CS162
Operating Systems and Systems Programming
Lecture 3

Processes (con't), System Calls, Fork,

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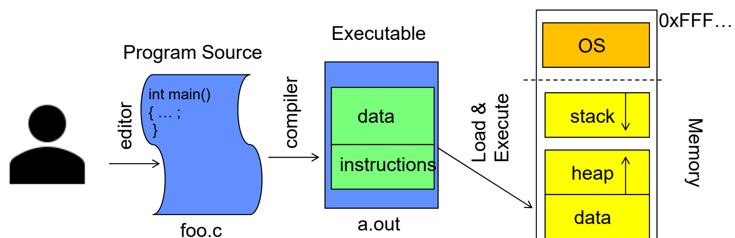
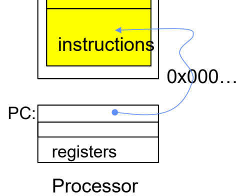
http://cs162.eecs.Berkeley.edu

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

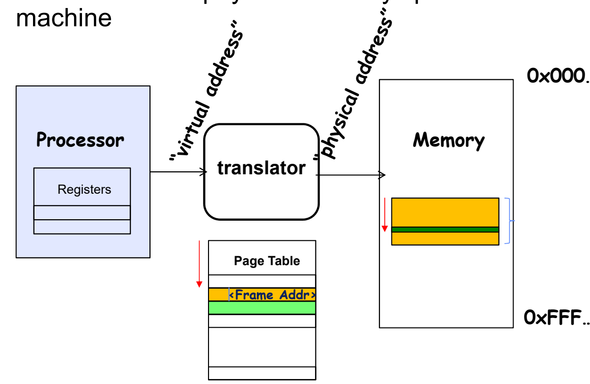




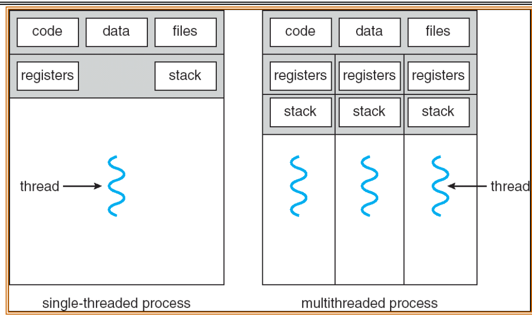
- Create OS "PCB", address space, stack and heap
- Load instruction and data segments of executable file into memory
- "Transfer control to program"
- Provide services to program
- While protecting OS and program

