Operating Systems Lecture Notes

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April 15, 2019

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2 Operating System Structure

2.1 Architectural impact

Architectural features affecting OS*s*

- These features were built primarily to support OS*s*:
  - timer (clock) operationg
  - synchronisation instructions
  - memory protection
  - I/O control operations
  - interrupts and exceptions
  - protected modes of operation (kernel vs. user mode)
  - privileged instructions
  - system calls (including software interrupts)
  - virtualisation architectures
- ASPLOS

2.2 User operating interaction

2.2.1 User v.s. kernel

Privileged instructions

- Some instructions are restricted to the OS
  - known as *privileged* instructions
- Only the OS can:
  - directly access I/O devices
  - manipulate memory state management (page table pointers, TLB loads, etc.)
  - manipulate special *mode bits* (interrupt priority level)
- Restrictions provide safety and security

OS protections

- So how does the process know if a privileged instruction should be executed?
  - the architecture must support at least two modes of operation: kernel mode, and user mode
  - mode is set by status bit in a protected processor register.
    * user programs execute in user mode
    * OS executes in kernel (privileged) mode (OS == kernel)
  - Privileged instructions can only be executed in kernel (privileged) mode
    * if code running in user mode attempts to execute a privileged instruction, the illegal execution trap.

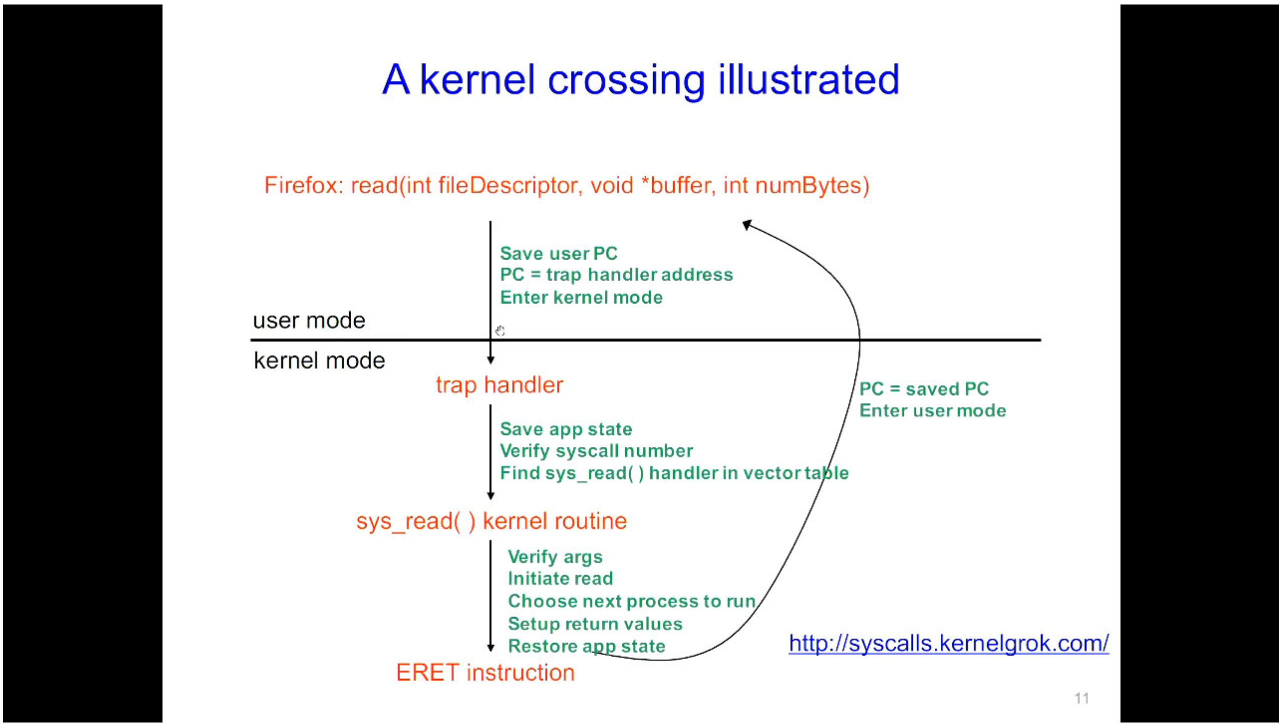
Crossing protection boundaries

- So how do user programs do something privileged?
  - e.g. how can you write to a disk if you can't execute any I/O instructions?
- User programs must call on OS procedure — that is to ask the OS to do it for them.
  - OS defines a set of system calls
  - User-mode program executes system call instruction
- Syscall instruction
  - like a protected procedure call

2.2.2 Syscall

Syscall

- The syscall instruction *atomically*:
  - saves the current PC
  - sets the execution mode to privileged
  - sets the PC to a handler address
- Similar to a procedure call
  - Caller puts arguments in a place the callee expects (registers, or stack)
    - One of the args is a syscall number, indicating which OS function to invoke
  - Callee (OS) saves caller's state (registers, other control states) so it can use the CPU
  - OS function code runs
    - OS must verify caller's arguments (e.g. pointers)
  - OS returns using a special instruction
    - Automatically sets PC to return address and sets execution mode to user.



System call issues

- A syscall is not a subroutine call, with the caller specifying the next PC.
  - the caller knows where the subroutines are located in memory; therefore they can be the target of an attack.
- The kernel saves state?
  - Prevents overwriting of values
- The kernel verify arguments
  - Prevents buggy code crashing the system
- Referring to kernel objects as arguments
  - Data copied between user buffer and kernel buffer.

Exception handling and protection

- *All* entries to the OS occur via the mechanism just shown
  - Acquiring privileged mode and branching to the trap handler are inseparable
- Terminology
  - *Interrupt*: asynchronous; caused by an external device
  - *Exception*: synchronous; unexpected problem with instruction
  - *Trap*: synchronous; intended transition to OS due to an instruction

  In all three cases, they are instances of where something strange happens, and the OS takes control: whether by accident, or by intention.
- Privileged instructions and resources are the basis for most everything: memory protection, protected I/O, limiting user resource consumption.

2.3 Operating System structure

2.3.1 Layers

Operating System structure

- The OS sits between application programs and the hardware
  - it mediates access and abstracts away ugliness
  - programs request services via traps or exceptions
  - devices request attention via interrupts

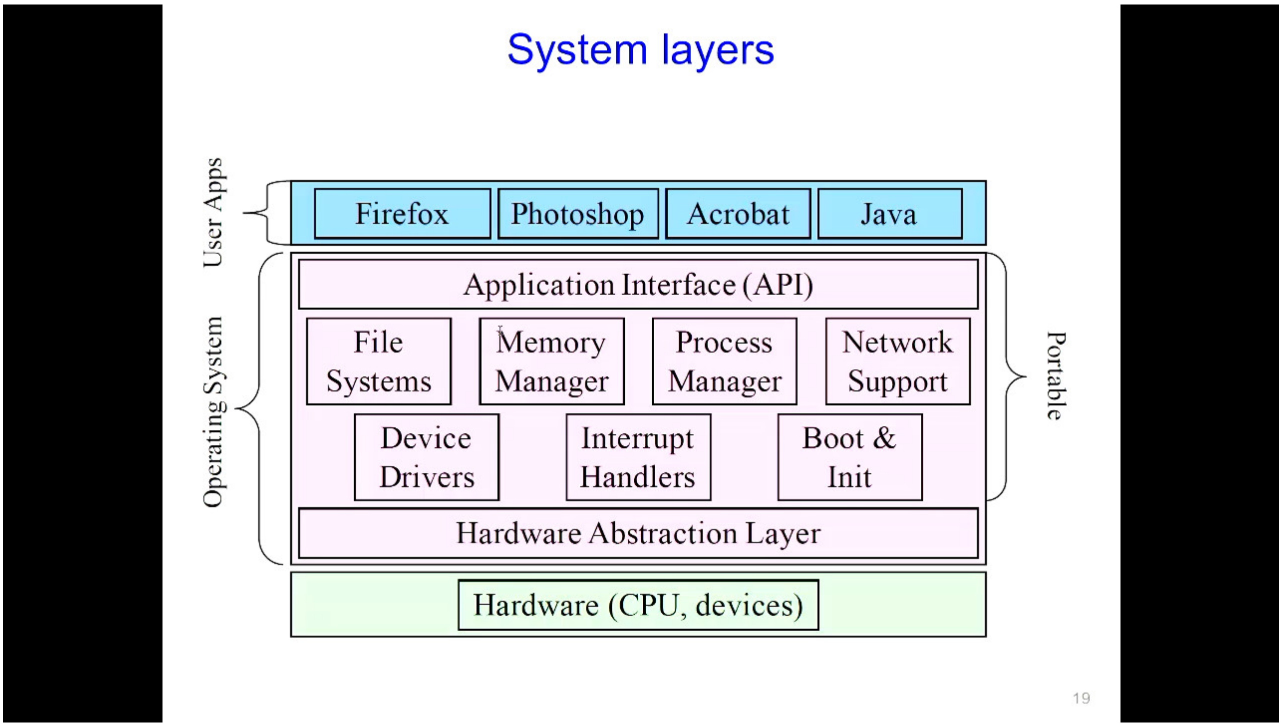
Operating system design and implementation

- Design and implementation of OS not "solvable", but some approaches have proven successful.
- Internal structure of different OS*s* can vary widely.
- Start the design by defining goals and specifications.
- Affected by choice of hardware, type of system.
- *User* goals, and *system* goals
  - User goals: OS should be convenient to use, easy to learn, reliable, safe, and fast
  - System goals: OS should be easy to design, implement, and maintain, as well as flexible, reliable, error-free, and efficient.
- Important principle to separate

- **Policy**: *What* will be done?
- **Mechanism**: *How* to do it?

- Mechanisms determine how to do something, policies decide what will be done.
- The separation of policy from mechanism is a very important principle, it allows maximum flexibility if policy decisions are to be changed later (e.g. timer).
- Specifying and designing an OS is a highly creative task of *software engineering*.

System layers



Major OS components

- processes
- memory
- I/O
- secondary storage
- file systems
- protection
- shells
- GUI
- networking

OS structure

- There's no clear hierarchy within an OS — each of them needs access to different things.
- An OS consists of all these components, plus:
  - many other components
  - system programs (privileged, and non-privileged)

- Major issue:
  - how do we organize all this?
  - what are all of the code modules, and where do they exist?
  - how do they cooperate?
- Massive software engineering and design problem
  - design a large, complex program that: performs well, is reliable, is extensible, and is backwards compatible.

2.3.2 Examples

Monolithic design

- Traditionally, OS*s* (like UNIX) were built as a *monolithic* entity User programs — OS (everything) — hardware
- Major advantage: cost of module interactions is low (procedure call)
- Disadvantages:
  - hard to understand
  - hard to modify
  - unreliable (no isolation between system modules)
  - hard to maintain
- What is the alternative?
  Find a way to organise the OS in order to simplify its design and implementation.

Layering

- The traditional approach is layering
  - implement OS as a set of layers
  - each layer presents an enhanced *virtual machine* to the layer above
- The first description of this approach was Dijkstra's THE system
  - Layer 5: *Job managers* execute users' programs
  - Layer 4: *Device managers* handle devices and provide buffering
  - Layer 3: *Console manager* implements virtual consoles
  - Layer 2: *Page manager* implements virtual memories for each process
  - Layer 1: *Kernel* implements a virtual processor for each process
  - Layer 0: *Hardware*
- Each layer can be tested and verified independently
- Imposes a hierarchical stricture
  - but real systems are more complex: file systems require VM services (buffer); VM would like to use files for its backing store
  - strict layering isn't flexible enough
- Poor performance: each layer crossing has *overhead* associated with it

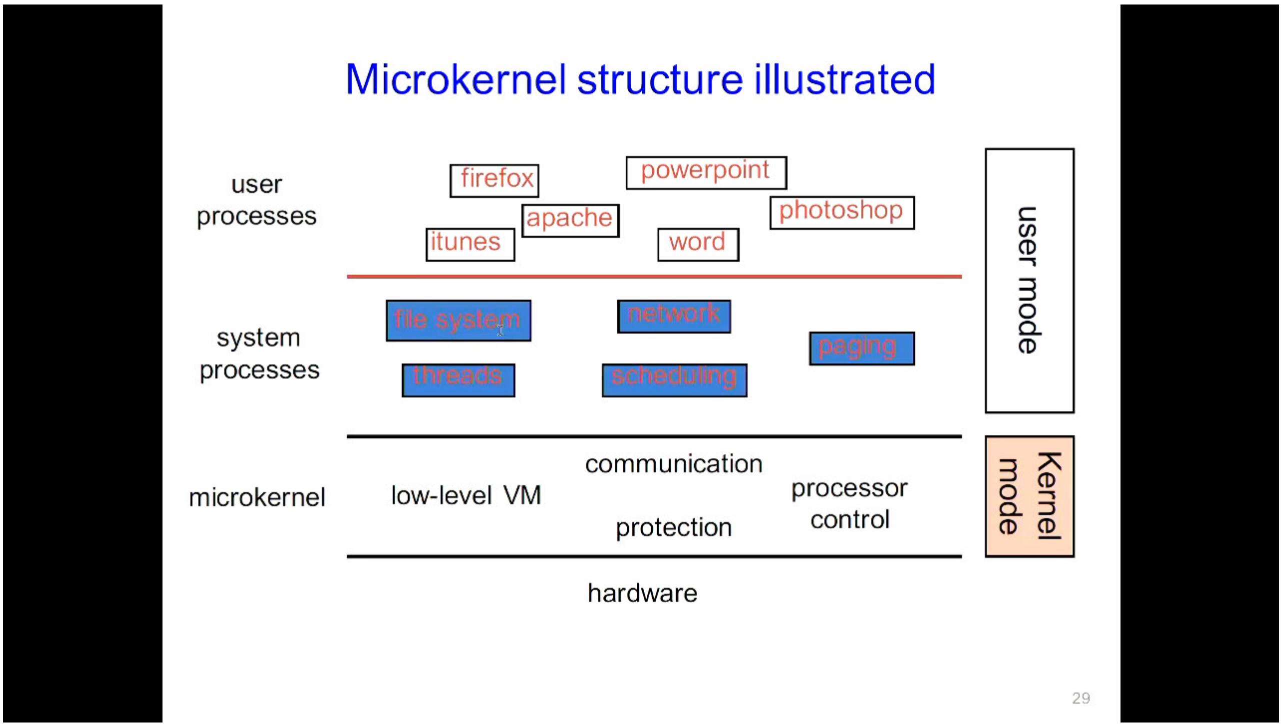
- Disjunction between model and reality: systems modelled as layers, but not really built that way.

