The Operating System Machine Level

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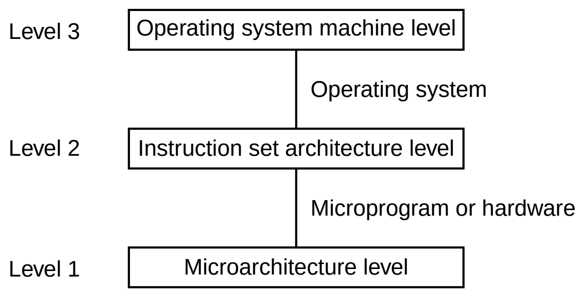
The Operating System Machine (OSM)

The OSM is implemented by the operating system.

- Operating System (OS):
  - Program that adds new instructions and features to the ISA.
    - The new instructions are called system calls.
  - Implemented in software but can be also considered as a (virtual) machine.
    - OS is an interpreter for a system call.



Instruction set available to application programmers.

Operating System Services

An OS provides important services to the application programmer.

- Process control:
  - Let a processor “simultaneously” execute multiple processes.
- Memory control:
  - Let machine appear to have more memory than it actually has.
- File control:
  - Pretend that files are linear sequences of bytes.

Prominent examples are Unix/Linux and Windows NT/2000/XP.

Process Control

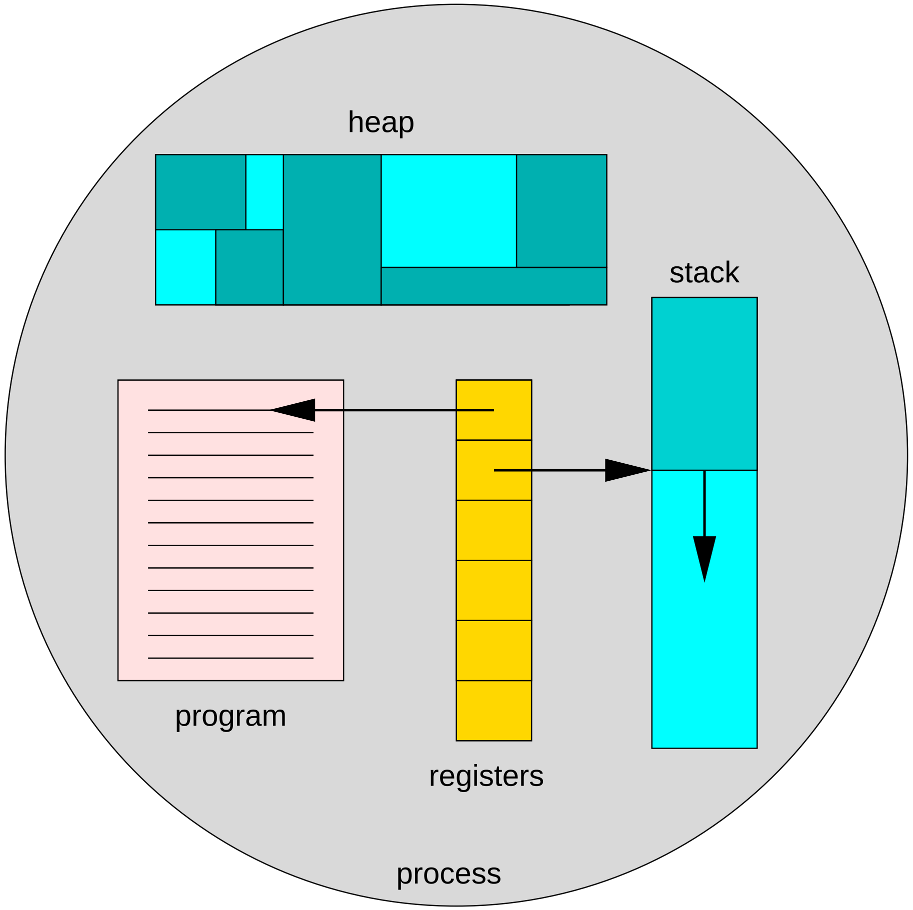
Processes

A process is an application program in execution.

- When the user starts a program, a new process is created.
  - The operation system manages process execution.
- Process consists of various components:
  - executable code loaded from disk into memory,
  - the stack, a memory are where program data are located,
  - the heap, a memory area where the program may allocate additional data space,
  - the (contents of the) program registers including the program counter and a stack pointer,
  - other information such as user privileges.

Windows: CTRL-ALT-DEL ⇒ task manager.

