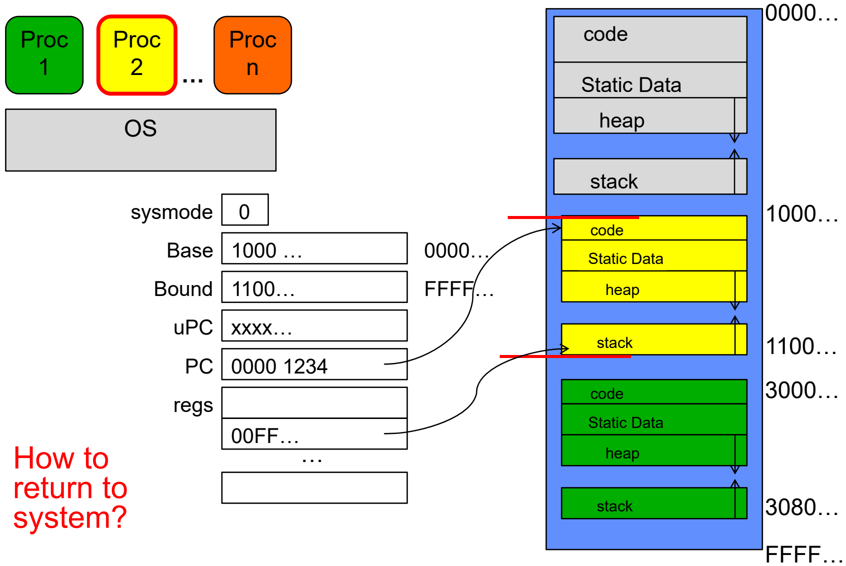
- Threads encapsulate concurrency: "Active" component
- Address spaces encapsulate protection: "Passive" part
  - Keeps buggy program from trashing the system
- Why have multiple threads per address space?

Recall: Simple address translation with Base and Bound



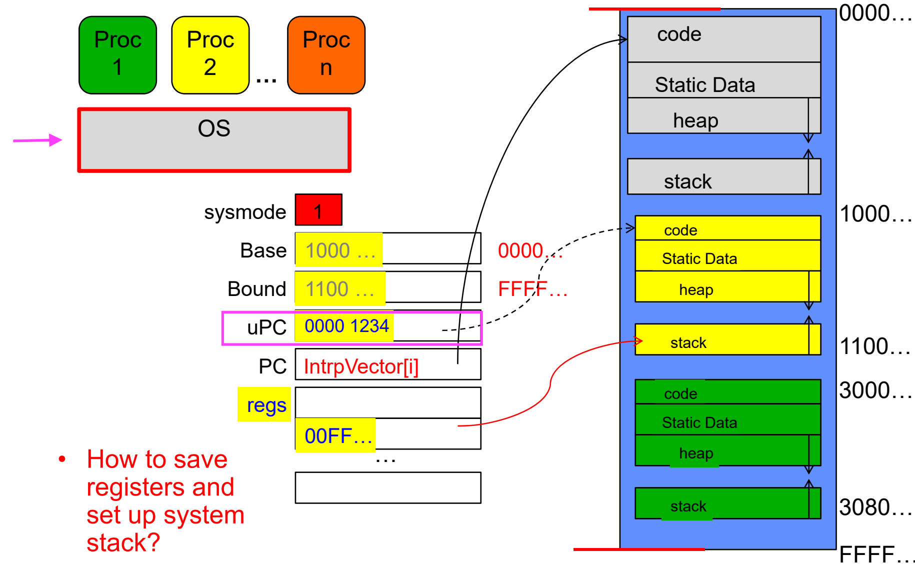
- Can the program touch OS?
- Can it touch other programs?

Simple B&B: User => Kernel



- How to return to system?

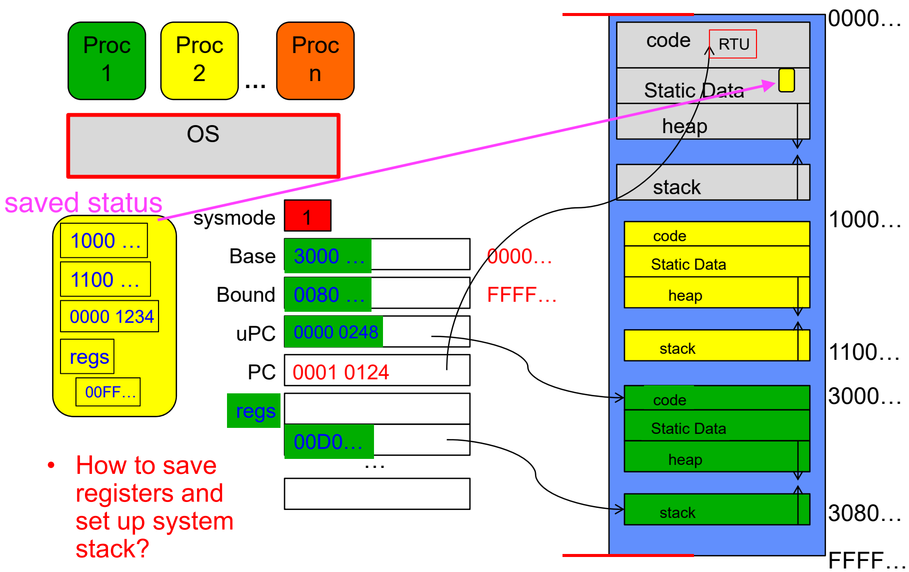
Simple B&B: Interrupt



- How to save registers and set up system stack?

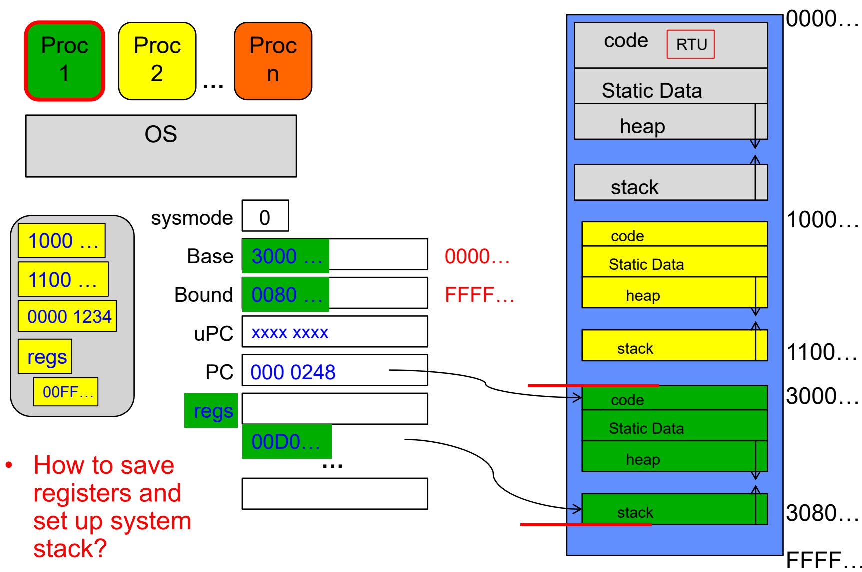
IntrpVector decides where to go in the OS. Timer interrupt handler says ok yellow is done, let's do something else.

Simple B&B: Switch User Process



- How to save registers and set up system stack?

Simple B&B: "resume"



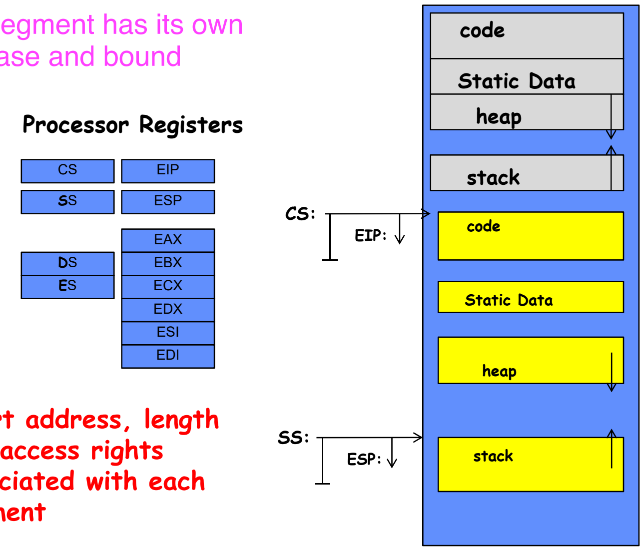
- How to save registers and set up system stack?

Is Branch and Bound a Good-Enough Protection Mechanism?

