Announcements

• HW 5 is out!
• Sigma-Xi Speaker: Daricia Wilkinson – “AI, Ethics, Privacy”
  • Scheuer Room: 4.30 – 5.30pm
• Research @ CS: Tomorrow
  • Wednesday, Nov. 15: SCI 199: 12.30 – 1.30pm
Last class: The Memory Hierarchy

- **Local secondary storage (disk)**
  - Larger
  - Slower
  - Cheaper per byte

- **Remote secondary storage**
  - Tapes, Web servers / Internet
  - Slower than local disk to access

- **Main memory (DRAM)**
  - ~100 cycles to access

- **Cache(s) (SRAM)**
  - ~10’s of cycles to access

- **Registers**
  - 1 cycle to access

- **On Chip Storage**
  - CPU instrs can directly access

- **Smaller**
- **Faster**
- **Costlier per byte**
A. Direct-Mapped: In exactly one place
   • Every location in memory is directly mapped to one place in the cache.
   • Easy to find data.

B. Set-Associative: In a few places.
   • A memory location can be mapped to \((2, 4, 8)\) locations in the cache.
   • Middle ground.

C. In most places, but not all.

D. “Fully associative”: Anywhere in the cache.
   • No restrictions on where memory can be placed in the cache.
   • Fewer conflict misses, more searching.
Direct-Mapped Example

• Suppose our addresses are 16 bits long.

• Our cache has 16 entries, block size of 16 bytes
  – 4 bits in address for the index
  – 4 bits in address for byte offset
  – Remaining bits (8): tag
How would the cache change if we performed the following memory operations?

Read 01000100 (Value: 5)
Read 11100010 (Value: 17)
Write 01110000 (Value: 7)
Read 10101010 (Value: 12)
Write 01101100 (Value: 2)

1. Write dirty line to memory.
2. Load new value, set it to 2, mark it dirty (write).
Associativity

• Problem: suppose we’re only using a small amount of data (e.g., 8 bytes, 4-byte block size)

• Bad luck: (both) blocks map to same cache line
  – Constantly evicting one another
  – Rest of cache is going unused!

• Associativity: allow a set blocks to be stored at the same index. Goal: reduce conflict misses.
Comparison

Direct-mapped

• Tag tells you if you found the correct data.
• Offset specifies which byte within block.
• Middle bits (index) tell you which line to check.
• (+) Low complexity, fast.
• (-) Conflict misses.

N-way set associative

• Tag tells you if you found the correct data.
• Offset specifies which byte within block.
• Middle bits (set) tell you which lines to check.
• (+) Fewer conflict misses.
• (-) More complex, slower, consumes more power.
Comparison: 1024 Lines
(For the same cache size, in bytes.)

Direct-mapped
• 1024 indices (10 bits)

2-way set associative
• 512 sets (9 bits)
  – Tag larger by 1 bit

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Same capacity as previous example:
1024 rows with 1 entry vs. 512 rows with 2 entries

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Check all locations in the set, in parallel.

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Select correct value.
4-Way Set Associative Cache

Clearly, more complexity here!
Eviction

• Mechanism is the same...
  – Overwrite bits in cache line: update tag, valid, data

• Policy: choose which line in the set to evict
  – Pick a random line in set
  – Choose an invalid line first
  – Choose the least recently used block
    • Has exhibited the least locality, kick it out!
Least Recently Used (LRU)

- Intuition: if it hasn’t been used in a while, we have no reason to believe it will be used soon.

- Need extra state to keep track of LRU info.

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Least Recently Used (LRU)

• Intuition: if it hasn’t been used in a while, we have no reason to believe it will be used soon.

• Need extra state to keep track of LRU info.

• For perfect LRU info:
  – 2-way: 1 bit
  – 4-way: 8 bits
  – N-way: $N \times \log_2 N$ bits

Another reason why associativity often maxes out at 8 or 16.

These are metadata bits, not “useful” program data storage.

