CS162
Operating Systems and Systems Programming
Lecture 4

Processes (con't), Threads, Concurrency

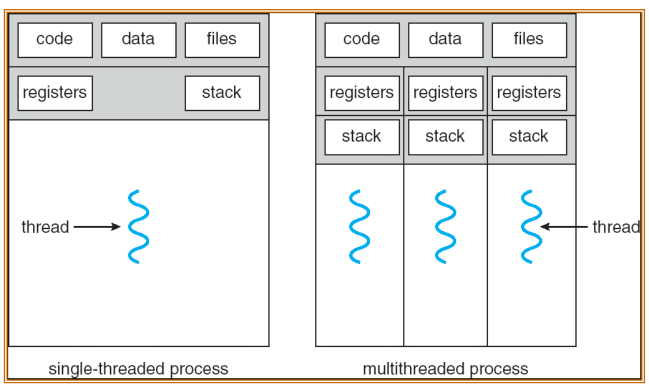
January 30th, 2020

Prof. John Kubiatowicz
http://cs162.eecs.Berkeley.edu

Recall: Modern Process with Threads

- Process: **execution environment with restricted rights**
  - Address Space with One or More Threads
    - » *One Page table per process!*
  - Owns memory (mapped pages)
  - Owns file descriptors, file system context, …
  - Encapsulates one or more threads sharing process resources
- Thread: *a sequential execution stream within process* (Sometimes called a "Lightweight process")
  - Process still contains a single Address Space
  - No protection between threads
- Multithreading: *a single program made up of a number of different concurrent activities*
  - Sometimes called multitasking, as in Ada …
- Why separate the concept of a thread from that of a process?
  - Discuss the "thread" part of a process (concurrency)
  - Separate from the "address space" (protection)
  - Heavyweight Process ≡ Process with one thread

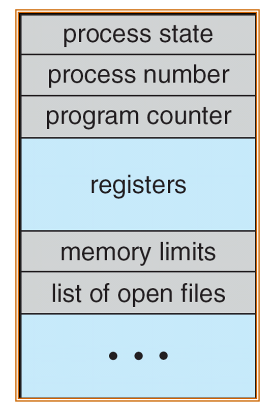
Recall: Single and Multithreaded Processes



- 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?

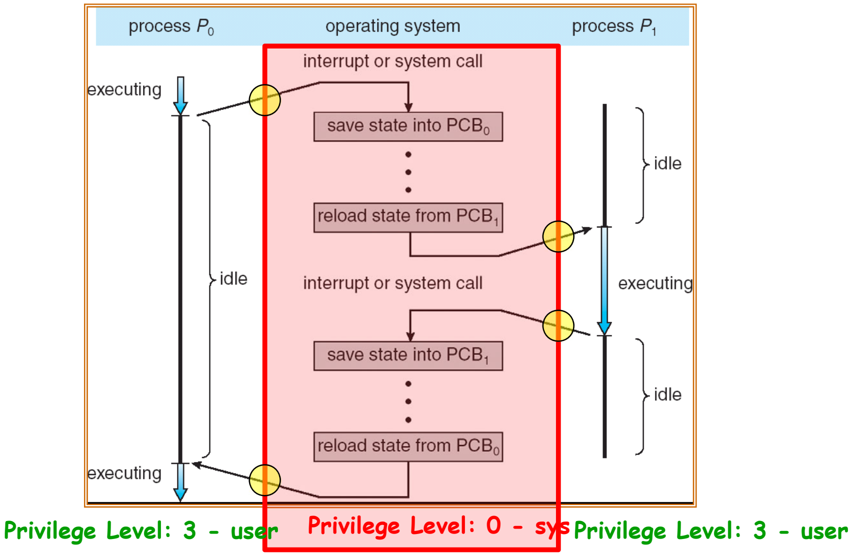
Recall: How do we Multiplex Processes?

- The current state of process held in a process control block (PCB):
  - This is a "snapshot" of the execution and protection environment
  - Only one PCB active at a time
- Give out CPU time to different processes (Scheduling):
  - Only one process "running" at a time
  - Give more time to important processes
- Give pieces of resources to different processes (Protection):
  - Controlled access to non-CPU resources
  - Example mechanisms:
    - » Memory Translation: Give each process their own (protected) address space
    - » Kernel/User duality: Arbitrary multiplexing of I/O through system calls

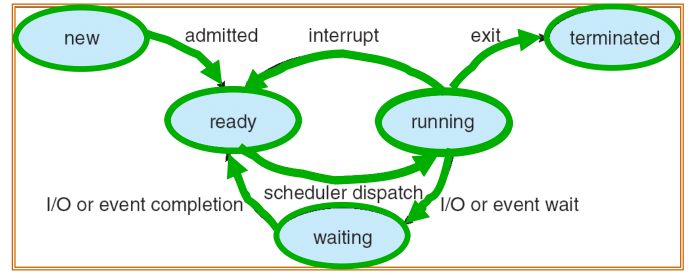


Process Control Block

Recall: Context Switch



Recall: Lifecycle of a Process

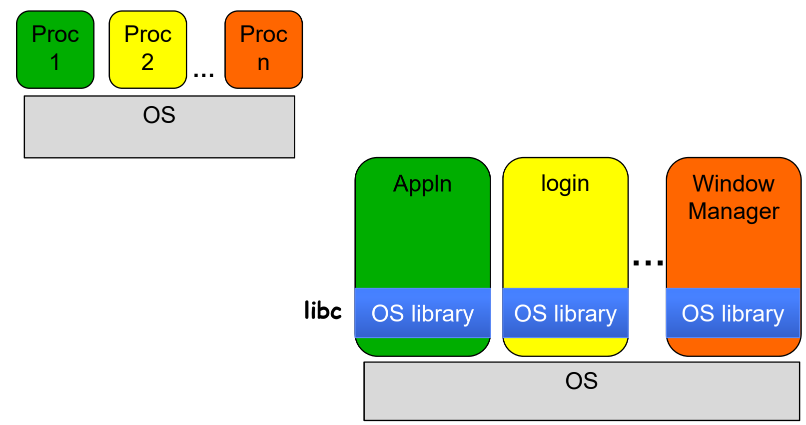


- As a process executes, it changes state:
  - new: The process is being created
  - ready: The process is waiting to run
  - running: Instructions are being executed
  - waiting: Process waiting for some event to occur
  - terminated: The process has finished execution

