PB152 Operating Systems

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Part A: Preliminaries

These are lecture notes for PB152. Everything that you need to know to pass the subject (excluding the seminar, which is a separate subject – PB152cv) is contained in this document. The lectures cover the same material in a different format (the slides which you see in this document are the slides used in the lectures).

Tests and Exam

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- 3 short interim tests (4 lectures each)
  - 2 of the review questions per lecture (8 total)
  - must pass 2 out of 3 tests (otherwise X)
- exam at the end
  - part 1: review questions
  - part 2: in-depth understanding
- all tests are one-way (no revision of answers)

To pass the subject, you will need to take at least 2 of the 3 interim tests that will be made available in the IS. Each of those tests will cover 4 lectures – you will get 2 of the review questions (which are listed at the end of each lecture) for each of them. You are allowed one mistake (i.e. you must answer 7 out of the 8 questions correctly for the test to count as passed). If you fail 2 of the 3 tests, you will be graded X.

If you pass 2 (or all 3) tests, you can take the exam, which will have two parts – the first will be like the interim tests, only there will be 12 questions on it, one from each lecture. You are likewise allowed to make 1 mistake. If you pass, you proceed to the second part, which is more about in-depth understanding, and which will decide your final grade. You must pass both parts of the exam together – if you fail one, you need to retake both.

All tests (i.e. the interim tests and both parts of the exam) will be done in the IS and will show you one question at a time, which you must answer before you can look at the next question. You won't be able to revisit answers that you have already submitted. The training tests will be like this too, so that you can get a feel for how to best allocate your time.

Interim Tests

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- 8 questions, 15 minutes, at most 1 mistake
- training test 1 week prior, unlimited attempts
- when – between 16:00 and 16:30 on:
  - 9th of April
  - 7th of May
  - 4th of June

The interim tests will be held on Fridays in the afternoon. You will have 4 weeks to study the corresponding 4 lectures, then one week to review (with the help of a training test, if you like). The training test will be open starting the Friday prior and will be open until the interim test starts. You can take the training test as many times as you like.

You will get an email reminder about each interim test one week prior (at the same time the training test is published) and in the morning on the day of the test.

Exam

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- part 1: 12 review questions, 20 minutes
  - 10 or less = F, 11+ = go to part 2
- part 2: 12 questions, 90 minutes
  - assess the truth of more complex statements
  - +1 / -0.5 points per question
  - 6+ = E, 7+ = D, 8+ = C, 9+ = B, 10+ = A
- training tests in May, unlimited attempts

In May, a training version of both parts will be made available. You will be able to take either any number of times, though the selection of questions (and answers) will be limited, compared to the real test.

In the second part, each question will present 4 statements (a short paragraph) about some aspect of operating systems. There will be two possible scenarios: either

- 3 statements are false and 1 is true (in which case you select the true one), or
- 3 statements are true and 1 is false (in which case you select the false one).

All tests and exams will be in Czech, with each technical term also appearing in English (in brackets). If you want to take the exam in English, contact me by 19th of March at the latest.

Seminars

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- a separate, optional course (code PB152cv)
- covers operating systems from a practical perspective
- get your hands on the things we'll talk about here
- offers additional practice with C programming

The seminar is a good way to gain some practical experience with operating systems. It will mainly focus on interaction of programs with OS services, but will also cover user-level issues like virtualisation, OS installation and shell scripting.

Study Materials

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- lecture notes are the main study text
  - these include the slides used in the lecture
  - mostly self-contained with minimal dependencies
  - English version already available in the IS
  - translated chapters will be published weekly
- lecture recordings
  - from the 2019 run, as supplementary material

You are reading the lecture notes for the course PB152 Operating Systems. This is your main study resource; it is based on the lecture slides, but with additional details that would not fit into the slide format. These lecture notes should be self-contained in the sense that they only rely on knowledge you have from other courses, like PB150 Computer Systems (or PB151) or PB071 Principles of Low-Level programming. Likewise, being familiar with the topics covered in these lecture notes is sufficient to pass the exam.