Recall: Protected Address Space

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

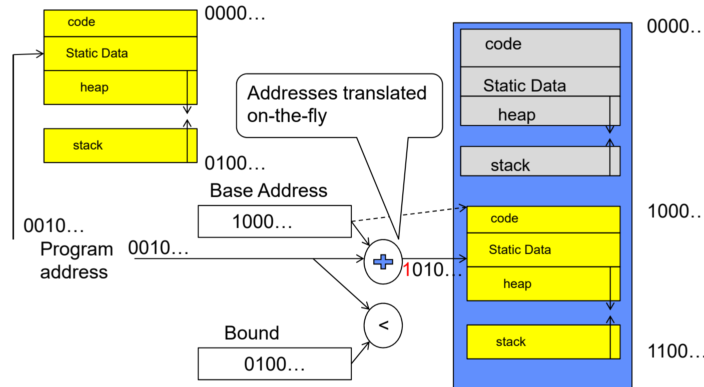


Recall: Single and Multithreaded Processes



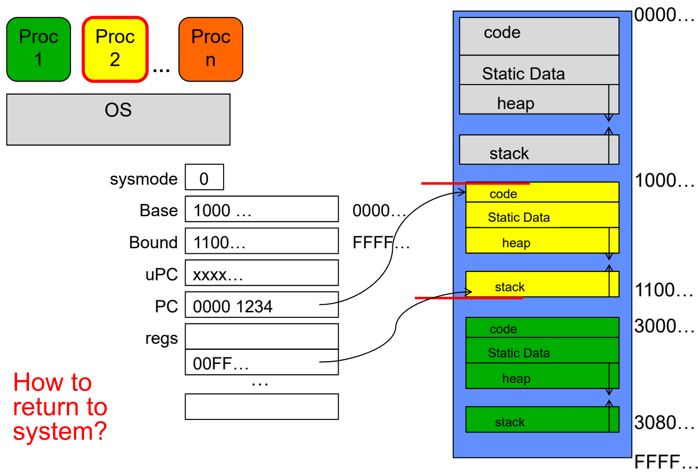
- Threads encapsulate concurrency: "Active" component
- Address spaces encapsulate protection: "Passive" part
  – Keeps buggy program from trashing the system
- Why have multiple threads per address space?

Recall: Simple address translation with Base and Bound



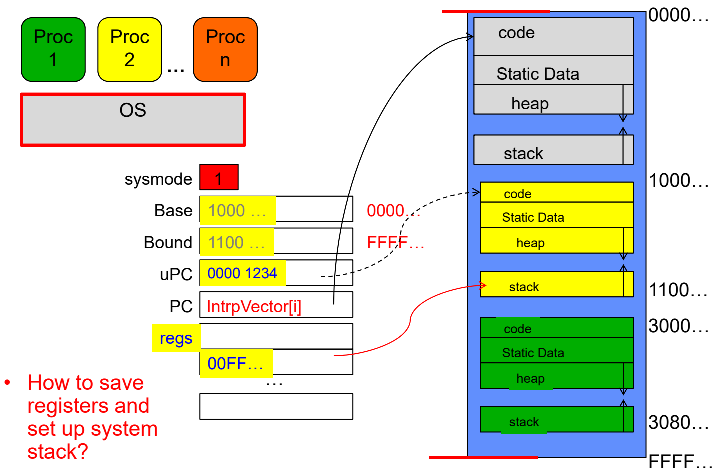
- Can the program touch OS?
- Can it touch other programs?

Simple B&B: User => Kernel



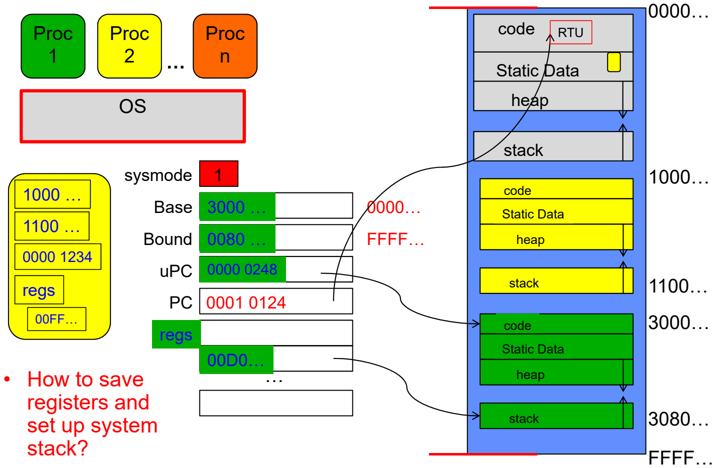
- How to return to system?

Simple B&B: Interrupt



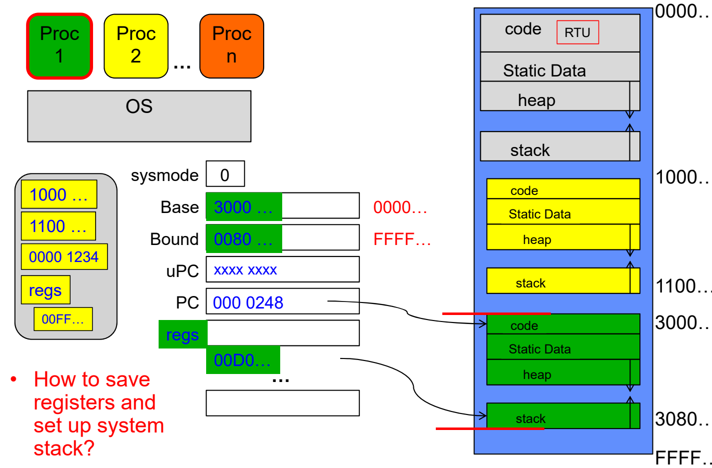
- How to save registers and set up system stack?

