

Operating Systems Lecture Notes

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1 Introduction

2 Operating System Structure

2.1 Architectural impact

Architectural features affecting OSs

- These features were built primarily to support OSs:
 - timer (clock) operations
 - 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

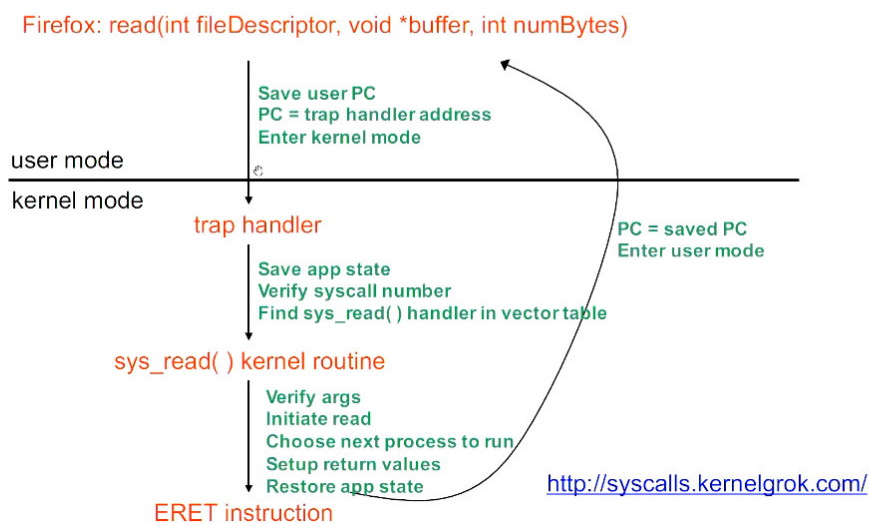
- So how do user programs do something privileged?
 - e.g. how can you write to a disk if you can't execute any I/O instructions?
- User programs must call on OS procedure — that is to ask the OS to do it for them.
 - OS defines a set of system calls
 - User-mode program executes system call instruction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

A kernel crossing illustrated



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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

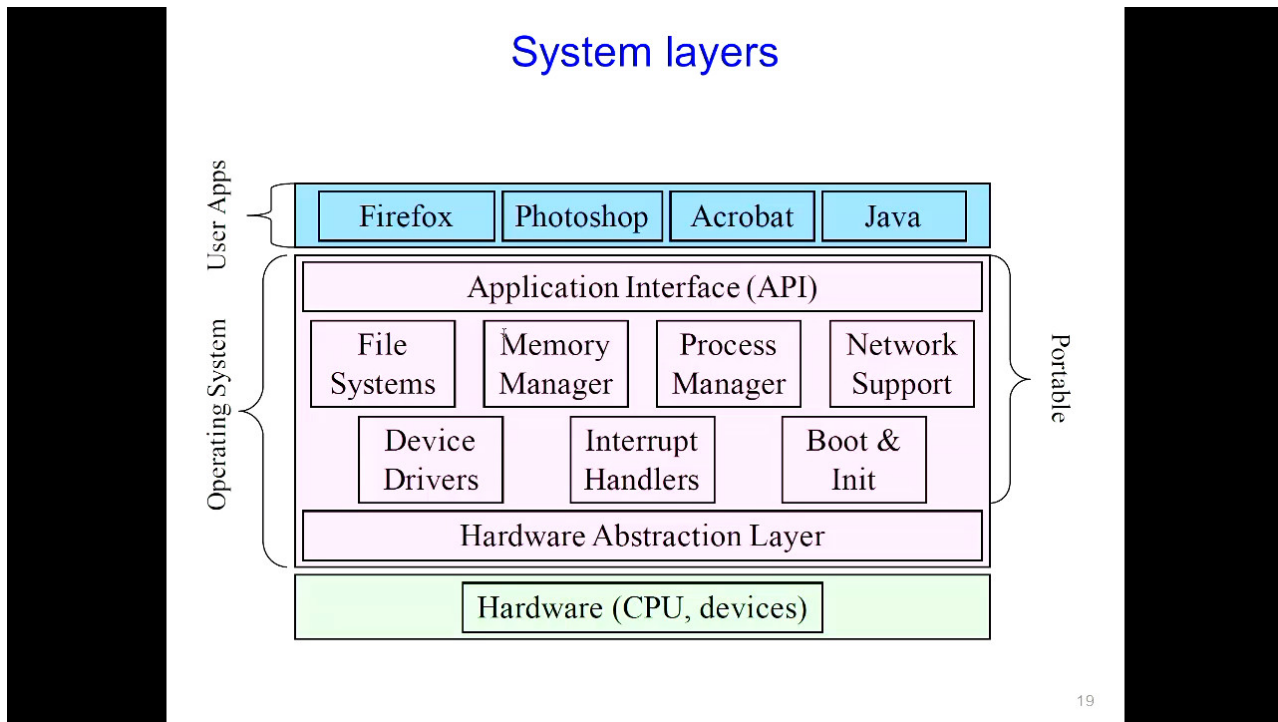
- The OS sits between application programs and the hardware
 - it mediates access and abstracts away ugliness
 - programs request services via traps or exceptions
 - devices request attention via interrupts

Operating system design and implementation

- Design and implementation of OS not “solvable”, but some approaches have proven successful.
- Internal structure of different OSs 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



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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, OSs (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 structure
 - 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

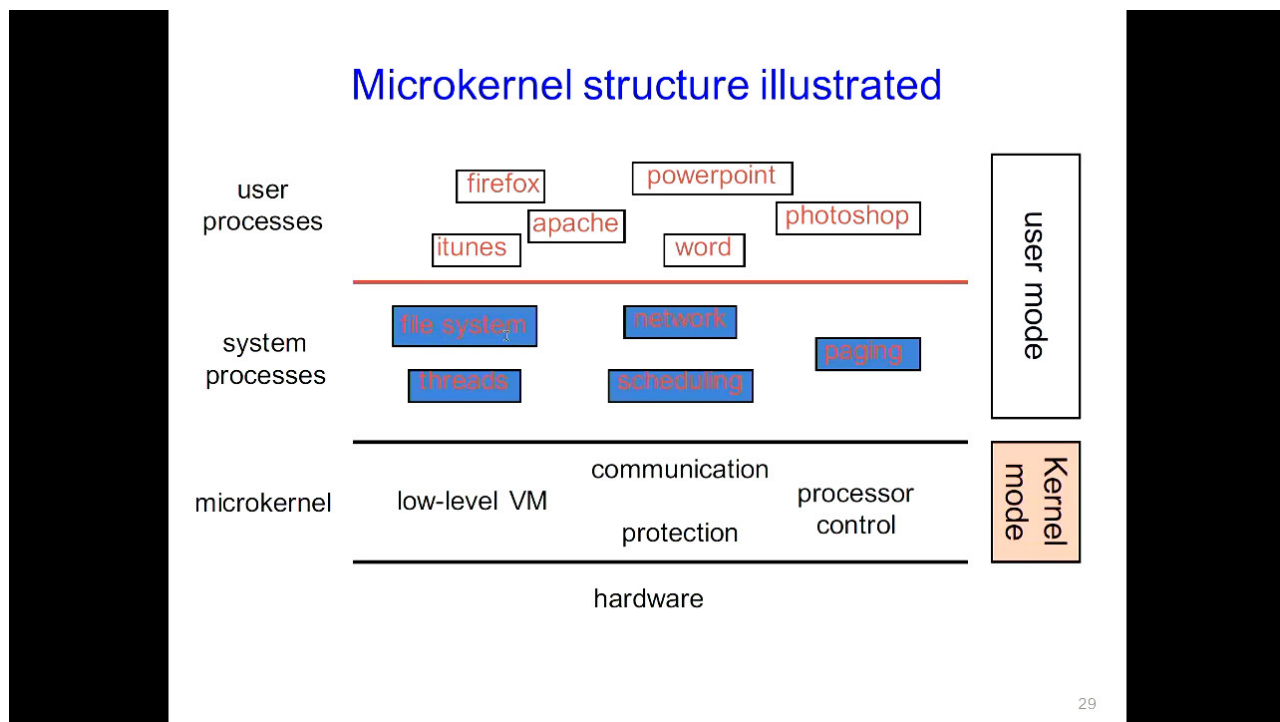
- Disjunction between model and reality: systems modelled as layers, but not really built that way.

