Processor controls hardware and executes instructions.

Memory stores data and code.

I/O components read and write from I/O devices.

System bus interconnects different components and provides communication between them.

OS must make **efficient** use of available resources and must **share** resources (CPU cores, caches, RAM, GPUs, clocks, timers, persistent storage) among multiple users.

Providing clean interfaces allows us to convert raw hardware into a usable computer system by keeping **details** hidden from user-level software.

Must support several simultaneous parallel activities, and may switch activities at arbitrary times, so must ensure **safe concurrency**.

MULTIPROCESSORS (Windows, macOS, Linux) have many CPU cores and CPUs.

SERVER OS (Solaris, FreeBSD, Linux) shares hardware/software resources.

MAINFRAMES have bespoke hardware, limited workload.

SMARTPHONES have power-efficient CPUs.

EMBEDDED OSs (QNX, VXWorks) are used for home utilities, and only run trusted software.

REAL-TIME OSs are time-oriented (not performance/IO).

SENSOR NETWORK OS (Tiny OS) is resource efficient.

The OS **kernel** is a privileged program that implements OS functionality.

Monolithic kernels are a single black box with all functionality. One executable with its own address space. Easier to write kernel components but overall design is complex, with no protection between them.

Microkernels have as little functionality in the kernel as possible, functionality passed to a user-level server. Kernel does IPC between servers - separate ones for I/O, file access, scheduling, but this leads to high overhead. Less error-prone and servers have clean interfaces.

Hybrid kernels combine features of both.

LINUX is a variant of Unix. **Interrupt handlers** are the primary means to interact with devices. I/O scheduler orders disk operations. Supports static in-kernel components and dynamically loadable **modules**.

NTOS provides **system calls** in **WINDOWS**. Programs are built on top of **dynamic code libraries**. NTOS loaded from *ntoskrnl.exe* at boot, consists of **executive** and **kernel** layers. **Device drivers** loaded into kernel memory. NT structured like a **microkernel**, most components run in same address space. **Hardware Abstraction Layer** abstracts out BIOS config, CPU types, etc…

PROCESSES

PROCESSES allow a single processor to run multiple programs "**simultaneously**". Provides concurrency, isolation between programs, allows better resource utilisation, simplifies programming.

Pseudo concurrency — single physical processor is switched between processes by interleaving.

Real concurrency utilises multiple physical processors.

On a **context switch**, the processor switches from executing process A to executing process B. May occur in response to events/interrupts, or as a result of periodic scheduling. Process may be **restarted later**, so all information needed should be stored in **process descriptor** / **control block**, kept in the **process table**.

Process Control Block — process has its own VM, should store PC, page table register, stack pointer, …, process management info, file management info.

Context switches are expensive, so avoid unnecessary usage. *Direct cost* — save/restore process state. *Indirect cost* — perturbation of memory caches.
^ Flushing TLB & pipeline flushing

UNIX allows processes to create hierarchies. Windows has no notion of this.

int fork(void) — Creates new child process, to be executed concurrently, by making exact copy (same resources) of parent process image. Returns child PID in **parent** process and 0 in **child** process. No child created, and -1 returned to parent on error.

int execve(char *path, char *argv[], char *envp[]) — Changes process image and runs new process. Lots of useful wrappers.

int waitpid(int pid, int* status, int options) — Suspends execution of calling process until process *pid* terminates normally or signal received. Can wait for more than one child.

Simple design philosophy, so process API made up of basic blocks that can be easily combined.

CreateProcess() (equivalent of *fork()* & *execve()*) has 10 parameters!

Termination — normally process completes execution of body, calls *exit()*. **Abnormal exit** — runs into error or unhandled exception. **Aborted** — another process has overruled execution. Some run in an endless loop.

void exit(int status) — Terminates a process. Never returns in the calling process.
int kill(int pid, int sig) — sends signal sig to process pid.

SIGINT	Interrupt from keyboard
SIGABRT	Abort signal from abort
SIGFPE	Floating point exception
SIGKILL	Kill signal
SIGSEGV	Invalid memory reference
SIGPIPE	Broken pipe: write to pipe with no readers
SIGALRM	Timer signal from alarm
SIGTERM	Termination signal

SIGNALS are an IPC mechanism — **delivery** similar to delivery of hardware interrupts. Process can send signal to another process, if it has permission. Generated when an exception occurs, when kernel wants to notify process of an event, when certain key combinations typed in terminal, or programmatically using *int kill()*.

Default action for most signals is to terminate process, but receiving process may ignore/handle it instead (unless *SIGKILL* or *SIGSTOP*).

PIPES — method of connecting stdout of one process to stdin of another. **Named** or **unnamed**. Sender should close the read end, receiver should close the write end.

Named Pipes / **FIFOs** are persistent pipes that outlive processes which created them. Stored on file system. Any process can open it like a regular file.

int pipe(int fd[2]) — returns two file descriptors: read end *fd[0]*, write end *fd[1]*.

THREADS

THREADS are execution streams that share the **same address space**. **Multithreading** — each process can contain multiple threads.

Useful for applications which contain multiple parallel activities that read/write the same data. Processes are too heavyweight — it is difficult to communicate between address spaces, and expensive to context switch between them & create/destroy activities.

Shared address space can lead to memory corruption and concurrency bugs. How to handle **forking** and **signals**?