Simple B&B: Switch User Process



- How to save registers and set up system stack?

Simple B&B: "resume"



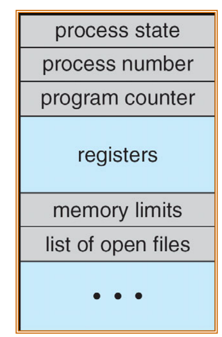
- How to save registers and set up system stack?

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 user processes in the OS?
  – 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?

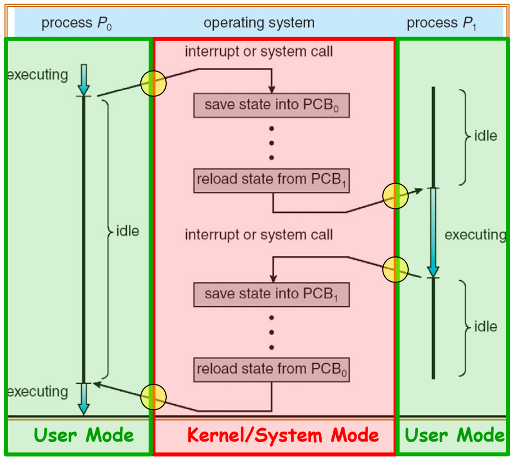
Multiplexing Processes: The Process Control Block

