CS240 – Advanced Topics in Operating Systems

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Administrivia

- **Class web page:** `http://cs240.scs.stanford.edu/`
- **All handouts and lecture notes on-line**
  - Please print them out yourselves
- **Part of each class will be spent discussing papers**
  - Print, read the papers before class
- **Slides and lecture notes will be on-line**
- **Grading based on two factors**
  - Midterm and final (bring all papers): ∼60%
  - Participation in discussion: ∼40%

Exams

- **Both midterm and final open-book**
  - Bring (marked up) print-outs of all papers
  - Bring any lecture notes and slides you wish
  - *Don't* bring your laptop (open book, not laptop)
- **Goal is to test your understanding of papers**
  - Not a memory of vocab quiz
  - But definitely won't have time to read papers during exam!
- **Grade is based on** $\max\left(\left(\text{midterm} + \text{final}\right)/2, \text{final}\right)$
  - Score will be used to rank students for grading

Class participation

- **Class participation an important component of grade**
  - Grading curve based mostly on participation
- **If you need to miss class please email staff**
  - Otherwise will hurt your final grade
- **Read the papers before class!**
- **I need to learn who you are**
  - End class early today to take photos
  - Please write your name in large letters on back of handout to hold up for photo
  - Make sure name takes up entire sheet of paper

Class structure

- **Some classes start w. mini-lecture on background**
  - Slides will be posted on web site
- **Discussion notes will also be posted**
  - I need to make notes to myself to lead discussion
  - Will post these on-line after class in ASCII format
  - Primarily intended for me, but will remind you of what happened during class
  - Should reduce the need to take notes for those who prefer not to
- **Will sometimes cite papers w. first author in brackets**
  - Look up with search engine or ask staff for more info
- **If you have questions on papers you read, email us by 12pm on day of lecture**
  - I will try to address your questions in discussion
  - Good questions may earn participation points

More administrivia

- **Class email list:** `cs240@scs.stanford.edu`
  - Should reach all students
  - Let us know if you don't get mail test mail tonight (or if you want to subscribe under a different address)
  - Feel free to discuss papers on the list
- **Staff email list:** `cs240-staff@scs.stanford.edu`
  - Please mail staff list rather than Instructor or CA (class mail gets much higher priority in my mail queue)

Prerequisites & Goal

- **We assume some familiarity with C**
- **Some familiarity with Unix may help**
- **An undergraduate "textbook" OS class (e.g., CS140)**
  - Familiar with concepts like Virtual Memory, processes, etc.
  - Enough to read papers that employ these concepts
- **Goals of class:**
  - Get to the point of being able to read and understand contemporary OS papers
  - Provide background if you are interested in doing OS research

Course topics

- **Concurrency & synchronization**
- **Scheduling**
- **Virtual memory**
- **Virtual machines**
- **File systems & storage**
- **Network stack implementation**
- **Distributed storage systems**
- **Kernel architectures**
- **OS Security and reliability**

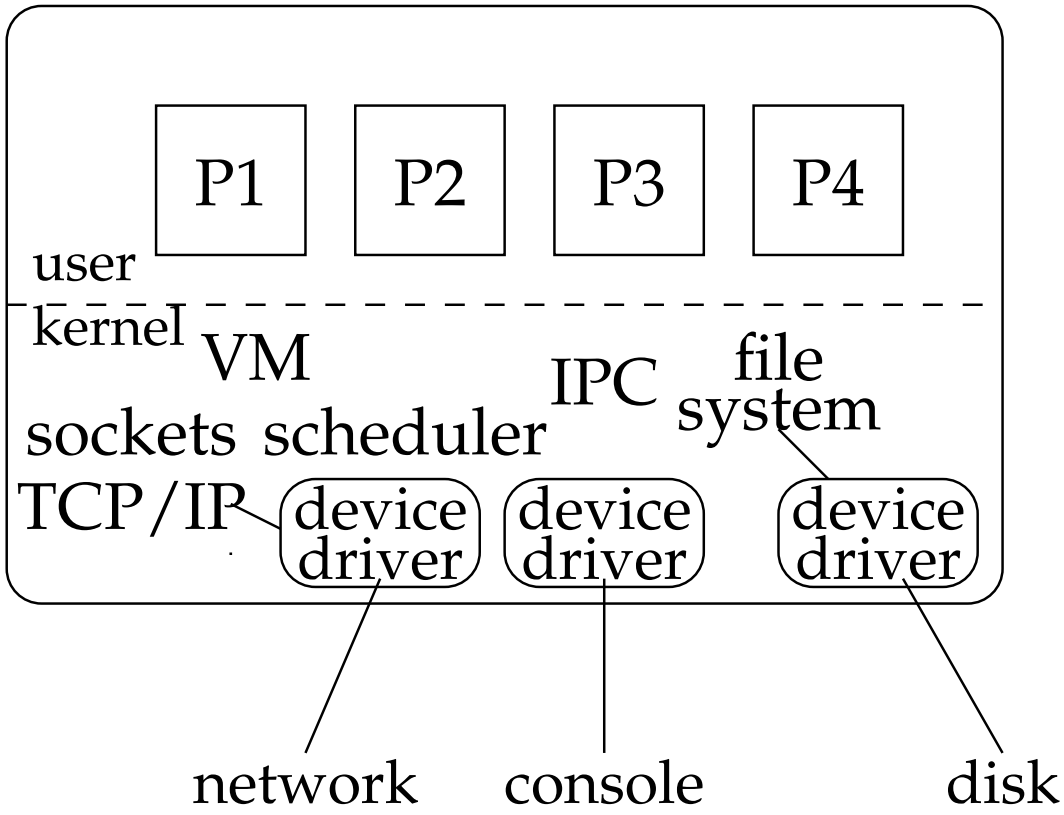
What is an operating system?