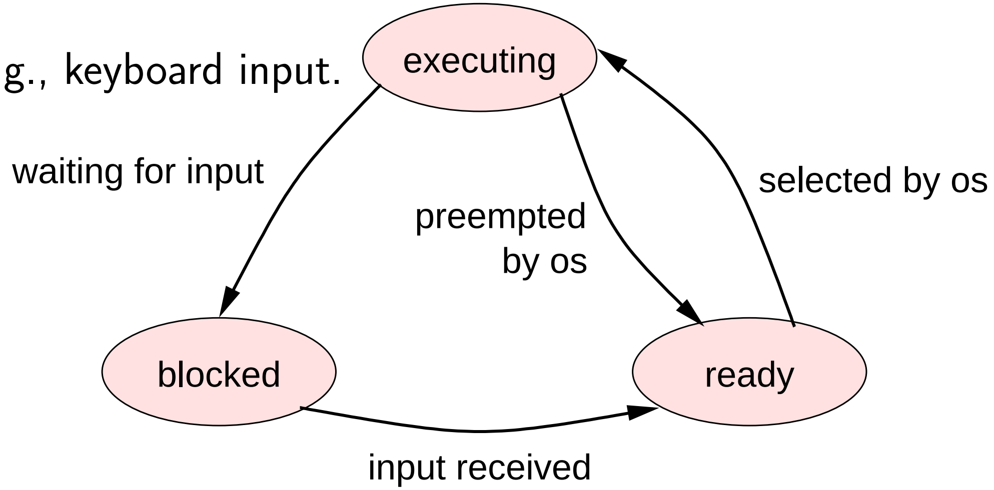
Process



Process Scheduling

Process may be in one of three states:

- Executing:
  - The processor executes instructions of this process.
- Ready:
  - The process is ready for execution but the processor executes instructions of another process.
- Blocked:
  - The process waits for some event, e.g., keyboard input.

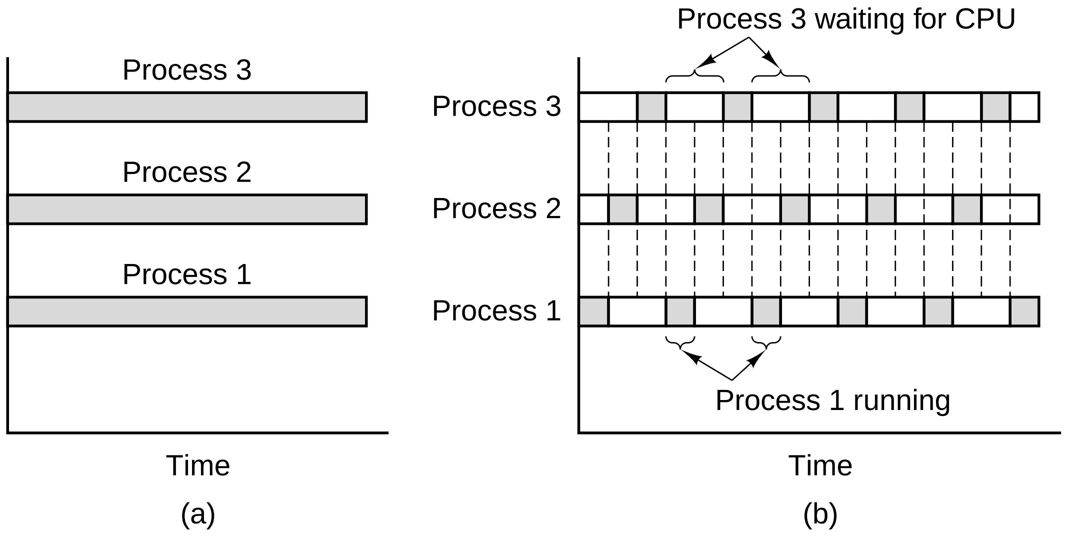


Process Management

- At any time, the OS holds a pool of ready processes.
  - At most one process is executing.
- Preemptive Scheduling:
  - Executing process receives a certain time slice.
  - After the time slice has expired, OS preempts process.
  - Process is put into ready pool, another ready process is scheduled for execution.
  - Rapid switching (say every 50 ms) creates the illusion that processes are simultaneously active.
- To request an OS service, a process performs a system call (trap):
  - Special processor instruction that gives control to the OS.
  - OS takes data from registers and determines which service to perform (e.g. output).
  - OS invokes system service that interacts with hardware device.
  - OS returns control to application.

Multi-Processing

The OS schedules the CPU among multiple processes.



Multi-processing: multiple processes may run at the "same" time.

Memory Control

Virtual Memory

Program may need more memory than computer has.

