Operating Systems

INF-333

Burak Arslan
ext-inf333@burakarslan.com

Galatasaray Üniversitesi

Lecture III
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Course website

burakarslan.com/inf333

Based On

cs111.stanford.edu

cs212.stanford.edu

OSC-10 Slides

News

About deadlines:

- **You can't miss lab deadlines.**

  Past the deadline, it's just zero.

- **You can't miss homework deadlines.**

  However, if you need an extension, we can grant you some extra time (for a limited numer of times) provided that you clearly explain how many hours you need to complete which missing work.

  - We may not accept your excuse anyway so don't bet on it.

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[1] model and orchestrate program execution via certain entities:

- Process
- Thread
- Procedure

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

Processes

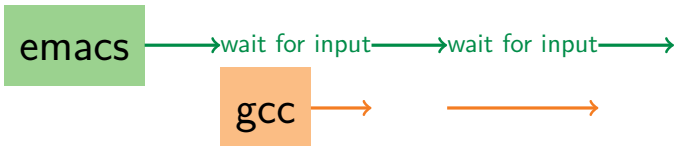
A **process** is an instance of a program running.

- 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 you 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

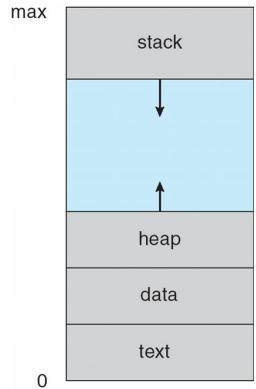
A process's view of the world

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

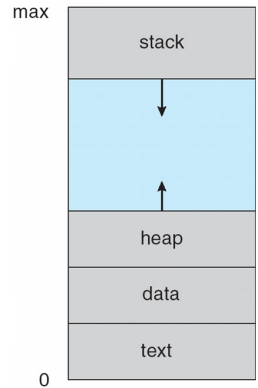
- `gcc` does not care that `firefox` is running



A process's view of the world

Sometimes want interaction between processes

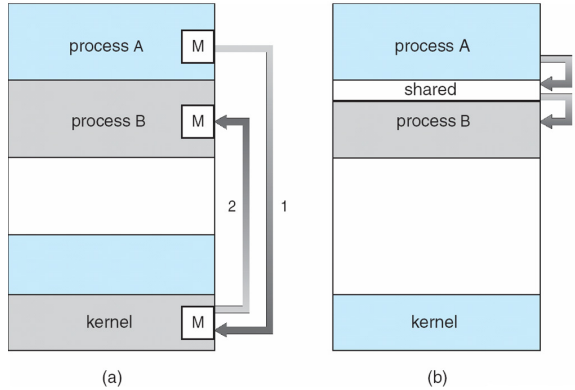
- Simplest is through files: `emacs` edits file, `gcc` compiles it
- More complicated: Shell/command, Window manager/app.



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"

`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` (shifted)
- By convention, `status` of 0 is success, non-zero error

`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[2]

```
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)

[2] 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`, …

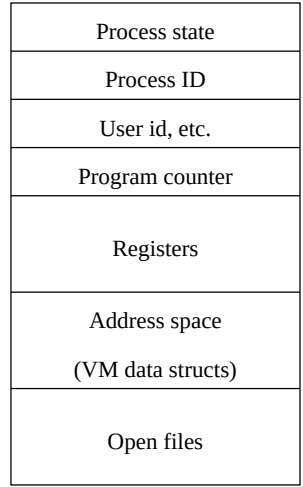
Spawning a process without fork II

```
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):

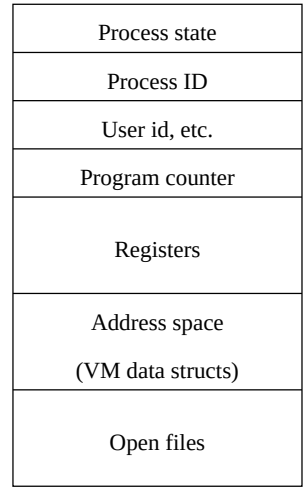
- Holds all the data for each process
  - Called `proc` in Unix, `task_struct` in Linux, and just `struct thread` in Pintos
- Tracks *state* of the process
  - Running, ready (runnable), waiting, etc.