- **Makes hardware useful to the programmer**
- **Provides abstractions for applications**
  - Manages and hides details of hardware
  - Accesses hardware through low/level interfaces unavailable to applications
- **Provides protection**
  - Prevents one process/user from clobbering another

Why study operating systems?

- **Operating systems are a maturing field**
  - Most people use a handful of mature OSes
  - Hard to get people to switch operating systems
  - Hard to have impact with a new OS
- **High-performance servers are an OS issue**
  - Face many of the same issues as OSes
- **Resource consumption is an OS issue**
  - Battery life, radio spectrum, etc.
- **Security is an OS issue**
  - Hard to achieve security without a solid foundation
- **New "smart" devices need new OSes**

Typical OS structure



- **Most software runs as user-level processes**
- **OS kernel handles "privileged" operations**
  - Creating/deleting processes
  - Access to hardware

Unix architecture

- **User-level**
- **Kernel "top half"**
  - System call, page fault handler, kernel-only process, etc.
- **Software interrupt**
- **Device interrupt**
- **Timer interrupt (hardclock)**
- **Context switch code**

Transitions between contexts

- **User → top half:**
- **User/top half → device/timer interrupt:**
- **Top half → user/context switch:**
- **Top half → context switch:**
- **Context switch → user/top half**

Transitions between contexts

- **User → top half: syscall, page fault**
- **User/top half → device/timer interrupt: hardware**
- **Top half → user/context switch: return**
- **Top half → context switch: sleep**
- **Context switch → user/top half**

System calls

- **Goal: invoke kernel from user-level code**
  - Like a library call, but into more privileged OS code
- **Applications request operations from kernel**
- **Kernel supplies well-defined *system call* interface**
  - Applications set up syscall arguments and *trap* to kernel
  - Kernel performs operation and returns result
- **Higher-level functions built on syscall interface**
  - `printf`, `scanf`, `gets`, etc. all user-level code

Example: POSIX/Unix interface

- **Applications "open" files/devices by name**
  - I/O happens through open files
- `int open(char *path, int flags, ...);`
  - Returns file descriptor—used for all I/O to file
- `int read (int fd, void *buf, int nbytes);`
- `int write (int fd, void *buf, int nbytes);`
- `int close (int fd);`

Example 2: Exokernel [Engler]

- **Only one kernel context**
  - Single kernel stack; interrupts disabled & never sleep in kernel
- `bc_read_insert (dev, offset, len, u_int *res);`
  - Schedule DMA from disk to new physical page
- `insert_pte (capability, page-tranlation, VA, capability, target-process);`
  - Sets a particular page table entry for process
- `wkpred (wk_term *pred, int size);`
  - Put process to sleep until particular condition is met
  - Condition is described in "wake predicate" language
  - `pred` is a program in this little language
- **Can also implement `printf`, etc., with these**
- **Why would you want to?**

System Interfaces

- **System call interface is interface to kernel**
- **Historically also interface "most programmers" need**
  - But most programmers $\neq$ all programmers
  - Standard OSes thwart many types of application
- **No inherent reason for two interfaces to be the same**
  - Exokernel possibly most extreme example
  - Philosophy: provide protection in kernel, but abstraction only in user-level libraries

What is OS research?

- **New kernel architectures**
  - Typically <10% of papers in top OS conferences!
- **New kernel components**
  - E.g., new VM or network stack implementation, process or disk scheduling algorithm, buffer cache, file system, etc.
  - Also only a small fraction of papers
- **User-level code running on an existing kernel**
  - Challenging applications often face OS issues
  - Either hit your head against OS which does the wrong thing
  - Or have to re-implement OS-like abstractions (for better performance, distributed operation, etc.)