PTHREADS implemented by most Unix systems.

int pthread_create(…) — Creates a new thread.

void pthread_exit(void value_ptr) — Terminates the thread and makes *value_ptr* available to any successful join with terminating thread. Called implicitly when the thread's start routine returns.

int pthread_yield(void) — Releases CPU to let another thread run. Returns 0 on success (always), or error code.

int pthread_join(…) — Blocks until thread terminates.

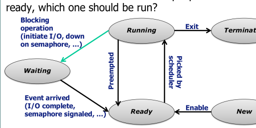
User-level threads — OS kernel not aware of threads, each process manages its own threads. Better performance, and each application can have its own scheduling algorithm. But blocking system calls (e.g. during page fault) stop **all threads** in process.

Kernel-level threads — Blocking syscalls / page faults can be easily accommodated. But thread operations are more expensive. No application-specific schedulers.

Hybrid approaches use kernel threads and multiplex user-level threads onto some of these.

SCHEDULING

SCHEDULING — if multiple processes are ready, which one should be run?



Goals of Scheduling Algorithms => **Ensure fairness**: Comparable processes should get comparable services; **Avoid indefinite postponement**: No process should starve; **Enforce policy**: E.g. priorities; **Maximize resource utilization**: CPU, I/O devices; **Minimize overhead**: From context switches, scheduling decisions
For Batch Systems => **Throughput**: Jobs per unit of time; **Turnaround time**: Time between job submission & completion
For Interactive Systems => **Response time**: Time between request issued and first response

Non-preemptive scheduling lets process run until it blocks / releases CPU. **Preemptive** scheduling lets process run for a maximum amount of fixed time.

FIRST-COME FIRST-SERVE — No indefinite postponement. Easy implementation. But suffers from "head-of-line blocking" if long job followed by many short jobs.

ROUND-ROBIN — Process runs until it blocks or time quantum exceeded. Fair, and good response time. Poor turnaround time when jobs have similar run-times.
^ Good avg. turnaround time when different runtimes. ***RR quantum (time slice)*** => should be larger than context switch cost, but still provide decent response time; ***RR overhead*** => RR quantum/(RR quantum + ctx. switch time).

Pick the **SHORTEST JOB FIRST** with run-times known in advance. Optimal when all jobs available simultaneously.

Pick the process with **SHORTEST REMAINING TIME**. Allows new short jobs to get good service.

Run-times usually not available in advance. Compute CPU
FAIR-SHARE SCHEDULING — Users assigned some fraction of the CPU.
^ within each user can use RR to schedule.

PRIORITY SCHEDULING — Jobs run based on their priority. Can be **externally-defined**, based on some **process-specific metrics**. Can be static or dynamic.

Generally, favour short and I/O-bound jobs. Quickly determine the nature of job and adapt to changes.

MULTILEVEL FEEDBACK QUEUES — Form of priority scheduling. One queue for each priority level. Within each queue, can use diff. scheduling (usually RR). Need to determine current nature of job, worry about starvation of lower-priority jobs. *Feedback* comes from periodically recomputing priorities => e.g. based on how much CPU they used recently, increase job's priority as it ages, exponentially weighed moving average. Not very flexible, does not react quickly to changes, cheating is a concern.

LOTTERY SCHEDULING — Jobs receive lottery tickets for various resources — random ticket chosen at each scheduling decision. Number of lottery tickets is meaningful as a result. Highly responsive with no starvation. Jobs can exchange tickets. But unpredictable response time.

SYNCHRONISE

How do processes **SYNCHRONISE** their operations to perform a task?

Critical section — processes access a shared resource. **Synchronisation mechanism** required at entry/exit of critical section.

Race condition occurs when multiple threads read and write shared data within critical section => their execution interleaved non-deterministically.

Assume **sequential consistency** throughout — operations of each thread appear in program order, operations of all threads executed in sequential order atomically.

Synchronisation mechanism required at entry/exit of critical section => mediate concurrent access & prevent race conditions.

An **atomic operation** is a sequence of 1+ statements that are/appear to be indivisible.

TEST & SET LOCK is an atomic instruction TSL(L) provided by most CPUs. Sets memory location L to 1 and returns old value; locks using busy waiting (e.g. while (TSL(L) != 0) /*wait*/;) are **spin locks**.

DISABLING INTERRUPTS only works on single-processor systems. Misbehaving/buggy processes may never release the CPU.

STRICT ALTERNATION fails to meet rules of mutual exclusion => if T_0's non-crit. section is long enough, it will prevent T_1 from entering crit. section. ⇓⇓⇓

T_0 — turn 0 — T_1

```
while (true) {
   while (turn != 0)
     /* loop */ ;
   critical_section()
   turn = 1;

noncritical_section0();
}
```

```
while (true) {
   while (turn != 1)
     /* loop */ ;
   critical_section()
   turn = 0;

noncritical_section1();
}
```

PETERSON'S SOLUTION fixes issues w/ strict alternation; thread T_k calls enter/leave_critical(k); ⇓⇓

```
int turn = 0;
int interested[2] = {0, 0};
```

```
void leave_critical(int thread)
{
   interested[thread] = 0;
}
```

```
// thread is 0 or 1
void enter_critical(int thread)
{
   int other = 1 - thread;
   interested[thread] = 1;
   turn = other;
   while (turn == other &&
          interested[other])
      /* loop */ ;
}
```

Busy waiting => synch. mechanism for which the waiting thread remains in running state *(e.g. spin locks)* which wastes CPU cycles, and runs into **Priority Inversion Problem** => if higher-priority H is busy-waiting on lock held by lower-priority L, then H is always scheduled meaning L cannot make progress, i.e. neither can make progress.