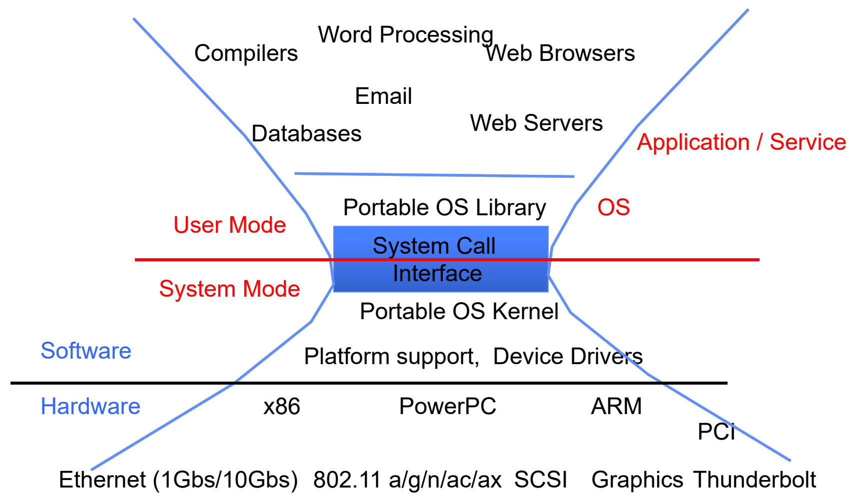
Discussion

- Process is an *instance* of an *executing* program
  - The fundamental OS responsibility
  - Each instance has an identity (Process ID) or PID
- Processes do their work by processing and calling file system operations
  - This involves interacting with the Kernel!
  - How do we do that?
- Are their any operations on processes themselves?
  - create (fork) ?
  - terminate (exit) ?
  - sleep (sleep) ?
  - communicate with (e.g. signal)?

OS Run-Time Library



A Narrow Waist



pid.c

ps anyone?

```
#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);
}
```


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

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
  - This means everything!
  - 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
- If no error: State of original process duplicated in *both* Parent and Child!
  - Address Space (Memory), File Descriptors (covered later), etc…
  - Not as bad as it seems – really only copy page table [more later]

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

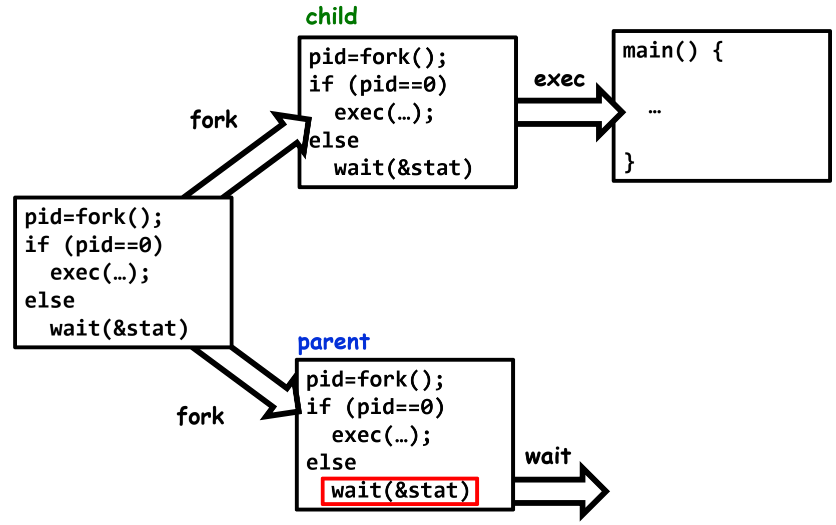
`fork2.c` – parent waits for child to finish

```
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);
  exit(42);
}
…
```

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?

Administrivia

- Kubiatowicz Office Hours:
  - 1-2pm, Monday & Thursday
- No one left on WaitList or Concurrent Enrollment List!
  - Everyone who wants to be in the class.
- TOMORROW (Friday) is Drop Deadline!
  VERY HARD TO DROP LATER!
- Recommendation: Read assigned readings *before* lecture
- You should be going to sections now – Important information covered in section
  - Any section will do until groups assigned
- 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 next week

Reminder: Definitions

- A *thread* is a single execution sequence that represents a separately schedulable task
- Protection is an orthogonal concept
  - Can have one or many threads per protection domain
  - Single threaded user program: one thread, one protection domain
  - Multi-threaded user program: multiple threads, sharing same data structures, isolated from other user programs
  - Multi-threaded kernel: multiple threads, sharing kernel data structures, capable of using privileged instructions

Threads Motivation

- Operating systems need to be able to handle *multiple things at once* (MTAO)
  - processes, interrupts, background system maintenance
- Servers need to handle MTAO
  - Multiple connections handled simultaneously
- Parallel programs need to handle MTAO
  - To achieve better performance
- Programs with user interfaces often need to handle MTAO
  - To achieve user responsiveness while doing computation
- Network and disk bound programs need to handle MTAO
  - To hide network/disk latency
  - Sequence steps in access or communication

Silly Example for Threads

Imagine the following program:

```
main() {
    ComputePI("pi.txt");
    PrintClassList("classlist.txt");
}
```

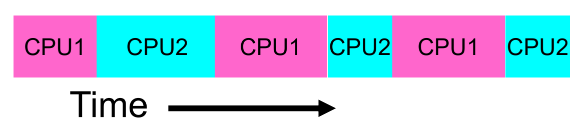
- What is the behavior here?
  - Program would never print out class list
  - Why? `ComputePI` would never finish

Adding Threads

- Version of program with Threads (loose syntax):

```
main() {
    thread_fork(ComputePI, "pi.txt" ));
    thread_fork(PrintClassList, "classlist.txt"));
}
```

- `thread_fork`: Start independent thread running given procedure
- What is the behavior here?
  - Now, you would actually see the class list
  - This *should* behave as if there are two separate CPUs



More Practical Motivation

Back to Jeff Dean's "Numbers everyone should know“:

Handle I/O in separate thread, avoid blocking other progress

L1 cache reference	0.5 ns
Branch mispredict	5 ns
L2 cache reference	7 ns
Mutex lock/unlock	25 ns
Main memory reference	100 ns
Compress 1K bytes with Zippy	3,000 ns
Send 2K bytes over 1 Gbps network	20,000 ns
Read 1 MB sequentially from memory	250,000 ns
Round trip within same datacenter	500,000 ns
Disk seek	10,000,000 ns
Read 1 MB sequentially from disk	20,000,000 ns
Send packet CA->Netherlands->CA	150,000,000 ns

Little Better Example for Threads?