PCB

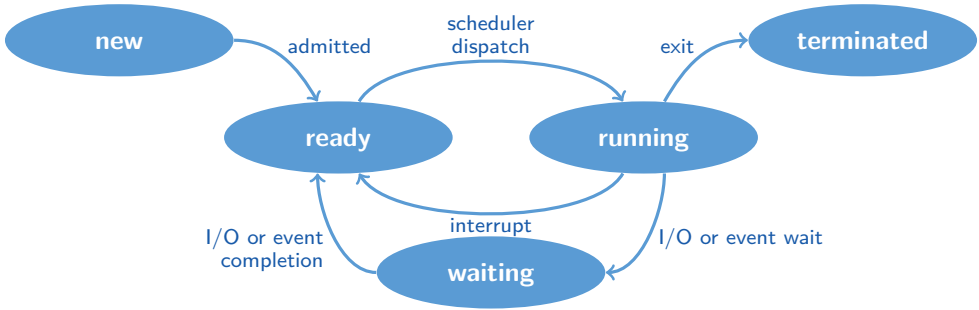
Implementing processes II

- 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, ...



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

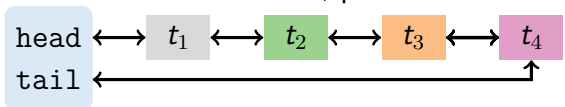
Which process should kernel run?

- 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

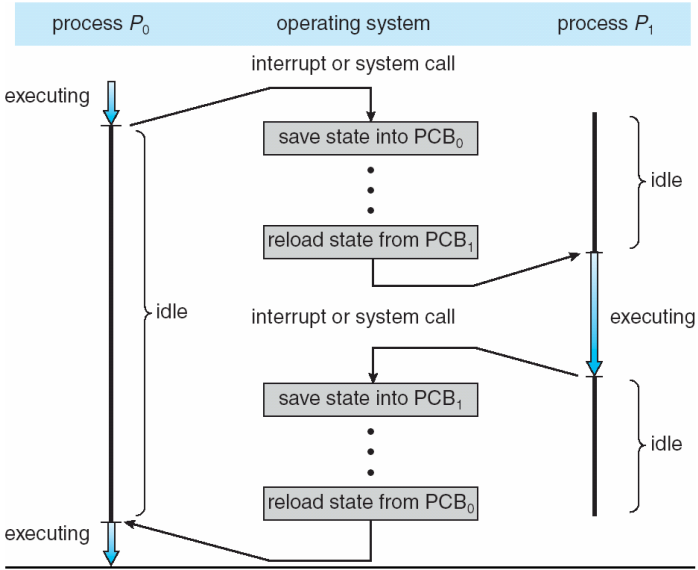
Kernel needs to gets control:

- 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 running process is called
a **context switch**

Context Switch



Context Switch I

Typical operations include:

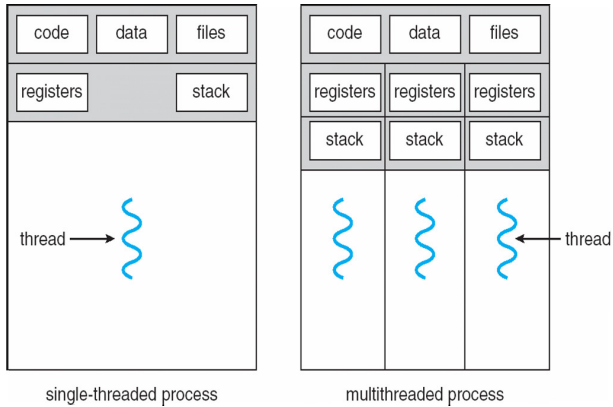
- Save program counter and integer registers (always)
- Save floating point or other special registers
- Save condition codes
- Change virtual address translations

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
code
data
files
registers
registers
registers
stack
stack
stack
thread
single-threaded process
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);
```

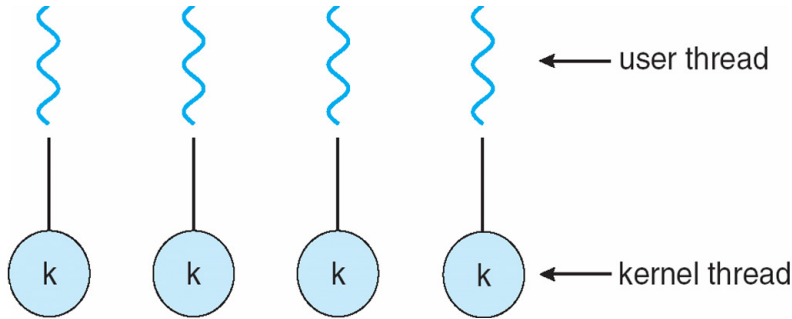
- Wait for thread `thread` to exit

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

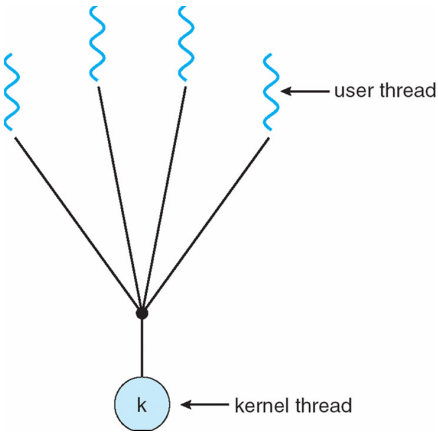
`thread_create` can be implemented as a system call:

- 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
  );
  ```