Mutual exclusion ensures if a process executes its critical section, no other process can be executing it.

1. No two processes may be simultaneously inside a critical section.
2. No process running outside critical section may prevent other processes entering the critical section.
3. No process requiring access to its critical section can be delayed forever.
4. No assumptions made about the relative speed of processes.

^ a commonly desired feature of synchronisation mechanisms.
Example implementations => disabling interrupts, strict alternation, Peterson's solution, spin locks, binary semaphores w/ init. *counter*=1.

LOCK/MUTEX => mutual exclusion mechanism owned by actively excluding thread; **lock** is usually user/process object while **mutex** is same thing but OS/Kernel object.
Lock granularity => the amount of data a lock is protecting.
Lock overhead => cost of using locks, e.g. memory space, initialization, time required to acquire/release locks.
Lock contention => number of processes waiting for lock; more contention => less parallelism.
Read/Write Locks can be used to minimize lock contention & maximize concurrency => exclusive access in write mode but multiple threads can acquire in read mode.

SEMAPHORES — processes cooperate by means of signals. Special variables, accessible via (atomic) *down(s)*, *up(s)*, *init(s, i)*. Two private components — a **counter** and a **queue** of processes waiting on the semaphore.

In a **binary** semaphore, counter initialised to –1.

```
init(s, i) ::= counter(s) = i
               queue(s) = {}

down(s) ::= if counter(s) > 0
               counter(s) = counter(s) - 1
            else
               add P to queue(s)
               suspend current process P

up(s) ::= if queue(s) not empty
             resume one process in queue(s)
          else
             counter(s) = counter(s) + 1
```

MONITORS on COND-VARS:
- **Monitors** regulate access to shared data & consist of (implicit) ***monitor lock*** and ≥ 1 ***cond-vars***; ***entry*** procedures called from outside the monitor, ***internal*** procedures only callable from monitor procedures, processes can only call entry procedures — only one process can be in the monitor at one time
- **Cond-vars** associated with high-level conditions; if ***cond-var*** signalled w/ no one waiting for it then the signal is lost; has operations:
  - *wait(c)* => release monitor lock & wait for *c* to be signalled
  - *signal(c)* => wake up one process waiting for *c*
  - *broadcast(c)* => wake up all processes waiting for *c*
- **Monitors** are a *language construct* and *not supported by C (supported by PintOS via explicit monitor locks)*. Java supports variant of monitors via **synchronized** methods, but they lack condition variables, i.e. no wait()/notify()

Producer/consumer example w/ monitors ⇓⇓

```
monitor ProducerConsumer
   condition not_full, not_empty;
   integer count = 0;

   entry procedure insert(item)
      while (count == N) wait(not_full);
      insert_item(item); count++;
      signal(not_empty);

   entry procedure remove(item)
      while (count == 0) wait(not_empty);
      remove_item(item); count--;
      signal(not_full);
end monitor
```

^ producer inserts & consumer removes items w/ max. capacity N => only insert/remove if mutual exclusion achieved => only insert if non-full & remove if non-empty.

DEADLOCK

Set of processes is **DEADLOCKED** if each process is waiting for an event only another process can cause.

Resource deadlock the most common:
1. Mutual exclusion,
2. Hold and wait (process can request resources while it holds other resources earlier),
3. No pre-emption,
4. Circular wait (set of processes in circular waiting chain).

RESOURCE ALLOCATION GRAPH — directed graph models resource allocation => resource-to-process edge means process currently owns that resource => process-to-resource edge means process blocked waiting for that resource => cycle means deadlock

How to deal with deadlocks?
Ignore it — If contention fore resources is low, then deadlocks are infrequent
Detection & Recovery:
- After system deadlocked, dynamically build resource ownership graph and look for cycles => e.g. DFS search to look for cycles: when an edge has been inspected, it is marked and not visited again.
- Recover from deadlock by preemption *(temporarily take resource from owner and give to another)* => rollback *(periodic checkpoints are made for process state)* => kill random process :)))

Dynamic avoidance — Dynamically consider every request and decide whether safe to grant — needs resource usage information.

Prevention — Ensure ≥ 1 conditions cannot hold:
- Mutual exclusion => share the resource, use atomic operations, non-blocking algorithms??
- Hold and wait => require all processes to request resources before start; if not all available then wait - can be enforced by protecting lock acquisition w/ global lock; issues: need to know what you need in advance; often lead to starvation
- No preemption => allow processes to be preempted, i.e. temporarily lose locks they own
- Circular wait => e.g by acquiring resources in a total order

Communication Deadlock — A sends message to B, blocks waiting on B's reply. B didn't get A's message, then A is blocked, and B is blocked waiting on message!

LIVELOCKS — Processes/threads not blocked but they/system are not making progress.

Starvation is a policy concern — who gets what resource when?

^ **livelocks** are special type of starvation, related to priority inversion problem

MEMORY MANAGEMENT

MEMORY MANAGEMENT needs to provide allocation and protection. Needs to operate with no knowledge of how memory addresses **generated** or what they are **used for**.

HARDWARE — consider CPU registers (access in one clock cycle) and main memory (takes many cycles). Cache sits in between.