Imagine the following program:

```
main() {
  …
    ReadLargeFile(“pi.txt”);
    RenderUserInterface();
}
```

- What is the behavior here?
  – Still respond to user input
  – While reading file in the background

Voluntarily Giving Up Control

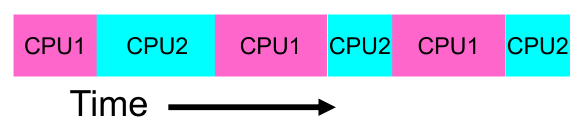
- I/O – e.g. keypress
- Waiting for a signal from another thread
  – Thread makes system call to *wait*
- Thread executes `thread_yield()`
  – Relinquishes CPU but puts calling thread back on ready queue

Adding Threads

- Version of program with Threads (loose syntax):

```
main() {
    thread_fork(ReadLargeFile, “pi.txt” );
    thread_fork(RenderUserInterface, “classlist.txt”);
}
```

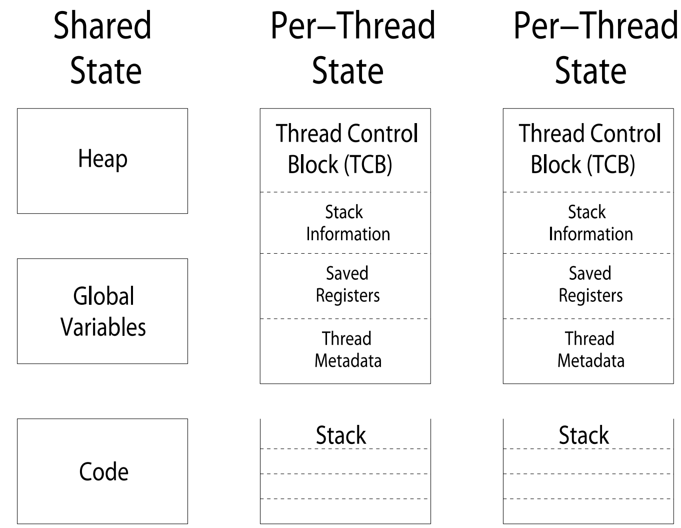
- `thread_fork`: Start independent thread running given procedure
- What is the behavior here?
  – Now, you would actually see the class list
  – This *should* behave as if there are two separate CPUs



Thread State

- State shared by all threads in process/address space
  – Content of memory (global variables, heap)
  – I/O state (file descriptors, network connections, etc)
- State "private" to each thread
  – Kept in TCB ≡ Thread Control Block
  – CPU registers (including, program counter)
  – Execution stack – what is this?
- Execution Stack
  – Parameters, temporary variables
  – Return PCs are kept while called procedures are executing

Shared vs. Per-Thread State



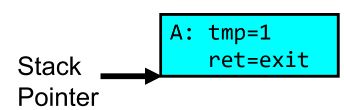
Execution Stack Example

```
      A(int tmp) {
A:      if (tmp<2)
A+1:      B();
A+2:    printf(tmp);
      }
      B() {
B:      C();
B+1:  }
      C() {
C:      A(2);
C+1:  }
      A(1);
exit:
```

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
      A(int tmp) {
A:      if (tmp<2)
A+1:      B();
A+2:    printf(tmp);
      }
      B() {
B:      C();
B+1:  }
      C() {
C:      A(2);
C+1:  }
      A(1);
exit:
```



- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
     A(int tmp) {
  A:   if (tmp<2)
A+1:     B();
A+2:   printf(tmp);
     }
     B() {
  B:   C();
B+1: }
     C() {
  C:   A(2);
C+1: }
     A(1);
exit:
```

Stack Pointer →

```
A: tmp=1
   ret=exit
```

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
     A(int tmp) {
  A:   if (tmp<2)
A+1:     B();
A+2:   printf(tmp);
     }
     B() {
  B:   C();
B+1: }
     C() {
  C:   A(2);
C+1: }
     A(1);
exit:
```

Stack Pointer →

```
A: tmp=1
   ret=exit
```

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
     A(int tmp) {
  A:   if (tmp<2)
A+1:     B();
A+2:   printf(tmp);
     }
     B() {
  B:   C();
B+1: }
     C() {
  C:   A(2);
C+1: }
     A(1);
exit:
```

```
A: tmp=1
   ret=exit
B: ret=A+2
```

Stack Pointer →

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
     A(int tmp) {
  A:   if (tmp<2)
A+1:     B();
A+2:   printf(tmp);
     }
     B() {
  B:   C();
B+1: }
     C() {
  C:   A(2);
C+1: }
     A(1);
exit:
```

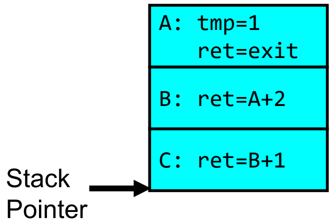
```
A: tmp=1
   ret=exit
B: ret=A+2
```

Stack Pointer →

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

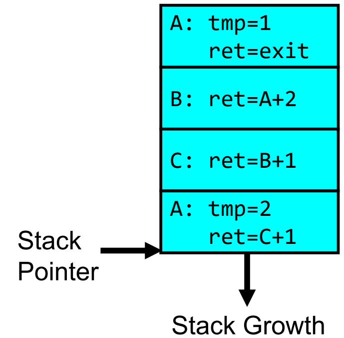
```
      A(int tmp) {
A:      if (tmp<2)
A+1:      B();
A+2:    printf(tmp);
      }
      B() {
B:      C();
B+1:  }
      C() {
C:      A(2);
C+1:  }
      A(1);
exit:
```



- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

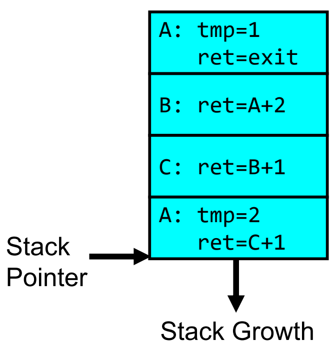
```
      A(int tmp) {
A:      if (tmp<2)
A+1:      B();
A+2:    printf(tmp);
      }
      B() {
B:      C();
B+1:  }
      C() {
C:      A(2);
C+1:  }
      A(1);
exit:
```



- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
      A(int tmp) {
A:      if (tmp<2)
A+1:      B();
A+2:    printf(tmp);
      }
      B() {
B:      C();
B+1:  }
      C() {
C:      A(2);
C+1:  }
      A(1);
exit:
```

