# INF333 - Operating Systems

## Lecture III

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Lecture III
2025-02-26

# Course website

burakarslan.com/inf333

# Based On

cs111.stanford.edu

cs212.stanford.edu

OSC-10 Slides

# Protection

**Protection**: Mechanisms to isolate programs

# Protection

## Pre-emption

Pre-emption:

- Give application a resource, take it away if needed elsewhere

# Protection

## Mediation

Interposition/mediation:

- Place OS between application and resources
- Keep track all pieces that application allowed to use
- On every access, ensure that access is valid/allowed

# Protection

## CPU Privilege Modes

CPU Privilege Modes aka. **Rings** in Intel parlance:

Privileged & unprivileged modes in CPUs

- Applications un in unprivileged mode (user mode)
- OS runs in privileged mode (supervisor/kernel mode)
- Protection operations can only be done in privileged mode
- Rings 0 (real mode) through 4 (user mode), later negative rings were added[1]

[1] Not hardware-enforced

# Protection

## Example: CPU preemption

**CPU preemption**:

Protection mechanism to prevent monopolizing CPU

# Protection

## Example: CPU preemption

### How?

One way is for the kernel to program a timer to interrupt every, say, 10 ms

- Must be in supervisor mode to write to appropriate I/O registers
- User code cannot re-program interval timer
- This is called a **tick**. [2]

[2] It's popular yet suboptimal way: See "(Nearly) full tickless operation in [Linux] 3.10"

# Protection

## Example: CPU preemption

Kernel sets interrupt service routine to return to kernel:

- Regains control whenever interval timer fires
- Gives CPU to another process if someone else needs it
- No way for user code to hijack interrupt handler

**Result:** Cannot monopolize CPU with infinite loop

- At worst get 1/N of CPU with N CPU-hungry processes

# Protection

## Example: CPU preemption

This is technique doesn't protect against:

- A malicious user constantly starting new processes
- A malicious user constantly allocating memory

Possible solutions:

- Yell at the guy who's doing it (no, seriously)
- Remove that app from the play store
- Enforce per-user resource limits

# Protection

## Address translation

Goal of Address translation:

Protect memory of one program from actions of another

# Protection

## Address translation

Definitions:

- *Address space*: all memory locations a program can name
- *Virtual address*: addresses in process' address space
- *Physical address*: actual address of data in memory
- *Translation*: map virtual to physical addresses

# Protection

## Address translation

Translation done on every load, store, and instruction fetch

- Modern CPUs do this in hardware for speed

**Idea**: If you can't name it, you can't touch it

- Ensure one process' translations don't include any other process' memory

# Protection

## More memory protection

CPU allows kernel-only virtual addresses

- Kernel typically part of all address spaces,
  e.g., to handle system call in same address space
- But must ensure apps can't touch kernel memory

# Protection

## More memory protection

CPU lets OS disable (invalidate) particular virtual addresses

- Catch and halt buggy program that makes wild accesses
- Make virtual memory seem bigger than physical (e.g., bring a page in from disk only when accessed)

# Protection

## More memory protection

CPU-enforced read-only virtual addresses are quite useful

- E.g., allows sharing of code pages between processes
- Plus many other optimizations

CPU-enforced "execute disable[3]" of VAs

- Makes certain code injection attacks harder

---

[3] chmod -x for memory pages

# Protection

## Different system contexts I

At any point, a CPU (core) is in one of several contexts:

- *User-level* – CPU in user mode running application
- Kernel process context – i.e., running kernel code on behalf of a particular process
  - E.g., performing system call, handling exception (memory fault, numeric exception, etc.)
  - Or executing a kernel-only process (e.g., network file server)

# Protection

## Different system contexts II

(cont'd)

- Kernel code not associated with a process
  - Timer interrupt (hardclock)
  - Device interrupt
  - "Softirqs", "Tasklets" (Linux-specific terms)
- Context switch code – change which process is running
  - Requires changing the current address space
- Idle – nothing to do (bzero pages, put CPU in low-power state)

# Protection

## Transitions between contexts

CPU context transitions:

- User $\rightarrow$ kernel process context: syscall, page fault, ...
- User/process context $\rightarrow$ interrupt handler: hardware
- Process context $\rightarrow$ user/context switch: return
- Process context $\rightarrow$ context switch: sleep
- Context switch $\rightarrow$ user/process context

# Protection

## Resource allocation & performance

Multitasking permits higher resource utilization.