Memory management binds **logical** address space (generated by CPU) to **physical** address space (seen by memory unit). This process performed by the MMU device.
^ They are same in compile/load-time, but different in execution-time address-binding scheme ^ MMU is hardware-implementation of mapping, i.e. $\text{MMU}(\text{CPU}_{\text{logical}}) = \text{Memory}_{\text{physical}}$

Main memory usually split into **kernel** *(usually lower in memory, along w/ interrupt vector)* and **user** partitions *(usually higher in memory)*.
CONTIGUOUS ALLOCATION with relocation registers — ***base register*** contains value of smallest physical address => ***limit register*** contains range of logical addresses => together they define the logical address space => each logical address must be less than limit register => ***protection*** check base ≤ addr < base + limit to protect user processes from each other, and changing OS code/data.
MULTIPLE-PARTITION ALLOCATION:
- **Hole** is a block of available memory. When new process arrives, allocate memory from large-enough hole.
- OS maintains info on allocated & free partitions *(holes)*
- **Dynamic Storage Allocation** is satisfying request of size n, given list of free holes => ***First-fit***: allocate first hole big enough => ***Best-fit***: allocate smallest hole big enough => ***Worst-fit***: allocate largest hole.

External fragmentation — total memory exists to satisfy request, but not contiguous. Reduced by compaction *(place all free memory in one large block)*, but this does lead to I/O bottlenecks.
Internal fragmentation — allocated memory larger than requested memory.
Swapping process memory temporarily out of memory to disk => transfer time is major part of swap time.

VIRTUAL MEMORY — Separation of user logical memory from physical memory. Only part of process in memory for execution. Logical address space much larger than physical, can be shared by several processes.

PAGING — Logical address space of process can be non-contiguous. **Frames** are fixed-size blocks of physical memory, **pages** are same-size blocks of logical memory. We keep track of all free frames and set up a **page table** to translate logical → physical addresses.
^ smaller pages => less internal fragmentation; larger pages => smaller memory map + less address-translation overhead + quicker memory access
^ when context switches => OS locates new process' page table => sets base register in MMU to point to page table => clear cache/TLB

Address Translation: One-Level Paging
- For a given logical address space 2^m and page size 2^n
  - 2^m **bits** of address space, where each address refers to a **byte** in memory
  - 2^n **bytes** of page size, spanned by 2^n **bits** of address space
- First $m - n$ MSBs of logical address is **page number** p => used to index into page table $PT[p] = f$ to get frame base address f
- Last n LSBs of logical address is **page offset** d => offset into frame f => combined with frame base address f to get physical address
- ***Protection*** implemented associating protection bits with pages => valid-invalid bit is attached to each page table entry (PTE)
- Page-tables kept in memory, along w/ page-table base register (PTBR) & page-table length register (PTLR)
- Entry-per-page means we run out of memory quickly, e.g. 64-bit machine & 4kB page & 8B per-entry is 30,000TB for frame table => store entry-per-frame instead, *e.g. hashed page tables, inverted page tables*

We can use special fast-lookup hardware cache *(in the CPU)* called **associative memory** to store portions of the page table. This associative memory, when used for the purpose of caching page tables, is called **Translation Look-aside Buffers (TLBs):**
- To translate an address (p, d) — if p found in TLB then get cached frame f out, otherwise get f from page table *(the usual way.)*
- Some TLBs store **address-space ids (ASIDs)** in entries => uniquely identifies each process to provide address-space protection for that process
- TLBs usually flushed after context switch => substantial overhead

Performance: Effective Access Time
- ε = Associative Lookup; M = Memory Cycle Time; α = Hit Ratio; for n-**level tables** => $EAT = (\varepsilon + M)\cdot\alpha + (\varepsilon + M + nM)\cdot(1-\alpha) = \varepsilon + M\cdot[1 + n\cdot(1-\alpha)]$
- e.g. for $n = 1$ & $M = 1\mu\text{sec}$ => $EAT = 2 + \varepsilon - \alpha$,
- e.g. for $n = 4$ & $M = 1\mu\text{sec}$ => $EAT = 5 + \varepsilon - 4\alpha$, etc.

Address Translation: n-Level Paging also know as **Hierarchical Page Tables** => breaks up **page number** p into n pieces, e.g. $\text{addr} = (p_1, \dots, p_n, d)$ => each p_i corresponds to page table PT_i => each indexing $PT_i[p_i] = PT_{i+1}$ is pointer to next page table PT_{i+1} => the last indexing $PT_n[p_n] = f$ is frame base address f.
Two-Level Paging and **Three-Level Paging** are most common Hierarchical Page Tables.

HASHED PAGE TABLE hashes virtual page number into page table so the page table contains a chain of elements hashing to the same location.
^ literally just a hash-table with $(K,V) = (p, f)$

INVERTED PAGE TABLE contains an entry for each page frame of memory, consisting of the virtual address of the page stored in that location, and information about the process owning the page. Decreases memory needed, but increases time to search table.
^ $\text{logical\_addr} = (pid, p, d)$ => search PT to find i s.t. $PT[i] = (pid, p)$ => $\text{logical\_addr} = (i, d)$

Processes can set up **shared memory** areas. After shared memory established, no need for kernel.

Paging gives 1D virtual address space. A **SEGMENT** is an independent address space from 0 to some maximum that can grow/shrink independently. Supports different kinds of protection. Memory allocation harder due to variable size.

32-BIT VIRTUAL MEMORY LAYOUT
Processes map kernel to 3-4 GB virtual address range. Kernel maps lower 896 MB of physical memory to its virtual address space. Two-level page table. May not page fault in illegal access, as relevant program path may not be taken. Discard values after page fault in said path.

Copy-on-Write allows parent/child processes to initially share same pages in memory. Efficient process creation.

