Computer Science 432/563
Operating Systems
The College of Saint Rose
Spring 2016

Topic Notes: Introduction and Overview

Welcome to Operating Systems!

What do you think of when you talk about an operating system? ("I installed a new operating system", "Windows is my least favorite operating system", "That must be a bug in the operating system", "What operating system is on your phone?")

What do you expect to learn in a course about operating systems?

Operating system topics are always in the news – there are daily developments in the operating system world. Things change quickly. This course is partially reinvented each time around as new hardware and operating systems are in fashion, though the concepts remain the same.

Where This Fits In

You learned high-level language programming in your introductory sequence and data structures courses.

Many of you have learned about hardware and assembly language in 332, 502, or an equivalent. Those who have taken that course have a notion of how to get from circuits to CPUs and memory.

A course in compilers and/or programming languages would teach you about how high-level languages let you program the hardware in a more convenient way.

Many of the things that fit between those (compiled) high-level language programs and the hardware are topics for this course.

We want to think about what it takes to get from the basic hardware you study in computer organization courses to the multi-user systems we are used to on modern computers.

A computer system is made up of a collection of resources, such as processors, memory, disks, a keyboard, printers, and network interfaces.

The operating system attempts to regulate the use of these resources for efficiency, fairness when multiple users or processes want to use them, and safety to make sure multiple users don't interfere with each other.

We will consider the operating system from two points of view: users and systems.

To a user, the operating system provides a more convenient interface. This allows the user to log in, manipulate files and run programs in a reasonably intuitive and convenient manner. Meanwhile, it provides protection of the user's data from unauthorized access, and ensures that the user is allocated a fair share of the computer's resources.

The user would like to do things like run programs and read and write files and communicate over the network without worrying about the details of what goes on at the lower levels. The overriding theme here (as in so much of computer science) is *abstraction!*

To a system, the operating system provides safe and efficient access to the actual hardware. The operating system tries to share resources when safe to do so and restrict access when necessary.

We can think of the operating system as a big resource manager.

Examples of Problems

Many important ideas in Computer Science arise in the study of Operating Systems:

- There are 3 users, each wishing to use the computer at the same time. Each has a program that needs to run for 5 minutes. Is it better for the system to run the first to completion, then the second to completion, then the third? Should it switch among them once a minute? Once a second? Once a millisecond? After every instruction? Which makes the most efficient use of the system's resources? Which makes the users happiest? Does the answer depend on what the program is doing for those 5 minutes?
- Suppose we have two programs, one that generates output values that are used as inputs to the other. We either do not want to or cannot have the second program wait for completion of the first before it starts to work: the programs must execute concurrently. How can we manage this situation if values may be generated by the first more quickly than they can be processed by the second? Or vice versa? Or if the situation changes over time?
- Suppose we have a one-lane bridge. How can you most efficiently manage traffic across the bridge? This sounds simple enough, but the best answer is not always clear. Some ideas include: just let people take turns, have a traffic light that alternates turns, have a pair of flaggers, give one direction precedence. But there are many potential problems: what if cars come in on both sides and meet in the middle? Someone's going to have to back up. The traffic light can be pretty annoying if you're stuck at the red and you wait and wait and don't see anyone come the other way. This is an unnecessary wait.
- Suppose we have a shared printer. If multiple people want to print at the same time something has to make sure the jobs don't get intermingled.
- The one-lane bridge example is one example where a deadlock can arise. It can come up in more subtle ways. Think of this like gridlock. Everyone is waiting for someone else to do something before they can proceed. No one gets anywhere.

  In a computer system, this could be a situation where two users need exclusive access to two resources.

  A simple example is two users who need to copy tapes (or in a more modern environment, substitute any removeable media that requires a hardward device). The system has two tape drives, and a tape drive is necessarily granted to one user at a time. User 1 requests a drive and gets it. User 2 requests a drive and gets it. User 1 requests a second drive, but must wait until User 2 finishes with the one he has. User 2 requests a second drive, but must wait until User 1 finished with the one he has. Uh oh. We can think of this as two antagonistic users, but even "friendly" users may not be aware that they are holding a resource that is preventing the other resource they need from ever becoming available.