Simple example:

- Process downloading large file mostly waits for network
- You play a game while downloading the file
- Higher CPU utilization than if just downloading

# Protection

## Transitions between contexts

Complexity arises with cost of switching:

Example: Say disk 1,000 times slower than memory:

- 1 GiB memory in machine
- 2 Processes want to run, each use 1 GiB
- Can switch processes by swapping them out to disk
- Faster to run one at a time than keep context switching

# Processes, Threads, Procedures

# Programs

A **program** is (among other things) a sequence of instructions.

- All programs need to have at least one entry point

# Programs

Operating systems[4] model and orchestrate program execution via certain entities:

- Process
- Thread
- Procedure

[4] and/or threading libraries, compilers and interpreters/virtual machines

# Processes

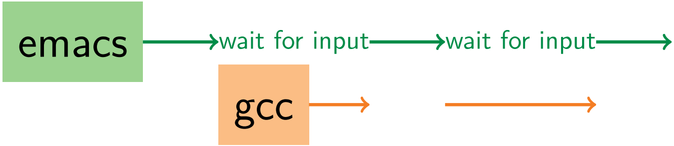
A **process** is an instance of a program running.

- It's a specific way of calling the `main()` function.
- Examples (can all run simultaneously):
  - `gcc file_A.c` – compiler running on file A
  - `gcc file_B.c` – compiler running on file B
  - `emacs` – text editor
  - `firefox` – web browser

# Better Resource Utilization

Multiple processes can increase CPU utilization

- Overlap one process's computation with another's wait

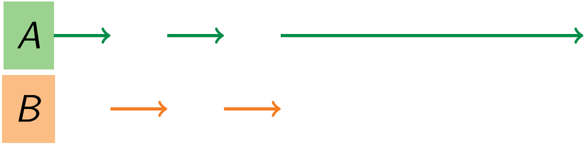


# Better Resource Utilization

Multiple processes can reduce latency

- Running $A$ then $B$ requires 100 sec for $B$ to complete


- Running $A$ and $B$ concurrently makes $B$ finish faster




- $A$ is slower than if it had whole machine to itself, but still $< 100$ sec unless both $A$ and $B$ completely CPU-bound

# Processes in the real world I

Processes and parallelism have been a fact of life much longer than OSes have been around

- E.g., say it takes 1 worker 10 months to make 1 widget
- Company may hire 100 workers to make 100 widgets
- Latency for first widget $\gg 1/10$ month
- Throughput may be $< 10$ widgets per month
  (if can't perfectly parallelize task)
- Or 100 workers making 10,000 widgets may achieve $> 10$ widgets/month (e.g., if workers never idly wait for paint to dry)

# Processes in the real world II

You will see these effects in your Pintos project group

- May block waiting for partner to complete task
- Takes time to coordinate/explain/understand one another's code
- Labs will take $> 1/2$ time with two people
- But you will graduate faster than if you took only 1 class at a time

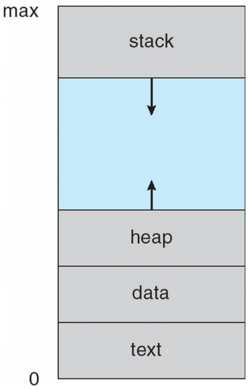
# A process's view of the world

Each process has own view of machine

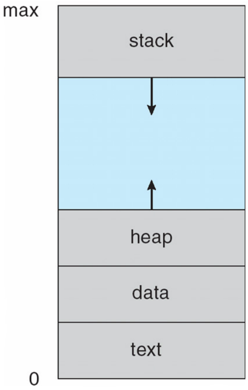
- Its own address space – `*(char *)0xc000` different in $P_1$ & $P_2$
- Its own open files
- Its own virtual CPU (through preemptive multitasking)

Simplifies programming model

- `gcc` does not care that `firefox` is running



# A process's view of the world




Sometimes want interaction between processes

- Simplest is through files: `emacs` edits file, `gcc` compiles it
- More complicated: Shell/command, Window manager/app.

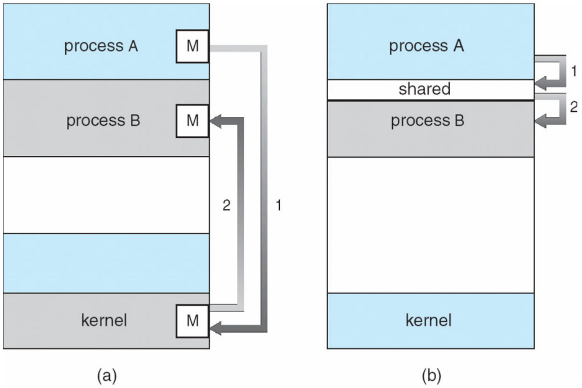
# Inter-Process Communication

How can processes interact in real time?