Memory-mapped files — Map file into virtual address space with paging. Simplifies programming model for I/O.

fork() needs to be optimised so it doesn't copy the entire address space when making an exact copy of parent process image. Can modify **COW** to give child its own page table with read-only pointers to parent's pages.

DEMAND PAGING brings page into memory only when needed. Uses a valid-invalid bit, initially set to 0 on all entries. If 0 during address translation, **page fault** — OS looks at another table to decide if invalid reference (& aborts) or valid reference but not in memory (& handles request — gets empty frame, swaps page into frame, resets tables with valid bit = 1, restarts last instruction).
Performance (of DP) — let p be the page fault rate. $EAT = (1-p) \times$ memory access $+ p$ (page fault overhead + swap page out + swap page in + restart overhead)
^ $0 \le p < 1$

PAGE REPLACEMENT strategy needed if no free frame. We want lowest page-fault rate possible. A **basic** strategy is to find location of desired page on disk => find free frame => if not found, read desired page into newly freed frame *(selected using **replacement algorithm**)* => update page and frame tables => restart process.

FIFO — Replace oldest page. **Belady's Anomaly** — more frames leads to more page faults.

Optimal Algorithm replaces page which won't be used for longest period of time — practically impossible, but a useful performance benchmark.

LEAST RECENTLY USED (LRU) — Each page entry has a counter. When page referenced, copy clock into counter. When page needs to be replaced, choose the lowest counter.
Proper LRU is expensive, so use approximations:
- With each page associate **reference bit** r. When page referenced, set $r = 1$. Periodically reset reference bits. Does not provide proper order for LRU.
- **Second chance (or clock) replacement** combines round-robin w/ reference bit r. If page to be replaced has $r = 1$, set $r = 0$, increment RR frame index. Repeat. If $r = 0$, replace page and increment RR index.

Counting algorithms keep a **counter** of #references made to each page — **Least Frequently Used (LFU)** replaces smallest count => never forgets heavy page usage; **Most Frequently Used (MFU)** replaces largest count => accounts for small-count pages being new.

Locality of Reference — Programs tend to request same pages in space/time. If program's favoured subset not kept in main memory, we end up with **thrashing** — excessive paging activity causing low CPU utilisation.

Working set of pages $W(t, w)$ is the set of pages referenced by a process in time interval $[t-w, t]$.
WS Clock Algorithm adds a time of last use to the second-chance algorithm => On each page fault => if $r = 1$ set $r := 0$ move to next page => if $r = 0$ calculate age & if age < w move to next page (page is in working set) => if age >= w then { if the page is clean, replace, otherwise trigger a write back and move to next page }
^ can choose w based on **page fault frequency** => if too small then page fault frequency will be high => if too large then working set won't fit into memory.
^ processes transition between working sets, so temporarily maintains in-memory pages outside of current working set.

Local page replacement — each process gets fixed allocation of physical memory. Need to pick up changes in working set size.

Global page replacement — dynamically share memory between runnable processes. Initially allocate memory proportional to process size.

Linux uses variation of clock algorithm to approximate LRU page-replacement strategy. MMU uses two linked lists.

I/O Devices: Block, Character, Other

I/O devices can be roughly divided into two categories: ***block devices*** and ***character devices***:
- ***Block devices***: store data in fixed-size blocks, each block one with its own address
  - Transfers in units of *one or more* entire (consecutive) blocks
  - Possible to read/write each block independently of the other blocks
  - e.g. HDDs, SSDs, magnetic tape drives, etc.
- ***Character devices***: delivers/accepts a stream of characters, disregarding any block structure
  - Not addressable and has no seek operation
  - e.g. printers, network interfaces, mice, etc.

This classification scheme is not perfect. Some devices do not fit in:
- ***Clocks***:
  - not block addressable & don't generate/accept character streams
  - They just cause interrupts at well-defined intervals
- ***Memory-mapped screens***: don't fit into this model
- ***Touch screens:*** don't fit into this model

Device Controllers/Adapters

I/O units often consist of a mechanical component and an electronic component. The electronic component is called the ***device controller*** or ***adapter***.
- On PCs it is often a chip on the motherboard or a PCB which can be inserted into a (PCIe) expansion slot
- Controller usually has a connector on it, into which a cable leading to the device itself can be plugged
- Many controllers can handle multiple devices
- If the interface between the controller & device is standard, companies make controllers/devices that fit that interface
  - e.g. SATA, SCSI, USB, etc.

Each controller has a few registers that are used for communicating with the CPU:
- Writing into these registers: commands the device to deliver data/accept data/switch itself on or off/etc.
- Reading from these registers: learn what the device's state is, e.g. is is prepared to accept a new command, etc

Many ***devices*** have a data buffer that can be read+written to:
- e.g. a common way for computers to display pixels on the screen is video RAM
  - a data buffer for programs/OS to write into

Memory-Mapped & Port-Mapped I/O

The ***Port-Mapped I/O*** approach assigns an ***I/O port*** number to control registers and buffers:
- Set of all the ***I/O ports*** form the I/O port space
- Access to ***I/O ports*** is protected
  - ordinary user programs cannot access it
  - only the operating system can
- Access is done with special I/O instructions, e.g. `IN REG,PORT` and `OUT PORT,REG`
- Most early computers worked this way