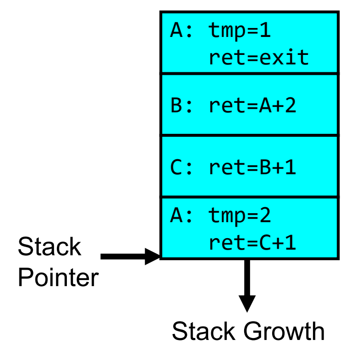


Output: >2

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
      A(int tmp) {
A:      if (tmp<2)
A+1:      B();
A+2:    printf(tmp);
      }
      B() {
B:      C();
B+1:  }
      C() {
C:      A(2);
C+1:  }
      A(1);
exit:
```



Output: >2

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
        A(int tmp) {
A:        if (tmp<2)
A+1:        B();
A+2:      printf(tmp);
        }
        B() {
B:        C();
B+1:    }
        C() {
C:        A(2);
C+1:    }
        A(1);
exit:
```

```
A: tmp=1
   ret=exit
B: ret=A+2
C: ret=B+1
```

Stack Pointer

Output: >2

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
        A(int tmp) {
A:        if (tmp<2)
A+1:        B();
A+2:      printf(tmp);
        }
        B() {
B:        C();
B+1:    }
        C() {
C:        A(2);
C+1:    }
        A(1);
exit:
```

```
A: tmp=1
   ret=exit
B: ret=A+2
```

Stack Pointer

Output: >2

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
        A(int tmp) {
A:        if (tmp<2)
A+1:        B();
A+2:      printf(tmp);
        }
        B() {
B:        C();
B+1:    }
        C() {
C:        A(2);
C+1:    }
        A(1);
exit:
```

```
A: tmp=1
   ret=exit
```

Stack Pointer

Output: >2 1

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
        A(int tmp) {
A:        if (tmp<2)
A+1:        B();
A+2:      printf(tmp);
        }
        B() {
B:        C();
B+1:    }
        C() {
C:        A(2);
C+1:    }
        A(1);
exit:
```

```
A: tmp=1
   ret=exit
```

Stack Pointer

Output: >2 1

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

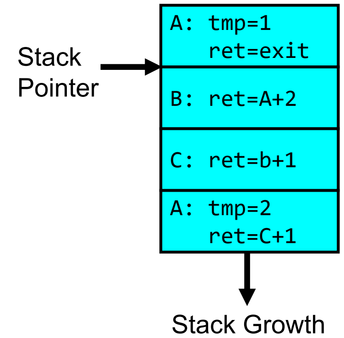
```
A(int tmp) {
  if (tmp<2)
    B();
  printf(tmp);
}
B() {
  C();
}
C() {
  A(2);
}
A(1);
```

Output: `>2 1`

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

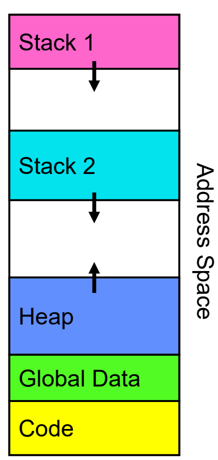
```
A(int tmp) {
  if (tmp<2)
    B();
  printf(tmp);
}
B() {
  C();
}
C() {
  A(2);
}
A(1);
```



- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Memory Footprint: Two-Threads

- If we stopped this program and examined it with a debugger, we would see
  - Two sets of CPU registers
  - Two sets of Stacks
- Questions:
  - How do we position stacks relative to each other?
  - What maximum size should we choose for the stacks?
  - What happens if threads violate this?
  - How might you catch violations?



Actual Thread Operations

- `thread_fork(func, args)`
  - Create a new thread to run func(args)
  - Pintos: `thread_create`
- `thread_yield()`
  - Relinquish processor voluntarily
  - Pintos: `thread_yield`
- `thread_join(thread)`
  - In parent, wait for forked thread to exit, then return
  - Pintos: `thread_join`
- `thread_exit`
  - Quit thread and clean up, wake up joiner if any
  - Pintos: `thread_exit`
- `pThreads`: POSIX standard for thread programming [POSIX.1c, Threads extensions (IEEE Std 1003.1c-1995)]

Dispatch Loop

- Conceptually, the dispatching loop of the operating system looks as follows:

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

- This is an *infinite* loop
  – One could argue that this is all that the OS does
- Should we ever exit this loop???
  – When would that be?

Running a thread

Consider first portion: `RunThread()`

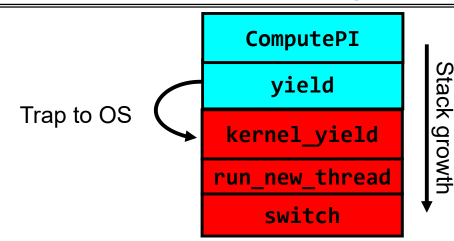
- How do I run a thread?
  – Load its state (registers, PC, stack pointer) into CPU
  – Load environment (virtual memory space, etc)
  – Jump to the PC
- How does the dispatcher get control back?
  – Internal events: thread returns control voluntarily
  – External events: thread gets *preempted*

Internal Events

- Blocking on I/O
  – The act of requesting I/O implicitly yields the CPU
- Waiting on a "signal" from other thread
  – Thread asks to wait and thus yields the CPU
- Thread executes a `yield()`
  – Thread volunteers to give up CPU

