Administrivia

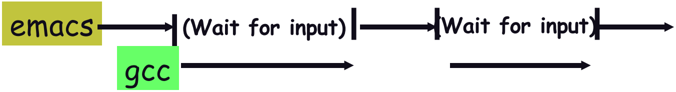
- **Section scheduled at 2:15pm in Gates B03 (next door)**
  - Please attend this Friday to learn about lab 1
- **Lab 1 will be distributed Friday**
  - Already on-line, but we are beta testing it
  - Due Friday Jan. 23 at noon
- **Ask `cs140-staff` for extension if you can't finish**
  - Tell us where you are with the project,
  - How much more you need to do, and
  - How much longer you need to finish
- **No credit for late assignments w/o extension**
- **If you are enrolled pass/fail, please disclose to your partners**
  - We don't recommend pass/fail, but it is allowed

Processes

- **A *process* is an instance of a program running**
- **Modern OSes run multiple processes simultaneously**
- **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
- **Non-examples (implemented as one process):**
  - Multiple firefox windows or emacs frames (still one process)
- **Why processes?**
  - Simplicity of programming
  - Higher throughput (better CPU utilization), lower latency

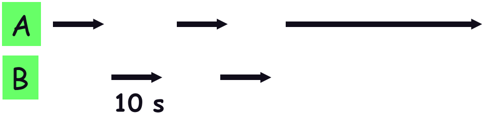
Speed

- **Multiple processes can increase CPU utilization**
  - Overlap one process's computation with another's wait



- **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

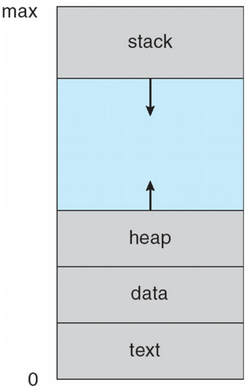


  - *A* is slower than if it had whole machine to itself, but still $<$ 100 sec unless both *A* and *B* completely CPU-bound

Processes in the real world

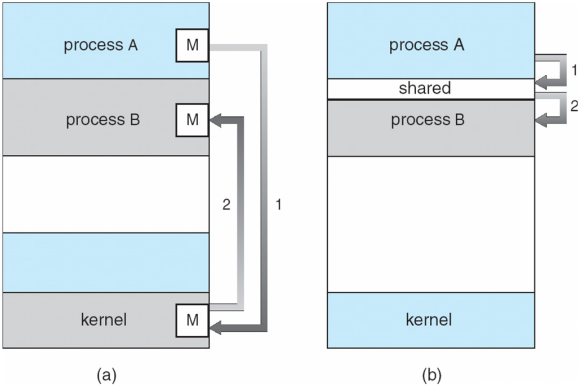
- **Processes, parallelism fact of life much longer than OSes have been around**
  - E.g., say takes 1 worker 10 months to make 1 widget
  - Company may hire 100 workers to make 100 widgets
  - Latency for first widget $\gg 1/10$ month
  - Throughput may be < 10 widgets per month (if can't perfectly parallelize task)
  - And 100 workers making 10,000 widgets may achieve > 10 widgets/month (e.g., if workers never idly wait for paint to dry)
- **You will see these effects in you Pintos project group**
  - May block waiting for partner or need time to coordinate
  - Labs won't take 1/3 time with three people

A process's view of the world



- **Each process has own view of machine**
  - Its own address space
  - Its own open files
  - Its own virtual CPU (through preemptive multitasking)
- `*(char *)0xc000` **different in P_1 & P_2**
- **Simplifies programming model**
  - `gcc` does not care that `firefox` is running
- **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

Rest of lecture

- **User view of processes**
  - Crash course in basic Unix/Linux system call interface
  - How to create, kill, and communicate between processes
  - Running example: how to implement a shell
- **Kernel view of processes**
  - Implementing processes in the kernel
- **Threads**
- **How to implement threads**

Outline

1. User view of processes
2. Kernel view of processes
3. Threads
4. How to implement threads

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

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

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
- **Warning: Pintos** `exec` **more like combined fork/exec**

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

- `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)
- `int fcntl (int fd, F_SETFD, int val)`
  - Sets *close on exec* flag if `val` = 1, clears if `val` = 0
  - Makes file descriptor non-inheritable by spawned programs
- **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