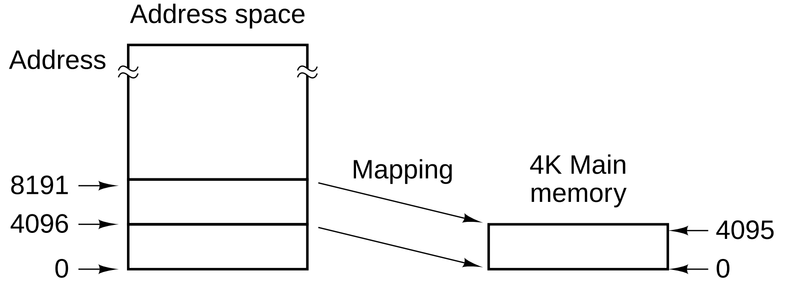
- Tradition solution was the use of overlays.
  - Programmer divided a program into a number of overlays (pieces).
  - Overlays could be stored on secondary memory (disks).
  - Only one overlay was in computer memory at a time.
- Programmer was in charge for managing the overlays.
  - Reading overlays from disk to memory, writing overlays from memory to disk.
  - Difficult and error-prone task.
- Still used in the 1990s for DOS/Windows 3.x programs.

Virtual memory emerged from the automation of overlay management.

Address Spaces

Idea: separate the address space from physical memory locations.

- Virtual address space.
  - Set of addresses to which program can refer.
  - Size depends on needs of program.
- Physical address space.
  - Set of adddresses where data can be stored.
  - Size restricted by cost of hardware.
- Pages: blocks of addresses of fixes size.
  - E.g. 4096 bytes: page 0–4095, page 4096–8191, page 8192–12287, . . .
  - Virtual address space is organized in pages.



Virtual addresses are mapped to physical addresses.

Pages and Page Frames

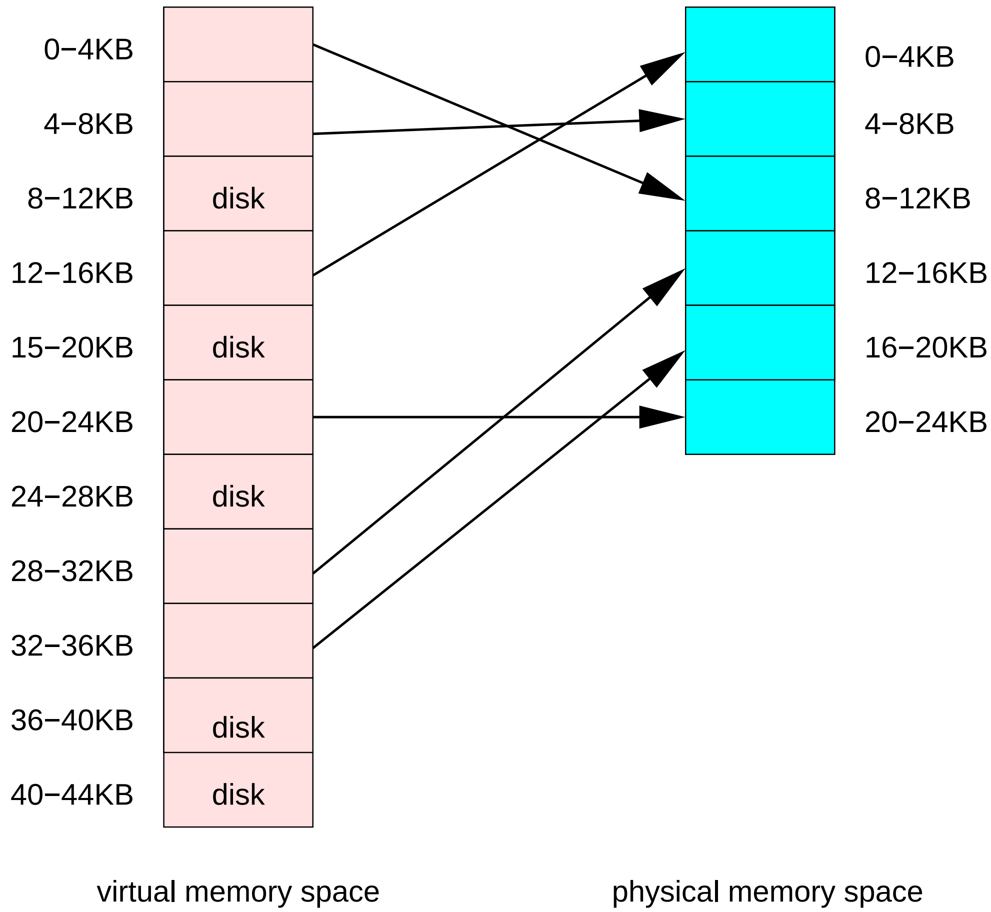
Physical memory has frames that can hold virtual memory pages.