```
computePI() {
   while(TRUE) {
      ComputeNextDigit();
      yield();
   }
}
```


Stack for Yielding Thread



- How do we run a new thread?

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

- How does dispatcher switch to a new thread?
  – Save anything next thread may trash: PC, regs, stack pointer
  – Maintain isolation for each thread

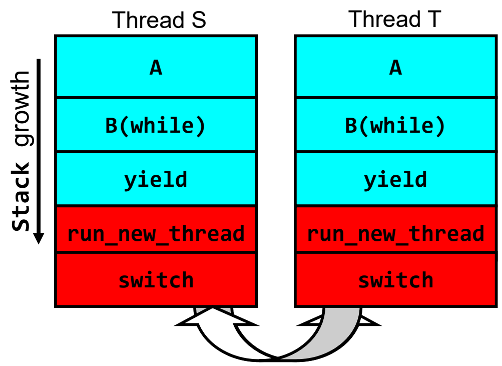
What Do the Stacks Look Like?

- 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 */
}
```

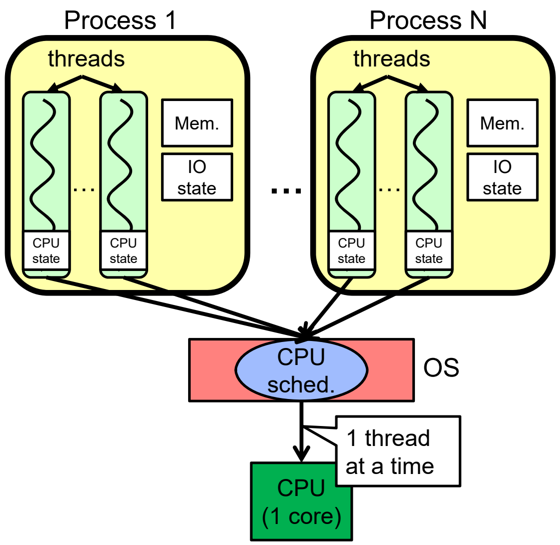

Switch Details (continued)

- What if you make a mistake in implementing switch?
  – Suppose you forget to save/restore register 32
  – Get intermittent failures depending on when context switch occurred and whether new thread uses register 32
  – System will give wrong result without warning
- Can you devise an exhaustive test to test switch code?
  – No! Too many combinations and inter-leavings
- Cautionary tale:
  – For speed, Topaz kernel saved one instruction in switch()
  – Carefully documented! Only works as long as kernel size < 1MB
  – What happened?
    » Time passed, People forgot
    » Later, they added features to kernel (no one removes features!)
    » Very weird behavior started happening
  – Moral of story: Design for simplicity

Aren't we still switching contexts?

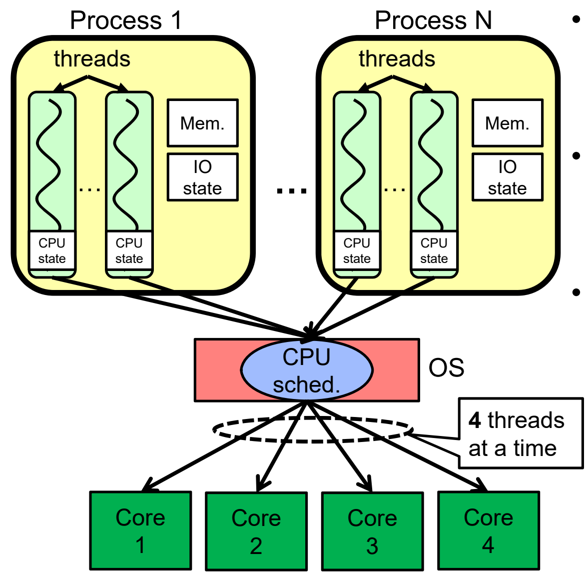
- Yes, but much cheaper than switching processes
  – No need to change address space
- Some numbers from Linux:
  – Frequency of context switch: 10-100ms
  – Switching between processes: 3-4 μsec.
  – Switching between threads: 100 ns

Processes vs. Threads



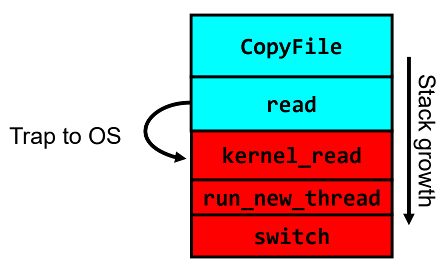
- Switch overhead:
  - Same process: **low**
  - Different proc.: **high**
- Protection
  - Same proc: **low**
  - Different proc: **high**
- Sharing overhead
  - Same proc: **low**
  - Different proc: **high**

Processes vs. Threads



- Switch overhead:
  - Same process: **low**
  - Different proc.: **high**
- Protection
  - Same proc: **low**
  - Different proc: **high**
- Sharing overhead
  - Same proc: **low**
  - Different proc: **high**

What happens when thread blocks on I/O?

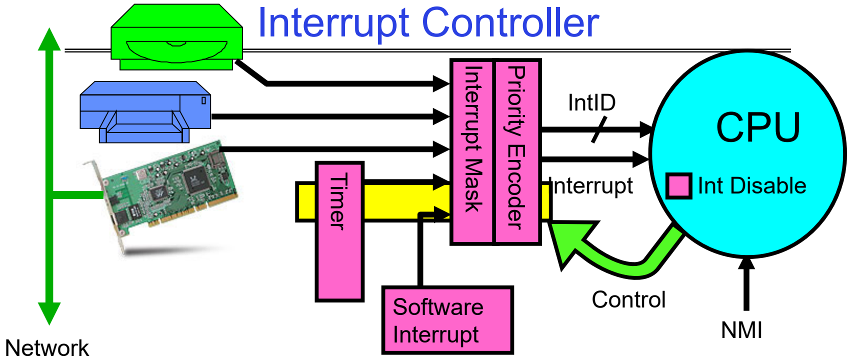


- What happens when a thread requests a block of data from the file system?
  - User code invokes a system call
  - Read operation is initiated
  - Run new thread/switch
- Thread communication similar
  - Wait for Signal/Join
  - Networking