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)

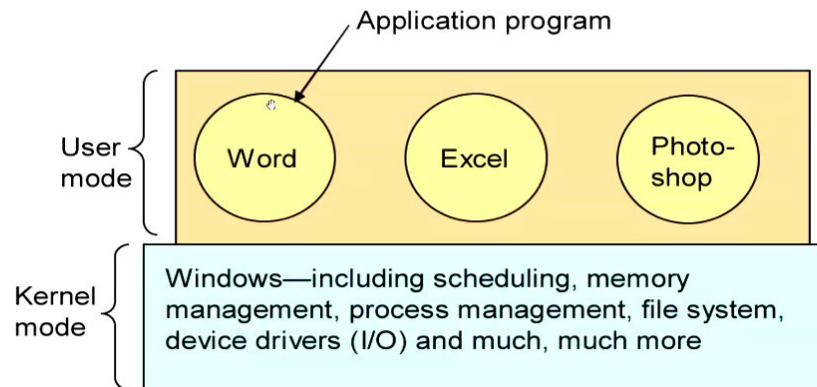


Comparison of OS structures

Windows

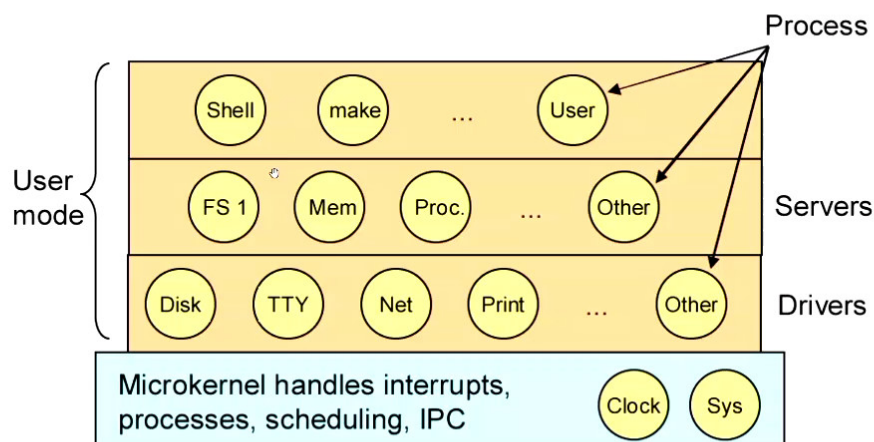
Monolithic

EXAMPLE: WINDOWS



MINIX 3

ARCHITECTURE OF 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

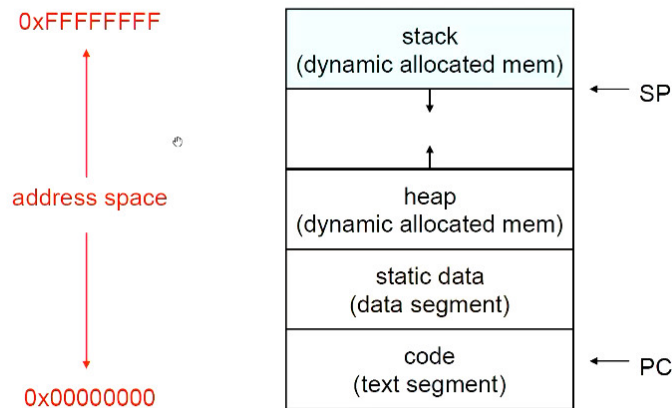
What is a “process”?

- 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).

A process's address space (idealized)



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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

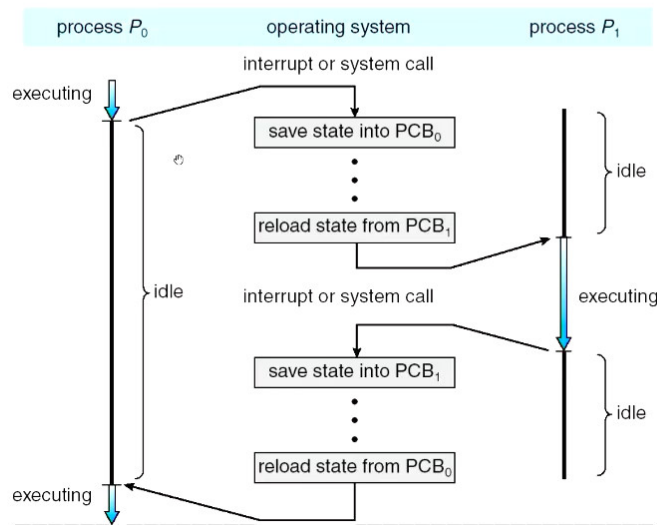
- address space info
- UNIX user id, group id
- scheduling priority
- accounting info
- pointers for state queues
- In Linux:
 - defined in `task_struct` (`include/linux/sched.h`)
 - Over 95 fields!

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 context switch

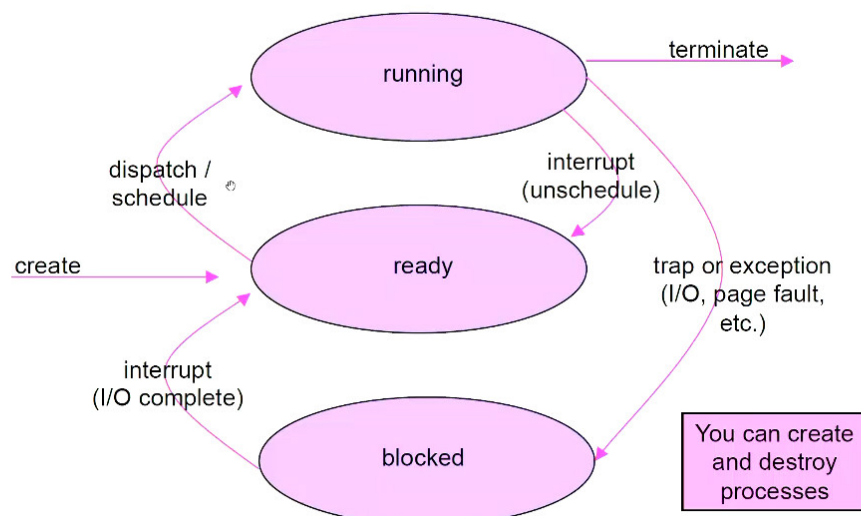


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Process execution states

- 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 message 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?

Process states and state transitions



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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`).

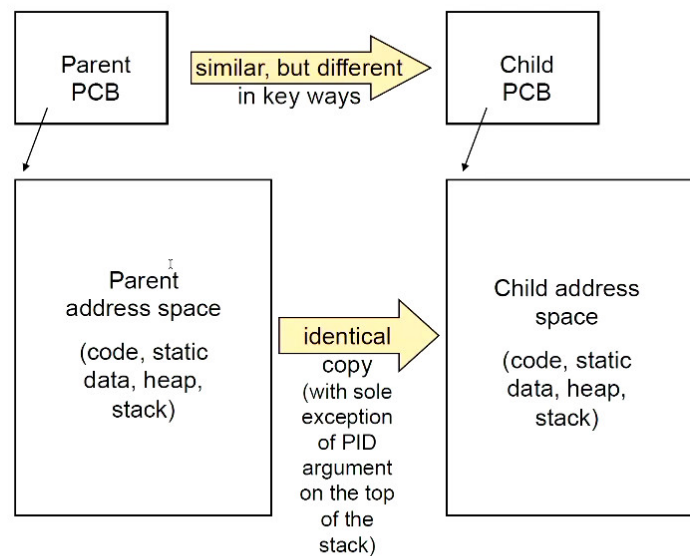
Process creation semantics

- (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.



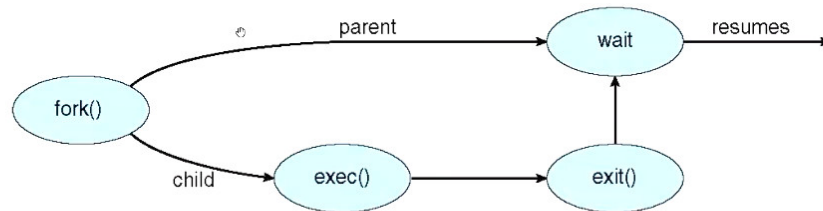
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exec v.s. fork

- 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!*

exec() and fork()



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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 OSs 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.

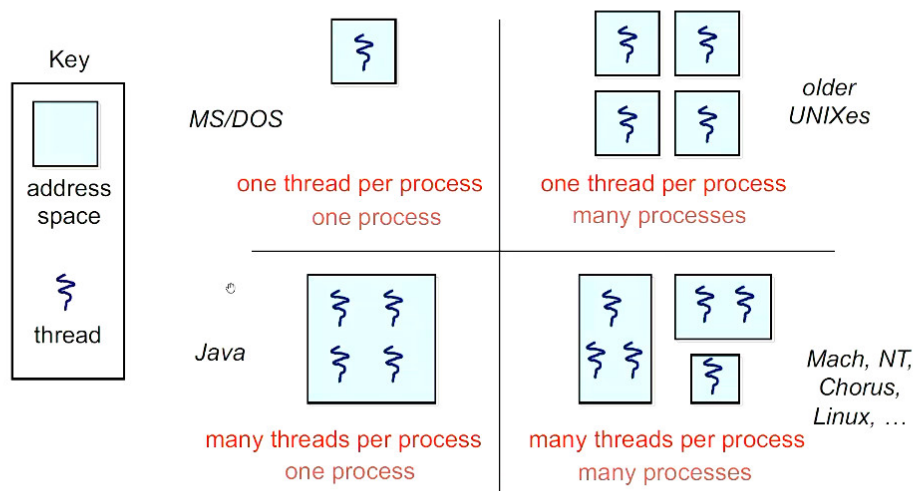
4.2 Concurrency

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

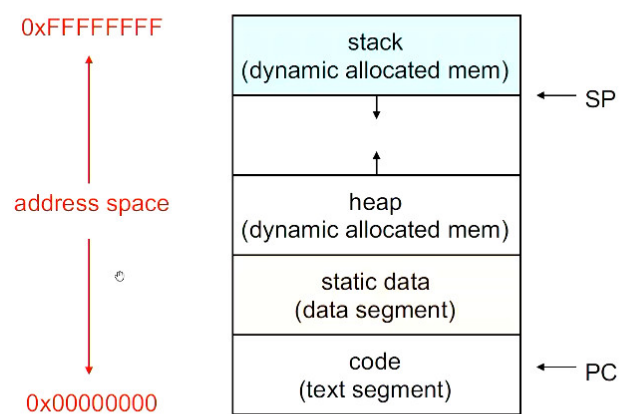
The design space



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Process address space

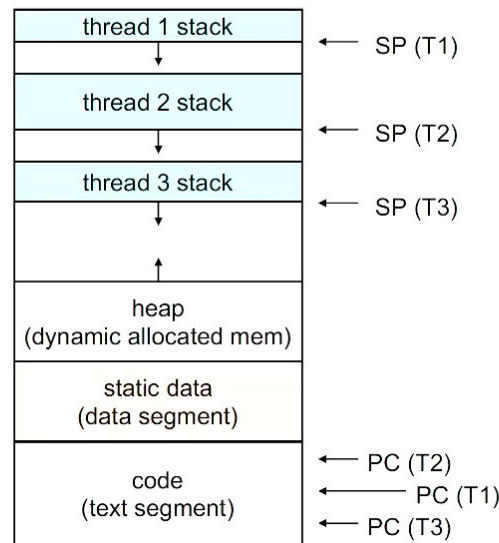
(old) Process address space



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(new) Address space with threads

