Introduction to Operating Systems

David Marchant
Based on slides by Troels Henriksen

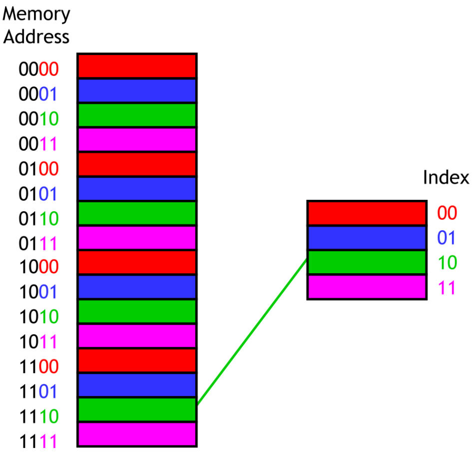
2022-09-27

Incorporating material by Mathias Payer
(`https://github.com/HexHive/OSTEP-slides`).

A bit more on cache

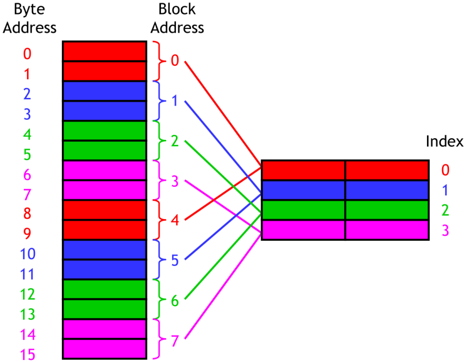
- Got a lot of questions so I don't think I explained this very well...
- Blocks vs bytes vs lines
- What are tags and how are the derived.
- Note that some confusion seems to come from the distinction between direct-mapped cache (shown in the book), fully associative mapping (most online examples), and set-associative mapping (the last lecture)
- Time was limited on adding these slides so pics shamelessly taken from: https://courses.cs.washington.edu/courses/cse378/09wi/lectures/lec15.pdf

Direct Mapping



- Each memory address maps to one cache block.
- Least significant bits of the address gives us the *tag* in the cache.
- Gives rise to conflict misses if we keep using say memory address 0000, 1000, 0000, 1000.
- But its quick and easy to implement (the quick is often the enemy of the good).

Block sizes



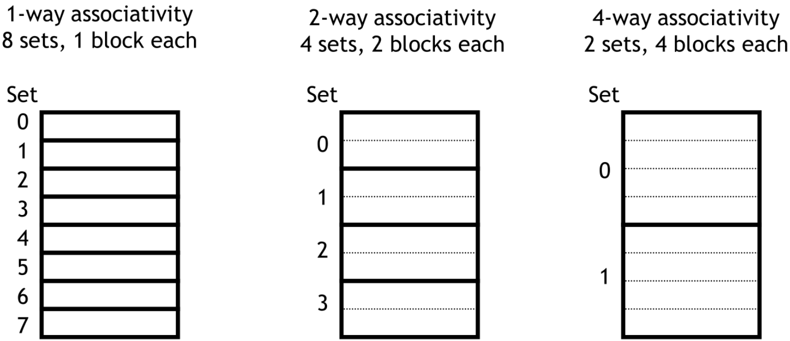
- We always store more than a single byte at a time in practice.
- Typically 4-32 KiBs, though this can differ by hardware.
- If we only stored single bytes, then spatial locality would mean nothing...
- Most examples present as though only a single byte for space/simplicity.
- Note the distinction between the memory address and the block address.

Fully associative Mapping

- Lets remove conflict misses by saying any block can be stored anywhere in cache.
- But now there's no clever indexing or tagging, so the entire memory address must be used as the tag.
- And we also now have to check the tag of every cache entirely
- This makes it very expensive to implement (both in hardware and clock cycles)
- So we don't tend to use it (hence no picture)