**(a)** By passing messages through the kernel

**(b)** By sharing a region of physical memory

**(c)** Through asynchronous signals or alerts



# Process Management

## Creating processes

```
int fork(void);
```

- Create new process that is exact copy of current one
- Returns *process ID* of new process in “parent”
- Returns 0 in “child”

# Process Management

## Deleting processes

```
int waitpid(int pid, int *stat, int opt);
```

- `pid` – process to wait for, or -1 for any
- `stat` – will contain exit value, or signal
- `opt` – usually 0 or `WNOHANG`
- Returns process ID or -1 on error

# Process Management

## Deleting processes

```
void exit(int status);
```

- Current process ceases to exist
- `status` shows up in `waitpid`
- By convention, `status` of 0 is success, non-zero error

# Process Management

## Deleting processes

```
int kill (int pid, int sig);
```

- Sends signal `sig` to process `pid`
- `SIGTERM` most common value, kills process by default (but application can catch it for "cleanup")
- `SIGKILL` stronger, kills process always

# Process Management

## Running programs

`int execve (char *prog, char **argv, char **envp);`

- `prog` – full pathname of program to run
- `argv` – argument vector that gets passed to `main`
- `envp` – environment variables, e.g., `PATH`, `HOME`

Generally called through a wrapper functions

- `int execvp (char *prog, char **argv);`
  Search `PATH` for prog, use current environment
- `int execlp (char *prog, char *arg, ...);`
  List arguments one at a time, finish with `NULL`

Example: `minish.c`

- Loop that reads a command, then executes it

# minish.c (simplified)

```
pid_t pid; char **av;
void doexec () {
  execvp (av[0], av);
  perror (av[0]);
  exit (1);
}
    /* ... main loop: */
    for (;;) {
      parse_next_line_of_input (&av, stdin);
      switch (pid = fork ()) {
      case -1:
        perror ("fork"); break;
      case 0:
        doexec ();
      default:
        waitpid (pid, NULL, 0); break;
      }
    }
```

# Manipulating file descriptors I

```
int dup2 (int oldfd, int newfd);
```

- Closes `newfd`, if it was a valid descriptor
- Makes `newfd` an exact copy of `oldfd`
- Two file descriptors will share same offset (`lseek` on one will affect both)

# Manipulating file descriptors II

`int fcntl (int fd, int cmd, ...)`: Misc fd config

- `fcntl (fd, F_SETFD, val)` sets close-on-exec flag.
  - When `val` $\neq 0$, `fd` is not inherited by spawned programs
- `fcntl (fd, F_GETFL)` – get misc fd flags
- `fcntl (fd, F_SETFL, val)` – set misc fd flags

# Manipulating file descriptors III

Example: `redirsh.c`

- Loop that reads a command and executes it
- Recognizes `command < input > output 2> errlog`

# redirsh.c

```
void doexec (void) {
  int fd;
  if (infile) {     /* non-NULL for "command < infile" */
    if ((fd = open (infile, O_RDONLY)) < 0) {
      perror (infile);
      exit (1);
    }
    if (fd != 0) {
      dup2 (fd, 0);
      close (fd);
    }
  }
  /* ... do same for outfile→fd 1, errfile→fd 2 ... */
  execvp (av[0], av);
  perror (av[0]);
  exit (1);
}
```

# Pipes I

```
int pipe (int fds[2]);
```

- Returns two file descriptors in `fds[0]` and `fds[1]`
- Data written to `fds[1]` will be returned by `read` on `fds[0]`
- When last copy of `fds[1]` closed, `fds[0]` will return EOF
- Returns 0 on success, -1 on error

# Pipes II

Operations on pipes

- `read`/`write`/`close` – as with files
- When `fds[1]` closed, `read(fds[0])` returns 0 bytes
- When `fds[0]` closed, `write(fds[1])`:
  - Kills process with `SIGPIPE`
  - Or if signal ignored, fails with EPIPE

Example: `pipesh.c`

- Sets up pipeline `command1 | command2 | command3 ...`

# pipesh.c (simplified)

```
void doexec(void) {
  while (outcmd) {
    int pipefds[2]; pipe(pipefds);
    switch (fork()) {
    case -1:
      perror("fork"); exit(1);
    case 0:
      dup2(pipefds[1], 1);
      close(pipefds[0]); close(pipefds[1]);
      outcmd = NULL;
      break;
    default:
      dup2(pipefds[0], 0);
      close(pipefds[0]); close(pipefds[1]);
      parse_command_line(&av, &outcmd, outcmd);
    }
  }
  :
```