- `int pipe (int fds[2]);`
  - Returns two file descriptors in `fds[0]` and `fds[1]`
  - Writes to `fds[1]` will be read on `fds[0]`
  - When last copy of `fds[1]` closed, `fds[0]` will return EOF
  - Returns 0 on success, -1 on error
- **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);
      break;
    }
  }
```

Why fork?

- **Most calls to `fork` followed by `execve`**
- **Could also combine into one *spawn* system call**
  - This is what Pintos `exec` does
- **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, environment, resource limits, etc.
  - Yet `fork` requires *no* arguments at all

Spawning process w/o fork

- **Without fork, require tons of different options**
- **Example: Windows `CreateProcess` system call**
  - Also `CreateProcessAsUser`, `CreateProcessWithLogonW`, `CreateProcessWithTokenW`, ...

```
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
);
```

Outline

1. User view of processes
2. Kernel view of processes
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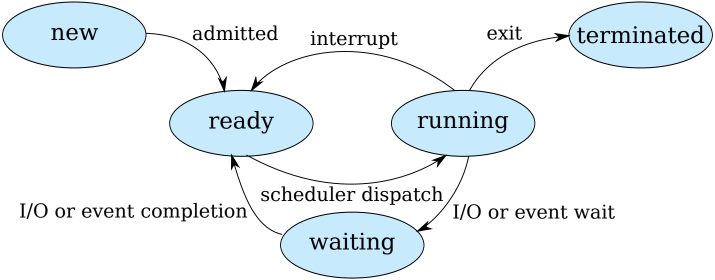
Implementing processes

- **OS keeps data structure for each proc**
  - Process Control Block (PCB)
  - Called `proc` in Unix, `task_struct` in Linux, and just `struct thread` in Pintos
- **Tracks *state* of the process**
  - Running, ready (runnable), blocked, etc.
- **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 (VM data structs)
Open files

PCB

Process states



- **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
- **Which process should kernel run?**
  - if 0 runnable, run idle loop (or halt CPU), if 1 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: `thread.c`)
- **Priority?**
  - Give some threads a better shot at the CPU

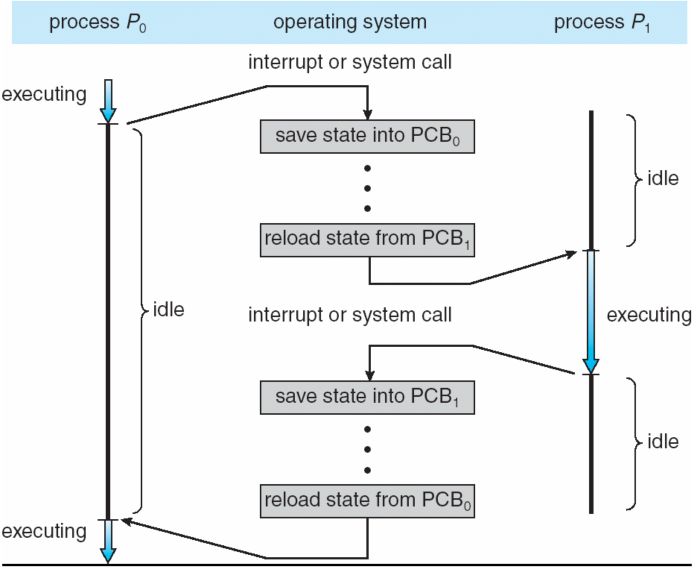
Scheduling policy

- **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
- **No universal policy**
  - Many variables, can't optimize for all
  - Conflicting goals (e.g., throughput or priority vs. fairness)
- **We will spend a whole lecture on this topic**

Preemption

- **Can preempt a process when kernel gets control**
- **Running process can vector control to kernel**
  - 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**
  - If running process used up quantum, schedule another
- **Device interrupt**
  - Disk request completed, or packet arrived on network
  - Previously waiting process becomes runnable
  - Schedule if higher priority than current running proc.
- **Changing running process is called a *context switch***

Context switch



Context switch details

- **Very machine dependent. Typical things include:**
  - Save program counter and integer registers (always)
  - Save floating point or other special registers
  - Save condition codes
  - Change virtual address translations
- **Non-negligible cost**
  - Save/restore floating point registers expensive
    - ▹ Optimization: only save if process used floating point
  - May require flushing TLB (memory translation hardware)
    - ▹ 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)

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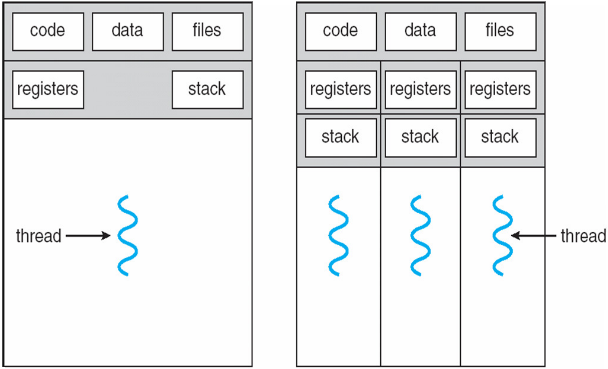
Threads



single-threaded process multithreaded process

- **A thread is a schedulable execution context**
  - Program counter, stack, registers, ...
- **Simple programs use one thread per process**