Books

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- there are a few good OS books
- you are encouraged to get and read them

- A. Tanenbaum: Modern Operating Systems
- A. Silberschatz et al.: Operating System Concepts
- L. Skočovský: Principy a problémy OS UNIX
- W. Stallings: Operating Systems, Internals and Design
- many others, feel free to explore

The books mentioned here usually cover a lot more ground than it is possible to include in a single-semester course. The study of operating systems is, however, very important in many sub-fields of computer science, and also in most programming disciplines. Spending extra time on this topic will likely be well worth your time.

Topics

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1. Anatomy of an OS
2. System Libraries and APIs
3. The Kernel
4. File Systems
5. Basic Resources and Multiplexing
6. Concurrency and Locking

In the first half of the semester, we will deal with the basic components and abstractions used in general-purpose operating systems. The first lecture will simply give an overview of the entire OS and will attempt to give you an idea how the parts fit together. In the second lecture, we will cover the basic programming interfaces provided by the OS, provided mainly by system libraries.

Topics (cont'd)

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7. Device Drivers
8. Network Stack
9. Command Interpreters & User Interfaces
10. Users and Permissions
11. Virtualisation & Containers
12. Special-Purpose Operating Systems

The second half of the semester will start with device drivers, which form an important part of operating systems in general, since they mediate communication between application software and hardware peripherals connected to the computer. In a similar fashion, the network stack allows programs to communicate with other computers (and software running on those other computers) that are attached to a computer network.

Related Courses

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- PB150/PB151 Computer Systems
- PB153 Operating Systems and their Interfaces
- PA150 Advanced OS Concepts
- PV062 File Structures
- PB071 Principles of Low-level programming
- PB173 Domain-specific Development in C/C++

There is a number of courses that overlap, provide prerequisite knowledge or extend what you will learn here. The list above is incomplete. The course PB153 is an alternative to this course. Most students are expected to take PB071 in parallel with this course, even though knowledge of C won't be required for the theory we cover. However, C basics will be needed for the optional seminar (PB152cv).

Organisation of the Semester

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- generally, one lecture = one topic
- there will be most likely 13 lectures
- the 13th lecture will be review
- 3 interim tests: 2.4., 30.4., 28.5.

Part B: Semester Overview

This section gives a high-level overview of the topics that will be covered in individual lectures. Think of it as an extended table of contents, or as a collection of abstracts, one for each of the upcoming lectures.

2 System Libraries and APIs

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- POSIX: Portable Operating System Interface
- UNIX: (almost) everything is a file
- the least common denominator of programs: C
- user view: objects, archives, shared libraries
- compiler, linker

System libraries and their APIs provide the most direct access to operating system services. In the second lecture, we will explore how programs access those services and how the system libraries tie into the C programming language. We will also deal with basic artifacts that make up programs: object files, archive files, shared libraries and how those come about: how we go from a C source file all the way to an executable file through compilation and linking.
Throughout this lecture, we will use POSIX as our go-to source of examples, since it is the operating system interface that is most widely implemented. Moreover, there is abundance of documentation and resources both online and offline.

3 The Kernel

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- privileged CPU mode
- the boot process
- boundary enforcement
- kernel designs: micro, mono, exo, ...
- system calls

In the third lecture, we will focus on the kernel, arguably the most important (and often the most complicated) part of an operating system.

We will start from the beginning, with the boot process: how the kernel is loaded into memory, initialises the hardware and starts the user-space components (that is, everything that is not the kernel) of the operating system.
We will then talk about boundary enforcement: how the kernel polices user processes so they cannot interfere with each other, or with the underlying hardware devices. We will touch on how this enforcement makes it possible to allow multiple users to share a single computer without infringing on each other (or at least limiting any such infringement).
Another topic of considerable interest will be how kernels are designed and what is and what isn't part of the kernel proper. We will explore some of the trade-offs involved in the various designs, especially with regards to security and correctness vs performance.
Finally, we will look at the system call mechanism, which is how the user-space communicates with the kernel, and requests various low-level operating system services.

4 File Systems

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- why and how
- abstraction over shared block storage
- directory hierarchy
- everything is a file revisited
- i-nodes, directories, hard & soft links

Next up are file systems, which are a very widely used abstraction on top of persistent block storage, which is what hardware storage devices provide. We will ask ourselves, first of all, why filesystems are important and why they are so pervasively implemented in operating systems, and then we will look at how they work on the inside. In particular, we will explore the traditional UNIX filesystem, which offers important insights about the architecture of the operating system as a whole, and about important aspects of the POSIX file semantics.