Hardware abstraction layer

- An example of layering in modern operating systems
- Goal: separates hardware-specific routines from the *core* OS
  - Provides portability
  - Improves readability

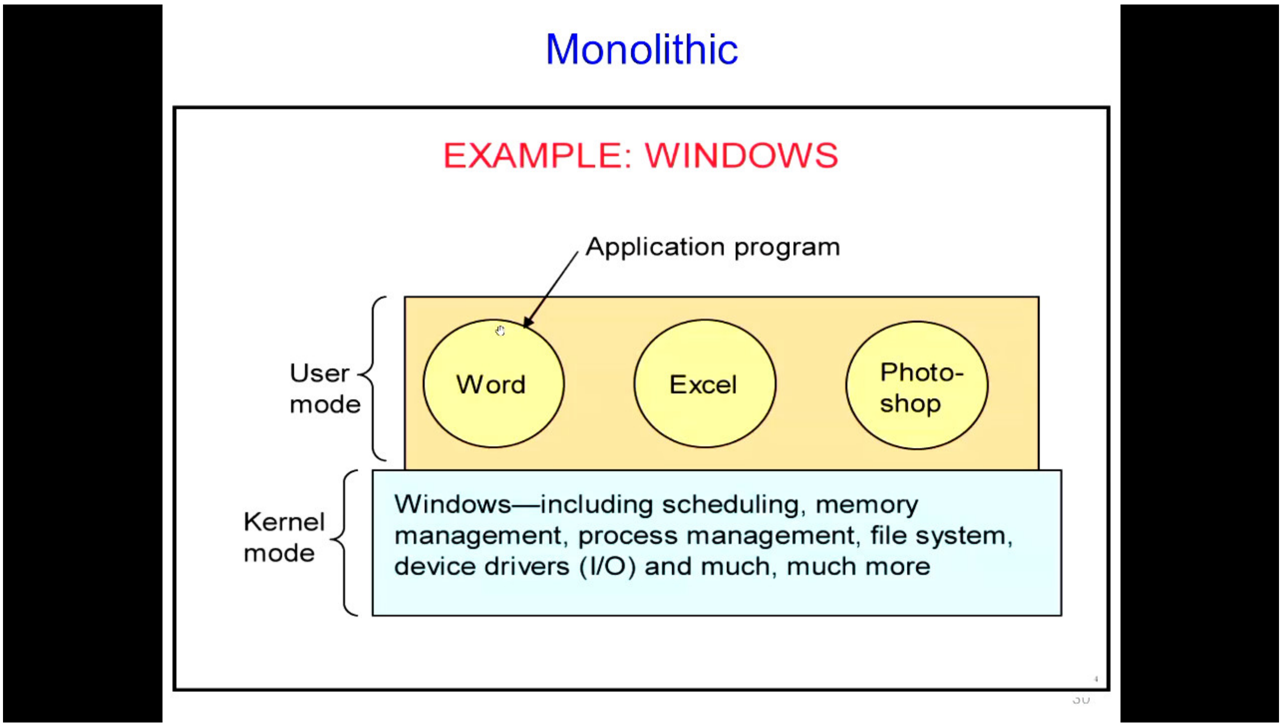
Microkernels

- Popular in the late 80s, early 90s
- Goal: minimize what happens in kernel; item organize rest of OS as user-level processes.
- This results in:
  - better reliability (isolation between components)
  - easy of extension and customisation
  - poor performance (user/kernel boundary crossings)
- First microkernel system was Hydra (CMU, 1970)
  - Contemporaries: Mach (CMU), Chorus (French UNIX-like OS), OS X (Apple), in some ways NT (Microsoft)

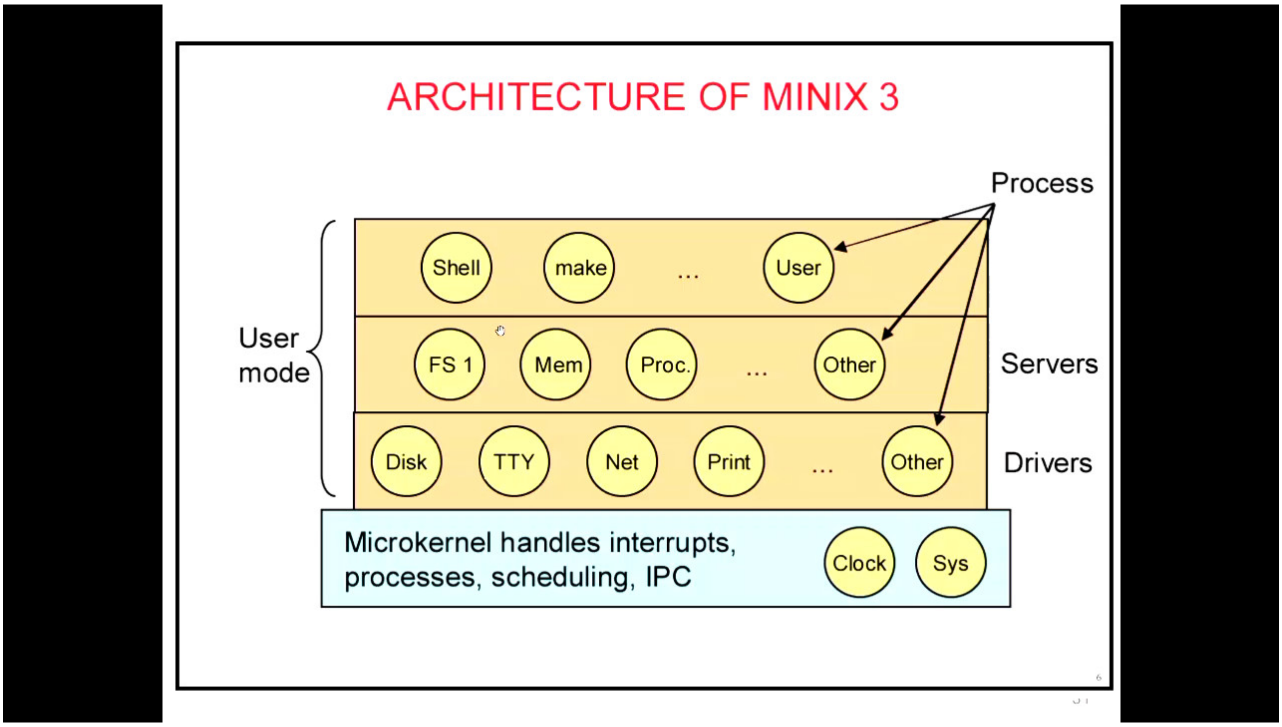


Comparison of OS structures

Windows



MINIX 3



Loadable kernel modules

- (Perhaps) the best practice for OS design
- Core services in the kernel, and others dynamically loaded
- Common implementations include: Solaris, Linux, etc.
- Advantages
  - convenient: no need for rebooting for newly added modules
  - efficient: no need for message passing unlike micro-kernel

  - flexible: any module can call any other module unlike layered model

2.4 Summary

- Fundamental distinction between user and privileged mode supported by most hardware
- OS design has been an evolutionary process of trial and error.
- Successful OS designs have run the spectrum from monolithic, to layered, to micro-kernels
- The role and design of an OS are still evolving
- It is impossible to pick one “correct” way to structure an OS

3 Processes

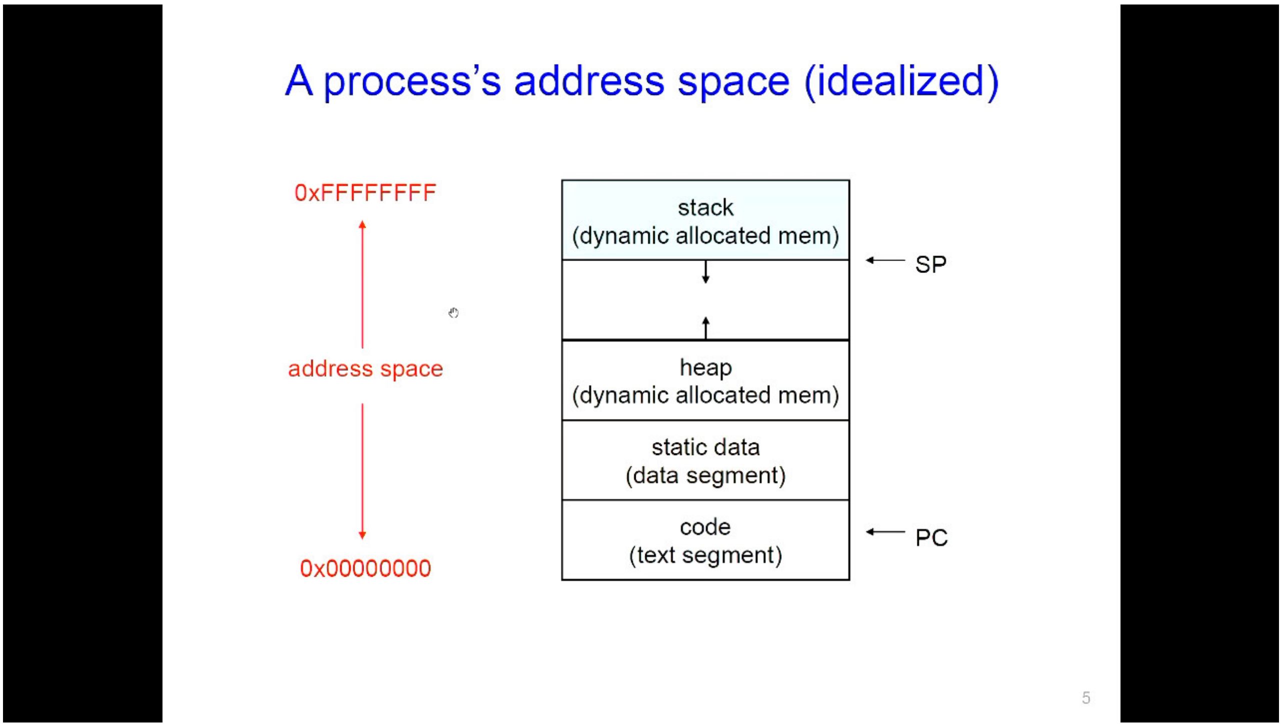
3.1 Process

What is a "process"?

- The process is the OS*s* abstraction for execution
  - A process is a program in execution
- Simplest (classic) case: a *sequential process*
  - An address space (an abstraction of memory)
  - A single thread of execution (an abstraction of the CPU)
- A sequential process is:
  - The unit of execution
  - The unit of scheduling
  - The dynamic (active) execution context (as opposed to the program — static, just a bunch of bytes)

What's "in" a process?

- A process consists of (at least):
  - An *address space*, containing:
    * the code (instructions) for the running program
    * the data for the running program (static data, heap data, stack)
  - *CPU state*, consisting of:
    * the program counter (PC), indicating the next instruction;
    * the stack pointer;
    * other general purpose register values.
  - A set of *OS resources*
    * open files, network connections, sound channels, ...
  - In other words, everything needed to run the program (or to restart, if interrupted).



The OS process namespace

- The particulars depend on the specific OS, but the principles are general;
- The name for a process is called a *process ID* (PID) (an integer);
- The PID namespace is global to the system;
- Operations that create processes return a PID (e.g. fork);
- Operations on processes take PIDs as an argument (e.g. kill, wait, nice).

3.2 Process control block

Representation of processes by the OS

- The OS maintains a data structure to keep track of a process's state
  - called the *process control block* (PCB) or *process descriptor*;
  - identified by the PID.
- OS keeps all of a process's execution state in (or linked from) the PCB when the process isn't running
  - PC, SP, registers, etc.
  - when a process is unscheduled, the state is transferred out of the hardware into the PCB
  - (when a process is running, its state is spread between the PCB and the CPU).