0xFFFFFFFF
↑
address space
↓
0x00000000



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4.3 Design space of process/threads

Process/thread separation

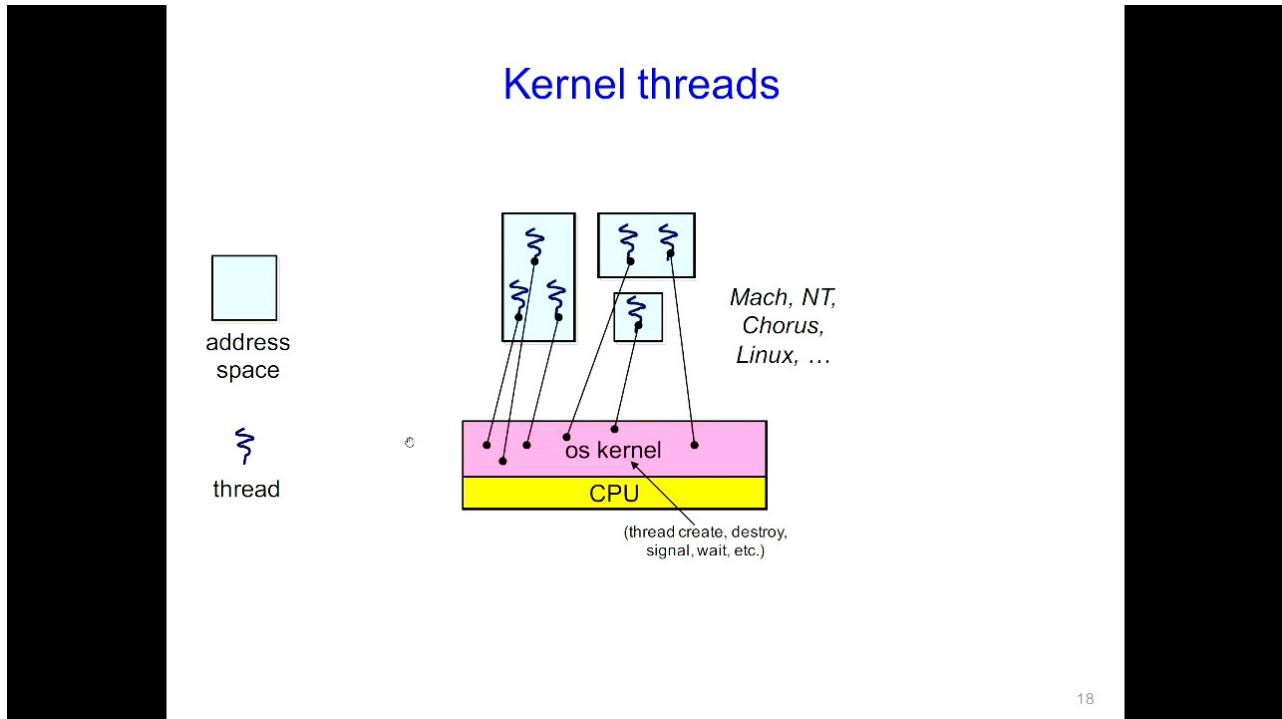
- Concurrency (multi-threading) is useful for:
 - handling concurrent events (e.g. web servers and clients)
 - building parallel programs (e.g. matrix multiply, ray tracing)
 - improving program structure (the Java argument),
- Multi-threading is useful even on a uniprocessor
 - even though only one 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



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Kernel Threads

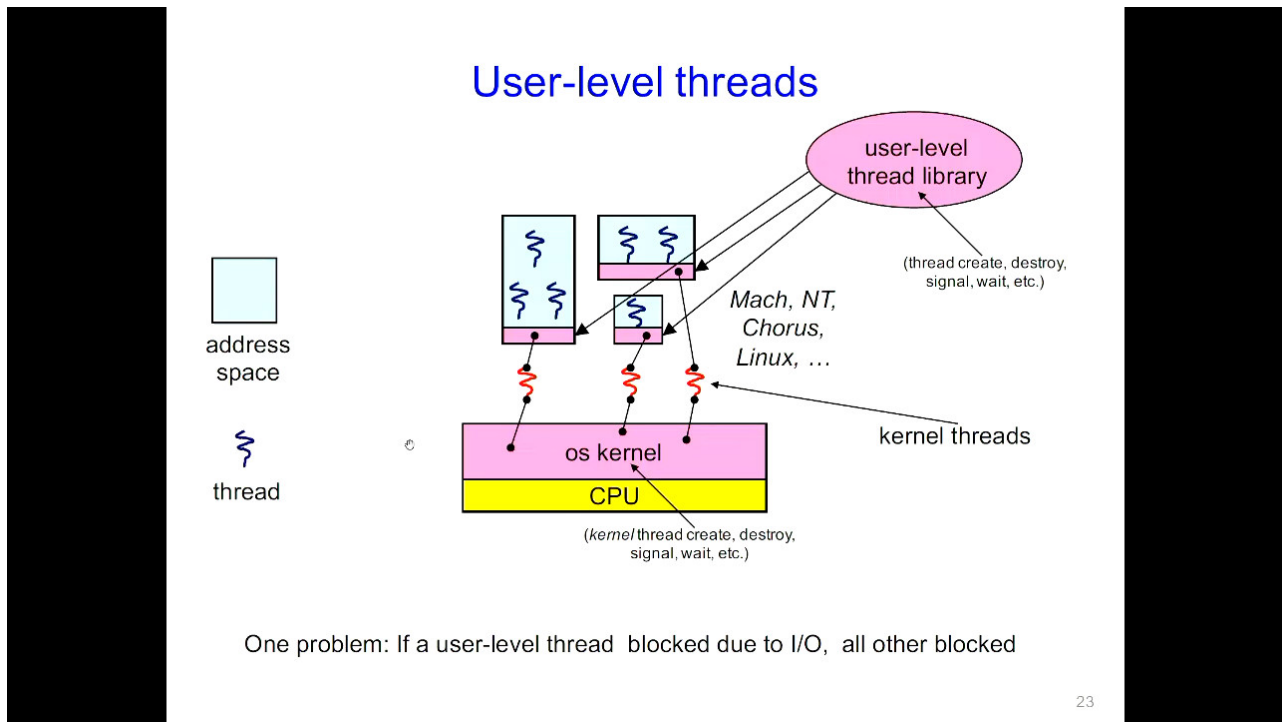
- OS now manages threads *and* processes / address spaces
 - all thread operations are implemented in the kernel
 - OS schedules all of the threads in a system
 - * if one thread in a process blocks (e.g. on I/O), the OS knows about it, and can run other threads from that process
 - * possible to overlap 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*



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User-level threads

- User-level threads are small and fast
 - managed entirely by user-level library (e.g. `pthread`s)
 - 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, obviously 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

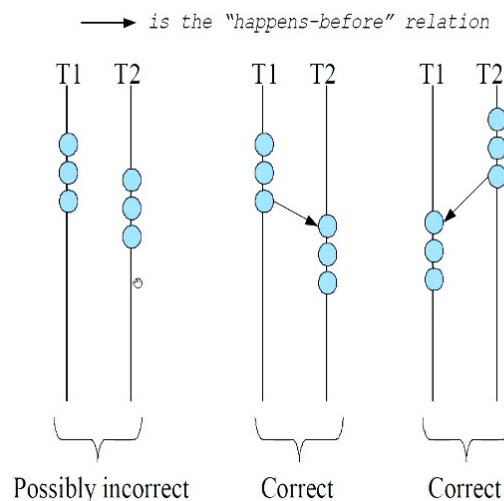
Temporal relations

- 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.

Critical sections



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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

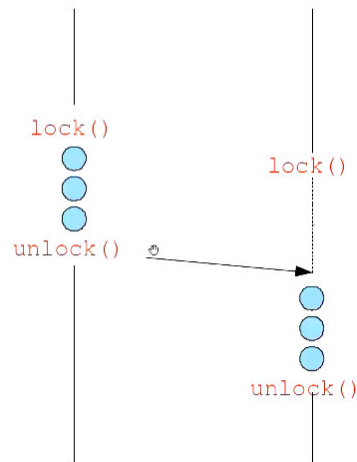
5.1 Locks

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

Locks: Example



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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

Bounded buffer using semaphores (both binary and counting)

```

var mutex: semaphore = 1    ; mutual exclusion to shared data
    empty: semaphore = n    ; count of empty slots (all empty to start)
    full: semaphore = 0     ; count of full slots (none full to start)

```

```

producer:
    P(empty) ; block if no slots available
    P(mutex) ; get access to pointers
    <add item to slot, adjust pointers>
    V(mutex) ; done with pointers
    V(full)  ; note one more full slot

```

```

consumer:
    P(full)  ; wait until there's a full slot
    P(mutex) ; get access to pointers
    <remove item from slot, adjust pointers>
    V(mutex) ; done with pointers
    V(empty) ; note there's an empty slot
    <use the item>

```

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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” ($\neq 0$), 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 there 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 “styling” the use of synchronisation
 - Language help is useful for this.