- 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

CPU Switch From Process A to Process B



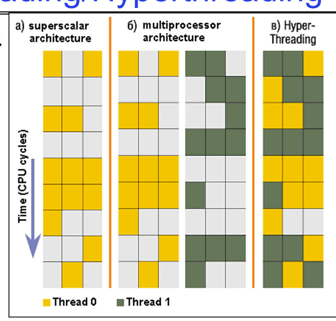
Scheduler

```
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 ..

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!

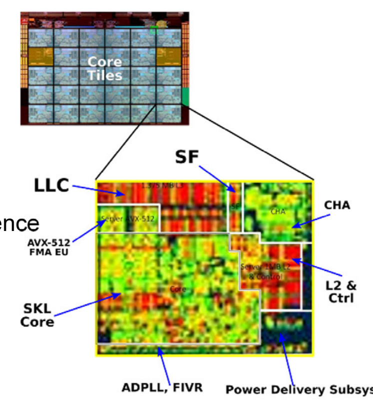


Colored blocks show instructions executed

- 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)

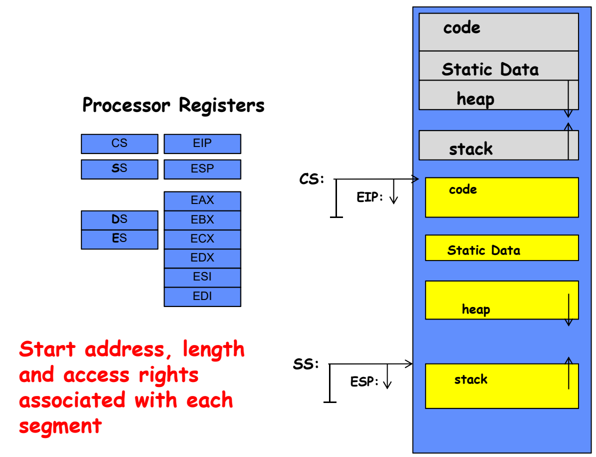
- Up to 28 Cores, 56 Threads
  – 694 mm² die size (estimated)
- Many different instructions
  – Security, Graphics
- Caches on chip:
  – L2: 28 MiB
  – Shared L3: 38.5 MiB (non-inclusive)
  – Directory-based cache coherence
- Network:
  – On-chip Mesh Interconnect
  – Fast off-chip network directlry supports 8-chips connected
- DRAM/chips
  – Up to 1.5 TiB
  – DDR4 memory



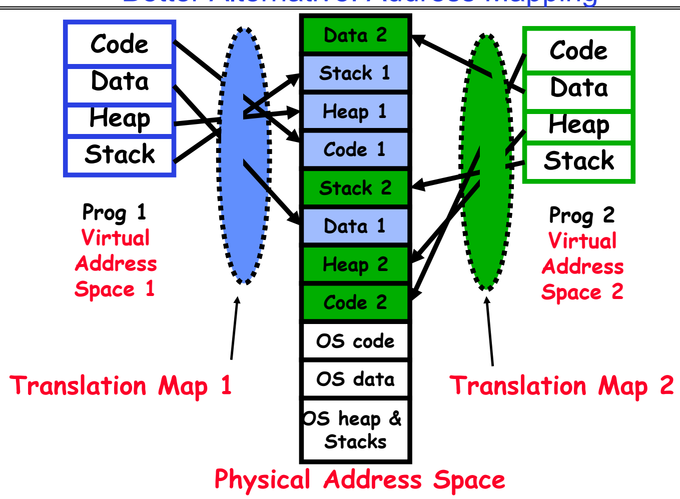
Is Base and Bound a Good-Enough Protection Mechanism?

- 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



Better Alternative: Address Mapping



Administrivia: Getting started!

- Kubiatowicz Office Hours:
  - 1-2pm, Monday & Thursday
- Homework 0 Due Tomorrow!
  - 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
- THIS Friday is Drop Deadline! HARD TO DROP LATER!
  - If you know you are going to drop, do so now to leave room for others on waitlist!
  - Why do we do this? So that groups aren't left without members!

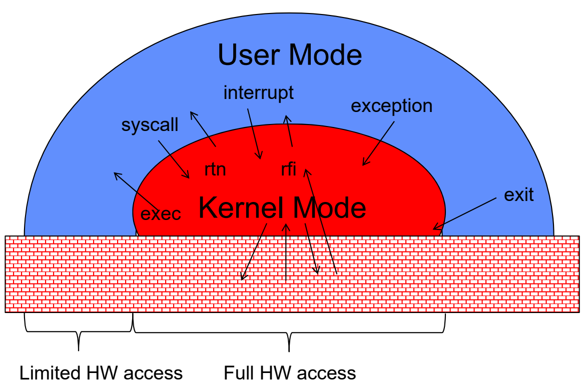
Administrivia (Con't)

- 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: 2/17
  - 7-9PM in person
  - We will say more about material when we get closer…
- Midterm 1 conflicts
  - We will handle these conflicts after have final class roster
  - Watch for queries by HeadTA to collect information

Recall: 3 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, …