The PCB

- The PCB is a data structure with many, many fields
  - PID
  - parent PID
  - execution state
  - PC, SP, registers

- address space info
- UNIX user id, group id
- scheduling priority
- accounting info
- pointers for state queues

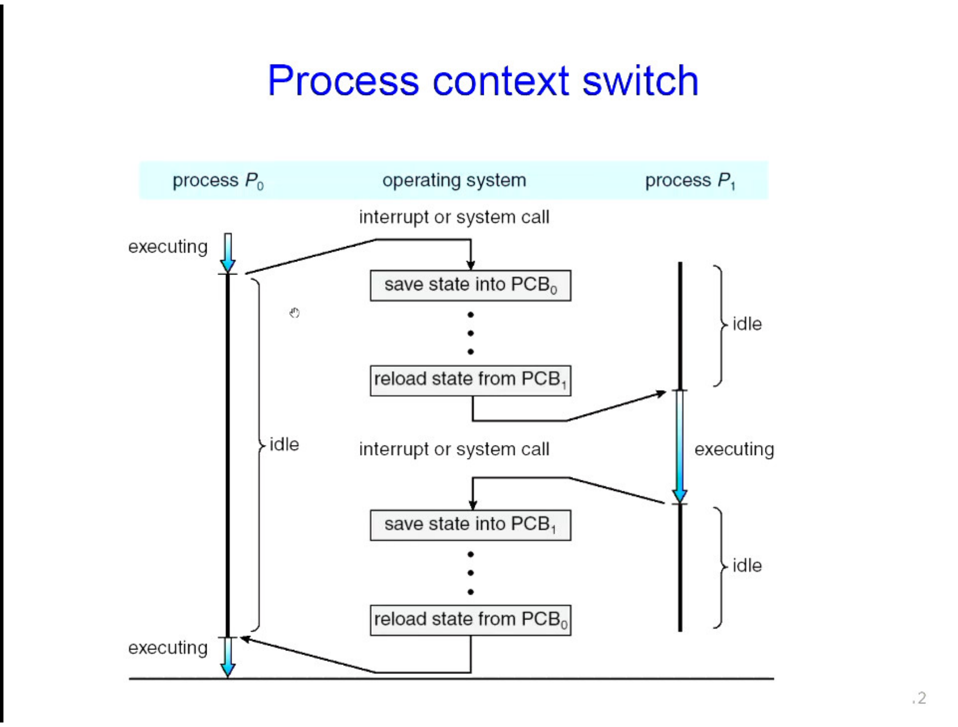
- In Linux:
  - defined in `task_struct (include/linux/sched.h)`
  - Over 95 fields!

3.3 Process state & context switch

PCBs and CPU state

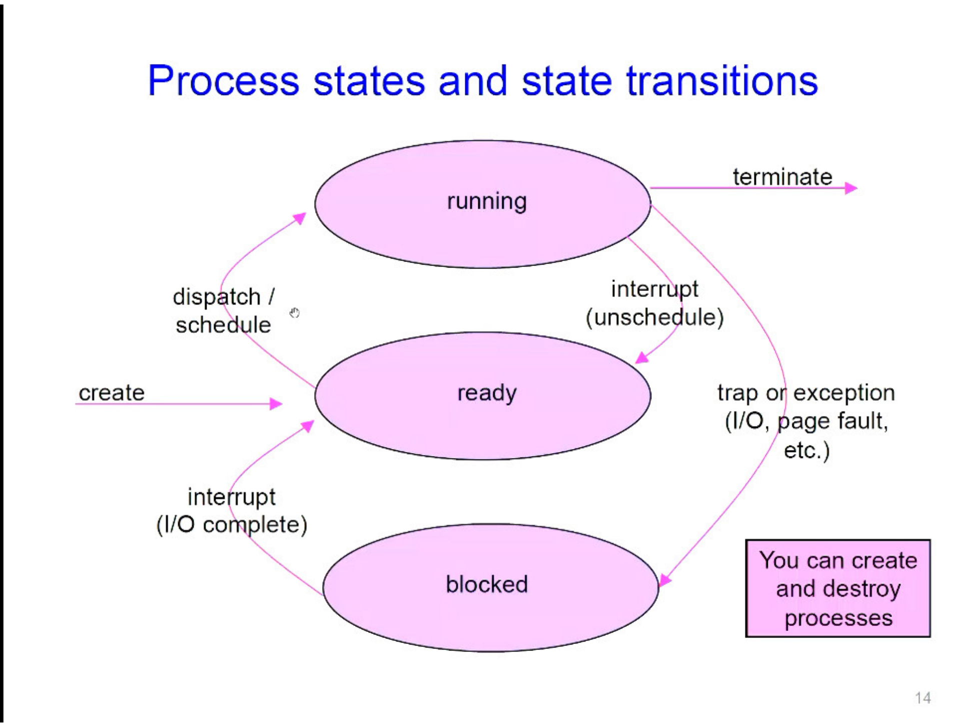
- When a process is running, its CPU state is inside the CPU
  - PC, SP, registers
  - CPU contains current values
- When the OS gets control because of a
  - *Trap*: program executes a syscall
  - *Exception*: program does something unexpected (e.g. page fault)
  - *Interrupt*: A hardware device requests service

  the OS saves the CPU state of the running process in that process's PCB.
- When the OS returns the process to the running state
  - it loads the hardware registers with values from that process's PCB
  - e.g. general purpose registers, SP, instruction pointer
- This act of switching the CPU from one process to another is called a *context switch*
  - systems may do 100s or 1000s of switches per second;
  - takes a few microseconds on today's hardware;
  - still expensive relative to thread-based context switches.
- Choosing which process to run next is called *scheduling*.



Process execution states

- Each process has an *execution state*, which indicates what it's currently doing
  - *ready*: waiting to be assigned to a CPU — could run, but another process has the CPU;
  - *running*: executing on a CPU — it's the process that currently controls the CPU;
  - *waiting* (aka "blocked"): waiting for an event, e.g. I/O completion, or a messing from (or the completion of) another process — cannot make progress until the event happens.
- As a process executes, it moves from state to state
  - UNIX: run `top`, STAT column shows current state
  - which state is a process most of the time?



State queues

- The OS maintains a collection of queues that represent the state of all processes in the system
  - typically one queue for each state (e.g. ready, waiting, ...);
  - each PCB is queued onto a state queue according to the current state of the process it represents;
  - as a process changes state, its PCB is unlinked from one queue, and linked onto another.
- The PCBs are moved between queues, which are represented as linked lists.
- There may be many wait queues, one for each type of wait (particular device, timer, message, ...).

PCBs and state queues

- PCBs are data structures
  - dynamically allocated inside OS memory.
- When a process is created:
  - OS allocates a PCB for it;
  - OS initializes PCB;
  - (OS does other things not related to the PCB);
  - OS puts PCB on the correct queue.
- As a process computes:
  - OS moves its PCB from queue to queue.
- When a process is terminated:
  - PCB may be retained for a while (to receive signals, etc.)
  - eventually, OS deallocates the PCB.

3.4 Process creation and termination

Process creation

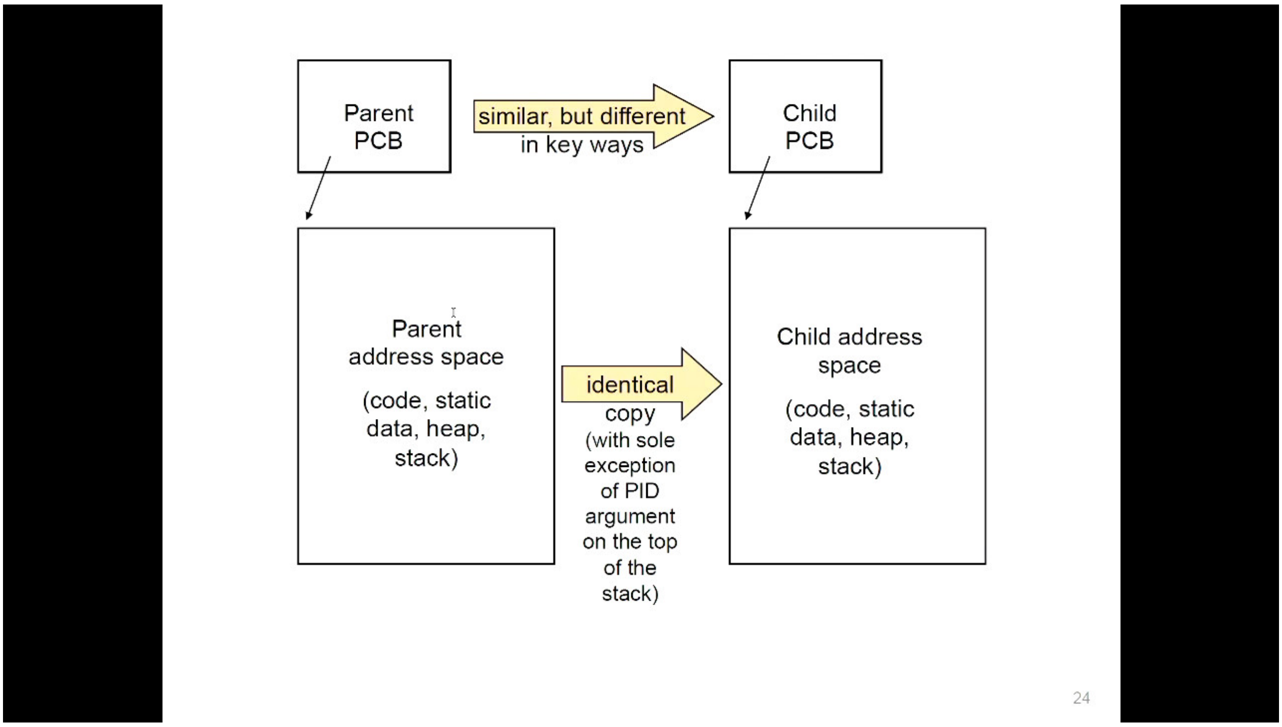
- New processes are created by existing processes
  - creator is called the *parent*;
  - created process is called the *child*;
    UNIX: do `ps -ef`, look for PPID field
  - what creates the first process, and when?
    on UNIX, this first process is init;
    on many Linux distributions, this is SystemD or Runit (on Void).

Process creation semantics

- (Depending on the OS) child processes inherit certain attributes of the parent. E.g.
  - Open file table: implies `stdin/stdout/stderr`;
  - On some systems, resource allocation to parent may be divided among children.
- (In Unix) when a child is created, the parent may either wait for the child to finish, or continue in parallel.

UNIX process creation details

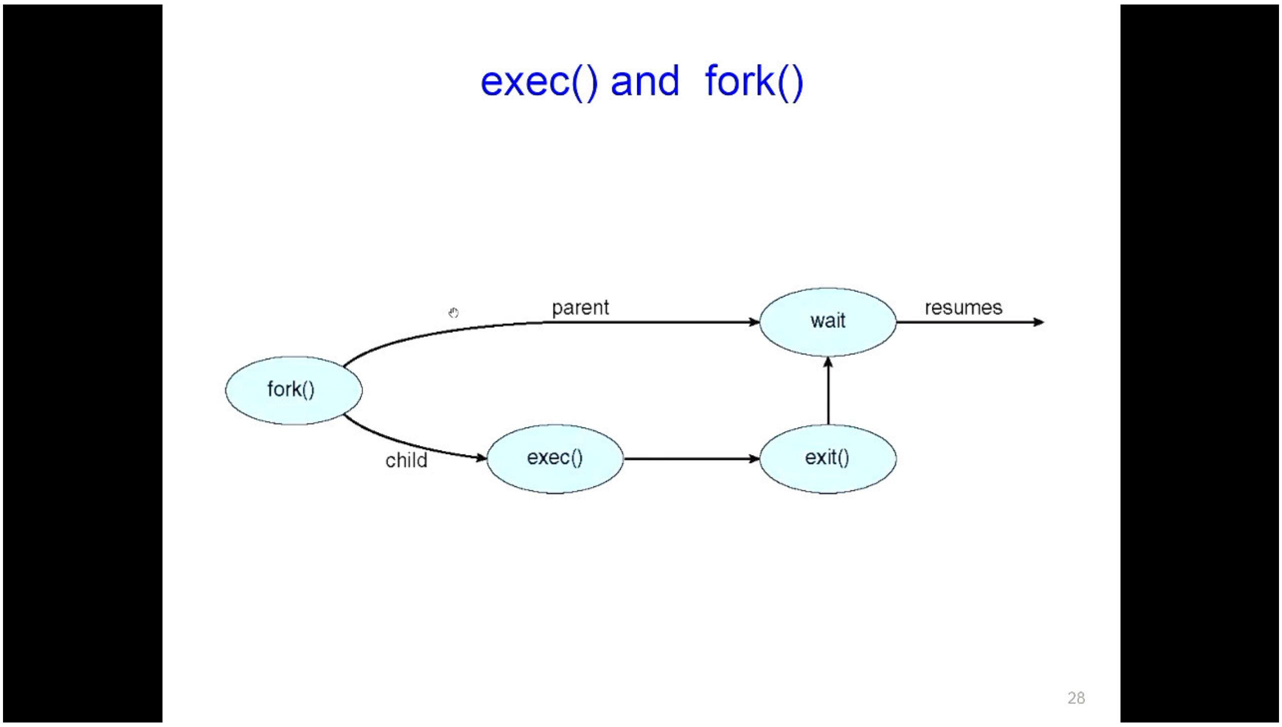
- UNIX process creation through `fork` system call
  - creates and initializes a new PCB
    - initializes kernel resources of new process with resources of parent (e.g. open files)
    - initializes PC, SP to be same as parent.
  - creates a new address space
    - initialises new address space with a copy of the entire contents of the address space of the parent
  - places new PCB on the ready queue.
- the `fork` system call "returns twice"
  - once into the parent, and once into the child
    - returns the child's PID to the parent
    - returns `0` to the child
- `fork` = "clone me".
  The return value is used to determine whether we're the clone or the original.