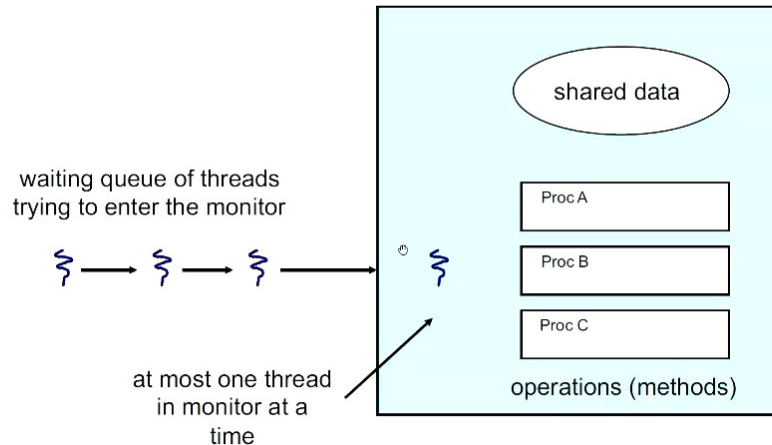
6.2 Monitors

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.

A monitor



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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 variables
 - `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

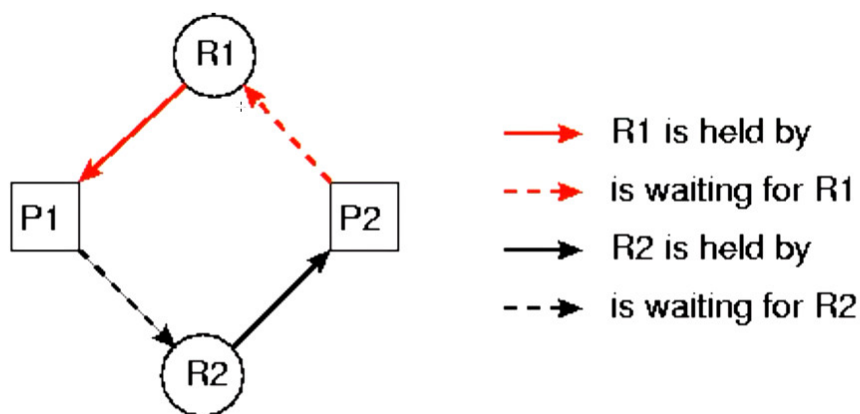
Definition

- 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

Deadlock



- A deadlock exists if there is an *irreducible cycle* in the resource graph (such as the one above)

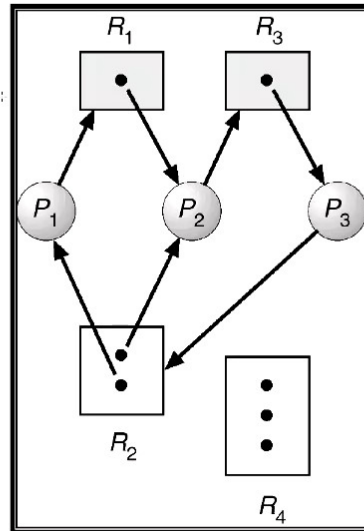
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7.1 Graph reduction

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.

Resource allocation graph with a deadlock



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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 resource, 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 $\langle P_1, P_2, \dots, P_n \rangle$ 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 R_j available.

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

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

Safety Algorithm

1. Let **Work** and **Finish** be vectors of length m and n , respectively. Initialise:
 $\text{Work} = \text{Available}$
 $\text{Finish}[i] = \text{false}$ for $i = 0..n-1$
2. Find an i such that both:
 - (a) $\text{Finish}[i] == \text{false}$
 - (b) $\text{Need}_i \leq \text{Work}$
 If no such i exists, go to step 4
3. $\text{Work} = \text{Work} + \text{Allocation}$
 $\text{Finish}[i] = \text{true}$
 go to step 2
4. If $\text{Finish}[i] == \text{true}$, for all i , then the system is in a safe state.

Resource-Request Algorithm for Process P_i

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

1. If $\text{Request}_i \leq \text{Need}_i$ go to step 2. Otherwise raise error condition, since process has exceeded its maximum claim.
2. If $\text{Request}_i \leq \text{Available}$, 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:
 $\text{Available} = \text{Available} - \text{Request}$
 $\text{Allocation}_i = \text{Allocation}_i + \text{Request}_i$
 $\text{Need}_i = \text{Need}_i - \text{Request}_i$
 - (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

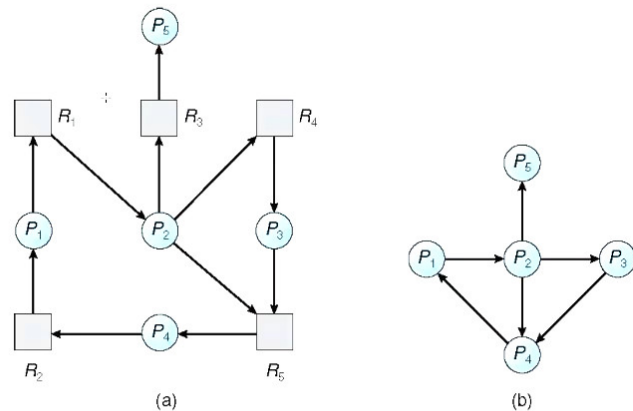
1. Allow system to enter deadlock state
2. Detection algorithm
3. Recovery scheme

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.

Resource-Allocation Graph and Wait-for Graph



Resource-Allocation Graph Corresponding wait-for 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 mine-fields.

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:

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

8.3 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 n th 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

8.4 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

9 Memory Management

9.1 Background

Goals and Tools of memory management

- Allocate memory resources among competing processes
 - maximising memory utilisation and system throughput
- Provide isolation between processes
 - Addressability and protection: orthogonal
- Convenient abstraction for programming
 - and compilers, etc.
- Tools
 - Base and limit registers
 - Swapping
 - Segmentation
 - Paging, page tables, and TLB
 - Virtual memory

Background

- Program must be brought (from disk) into memory and placed within a process for it to be run.
- Main memory and registers are only storage CPU can access directly.
- Memory unit only sees a stream of address + read requests, or addresses + data and write requests
- Register access in one CPU clock (or less)
- Main memory can take many cycles, causing a *stall*
- *Cache* sits between main memory and CPU registers.
- Protection of memory required to ensure correct operation.

Base and Limit Registers

- A pair of *base* and *limit* registers define the logical address space.
- CPU must check every memory access generated in user mode to be sure it is between base and limit for that user.

9.2 Logical/Virtual address space v.s. Physical address space

Virtual address for multiprogramming

- To make it easier to manage memory of multiple processes, make processes *use logical or virtual address*
 - Logical/virtual addresses are independent of location in physical memory data lives
 - * OS determines location in physical memory.
- Instructions issued by CPU reference logical/virtual addresses
 - e.g. pointers, arguments to load/store instructions, PC, etc.

- Logical/virtual addresses are translated by hardware into physical addresses (with some setup from OS).

Logical/Virtual Address Space

- The set of logical/virtual addresses a process can reference is its *address space*
 - many different possible mechanisms for translating logical/virtual addresses to physical addresses.
- Program issues addresses in a logical/virtual address space
 - must be *translated* to physical address space;
 - think of the program as having a contiguous logical/virtual address space that starts at 0; and a contiguous physical address space that starts somewhere else.
- *Logical/virtual address space* is the set of all logical addresses generated by a program.
- *Physical address space* is the set of all physical addresses generated by a program.

Memory-Management Unit (MMU)

- Hardware device
 - at runtime maps virtual to physical addresses
- Many methods possible
- Simple scheme: value in relocation register is added to every address generated by a user process at the time it is sent to memory.
 - Base register now called *relocation register*
- The user program deals with *logical* addresses — it never sees the *real* physical addresses.
 - Execution-time binding occurs when reference is made to location in memory.
 - Logical address bound to physical addresses.

9.3 Swapping

Swapping

- What if not enough memory to hold all processes?
- A process can be *swapped* temporarily
 - out of memory to a backing store,
 - brought back into memory for continued execution
 - total physical memory space of processes can exceed physical memory.
- *Backing store* — fast disk
 - large enough to accommodate copies of all memory images for all users;
 - must provide direct access to these memory images.
- *Roll out, roll in* — swapping variant
 - used for priority-based scheduling algorithms;
 - lower-priority process is swapped out so higher-priority processes can be loaded and executed.
- Major part of swap time is transfer time

- total transfer time is directly proportional to the amount of memory swapped.
- System maintains a *ready queue*
 - ready-to-run processes which have memory images on disk.

Context Switch Time including Swapping

- If next processes to be put on CPU is not in memory
 - need to swap out a process and swap in target process.
- Context switch time can then be very high
- Can reduce cost
 - reduce size of — by knowing how much memory really being used;
 - inform OS of memory use via `request_memory()` and `release_memory()`.
- Other constraints as well on swapping
 - Pending I/O — can't swap out as I/O would occur to wrong process.
- Or always transfer I/O to kernel space, then I/O device
 - known as *double buffering*, adds overhead.
- Standard swapping not used in modern operating systems
 - But modified version common
 - * Swap only when free memory extremely low.

9.4 Contiguous Memory Allocation

Contiguous Allocation

- Main memory must support both OS and user processes
- Limited resource, must allocate efficiently
- Contiguous allocation is one early method
- Main memory usually into two *partitions*:
 - Resident OS, usually held in low memory with interrupt vector;
 - User processes then held in high memory;
 - Each process contained in single contiguous section of memory.
- Relocation registers
 - used to protect user processes from each other, and from changing OS code and data;
 - base register contains value of smallest physical address;
 - limit register contains range of logical addresses — each logical address must be less than the limit register.
- MMU maps logical address *dynamically*
 - can then allow actions such as kernel code being *transient* and kernel changing size.