External Events

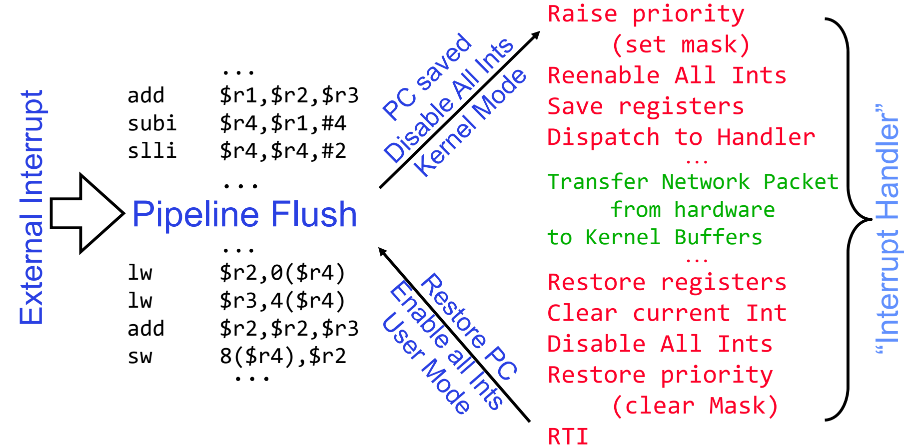
- What happens if thread never does any I/O, never waits, and never yields control?
  - Could the `ComputePI` program grab all resources and never release the processor?
    - » What if it didn't print to console?
  - Must find way that dispatcher can regain control!
- Answer: utilize external events
  - Interrupts: signals from hardware or software that stop the running code and jump to kernel
  - Timer: like an alarm clock that goes off every some milliseconds
- If we make sure that external events occur frequently enough, can ensure dispatcher runs

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

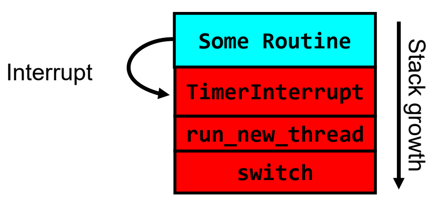
Example: Network Interrupt



- An interrupt is a hardware-invoked context switch
  - No separate step to choose what to run next
  - Always run the interrupt handler immediately

Use of Timer Interrupt to Return Control

- Solution to our dispatcher problem
  - Use the timer interrupt to force scheduling decisions



- Timer Interrupt routine:

```
TimerInterrupt() {
   DoPeriodicHouseKeeping();
   run_new_thread();
}
```


Hardware context switch support in x86

- 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);

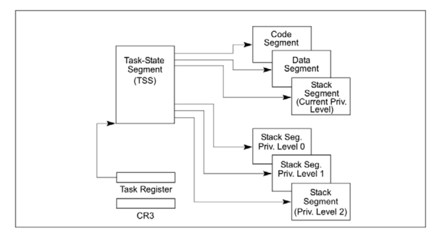
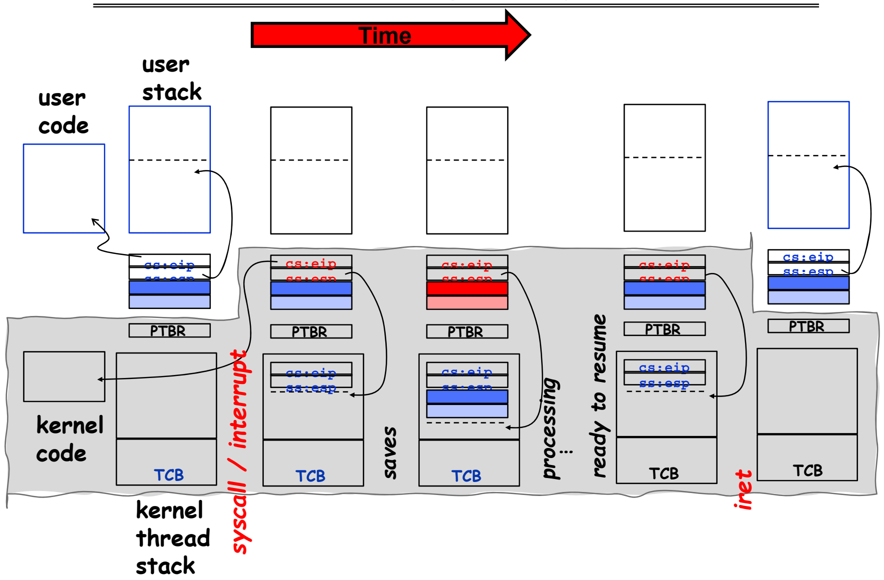


Figure 7-1. Structure of a Task

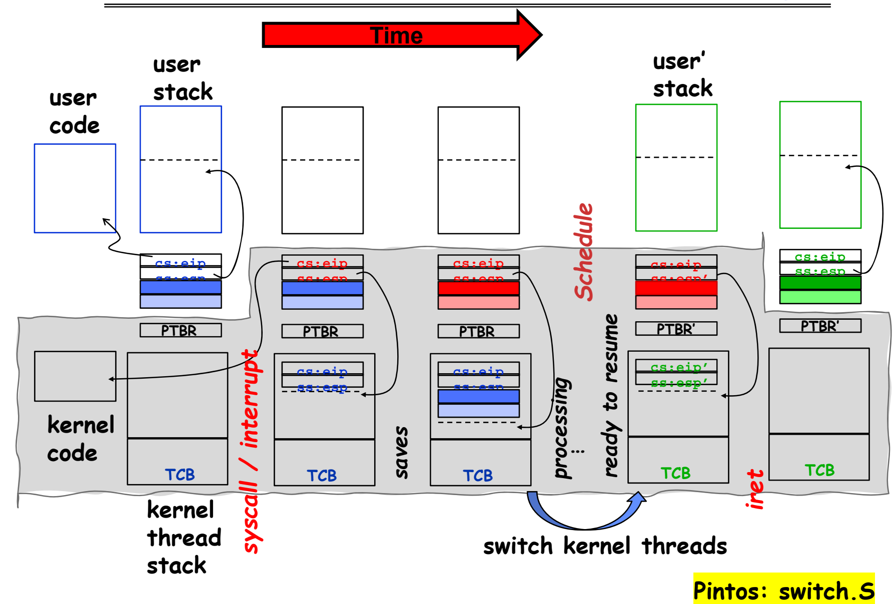
pg 2,942 of 4,922 of x86 reference manual