- **But can also have multi-threaded programs**
  - Multiple threads running in same process's address space

Why threads?

- **Most popular abstraction for concurrency**
  - Lighter-weight abstraction than processes
  - All threads in one process share memory, file descriptors, etc.
- **Allows one process to use multiple CPUs or cores**
- **Allows program to overlap I/O and computation**
  - Same benefit as OS running `emacs` & `gcc` simultaneously
  - E.g., threaded web server services clients simultaneously:

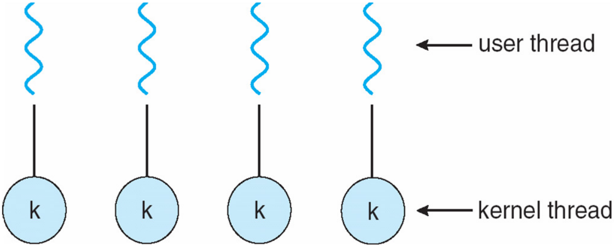
```
for (;;) {
  fd = accept_client ();
  thread_create (service_client, &fd);
}
```

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

Thread package API

- `tid thread_create (void (*fn) (void *), void *);`
  - 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
- **Plus lots of support for synchronization [in 3 weeks]**
- **See [Birell] for good introduction**
- **Can have preemptive or non-preemptive threads**
  - Preemptive causes more race conditions
  - Non-preemptive can't take advantage of multiple CPUs
  - Before prevalent SMPs, most kernels non-preemptive

Kernel threads

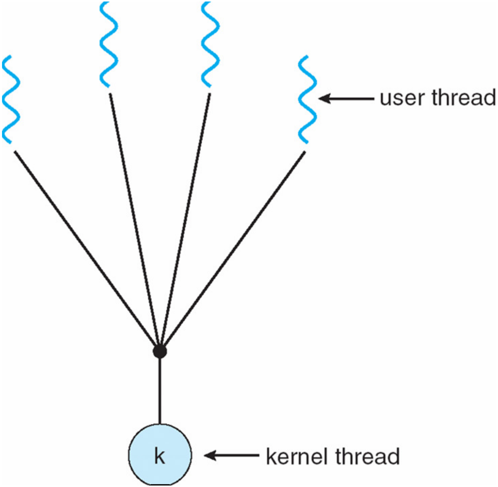


- **Can implement `thread_create` as a system call**
- **To add `thread_create` to an OS that doesn't have it:**
  - Start with process abstraction in kernel
  - `thread_create` like process creation with features stripped out
    - ▷ Keep same address space, file table, etc., in new process
    - ▷ `rfork`/`clone` syscalls actually allow individual control
- **Faster than a process, 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
  - On my laptop: syscall takes 100 cycles, fn call 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 threads



- **An alternative: implement in user-level library**
  - One kernel thread per process
  - `thread_create`, `thread_exit`, etc., just library functions

Implementing user-level threads

- **Allocate a new stack for each** `thread_create`
- **Keep a queue of runnable threads**
- **Replace networking 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 (preemption)
- **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

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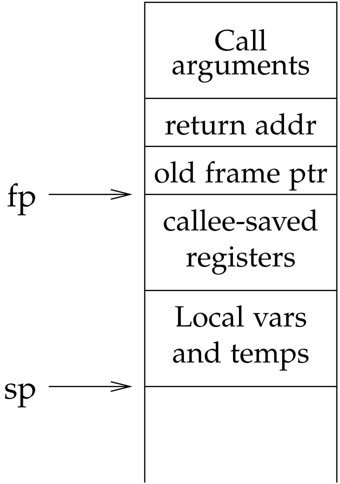
Background: calling conventions

- **Registers divided into 2 groups**
  - Functions free to clobber *caller-saved* regs (`%eax` [return val], `%edx`, & `%ecx` on x86)
  - But must restore *callee-saved* ones to original value upon return (on x86, `%ebx`, `%esi`, `%edi`, plus `%ebp` and `%esp`)
- ***sp* register always base of stack**
  - Frame pointer (*fp*) is old *sp*
- **Local variables stored in registers and on stack**
- **Function arguments go in caller-saved regs and on stack**
  - With x86, all arguments on stack



Background: procedure calls

save active caller registers
call foo → saves used callee registers
...do stuff...
restores callee registers
jumps back to pc → restore caller regs

- **Some state saved on stack**
  - Return address, caller-saved registers
- **Some state not 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:**
  - 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?

Example user threads implementation

- **Per-thread state in thread control block structure**