- Suppose we have a collection of processes that are cooperating on a task. They need to coordinate. We'll look in some detail at process synchronization both from the point of view of algorithms that use it and what hardware and operating system support is needed to make these kinds of programs correct and efficient.
- If you have a disk attached to the computer, and several users of the computer, how do we organize data on the disk so it
  - is convenient to write and read,
  - is organized efficiently (quick to access, not a lot of wasted space), and
  - enforces appropriate protection on the files, to make sure users can't read or worse yet modify or delete the files that belong to some other user, but preserving the ability to share data effectively when appropriate?
- Suppose we have a network of computers – like the college's public labs.

  If we have a collection of computers shared among a collection of users, how can we devise a system where the resources are efficient and easy to use, yet secure?

  An approach that works well in our lab, where the systems typically have only one user at a time – the one who is sitting in front of a given computer, might not work well in a lab where the computers are used for long, CPU intensive jobs, such as graphics rendering or scientific computation.

Most of the problems that come up are not specific to a given operating system or type of computer. In fact, many of these same problems have been evident from the eariest historical systems right up to current systems.

An interesting thing about operating systems, and in fact much of computer science, is that an important "historical example" is often no more than a few decades old.

Some of the historical examples will likely be very familiar to you. What old systems were in your childhood? Some from mine include the Commodore 64/128.

And even when you might think some of the issues that were important on your (or your parents'?) old Commodore 64 or Apple][keep coming back in your tablets and smartphones and watches or other smaller-scale special purpose computers.

The course is not about which is the best operating system (though I'll make my opinions known from time to time and you can do the same). One thing we'll see as we go is that different systems have strengths and weaknesses that make them appropriate in different situations.

When we compare approaches to a particular problem, trying to determine which approach is better, the answer will often be "it depends."

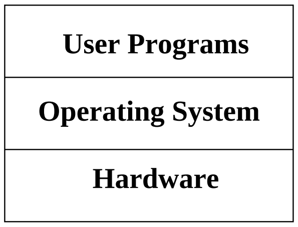
We use Unix-like operating systems as our model, but modern Windows systems have most of the same ideas underneath. Macs are really just Unix systems with a shiny user interface. Android devices run a variant of Unix. iOS devices run the XNU kernel from Darwin, which is a BSD-based Unix variant.

What is an Operating System?

One possible definition of an *operating system* (from our textbook): "a program that manages a computer's hardware."

It can be expanded just a bit to "a program that acts as an intermediary between a user of a computer and the computer hardware."

You can find similar definitions elsewhere.



The term *user* is (obviously) the person using a computer or and *user programs* are the programs being run on their behalf. It is the user program that makes use of the resources of the computer as managed by the operating system. Note that in some cases, we will think of a computer as the "user" of another computer.

At its most basic level, the operating system is a low-level program, which talks directly to computer hardware on behalf of user programs. The operating system *kernel* is the program that stays running on the computer at all times. The kernel decides what user programs can do and when they can do it, and provides facilities to make it more convenient for them to do it.

We often think of the "operating system" as including a lot more than the kernel – *system programs* and *application programs* as well. These utility programs, editors, office suites, etc., are not part of the kernel. There are also special programs called *bootstrap programs* that are loaded (from *firmware*) when the computer powers up that are responsible for loading and launching the operating system kernel. We will consider mostly things at the kernel level, but we will look at some system programs.

What is the hardware? It could be a small single-user PC, a workstation, mainframe, or a supercomputer. It will contain one or more CPUs, main memory, disk resources, and I/O devices. It could also now be something much smaller – an embedded system or a handheld computer.

Much of operating system theory focuses on large, *multiprogramming systems* – with multiple users and multiple programs with time sharing.

As desktop and portable computers have become more powerful, the issues that were formerly only the concern of larger systems have become important on the smaller scale. And issues that were formerly the concern of single-user desktops arise in tablet computers and smartphones.

We consider three main goals and functions of an operating system:

- to facilitate the use of the hardware by user programs (by providing *convenience*, *efficiency*, and *flexibility*)
- to *allocate* system resources (CPU, memory, I/O, file storage)
- to enforce *security* (controlled access to files, hardware resources, *authentication*)

These goals are often competing!