`exec` **v.s.** `fork`

- Q: So how do we start a new program, instead of just forking the old program?
- A: First `fork`, then `exec`.
- `exec`
  - stops the current process
  - loads program 'prog' into the address space (i.e. overwrites the existing process image)
  - initialises hardware context, args for new program
  - places PCB onto ready queue

  – *does not create a new process!*



Method 1: `vfork`

- `vfork` is the older (now uncommon) of the two approaches.
- Instead of "child's address space is a copy of the parent's", the semantics are "child's address space *is* the parent's",
  – with a "promise" that the child won't modify the address space before doing an `execve`.
  – When `execve` is called, a new address space is created and it's loaded with the new executable.
  – Parent is blocked until `execve` is executed by child.
  – Saves wasted effort of duplicating parent's address space.

Method 2: copy-on-write

- Retains the original semantics, but copies "only what is necessary" rather than the entire address space.
- On `fork`:
  – Create a new address space
  – Initialise page tables with same mappings as the parent's (i.e. they both point to the same physical memory).
    ∗ (No copying of address space contents have occurred at this point — with the sole exception of the top page of the stack.)
  – Set both parent and child page tables to make all pages read-only
  – If either parent or child writes to memory, an exception occurs.
  – When exception occurs, OS copies the page, adjusts page tables, etc.

3.5 Summary

- Process
- PCB
- Process state
- Context switch
- Process creation and termination

4 Threads

4.1 Process vs Threads

What's *in* a process?

- A process consists of (at least):
  - An *address space*, containing
    - the code (instructions) for the running program
    - the data for the running program
  - *Thread state*, consisting of
    - The PC, indicating the next instruction
    - The SP, indicating the position on the stack
    - Other general purpose registers
  - A set of *OS resources*
    - Open files, network connections, sound channels, ...
- Decompose ...
  - address space
  - *thread of control* (stack, SP, PC, registers)
  - OS resources

Motivation

- Threads are about *concurrency* and *parallelism*
- One way to get concurrency and parallelism is to use multiple processes
  - The programs (code) of distinct processes are isolated from each other
- Threads are another way to get concurrency and parallelism
  - Threads *share a process* — same address space, same OS resources
  - Threads have private stack, CPU state — are schedulable

What's needed?

- In many cases
  - Everybody wants to run the same code
  - Everybody wants to access the same data
  - Everybody has the same privileges
  - Everybody uses the same resources (open files, network connections, etc.)
- But you'd like to have multiple hardware execution states:
  - an execution stack and SP
    - traces state of procedure calls made
  - the PC, indicating the next instruction
  - a set of general-purpose processor registers and their values

How could we achieve this?

- Given the process abstraction as we know it:
  - for several processes
  - cause each to *map* to the *same* physical memory to share data (`shmget`),
- This is really inefficient
  - space: PCB, page tables, etc.
  - time: creating OS structures, fork/copy address space, etc.

Can we do better?

- Key idea:
  - separate the concept of a *process* (address space, OS resources)
  - ...from that of a minimal *thread of control* (execution state: stack, SP, PC, registers),
- This execution state is usually called a *thread*, or a *lightweight process.*

Threads and processes

- Most modern OS*s* support two entities:
  - the *process*, which defines the address space and general process attributes (such as open files, etc.)
  - the *thread*, which defines a sequential execution stream within a process.
- A thread is bound to a single process / address space
  - address spaces, however, can have multiple threads executing within them
  - sharing data between threads is cheap: all see the same address space
  - creating threads is cheap, too!
- *Threads become the unit of scheduling*
  - processes / address spaces are just *containers* in which threads execute.

Single and Multi-threaded Processes

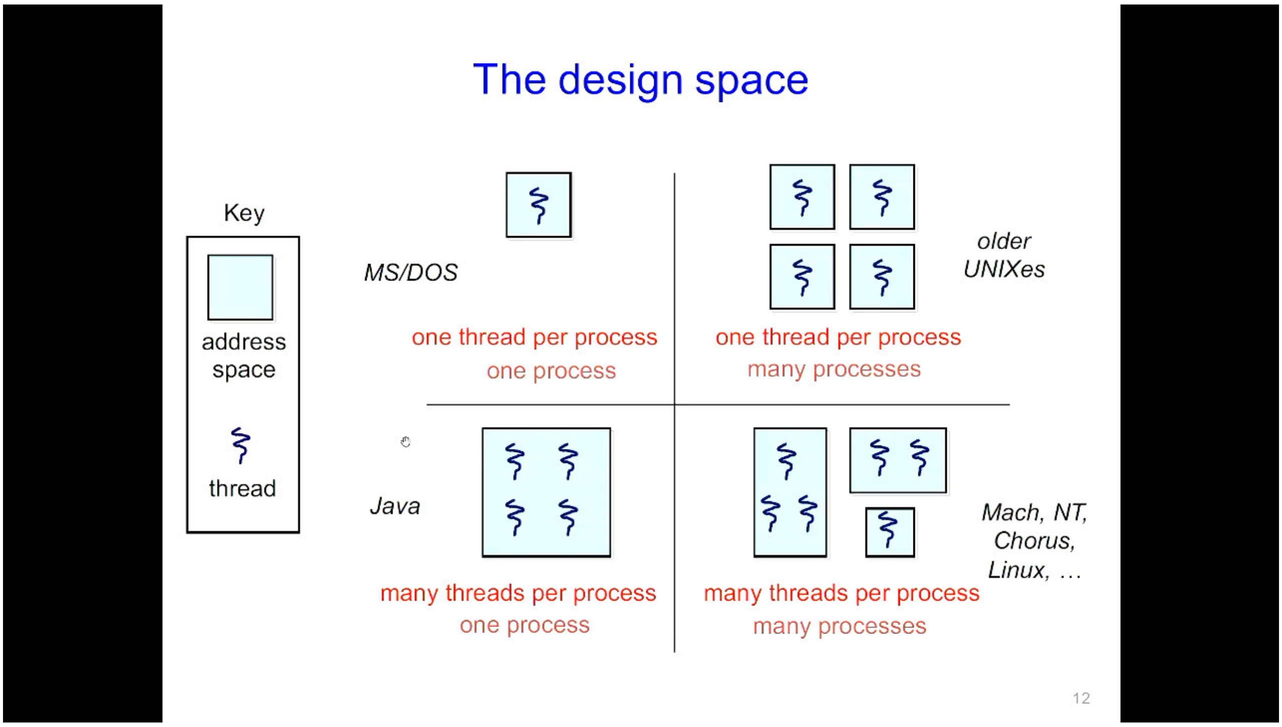
- Different threads in the same process have separate registers and stacks.
- This is cheaper than duplicating the instructions and PCB etc., as required by having multiple processes.

4.2 Concurrency

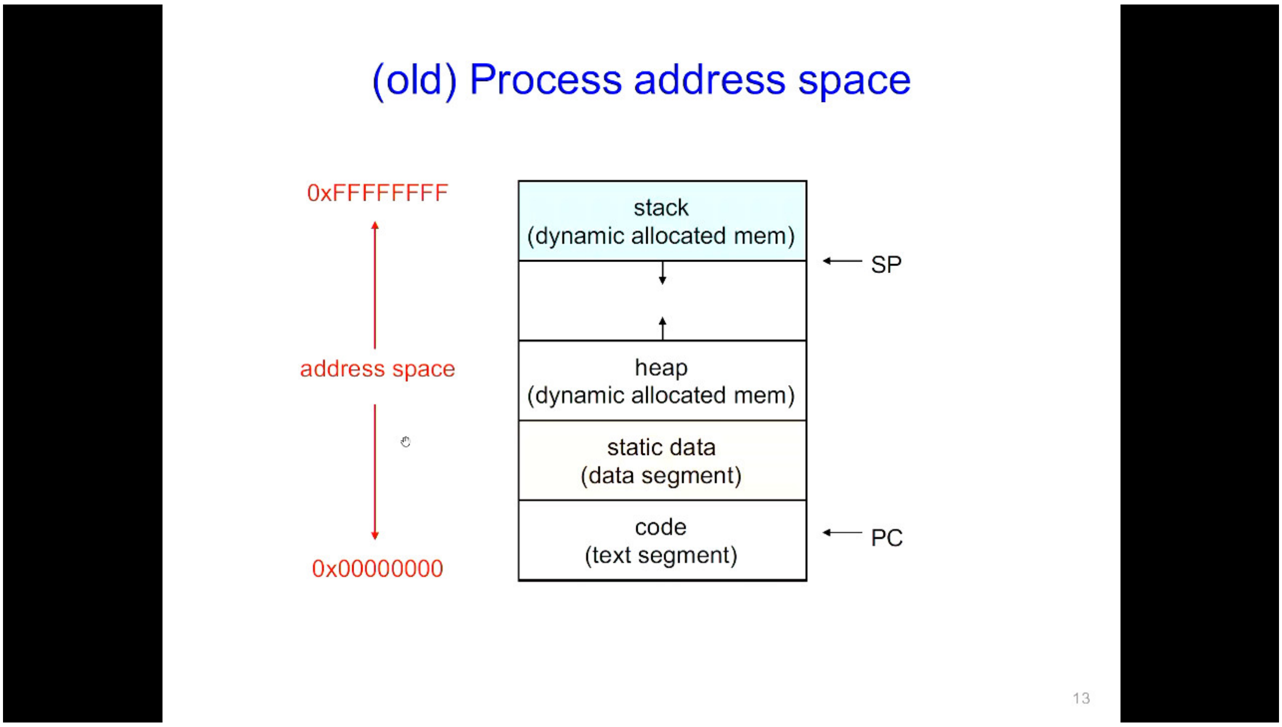
Communication

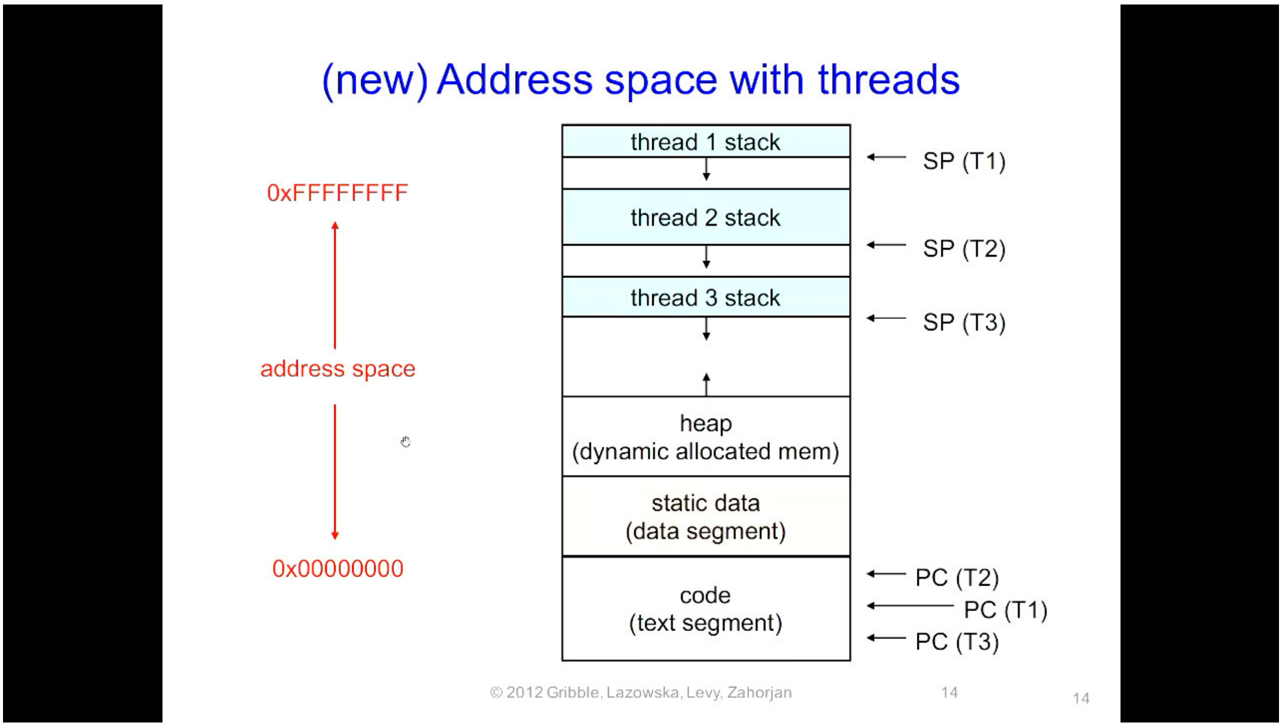
- Threads are concurrent executions sharing an address space (and some OS resources)
- Address spaces provide isolation
  - If you can't name an object, you can't read or write to it
- Hence, communicating between processes is expensive
  - Must go through the OS to move data from one address space to another
- Because threads are in the same address space, communication is simple/cheap
  - Just update a shared variable!