(Approximations make it not quite as bad.)
How would the cache change if we performed the following memory operations? (2-way set)

Read 01000100 (Value: 5)
Read 11100010 (Value: 17)
Write 01100100 (Value: 7)
Read 01000110 (Value: 5)
Write 01100000 (Value: 2)

LRU = 0 means: the left line in the set was least recently used.
LRU = 1 means: the right line in the set was least recently used.
Cache Conscious Programming

Knowing about caching and designing code around it can significantly affect performance.

(ex) 2D array accesses

```
for(i=0; i < N; i++) {
    for(j=0; j < M; j++) {
        sum += arr[i][j];
    }
}
```

Algorithmically, both $O(N \times M)$.

Is one faster than the other?
Cache Conscious Programming

Knowing about caching and designing code around it can significantly effect performance.

(ex) 2D array accesses

```
for(i=0; i < N; i++) {
    for(j=0; j < M; j++) {
        sum += arr[i][j];
    }
}
```

```
for(j=0; j < M; j++) {
    for(i=0; i < N; i++) {
        sum += arr[i][j];
    }
}
```

A. is faster.

B. is faster.

Algorithmically, both O(N * M).

Is one faster than the other?

C. Both would exhibit roughly equal performance.
Cache Conscious Programming

The first nested loop is more efficient if the cache block size is larger than a single array bucket (for arrays of basic C types, it will be).

```c
for(i=0; i < N; i++) {
    for(j=0; j < M; j++) {
        sum += arr[i][j];
    }
}
for(j=0; j < M; j++) {
    for(i=0; i < N; i++) {
        sum += arr[i][j];
    }
}
```

(ex) 1 miss every 4 buckets vs. 1 miss every bucket
Program Efficiency and Memory

• Be aware of how your program accesses data
  – Sequentially, in strides of size X, randomly, ...
  – How data is laid out in memory

• Will allow you to structure your code to run much more efficiently based on how it accesses its data

• Don’t go nuts...
  – Optimize the most important parts, ignore the rest
  – “Premature optimization is the root of all evil.” -Knuth
Amdahl’s Law

Idea: an optimization can improve total runtime at most by the fraction it contributes to total runtime

If program takes 100 secs to run, and you optimize a portion of the code that accounts for 2% of the runtime, the best your optimization can do is improve the runtime by 2 secs.

Amdahl’s Law tells us to focus our optimization efforts on the code that matters:

   Speed-up what is accounting for the largest portion of runtime to get the largest benefit. And, don’t waste time on the small stuff.
Up Next:

- Operating systems, Processes
- Virtual Memory
OS Big Picture Goals

- OS is a layer of code between user programs and hardware.

- Goal: Make life easier for users and programmers.

- How can the OS do that?
Abstraction

User / Programmer
Wants low complexity

Applications
Specific functionality

Software library
Reusable functionality

Operating system
Manage resources

Complex devices
Compute & I/O
Abstraction

User / Programmer
Wants low complexity

Applications
Specific functionality

Software library
Reusable functionality

Operating system
Manage resources

Complex devices
Compute & I/O
If you were asked to design a layer between user programs and the hardware, what might your layer provide?

- What sort of services might the programs you’ve written need?

- (Discuss with your neighbors.)
Key OS Responsibilities

1. Simplifying abstractions for programs

2. Resource allocation and/or sharing

3. Hardware gatekeeping and protection
OS: Turn undesirable into desirable

• Turn undesirable inconveniences: reality
  – Complexity of hardware
  – Single processor
  – Limited memory
Before Operating Systems

• One program executed at a time...
Why is it not ideal to have only a single program available to the hardware?

A. The hardware might run out of work to do.

B. The hardware won’t execute as quickly.

C. The hardware’s resources won’t be used as efficiently.

D. Some other reason(s). (What?)
Today: Multiprogramming

• Multiprogramming: have multiple programs available to the machine, even if you only have one CPU core that can execute them.
Multiprogramming on one core

Job 1 Running
Wait
Wait(for some resource)

Job 2 Running
Wait
Wait

Job 3 Running
Wait
Wait

Combined

CPU Time
How many programs do you think are running on a typical desktop computer?