- The user of a system wants: convenience, ease of use, reliability, safety, speed (performance)
- The system (owner/adminstrator) wants: ease of design, implementation, maintenance, good resource utilization, and also flexibilty and efficiency

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Common Operating System Components

Many of these components involve all three of the goals/functions we listed.

- *Command-line interpreter (CLI)*
  - Think: UNIX command line or an MS-DOS prompt.
  - Often referred to as the *shell*.
  - A CLI provides a convenient and efficient way to access files and run programs on the system.
  - Note that a graphical windowing system is often just a way to issue the same commands without having to type their names or perhaps without even knowing what they are.
- *Process Management*
  - A "process" is a program in execution.
  - The operating system is responsible for creation, deletion, scheduling, communication of processes.
- *Main-memory Management*
  - allocation: who gets to use which memory and when.
  - protection: make sure only those processes that are supposed to have access to a certain part of memory are granted access.

- *File Management*
  - creation, deletion, reading, writing.
  - file system and directory structures.
  - mapping files to hardware: convenience, efficiency, protection are key functions of the operating system.
- *I/O System Management*
  - safe, efficient, and convenient access to the wide array of devices.
  - device driver interface.
  - buffering.
- *Secondary Storage Management*
  - storage allocation, including free space management.
  - disk scheduling: efficiency improvements.
  - caching: efficiency.
- *Networking*
  - another device to manage, but one with high-speed information flow.
- *Protection System*
  - specification and enforcement of access controls.
- *Error Detection*
  - hardware or user program errors.
  - deal with them gracefully: terminate only one program rather than the whole system if possible.
  - detect serious hardware errors.

Mechanism vs. Policy: mechanisms are provided to perform tasks, policy determines what will actually be done. Separation of mechanism from policy is an important principle. Allowing policy to be changed later allows maximum flexibility.

Some History

We take a brief look at the historical development of computer systems from the point of view of operating systems.

Very Early Systems

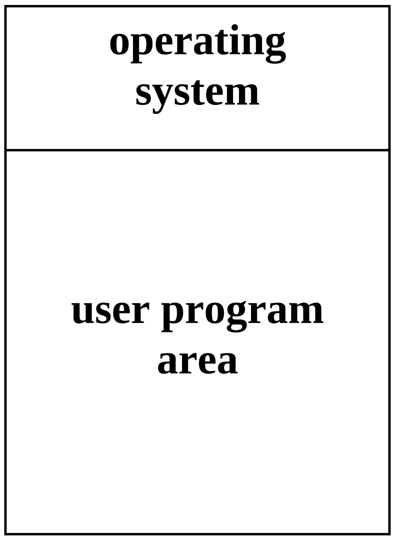
The earliest computer systems had just one user at a time, and everyone involved is an expert. A user would sign up for a block of time to go program the computer (possibly involving plugboards) and run the program.

This was obviously very expensive. The machines were huge and very expensive and they needed to sit idle all too frequently while waiting for people or card readers or other very slow things to complete their parts of the process.

Early Mainframe/Batch Systems

In these systems, there was still just one job in the system at a time. But the jobs are "batch processes" – non-interactive process. A user would need to set everything up beforehand, wait for his/her turn, at which time the program runs, and output is produced.

System memory is organized very simply:



Card Reader (input) $\longrightarrow$ Memory/CPU (computation) $\longrightarrow$ Line Printer (output)

The problem remains here in that card readers and line printers are slow – what is this expensive CPU doing while the card reader is loading a program or while the output is being printed? It's idle. Not a good utilization of resources.

With disks able to provide direct access to information, the operating system of batch computers was able to use the faster disk (in relation to the card readers and printers anyway) to *spool* upcoming jobs and output. ("Spool" means "Simultaneous Peripheral Operation On-Line"). This means that the CPU can stay busier – still better *CPU utilization*.