# Multiple file descriptors I

- What if you have multiple pipes to multiple processes?
- `poll` system call lets you know which fd you can read/write[5]

```
typedef struct pollfd {
  int fd;
  short events;  // OR of POLLIN, POLLOUT, POLLERR, ...
  short revents; // ready events returned by kernel
};
int poll(struct pollfd *pfds, int nfds, int timeout);
```

# Multiple file descriptors II

- Also put pipes/sockets into *non-blocking* mode

```
if ((n = fcntl (s.fd_, F_GETFL)) == -1
    || fcntl (s.fd_, F_SETFL, n | O_NONBLOCK) == -1)
  perror("O_NONBLOCK");
```

  - Returns errno `EGAIN` instead of waiting for data
  - Does not work for normal files (see aio for that)

[5] In practice, more efficient to use `epoll` on linux or `kqueue` on *BSD

# More on Fork

- Most calls to `fork` followed by `execve`
- Could also combine into one *spawn* system call (like Pintos `exec`)
- Occasionally useful to fork one process
  - Unix *dump* utility backs up file system to tape
  - If tape fills up, must restart at some logical point
  - Implemented by forking to revert to old state if tape ends
- Real win is simplicity of interface
  - Tons of things you might want to do to child: Manipulate file descriptors, alter namespace, manipulate process limits ...
  - Yet `fork` requires *no* arguments at all

# Examples

- `login` – checks username/password, runs user shell
  - Runs with administrative privileges
  - Lowers privileges to user before exec'ing shell
  - Note doesn't need `fork` to run shell, just `execve`
- `chroot` – change root directory
  - Useful for setting/debugging different OS image in a subdirectory
- Some more linux-specific examples
  - `systemd-nspawn` – runs program in container-like environment
  - `ip netns` – runs program with different network namespace
  - `unshare` – decouple namespaces from parent and exec program

# Spawning a process without fork I

Example: Windows

- `CreateProcess` system call
  - Also `CreateProcessAsUser`, `CreateProcessWithLogonW`, `CreateProcessWithTokenW`, ...

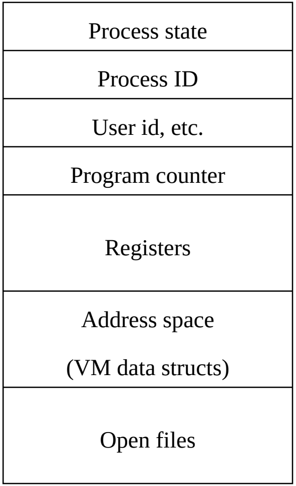
# Spawning a process without fork II

```
BOOL WINAPI CreateProcess(
  _In_opt_      LPCTSTR lpApplicationName,
  _Inout_opt_   LPTSTR lpCommandLine,
  _In_opt_      LPSECURITY_ATTRIBUTES lpProcessAttributes,
  _In_opt_      LPSECURITY_ATTRIBUTES lpThreadAttributes,
  _In_          BOOL bInheritHandles,
  _In_          DWORD dwCreationFlags,
  _In_opt_      LPVOID lpEnvironment,
  _In_opt_      LPCTSTR lpCurrentDirectory,
  _In_          LPSTARTUPINFO lpStartupInfo,
  _Out_         LPPROCESS_INFORMATION lpProcessInformation
);
```

# Implementing processes I

Process Control Block (PCB):

- Holds all the data for each process
  - Called `proc` in Unix, `task_struct` in Linux, and just `struct thread` in Pintos
- Tracks *state* of the process
  - Running, ready (runnable), waiting, etc.




PCB

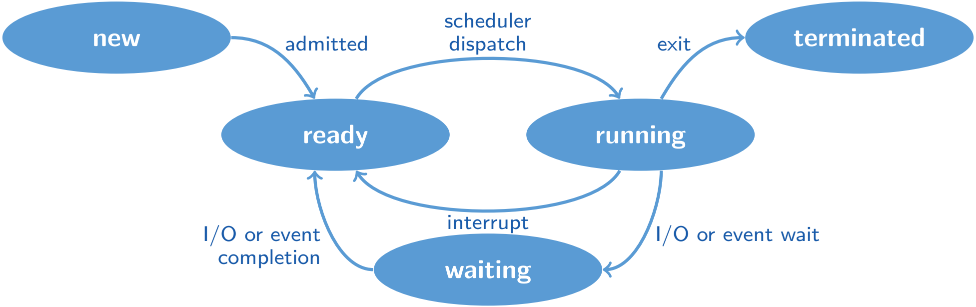
# Implementing processes II

- Includes information necessary to run:
  - Registers, virtual memory mappings, etc.
  - Open files (including memory mapped files)
- Various other data about the process:
  - Credentials (user/group ID), signal mask, controlling terminal, priority, accounting statistics, whether being debugged, which system call binary emulation in use, ...