Page	Virtual addresses
≈	≈
15	61440 – 65535
14	57344 – 61439
13	53248 – 57343
12	49152 – 53247
11	45056 – 49151
10	40960 – 45055
9	36864 – 40959
8	32768 – 36863
7	28672 – 32767
6	24576 – 28671
5	20480 – 24575
4	16384 – 20479
3	12288 – 16383
2	8192 – 12287
1	4096 – 8191
0	0 – 4095

Bottom 32K of main memory

Page frame	Physical addresses
7	28672 – 32767
6	24576 – 28671
5	20480 – 24575
4	16384 – 20479
3	12288 – 16383
2	8192 – 12287
1	4096 – 8191
0	0 – 4095

Page Table


0−4KB
4−8KB
8−12KB
12−16KB
15−20KB
20−24KB
24−28KB
28−32KB
32−36KB
36−40KB
40−44KB
disk
disk
disk
disk
disk
0−4KB
4−8KB
8−12KB
12−16KB
16−20KB
20−24KB
virtual memory space
physical memory space

Example

- Program needs 16 KB memory with addresses 0–16383 ($=2^{14}-1$).

Virtual Address	Physical Address
0	65536
4096	61440
8192	32768
12288	4096

- Page table maps page at address 4096 to physical address 61440.
- Process references memory word at virtual address 4201.
- Memory management unit looks up table and computes:
  - $(4201 - 4096) + 61440 = 105 + 61440 = 61545$
- Physical address 61545 is sent via system bus to main memory.

Paging Summary

The virtual address space is much larger than the physical space.

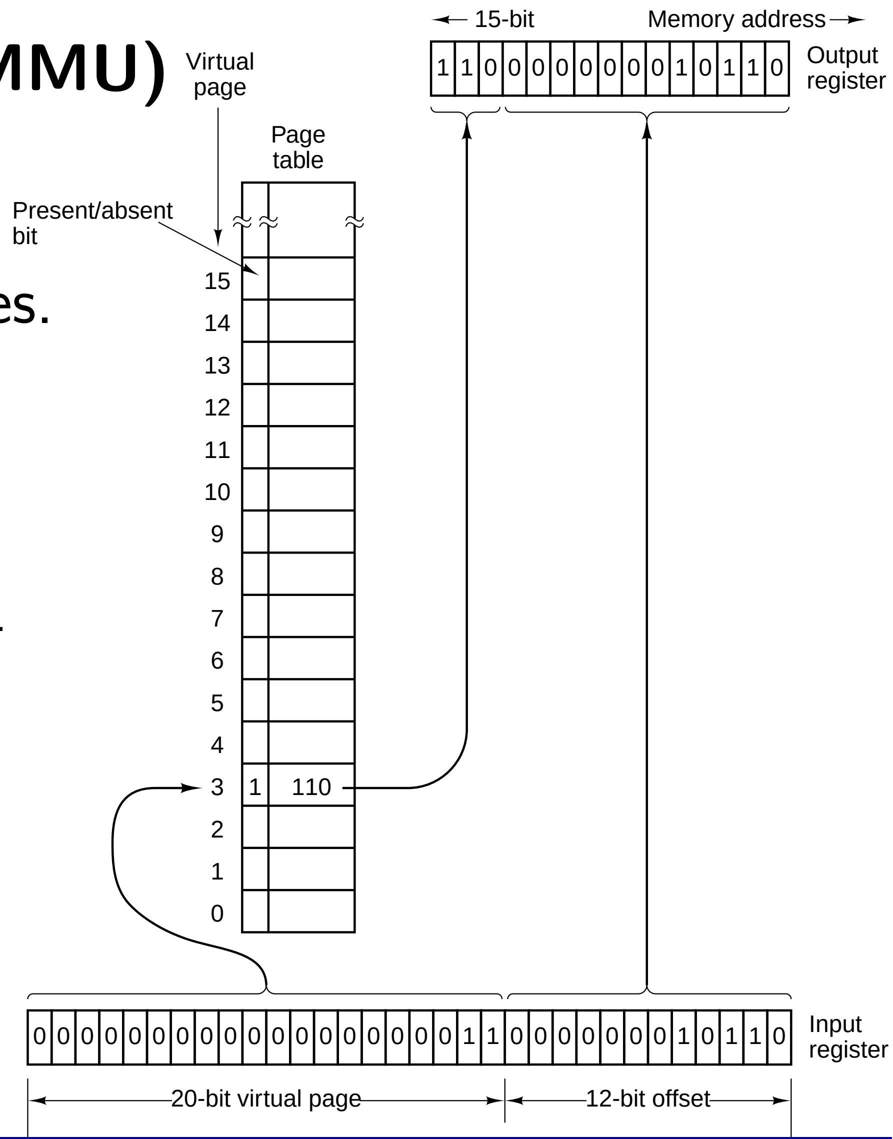
- Program may refer to virtual address not in memory.
  - Trap is generated that interrupts normal program execution.
  - Page currently loaded in main memory is saved to disk.
  - Referenced page is loaded from disk into main memory.
  - Address map is changed to map virtual page to main memory page.
  - Program execution continues in the normal way.
- Programs may assume arbitarily large virtual address space.
  - Pages are automatically loaded/stored from/to disk.
  - Transparency: programs need not be aware of virtual memory at all.