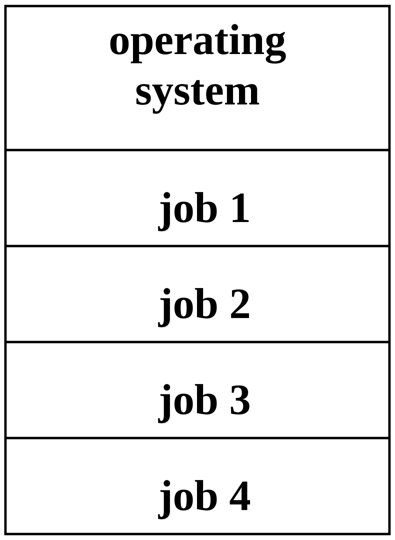
But, we still have some idle time for the CPU. Disk is much slower than the CPU, both then and today. When a job needs access to the disk (or any other I/O) while starting up, during the run, or when writing its output, the CPU is still idle or nearly idle. There's also the potential for infinite loops in programs. If some user's program goes into an infinite loop, it would probably have to be detected then stopped manually.

So we move on to...

Multiprogramming Batch Systems

Now, we have multiple jobs in the system simultaneously. The CPU can execute any job that is in memory.

To support this, system memory requires a bit more complexity in its organization:



When one job needs to access I/O or anything else that would cause the CPU to be idle, another job is selected to run while the I/O request is serviced.

This brings up some new issues that we will discuss later in the semester:

- A resident *monitor* program needs to coordinate all of this.
- Such a monitor program is **in charge**. It's allowed to do things that regular user programs can't do.
- This is the start of the dual nature of operating systems – monitor *vs.* user.
- I/O devices must be able to operate without the CPU, as the CPU would be busy with another job when I/O is taking place.
- I/O requests must be made through *system calls* – not direct to hardware. Imagine two jobs both sending lines of output to the printer any time they wanted.

  System calls have access to the hardware, whereas the user processes should not.

  The user process does not need to know or care how a system call works, just how to call it and what it's supposed to do.

To open a file, for example, a user mode program makes a system call which runs in monitor/kernel mode, which does the actual I/O.

The monitor program can then ensure safety of the I/O request as well as hand off the CPU to another job while the I/O request is processed.

- The monitor needs to choose which job to run next when one job makes an I/O request or terminates. This is *CPU scheduling*.
- The system needs to make sure that job 1 can't read or interfere with job 2's memory. *Memory management and protection.*

The dual mode operation requires some hardware support. The system needs to be able to distinguish things that users are allowed to do (*unprivileged* operations) and things that only the system can do (*privileged* operations).

This requires a *mode bit* or something similar to control whether the CPU should be allowed to perform privileged operations. The kernel needs to set this to *user mode* before calling user code and user code that needs to do anything that requires *system mode* must do so through a system call.

If a user program tries to perform a privileged instruction when in user mode, it will not be allowed – will *trap* to the operating system.

These ideas of traps and *interrupts* are very important. If a user program does something illegal (regardless of whether it is malicious) it should not crash the entire system – just "trap" to the operating system.

The operating system can do something appropriate by printing an error or killing the process, or maybe fixing a problem that caused the trap and allowing the process to continue.

The current readings look a bit more closely at interrupts, and we will look at these in more details soon.

But.. there are still significant limits...

Programs are not guaranteed to be perfect and could have infinite loops. And since the users are probably not closely watching their programs execute in a batch environment, it might not be noticed quickly.

We also would need to make sure that a severe program error (dereferencing bad pointers, division by 0, *etc.*) would halt the user program but not the entire system, as other programs would also be in progress.

But.. what about interactive processes?

Time-sharing Systems

The batch systems do not allow user interaction with the program. This is obviously not sufficient in all cases, so operating systems evolved to allow a more general *multitasking*.

Users can run *interactively* using a keyboard and a terminal display (or windowing system in a modern equivalent). A user typing at the keyboard is *much* slower than a computer.

People multitask all the time (for better or for worse). Consider for example lawyers who take multiple cases to keep themselves occupied (and racking up billable hours).

In an operating system, multitasking is accomplished by switching among user processes automatically and transparently. The goal for a CPU scheduler with interactive processes is to ensure that each interactive user gets a turn on the CPU quickly to achieve a good *response time*. We also need to be able to switch among processes quickly with an efficient *context switching* mechanism.