Multiple-partition allocation

- Degree of multiprogramming limited by number of partitions
- 2 approaches

- Fixed partition
- Variable partition

Old technique 1: Fixed partitions

- Physical memory is broken up into fixed partitions
 - partitions may have different sizes, but partitioning never changes
 - hardware requirement: *base/relocation register*, *limit register*
 - * $\text{physical address} = \text{logical address} + \text{base register}$
 - * base register loaded by OS when it switches to a process
- Advantages:
 - Simple
- Problems
 - *internal fragmentation*: the available partition is larger than what was requested.

Old technique 2: Variable partitions

- Obvious next step: physical memory is broken up into partitions dynamically — partitions are tailored to programs
 - hardware requirements: *base register*, *limit register*
 - $\text{physical address} = \text{logical address} + \text{base register}$
- Advantages
 - no internal fragmentation
 - * simply allocate partition size to be just big enough for process (assuming we know what that is!)
- Problems
 - *external fragmentation*
 - * as we load and unload jobs, holes are left scattered throughout physical memory.

Multiple-partition allocation

- *Variable-partition* sizes for efficiency (sized to a given process' needs).
- *Hole* — block of available memory; holes of various sizes are scattered throughout memory.
- When a process arrives, allocated memory from a hole large enough to accommodate it.
- Process exiting frees its partition, adjacent free partitions combined.
- OS maintains information about:
 1. allocated partitions,
 2. free partitions (hole)

Dynamic Storage-Allocation Problem

- *First-fit*: Allocate the *first* hole that is big enough
- *Best-fit*: Allocate the *smallest* hole that is big enough; must search entire list, unless ordered by size
 - produces the smallest leftover hole.

- *Worst-fit*: Allocates the *largest* hole; must also search the entire list
 - produces the largest leftover hole

First-fit and best-fit better than worst-fit in terms of speed and storage utilisation.

Fragmentation

- *External fragmentation*: total memory space exists to satisfy a request, but it is not contiguous;
- *Internal fragmentation*: allocated memory may be slightly larger than requested memory;
- First fit analysis reveals that given N blocks allocated, $0.5N$ blocks lost to fragmentation
- $\frac{1}{3}$ may be unusable \implies 50 percent rule.

Dealing with fragmentation

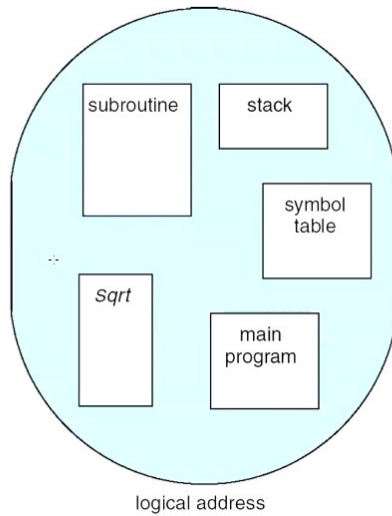
- Compact memory by copying
 - Swap a program out
 - Reload it, adjacent to another
 - Adjust its base register
 - Compaction is possible *only* if relocation is dynamic
 - I/O problem:
 - * Latch job in memory while it is involved in I/O
 - * Do I/O only into OS buffers

9.5 Segmentation

Segmentation

- Dealing with fragmentation
 - Why not remove the need for continuous addresses?
- Segmentation
 - partition an address space into *logical* units
 - * stack, code, heap, subroutines
 - a virtual address is <segment#, offset>
- Facilitates sharing and reuse
 - a segment is a natural unit of sharing — a subroutine or function
- A natural extension of variable-sized partitions
 - variable-sized partition = 1 segment per process
 - segmentation = many segments per process.

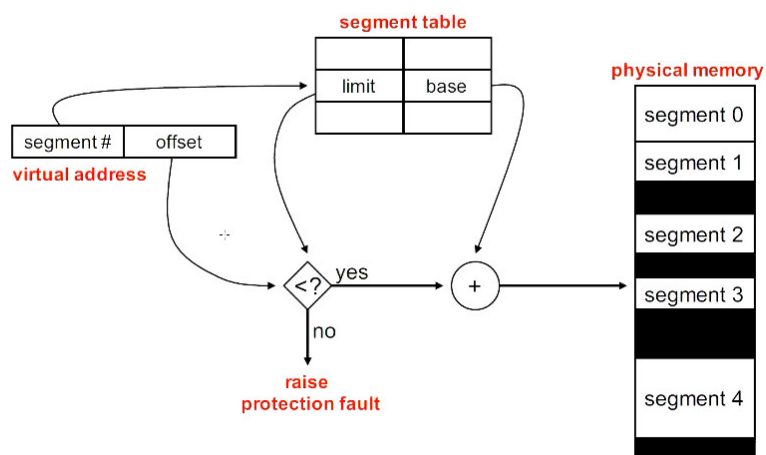
User's View of a Program



Hardware support

- Segment table
 - multiple base/limit pairs, *one per segment*
 - segments named by segment#, used as index into table
 - * a virtual address is <segment#, offset>
 - offset of virtual address added to base address of segment to yield physical address

Segment lookups



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Pros and Cons

- Logical and it facilitates sharing and reuse

- Allows non-contiguous physical addresses
 - Helps exploit varying sized holes
- But it has the complexity of a variable partition system
 - except that linking is simpler, and the “chunks” that must be allocated are smaller than a “typical” linear address space.
- Segmentation rarely used alone
 - Paging is the basis for modern memory management

9.6 Summary

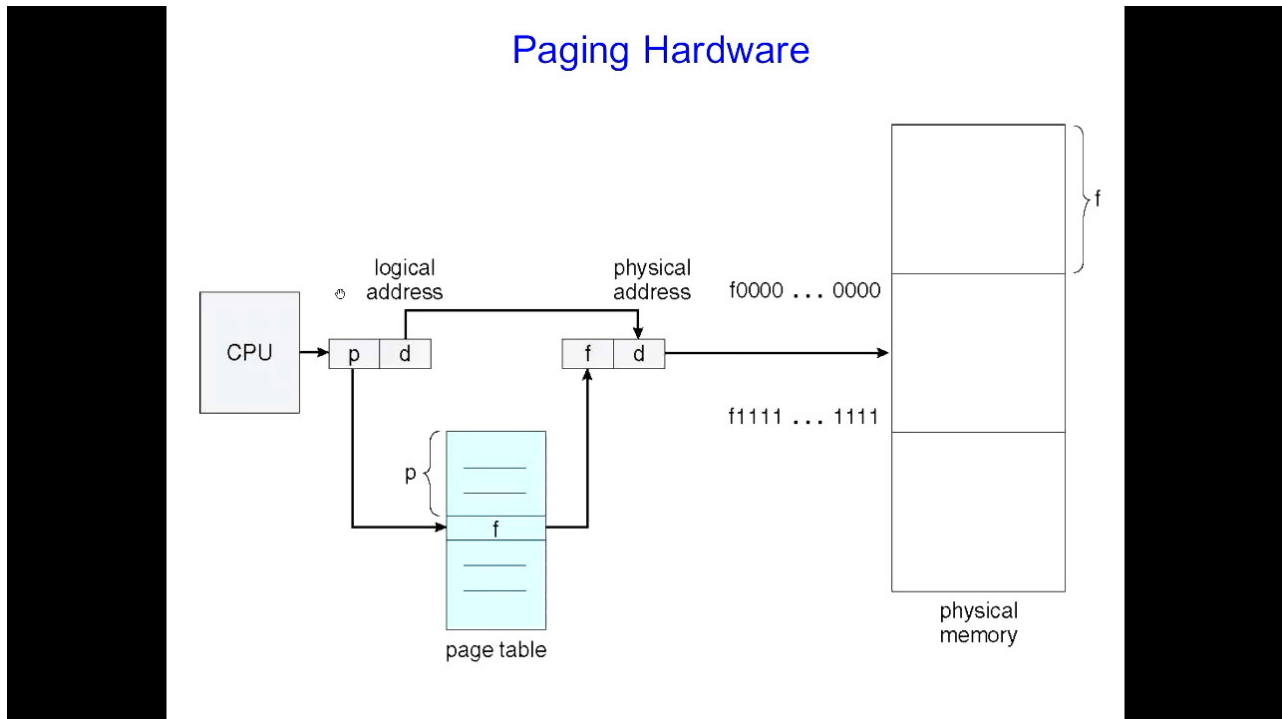
- Logical/Virtual Address Space v.s. Physical Address Space
- Swapping
- Contiguous memory allocation
- Fragmentation
- Segmentation
- Paging
 - A better solution

10 Paging

10.1 Paging

Address translation scheme

- Address generated by CPU is divided into:
 - *Page number (p)* — used as an index into a *page table* which contains base address of each page in physical memory
 - *Page offset (d)* — combined with base address to define the physical memory address that is sent to the memory unit