Paging frees program writers from memory constraints.

Memory Management Unit (MMU)

Chip for address translation.

- Maps virtual to physical addresses.
  - Virtual: 32 bit.
  - Physical: 15 bit (e.g.).
- Virtual address is decomposed.
  - Virtual address = virtual page : page offset.
  - Page size: 4096 bytes (e.g.)
  - 12 bit page offsets ($2^{12} = 4096$).
  - 20 bit virtual page ($32 - 12 = 20$).
- Page table gives page address:
  - Indexed by virtual page.
  - Gives higher order bits for physical address.

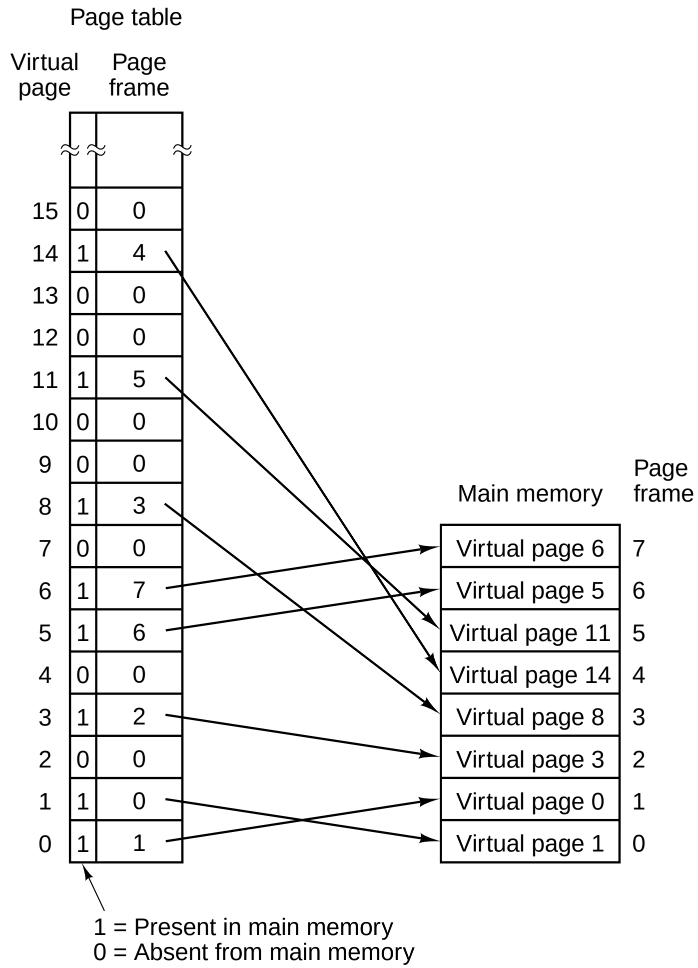


MMU Mapping

Not all pages are in memory.

- Presence/absence bit.
  - Tells which table entries are in memory.
  - Other entries are located on disk.

One-to-one mapping of present pages to page frames.



Demand Paging

When a referenced page is not in memory, a page fault occurs.

- OS must handle page fault.
  - Read required page from disk.
  - Enter its physical memory location in the page table.
  - Repeat the instruction that caused the fault.
- Initially: no page in memory.
  - All present bits are set to 0.
  - When CPU tries to fetch instruction, first page is loaded.
  - If program refers to other pages, these pages are also loaded.
  - The set of pages required by the program (its working set) is eventually loaded.

Pages are only loaded by page faults (i.e., on demand).

Page Replacement

For each page to be loaded, another one must be stored on disk.

- A page replacement policy is needed.
  - Algorithm that tries to predict which page in memory is least useful.
    - Its absence would have the smallest adverse effect on the running program.
  - Select page that is not needed for the longest time in the future.
    - Problem is that OS cannot look in the future.
- Least Recently Used (LRU) algorithm.
  - Select page that was least recently used.
  - Probability that this page is not in the program's current working set is high.
  - Nevertheless pathalogical situations may occur.