- NO: Too simplistic for real systems
- Inflexible/Wasteful:
  – Must dedicate physical memory for *potential* future use
  – (Think stack and heap!)
- Fragmentation:
  – Kernel has to somehow fit whole processes into contiguous block of memory
  – After a while, memory becomes fragmented!
- Sharing:
  – Very hard to share any data between Processes or between Process and Kernel
  – Need to communicate indirectly through the kernel…

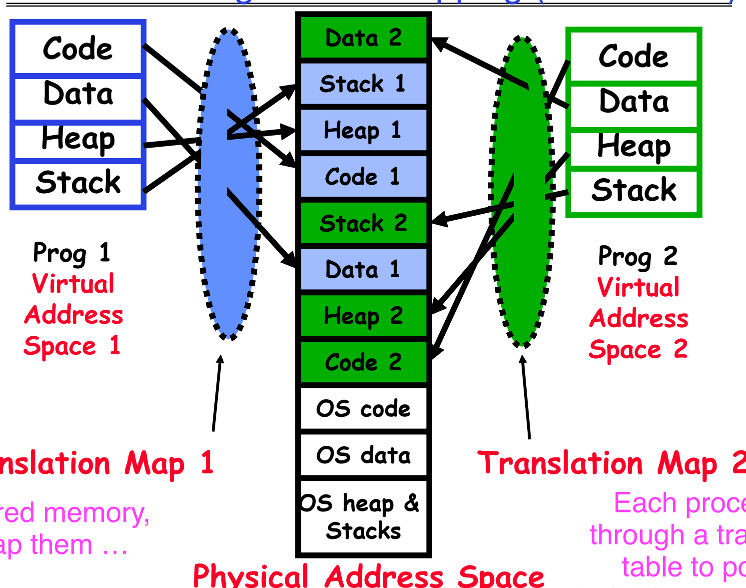
Better: x86 – segments and stacks

each segment has its own base and bound



Start address, length and access rights associated with each segment

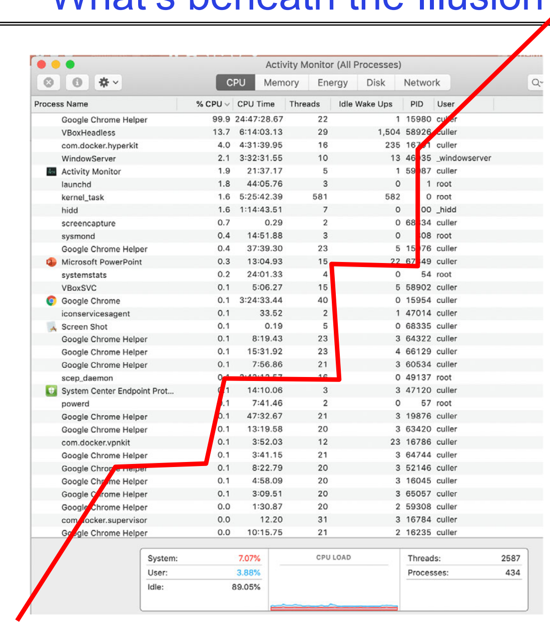
Alternative: Page Table Mapping (More soon!)



for shared memory, overlap them …

Each process go through a translation table to point at individual pages in the main memory.

What's beneath the Illusion?

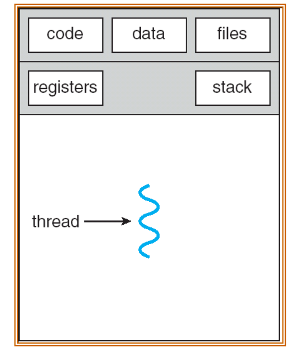


Today: How does the Operating System create the Process Abstraction?

- What data structures are used?
- What machine structures are employed?
  – Focus on x86, since will use in projects (and everywhere)

Starting Point: Single Threaded Process

- Process: OS abstraction of what is needed to run a single program
  1. Sequential program execution stream
     » Sequential stream of execution (thread)
     » State of CPU registers
  2. Protected resources
     » Contents of Address Space
     » I/O state (more on this later)

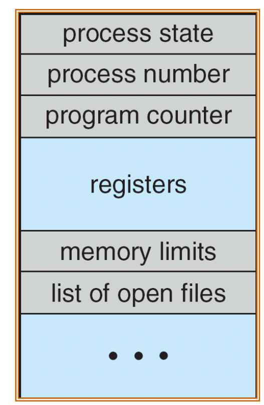


Running Many Programs

- We have the basic mechanism to
  – switch between user processes and the kernel,
  – the kernel can switch among user processes,
  – Protect OS from user processes and processes from each other
- Questions ???
  – How do we represent each process in the kernel?
  – How do we decide which user process to run?
  – How do we pack up the process and set it aside?
  – How do we get a stack and heap for the kernel?
  – Aren't we wasting are lot of memory?

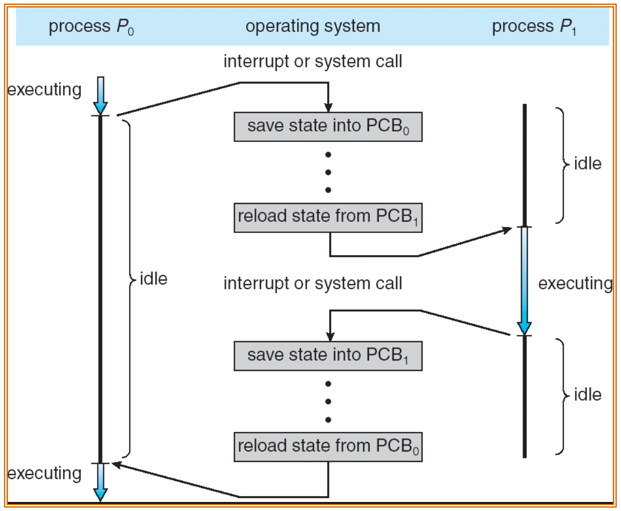
Multiplexing Processes: The Process Control Block

- Kernel represents each process as a process control block (PCB)
  – Status (running, ready, blocked, …)
  – Register state (when not ready)
  – Process ID (PID), User, Executable, Priority, …
  – Execution time, …
  – Memory space, translation, …
- Kernel *Scheduler* maintains a data structure containing the PCBs
  – Give out CPU to different processes
  – This is a Policy Decision
- Give out non-CPU resources
  – Memory/IO
  – Another policy decision

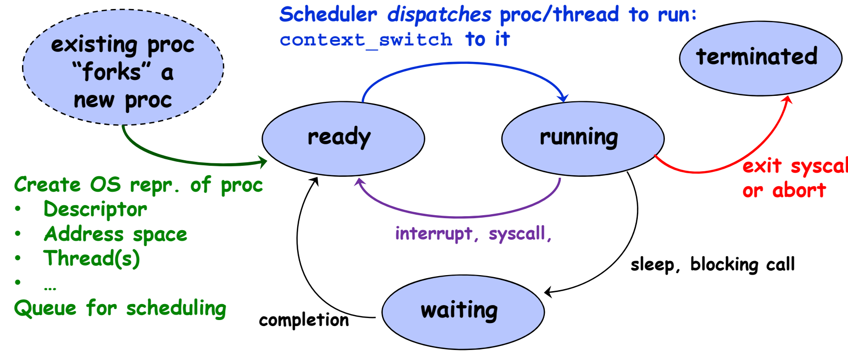


Process Control Block

Context Switch



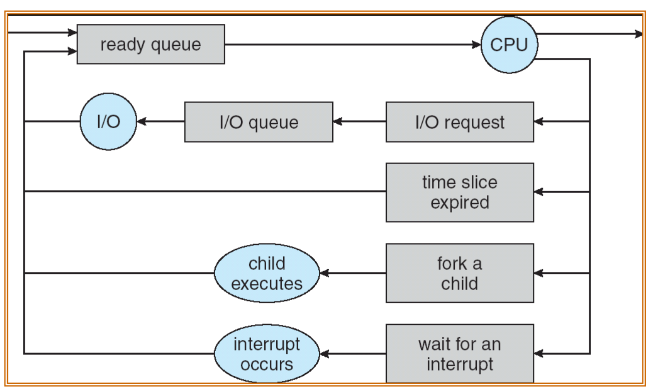
Lifecycle of a process / thread



- OS juggles many process/threads using kernel data structures
- Proc's may create other process (fork/exec)
  - All starts with init process at boot

Pintos: process.c

Scheduling: All About Queues



- PCBs move from queue to queue
- **Scheduling:** which order to remove from queue
  - Much more on this soon

Scheduler

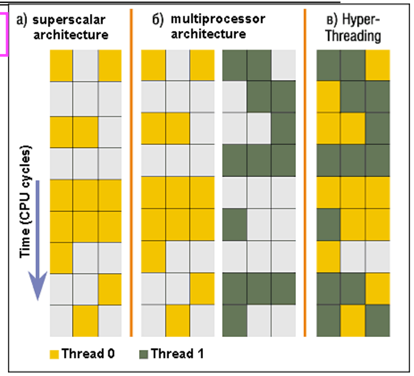
```
if ( readyProcesses(PCBs) ) {
       nextPCB = selectProcess(PCBs);
       run( nextPCB );
} else {
       run_idle_process();
}
```

- Scheduling: Mechanism for deciding which processes/threads receive the CPU
- Lots of different scheduling policies provide …
  - Fairness or
  - Realtime guarantees or
  - Latency optimization or ..