Pintos: tss.c, intr-stubs.S

Pintos: Kernel Crossing on Syscall or Interrupt



Pintos: Context Switch – Scheduling

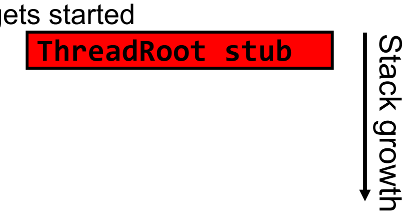


`ThreadFork()`: Create a New Thread

- `ThreadFork()` is a user-level procedure that creates a new thread and places it on ready queue
- Arguments to `ThreadFork()`
  - Pointer to application routine (`fcnPtr`)
  - Pointer to array of arguments (`fcnArgPtr`)
  - Size of stack to allocate
- Implementation
  - Sanity check arguments
  - Enter Kernel-mode and Sanity Check arguments again
  - Allocate new Stack and TCB
  - Initialize TCB and place on ready list (Runnable)

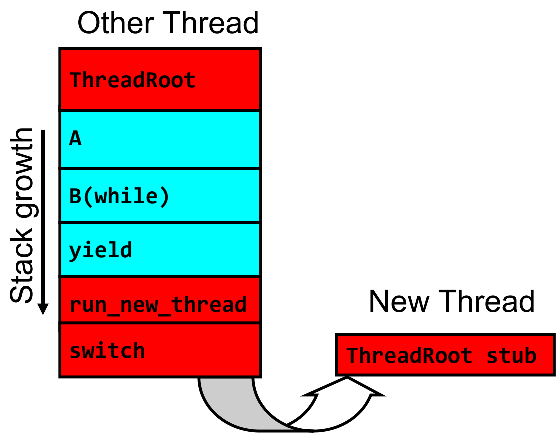
How do we initialize TCB and Stack?

- Initialize Register fields of TCB
  - Stack pointer made to point at stack
  - PC return address ⇒ OS (asm) routine `ThreadRoot()`
  - Two arg registers (a0 and a1) initialized to `fcnPtr` and `fcnArgPtr`, respectively
- Initialize stack data?
  - No. Important part of stack frame is in registers (ra)
  - Think of stack frame as just before body of `ThreadRoot()` really gets started



Initial Stack

How does Thread get started?

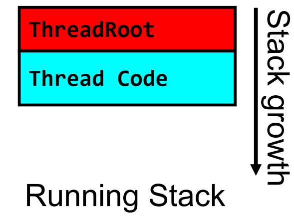


- Eventually, `run_new_thread()` will select this TCB and return into beginning of `ThreadRoot()`
  - This really starts the new thread

What does `ThreadRoot()` look like?

- `ThreadRoot()` is the root for the thread routine:

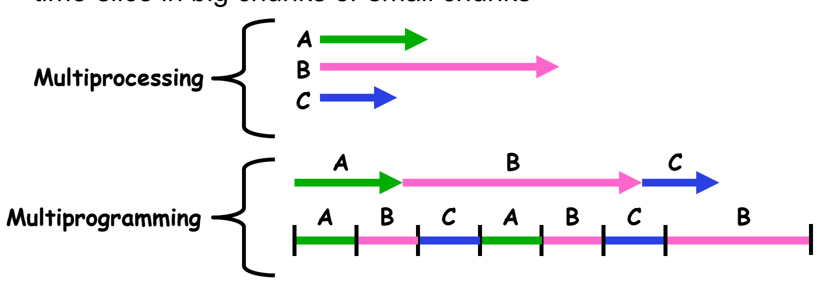
```
ThreadRoot() {
   DoStartupHousekeeping();
   UserModeSwitch(); /* enter user mode */
   Call fcnPtr(fcnArgPtr);
   ThreadFinish();
}
```



- Startup Housekeeping
  - Includes things like recording start time of thread
  - Other statistics
- Stack will grow and shrink with execution of thread
- Final return from thread returns into `ThreadRoot()` which calls `ThreadFinish()`
  - `ThreadFinish()` wake up sleeping threads

Multiprocessing vs Multiprogramming

- Remember Definitions:
  - Multiprocessing ≡ Multiple CPUs
  - Multiprogramming ≡ Multiple Jobs or Processes
  - Multithreading ≡ Multiple threads per Process
- What does it mean to run two threads "concurrently"?
  - Scheduler is free to run threads in any order and interleaving: FIFO, Random, …
  - Dispatcher can choose to run each thread to completion or time-slice in big chunks or small chunks



Correctness for systems with concurrent threads

- If dispatcher can schedule threads in any way, programs must work under all circumstances
  - Can you test for this?
  - How can you know if your program works?
- Independent Threads:
  - No state shared with other threads
  - Deterministic ⇒ Input state determines results
  - Reproducible ⇒ Can recreate Starting Conditions, I/O
  - Scheduling order doesn't matter (if `switch()` works!!!)
- Cooperating Threads:
  - Shared State between multiple threads
  - Non-deterministic
  - Non-reproducible
- Non-deterministic and Non-reproducible means that bugs can be intermittent
  - Sometimes called "Heisenbugs"

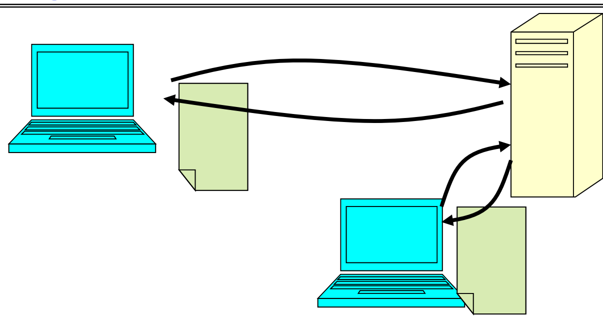
Interactions Complicate Debugging

- Is any program truly independent?
  - Every process shares the file system, OS resources, network, etc
  - Extreme example: buggy device driver causes thread A to crash "independent thread" B
- You probably don't realize how much you depend on reproducibility:
  - Example: Evil C compiler
    - » Modifies files behind your back by inserting errors into C program unless you insert debugging code
  - Example: Debugging statements can overrun stack
- Non-deterministic errors are really difficult to find
  - Example: Memory layout of kernel+user programs
    - » depends on scheduling, which depends on timer/other things
    - » Original UNIX had a bunch of non-deterministic errors
  - Example: Something which does interesting I/O
    - » User typing of letters used to help generate secure keys

Why allow cooperating threads?