Recall: User/Kernel (Privileged) Mode



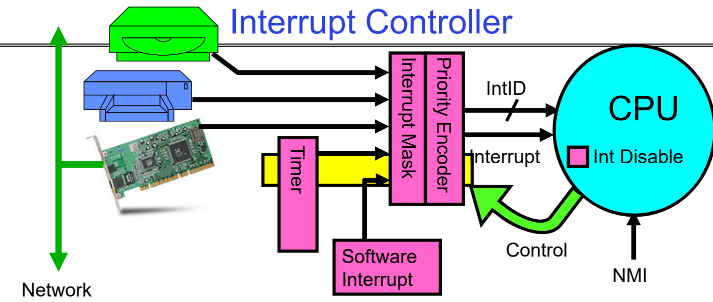
Implementing Safe Kernel Mode Transfers

- 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
  - More on this next time
- Should be impossible for buggy or malicious user program to cause the kernel to corrupt itself!

Hardware support: Interrupt Control

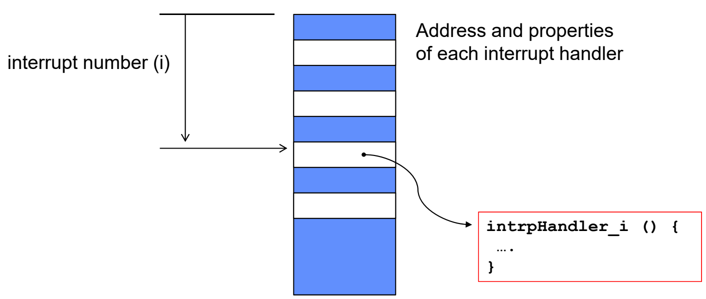
- Interrupt processing not visible to the user process:
  - Occurs between instructions, restarted transparently
  - No change to process state
  - What can be observed even with perfect interrupt processing?
- Interrupt Handler invoked with interrupts 'disabled'
  - Re-enabled upon completion
  - Non-blocking (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

Interrupt Controller



- Interrupts invoked with interrupt lines from devices
- Interrupt controller chooses interrupt request to honor
  - Interrupt identity specified with ID line
  - Mask enables/disables interrupts
  - Priority encoder picks highest enabled interrupt
  - Software Interrupt Set/Cleared by Software
- CPU can disable all interrupts with internal flag
- Non-Maskable Interrupt line (NMI) can't be disabled

Interrupt Vector



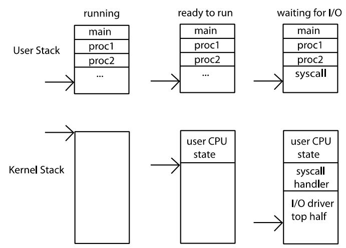
- Where else do you see this dispatch pattern?
  - System Call
  - Exceptions

How do we take interrupts safely?

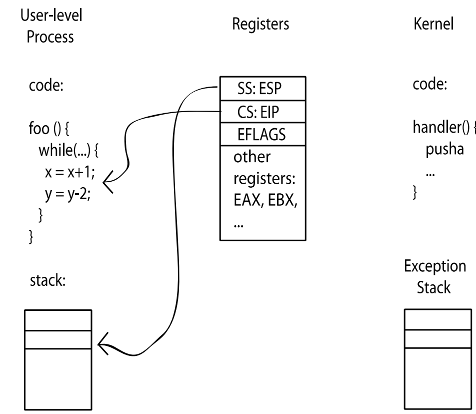
- Interrupt vector
  - Limited number of entry points into kernel
- Kernel interrupt stack
  - Handler works regardless of state of user code
- Interrupt masking
  - Handler is non-blocking
- Atomic transfer of control
  - "Single instruction"-like to change:
    - » Program counter
    - » Stack pointer
    - » Memory protection
    - » Kernel/user mode