The idle process typically tries to put the processor in a low-power status.

Simultaneous MultiThreading/Hyperthreading

- Hardware scheduling technique
  - Superscalar processors can execute multiple instructions that are independent.
  - Hyperthreading duplicates register state to make a second "thread," allowing more instructions to run.
- Can schedule each thread as if were separate CPU
  - But, sub-linear speedup!

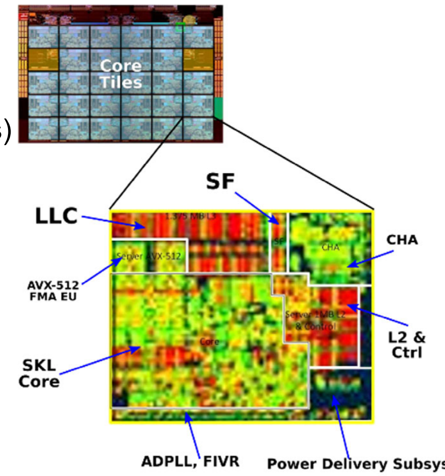


Colored blocks show instructions executed

- Original technique called "Simultaneous Multithreading"
  - http://www.cs.washington.edu/research/smt/index.html
  - SPARC, Pentium 4/Xeon ("Hyperthreading"), Power 5

Also Recall: The World Is Parallel

- Intel Skylake (2017)
  - 28 Cores
  - Each core has two hyperthreads!
  - So: 54 Program Counters(PCs)
- Scheduling here means:
  - Pick which core
  - Pick which thread
- Space of possible scheduling much more interesting
  - Can afford to dedicate certain cores to housekeeping tasks
  - Or, can devote cores to services (e.g. Filesystem)



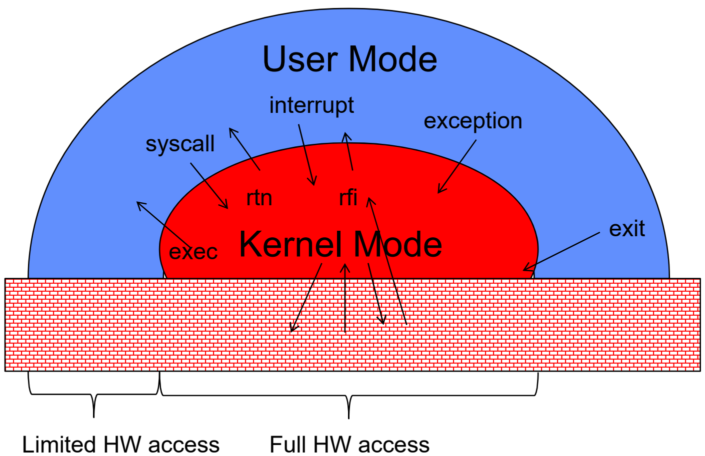
Administrivia: Getting started

- Kubiatowicz Office Hours:
  - 1-2pm, Monday & Thursday
- Homework 0 Due Friday!
  - Get familiar with the cs162 tools
  - configure your VM, submit via git
  - Practice finding out information:
    - » How to use GDB? How to understand output of unix tools?
    - » We don't assume that you already know everything!
    - » Learn to use "man" (command line), "help" (in gdb, etc), google
- Should be going to sections now – Important information there
  - Any section will do until groups assigned
- Class status: All regular students made it!
  - Concurrent enrollment will be added as possible. Over half will be admitted already. Perhaps more.
- THIS Friday is Drop Deadline! HARD TO DROP LATER!
  - If you know you are going to drop, please do so to leave room for others!

Administrivia (Con't)

- Group sign up via autograder form next week
  - Get finding groups of 4 people ASAP
  - Priority for same section; if cannot make this work, keep same TA
  - Remember: Your TA needs to see you in section!
- Midterm 1 conflicts
  - We will handle these conflicts after have final class roster
  - I know about one problem with Midterm 1 scheduling, and it can be dealt with. Have I missed any others?
  - Watch for queries by HeadTA to collect information

Recall: User/Kernel (Privileged) Mode



Three types of Kernel Mode Transfer

- Syscall
  - Process requests a system service, e.g., exit
  - Like a function call, but "outside" the process
  - Does not have the address of the system function to call
  - Like a Remote Procedure Call (RPC) – for later
  - Marshall the syscall id and args in registers and exec syscall
- Interrupt
  - External asynchronous event triggers context switch
  - eg. Timer, I/O device
  - Independent of user process
- Trap or Exception
  - Internal synchronous event in process triggers context switch
  - e.g., Protection violation (segmentation fault), Divide by zero, …

So how do we safely let user hand over a task to kernel ?

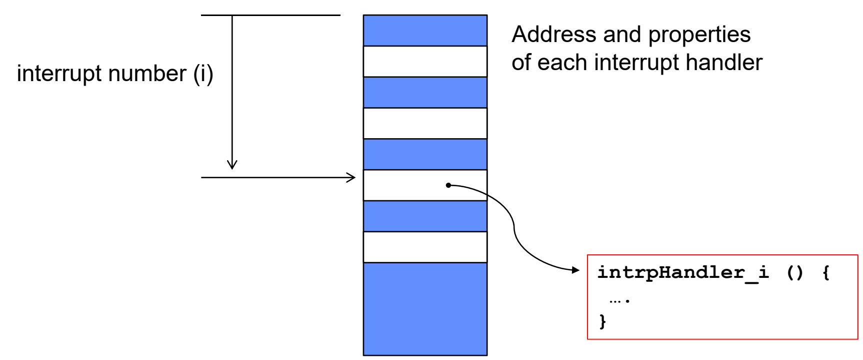
Implementing Safe Kernel Mode Transfers

- Important aspects:
  - Controlled transfer into kernel (e.g., syscall table)
  - Separate kernel stack
- Carefully constructed kernel code packs up the user process state and sets it aside
  - Details depend on the machine architecture

Trust NOTHING !

- Should be impossible for buggy or malicious user program to cause the kernel to corrupt itself

Interrupt Vector

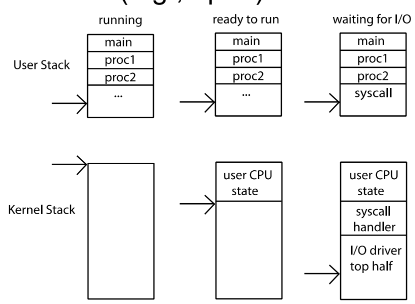


- Where else do you see this dispatch pattern?

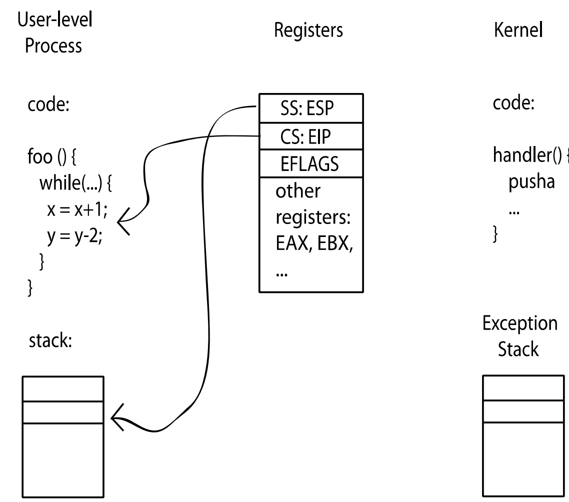
Need for Separate Kernel Stacks

- Kernel needs space to work
- Cannot put anything on the user stack (Why?)
- Two-stack model
  – OS thread has interrupt stack (located in kernel memory) plus User stack (located in user memory)
  – Syscall handler copies user args to kernel space before invoking specific function (e.g., open)
  – Interrupts (???)