10.2 Page Tables

Implementation of Page Table

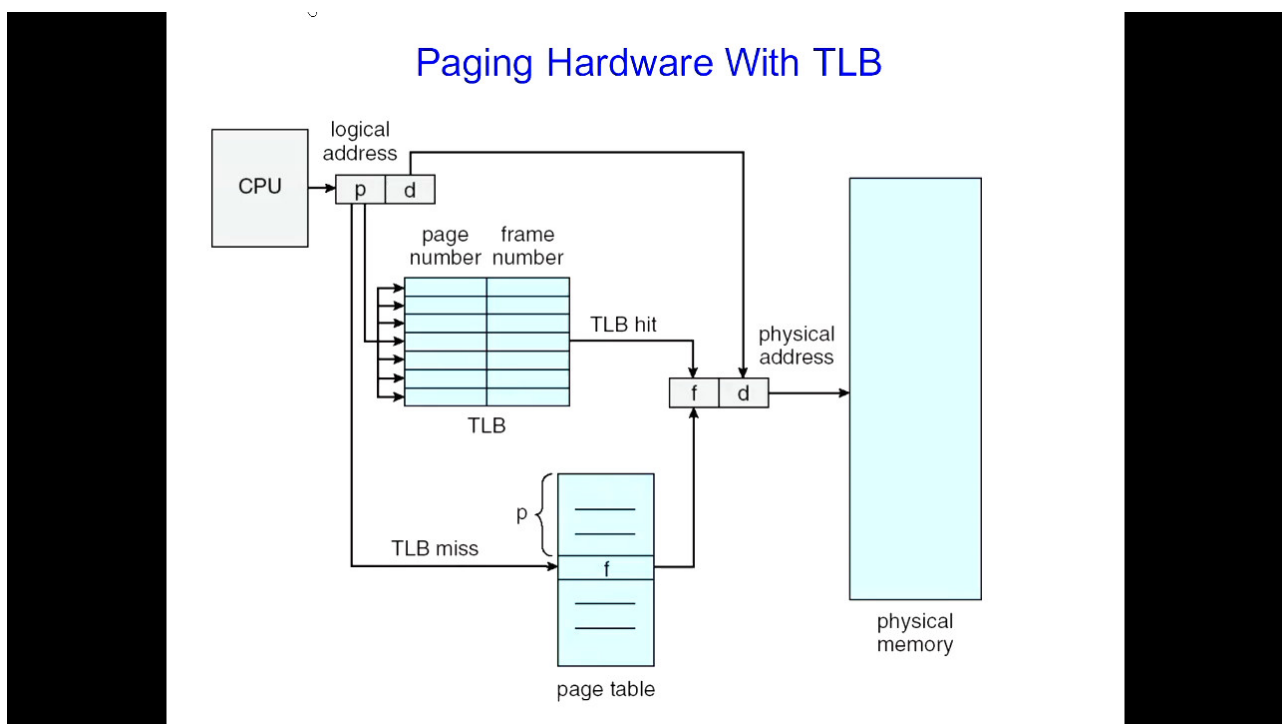
- Page table is kept in main memory
- Page-table base register (PTBR) points to the page table
- Page-table length register (PTLR) indicates the size of the page table
- In this scheme, every data/instruction access requires two memory access
 - one for the page table, and one for the data/instruction
- The two memory access problem can be solved
 - by the use of a special fast-lookup hardware cache
 - called *associative memory* or *translation look-aside buffers* (TLBs)
- Some TLBs store *address-space identifiers* (ASIDs) in each TLB entry
 - uniquely identifies each process;
 - provides address-space protection for that process;
 - otherwise need to flush at every context switch.

- TLBs typically small (64–1,024 entries)
- On a TLB miss, value is loaded into the TLB for faster access next time.
 - Replacement policies must be considered.
 - Some entries can be *wired down* for permanent fast access.

10.3 TLB

Associative Memory

- Associative memory — parallel search
- Address translation (p, d)
 - if p is in associative register, get frame# out;
 - otherwise get frame# from page table in memory.



Effective Access Time

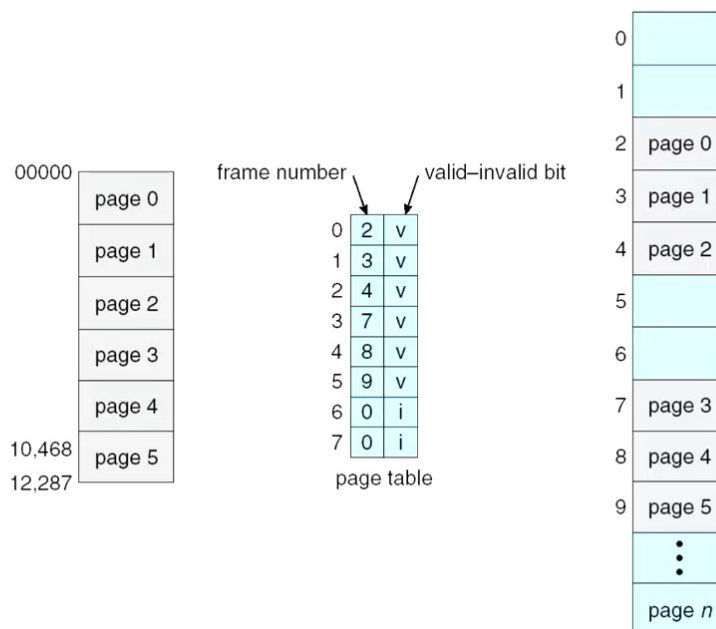
- Associative lookup
 - Extremely fast
- Hit ratio = α
 - Hit ratio — percentage of times that a page number is found in the associative memory;
- Consider $\alpha = 80\%$, 100ns for memory access
 - $EAT = 0.80 \times 100 + 0.20 \times 200 = 120\text{ns}$
- Consider hit ratio $\alpha = 99$, 100ns for memory access
 - $EAT = 0.99 \times 100 + 0.01 \times 200 = 101\text{ns}$

Memory Protection

- Memory protection implemented
 - by associating protection bit with each frame

- to indicate if read-only or read-write access is allowed.
- Can also add more bits to indicate page execute-only, and so on.
- *Valid-invalid* bit attached to each entry in the page table:
 - *valid* indicates that the associated page
 - * is in the process' logical address space, and is thus a legal page
 - *invalid* indicates that the page
 - * is not in the process' logical address space.
 - Or use Page-Table Length Register (PTLR)
 - Page Table Entries (PTEs) can contain more information.
- Any violations result in a trap to the kernel.

Valid (v) or Invalid (i) Bit In A Page Table

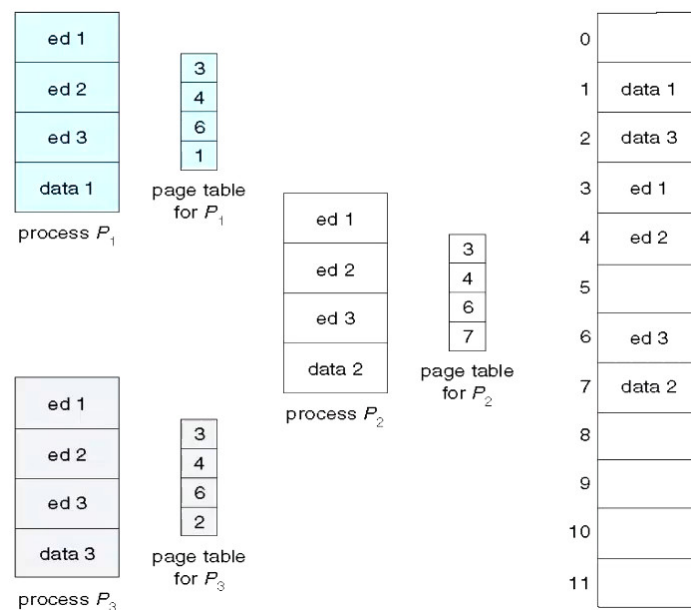


10.4 Shared Pages

Shared Pages

- *Shared Code*
 - One copy of read-only (*re-entrant*) code shared among processes (i.e. text editors, compilers, window systems).
 - Similar to multiple threads sharing the same process space.
 - Also useful for interprocess communication if sharing or read-write pages is allowed.
- *Private code and data*
 - Each process keeps a separate copy of the data.
 - The pages for the private code and data can appear anywhere in the logical address space.

Shared Pages Example



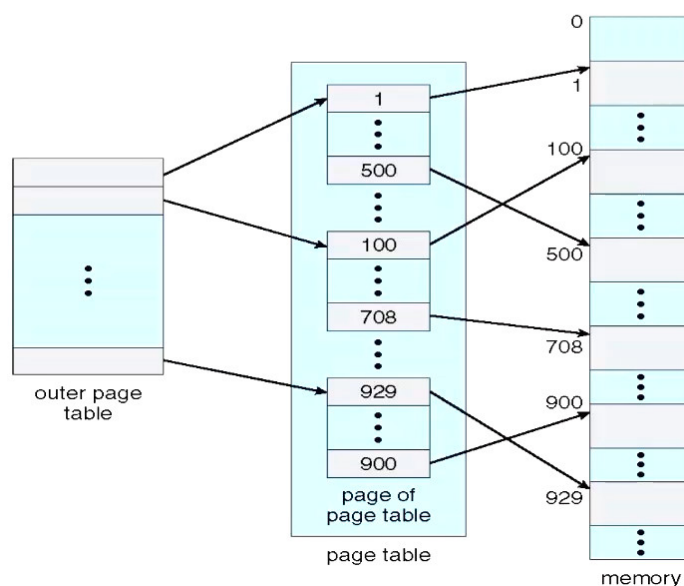
Structure of the Page Table

- Memory structures for paging can get huge using straightforward methods
 - Consider 32-bit logical address space as on modern computers
 - Page size of 4KB (2^{12})
 - Page table would have 1 million entries ($\frac{2^{32}}{2^{12}}$)
 - If each entry is 4 bytes \Rightarrow 4MB of physical address space / memory for page table alone.
 - * That amount of memory used to cost a lot
 - * Don't want to allocate that contiguously in main memory.
- Hierarchical paging
- Hashed page tables
- Inverted page tables

10.5 Hierarchical Pages

- Break up the logical address space into multiple page tables
- A simple technique is a two-level page table
- We then page the page table

Two-Level Page-Table Scheme



Two-level paging example

- A logical address (on 32-bit machines with 1K page size) is divided into:
 - a page number consisting of 22 bits
 - a page offset consisting of 10 bits
- Since the page table is paged, the page number is further divided into:
 - a 12-bit page number
 - a 10-bit page offset
- Thus a logical address is as follows

page number		page offset
p_1	p_2	d
12	10	10

where p_1 is an index into the outer page table, and p_2 is the displacement within the page of the inner page table.