- Transparent restartable execution
  - User program does not know interrupt occurred

Need for Separate Kernel Stacks

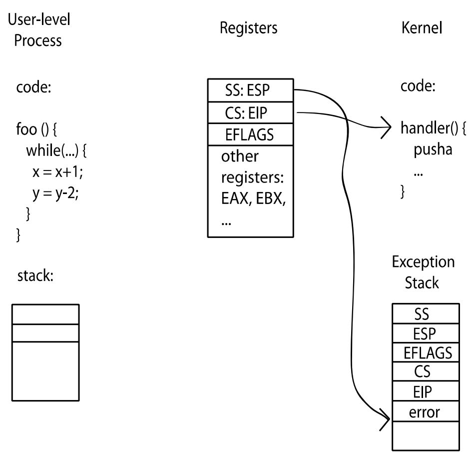
- Kernel needs space to work
- Cannot put anything on the user stack (Why?)
- Two-stack model
  – OS thread has interrupt stack (located in kernel memory) plus User stack (located in user memory)
  – Syscall handler copies user args to kernel space before invoking specific function (e.g., open)
  – Interrupts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



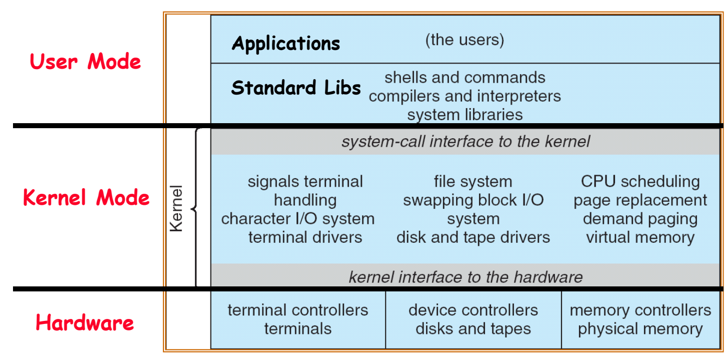
Before



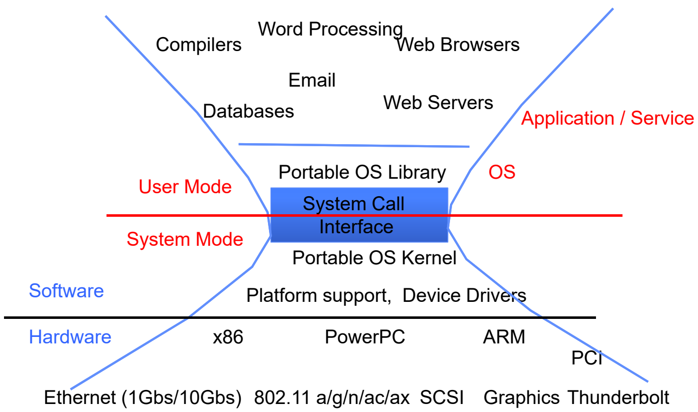
During Interrupt/System Call



Recall: UNIX System Structure



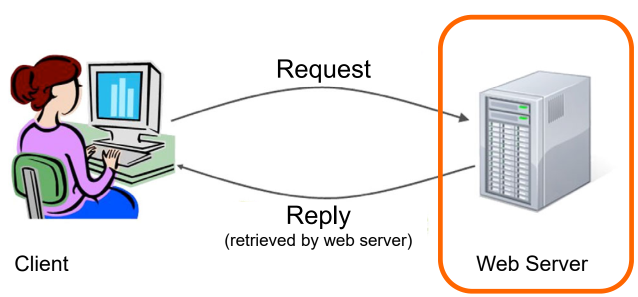
A Narrow Waist



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

Putting it together: web server



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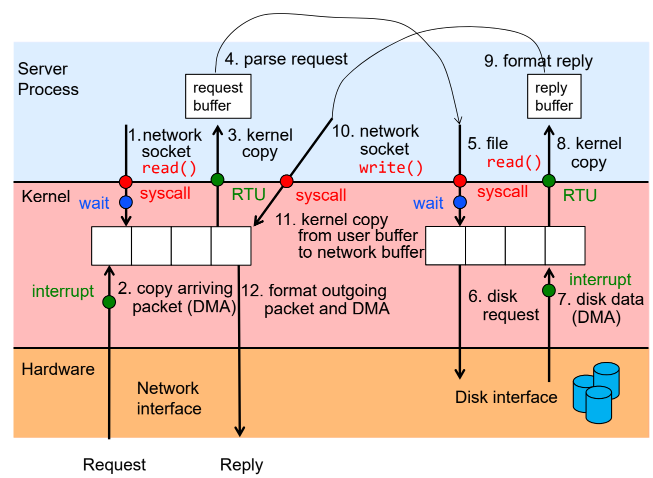
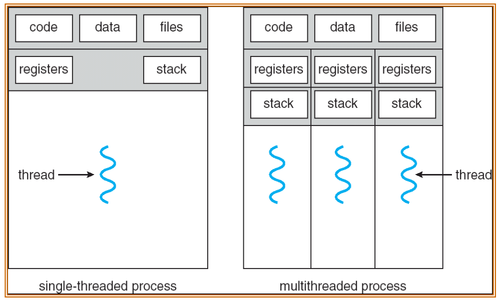


Recall: Processes

- How to manage process state?
  - How to create a process?
  - How to exit from a process?
- Remember: Everything outside of the kernel is running in a process!
  - Including the shell! (Homework 2)
- Processes are created and managed… by processes!



Bootstrapping

- If processes are created by other processes, how does the first process start?
- First process is started by the kernel
  - Often configured as an argument to the kernel *before* the kernel boots
  - Often called the "init" process
- After this, all processes on the system are created by other processes

Process Management API

- `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

Process Management API

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pid.c

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

  exit(0);
}
```