2 threads, 1 entering kernel mode

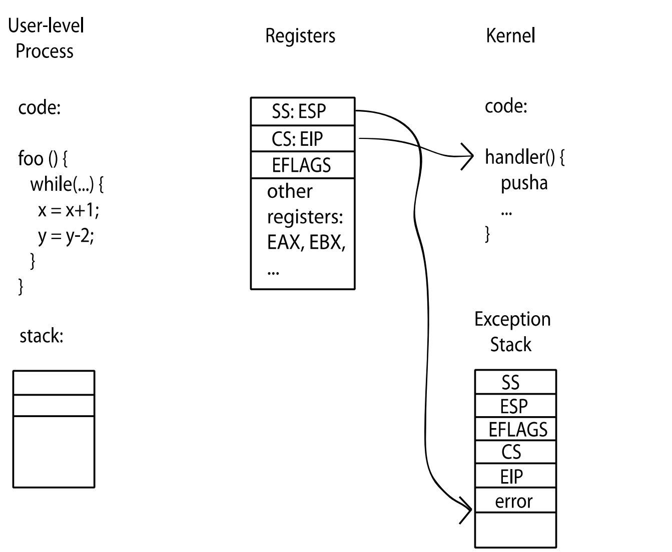


Before



During

During The Interrupt



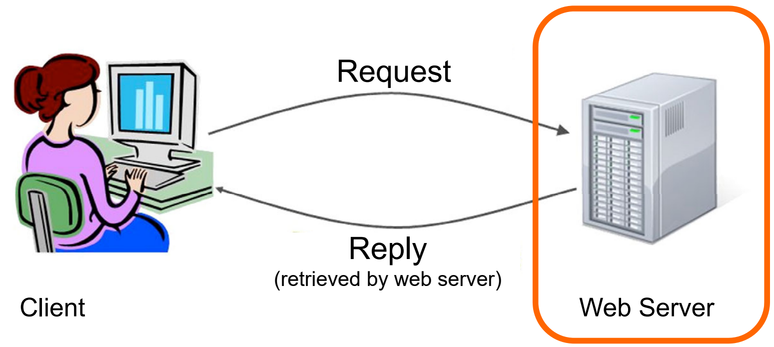
Kernel System Call Handler

- Vector through well-defined syscall entry points!
  – Table mapping system call number to handler
- Locate arguments
  – In registers or on user (!) stack
- Copy arguments
  – From user memory into kernel memory
  – Protect kernel from malicious code evading checks
- Validate arguments
  – Protect kernel from errors in user code
- Copy results back
  – Into user memory

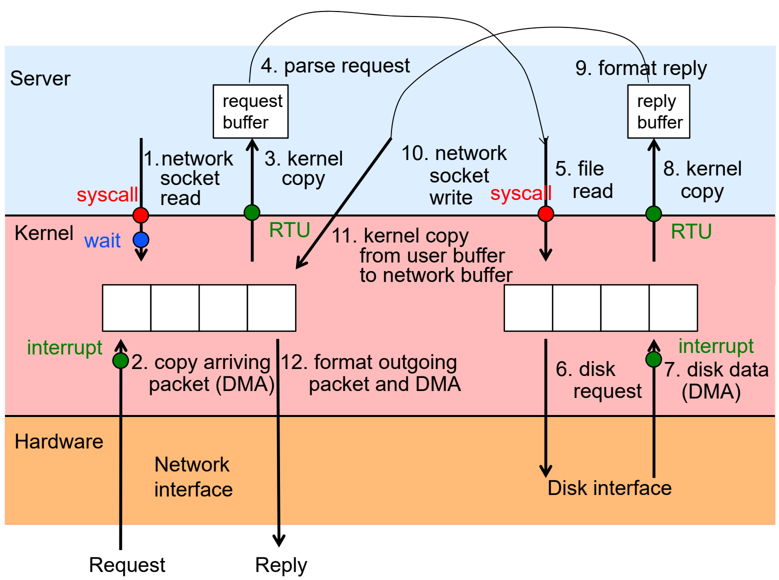
Hardware support: Interrupt Control

- Interrupt processing not visible to the user process:
  - – Occurs between instructions, restarted transparently
  - – No change to process state
  - – What can be observed even with perfect interrupt processing?
- Interrupt Handler invoked with interrupts ‘disabled’
  - – Re-enabled upon completion
  - – Non-blocking (run to completion, no waits)
  - – Pack up in a queue and pass off to an OS thread for hard work
    - » wake up an existing OS thread

Putting it together: web server



Putting it together: web server



A DEEP Dive into Pintos

and

Where we are Going!

Project 1: Processes

- Allocate and initialize Process object
- Allocate and initialize kernel thread mini-stack and associated Thread object
- Allocate and initialize page table for process
- Load code and static data into user pages
- Build initial User Stack
  - Initial register contents
- Schedule (post) process thread for execution
- …
- Eventually switch to user thread …
- Several lists of various types

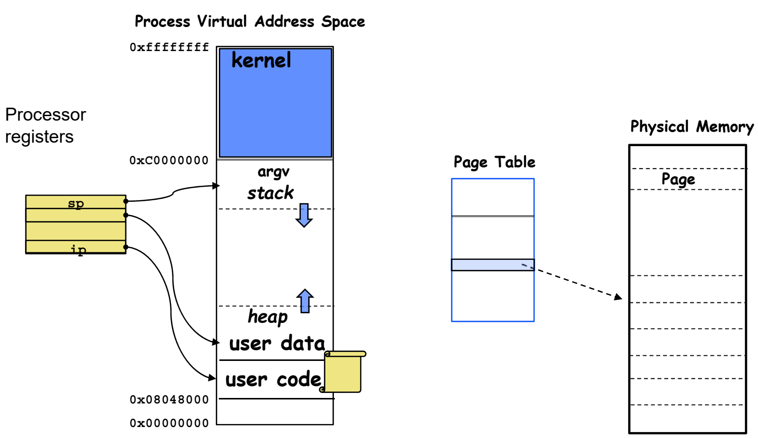
Project 1

Pintos: process.c, thread.c

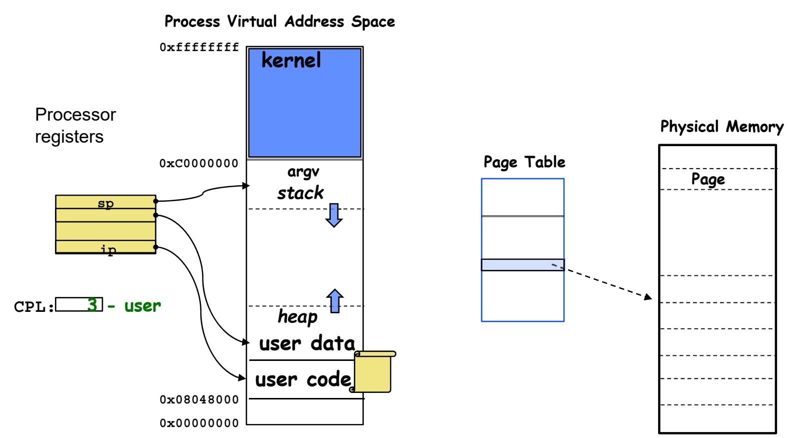
Understanding "Address Space"

- Page table is the primary mechanism
- Privilege Level determines which regions can be accessed
  - Which entries can be used
- System (PL=0) can access all, User (PL=3) only part
- Each process has its own address space
- The "System" part of all of them is the same
  ⇒ All system threads share the same system address space and same memory
- This address pattern less (not?) common now after the Meltdown attack was discovered in 2017
  - More Later in Term!!

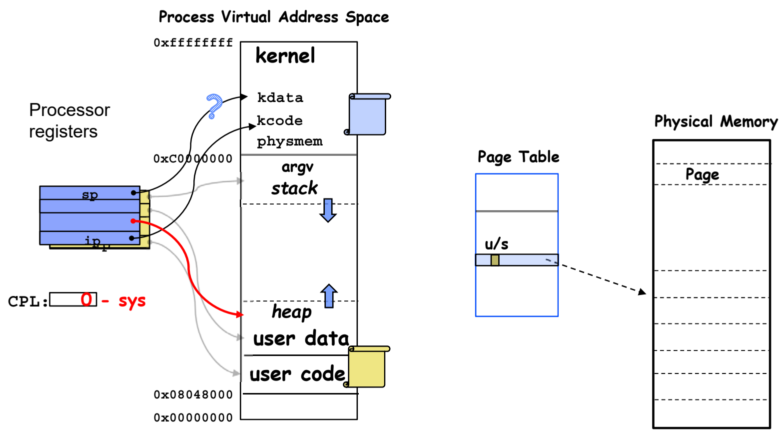
User Process View



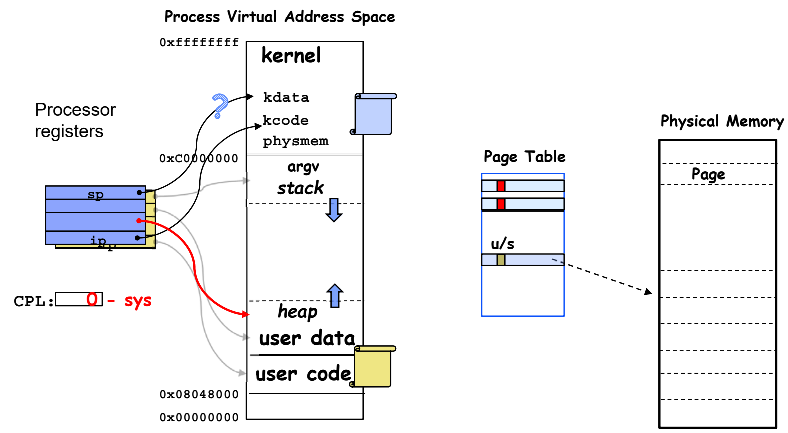
Processor Mode (Privilege Level)