A. 1-10
B. 20-40
C. 40-80
D. 80-160
E. 160+
Running multiple programs

More than 200 processes running on a typical desktop!

• **Benefits:** when I/O issued, CPU not needed
  – Allow another program to run
  – Requires yielding and sharing memory

• **Challenges:** what if one running program...
  – Monopolizes CPU, memory?
  – Reads/writes another’s memory?
  – Uses I/O device being used by another?
OS: Turn undesirable into desirable

- Turn undesirable inconveniences: reality
  - Complexity of hardware
  - Single processor
  - Limited memory
- Into desirable conveniences: illusions
  - Simple, easy-to-use resources
  - Multiple/unlimited number of processors
  - Large/unlimited amount of memory
Virtualization

• Rather than exposing real hardware, introduce a “virtual”, abstract notion of the resource

• Multiple virtual processors
  – By rapidly switching CPU use

• Multiple virtual memories
  – By memory partitioning and re-addressing

• Virtualized devices
  – By simplifying interfaces, and using other resources to enhance function
We’ll focus on the OS ‘kernel’

• “Operating system” has many interpretations
  – E.g., all software on machine minus applications
    (user or even limited to 3rd party)

• Our focus is the kernel
  – What’s necessary for everything else to work
  – Low-level resource control
  – Originally called the nucleus in the 60’s
The Kernel

- All programs depend on it
  - Loads and runs them
  - Exports system calls to programs
- Works closely with hardware
  - Accesses devices
  - Responds to interrupts (hardware events)
- Allocates basic resources
  - CPU time, memory space
  - Controls I/O devices: display, keyboard, disk, network
Kernel provides common functions

• Some functions useful to many programs
  – I/O device control
  – Memory allocation

• Place these functions in central place (kernel)
  – Called by programs ("system calls")
  – Or accessed in response to hardware events

• What should functions be?
  – How many programs should benefit?
  – Might kernel get too big?
OS Kernel

• **Big Design Issue:** How do we make the OS efficient, reliable, and extensible?

• **General OS Philosophy:** The design and implementation of an OS involves a constant tradeoff between simplicity and performance.

• As a general rule, strive for simplicity.
  – except when you have a strong reason to believe that you need to make a particular component complicated to achieve acceptable performance
  – *(strong reason = simulation or evaluation study)*
Main Abstraction: The Process

• Abstraction of a running program
  – “a program in execution”

• Dynamic
  – Has state, changes over time
  – Whereas a program is static

• Basic operations
  – Start/end
  – Suspend/resume
Basic Resources for Processes

• To run, process needs some basic resources:
  – CPU
    • Processing cycles (time)
    • To execute instructions
  – Memory
    • Bytes or words (space)
    • To maintain state
  – Other resources (e.g., I/O)
    • Network, disk, terminal, printer, etc.
What sort of information might the OS need to store to keep track of a running process?

• That is, what MUST an OS know about a process?

• (Discuss with your neighbors.)
Machine State of a Process

- CPU or processor context
  - PC (program counter)
  - SP (stack pointer)
  - General purpose registers

- Memory
  - Code
  - Global Variables
  - Stack of activation records / frames
  - Other (registers, memory, kernel-related state)

Must keep track of these for every running process!
Resource Sharing

**Reality**
- Multiple processes
- Small number of CPUs
- Finite memory

**Abstraction**
- Process is all alone
- Process is always running
- Process has all the memory

Diagram:
- CPU: Time
- Memory: Space
- Processes $P_1$, $P_2$, $P_3$ over time.
Resource: CPU

• Many processes, limited number of CPUs.

• Each process needs to make progress over time. Insight: processes don’t know how quickly they should be making progress.

• Illusion: every process is making progress in parallel.
Timesharing: Sharing the CPUs

- **Abstraction goal**: make every process *think* it’s running on the CPU all the time.
  - Alternatively: If a process was removed from the CPU and then given it back, it shouldn’t be able to tell

- **Reality**: put a process on CPU, let it run for a short time (~10 ms), switch to another, ... ("context switching")
How is Timesharing Implemented?