| |
|---|
| Process state |
| Process ID |
| User id, etc. |
| Program counter |
| Registers |
| Address space<br>(VM data structs) |
| Open files |

PCB

# Process states I



# Process states II

Process can be in one of several states:

- *new* & *terminated* at beginning & end of life
- *running* – currently executing (or will execute on kernel return)
- *ready* – can run, but kernel has chosen different process to run
- *waiting* – needs async event (e.g., disk operation) to proceed

# Process states III

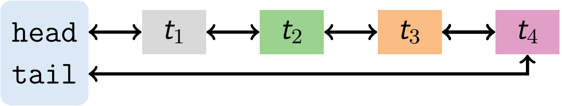
Which process should the kernel run?

- if 0 processes are runnable, run idle loop (or halt CPU)
- if 1 process is runnable, run it
- if $>$1 runnable, must make scheduling decision

# Scheduling

How to pick which process to run?

- Scan process table for first runnable?
  - Expensive. Weird priorities (small pids do better)
  - Divide into runnable and blocked processes
- FIFO?
  - Put threads on back of list, pull them from front:




  - Pintos does this—see `ready_list` in `thread.c`
- Priority?
  - Give some threads a better shot at the CPU

# Scheduling policy I

Want to balance multiple goals:

- *Fairness* – don't starve processes
- *Priority* – reflect relative importance of procs
- *Deadlines* – must do $X$ (play audio) by certain time
- *Throughput* – want good overall performance
- *Efficiency* – minimize overhead of scheduler itself

# Scheduling policy II

No universal policy

- Many variables, can't optimize for all
- Conflicting goals (e.g., throughput or priority vs. fairness)

# Preemption

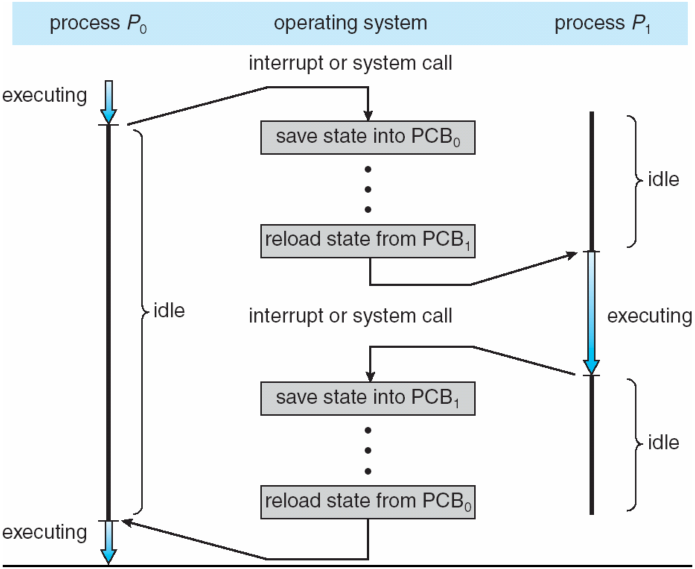
Kernel needs to gets control:

- Running process can vector control to kernel (voluntary)
  - System call, page fault, illegal instruction, etc.
  - May put current process to sleep—e.g., read from disk
  - May make other process runnable—e.g., fork, write to pipe
- Periodic timer interrupt (involuntary)
  - If running process used up quantum, schedule another
- Device interrupt (involuntary)
  - Disk request completed, or packet arrived on network
  - Previously waiting process becomes runnable
  - Schedule if higher priority than current running proc.

# Preemption

Changing the running process is called
a **context switch**

# Context Switch



# Context Switch I

Typical operations include:

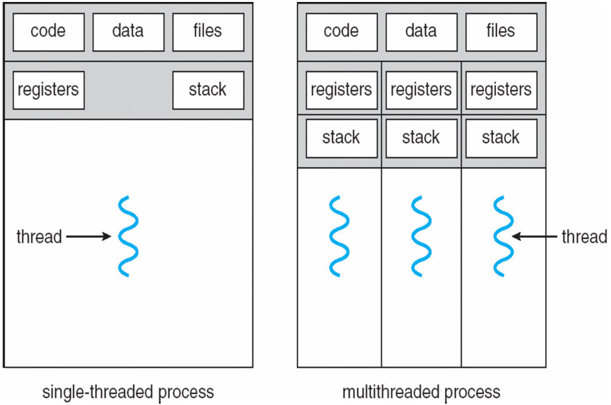
- Save program counter and integer registers (always)
- Save floating point or other special registers
- Save condition codes
- Change virtual address translations