- Known as *forward-mapped page table*.

64-bit logical address space

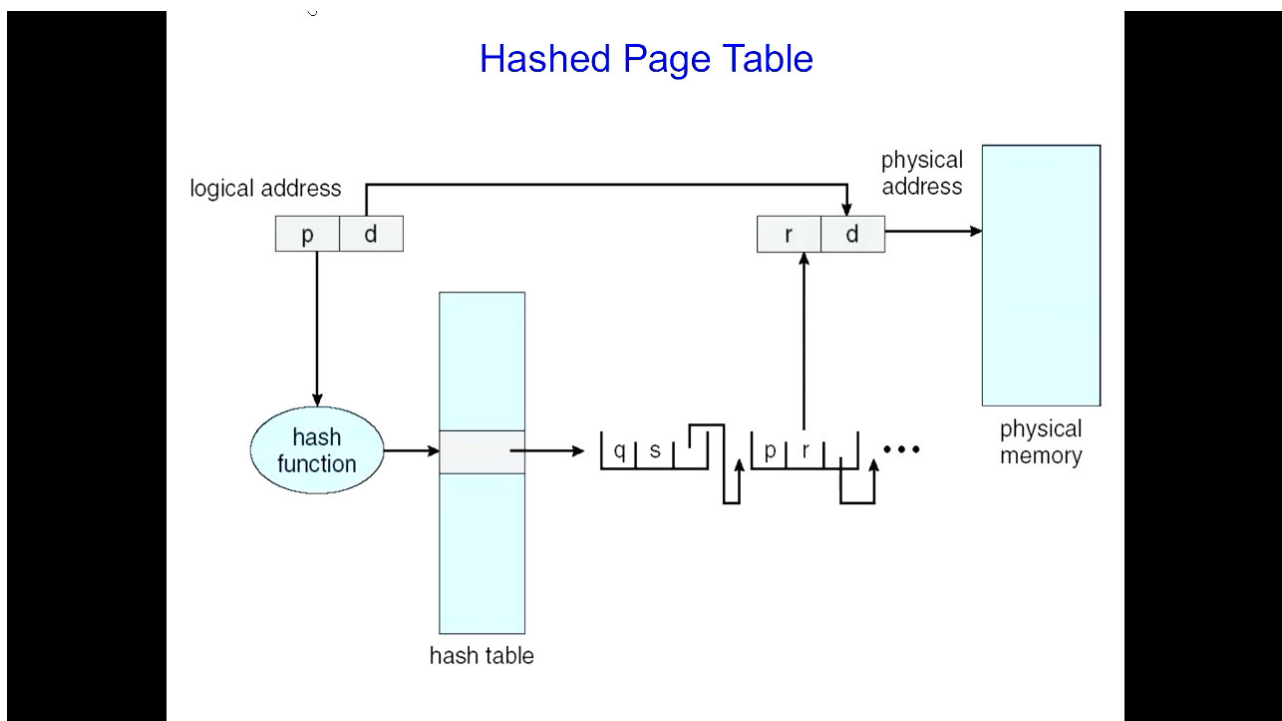
- Even two-level paging scheme not sufficient
- If page size is 4KB (2^{12})
 - Then page table has 2^{52} entries
 - If two level scheme, inner page tables could be 2^{10} 4-byte entries
 - Addresses would look like

outer page	inner page	page offset
p_1	p_2	d
42	10	12

- Outer page table has 2^{42} entries or 2^{44} bytes
- One solution is to add a second outer page table
- But in the following example, the second outer page table is still 2^{34} bytes in size,
 - * And possibly 4 memory access to get one physical memory location.

10.6 Hashed Pages

- Common in address spaces > 32 bits
- The virtual page number is hashed into a page table
 - This page table contains a chain of elements hashing to the same location
- Each element contains
 1. the virtual page number
 2. the value of the mapped page frame
 3. a pointer to the next element
- Virtual page numbers are compared in this chain searching for a match
 - If a match is found, the corresponding physical frame is extracted.
- Variation for 64-bit addresses is *clustered page tables*
 - Similar to hashed but each entry refers to several pages (such as 16) rather than 1.
 - Especially useful for *sparse* address spaces (where memory references are non-contiguous and scattered).



10.7 Inverted Pages

- Rather than each process having a page table and keeping track of all possible logical pages,
 - track all physical pages.
- One entry for each real page of memory.

- Entry consists of
 - the virtual address of the page stored in that real memory location,
 - information about the process that owns that page.
- Decreases memory needed to store each page table
 - but increases time needed to search the table when a page reference occurs.
- Use hash table to limit the search to one/few page-table entries
 - TLB can accelerate access.
- But how to implement shared memory?
 - One mapping of a virtual address to the shared physical address.

10.8 Uses

Functionality enhanced by page tables

- Code (instructions) is read-only
 - A bad pointer can't change the program code
- Dereferencing a null pointer is an error caught by hardware
 - Don't use the first page of the virtual address space — mark it as invalid — so references to address 0 cause an interrupt.
- Inter-process memory protection
 - My address XYZ is different to your address XYZ
- Shared libraries
 - All running C programs use libc
 - Have only one (partial) copy in physical memory, not one per process
 - All page table entries mapping libc point to the same set of physical frames
 - * DLLs in Windows
- Generalising the use of “shared memory”
 - Regions of two separate processes' address spaces map to the same physical frames
 - Faster inter-process communication
 - * just read/write from/to shared memory Don't have to make a syscall
 - Will have separate Page Table Entries (PTEs) per process, so can give different processes different access rights
 - * E.g. one reader, one writer.
- Copy-on-write (CoW), e.g. on `fork()`
 - Instead of copying all pages, create shared mappings of parent pages in child address space
 - * Make shared mappings read-only for both processes
 - * When either process writes, fault occurs, OS “splits” the page

Less familiar uses

- Memory-mapped files

- instead of using open, read, write, close
 - * “map” a file into a region of the virtual address space
 - e.g. into region with base X
 - * accessing virtual address $X + N$ refers to offset N in file
 - * initially, all pages in mapped region marked as invalid
- OS reads a page from file whenever invalid page accessed
- OS writes a page to file when evicted from physical memory
 - * only necessary if page is dirty.

More unusual use

- Use “soft faults”
 - faults on pages that are actually in memory
 - but whose PTE entries have artificially been marked as invalid
- That idea can be used whenever it would be useful to trap on a reference to some data item.
 - Example: debugger watchpoints
- Limited by the fact that the granularity of detection is the page.

11 Virtual Memory

11.1 Virtual memory

Paged virtual memory

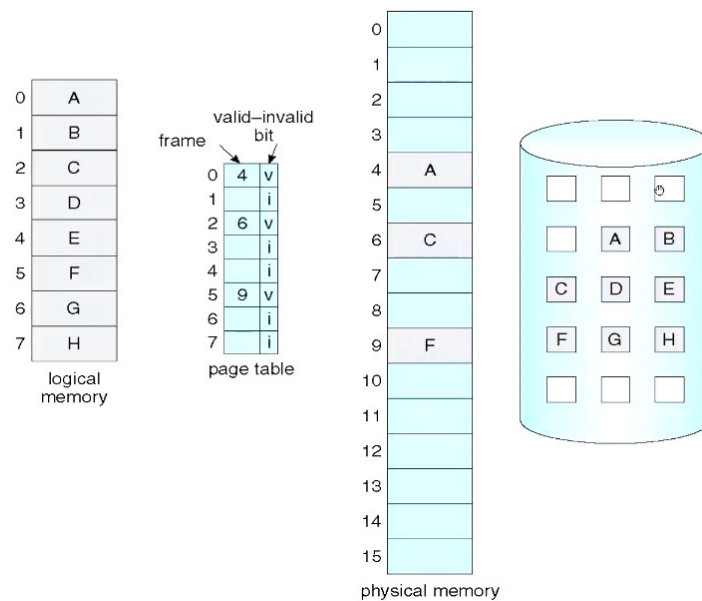
- Allows a larger logical address space than physical memory
- All pages of address space do not need to be in memory
 - the full (used) address space on disk in page-sized blocks
 - main memory used as a (page) cache
- Needed page transferred to a free page frame
 - if no free page frames, evict a page
 - * evicted pages go to disk only if *dirty*
 - Transparent to the application, except for performance
 - Managed by hardware and OS
- Traditionally called *paged virtual memory*