The design space



Process address space





4.3 Design space of process/threads

Process/thread separation

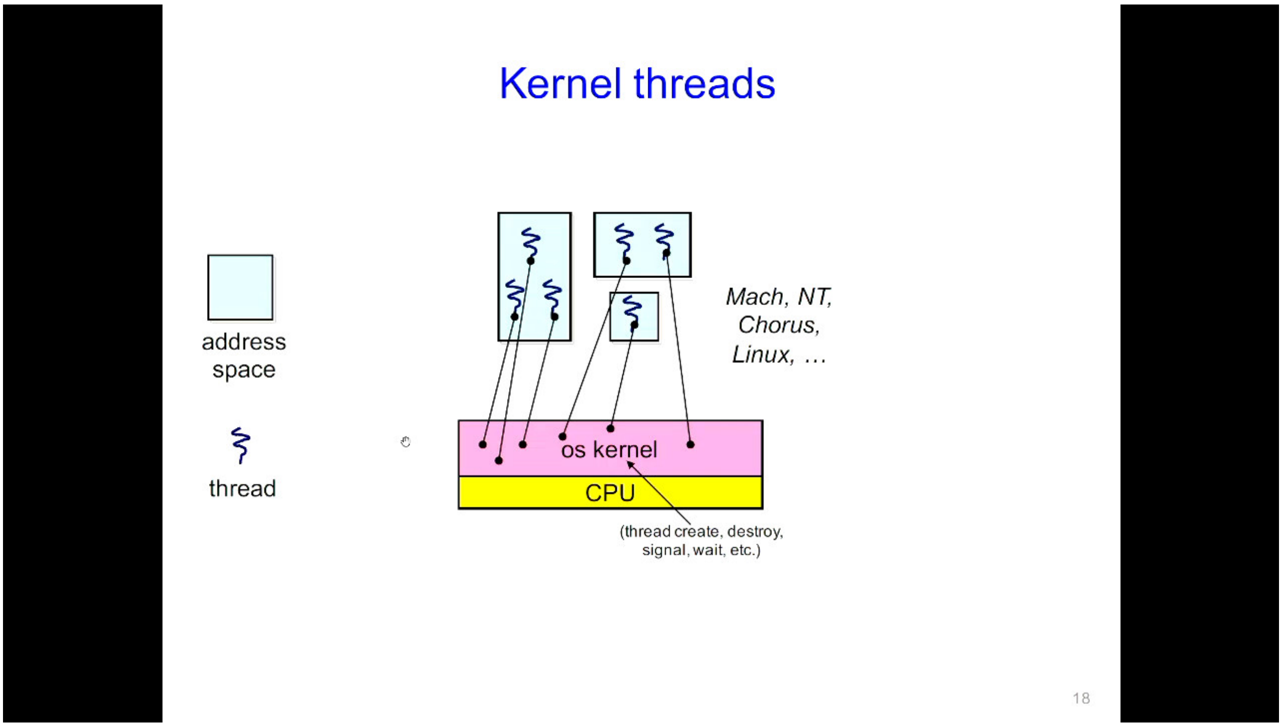
- Concurrency (multi-threading) is useful for:
  - handling concurrent events (e.g. web servers and clients)
  - building parallel programs (e.g. matrix multiply, ray tracing)
  - improving program structure (the Java argument),
- Multi-threading is useful even on a uniprocessor
  - even though only one thread can run at a time
- Supporting multi-threading — that is, separating the concept of a *process* (address space, files, etc.) from that of a minimal *thread of control* (execution state), is a big win
  - creating concurrency does not require creating new processes
  - "faster / better / cheaper"

4.4 Kernel threads

Where do threads come from?

- Natural answer: the OS is responsible for creating/managing threads
  For example, the kernel call to create a new thread would
  - allocate an execution stack within the process address space
  - create and initialize a *Thread Control block*
    (SP, PC, register values)
  - stick it on the ready queue
- We call these *kernel threads*
  There is a "thread name space"
  - Thread IDs (TIDs)

– TIDs are integers



Kernel Threads

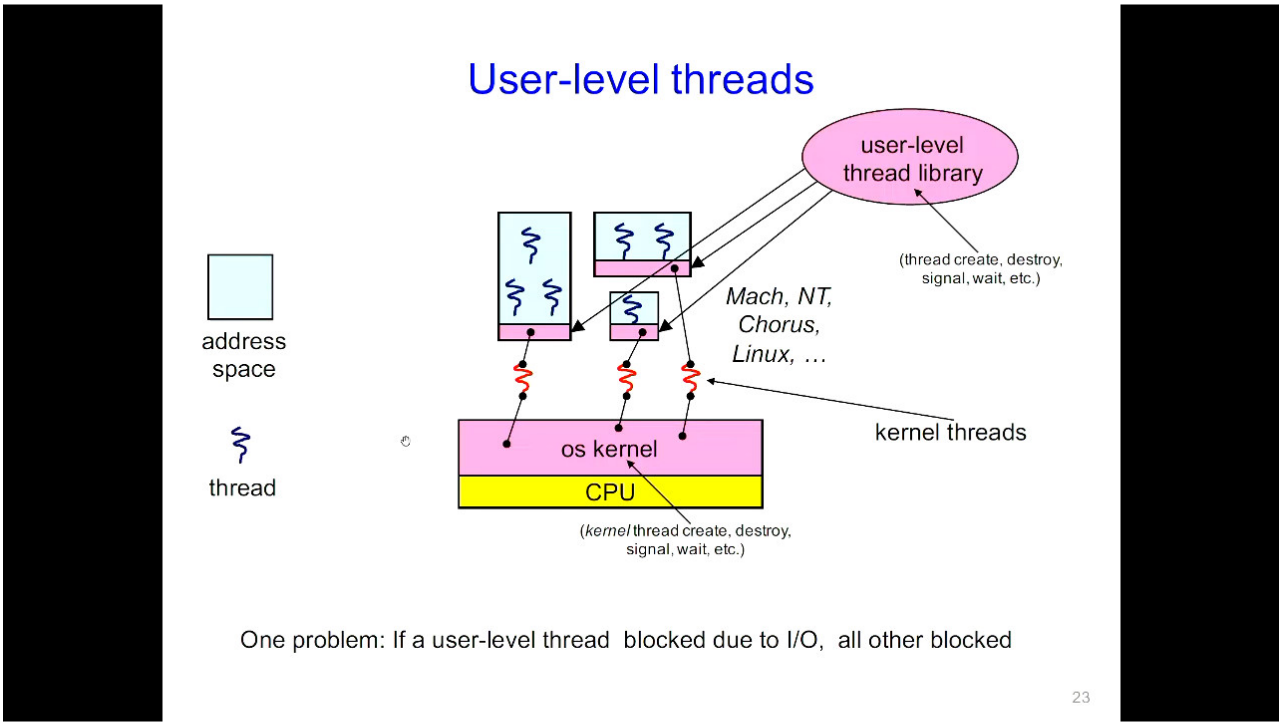
- OS now manages threads *and* processes / address spaces
  - all thread operations are implemented in the kernel
  - OS schedules all of the threads in a system
    - ∗ if one thread in a process blocks (e.g. on I/O), the OS knows about it, and can run other threads from that process
    - ∗ possible to overlap I/O and computation *inside* a process
- Kernel threads are cheaper than processes
  - less state to allocate and initialise
- But, they're still pretty expensive for fine-grained use
  - orders of magnitude more expensive than a procedure call
  - thread operations are all *system calls*
    - ∗ context switch
    - ∗ argument checks
  - must maintain kernel state for each thread

4.5 User-level threads

Cheaper alternative

- There is an alternative to kernel threads
- Threads can also be managed at the user level (within the process)
  - a library linked into the program manages the threads

        * the thread manager doesn't need to manipulate address spaces (which only the kernel can do)
        * threads differ (roughly) only in hardware contexts (PC, SP, registers), which can be manipulated by user-level code
        * the *thread package* multiplexes user-level threads on top of kernel threads
        * each kernel thread is treated as a *virtual processor*
    - we call these *user-level threads*



User-level threads

- User-level threads are small and fast
    - managed entirely by user-level library (e.g. `pthreads`)
    - each thread is represented by a PC, registers, a stack, and a small *thread control block* (TCB)
    - creating a thread, switching between threads, and synchronising threads are done *via procedure calls*
        * no kernel involvement necessary!
- User-level thread operations can be 10–100x faster than kernel threads as a result.

User-level thread implementation

- The OS schedules the kernel thread
- The kernel thread executes user code, including the thread support library and its associated thread scheduler
- The thread scheduler determines when a user-level thread runs
    - it uses queues to keep track of what threads are doing: run, ready, wait
        * just like the OS and processes
        * but, implemented at user-level as a library

Thread context switch

- Very simple for user-level threads:
  - save context of currently running thread
    * push CPU state onto thread stack
  - restore context of the next thread
    * pop CPU state from next thread's stack
  - return as the new thread
    * execution resume at PC of next thread
  - Note: no changes to memory mapping required
- This is all done in assembly language
  - it works at the level of the procedure calling convention

How to keep a user-level thread from hogging the CPU?

- Strategy 1: force everyone to cooperate
  - a thread willingly gives up the CPU by calling `yield`
  - `yield` calls into the scheduler, which context switches to another ready thread
  - what happens if a thread never calls `yield`?
- Strategy 2: use presumption
  - scheduler requests that a timer interrupt be delivered by the OS periodically
    * usually delivered as a UNIX signal (`man signal`)
    * signals are just like software interrupts, but delivered to user-level by the OS instead of delivered to the OS by hardware
  - at each timer interrupt, scheduler gains control and context switches as appropriate.

What if a thread tries to do I/O

- The kernel thread "powering" it is lost for the duration of (synchronous) I/O operation!
  - The kernel thread blocks in the OS, as always
  - It maroons with it the state of the user-level thread
- Could have one kernel thread "powering" each user-level thread
  - "common case" operations (e.g. synchronisation) would be quick
- Could have a limited-size "pool" of kernel threads "powering" all the user-level threads in the address space
  - the kernel will be scheduling these threads, obliviously to what's going on at user-level.

4.6 Summary

- Multiple threads per address space
- Kernel threads are much more efficient than processes, but still expensive
  - all operations require a kernel call and parameter validation
- User-level threads are:

  - much cheaper and faster
  - great for common-case operations
    * creation, synchronisation, destruction
  - can suffer in uncommon cases due to kernel obliviousness
    * I/O
    * pre-emption of a lock-holder

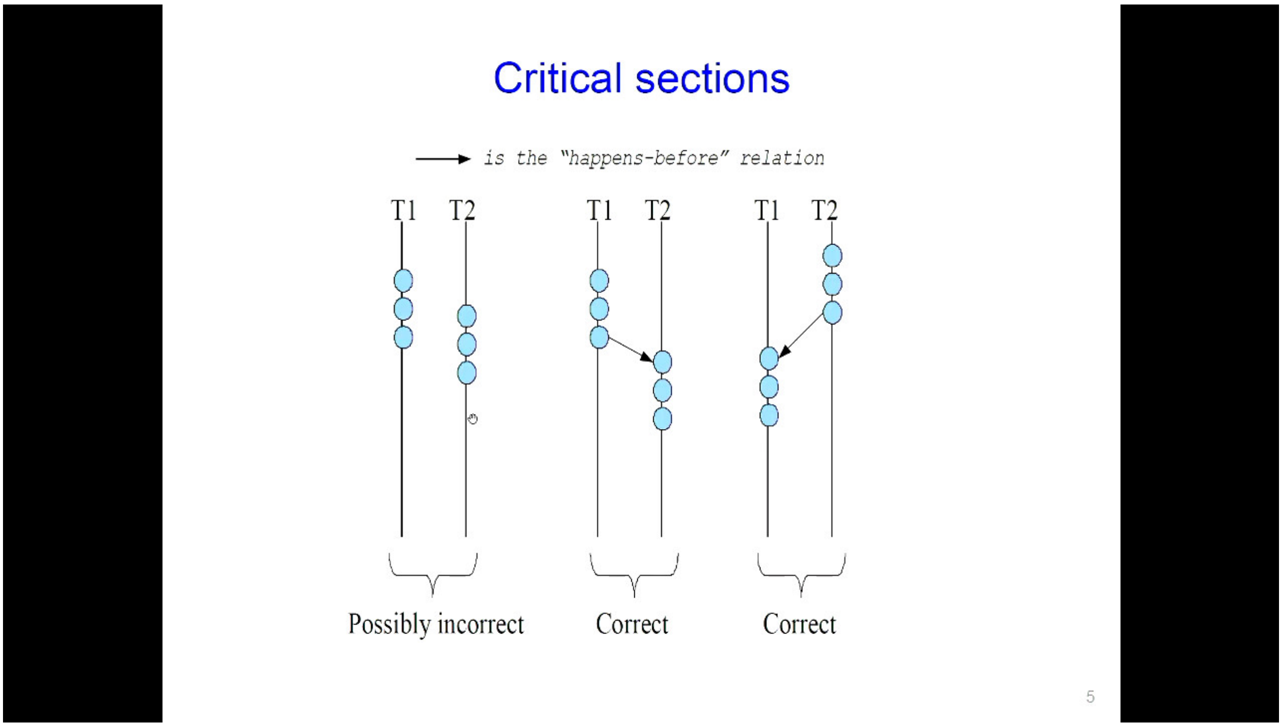
5 Synchronisation

Temporal relations

- User view of parallel threads
  - Instructions executed by a single thread are totally ordered
    * $A < B < C < \dots$
  - In absence of *synchronisation*:
    * instructions executed by distinct threads must be considered unordered / simultaneous
    * Not $X < X'$, and not $X' < X$
- Hardware largely supports this

Critical sections / mutual exclusion

- Sequences of instructions that may get incorrect results if executed simultaneously are called *critical sections*.
- *Race condition* results depend on timing
- *Mutual exclusion* means "not simultaneously"
  - $A < B$ or $B < A$
  - We don't care which
- Forcing mutual exclusion between two critical section executions
  - is sufficient to ensure correct execution
  - guarantees ordering.



When do critical sections arise?