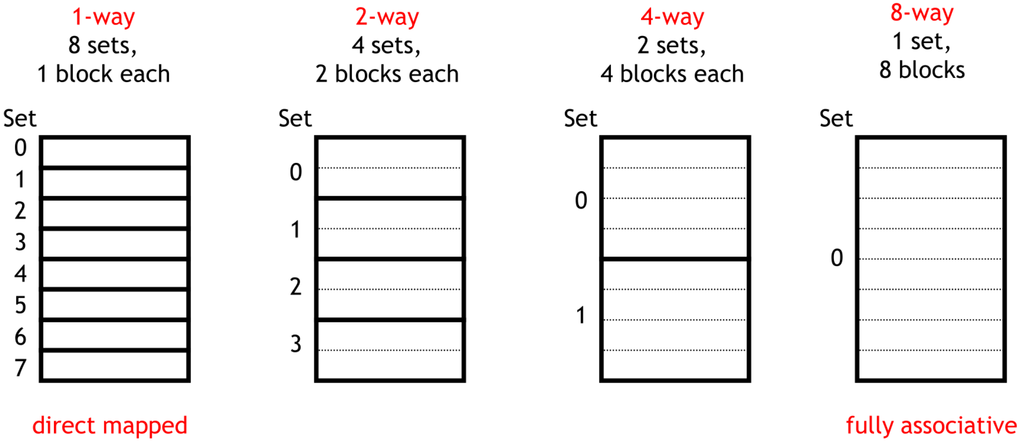
Set-associative Mapping

- Combination of direct and fully associative
- We group blocks into *sets*
- Each memory address maps to exactly one cache set, but can be placed in any block within the set
- Can be organised multiple ways.



Everything is Sets

Depending on how many sets we use, we can actually create anything from direct mapping to fully associative caches



Addressing within Sets

- Note this differs from the explanation in the book pg 400 (direct mapping).
- Look to pg 420 instead.

When $S = 2^n$, $B = 2^m$ we can easily split a w-bit address into *fields*, writing x_i for bit i.

$$\underbrace{x_{w-1} \cdots x_{m+n+1}}_{\text{tag}}\ \underbrace{x_{m+n} \cdots x_m}_{\text{set index}}\ \underbrace{x_{m-1} \cdots x_0}_{\text{block offset}}$$

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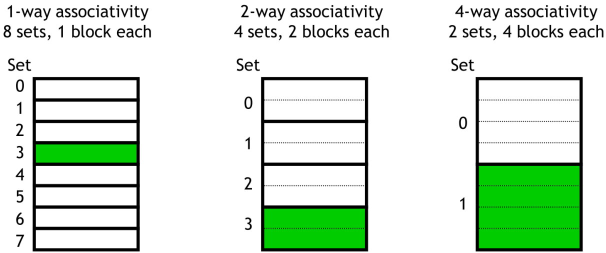
- Lets work out where we might cache something stored at memory address 6195
- 6195 in binary is 00...0110000110011
- The offest is used to find a byte within the block, so must address all bytes in a block
- Assuming each block has 16 bytes, the lowest 4 bits are the offset
- Note only 16 bytes would be low for a real world example.

Addressing within Sets

- 6195 in binary is 00...0110000110011
- Now determining our set index depends on how many sets we have in our cache
  - For 1-way associative cache, the next 3 bits (011) are the set index.
  - For 2-way associative cache, the next 2 bits (11) are the set index.
  - For 4-way associative cache, the next bit (1) is the set index.
- Whatever is left is used as the tag to identify the block within the set (see previous lecture)



A Written Example (Hint hint)

Problem:
A computer uses 32-bit byte addressing. The computer uses a 2-way associative cache with a capacity of 32KB. Each cache block contains 16 bytes. Calculate the number of bits in the TAG, SET, and OFFSET fields of a main memory address.

A Written Example (Hint hint)

Problem:
A computer uses 32-bit byte addressing. The computer uses a 2-way associative cache with a capacity of 32KB. Each cache block contains 16 bytes. Calculate the number of bits in the TAG, SET, and OFFSET fields of a main memory address.
Solution:
Since there are 16 bytes in a cache block, the OFFSET field must contain 4 bits (24 = 16). To determine the number of bits in the SET field, we need to determine the number of sets. Each set contains 2 cache blocks (2-way associative) so a set contains 32 bytes. There are 32KB bytes in the entire cache, so there are 32KB/32B = 1K sets. Thus the set field contains 10 bits (210 = 1K).
Finally, the TAG field contains the remaining 18 bits (32 - 4 - 10). Thus a main memory address is decomposed as shown below.

TAG = 18 bits	SET = 10 bits	OFFSET = 4 bits

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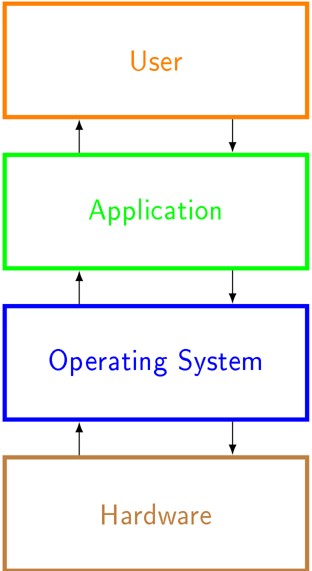
What is an operating system?



OS is middleware between applications and hardware.