```
typedef struct tcb {
  uintptr_t long md_esp; /* Stack pointer of thread */
  char *t_stack;         /* Bottom of thread's stack */
  /* ... */
};
```

- **Machine-dependent thread-switch function:**
  - `void thread_md_switch (tcb *current, tcb *next);`
- **Machine-dependent thread initialization function:**
  - `void thread_md_init (tcb *t, void (*fn) (void *), void *arg);`

i386 thread_md_switch

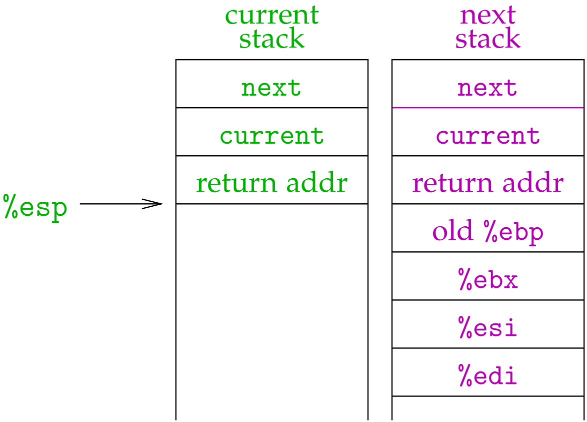
```
pushl %ebp; movl %esp,%ebp          # Save frame pointer
pushl %ebx; pushl %esi; pushl %edi  # Save callee-saved regs

movl 8(%ebp),%edx                   # %edx = thread_current
movl 12(%ebp),%eax                  # %eax = thread_next
movl %esp,(%edx)                    # %edx->md_esp = %esp
movl (%eax),%esp                    # %esp = %eax->md_esp