User → Kernel: PL = 0

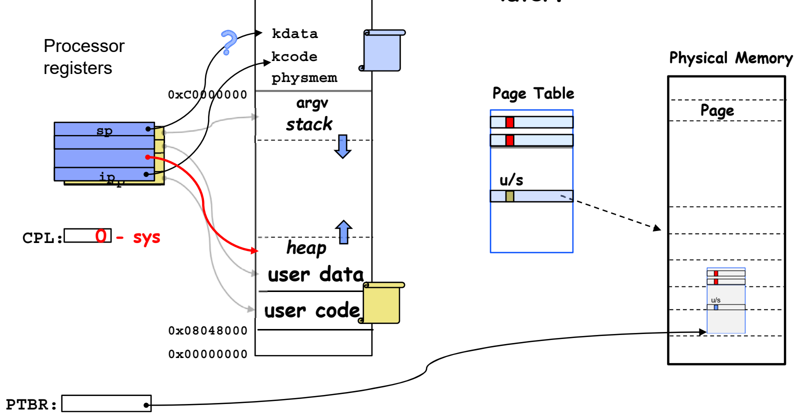


Page Table enforces PL

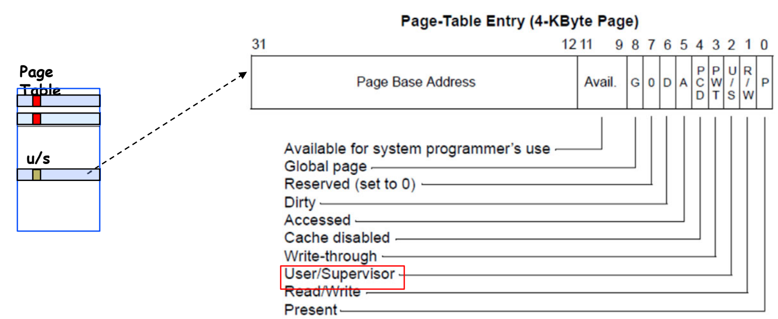


Page Table resides in memory*

* In the simplest case. Actually more complex. More later.



x86 (32-bit) Page Table Entry



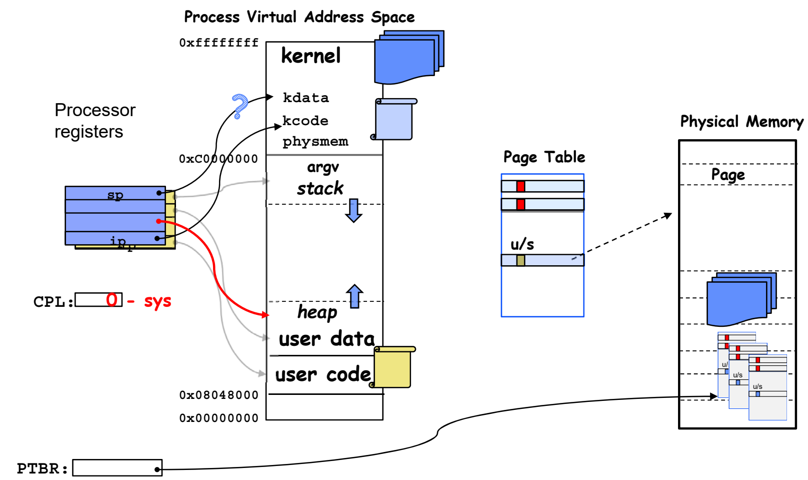
- Controls many aspects of access
- Later – discuss page table organization
  - For 32 (64?) bit VAS, how large? vs size of memory?
  - Use sparsely. Very very fast HW access

Pintos: page_dir.c

Kernel Portion of Address Space

- Contains the kernel code
  – Loaded when the machine booted
- Explicitly mapped to physical memory
  – OS creates the page table
- Used to contain all kernel data structures
  – List of all the processes and threads
  – The page tables for those processes
  – Other system resources (files, sockets, ttys, …)
- Also contains (little) stacks for "kernel threads"
  – Early OS design serviced all processes on a single execution thread
    » Event driven programming
  – Today: Each Process Thread supported by (little) Kernel Thread

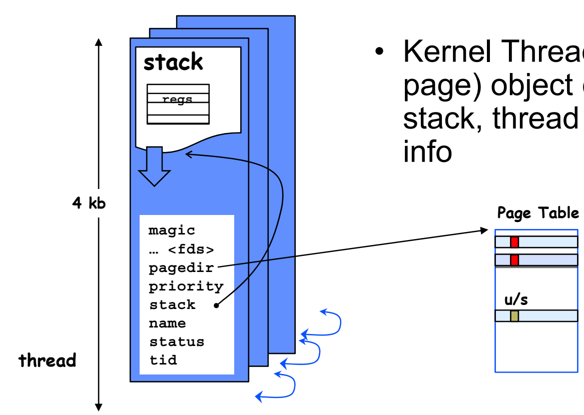
1 Kernel Code, many Kernel "stacks"



From Machine Structure to OS Data Structures

- Traditional Unix, etc. design maintains a Process Control Block (PCB) per process
- Each with a Thread Control Block (TCB) per thread of that process
- Today, assume *single* thread per process
  – PINTOS model
- Linux organized around threads with "groups of threads" associated with a process

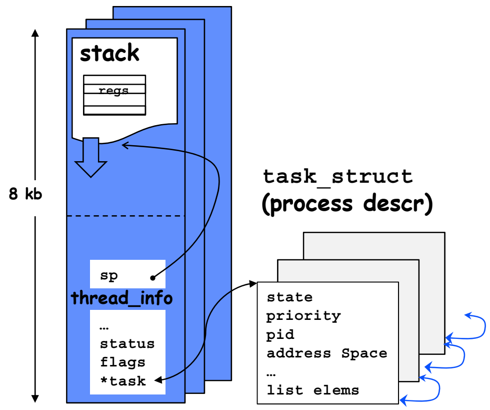
PINTOS Thread



- Kernel Thread as 4 kb (2 page) object containing stack, thread info, process info

Pintos: thread.c

Linux "Task"



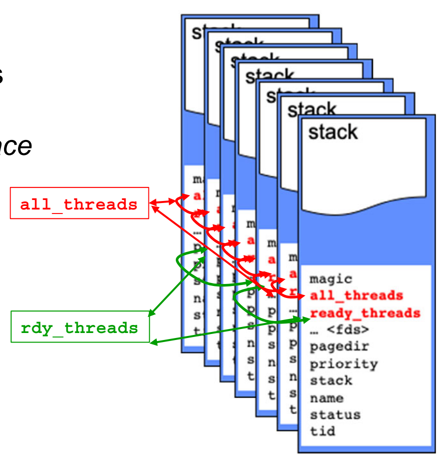
- Kernel Thread as 8 kb (2 page) object containing stack and thread information + process decriptor

Process Creation

- Allocate and initialize Process object
- Allocate and initialize kernel thread mini-stack and associated Thread object
- Allocate and initialize page table for process
  - Referenced by process object
- Load code and static data into user pages
- Build initial User Stack
  - Initial register contents, argv, …
- Schedule (post) process thread for execution
- …
- Eventually *switch* to user thread …
- Several lists of various types

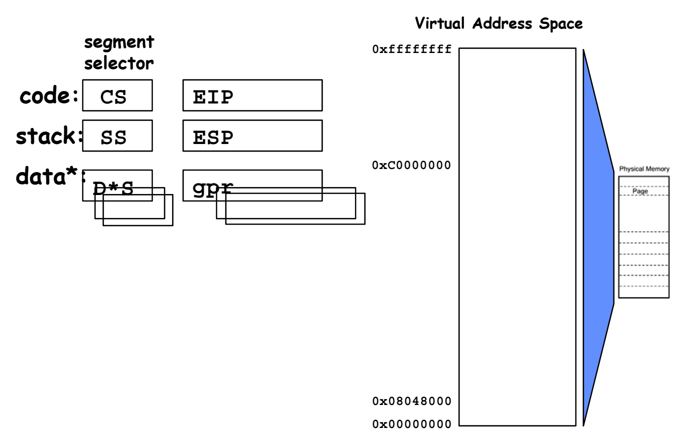
Aside: Polymorphic lists in C

- Many places in the kernel need to maintain a "list of X"
  - This is tricky in C, which has no polymorphism
  - Essentially adding an *interface* to a package (ala Go)
- In Linux and Pintos this is done by embedding a `list_elem` in the struct
  - Macros allow shift of view between object and list
  - You'll practice in HW1 – before getting into PINTOS