# Context Switch II

Context switches incur a non-negligible cost:

- Saving/restoring FP registers is expensive
  - Optimization: only save when used
- May require flushing the *Translation Lookaside Buffer* (TLB)
  - HW Optimization 1: don't flush kernel's own data from TLB
  - HW Optimization 2: use tag to avoid flushing any data
- Usually causes more cache misses (switch working sets)

# Threads


code
data
files
registers
stack
thread
single-threaded process
code
data
files
registers
registers
registers
stack
stack
stack
thread
multithreaded process

# Threads

A thread is a schedulable execution context:

- Another way of calling a procedure
  (not necessarily `main()` this time)
- Program counter, stack, registers, ...
- Shares code, data, files etc with the parent process

# Why threads?

Lighter-weight and more popular abstraction for concurrency:

- Allows one process to use multiple CPUs or cores
- Allows program to overlap I/O and computation
  - E.g., threaded web server services clients simultaneously:

```
for (;;) {
  c = accept_client();
  thread_create(service_client, c);
}
```

- Most kernels have threads, too
  - Typically at least one kernel thread for every process
  - Switch kernel threads when preempting process

# Thread package API

```
tid thread_create (void (*fn) (void *), void *arg);
```

- Create a new thread, run `fn` with `arg`

```
void thread_exit ();
```

- Destroy current thread

```
void thread_join (tid thread);
```

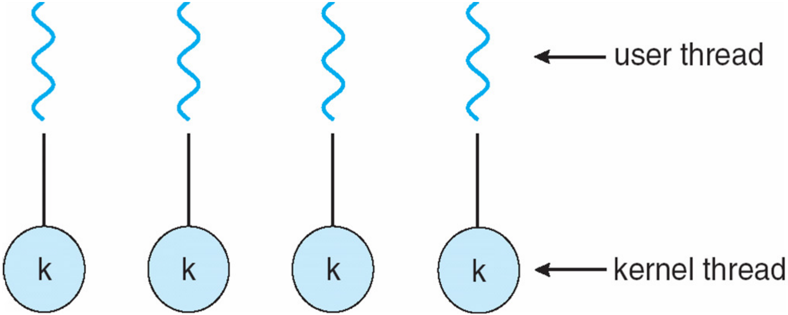
- Wait for thread `thread` to exit

# Thread package API

Can have kernel-level or user-level threads

- Kernel-level causes more race conditions
- User-level can't take advantage of multiple cores

# Kernel-level threads



# Kernel-level threads

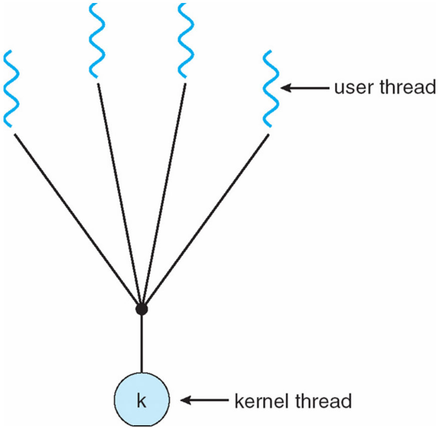
`thread_create` can be implemented as a system call:

- It's same as process creation minus some features:
  - Keep same address space, file table, etc., in new process
  - `rfork`/`clone` syscalls actually allow individual control
- Faster than process creation, but still very heavy weight

# Limitations of kernel-level threads

- Every thread operation must go through kernel
  - create, exit, join, synchronize, or switch for any reason
  - A syscall can take 100 cycles, wheres a fn call can take 5 cycles
  - Result: threads 10x-30x slower when implemented in kernel
- One-size fits all thread implementation
  - Kernel threads must please all people
  - Maybe pay for fancy features (priority, etc.) you don't need
- General heavy-weight memory requirements
  - E.g., requires a fixed-size stack within kernel
  - Other data structures designed for heavier-weight processes

# User-level threads




Implement as user-level library (a.k.a. *green* threads)

- One kernel thread per process
- `thread_create`, `thread_exit`, etc., are just library functions

# User-level threads: Implementation I

- Allocate a new stack for each `thread_create`
- Keep a queue of runnable threads
- Replace blocking system calls (`read`/`write`/etc.)
  - If operation would block, switch and run different thread
- Schedule periodic timer signal (`setitimer`)
  - Switch to another thread on timer signals (if preemption is desired)

# User-level threads: Implementation II

Multi-threaded web server example:

- Thread calls `read` to get data from remote web browser
- "Fake" `read` *function* makes `read` *syscall* in non-blocking mode
- No data? schedule another thread
- On timer or when idle check which connections have new data

# Background: procedure calls

**Procedure call**

→save active caller registers

→push arguments to stack

→call `foo` (pushes pc)

→save needed callee registers

→...do stuff...