The ***Memory-Mapped I/O*** approach maps all control registers and buffers to the memory address space:
- Commonly at/near the top of the address space
- ***Pros***:
  - no need for special ASM instructions, so device drivers can be written entirely in C/C++
  - no special protection to memory-mapped addresses, so the OS can be flexible with how it delegates device access
    - e.g. omit memory-mapped addresses from user's virtual address space
    - e.g. give some users control over specific devices but not others, allowing device drivers to run in User Mode
      - prevents a driver crash from taking down the entire system
  - reuse the same ASM instructions as those used on normal memory
    - one instruction can do two things, e.g. instead of first reading an ***I/O port*** then doing something with it, you can just do that thing in one go
    - this reduces the number of instructions needed to be executed, therefore more efficient
- ***Cons***:
  - Modern computers often cache memory but caching memory-mapped addresses is ***DISASTEROUS***
    - both hardware & OS have to be designed to selectively disable caching which can be very complex
  - Modern systems also have multiple buses (memory, PCIe, SCSI, and USB)
    - I/O devices have no way of seeing memory addresses as they go by on the memory bus
    - Additional hardware/software complexity is needed to resolve this issue
      - e.g. CPU uses non-memory buses as fallback if memory bus fails to respond
      - e.g. put a snooping device on memory bus & pass all addresses presented to potentially interested I/O devices
      - e.g. preload address-ranges to memory-controller chip at boot time & it will redirect addresses to the appropriate bus thereafter

Direct Memory Access (DMA)

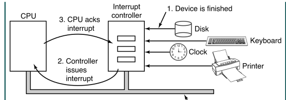
The CPU can requesting data from an I/O controller one byte at a time wastes its time, so ***DMA (Direct Memory Access)*** is often used:
- Can only use ***DMA*** if hardware has a DMA controller, most systems do
- Most commonly its a single DMA controller (e.g. on the motherboard)
  - for regulating transfers to multiple devices,
  - often concurrently
- DMA controller has access to system bus independent of the CPU
- Contains several registers that can be written/read by CPU
  - e.g. memory address register, byte count register, control registers, etc.
  - these specify the I/O port to use, direction of transfer, transfer unit, number of bytes to transfer in one burst, etc.

The CPU programs the DMA controller and lets it run parallel to the CPUs execution:
- The DMA controller instructs the device I/O controllers to perform the appropriate operations
- When one unit of work is done, the device I/O controllers sends an acknowledgment signal to the DMA controller
- For each acknowledgment signal, the DMA controller decrements a counter which keeps track of progress
- When the counter reaches 0, the workload is complete and the DMA controller sends an appropriate interrupt to the CPU

The above are simple cases of DMA controllers, but ones with more complex capabilities exist:
- Can be programmed to handle multiple transfers at the same time
  - multiple sets of control registers internally, one for each channel
  - may use round-robin or priority queue internally to decide which device to service next
  - often each device controller being serviced gets a separate channel for acknowledgment signals
- Buses can often operate in two modes: word-at-a-time & block mode
- Often, DMA controllers can also operate in either mode
- In word-at-a-time mode: the DMA controller requests the transfer of one word and gets it
  - If the CPU also wants the bus, it has to wait
  - The mechanism is called cycle stealing
- In block mode: DMA controller tells the device to acquire the bus, issue a series of transfers, then release the bus
  - this is called ***burst mode***
  - multiple words can be transferred for the price of one bus acquisition
  - can block the CPU and other devices for a substantial period if a long burst is being transferred
- In the above model (fly-by-mode), the the DMA controller tells the device controller to transfer the data directly to main memory
  - some DMA controllers have the device controller send the word to the DMA controller,
    - which then writes the word to wherever it is supposed to go
  - This scheme requires an extra bus cycle per word transferred,
    - but is more flexible in that it can also perform device-to-device copies and even memory-to-memory copies

Interrupt handlers for hardware interrupts

- For block devices: on transfer completion, signal device handler
- For character devices: when character transferred, process next character



Goals of I/O Software

Device independence: write programs that can access any I/O device without having to specify the device type or device instance in advance
- Some differences which the OS has to abstract are:
  - Unit of data transfer: character or block
  - Supported operations: e.g. read, write, seek
  - Synchronous or asynchronous operation
  - Speed differences
  - Sharable (e.g. disks) or single user (e.g. printer, DVD-RW)
  - Types of error conditions

Uniform naming: name of file/device should be a string/integer not dependent on device in any way
Error handling: should be handled as close to the hardware as possible
- Either the controller or driver should handle the error transparently
- Only if the lower layers are not able to deal with the problem should the upper layers be told about it

Synchronous (blocking) vs. asynchronous (interrupt-driven):
- Most physical I/O is asynchronous
- Most I/O code is easier to write synchronously
- The OS must make interrupt-driven operations appear blocking to the user programs
- The OS must *still* provide asynchronous API for use in performance-critical user programs

Buffered vs. non-buffered I/O: often data that come off a device cannot be stored directly in their final destination
- e.g. packets coming off a network cannot be directed to the right place until they have been stored and inspected for their port number
- some destination devices (e.g. digital audio devices) have limitations on data-transfer rates, so a buffer is used to "normalize" those
- Buffering involves considerable copying and often has a major impact on I/O performance

Dedicated device — Open fails if already opened; alternatively, queue open requests. Allocated for long periods.

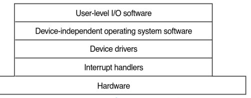
Shared device — OS provides file system for disks.