- Provides standardized interface to resources.
- Manages hardware.
- Orchestrates currently executing processes.
- Responds to resource access requests.
- Handles access control.

Why study operating systems?

Inspirational

- One of the most potent *abstractions* in computing.
  - Each process thinks it has machine to iself.
  - Controlled communication.
  - Abstracts over hardware differences.

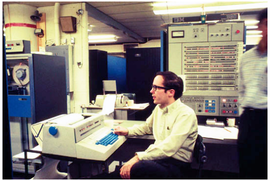
Practical

- You almost always use an operating system.
- Its performance characteristics are important to understand.
- It often determines what is fundamentally possible.

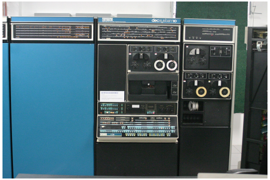
They are where the magic happens.

In the old days

Each brand of machine would have its own operating system.



IBM System/360 running OS/360 (man not part of computer)

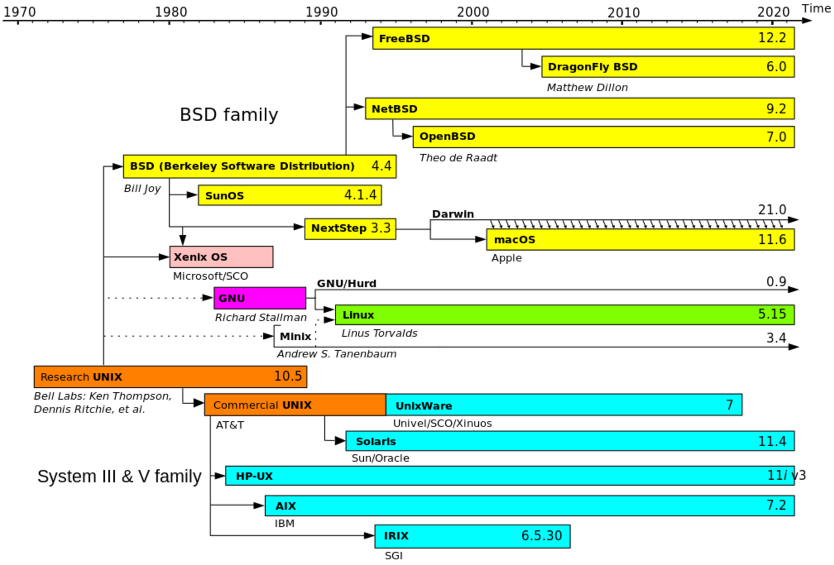


DEC PDP-10 running TENEX

VAX 11/780 running VMS

- PDP-11 running early UNIX, written in C.
- Developed at AT&T, who were banned from selling UNIX.
- Shared it (almost) freely with others, who *ported* UNIX to every machine under the sun.
- Unix was *popular*, *good enough*, and *cheap*.

Unix lifetime



What is Unix

What?

- Unix is a family of operating systems derived from original UNIX developed in the 1970s by Ken Thompson and Dennis Ritchie.
- Most modern operating systems are heavily influenced by Unix (even Windows).
- Many operating systems are *direct descendants*: Linux, iOS, macOS, the BSDs, etc.

Why?

- We teach Unix because it is *simple* and *representative* of modern systems.
- We use Unix designs for all examples.
- ...does not mean Unix is always *good* design.

The purpose of operating systems

Kernel and Processes

System calls

Process management in Unix

Main takeaways

More than one process

- So far we've made strictly *sequential* code that does one thing after another until it is done.
- This is a useful (and not inaccurate) concept for how our programs run.
- But is also not entirely true...

More than one process

- So far we've made strictly *sequential* code that does one thing after another until it is done.
- This is a useful (and not inaccurate) concept for how our programs run.
- But is also not entirely true...
- Modern computers run many processes at once, to manage different devices and services.
- If all processes ran entirely sequentially then we'd have to wait for the clock to finish before we could browse the internet
- A key abstraction the OS provides us is the concept of a process, to allow different sequential systems to be interleved.

Processes contra programs

Program: is a file containing code. Stateless and **dead**.

Process: a running *instance* of a program. The same program can be running in multiple instances. Stateful and **alive**.

They are not the same thing, although we informally often say *program* when we really mean *process*.

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- Operating systems manage *processes*.
  - Switching between multiple *concurrent* processes.
  - Handling process termination.
  - Starting new processes (perhaps from a given *program file*).

The kernel

- Technically, *operating systems* encompass lots of parts: shell, GUI, C library, maybe bundled applications (mail reader etc).
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Kernel

Always-resident code that services requests from the hardware and manages processes.
It is not a process.