- Kernel keeps track of progress of each process
- Characterizes state of process’s progress
  - Running: actually making progress, using CPU
  - Ready: able to make progress, but not using CPU
  - Blocked: not able to make progress, can’t use CPU
- Kernel selects a ready process, lets it run
  - Eventually, the kernel gets back control
  - Selects another ready process to run, ...
Multiprogramming

• Given a running process
  – At some point, it needs a resource, e.g., I/O device
  – If resource is busy (or slow), process can’t proceed
  – “Voluntarily” gives up CPU to another process

• Mechanism: Context switching
Time Sharing / Multiprogramming

• Given a running process
  – At some point, it needs a resource, e.g., I/O device
  – If resource is busy (or slow), process can’t proceed
  – “Voluntarily” gives up CPU to another process

• Mechanism: Context switching
• Policy: CPU scheduling
Abstraction goal: make every process think it has the same memory layout.

– MUCH simpler for compiler if the stack always starts at 0xFFFFFFFF, etc.
Memory

• **Abstraction goal:** make every process think it has the same memory layout.
  – MUCH simpler for compiler if the stack always starts at 0xFFFFFFFF, etc.

• **Reality:** there’s only so much memory to go around
  – no two processes should use the same (physical) memory addresses (unless they’re sharing).

OS (with help from hardware) will keep track of who’s using each memory region.
Virtual Memory: Sharing Storage

- Like CPU cache, memory is a cache for disk.

- Processes never need to know where their memory truly is, OS translates virtual addresses into physical addresses for them.
Kernel Execution

• Great, the OS is going to somehow give us these nice abstractions.

• So...how / when should the kernel execute to make all this stuff happen?
The operating system kernel...

A. Executes as a process.

B. Is always executing, in support of other processes.

C. Should execute as little as possible.

D. More than one of the above. (Which ones?)

E. None of the above.
Process vs. Kernel

• Is the kernel itself a process?
  – No, it supports processes and devices

• OS only runs when necessary...
  – as an extension of a process making system call
  – in response to a device issuing an interrupt
Process vs. Kernel

• The kernel is the code that supports processes
  – System calls: fork ( ), exit ( ), read ( ), write ( ), ...
  – System management: context switching, scheduling, memory management
Kernel vs. Userspace: Model
Kernel vs. Userspace: Model
Kernel vs. Userspace: Model

- **Kernel**: System Calls, Context Switching, Scheduling
- **Process 1**: OS (Text, Data, Heap, Stack)
- **Process 2**: OS (Text, Data, Heap, Stack)
- **Process N**: OS (Text, Data, Heap, Stack)

Makes system call. OS accesses device, assigns resource, etc.
Kernel vs. Userspace: Model

OS has control. It will take care of process’s request, but it might take a while. It can context switch (and usually does at this point).
Kernel vs. Userspace: Model

OS returns control to a process (usually not the same one).
Kernel vs. Userspace: Model

Transition is expensive, but often necessary.
C program invoking printf() library call, which calls write() system call
Control over the CPU

• To context switch processes, kernel must get control:

1. Running process can give up control voluntarily
   – To block, call yield () to give up CPU
   – Process makes a blocking system call, e.g., read()
   – Control goes to kernel, which dispatches new process

2. CPU is forcibly taken away: preemption
How might the OS forcibly take control of a CPU?

A. Ask the user to give it the CPU.

B. Require a program to make a system call.

C. Enlist the help of a hardware device.

D. Some other means of seizing control (how?).
CPU Preemption

1. While kernel is running, set a hardware timer.

2. When timer expires, a hardware interrupt is generated. (device asking for attention)

3. Interrupt pauses process on CPU, forces control to go to OS kernel.

4. OS is free to perform a context switch.
Up next…

• How we create/manage processes.

• How we provide the illusion of the same enormous memory space for all processes.