Pintos: list.c

Bit of x86 thread/process/VAS management



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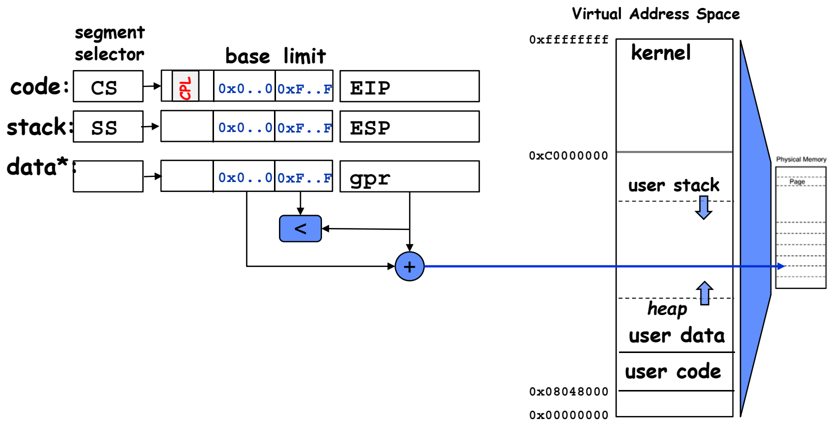
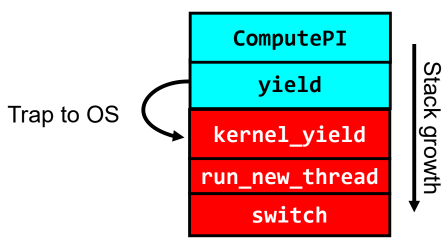


Pintos: loader.h

Recall: 3 types of U→K Mode Transfer

- Syscall
  - Process requests a system service, e.g., exit
  - Like a function call, but "outside" the process
  - Does not have the address of the system function to call
  - Like a Remote Procedure Call (RPC) – for later
  - Marshall the syscall id and args in registers and exec syscall
- Interrupt
  - External asynchronous event triggers context switch
  - eg. Timer, I/O device
  - Independent of user process
- Trap
  - Internal synchronous event in process triggers context switch
  - e.g., Protection violation (segmentation fault), Divide by zero, …
- All 3 *exceptions* are an UNPROGRAMMED CONTROL TRANSFER
  - Where does it go? (To handler specified in interrupt vector)
  - Are interrupts enabled or disabled when get there?

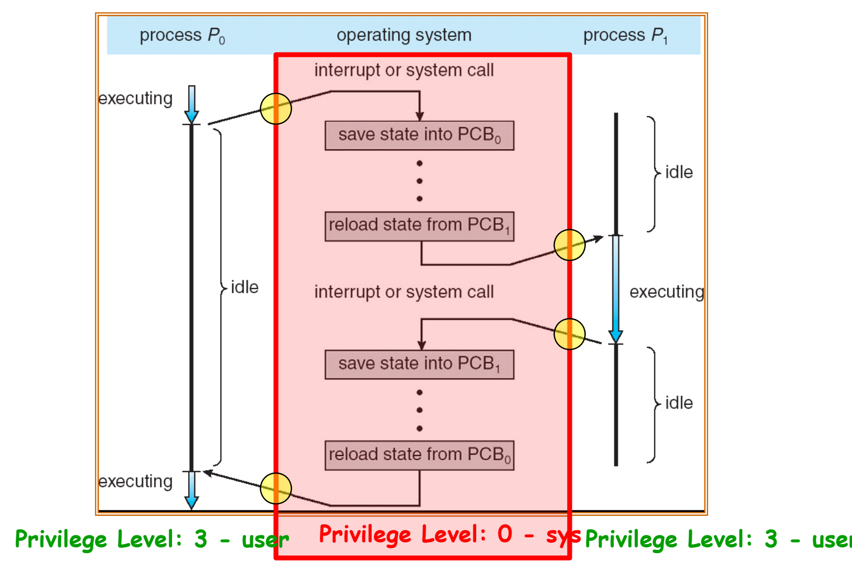
Stack for Thread Transition



Cyan = User Stack; Red = Kernel Stack

```
run_new_thread() {
  newThread = PickNewThread();
  switch(curThread, newThread);   Scheduling: Policy Decision
  ThreadHouseKeeping(); /* Do any cleanup */
}
```


A Privileged View of the Context Switch



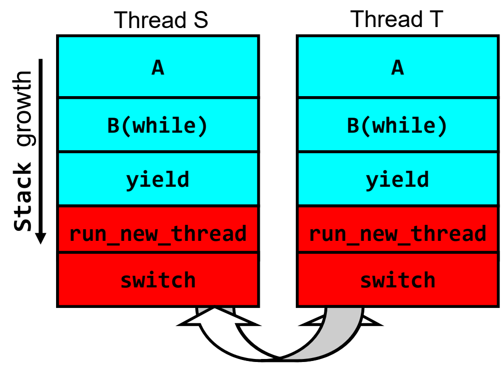
Stacks During Context Switch

- Consider the following code blocks:

```
proc A() {
   B();

}
proc B() {
   while(TRUE) {
      yield();
   }
}
```

- Suppose we have 2 threads:
  – Threads S and T



Thread S's switch returns to Thread T's (and vice versa)

Saving/Restoring state (often called "Context Switch)

```
Switch(tCur,tNew) {
   /* Unload old thread */
   TCB[tCur].regs.r7 = CPU.r7;
         …
   TCB[tCur].regs.r0 = CPU.r0;
   TCB[tCur].regs.sp = CPU.sp;
   TCB[tCur].regs.retpc = CPU.retpc; /*return addr*/

   /* Load and execute new thread */
   CPU.r7 = TCB[tNew].regs.r7;
         …
   CPU.r0 = TCB[tNew].regs.r0;
   CPU.sp = TCB[tNew].regs.sp;
   CPU.retpc = TCB[tNew].regs.retpc;
   return; /* Return to CPU.retpc */
}
```


Hardware context switch support

- Syscall/Intr (U → K)
  – PL 3 → 0;
  – TSS ← EFLAGS, CS:EIP;
  – SS:SP ← k-thread stack (TSS PL 0);
  – push (old) SS:ESP onto (new) k-stack
  – push (old) eflags, cs:eip, <err>
  – CS:EIP ← <k target handler>
- Then
  – *Handler then saves other regs, etc*
  – *Does all its works, possibly choosing other threads, changing PTBR (CR3)*

  – kernel thread has set up user GPRs
- iret (K → U)
  – PL 0 → 3;
  – Eflags, CS:EIP ← popped off k-stack
  – SS:SP ← user thread stack (TSS PL 3);

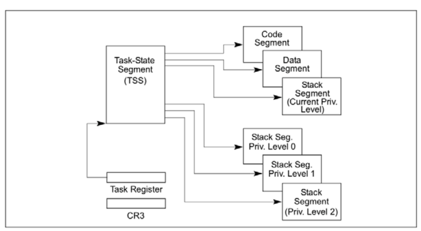
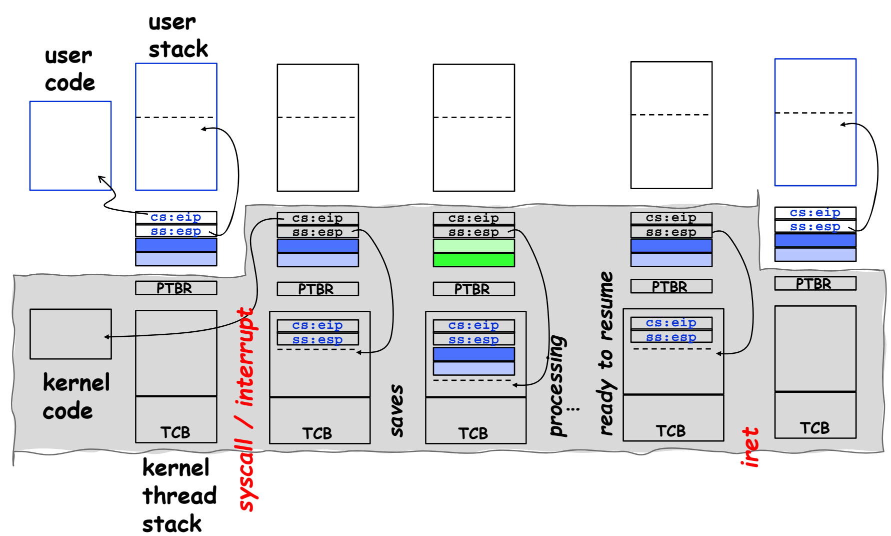