Ways to do I/O

- ***Programmed I/O***: CPU programs I/O control registers directly and blocks until the operation is done
  - This is done via ***polling*** the device until its done, called ***busy waiting***
  - Wastes CPU time and inefficient
- ***Interrupt-Driven I/O***: The CPU programs I/O control registers directly and continues doing other things
  - the device will send an interrupt to the CPU once done
  - can still be very inefficient with unbuffered character devices which will interrupt on every character
- ***I/O using Direct Memory Access (DMA)***: The CPU programs a DMA controller and continues doing other things
  - the DMA controller will perform the entire operation and send an interrupt to the CPU once done
  - may be inefficient in certain circumstances, because DMA controllers are usually much slower than the CPU

I/O Software Layers

I/O software is typically organized in four layers. Each layer has a well-defined function to perform and a well-defined interface to the adjacent layers



Interrupt-Handlers in the Software Layers

Interrupt handlers should aim to be as buried as possible, doing as little as possible.
- e.g. have a driver start an I/O operation and block (like by downing a semaphore) and the interrupt-handler only unblocks it (like by upping that semaphore)
- e.g. for others its a condvar signal or other kind of message etc. which will make the device driver resume
- the above works best if the driver is structured as a process

Device Drivers

Handles one device type, but many devices of that type. Its functions are implementing block read/write, accessing device registers, initiating operations, scheduling requests, handling errors.
Most operating systems define a standard interface that all block drivers must support and a second standard interface that all character drivers must support.

Device-Independent I/O software

The basic function of the ***device-independent software*** is to perform the I/O functions that are common to all devices and to provide a uniform interface to the user-level software =>
uniform interfacing for device drivers => buffering => error reporting => allocating and releasing dedicated devices => providing a device-independent block size

Uniform Interfacing for Device Drivers

A major issue in an OS is how to make all I/O devices and drivers look more or less the same. If they weren't the same, we would have to hack on the OS for each new device
Not all devices are absolutely identical, but there are only a small number of device types which need to be accounted for
- e.g. classes of device like disks, printers, network stream
- OS defines a set of functions that the driver of a specific device type must supply The device-independent software takes care of mapping symbolic device names onto the proper driver:
  - e.g. for UNIX a device name, such as /dev/disk0, uniquely specifies the i-node for a special file
    - this i-node contains the major device number, which is used to locate the appropriate driver
    - The i-node also contains the minor device number, which is passed as a parameter to the driver in order to specify the unit to be read or written

Buffering

Buffered I/O — User data transferred to OS output buffer. Process continues, only suspends when buffer full. OS reads ahead but process blocks when buffer empty.
Unbuffered I/O — Data transferred directly to/from user space from/to device. Device handler used for each transfer as each read/write is causing physical I/O. High process switching overhead.
I/O operations — open, close, read, write, seek.

Device-Independent Block Size

Different SSDs have different flash page sizes, while different disks may have different sector sizes. It is up to the device-independent software to hide this fact and provide a uniform block size to higher layers

User-Space I/O Software

User-Space I/O Libraries

Most user-space I/O code is library code which simply arranges arguments in the right way for a SYSCALL,
- sometimes more complex logic is done i.e. `printf` and `scanf` in C

Spooling Daemons

Blocking user access to allocated, nonsharable devices?
- Causes delays and bottlenecks
- ☛ Spool to intermediate medium (disk file)

Spooled devices (e.g. printers)
1. Printer output saved to disk file
2. File printed later by **spooler daemon**
   - Printer only allocated to spooler daemon
   - No normal process allowed direct access

- Provides sharing of nonsharable devices
- Reduces I/O time ➔ gives greater throughput

Device management on Linux

Loadable kernel modules provide device drivers. Object code is loaded **on-demand** and dynamically linked to running kernel. Does require **binary compatibility**. Every LKM consists of an initialisation and a clean shutdown function.

Kernel provides common interface for I/O syscalls to the **virtual file system**. Devices grouped into **device classes** of similar functions. **Major**/**minor** ID numbers used by device drivers to identify their devices. Same major no. → controlled by same driver.

Most devices represented by **device special files** — entries in */dev* directory that provide device access.

ioctl system call supports special tasks (ejecting CD tray).

Character device transmits data as stream of bytes. *file_operations* structure maintains operations supported by device driver.

Block I/O subsystem contains a number of layers — can modularise block I/O operations by placing common code in each layer. Can cache data and cluster I/O operations to reduce time spent accessing block devices.

Block Device Caching — when data first requested, kernel first searches cache — data copied to process's address space if found, or added to request queue.

Direct I/O — device bypasses kernel cache when accessing device.

SOCKETS (TCP/UDP) allow bidirectional communication. Used to exchange information locally, or across network.

Each process has its own **file descriptor table**. FDs refer to terminal from which program was started by default (e.g. 0 → stdin).

DISK MANAGEMENT

HDDs — Data is organised into concentric circular **tracks** on each platter. **Cylinder** is the set of tracks located at the same position across all platters. Physical **hardware address** references cylinder, then surface, then sector. Modern disks use **logical sector addressing** to hide the actual geometry from the OS — number sectors 0…n.

Disk must be **formatted** — **low-level** or **high-level**.

Disk scheduling — minimise seek and/or latency times (seek approx. 2-3x larger than latency) and order pending disk requests with respect to **head position**.

HDD PERFORMANCE
Seek time t_{seek}, latency time $t_{latency} = 1/2r$, transfer time $t_{transfer} = b/rN$, where b: number of bytes to be transferred, N: no. bytes per track, r: rotation speed in rev/s. Total access time: $t_{access} = t_{seek} + t_{latency} + t_{transfer}$.

HDD SCHEDULING
FCFS — No ordering of requests: random seek patterns. OK for lightly-loaded disks but poor performance for heavy loads. Fair algorithm.