Q: What if we let main return without ever calling exit?
- The OS Library calls exit() for us!
- The entrypoint of the executable is in the OS library
- OS library calls main
- If main returns, OS library calls exit
- You'll see this in Project 0: init.c

Process Management API

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Creating Processes

- `pid_t fork()` – copy the current process
  - New process has different pid
  - New process contains a single thread
- 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;
pid_t 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);
  }
}
```

Recall: a process consists of one or more threads executing in an address space
- Here, each process has a single thread
- These threads execute concurrently

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

Running Another Program

- With threads, we could call `pthread_create` to create a new thread executing a separate function
- With processes, the equivalent would be spawning a new process executing a different program
- How can we do this?

Process Management API

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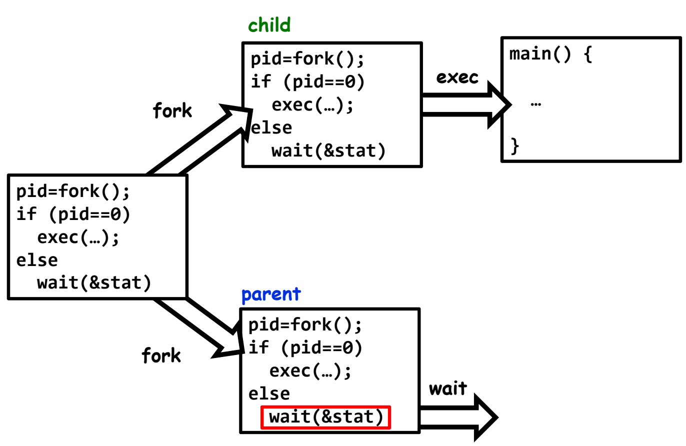
fork3.c

```
…
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);
}
…
```


Process Management



Process Management API

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- `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);
  exit(42);
}
…
```


Process Management API

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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) {}
}
```

Q: What would happen if the process receives a SIGINT signal, but does not register a signal handler?
A: The process dies!

For each signal, there is a default handler defined by the system

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 with `sigaction`
  - Why?

Shell

- A shell is a job control system
  - Allows programmer to create and manage a set of programs to do some task
- You will build your own shell in Homework 2…
  - … using `fork` and `exec` system calls to create new processes…
  - … and the File I/O system calls we'll see next time to link them together

Process vs. Thread APIs

- Why have `fork()` and `exec()` system calls for processes, but just a `pthread_create()` function for threads?
  - Convenient to `fork` without `exec`: put code for parent and child in one executable instead of multiple
  - It will allow us to programmatically control child process' state
    - » By executing code before calling `exec()` in the child
  - We'll see this in the case of File I/O next time
- Windows uses `CreateProcess()` instead of `fork()`
  - Also works, but a more complicated interface

Threads vs. Processes

- If we have two tasks to run concurrently, do we run them in separate threads, or do we run them in separate processes?
- Depends on how much isolation we want
  - Threads are lighter weight [why?]
  - Processes are more strongly isolated

Conclusion

- Process: execution environment with Restricted Rights
  - Address Space with One or More Threads
  - Owns memory (address space)
  - Owns file descriptors, file system context, …
  - Encapsulate one or more threads sharing process resources
- Interrupts
  - Hardware mechanism for regaining control from user
  - Notification that events have occurred
  - User-level equivalent: Signals
- Native control of Process
  - Fork, Exec, Wait, Signal