- The kernel uses the same CPU, memory, and other hardware as ordinary code.
- When running process code, the CPU is in *unprivileged state*, and many operations are restricted (e.g. access to hardware devices).
  - When an *interrupt* happens, the CPU switches to *privileged state* and jumps to kernel code, which handles it and then resumes the previously running process.
    - Think of it like a sudden and unplanned procedure call.
  - Interrupts can be outside events (keyboard press, network traffic) or special instructions (invalid memory accesses, *system calls*).

Virtualising the CPU

Goal Give each process the illusion of exclusive CPU access.

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Solution: **context switching**

- Only one process gets to run at a time.
- ...but we regularly switch between available processes.
- Doing this often and rapidly creates the illusion of simultaneous execution.

Context switching

Intuition Pausing a process, saving its entire *state*, then resuming some other process based on its saved state.

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So when do we do this?

- Regular *timer interrupts* transfer control to the kernel, whose *scheduler* decides the next process to run.
  - Scheduling is a big and interesting topic that we don't have time to go into.

We've seen this before...

- Recall from our time with Assembler we discussed procedures
- In that context we presented the shift in control as between different function calls
- The same principle applies here, control is shifted from one process to another, though *usually* lacks a direct communication between them.
- But the same principle applies, memory must be saved and maintainted between switches.
- But in this context, EVERYTHING must be saved.

System calls

- Only the kernel has direct access to hardware and system memory.
- Whenever we want to do IO we have to perform a *system call*.

System calls

A request by a process that the kernel carries out some operation on its behalf.

- Much like a function call, but implemented very differently.

System calls in RISC-V

- The `ecall` (*environment call*) instruction transfers control to the kernel.
  - Kernel then inspects registers (mostly `a0-a7`) to see what it has been asked to do.
  - Specific interpretation varies between operating systems.
  - System call identified by a number.

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In RARS

`https://github.com/TheThirdOne/rars/wiki/Environment-Calls`

- System call number passed in `a7`.
- Excerpt;

Human name	**Number**	**Description**	**Reads**	**Writes**
`PrintInt`	1	Prints int to console.	`a0`	
`ReadInt`	5	Reads int from console.		`a0`

How does that work?

- These system calls are both very basic, but also 'higher level' than assembly calls;
- Recall that most input/output really is just file manipulation.
- Many of these OS calls are really just shortcuts to reading or writing to certain files.

Used in A0's `io.s` (Not any more :P)

```
read_loop:
        beq     t1, t2, read_done
        li      a7, 5
        ecall                           # read int
        sw      a0, 0(t0)
        addi    t0, t0, 4               # next output addr
        addi    t1, t1, 1               # increment count
        jal     zero, read_loop
```

System calls in C

- C exposes system calls as functions.
  - Internally use `ecall` instruction or architecture-specific equivalent.
- Not observably distinct from other C functions, except typically more primitive and tedious to use.

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Example

```
// system calls
int open(const char *pathname, int flags);
ssize_t write(int fd, const void *buf, size_t count);

// stdio functions
FILE *fopen(const char *pathname, const char *mode);
size_t fwrite(const void *ptr, size_t size, size_t nmemb,
              FILE *stream);
```

File descriptors

```
int open(const char *pathname, int flags);

ssize_t write(int fd, const void *buf, size_t count);
```

- The `int` returned by `open` is a *file descriptor*.
- Has no significance in itself, but allows the kernel to recognise the open file when passed to other system calls.
  - Typically an index into some kernel-side table.
  - Such values are known as *handles*.
- Passing complex data structures or pointers between *kernel space* and *user space* is annoying and fragile, so we usually use numeric identifiers instead.

Basic principles

- Each process in Unix has a *process ID* (PID).
- Each process has a *parent*.
  - ...except the *initial process* (`init`) with PID 1.
- A process may have multiple *children*.
- Implies processes are organised as a *tree* (`pstree` command shows it).
- **Creating processes:** `fork()`.
- **Terminating current process:** `exit()`.
- **Loading program code from disk into current process:** `exec()`.
- **Waiting for a specific child to die:** `waitpid()`.
- **Getting PID of running process:** `getpid()`.

Main takeaways

- Hardware provides *mechanisms* such as interrupts, privileged/unprivileged mode, and *virtual memory* (next week).
  - Kernels implement *policy* and *abstractions* on top.
- Processes are a *purely virtual concept*—CPU has no idea what they are.
- Processes are *isolated* from each other.
- Processes can only directly interact with the outside world through *system calls*, mediated by the kernel.