5 Basic Resources and Multiplexing

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- virtual memory, processes
- sharing CPUs & scheduling
- processes vs threads
- interrupts, clocks

One of the basic roles of the operating system is management of various resources, starting with the most basic: the CPU cores and the RAM. Since those resources are very important to every process or program, we will spend the entire lecture on them. In particular, we will look at the basic units of resource assignment: threads for the CPU and processes for memory. We will also look at the mechanisms used by the kernel to implement assignment and protection of those resources, namely the virtual memory subsystem and the scheduler.

6 Concurrency and Locking

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- inter-process communication
- accessing shared resources
- mutual exclusion
- deadlocks and deadlock prevention

Scheduling and slicing of CPU time is closely related to another important topic that pervades operating system design: concurrency. We will take a high-level, introductory look at this topic, since the details are often complicated, architecture-specific and require deep understanding of both hardware (SMP, cache hierarchies) and of kernels.

7 Device Drivers

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- user vs kernel drivers
- interrupts &c.
- GPU
- PCI &c.
- block storage
- network devices, wifi
- USB
- bluetooth

One of the fundamental roles of an operating system is to mediate access to hardware devices. Some of the code that provides hardware access deals mainly with the software interfaces and APIs – this is known as hardware abstraction. However, to make this abstraction work, there is often a large amount of device-specific (or at least device-class-specific) 'glue' – also known as device drivers.
One of the important questions will be the interplay between processor-level protections and direct hardware access and what this means for drivers. We will see that for some (but not all) types of hardware, only privileged programs (either inside the kernel, or close to it) can reasonably mediate between hardware itself and between higher levels of the system (hardware abstraction layer, application software, etc.).

8 Network Stack

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- TCP/IP
- name resolution
- socket APIs
- firewalls and packet filters
- network file systems

While there is a dedicated course about networking, we will spend one of our lectures talking about networks: in modern operating systems, networking is an integral part of the package and networking considerations often influence other parts of the system. We will look at the ubiquitous TCP/IP stack, how it integrates into an operating system and what are the APIs that applications can use to take advantage of network services. We will also touch on network-related functionality that is often deeply integrated into operating systems: packet filtering and network file systems.

9 Command Interpreters & User Interfaces

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- interactive systems
- history: consoles and terminals
- text-based terminals, RS-232
- bash and other Bourne-style shells, POSIX
- graphical: X11, Wayland, OS X, Windows, Android, iOS

The next lecture will focus on human-computer interaction, which is clearly a central aspect of the experience of using a computer and is therefore an important part of most general-purpose operating systems. Even computers that do not directly (physically) interact with humans usually present some form of an interface, usually mediated over the network.
We will first look at 'traditional' text-based interfaces, which are still in common use among system and network engineers and computer programmers, but we will also look in some depth at the graphics stacks that power modern devices (up to and including smartphones).

10 Users and Permissions

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- multi-user systems
- isolation, ownership
- file system permissions
- capabilities

There are two important use-cases for computers (and hence operating systems) in which higher-level access control and permission management is important: first, when a single computer is shared by multiple users (this is the more traditional case), but in more modern times, also whenever we execute untrusted or semi-trusted programs on our devices (think application permissions on smartphones, web pages that execute javascript on your laptop and so on).

11 Virtualisation & Containers

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- resource multiplexing redux
- isolation redux
- multiple kernels on a single system
- type 1 and type 2 hypervisors
- `virtio`

A computer, along with its operating system, is a natural 'unit' of computation resources – it conveniently packages up the resources themselves, with a software stack and configuration. Unfortunately, computers – being physical devices – are somewhat inflexible and unwieldy: they have to be procured, placed in racks in air-conditioned rooms, attached to a power source, to each other and to the larger network. Their physical components are prone to wear and failure, and need to be replaced or repaired regularly.

Virtualization makes it possible to detach the logical aspects of a computer – its installed software, data storage and configuration – from the physical box. This improves hardware utilization, decouples hardware maintenance from software aspects and makes everyone's life easier (most of the time, anyway).

In this lecture, we will peek under the hood of modern hypervisor-based virtual machines and how they are implemented in the current generation of operating systems.