11.2 Page Fault

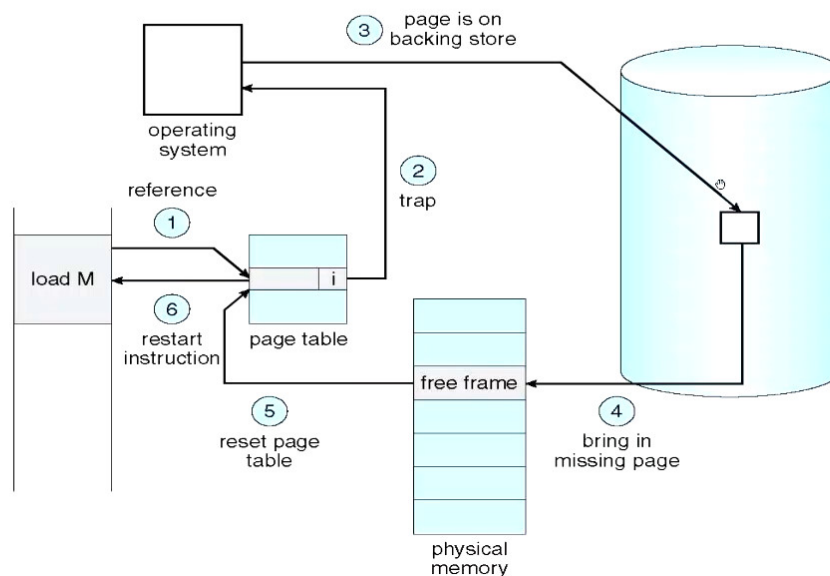
Page Fault

- If there is a reference to a page, first reference to that page will trap to OS:
page fault
1. OS looks at another table to decide
 - invalid reference \implies abort
 - just not in memory
 2. Find free frame
 3. Swap page into frame via scheduled disk operation
 4. Reset tables to indicate page now in memory
Set validation bit = v
 5. Restart the instruction that caused the page fault

Page Table When Some Pages Are Not in Main Memory



Steps in Handling a Page Fault



11.3 Demand Paging

Demand paging

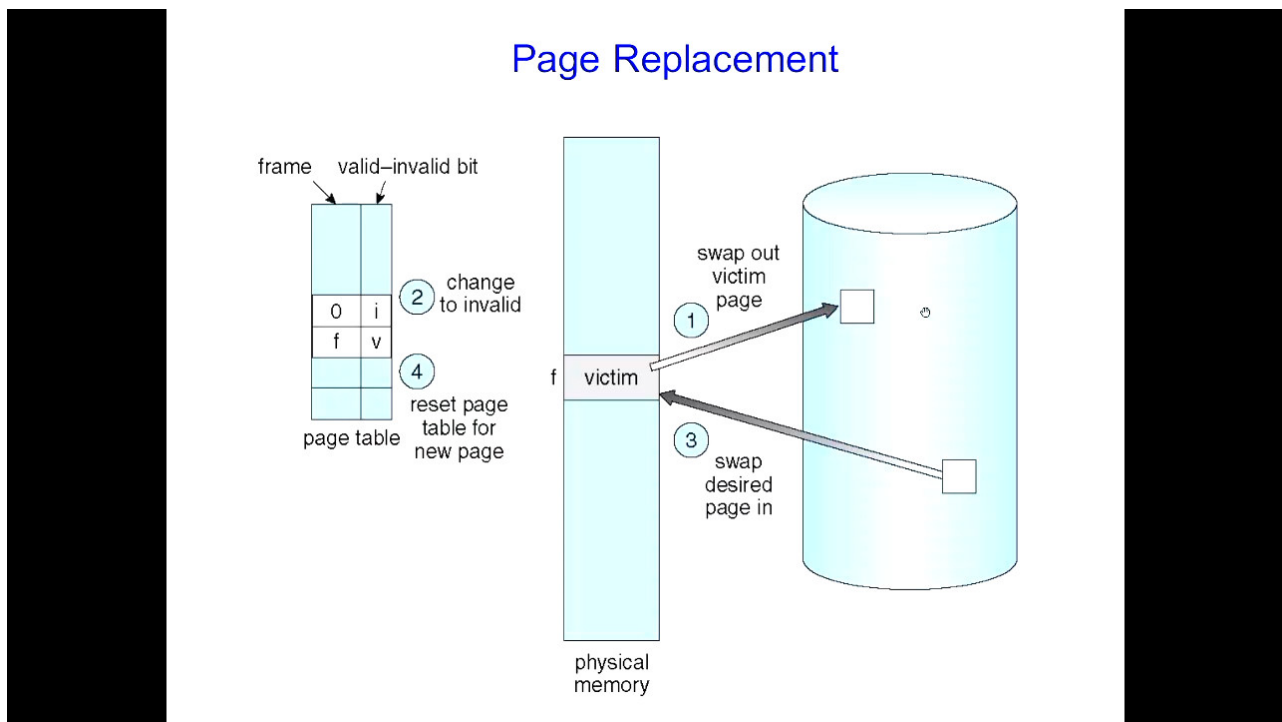
- Pages only brought into memory when referenced
 - Only code/data that is needed by a process needs to be loaded
 - * What's needed changes over time
 - Hence, it's called *demand paging*
- Few systems try to anticipate future needs
- But sometimes cluster pages

- OS keeps track of pages that should come and go together
- bring in all when one is referenced
- interface may allow programmer or compiler to identify clusters

11.4 Page replacement

Page replacement

- When you read in a page, where does it go?
 - if there are free page frames, grab one
 - if not, must evict something else
 - * this is called *page replacement*
- Page replacement algorithms
 - try to pick a page that won't be needed in the near future
 - try to pick a page that hasn't been modified (thus saving the disk write)
- OS tries to keep a pool of free pages around
 - so that allocations don't inevitably cause evictions
- OS tries to keep some "clean" pages around
 - so that even if you have to evict a page, you won't have to write it



Evicting the best page

- The goal of the page replacement algorithm:
 - reduce fault rate by selecting best victim page to remove
 - the best page to evict is one that will never be touched again
 - Belady's proof:

- * evicting the page that won't be used for the longest period of time minimises the page fault rate
- Examine *page replacement algorithms*
 - assume that a process pages against itself
 - using a fixed number of page frames
- Number of frames available impacts page fault rate
 - Note Belady's anomaly

11.5 Page replacement algorithms

First-In-First-Out (FIFO) Algorithm

- Not always the best page replacement behaviour.

Belady's Optimal Algorithm

- Replace page that will not be used for longest period of time
- How do you know this?
 - Can't predict the future
- Used for measuring how well your algorithm performs

Least Recently Used (LRU) algorithm

- Use past knowledge rather than future
- Replace page that has not been used in the most amount of time
- Associate time of last use with each page
- 12 pages — better than FIFO but works than Belady's/OPT
- Generally good algorithm and frequently used
- But how to implement?

Approximating LRU

- Many approximations, all use the PTE's referenced but
 - keep a counter for each page
 - at some regular interval, for each page, do:
 - * if reference bit = 0, increment the counter (hasn't been used)
 - * if reference bit = 1, zero the counter (hasn't been used)
 - * regardless, zero bit ref
 - the counter will contain the number of intervals since the last reference to the page
 - * page with largest counter is least recently used
- Some architectures don't have PTE reference bits
 - can simulate reference bit using the valid bit to induce faults

Second-chance clock

- Not Recently Used (NRU) or Second Change
 - replace page that is "old enough"

- logically, arrange all physical page frames in a big circle (clock)
 - * just a circular linked list
- A “clock hand” is used to select a good LRU candidate
 - sweep through the pages in circular order like a clock
- If reference bit is off, it hasn’t been used recently, and we have a victim
- If reference bit is on, turn it off and go to next page
 - arm moves quickly when pages are needed.

Allocation of frames among processes

- FIFO and LRU Clock each can be implemented as either *local* or *global* replacement algorithms
 - local
 - * each process is given a limit of pages it can use
 - * it “pages against itself” (evicts its own pages)
 - global
 - * the “victim” is chosen from among all page frames, regardless of owner
 - * processes’ page frame allocation can vary dynamically
- Issues with local replacement?
 - poor utilisation of free page frames, long access time
- Issues with global replacement
 - Linux uses global replacement: global thrashing.

11.6 Working set

The *working set model of program behaviour*

- *Working set* of a process is used to model the dynamic locality of its memory usage
 - works set = set of pages a process currently “needs”
 - formally defined by Peter Denning in the 1960s.
- Definition:
 - $WS(t, w) = \{\text{pages } P \text{ such that } P \text{ was referenced in the time interval } (t, t - w)\}$
 - * t time
 - * w working set *window* (measured in page references)
 - * a page in WS only if it was referenced in the last w references
- Working set varies over the life of the program
 - so does the *working set size*

Working set size

- The working set size, $|WS(t, w)|$
 - changes with program locality
- During periods of poor locality

- more pages are referenced
- Within that period of time
 - the working set size is larger
- Intuitively, the working set must be in memory
 - otherwise you'll experience heavy faulting
 - *thrashing*

Hypothetical Working Set Algorithm

- Estimate $|\text{WS}(0, w)|$ for a process
 - Allow that process to start only if you can allocate it that many page frames
- Use a local replacement algorithm (LRU Clock?)
 - make sure that the working set are occupying the process's frames
- Track each process's working set size,
 - and re-allocate page frames among processes dynamically
- Problem
 - keep track of working set size
- Use reference bit with a fixed-interval timer interrupt.

Working Sets and Page Fault Rates

- Direct relationship between working set of a process and its page-fault rate
- Working set changes over time
- Peaks and valleys over time

Page-Fault frequency

- More direct approach than WSS
- Establish “acceptable” *page-fault frequency (PFF)* rate and use local replacement policy
 - If actual rate too low, process loses frame
 - If actual rate too high, process gains frame

11.7 Thrashing

Thrashing

- Thrashing
 - when the system spends most of its time servicing page faults, little time doing useful work
- Could be that there is enough memory
 - but a poor replacement algorithm — incompatible with program behaviour
- Could be that memory is over-committed
 - OS sees CPU poorly utilised and adds more processes
 - * too many active processes
 - Makes problem worse

12 File Systems

13 Secondary Storage

14 Virtualisation