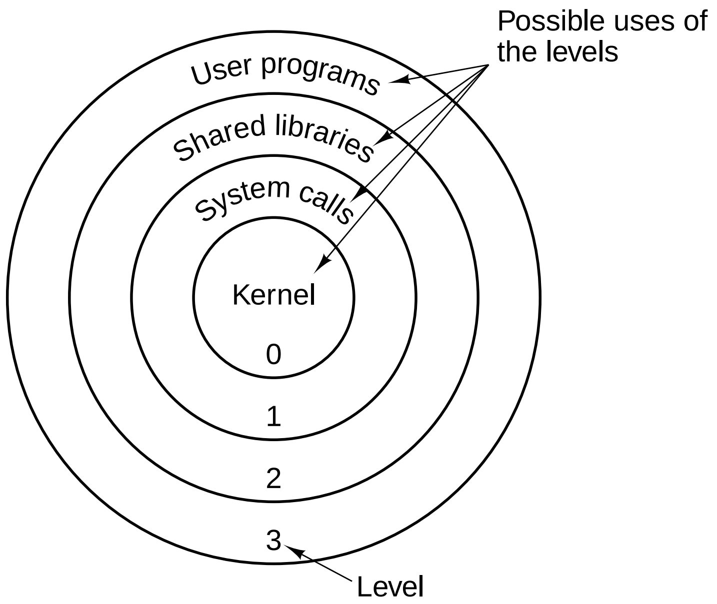
A variant of LRU is used in most operating systems.

Paging

- Paging frees applications from the limits of physical memory.
  - Virtual address space of a process may be much larger than physical address space.
  - Only the available disk space limits the size of a program.
  - Have some swap space available in your PC (e.g., 128 MB swap space for 256 MB main memory).
- But paging is slow:
  - Memory access time: 1 ns; disk access time: 10 ms.
  - Reading a page from disk is one million times slower than reading a memory cell.

Buy more memory rather than a faster processor.

Memory Protection



- At each instant, a program operates in one protection level.
  - Indicated by 2-bit field in PSW (Program Status Word) register.
  - Access to data at lower level are illegal.
    - A trap is generated.
  - Only procedures at lower levels may be called.
    - Only access to official entry points in lower level.

File Control

Files

A file is a core abstraction of the virtual I/O.

- File: sequence of bytes written to an I/O device.
  - Device may be a disk: data can be read back later.
  - Device may be a printer: data cannot be read back.
  - Further file structure is up to application programs.
- File I/O: sequence of system calls.
  1. Open a file: locate file on disk and bring into memory information necessary to access it.
  2. Read or write data from/to file.
  3. Close the file: free space used to hold file information.

OS provides abstraction from concrete hardware control.

Reading a File

Copy data from file to memory.

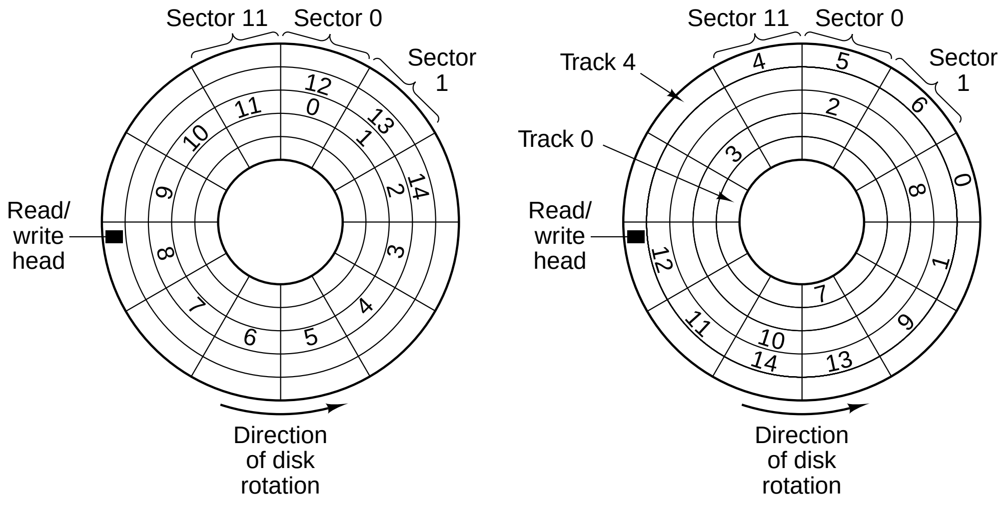
- System call `read`:
  - Indication of which (open) file is to be read.
  - Pointer to a memory buffer in which to put the data read.
  - Number of bytes to be read.
- Each open file has a pointer to the next byte position to be read.
  - `read` puts a certain number of bytes into buffer.
  - Pointer is advanced by the number of bytes read.
  - `read` returns number of bytes read.

Subsequent `read` calls read consecutive blocks of data.

File Organization

How is the space for a file organized on a disk?

- File may be organized in consecutive sectors.
  - Used for CD-ROM file systems (file size known in advance).
- File may be organized random sectors.
  - Used for hard disk file systems (file grows dynamically).



File View

OS sees file different than application programmer.

- OS sees a file as a collection of blocks on disk.
  - Application programmer sees a linear sequence of bytes.
- File index holds disk addresses of file blocks.
  - Typically organized as a list of disk block addresses.