Example: Video Server

- **Buy hardware with the following capabilities:**
  - 40 MByte/sec SCSI disk
  - 100 Mbit/sec ethernet
- **Application requirements:**
  - Serve 200 Kbit/sec video streams
  - Many users spread around the Internet
  - Access control
- **Maximum capacity: 500 clients???**

Reality: Much lower capacity

- **CPU bottleneck**
  - Software structure may impose many context switches
  - Concurrency may introduce lock contention
- **Disk I/O limitations**
  - Multiple streams introduce disk seeks:
    E.g., 5ms/8K read = 1.6 MByte/sec
  - Must pipeline disk requests—requires prefetching
  - But then OS buffer cache may fill memory and induce paging
- **Network stack limitations**
  - OS may buffer stale data (dropped frames)
  - Congestion control improperly prioritizes packets

Maximizing throughput

- **Goal: Service maximum number of clients over time**
- **Avoid letting resources stay idle**
  - Different resources: CPU, disk, network
  - E.g., don't leave disk idle while waiting for network
- **Key technique: Concurrency**
  - Concurrency ensures each resource can be utilized
- **Example: while waiting for a disk read for one client**
  - . . . can use CPU to compute data for another client
  - . . . can transmit data to a third client over network

Disks

- **For many systems, disks are the limiting factor**
- **Can limit *throughput* far below network capacity**
  - E.g., cut naïve video server throughput by factor of 7–8
- **Can also limit *capacity* of a system**
- **Example: build a system to index CS240 lecture notes**
  - Scan all files, create index file
  - Rely on kernel for low-level details of storage management
- **Example: build a system to index the web**
  - Can't stuff enough disks in one computer to hold index
  - Need a user-level distributed storage system

Anatomy of a disk

- **Stack of magnetic platters**
  - Rotate together on a central spindle @3,600-15,000 RPM
  - Drive speed drifts slowly over time
  - Can't predict rotational position after 100-200 revolutions
- **Disk arm assembly**
  - Arms rotate around pivot, all move together
  - Pivot offers some resistance to linear shocks
  - Arms contain disk heads–one for each recording surface
  - Heads read and write data to platters

Disk positioning system

- **Move head to specific track and keep it there**
  - Resist physical socks, imperfect tracks, etc.
- **A *seek* consists of up to four phases:**
  - *speedup*–accelerate arm to max speed or half way point
  - *coast*–at max speed (for long seeks)
  - *slowdown*–stops arm near destination
  - *settle*–adjusts head to actual desired track
- **Very short seeks dominated by settle time ($\sim$1 ms)**
- **Short (200-400 cyl.) seeks dominated by speedup**
  - Accelerations of 40g

Seek details

- **Head switches comparable to short seeks**
  - May also require head adjustment
  - Settles take longer for writes than reads
- **Disk keeps table of pivot motor power**
  - Maps seek distance to power and time
  - Disk interpolates over entries in table
  - Table set by periodic "thermal recalibration"
  - 500 ms recalibration every 25 min, bad for AV
- **"Average seek time" quoted can be many things**
  - Time to seek 1/3 disk, 1/3 time to seek whole disk,

What does this mean for systems?

- **More concurrency can mean higher throughput**
  - If you have n requests, you can sort them
  - Ask disk/controller to perform them in optimal order
  - Can vastly reduce seek times, increase throughput
- **Cache data you will use again in faster memory**
- **More efficient to access nearby data than far**
  - E.g., good idea to put related data close together (e.g., put file near metadata)
- **Larger requests mean higher throughput**
  - Sequential throughput much higher than random
- **Note: Last three may require bypassing the OS**

Preview of disk techniques

- **Make many disks seem like one large disk (RAID)**
- **Structure storage for large writes (Logs)**
- **Expose information/control to applications**
  - What pages are in virtual memory
  - What pages have been accessed
  - How should OS manage cache
  - What threads are blocked waiting for disk I/O

Network

- **Many machines serve clients over the Internet**
  - Speed of light means typical RTTs in 10s of milliseconds
- **Often have to wait for client**
  - E.g., send back HTML page, wait for image requests
  - Congestion control may require limiting send rate
- **Again, concurrency achieves good throughput**
- **Also may care about *space***
  - E.g., if client takes one second to service and requires 10 MByte of memory, memory will be limiting factor
- **Many kernels impose other limitations:**
  - Number of file descriptors or processes
  - Size of hash table for TCP connections (mostly fixed today)

Achieving concurrency

- **Can use OS processes**
  - Heavy weight (expensive to create) and memory intensive
- **Can use non-blocking I/O operations**
  - read/write, but return immediately if not possible
  - Single process handles many clients
  - Not good for disk concurrency
- **Can use threads implemented at user level**
  - Build on non-blocking I/O primitives
- **Can use kernel-level threads**
  - But more heavy weight than user-level threads
- **More on threads in next few lextures…**