- People cooperate; computers help/enhance people's lives, so computers must cooperate
  - By analogy, the non-reproducibility/non-determinism of people is a notable problem for "carefully laid plans"
- Advantage 1: Share resources
  - One computer, many users
  - One bank balance, many ATMs
    - » What if ATMs were only updated at night?
  - Embedded systems (robot control: coordinate arm & hand)
- Advantage 2: Speedup
  - Overlap I/O and computation
    - » Many different file systems do read-ahead
  - Multiprocessors – chop up program into parallel pieces
- Advantage 3: Modularity
  - More important than you might think
  - Chop large problem up into simpler pieces
    - » To compile, for instance, gcc calls cpp | cc1 | cc2 | as | ld
    - » Makes system easier to extend

High-level Example: Web Server



- Server must handle many requests
- Non-cooperating version:

```
serverLoop() {
    con = AcceptCon();
    ProcessFork(ServiceWebPage(),con);
}
```

- What are some disadvantages of this technique?

Threaded Web Server

- Now, use a single process
- Multithreaded (cooperating) version:

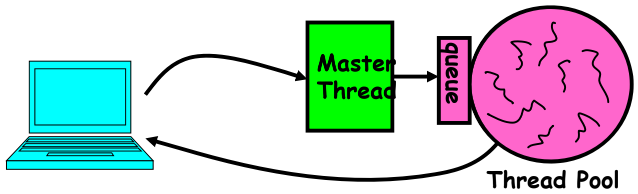
```
serverLoop() {
    connection = AcceptCon();
    ThreadFork(ServiceWebPage(),connection);
}
```

- Looks almost the same, but has many advantages:
  - Can share file caches kept in memory, results of CGI scripts, other things
  - Threads are *much* cheaper to create than processes, so this has a lower per-request overhead
- Question: would a user-level (say one-to-many) thread package make sense here?
  - When one request blocks on disk, all block…
- What about Denial of Service attacks or digg / Slash-dot effects?

digg Slashdot News for Nerds. Stuff that matters.

Thread Pools

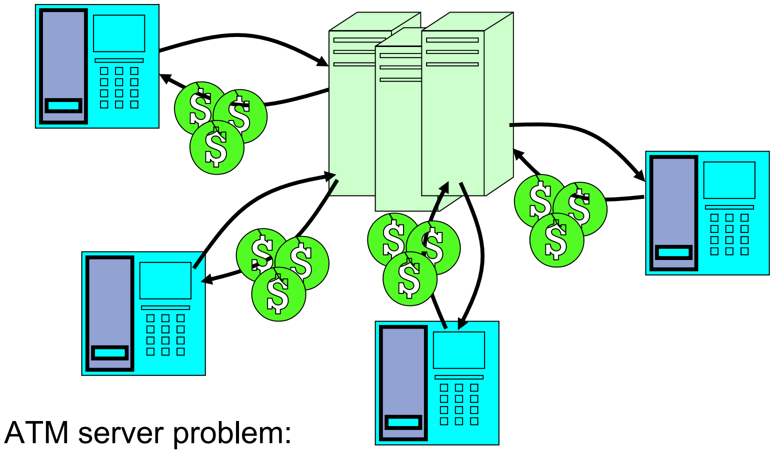
- Problem with previous version: Unbounded Threads
  – When web-site becomes too popular – throughput sinks
- Instead, allocate a bounded "pool" of worker threads, representing the maximum level of multiprogramming




```
master() {
    allocThreads(worker,queue);
    while(TRUE) {
        con=AcceptCon();
        Enqueue(queue,con);
        wakeUp(queue);
    }
}
```

```
worker(queue) {
    while(TRUE) {
        con=Dequeue(queue);
        if (con==null)
            sleepOn(queue);
        else
            ServiceWebPage(con);
    }
}
```


ATM Bank Server



- ATM server problem:
  – Service a set of requests
  – Do so without corrupting database
  – Don't hand out too much money

ATM bank server example

- Suppose we wanted to implement a server process to handle requests from an ATM network:

```
BankServer() {
    while (TRUE) {
        ReceiveRequest(&op, &acctId, &amount);
        ProcessRequest(op, acctId, amount);
    }
}
ProcessRequest(op, acctId, amount) {
    if (op == deposit) Deposit(acctId, amount);
    else if …
}
Deposit(acctId, amount) {
    acct = GetAccount(acctId); /* may use disk I/O */
    acct->balance += amount;
    StoreAccount(acct); /* Involves disk I/O */
}
```

- How could we speed this up?
  – More than one request being processed at once
  – Event driven (overlap computation and I/O)
  – Multiple threads (multi-proc, or overlap comp and I/O)

Event Driven Version of ATM server

- Suppose we only had one CPU
  – Still like to overlap I/O with computation
  – Without threads, we would have to rewrite in event-driven style
- Example

```
BankServer() {
    while(TRUE) {
        event = WaitForNextEvent();
        if (event == ATMRequest)
            StartOnRequest();
        else if (event == AcctAvail)
            ContinueRequest();
        else if (event == AcctStored)
            FinishRequest();
    }
}
```

  – What if we missed a blocking I/O step?
  – What if we have to split code into hundreds of pieces which could be blocking?
  – This technique is used for graphical programming

Can Threads Make This Easier?

- Threads yield overlapped I/O and computation without “deconstructing” code into non-blocking fragments
  – One thread per request
- Requests proceeds to completion, blocking as required:

```
Deposit(acctId, amount) {
  acct = GetAccount(actId); /* May use disk I/O */
  acct->balance += amount;
  StoreAccount(acct);      /* Involves disk I/O */
}
```

- Unfortunately, shared state can get corrupted:

```
        Thread 1                          Thread 2
load r1, acct->balance
                                  load r1, acct->balance
                                  add r1, amount2
                                  store r1, acct->balance
add r1, amount1
store r1, acct->balance
```


Summary

- Processes have two parts
  – One or more Threads (Concurrency)
  – Address Spaces (Protection)
- Threads: unit of concurrent execution
  – Useful for parallelism, overlapping computation and IO, organizing sequences of interactions (protocols)
  – Require: multiple stacks per address space
  – Thread switch:
    » Save/Restore registers, "return" from new thread's `switch` routine
- Concurrency accomplished by multiplexing CPU Time:
  – Unloading current thread (PC, registers)
  – Loading new thread (PC, registers)
  – Such context switching may be voluntary (`yield()`, I/O operations) or involuntary (timer, other interrupts)
- Concurrent threads introduce problems when accessing shared data
  – Programs must be insensitive to arbitrary interleavings
  – Without careful design, shared variables can become completely inconsistent