Figure 7-1. Structure of a Task

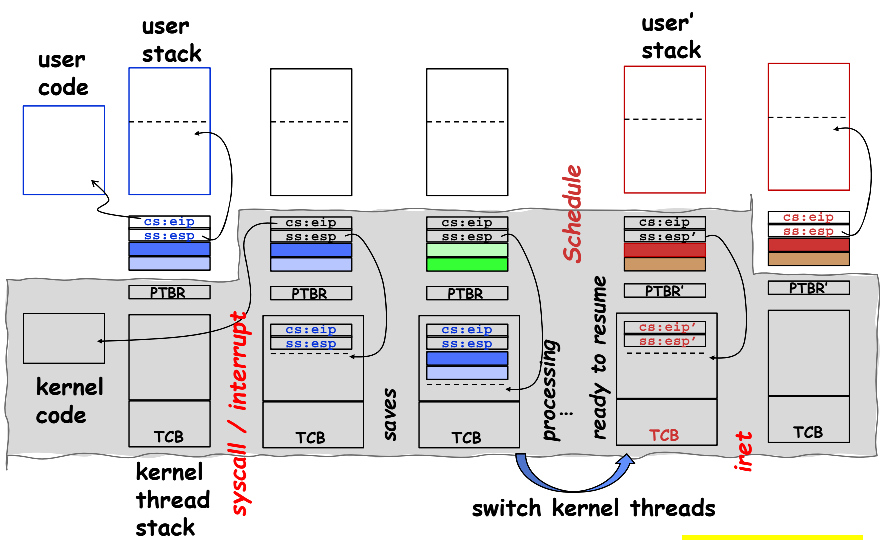
pg 2,942 of 4,922 of x86 reference manual

Pintos: tss.c, intr-stubs.S

Context Switch – in pictures



Context Switch – Scheduling



Pintos: switch.S

Concurrency

- But, … ???
- With all these threads in the kernel, won't they step on each other?
  - For example, while one is loading a program, other threads should run …
  - Processes are isolated from each other, but all the threads in the kernel share the kernel address space, memory, data structures
- We will study synchronization soon
- The kernel controls whether hardware interrupts are enabled or not
  - Disabled on entry, selectively enable
  - Atomic operations, …

Dispatch Loop

```
Loop {
  RunThread();
  ChooseNextThread();
  SaveStateOfCPU(curTCB);
  LoadStateOfCPU(newTCB);
}
```

- *Conceptually* all the OS executes
- Infinite Loop
  - When would we ever "exit?"
  - Can we assume some thread is always ready?

Dispatch Loop

```
Loop {
  RunThread();
  ChooseNextThread();
  SaveStateOfCPU(curTCB);
  LoadStateOfCPU(newTCB);
}
```

How to run a new thread?
- Load thread's registers into CPU
- Load its environment (address space, if in different process)
- Jump to thread's PC

How does dispatch loop get control again?
- Thread returns control voluntarily – `yield`, I/O
- External events: thread is *preempted*

Thread Operations in Pintos

- `thread_create(name, priority, func, args)`
  - Create a new thread to run func(args)
- `thread_yield()`
  - Relinquish processor voluntarily
- `thread_join(thread)`
  - Wait (put in queue) until thread exits, then return
- `thread_exit`
  - Quit thread and clean up, wake up joiner if any

More later, incl. synch ops

Meta-Question

- Process is an instance of a program executing.
  - The fundamental OS responsibility
- Processes do their work by processing and calling file system operations
- Are their any operations on processes themselves?
- exit ?

pid.c

```
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include <unistd.h>
#include <sys/types.h>
int main(int argc, char *argv[])
{
  pid_t pid = getpid();   /* get current processes PID */

  printf("My pid: %d\n", pid);

  exit(0);
}
```

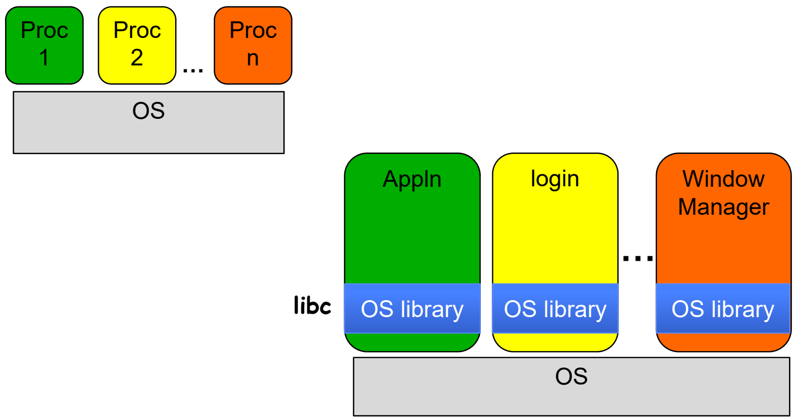
ps anyone?

Can a process create a process ?

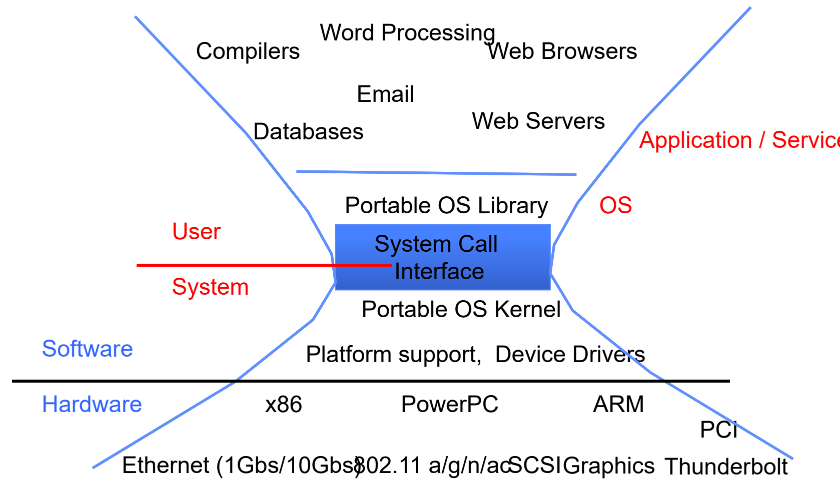
- Yes
- Fork creates a copy of process
- What about the program you want to run?

see Lec 3.80

OS Run-Time Library



A Narrow Waist



POSIX/Unix

- **P**ortable **O**perating **S**ystem **I**nterface [**X**?]
- Defines “Unix”, derived from AT&T Unix
  – Created to bring order to many Unix-derived OSs
- Interface for **application programmers** (mostly)

System Calls

Application:

```
fd = open(pathname);
```

Library:

```
File *open(pathname) {
   asm code … syscall # into ax
   put args into registers bx, …
   special trap instruction
```

Operating System:

```
get args from regs
dispatch to system func
process, schedule, …
complete, resume process
```

```
   get results from regs
};
```

```
Continue with results
```

Pintos: userprog/syscall.c, lib/user/syscall.c

SYSCALLs (of over 300)

%eax	Name	Source	%ebx	%ecx	%edx	%esi	%edi
1	sys_exit	kernel/exit.c	int	-	-	-	-
2	sys_fork	arch/i386/kernel/process.c	struct pt_regs	-	-	-	-
3	sys_read	fs/read_write.c	unsigned int	char *	size_t	-	-
4	sys_write	fs/read_write.c	unsigned int	const char *	size_t	-	-
5	sys_open	fs/open.c	const char *	int	int	-	-
6	sys_close	fs/open.c	unsigned int	-	-	-	-
7	sys_waitpid	kernel/exit.c	pid_t	unsigned int *	int	-	-
8	sys_creat	fs/open.c	const char *	int	-	-	-
9	sys_link	fs/namei.c	const char *	const char *	-	-	-
10	sys_unlink	fs/namei.c	const char *	-	-	-	-
11	sys_execve	arch/i386/kernel/process.c	struct pt_regs	-	-	-	-
12	sys_chdir	fs/open.c	const char *	-	-	-	-
13	sys_time	kernel/time.c	int *	-	-	-	-
14	sys_mknod	fs/namei.c	const char *	int	dev_t	-	-
15	sys_chmod	fs/open.c	const char *	mode_t	-	-	-
16	sys_lchown	fs/open.c	const char *	uid_t	gid_t	-	-
18	sys_stat	fs/stat.c	char *	struct __old_kernel_stat *	-	-	-
19	sys_lseek	fs/read_write.c	unsigned int	off_t	unsigned int	-	-
20	sys_getpid	kernel/sched.c	-	-	-	-	-
21	sys_mount	fs/super.c	char *	char *	char *	-	-
22	sys_oldumount	fs/super.c	char *	-	-	-	-
23	sys_setuid	kernel/sys.c	uid_t	-	-	-	-
24	sys_getuid	kernel/sched.c	-	-	-	-	-
25	sys_stime	kernel/time.c	int *	-	-	-	-
26	sys_ptrace	arch/i386/kernel/ptrace.c	long	long	long	long	-
27	sys_alarm	kernel/sched.c	unsigned int	-	-	-	-
28	sys_fstat	fs/stat.c	unsigned int	struct __old_kernel_stat *	-	-	-
29	sys_pause	arch/i386/kernel/sys_i386.c	-	-	-	-	-
30	sys_utime	fs/open.c	char *	struct utimbuf *	-	-	-