OS maps file index information to linear byte sequence.

Free Blocks

OS must know which sectors on disk are free for allocation.

- **Free List:** a list of all “holes” on disk.
  - Position and size of each hole.
- **Bit map:** one bit per file block.
  - Bit 1 indicates that file block is in use.

Track	Sector	Number of sectors in hole
0	0	5
0	6	6
1	0	10
1	11	1
2	1	1
2	3	3
2	7	5
3	0	3
3	9	3
4	3	8

(a)

Track \ Sector	0	1	2	3	4	5	6	7	8	9	10	11
0	0	0	0	0	0	1	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	1	0
2	1	0	1	0	0	0	1	0	0	0	0	0
3	0	0	0	1	1	1	1	1	1	0	0	0
4	1	1	1	0	0	0	0	0	0	0	0	1

(b)

Block Sizes

How large should a file block be?

- Advantage of larger file blocks:
  - About 10 ms needed to seek file block.
  - Reading 1KB block takes about 0.125 ms, reading 8 KB block takes about 1 ms.
  - It is much better to read 8 KB at once than 8 times 1 KB.
- Advantage of smaller file blocks:
  - Mininimum file size is 1 block.
  - Also for larger files, half of the space of the last block is wasted in average.
  - If files are small, much disk space may be wasted.

Today, larger blocks are used, because transfer efficiency is critical.

Directory Management

Files are grouped in directories.

- Various system calls:
  - Create a file and enter it in a directory.
  - Delete a file from a directory.
  - Rename a file.
  - Change protection status of a file.
- Directory itself is a file.
  - May be listed in another directory.
  - Tree of directories emerges.

File 0
File 1
File 2
File 3
File 4
File 5
File 6
File 7
File 8
File 9
File 10

File name:	Rubber-ducky	
Length:	1840	
Type:	Anatidae dataram	
Creation date:	March 16, 1066	
Last access:	September 1, 1492	
Last change:	July 4, 1776	
Total accesses:	144	
Block 0:	Track 4	Sector 6
Block 1:	Track 19	Sector 9
Block 2:	Track 11	Sector 2
Block 3:	Track 77	Sector 0

Directory may keep various pieces of data on a file.

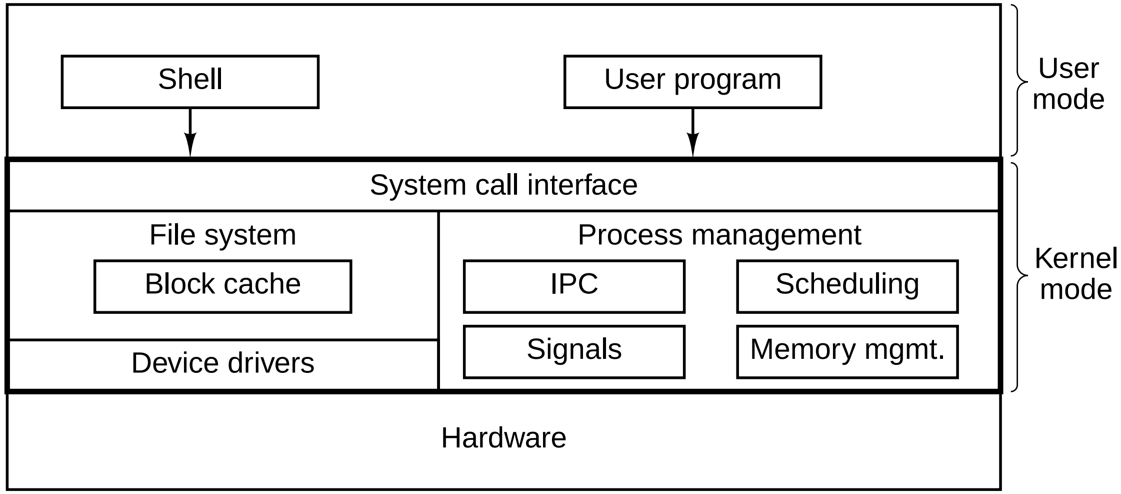
Example: Unix

Unix

- 1970: Ken Thompson, Dennies Ritchie at the AT&T Bell Labs.
  - Written for the PDP-7 in assembler; new version for the PDP-11 in C.
  - 1974 landmark paper in the Communications of the ACM.
- BSD Unix (Berkeley System Distribution).
  - Unix version by the University of California at Berkeley.
  - Inclusion of the TCP/IP protocol (later chosen for the Internet).
- 1984: System V Unix by AT&T.
  - Split in the Unix world between BSD and System V.
- IEEE P1003 standard: POSIX (Portable Operating System-IX).
  - Supported (and extended) by all Unix systems including Linux.
- 1990s: Linux (Linus Torvalds and many others)
  - Based on the GNU environment (Richard Stallman and many others).