Such systems depend heavily on the idea of interrupts, which allow devices or the operating system to take control of the CPU even when it is executing a user process.

The considerations are similar to what happens when you multitask. How many tasks can you switch among before getting overwhelmed? Is it better to work on each for a few seconds at a time, a few minutes, or a whole day? How often do your tasks get interrupted (by texts, tweets, facebook, or emails, or even another person talking to you in person, for example)?

Many of the concepts we'll talk about this term are present in multiprogramming and time-sharing systems.

Personal Computers

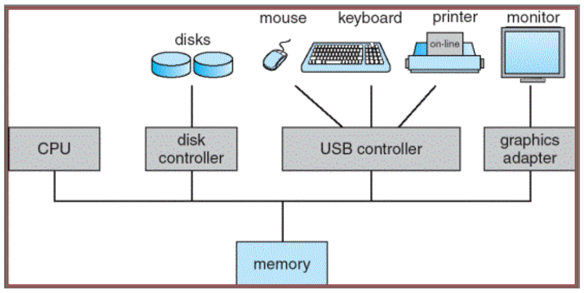
PC's appeared when computers became cheap enough that a single user to have one dedicated for his or her own use.

Such a system has different needs. CPU utilization is generally not the biggest concern, since there are no other jobs waiting to execute. User convenience and responsiveness are the top concerns. Having just one user means protection and security are not important.

As desktop computers became more and more powerful, the way people used them evolved into a *workstation* model. There are multiple processes, remote access, meaning many of the concerns originally only dealt with by multiprogrammed and time-shared systems are now addressed by PC operating systems.

In many circumstances, the user of a workstation will also make use of shared resources from a *server* (*e.g.*, additional computing power, storage, other remote data).

As many of you know (and if not, now you do), modern computers can be viewed as a collection of components connected by a bus.



This is the kind of system we will spend most of our time considering.

Parallel and Distributed Systems

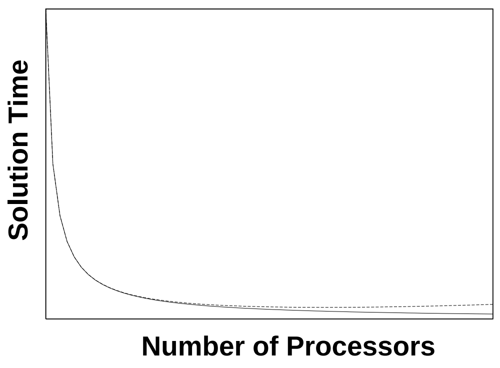
Many new issues arise when we introduce multiple CPUs. They might be in the same system, or they might be distributed across a number of systems. Or perhaps we have a whole collection of uniprocessor systems that might make sense to use or manage as a group.

Modern supercomputers can include hundreds of thousands of processors, with combinations of shared and distributed memory. Modern desktop and portable computers contain multiple `cores`, which are basically multiple CPUs from the perspective of the operating system.

Parallelism adds complexity, so why bother?

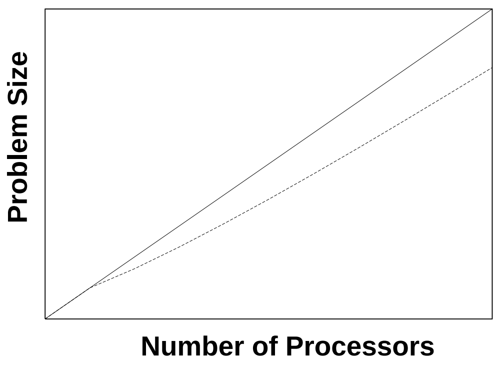
Traditionally, there are two major motivations.