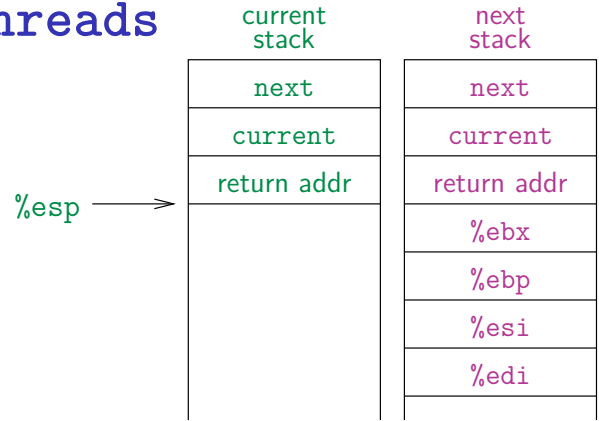
Also thread initialization function to create new stack:

- ```
  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
```

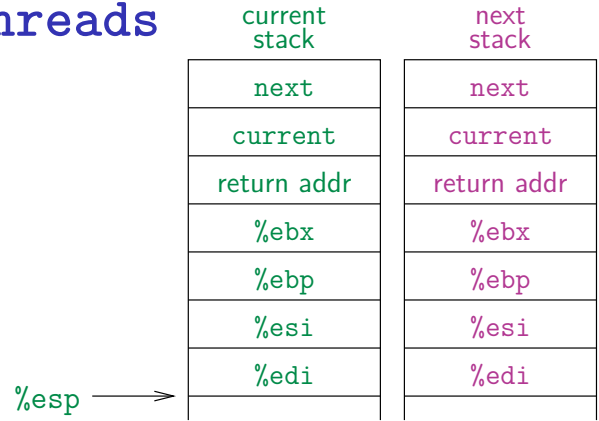
i386 switch_threads



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

- See Thread Switching in documentation

i386 switch_threads



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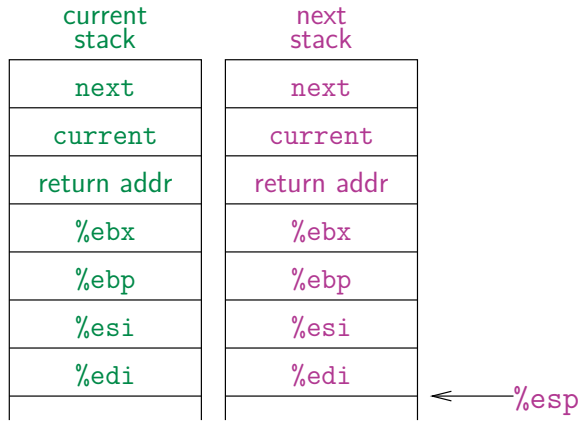

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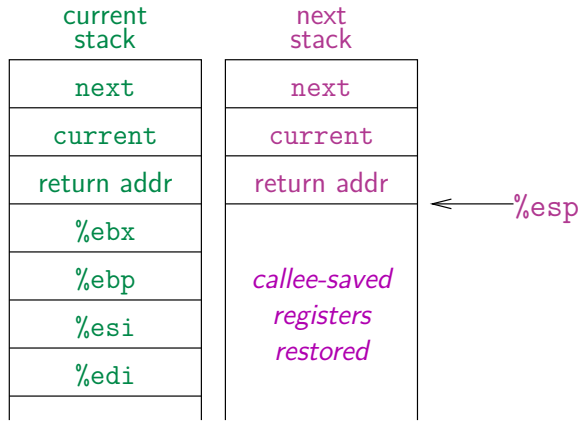
i386 switch_threads



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- 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

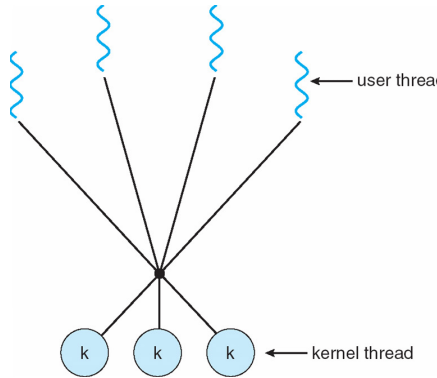
User threads on kernel threads

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...