popl %edi; popl %esi; popl %ebx     # Restore callee saved regs
popl %ebp                           # Restore frame pointer
ret                                 # Resume execution
```

- **This is literally switch code from simple thread library**
  - Nothing magic happens here
  - You will see very similar code in Pintos `switch.S`

i386 thread_md_switch



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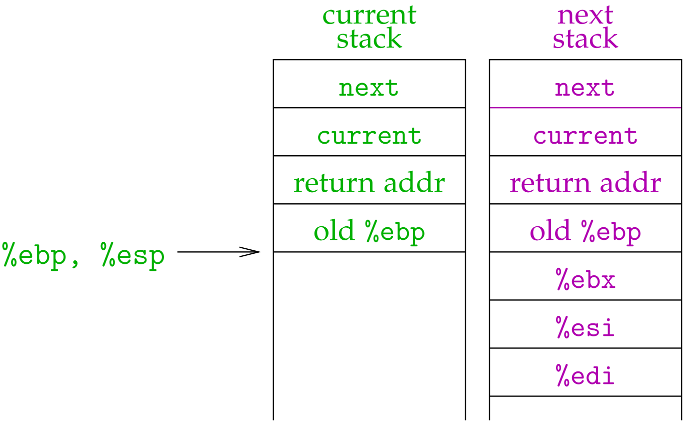

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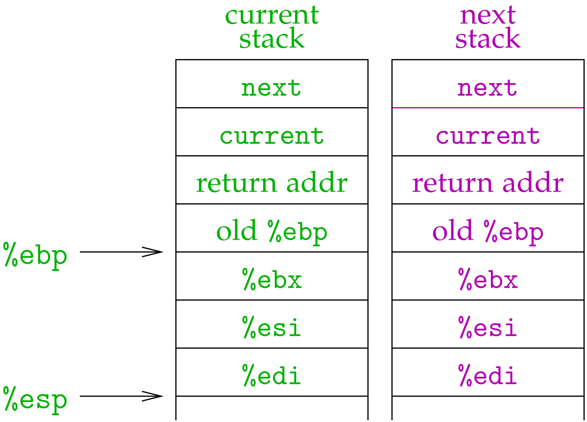

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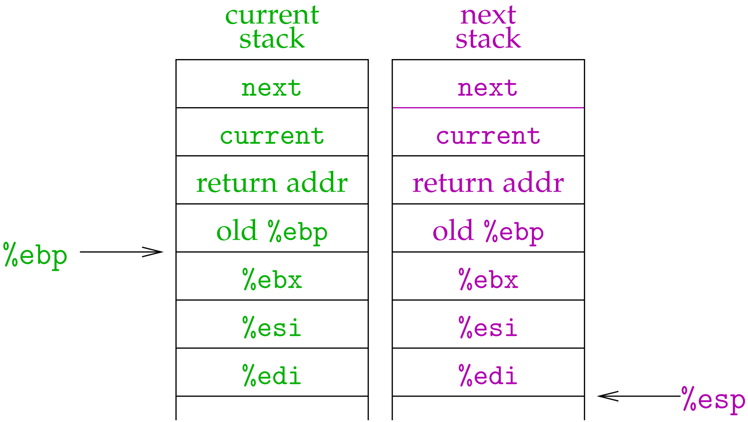

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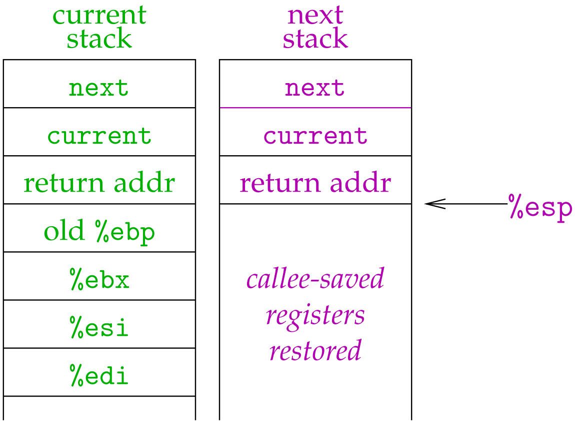

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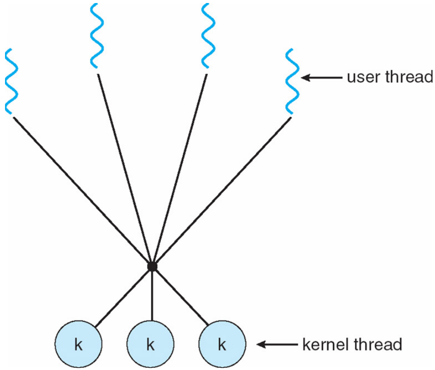
Limitations of user-level threads

- **Can't take advantage of multiple CPUs or cores**
- **A blocking system call blocks all threads**
  - Can replace `read` to handle network connections
  - But usually OSes don't let you do this for disk
  - So one uncached disk read blocks all threads
- **A page fault blocks all threads**
- **Possible deadlock if one thread blocks on another**
  - May block entire process and make no progress
  - [More on deadlock in future lectures.]

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

- **Many of same problems as $n : 1$ threads**
  - Blocked threads, deadlock, …
- **Hard to keep same # ktrheads 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, now Windows is trying it)
- **Today shouldn't dissuade you from using threads**
  - Standard user or kernel threads are 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
- **…though concurrency/synchronization lectures may**
  - Concurrency greatly increases the complexity of a program!
  - Leads to all kinds of nasty race conditions