- One common pattern:
  - read-modify-write of
  - a shared value (variable)
  - in code that can be executed by concurrent threads
- Shared variable:
  - Global and heap-allocated variables
  - NOT local variables (which are on the stack)

Race conditions

- A program has a *race condition* (data race) if the result of an execution depends on timing (i.e. it is non-deterministic)
- Typical symptoms
  - I run it on the same data, and sometimes it prints 0 and sometimes 4
  - I run it on the same data, and sometimes it prints 0 and sometimes crashes

Correct critical section requirements

- *Mutual exclusion*
  At most one thread is in the critical section.
- *Progress*
  If thread T is outside the critical section, then T cannot prevent thread S from entering the critical section.
- *Bounded waiting* (no *starvation*)
  If thread T is waiting on the critical section, then T will eventually enter the critical section (assumes threads eventually leave critical sections).

- *Performance*
  The overhead of entering and exiting the critical section is small with respect to the work being done within it.

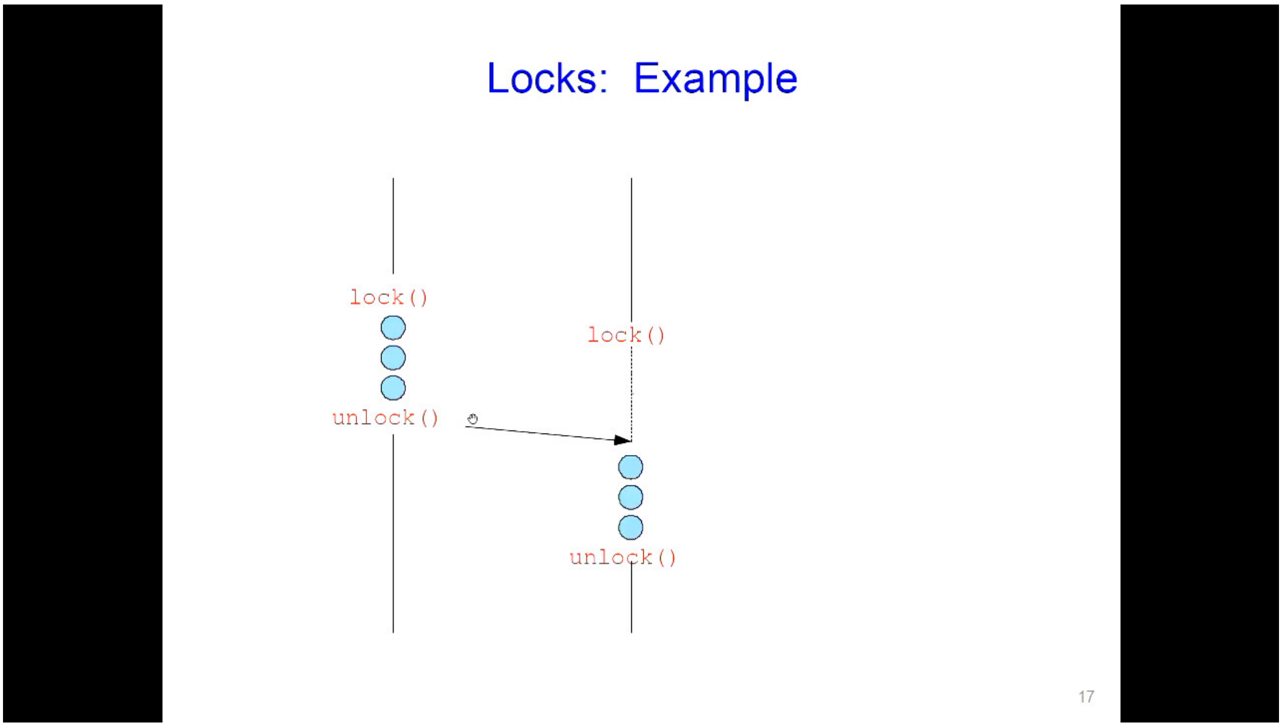
Mechanisms for building critical sections

- Spinlocks
  - primitive, minimal semantics — used to build others
- Semaphores (and non-spinning locks)
  - basic, easy to understand, somewhat hard to program with
- Monitors
  - higher level, requires language support, implicit operations
  - easier to program with; Java "`synchronised`", for example
- Messages
  - Simple model of communication and synchronisation based on (atomic) transfer of data across a channel
  - direct application to distributed systems

5.1 Locks

Locks

- A lock is a memory object with two operations:
  - `acquire`: obtain the right to enter the critical section
  - `release`: give up the right to be in the critical section
- `acquire` *prevents the progress of the thread until the lock can be acquired.*
- Note: terminology varies: acquire/release, lock/unlock



Acquire/release

- Threads pair up calls to `acquire` and `release`
  - between `acquire` and `release`, the thread *holds* the lock
  - `acquire` does not return until the caller "owns" (holds) the lock
    * at most one thread can hold a lock at a time
- What happens if the calls aren't paired
  - I acquire, but neglect to release?
- What happens if the two threads acquire different locks
  - I think that access to a particular shared data structure is mediated by lock A, and you think it's mediated by lock B?
- What is the right granularity of locking?

5.2 Spinlocks

Spinlocks

- How do we implement spinlocks? Here's one attempt:

```
struct lock_t {
    int held = 0;
}
void acquire(lock) {
    while (lock->held);
    lock->held = 1;
}
void release(lock) {
    lock->held = 0;
}
```

- Race condition in acquire.

Implementing spinlocks

- Problem is that implementation of spinlocks has critical sections, too!
  - the acquire/release must be *atomic*
  - compiler can hoist code that is invariant
- Need help from the hardware
  - atomic instructions
    test-and-set, compare-and-swap, ...

Spinlocks: Hardware Test-and-Set

- CPU provides the following as *one atomic instruction*:

```
bool test_and_set(bool *flag) {
    bool old = *flag;
    *flag = True;
    return old;
}
```

- This is a single *atomic* instruction

Implementing spinlocks using Test-and-Set

- So, to fix our broken spinlocks:

```
struct lock{
    int held = 0;
}
void acquire(lock) {
    while (test_and_set(&lock->held));
}
void release(lock) {
    lock->held = 0;
}
```

- *mutual exclusion?* (at most one thread in the critical section)
- *progress?* (`T` outside cannot prevent `S` from entering)
- *bounded waiting?* (waiting `T` will eventually enter)
- *performance?* (low overhead (modulo the spinning part...))

6 Semaphores, Condition Variables, and Monitors

6.1 Semaphore

Semaphore

- More sophisticated synchronisation mechanism
- Semaphore `S` — integer variable
- Can only be accessed via two atomic operations: `wait` and `signal` (originally called `P` and `V`).
- Definitions

```
wait(S) {
    while (S <= 0); // busy wait
    S--;
}
signal(S) {
    S++;
}
```

- These are performed *atomically*

Semaphore Usage

- *Counting semaphore*: integer value can range over an unrestricted domain
- *Binary semaphore*: integer value can range only between 0 and 1 (same as *lock*)
- Can solve various synchronisation problems
- Consider P_1 and P_2 that require S_1 to happen before S_2
  Create a semaphore "`synch`" initialised to 0

```
P1:
    S_1;
    signal(synch);
P2:
```

```
        wait(synch);
        S_2;
```

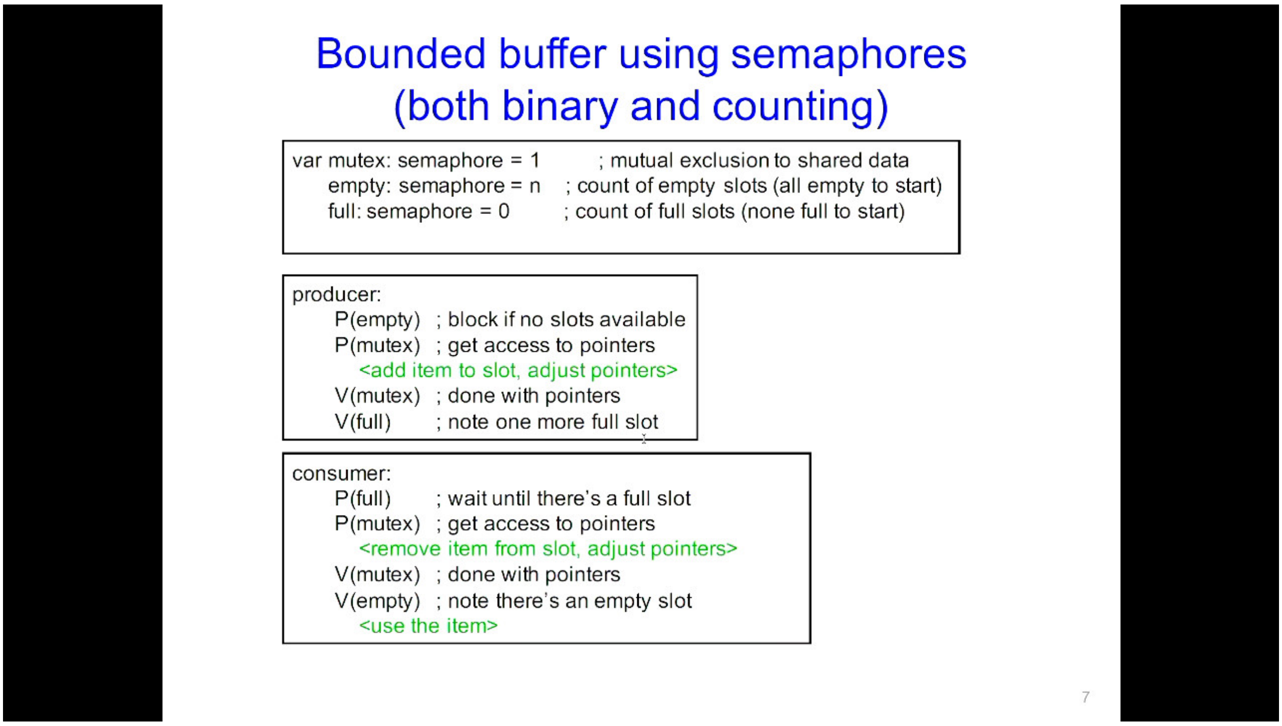
- Can implement a counting semaphore `S` as a binary semaphore.

Implementation with no Busy waiting

Each semaphore has an associated queue of threads

```
wait(semaphore *S) {
    S->value--;
    if (S->value < 0) {
        add this thread to S->list;
        block();
    }
}
signal(semaphore *S) {
    S->value++;
    if (S->value <= 0) {
        remove a thread T from S->list;
        wakeup(T);
    }
}
```

Examples



Readers/Writers using semaphores

```
var mutex: semaphore = 1      ; controls access to readcount
    wrt: semaphore = 1   ; control entry for a writer or first reader
    readcount: integer = 0      ; number of active readers
```

```
writer:
    P(wrt)           ; any writers or readers?
        <perform write operation>
    V(wrt)           ; allow others
```

```
reader:
    P(mutex)                        ; ensure exclusion
      readcount++                   ; one more reader
      if readcount == 1 then P(wrt)     ; if we're the first, synch with writers
    V(mutex)
        <perform read operation>
    P(mutex)                        ; ensure exclusion
      readcount--                   ; one fewer reader
      if readcount == 0 then V(wrt)     ; no more readers, allow a writer
    V(mutex)
```

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Semaphores v.s. Spinlocks

- Threads that are blocked at the level of program logic (that is, by the semaphore `P` operation) are placed on queues, rather than busy-waiting.
- Busy-waiting may be used for the "real" mutual exclusion required to implement `P` and `V`
  - but these are very short critical sections — totally independent of program logic
  - and they are not implemented by the application programmer.

Abstract implementation

- `P(sem)`
  - acquire "real" mutual exclusion
    - if `sem` is "available" (¿ 0), decrement sum; *release "real" mutual exclusion*; let thread continue
    - otherwise, place thread on associated queue; *release "real" mutual exclusion*; run some other thread.
- `V(sem)`
  - *acquire "real" mutual exclusion*
    - if threads are waiting on the associated queue, unblock one (place it on the ready queue)
    - if no threads are on the queue, `sem` is incremented
      the signal is "remembered" for the next time `P(sem)` is called
  - release "real" mutual exclusion
  - the "`V`-ing" thread continues execution.