System calls for using TCP

Client	Server
	`socket` – make socket
	`bind` – assign address
	`listen` – listen for clients
`socket` – make socket	
`bind` – assign address (optional)	
`connect` – connect to listening socket	
	`accept` – accept connection
`write` – send data	`read` – receive data
`read` – receive data	`write` – send data

- **Anything red might block, waiting for network**
  - Obviously bad for applications that need concurrency

Non-blocking I/O

- **Use `fcntl` to set `O_NONBLOCK` flag on descriptor**
- **Non-blocking semantics of system calls:**
  - `read` immediately returns -1 with `errno EAGAIN` if no data
  - `write` may not write all data, or may return `EAGAIN`
  - `connect` may "fail" with `EINPROGRESS` (or may succeed, or may fail with real error such as `ECONNREFUSED`)
  - `accept` may fail with `EAGAIN` if no pending connections

How to know when to read/write?

```
struct pollfd {
  int fd;         /* file descriptor */
  short events;   /* Events you are interested in */
  short revents;  /* Events that have happened (results) */
};

int poll(struct pollfd *fds, nfds_t nfds, int timeout);

/* Some possible events: */
#define POLLIN     0x0001  /* Can read fd without blocking */
#define POLLOUT    0x0004  /* Can write fd without blocking */
#define POLLERR    0x0008  /* Error on fd (only in revents) */
#define POLLHUP    0x0010  /* ``Hangup'' has occurred on fd */
```

- **Note: BSD used select to achieve same thing**
  - Most OSes support both `select` and `poll` today

epoll

- **Newer Linux provides** `epoll`
- **Interface allows more efficient implementation**
  - Register interest with `epoll_create`, `epoll_ctl` syscalls
  - Wait with `epoll_wait` syscall
  - Kernel doesn't have to re-scan `pollfd` array on each wait
- **New option bits reduce calls to** `epoll_ctl`
  - `EPOLLONESHOT` – only wait for event once
  - `EPOLLET` – "edge triggered" (as opposed to level triggered)
- `epoll` **is Linux specific**
  - But BSD has kqueue/kevent which is similar idea

epoll interface

```
typedef union epoll_data {
    int fd;
    /* ... */
} epoll_data_t;

struct epoll_event {
    __uint32_t events;      /* Epoll events */
    epoll_data_t data;      /* User data variable */
};

int epoll_create(int size);
int epoll_ctl(int epfd, int op, int fd,
              struct epoll_event *event);
int epoll_wait(int epfd, struct epoll_event *events,
               int maxevents, int timeout);
```

Asynchronous programming model

- **Many non-blocking file descriptors in one process**
  - Wait for pending I/O events on file many descriptors
  - Each event triggers some *callback* function
- **E.g., build "callback harness":**

```
/* Register callback for when fd is readable or writable */
void cb_add (int fd, int write, void (*fn)(void *), void *arg);

/* Unregister callback */
void cb_free (int fd, int write);

/* Loop forever checking callbacks */
void cb_check (void);
```

- **Often called *event-based programing***

Simplified example

```
struct state {
  int fd;
  /* ... */
};

void doit (void) {
  struct state *st = malloc (sizeof (*st));
  st->fd = create_new_tcp_socket ();
  connect (st->fd, &someplace, sizeof (someplace));
  cb_add (st->fd, 1, doit_2, st);
}
static void doit_2 (void *_st) {
  struct state *st = _st;
  write (st->fd, "request\n", 8);
  cb_free (st->fd, 1);
  cb_add (st->fd, 0, doit_3, st);
}
static void doit_3 (void *_st) {
  struct state *st = _st;
  /* read more from st->fd until you get full response */
}
```

Syntactic sugar

- **Problem: Need state from one callback to next**
- **E.g., C++ can implement `wrap` that bundles a function with its arguments**

```
callback<void, int>::ref errwrite = wrap (write, 2);
(*errwrite) ("hello", 5);  // calls write (2, "hello", 5);
```

- **Possible to build large event-driven apps this way**
  - E.g., I have built large library to do this
  - Debugging features include recording where callbacks created to facilitate tracing
- **Google reportedly does similar things**

Pros & cons of event-based code

- **Advantages**
  - Fewer nasty bugs than threads (will discuss next week)
  - No locking, so no coarse- vs. fine-grained locking issues
  - Works with legacy, non-reentrant code (e.g., strtok, getpwnam)
  - Very efficient in terms of memory per client
  - Callbacks usually more efficient than thread switches
- **Disadvantages**
  - "Stack ripping" makes code ugly (but see [Adya])
  - Long running events make program unresponsive
  - Harder to take advantage of multiprocessors (but [Zeldovich])
  - Harder to do non-blocking disk I/O with existing OSes