→restore callee saved registers

→jump back to calling function

→restore stack+caller regs.

# Background: procedure calls

Caller must save some state across function call

- Return address, caller-saved registers

Other state does not need to be saved

- Callee-saved regs, global variables, stack pointer

# Threads vs. procedures

- Threads may resume out of order:
  - Cannot use LIFO stack to save state
  - General solution: one stack per thread
- Threads switch less often than procedures:
  - Don't partition registers (why?)
- Threads can be involuntarily interrupted:
  - Synchronous: procedure call can use compiler to save state
  - Asynchronous: thread switch code saves all registers
- More than one than one thread can run at a time:
  - Procedure call scheduling obvious: Run called procedure
  - Thread scheduling: What to run next and on which CPU?

# Pintos thread implementation

Pintos implements user processes on top of its own threads:

- Code for threads in kernel very similar to green threads

Per-thread state in thread control block structure:

```
struct thread {
    ...
    uint8_t *stack;  /* Saved stack pointer. */
    ...
};
uint32_t thread_stack_ofs = offsetof(struct thread, stack);
```

# Pintos thread implementation

C declaration for asm thread-switch function:

- ```
  struct thread *switch_threads(
        struct thread *cur,
        struct thread *next
  );
  ```

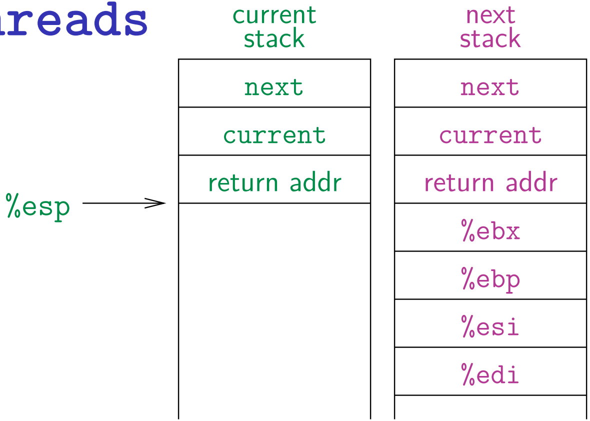
Also thread initialization function to create new stack:

- ```
  void thread_create(const char *name,
        thread_func *function, void *aux);
  ```

# i386 switch_threads

```
pushl %ebx; pushl %ebp           # Save callee-saved regs
pushl %esi; pushl %edi

mov thread_stack_ofs, %edx       # %edx = offset of stack field
                                 #         in thread struct

movl 20(%esp), %eax              # %eax = cur
movl %esp, (%eax,%edx,1)         # cur->stack = %esp

movl 24(%esp), %ecx              # %ecx = next
movl (%ecx,%edx,1), %esp         # %esp = next->stack

popl %edi; popl %esi             # Restore callee-saved regs
popl %ebp; popl %ebx

ret                              # Resume execution
```

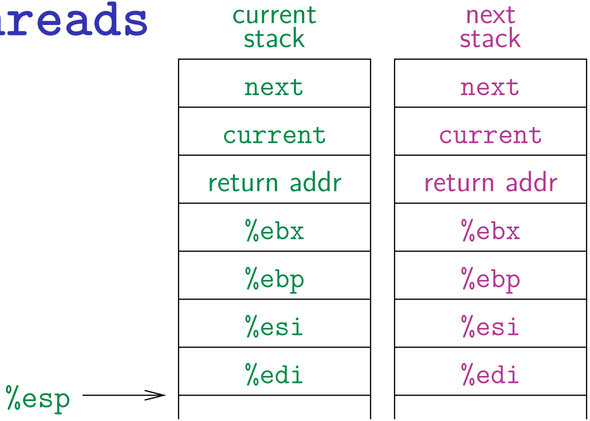
# i386 `switch_threads`




This is actual code from Pintos `switch.S` (slightly reformatted)

- See Thread Switching in documentation

# i386 switch_threads

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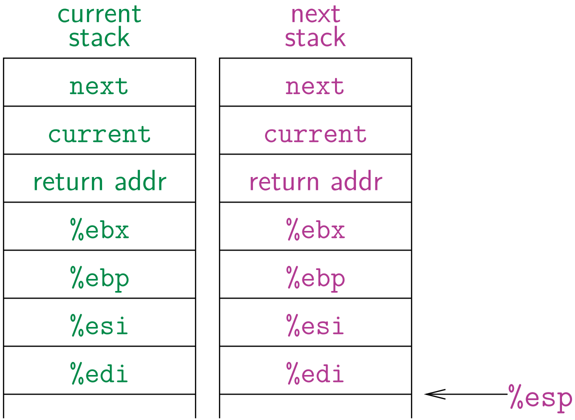
# i386 switch_threads