Pintos: syscall-nr.h

Recall: Kernel System Call Handler

- Locate arguments
  - In registers or on user(!) stack
- Copy arguments
  - From user memory into kernel memory
  - Protect kernel from malicious code evading checks
- Validate arguments
  - Protect kernel from errors in user code
- Copy results back
  - into user memory

Process Management

- `exit` – terminate a process
- **fork – copy the current process**
- `exec` – change the *program* being run by the current process
- `wait` – wait for a process to finish
- `kill` – send a *signal* (interrupt-like notification) to another process
- `sigaction` – set handlers for signals

Creating Processes

- pid_t fork(); -- copy the current process
  - New process has different pid
- Return value from **fork()**: pid (like an integer)
  - When > 0:
    - » Running in (original) Parent process
    - » return value is pid of new child
  - When = 0:
    - » Running in new Child process
  - When < 0:
    - » Error! Must handle somehow
    - » Running in original process
- State of original process duplicated in *both* Parent and Child!
  - Address Space (Memory), File Descriptors (covered later), etc…

fork1.c

```
#include <stdlib.h>
#include <stdio.h>
#include <unistd.h>
#include <sys/types.h>

int main(int argc, char *argv[]) {
  pid_t cpid, mypid;
  pid_t pid = getpid();            /* get current processes PID */
  printf("Parent pid: %d\n", pid);
  cpid = fork();
  if (cpid > 0) {                    /* Parent Process */
    mypid = getpid();
    printf("[%d] parent of [%d]\n", mypid, cpid);
  } else if (cpid == 0) {            /* Child Process */
    mypid = getpid();
    printf("[%d] child\n", mypid);
  } else {
    perror("Fork failed");
  }
}
```


fork1.c

```
#include <stdlib.h>
#include <stdio.h>
#include <unistd.h>
#include <sys/types.h>

int main(int argc, char *argv[]) {
  pid_t cpid, mypid;
  pid_t pid = getpid();            /* get current processes PID */
  printf("Parent pid: %d\n", pid);
  cpid = fork();
  if (cpid > 0) {                    /* Parent Process */
    mypid = getpid();
    printf("[%d] parent of [%d]\n", mypid, cpid);
  } else if (cpid == 0) {            /* Child Process */
    mypid = getpid();
    printf("[%d] child\n", mypid);
  } else {
    perror("Fork failed");
  }
}
```


fork1.c

```
#include <stdlib.h>
#include <stdio.h>
#include <unistd.h>
#include <sys/types.h>

int main(int argc, char *argv[]) {
  pid_t cpid, mypid;
  pid_t pid = getpid();            /* get current processes PID */
  printf("Parent pid: %d\n", pid);
  cpid = fork();
  if (cpid > 0) {                    /* Parent Process */
    mypid = getpid();
    printf("[%d] parent of [%d]\n", mypid, cpid);
  } else if (cpid == 0) {            /* Child Process */
    mypid = getpid();
    printf("[%d] child\n", mypid);
  } else {
    perror("Fork failed");
  }
}
```


fork_race.c

```
int i;
cpid = fork();
if (cpid > 0) {
  for (i = 0; i < 10; i++) {
    printf("Parent: %d\n", i);
    // sleep(1);
  }
} else if (cpid == 0) {
  for (i = 0; i > -10; i--) {
    printf("Child: %d\n", i);
    // sleep(1);
  }
}
```

- What does this print?
- Would adding the calls to `sleep` matter?

Fork "race"

```
int i;
cpid = fork();
if (cpid > 0) {
  for (i = 0; i < 10; i++) {
    printf("Parent: %d\n", i);
    // sleep(1);
  }
} else if (cpid == 0) {
  for (i = 0; i > -10; i--) {
    printf("Child: %d\n", i);
    // sleep(1);
  }
}
```

Process Management

- `fork` – copy the current process
- `exec` – change the *program* being run by the current process
- **`wait` – wait for a process to finish**
- `kill` – send a *signal* (interrupt-like notification) to another process
- `sigaction` – set handlers for signals

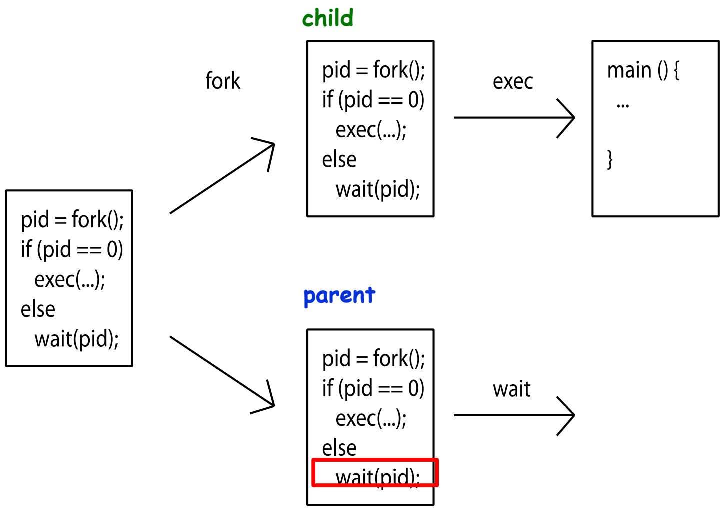
`fork2.c` – parent waits for child to finish

```
int status;
pid_t tcpid;
…
cpid = fork();
if (cpid > 0) {               /* Parent Process */
  mypid = getpid();
  printf("[%d] parent of [%d]\n", mypid, cpid);
  tcpid = wait(&status);
  printf("[%d] bye %d(%d)\n", mypid, tcpid, status);
} else if (cpid == 0) {      /* Child Process */
  mypid = getpid();
  printf("[%d] child\n", mypid);
}
…
```


Process Management

- `fork` – copy the current process
- **`exec` – change the *program* being run by the current process**
- `wait` – wait for a process to finish
- `kill` – send a *signal* (interrupt-like notification) to another process
- `sigaction` – set handlers for signals

Process Management



fork3.c

```
…
cpid = fork();
if (cpid > 0) {               /* Parent Process */
  tcpid = wait(&status);
} else if (cpid == 0) {      /* Child Process */
  char *args[] = {"ls", "-l", NULL};
  execv("/bin/ls", args);
  /* execv doesn't return when it works.
     So, if we got here, it failed! */
  perror("execv");
  exit(1);
}
…
```


Shell

- A shell is a job control system
  - Allows programmer to create and manage a set of programs to do some task
  - Windows, MacOS, Linux all have shells
- Example: to compile a C program

  cc –c sourcefile1.c

  cc –c sourcefile2.c

  ln –o program sourcefile1.o sourcefile2.o

  ./program

Process Management

- `fork` – copy the current process
- `exec` – change the *program* being run by the current process
- `wait` – wait for a process to finish
- `kill` – send a *signal* (interrupt-like notification) to another process
- **`sigaction` – set handlers for signals**

inf_loop.c

```
#include <stdlib.h>
#include <stdio.h>
#include <sys/types.h>
#include <unistd.h>
#include <signal.h>

void signal_callback_handler(int signum) {
  printf("Caught signal!\n");
  exit(1);
}
int main() {
  struct sigaction sa;
  sa.sa_flags = 0;
  sigemptyset(&sa.sa_mask);
  sa.sa_handler = signal_callback_handler;

  sigaction(SIGINT, &sa, NULL);
  while (1) {}
}
```


Common POSIX Signals

- `SIGINT` – control-C
- `SIGTERM` – default for `kill` shell command
- `SIGSTP` – control-Z (default action: stop process)

- `SIGKILL`, `SIGSTOP` – terminate/stop process
  - Can't be changed or disabled with `sigaction`
  - Why?

Summary

- Process consists of two pieces
  1. Address Space (Memory & Protection)
  2. One or more threads (Concurrency)
- Represented in kernel as
  - Process object (resources associated with process)
  - Thread object + (mini) stack
  - Hardware support critical in U → K → U context switch
  - Different privileges in different modes (CPL, Page Table)
- Variety of process management syscalls
  - fork, exec, wait, kill, sigaction
- Scheduling: Threads move between queues
- Threads: multiple stacks per address space
  - Context switch: Save/Restore registers, "return" from new thread's switch routine
  - So far, we've only seen kernel threads