Computational speedup



solve the same problem but in less time than on a single processor

Computational scaling



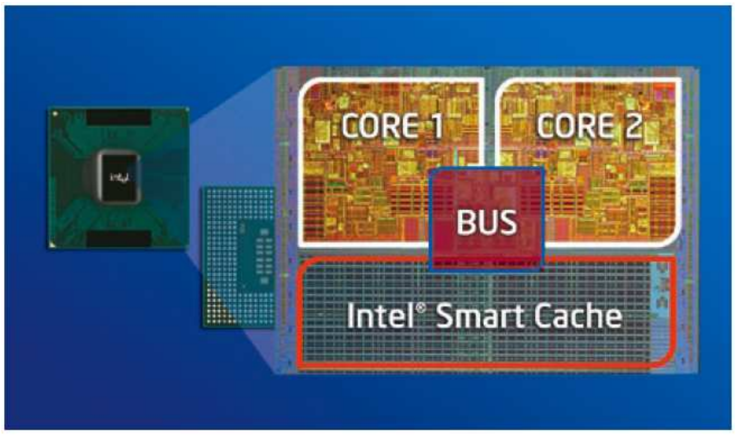
solve larger problems than could be solved *at all* on a single processor within time or space constraints

Symmetric multiprocessors (SMPs) have been common for decades in high-end workstations and servers.

Chip multiprocessors (CMPs)/multicore chips have become commonplace in the last decade or so.

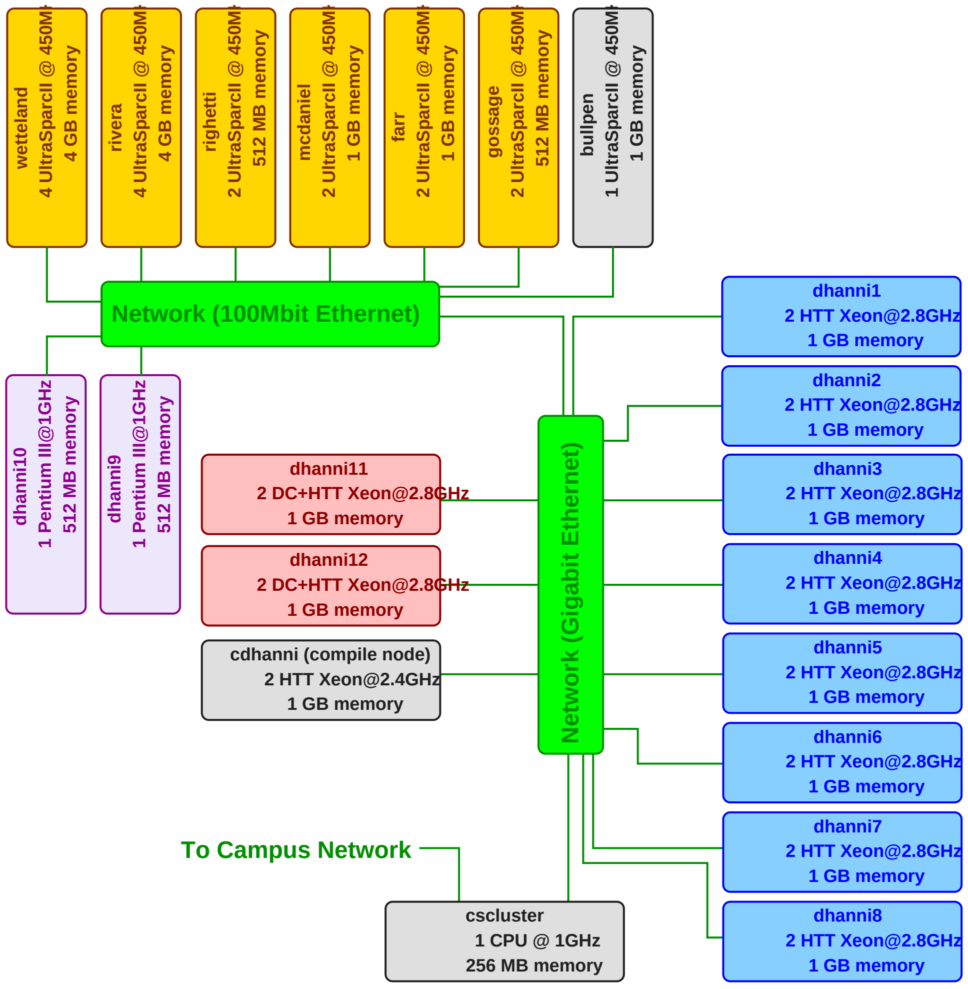
This includes most new desktops, portables, and even handhelds.

Workstations and servers may have *multiple* CMPs!