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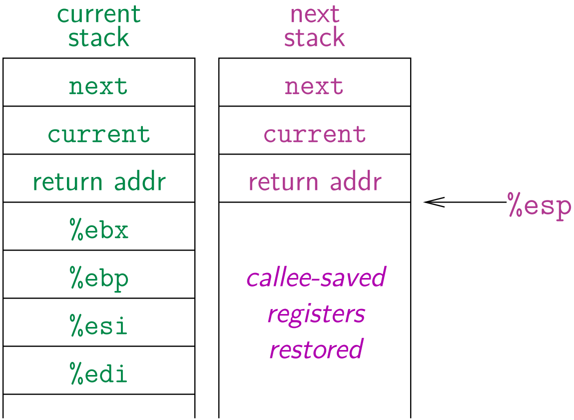
# i386 switch_threads




This is actual code from Pintos `switch.S` (slightly reformatted)

- See Thread Switching in documentation

# Limitations of user-level threads

A user-level thread can do the same operations as the kernel-level thread. But:

- Can't take advantage of multiple CPUs or cores
- A blocking system call blocks all user-level threads
- A page fault blocks all threads
- Possible deadlock if one thread blocks on another

# Limitations of user-level threads

A user-level thread can do the same operations as the kernel-level thread. But:

- Can't take advantage of multiple CPUs or cores
- A blocking system call blocks all user-level threads
  - Can use `O_NONBLOCK` to avoid blocking on network connections
  - But doesn't work for disk (e.g., even aio doesn't work for metadata)
  - So one uncached disk read/synchronous write blocks all threads
- A page fault blocks all threads
- Possible deadlock if one thread blocks on another

# Limitations of user-level threads

A user-level thread can do the same operations as the kernel-level thread. But:

- Can't take advantage of multiple CPUs or cores
- A blocking system call blocks all user-level threads
- A page fault blocks all threads
- Possible deadlock if one thread blocks on another
  - May block entire process and make no progress

# Limitations of user-level threads

## Nonblocking vs Asynchronous

- Blocking read system call: Blocks until *some* data is available: `int read(fd, void*, size);`
- Nonblocking read system call: If no data is available returns 0 immediately: `int read(fd, void*, size);`
- Asynchronous read system call: Returns immediately, invokes callback when data is available

  `int reada(fd, int(*)(const void *, size));`[6]

[6] NOT a real system call!!

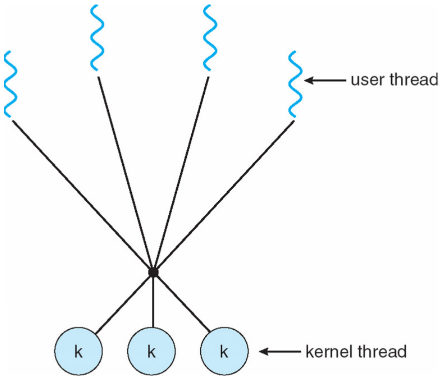
# User threads on kernel threads

User threads implemented on kernel threads

- Multiple kernel-level threads per process
- `thread_create`, `thread_exit` still library functions as before

Sometimes called $n : m$ threading

- Have $n$ user threads per $m$ kernel threads
  (Simple user-level threads are $n : 1$, kernel threads $1 : 1$)



# Limitations of $n : m$ threading

- Blocked threads, deadlock, ...
- Hard to keep same # kthreads as available CPUs
  - Kernel knows how many CPUs available
  - Kernel knows which kernel-level threads are blocked
  - But tries to hide these things from applications for transparency
  - So user-level thread scheduler might think a thread is running while underlying kernel thread is blocked
- Kernel doesn't know relative importance of threads
  - Might preempt kthread in which library holds important lock

# Lessons

- Threads best implemented as a library
  - But kernel threads not best interface on which to do this
- Better kernel interfaces have been suggested
  - See Scheduler Activations [Anderson et al.]
  - Maybe too complex to implement on existing OSes (some have added then removed such features)
- Standard threads still fine for most purposes
  - Use kernel threads if I/O concurrency main goal
  - Use $n : m$ threads for highly concurrent (e.g,. scientific applications) with many thread switches
- But concurrency greatly increases complexity
  - More on that in concurrency, synchronization lectures...