Unix Architecture

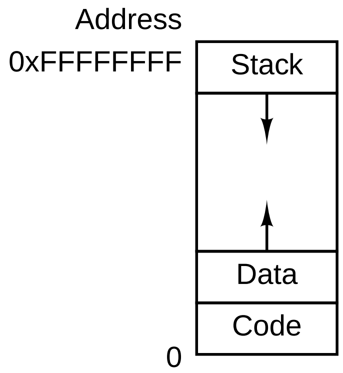
Small kernel with a modular layer of device drivers at the bottom.



GUIs (X-Windows based KDE or GNOME) operate in user mode.

Unix Virtual Memory

Linear address space (no segments) divided in three parts.



- Entire address space is paged.
  - Program may be larger than machine's physical memory.
  - (Portions of) files may be mapped into the address space.
    - Memory-mapped files may be used for inter-process communication.

Unix Virtual I/O

A file is a linear sequence of bytes.

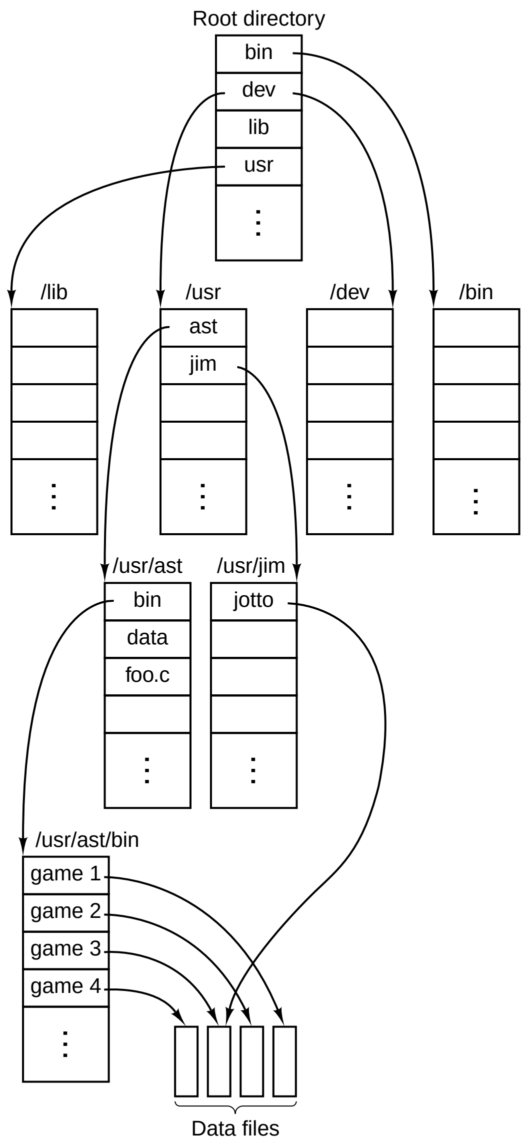
```
/* open the files */
in = open("infile", 0);
out = creat("outfile", PROTECTION);

/* copy data from one file to the other */
do {
  count = read(in, buffer, BSIZE);
  if (count > 0) write(out, buffer, count);
} while (count > 0);

/* close the files */
close(in);
close(out);
```

Unix Directory System

All disks are mounted in a single directory hierarchy.

- All files can be reached from the root:
  - An absolute path lists all directories from root to a file.

    /usr/jim/jotto
  - A relative path lists all directories from the working directory of a process.
    - Process working directory is /usr/ast.
    - Relative path bin/game3.
  - A file may be linked to another file.
    - Both paths /usr/ast/bin/game3 and /usr/jim/jotto refer to the same file.



Unix File Systems

To each file, a 64-byte i-node is associated.

- I-node (index node).
  - File type and protection, number of links to the file, owner's identity and group, file length.
  - The time the file was last read and written; the time the i-node was last changed.
  - 13 disk addresses.
    - The first 10 addresses point to data blocks.
    - Remaining addresses point to indirect blocks (blocks that point to data blocks or other indirect blocks: double indirect and triple indirect blocks).
- I-nodes are located at the beginning of the file system.
  - Given an i-node number, the i-node can be located.

Directory entries consist of file names and i-node numbers.

Unix Process Management

Unix supports multiple processes and multiple threads within a process.

- Processes:
  - A process can create a replica of itself (`fork`).
  - Both processes have separate address spaces.
  - The newly created child process can replace its program by any other program (`exec`).
  - Processes may communicate respectively synchronize via signals, pipes, semaphores, messages, shared memory.
- Threads:
  - Within a process, multiple threads (light-weight processes) may execute.
  - Threads share the data space of the process.
  - Threads within a process can communicate via shared variables and synchronize via mutexes and condition variables.