Problems with semaphores, locks

- They can be used to solve any of the traditional synchronisation problems, but it's easy to make mistakes

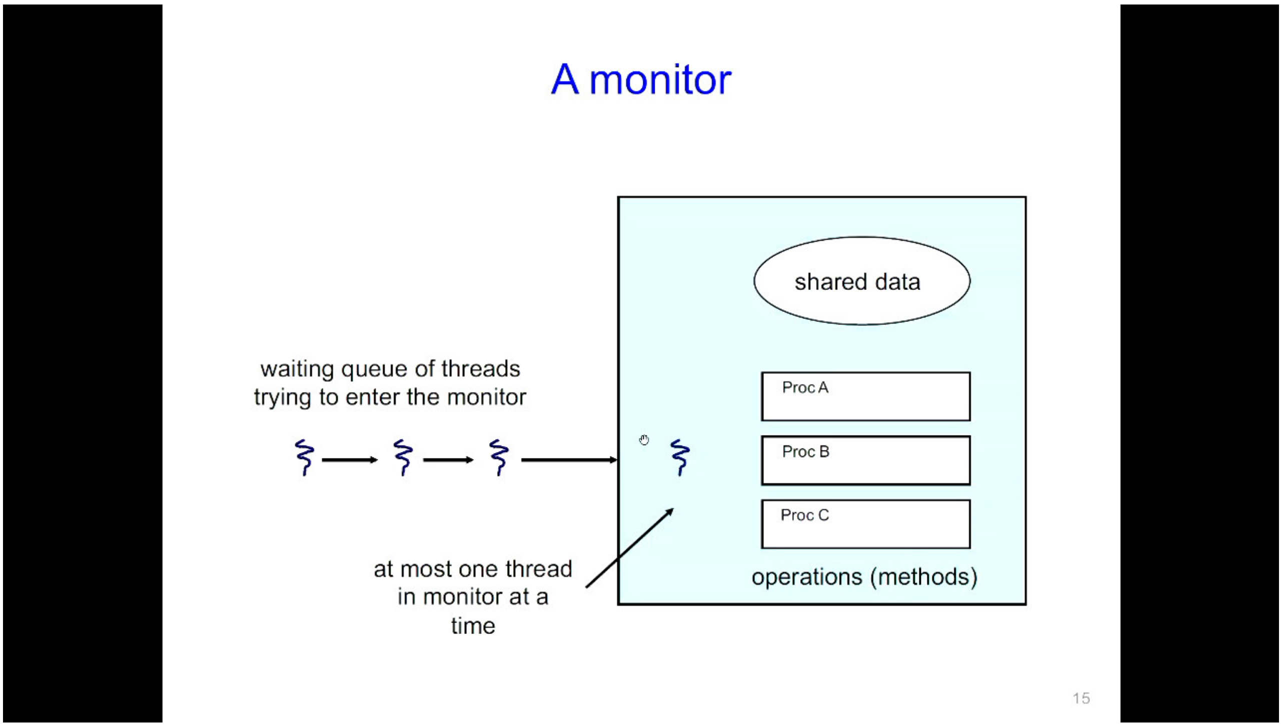
- they are essentially shared global variables
    * can be accessed from anywhere (bad software engineering)
- there is no connection between the synchronisation variable and the data being controlled by it
- no control over their use, no guarantee of proper usage
    * Semaphores: will here ever be a `V()`?
    * Locks: did you lock when necessary? Unlock at the right time? At all?

- Thus, they are prone to bugs
    - We can reduce the chance of bugs by "stylising" the use of synchronisation
    - Language help is useful for this.

6.2 Monitors

Monitors

- A programming language construct supports controlled shared data access
    - synchronisation code is added by the compiler.
- A class in which every method automatically acquires a lock on entry, and releases it on exit — it combines:
    - *shared data* structures (object);
    - *procedures* that operate on the shared data (object methods);
    - *synchronisation* between concurrent threads that invoke those procedures.
- Data can only be accessed from within the monitor
    - protects the data from unstructured access;
    - prevents ambiguity about what the synchronisation variable protects.
- Addresses the key usability issues that arise with semaphores.



Monitor facilities

- "Automatic" mutual exclusion
  - only one thread can be executing inside at any time
    - thus, synchronisation is implicitly associated with the monitor — it "comes for free";
  - if a second thread tries to execute a monitor procedure, it blocks until the first has left the monitor;
    - more restrictive than semaphores,
    - but easier to use (most of the time).
- But, there's a problem...
  Bounded buffer scenario.

Bounded Buffer scenario

- Monitors require condition variables
- Operations on condition varibales
  - `wait (c)`
    - release monitor lock, so somebody else can get in
    - wait for somebody else to signal condition
    - thus, condition variables have associated wait queues
  - `signal (c)`
    - wake up at most one waiting thread
      - · "Hoare" monitor: wakeup immediately, signaller steps outside
    - if no waiting threads, signal is lost
      - · this is different from semaphores — no history!
  - `broadcast (c)`

        * wake up all waiting threads.

Bounded buffer using (Hoare) monitors

```
Monitor bounded_buffer {
    buffer resources[];
    condition not_full;
    condition not_empty;

    produce(resource x) {
        if (array "resources" is full, determined maybe by a count) {
            wait(not_full);
        }
        insert "x" in array "resources";
        signal(not_empty);
    }

    consume(resource *x) {
        if (array "resources" is empty, determined maybe by a count) {
            wait(not_empty);
        }
        *x = get resource from array "resources";
        signal(not_full);
    }
}
```

Runtime system calls for (Hoare) monitors

- `EnterMonitor (m)` {guarantee mutual exclusion}
- `ExitMonitor (m)` {hit the road, letting someone else run}
- `Wait (c)` {step out until condition satisfied}
- `Signal (c)` {if someone's waiting, step out and let them run}
- `EnterMonitor` and `ExitMonitor` are inserted automatically by the compiler.
- This guarantees mutual exclusion for code inside of the monitor.

Monitor Summary

- Language supports monitors
- Compiler understands them
  - Compiler inserts calls to runtime routines for
    * monitor entry
    * monitor exit
  - Programmer inserts calls to runtime routines for
    * signal
    * wait
  - Language/object encapsulation ensures correctness
    * Sometimes! With conditions, you *still* need to think about synchronisation
- Runtime system implements these routines

– moves threads on and off queues

– *ensures mutual exclusion!*

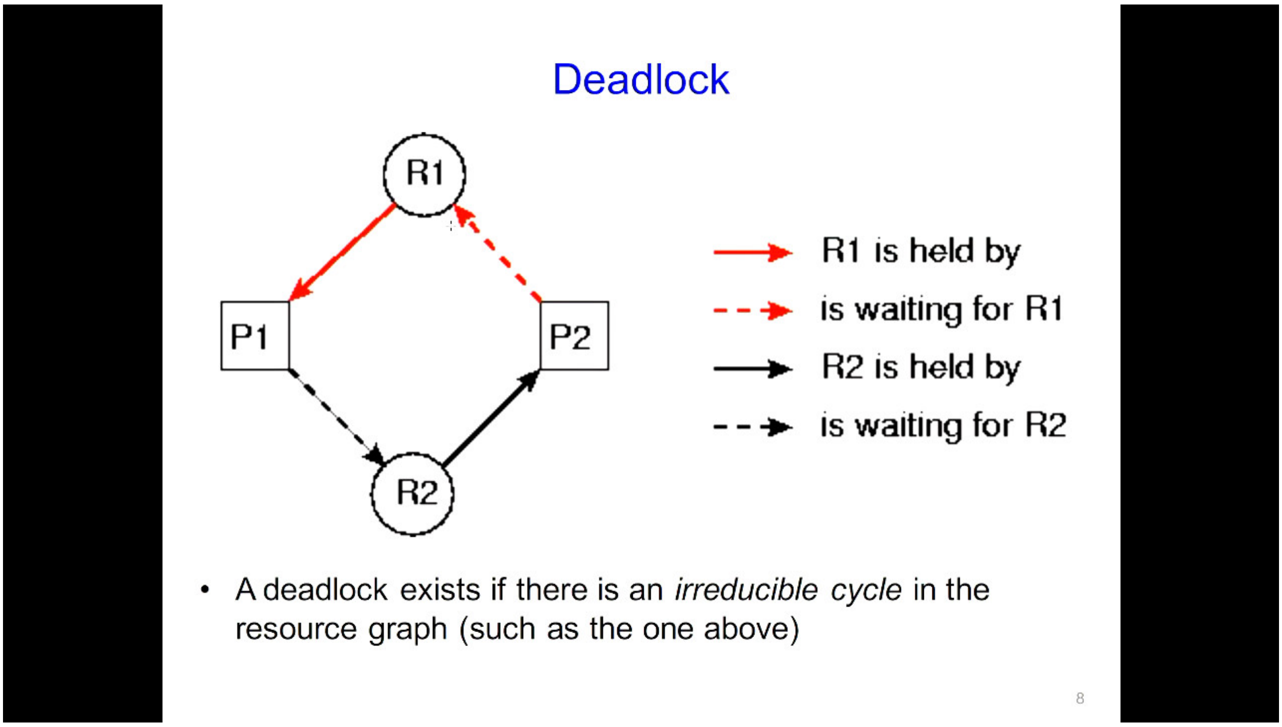
7 Deadlock

Definition

- A thread is deadlocked when it's waiting for an event that can never occur
- Thread `A` is in critical section 1
  waiting for access to critical section 2;
- Thread `B` is in critical section 2
  waiting for access to critical section 1

Four conditions must exist for deadlock to be possible

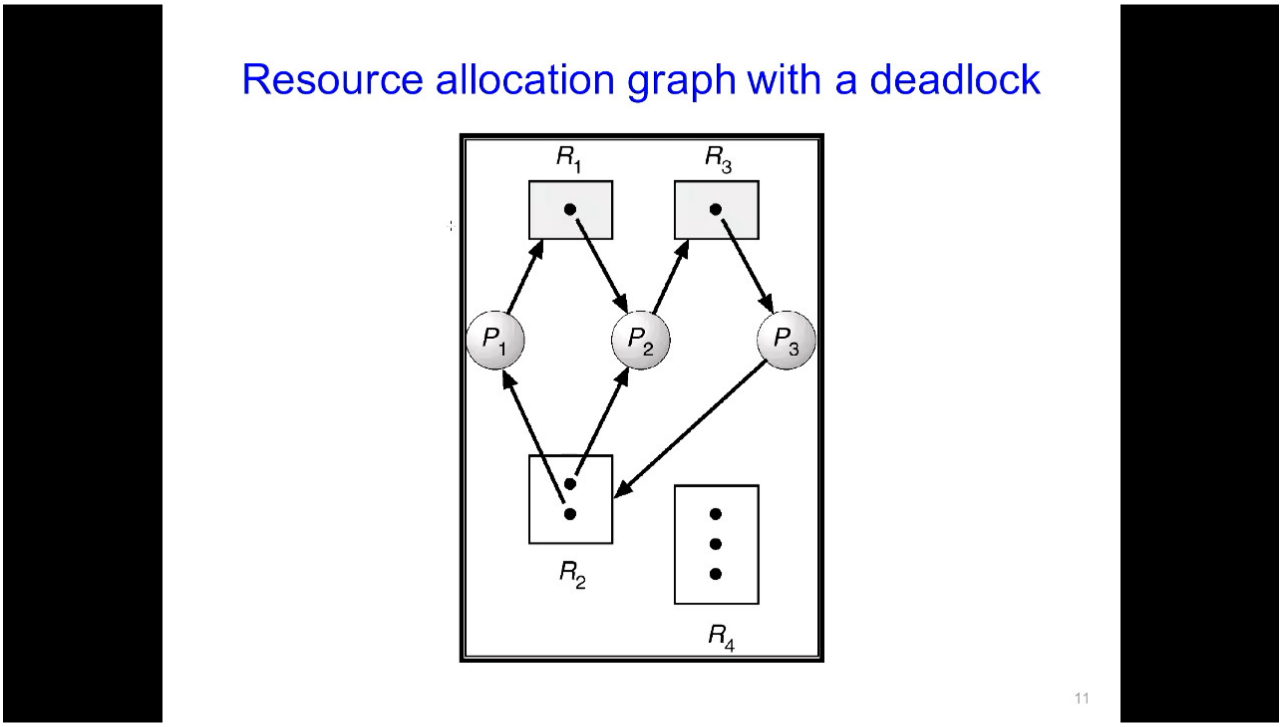
1. Mutual exclusion
2. Hold and wait
3. No pre-emption
4. Circular wait



7.1 Graph reduction

Graph reduction

- A graph can be *reduced* by a thread if all of that thread's requests can be granted
  – in this case, the thread eventually will terminate — all resources are freed — all arcs (allocations) to/from it in the graph are deleted.
- Miscellaneous theorems (Holt, Havender):
  – There are no deadlocked threads if and only if the graph is completely reducible.
  – The order of reductions is irrelevant.



Handling deadlock

- Eliminate one of the four required conditions
  - Mutual exclusion
  - Hold and Wait
  - No pre-emption
  - Circular wait
- Broadly classified as:
  - Prevention, or
  - Avoidance, or
  - Detection (and recovery)

Deadlock prevention
Restrain the ways requests can be made

- Mutual exclusion
  not required for sharable resources (e.g. read-only files); must hold for non-sharable resources.
- Hold and wait
  must guarantee that whenever a process requests a resources, it does not hold any other resources.
  - Low resources utilisation; starvation is possible.
- No (resource) Pre-emption
  - If a process holding some resources requests another unavailable resource all resources currently held are released.
  - Process will be restarted only when it can regain its old resources, as well as the new ones that it is requesting.
- Circular wait

- impose a total ordering of all resource types, and require that each process requests resources in an increasing order of enumeration.

Avoidance
Less severe restrictions on program behaviour.

- Eliminating circular wait
  - each thread states its maximum claim for every resource type;
  - system runs the Banker's Algorithm at each allocation request
    Banker $\implies$ highly conservative

7.2 Banker's Algorithm

Banker's Algorithm example

- Background
  - The set of controlled resources is known to the system.
  - The number of units of each resource is known to the system.
  - Each application must declare its maximum possible requirement of each resource type.
- The, the system can do the following:
  - When a request is made:
    * pretend you granted it;
    * pretend all other legal requests were made;
    * can the graph be reduced?
      · If so: allocate the requested resource.
      · If not, block the thread until some thread releases resources, and then try pretending again.

Safe state

- When requesting an available resource decide if allocation leaves the system in a safe state
- We're in a *safe state* if there exists a sequence $< P_1, P_2, \ldots, P_n >$ of *all* the processes in the systems
  - such that for each P_i, the resources that P_i can still request can be satisfied by currently available resources + resources held by all the P_j, with $j < i$.
- That is:
  - If P_i resource needs are not immediately available, then P_i can wait until all P_j have finished.
  - When P_j is finished, P_i can obtain needed resources, execute, return allocated resources, and terminate.
  - When P_i terminates, P_{i+1} can obtain its needed resources, and so on.