Fortunately, lots of the SMP technology developed over the years works on CMPs also: operating systems can schedule for multiple processors.

If SMP, CMP, and networked systems are combined (and they often are), the situation can become very complicated. Here is an example of a system I used in the later 2000's:



Many operating systems issues come up in such systems, and we'll talk about those throughout the semester. For example, scheduling processes among the cores within a system is more complicated than scheduling on a single core/CPU. The memory hierarchy is complicated by the fact that each core will have its own registers and might have some of its own cache (more on these terms below).

Virtualization

A very active field related to operating systems is *virtualization* and *emulation*.

The idea is not new, but the extent to which it has been used has grown significantly in recent years.

Some of the categories here:

- For emulation: a process running in an operating system on one kind of CPU runs programs intended to run on a possibly different kind of CPU by "pretending" to be that kind of CPU through interpretation of instructions.
- Operating systems running as processes within an operating system: this is what you'd be doing using Virtual Box for the first lab.
- A *virtual machine manager (VMM)* runs at the lowest level on the hardware, potentially time sharing among several guest operating system instances, each of which runs natively on the hardware. Example: mogul.

The popularity of virtualization has led to the development of *cloud computing*.

Many operating system-related issues arise in virtualized environments, and we will consider some of those.

Real-time systems

We will not focus on real-time systems, but will mention them from time to time. These are used for systems that perform tasks such as reading critical sensor values or controlling some device. The devices could range from kitchen appliance controls to Mars explorer robots.

Hard real-time systems for critical applications have very rigid restrictions: *e.g.*, automated vehicle (car, airplane, spacecraft) control. Missing a deadline is potentially disastrous.

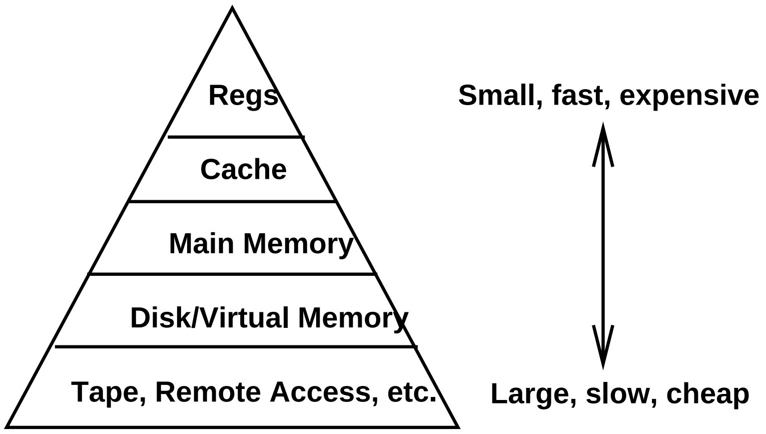
Soft real-time systems are less critical - visualization, robotics, multimedia.

Handheld systems

This is still a relatively new and quickly evolving category of computer. It started with PDAs, and cell phones with limited capabilities but now includes advanced smartphones and tablet computers. Many of the issues that have trickled down from the multiprogramming and time-shared systems to the personal computer and workstation world are now starting to get down to this level. These have relatively slower processors, smaller displays, and limited memory and non-volatile storage.

Modern Storage Hierarchy

We should also be thinking about the organization of memory in modern computers. We will refer to diagrams such as this one from time to time:



When we refer simply to "memory" we likely are talking about *main memory*. This is the normally *volatile* storage that contains the information being used by the CPU. This is *random access memory (RAM)*.

The "disk/virtual memory" layer is typically *nonvolatile* storage, and in many modern systems allows for a logical extension of memory.

This secondary storage level is most commonly built from *hard disks* (moving parts and magnetic material) or *solid-state storage* (several technologies, often faster).

The faster levels: *cache* and *registers*, allow the CPU to operate much more quickly than main memory by providing faster access to currently in-use data. As shown in the diagram, these levels are faster, but smaller and more expensive. When new data is used, it needs to be moved into cache, resulting in the need for something else to be removed. This *cache replacement* problem is one of the issues that arises with caching. Cache issues will come up in some detail at a few points in the course.