SCAN (Elevator) — Choose requests resulting in shortest seek time in preferred direction. Only change direction when reaching outermost/innermost cylinder.

I/O requests placed in **request list**. Block device drivers define **request** operation called by kernel. Some device drivers (e.g. RAID) order their own requests.

Default **scheduling algorithm** is a variation of SCAN algorithm. But **deadline scheduler** ensures reads performed by deadline and **anticipatory scheduler** delays after read request completes.

SSDs have **more bandwidth** and **smaller latencies** compared to HDDs. But, if you care about I/O-ops/$, choose SSDs. Decreasing price but not enough bandwidth.

RAID solves this problem with parallel disk I/O. Uses an array of physical drives appearing as a single virtual drive, uses redundant disk capacity to respond to disk failure.

RAID levels have different properties in terms of performance, level of redundancy, degree of space efficiency.

Level 0 (Striping) — Use multiple disks, spread out data. Disks can seek/transfer data concurrently. No redundancy → no fault tolerance.

Level 1 (Mirroring) — Mirror data across disks. Reads can be serviced by either disk (fast), writes update both disks in parallel (fast). Easy failure recovery.

Level 5 (Block-Level Distributed XOR) — Distributed parity information. Some potential for write concurrency. Good storage efficiency/redundancy trade-off.

DISK CACHE — Main memory **buffer** contains copy of disk sectors. Uses finite space, so need a **replacement policy** when buffer full.

LRU — Cache consists of stack of blocks, remove block in cache longest with no references. Use a stack of **pointers** instead of moving blocks around in main memory.

LFU — Replace block that has experienced fewest references. **Counter** associated with each block, incremented each time block accessed.

Frequency-Based — Divide LRU stack into new/old sections. Block referenced → move to top of stack. Only increment reference count if not already in *new*. Replace block with lowest count in *old*.
To prevent blocks "aging out" too quickly, could use three sections and still only replace blocks from *old*.

FILE SYSTEMS — we want:

Long term, nonvolatile, online **storage**. **Sharing** of information/software. **Concurrent access** to shared data. **Organisation** and management of data.

File — **named** collection of data of arbitrary size. Named with an extension based off what type of file they are.

File User Functions — *Create, Delete, Open, Close, Read, Write, Reposition/Seek, Truncate, Rename, Read attributes, Write attributes.*

File System Support Functions — Logical name to physical disk address translation, Management of disk space, File locking for exclusive access, Performance optimisation, Protection against system failure, Security.

File attributes may be held within given directory system — **basic** information (name/type/org/creator), **address** information (volume/start address/size used/size allocated), **access control** information (owner/authentication/permitted actions), **usage** information (creation timestamp/last modified/last read/last archived/expiry date/access activity counts).

File attributes can be accessed with the *stat* syscall. Returns information about specified file in *struct stat*.

ORGANISATION

Dynamic space management — space allocated in blocks as file size natural variable. Large block size wastes space for small files but small block size wastes space for large files. Various methods for accessing blocks.

Contiguous File Allocation — Place file data at contiguous addresses on storage device. Successive logical records physically adjacent. Can lead to external fragmentation, poor performance if files grow/shrink over time.

Block Linkage (Chaining) — Chain must be searched from beginning to locate data block. Wastes pointer space in each block. Insertion/deletion by modifying pointer in previous block. Large block sizes result in internal fragmentation. Small block sizes — data spread across multiple blocks, poor performance due to many seeks.

Block Allocation Table stores pointers to file blocks. **File Allocation Table** stored on disk, cached in memory for performance. Reduces number of lengthy seeks to access given record (but files become fragmented).

Each file has 1+ **index block** — contains list of pointers that point to file data blocks. May chain by reserving last few entries to store pointers to more index blocks. Searching may take place in the blocks themselves; if they are near corresponding data blocks → quick access to data.

Inodes are index blocks. On file *open*, OS opens **inode table**, structured as an inode on disk but including device number, inode number, no. processes with opened file, major/minor device number.

Use a **free list** — linked list of locations of free blocks — to manage storage device's free space. Low overhead to perform maintenance operations, files likely to be allocated in non-contiguous blocks.
Bitmap contains one bit in memory for each disk block, indicating whether in use. Can quickly determine available **contiguous** blocks at certain locations, but, unlike free list, may need to search entire bitmap to find free block.

Boot block	**LAYOUT** — Fixed disk layout with inodes — **superblock** contains crucial info about FS.
Super block	
Inode bitmap	**Directory** maps symbolic file names to logical disk locations.
Free block bitmap	In **hierarchical file system**, */root* indicates where on disk root directory begins, points to various directories. File names only need to be unique within given directory.
Data and inode blocks	File names usually given as a **path** from root directory to file (**absolute pathnames**).

Relative pathnames based off current working directory.

Directory Operations — *Open/Close, Search, Create/Delete, Link/Unlink, Change directory, List, Read/Write attributes, Mount.*

LINK — reference to directory/file in another part of FS. **Hard link** references address, **symbolic** (soft) **link** references full pathname.

MOUNT operation combines multiple FSs into one namespace, allows reference from single root dir. **Mount point** is the dir in native FS assigned to root of mounted FS. FSs manage mounted dirs with **mount tables**.

EXT2FS is a high-performance, robust FS with support for advanced features. Blocks are 1024/2048/4096/8192 bytes, with 5% of blocks reserved for root.

ext2 inode represents files/dirs. Provides fast access to small files, while supporting very large files.

Block groups are clusters of contiguous blocks — FS attempts to store related data in same block group to reduce seek time.