Safe $\implies$ no deadlock; deadlock $\implies$ unsafe

Data Structures for the Banker's Algorithm Let `n` = number of processes, and `m` = number of resource types.

- `Available`: Vector of length `m`. If `Available[j]` = `k`, there are `k` instances of resource type $\mathtt{R_j}$ available.

- Max $n \times m$ matrix. If Allocation[i,j] $=$ k, then P_i is currently allocated k instances of R_j
- Allocation: $n \times m$ matrix. If Need[i,j] $=$ k, then P_i may need k more instances of R_j to complete its task.

$$\texttt{Need[i,j]} = \texttt{Max[i,j]} - \texttt{Allocation[i,j]}$$

Safety Algorithm

1. Let Work and Finish be vectors of length m and n, respectively. Initialise:
   ```
   Work = Available
   Finish[i] = false for i = 0..n-1
   ```
2. Find an i such that both:
   (a) Finish[i] == false
   (b) $\texttt{Need}_i$ <= Work

   If no such i exists, go to step 4
3. ```
   Work = Work + Allocation
   Finish[i] = true
   ```
   go to step 2
4. If Finish[i] == true, for all i, then the system is in a safe state.

Resource-Request Algorithm for Process P_i

$\texttt{Request}_i$ = request vector for process P_i. If $\texttt{Request}_i$[j] == k then process P_i wants k instances of resource type R_j.

1. If $\texttt{Request}_i$ <= $\texttt{Need}_i$ go to step 2. Otherwise raise error condition, since process has exceeded its maximum claim.
2. If $\texttt{Request}_i$ <= Available, go to step 3. Otherwise P_i must wait, since resources are not available.
3. Pretend to allocate requested resources to P_i by modifying the state as follows:
   Available = Available - Request
   $\texttt{Allocation}_i$ = $\texttt{Allocation}_i$ + $\texttt{Request}_i$
   $\texttt{Need}_i$ = $\texttt{Need}_i$ - $\texttt{Request}_i$
   (a) If safe, then resources allocated to P_i
   (b) If unsafe, then P_i must wait, and the old resource-allocation state is restored.

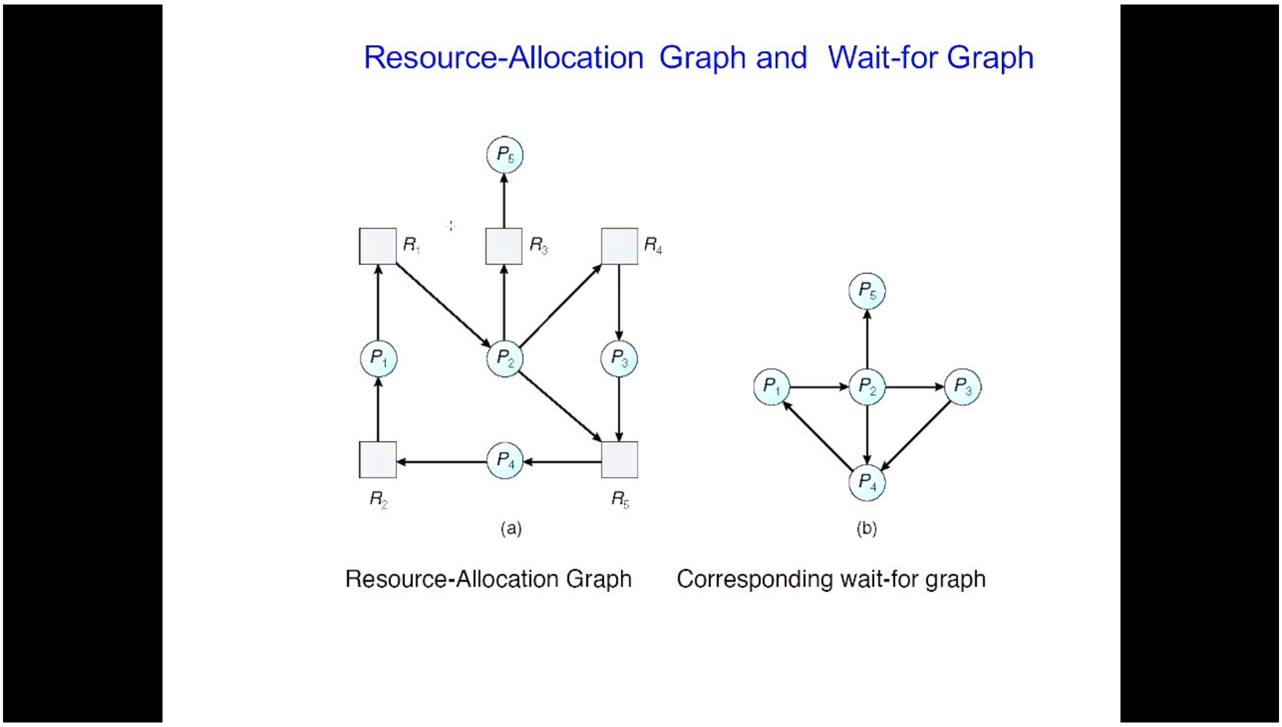
Deadlock Detection

1. Allow system to enter deadlock state
2. Detection algorithm
3. Recovery scheme

Single instance of each resource type

- Maintain a *wait-for* graph
  - Nodes are processes
  - $P_i \rightarrow P_j$ if P_i is waiting for P_j
- Periodically invoke an algorithm that searches for a cycle in the graph.
  - If there is a cycle, there exists a deadlock.
- An algorithm to detect a cycle in a graph
   ```

– has runtime complexity $\mathcal{O}(n^2)$ with n being the number of vertices in the graph.



Detection-Algorithm usage

- When, and how often to invoke depends on:
  - How often a deadlock is likely to occur?
  - How many processes will need to be rolled back?
    * One for each disjoint cycle.
- If detection algorithm is invoked arbitrarily:
  - there may be many cycles in the resource graph
  - we would not be able to tell which deadlocked processes "caused" the deadlock.

Recovery from deadlock

- Process termination
  - Abort all deadlocked processes
  - Abort one process at a time until the deadlock cycle is eliminated
  - In which order should we choose to abort?
- Resource pre-emption
  - *Select a victim* — minimise cost
  - *Rollback* — return to some safe state, restart process for that state.
  - *Starvation* — same process may always be picked as victim, include number of rollback in cost factor.

Summary

- Deadlock is bad!
- We can deal with it either statically (prevention) or dynamically (avoidance and/or detection)

- In practice, you'll encounter lock ordering, periodic deadlock detection/correction, and minefields.

8 Scheduling

Scheduling

- We have talked about *context switching*
  - an interrupt occurs (device completion, timer interrupt)
  - a thread causes a trap or execution
  - may need to choose a different thread/process to run
- Glossed over which process or thread to run next
  - "some thread from the ready queue"
- This decision is called *scheduling*
  - scheduling is a *policy*
  - context switching is a *mechanism*

Classes of Schedulers

- Batch
  - Throughput / utilisation oriented
  - Example: audit inter-bank funds transfers each night, Pixar rendering, Hadoop/MapReduce jobs.
- Interactive
  - Response time oriented
- Real time
  - Deadline driven
  - Example: embedded systems (cars, aeroplanes, etc.)
- Parallel
  - Speedup-driven
  - Example: "space-shared" use of a 1000-processor machine for large simulations.

Multiple levels of scheduling decisions

- Long term
  - Should a "job" be "initiated", or should it be held?
  - Typical of batch systems.
- Medium term
  - Should a running program be temporarily marked as non-runnable (e.g. swapped out)?
- Short term
  - Which thread should be given to the CPU next? For how long?
  - Which I/O operation should be sent to the disk next?
  - On a multiprocessor:

    * Should we attempt to coordinate the running of threads from the same address space in some way?
    * Should we worry about cache state (processor affinity)?

8.1 Scheduling Goals

Scheduling Goals I: Performance
Many possible metrics / performance goals (which sometimes conflict)

- maximise *CPU utilisation*
- maximise *throughput* (requests completed per second)
- minimise *average response time* (average time from submission of request to completion of response)
- minimise *average waiting time* (average time from submission of request to start of execution)
- minimise *energy* (joules per instruction) subject to some constraint (e.g. frames per second)

Scheduling Goals II: Fairness

- No single, compelling definition of "fair"
  - How to measure fairness?
  - Fair per-user? Per-process? Per-thread?
  - What if one process is CPU bound, and one is I/O bound?
- Sometimes the goal is to be unfair:
  - Explicitly favour some particular class of requests (priority system), but...
  - avoid starvation (be sure everyone gets at least some service).

When to assign?
Pre-emptive v.s. non-pre-emptive schedulers

- Non pre-emptive
  once you give somebody the green light, they've got it until they relinquish it
  - an I/O operation
  - allocation of memory in a system without swapping
- Pre-emptive
  - you can re-visit a decision
    * setting the timer allows you to pre-empt the CPU from a thread even if it doesn't relinquish it voluntarily.
  - Re-assignment always involves some overhead
    * Overhead doesn't contribute to the goal of any scheduler.

We'll assume "work conserving" policies

- Never leave a resource idle when someone wants it

8.2 Laws and properties

The Utilisation Law: $U = X \times S$

- U utilisation

- X throughput (requests per second)
- S average service time
- Utilisation is constant, independent of the schedule, so long as the workload can be processed

Little's Law: $N = X \times R$

- N average number in system
- X throughput
- R average response time
- a better average response time implies fewer in system, and vice versa.

Response Time R at a single server under FCFS scheduling:

- $R = \frac{S}{1-U}$
- $N = \frac{U}{1-U}$

9 Algorithms

Algorithm 1: First-come first-served (FCFS)

- schedule in the order that they arrive
- "real-world" scheduling of people in (single) lines
- jobs treated equally, no starvation
- Drawbacks:
  - Average response time can be poor: *convoy effect*
  - May lead to poor utilisation of other resources
    - if you send me on my way, I can go keep another resource busy
    - FCFS may result in poor overlap of CPU and I/O activity
  - The more copies of the resource there are to be scheduled
    - the less dramatic the impact of occasional very large jobs (so long as there is a single waiting line)
    - e.g. multiple cores v.s. single core

Algorithm 2: Shortest-job-first (SJF)

- Associate with each process the length of its next CPU burst
  - use these lengths to schedule the process with the shortest time
- SJF is optimal — gives minimum average waiting time for a given set of processes
  - the difficulty is knowing the length of the next CPU request
  - could ask the user.
- Determining the length of next CPU burst
  - Can only estimate the length — should be similar to the previous one
    - then pick process with shortest predicted next CPU burst.
  - Can be done by using the length of previous CPU bursts, using exponential averaging

1. t_n actual length of nth CPU burst
2. τ_{n+1} predicted value for the next CPU burst
3. $\alpha, 0 \leq \alpha \leq 1$
4. Define: $\tau_{n+1} = \alpha t_n + (1 - \alpha)\tau_n$

- Commonly, set $\alpha = 0.5$
- Pre-emptive version called *shortest-remaining-time-first*

Algorithm 3: Round Robin (RR)

- Each process gets a small unit of CPU time (*time quantum* q), usually 10–100 milliseconds.
  - After this time has elapsed, the process is pre-empted and added to the end of the ready queue.
- If there are n processes in the ready queue and the time quantum is q,
  - then each process gets $\frac{1}{n}$ of the CPU time in chunks of at most q time units at once.
  - No process waits more than $(n - 1)q$ time units.
- Timer interrupts every quantum to schedule next process
- Performance
  - q large $\implies$ FIFO
  - q small $\implies$ q must be large with respect to context switch, otherwise overhead is too high.
- Drawbacks:
  - What if all jobs are exactly the same length?
  - What do you set the quantum to be?
    * no value is "correct"
    * if small, then context switch often, incurring high overhead
    * if large, then the response time degrades.
  - Treats all jobs equally

Algorithm 4: Priority Scheduling

- A priority number (integer) is associated with each process
- The CPU is allocated to the process with the highest priority
- SJF is priority scheduling where priority is the inverse of predicted next CPU burst time.
- Problem: *starvation* — low priority processes may never execute.
- Solution: *ageing* — as time progresses, increase the priority of the process.

Multi-level Feedback Queues (MLFQ)

- It's been observed that workloads tend to have increasing residual life — "if you don't finish quickly, you're probably a lifer"
- This is exploited in practice by using a policy that discriminates against the old.
- MLFQ:
  - there is a hierarchy of queues

  - there is a priority ordering among the queues
  - new requests enter the highest priority queue
  - each queue is scheduling RR
  - requests move between queues based on execution history.

UNIX scheduling

- Canonical scheduler is pretty much MLFQ
  - 3–4 classes spanning ~ 170 priority levels
    - time-sharing: lowest 60 priorities
    - system: middle 40 priorities
    - real-time: highest 60 priorities
  - priority scheduling across queues, RR within
    - process with highest priority always run first
    - processes with same priority scheduled RR
  - processes dynamically change priority
    - increases over time if process blocks before end of quantum
    - decreases if process uses entire quantum
- Goals:
  - reward interactive behaviour over CPU hogs
    - interactive jobs typically have short bursts of CPU

9.1 Summary

- Scheduling takes place at many levels
- It can make a huge difference in performance
  - this difference increases with the variability in service requirements
- Multiple goals, sometimes conflicting
- There are many "pure" algorithms, most with some drawbacks in practice — FCFS, SJF, RR, Priority
- Real system use hybrids that exploit observed program behaviour
- Scheduling is important

10 Memory Management