12 Special-Purpose Operating Systems

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- general-purpose vs special-purpose
- embedded systems
- real-time systems
- high-assurance systems (seL4)

Throughout most of the course, we will have talked about general-purpose operating systems: those that run on personal computers and servers. The last lecture will be dedicated to more specialised systems: those that run in washing machines, on satellites or on the Mars rovers. We will also briefly cover high-assurance systems, which focus on extremely high reliability and/or security.

Part 1: Anatomy of an OS

In the first lecture, we will first pose the question "what is an operating system" and give some short, but largely unsatisfactory answers. Since an operating system is a complex system, it is built from a number of components. Each of those components is described more easily than the entire operating system, and for this reason, we will attempt to understand an operating system as the sum of its parts.

Lecture Overview

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1. Components
2. Interfaces
3. Classification

After talking about what is an operating system, we will give more details about its components and afterwards move on to the interfaces between those components. Finally, we will look at classifying operating systems: this is another angle that could help us pin down what an operating system is.

What is an OS?

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- the software that makes the hardware tick
- and makes other software easier to write

Also

- catch-all phrase for low-level software
- an abstraction layer over the machine
- but the boundaries are not always clear

Our first (very approximate) attempt at defining an OS is via its responsibilities towards hardware. Since it sits between hardware and the rest of software, in some sense, it is what makes the hardware work. Modern hardware alone is rarely capable of achieving anything useful on its own. It needs to be programmed, and the basic layer of programming is provided by the operating system.

What is not (part of) an OS?

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- firmware: (very) low level software
  - much more hardware-specific than an OS
  - often executes on auxiliary processors
- application software
  - runs on top of an operating system
  - this is what you got the computer for
  - e.g. games, spreadsheets, photo editing, ...

One approach to understanding what is an operating system could be to look at things that are related, but are not an operating system, nor a part of one. There is one additional software-ish layer below the operating system, usually known as firmware. In a typical computer, many pieces of firmware are present, but most of them execute on auxiliary processors – e.g. those in a WiFi card, or in the graphics subsystem, in the hard drive and so on. In contrast, the operating system runs on the main processor. There is one piece of firmware that typically runs on the main CPU: on older systems, it's known as BIOS, on modern systems it is simply known as "the firmware".

In the other direction, on top of an operating system, there is a whole bunch of application software. While some software of this type might be bundled with an operating system, it is not, strictly speaking, a part of it. Application software is the programs that you use to get things done, like text editors, word processors, but also programming IDEs (integrated development environment), computer games or web applications (do I say Facebook?). And so on and so forth.

What does an OS do?

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- interact with the user
- manage and multiplex hardware
- manage other software
- organises and manages data
- provides services for other programs
- enforces security

The tasks and duties that the operating system performs are rather varied. On one side, it takes care of the basic interaction with the user: a command interpreter, a graphical user interface or batch-mode job processing system with input provided as punch cards. Then there is the hardware, which needs to be managed and shared between individual programs and users. Installation of additional (application) software is another of the responsibilities of an operating system.
Organisation and management of data is a major task as well: this is what file systems do. This again includes access control and sharing among users of the underlying hardware which stores the actual bits and bytes.
Finally, there is the third side that the operating system interfaces with: the application software. In addition to the user and the hardware, application programs need operating services to be able to perform their function. Among other things, they need to interact with users and use hardware resources, after all. It is the operating system that is in charge of both.

Part 1.1: Components

In this section, we will consider what an operating system consists of, as means to understand what it is.

What is an OS made of?

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- the kernel
- system libraries
- system daemons / services
- user interface
- system utilities

Basically every OS has those.

Operating systems are made of a number of components, some more fundamental than others. Basically all of the above are present, in some form, in any operating system (excluding perhaps the smallest, most special-purpose systems). The kernel is the most fundamental and lowest layer of an operating system, while system libraries sit on top and use the services of the kernel. They also broker the services of the kernel to user-level programs and provide additional services (which do not need to be part of the kernel itself).
The remaining layers are mostly made of programs in the usual sense: other than being a part of the operating systems, there isn't much to distinguish them from user programs. The first category of such programs are system daemons or system services, which are typically long-running programs which react to requests or perform maintenance tasks.
The user interface is slightly more complicated, in the sense that it consists of multiple sub-components that align with other parts here. The bullet point here summarises those parts of the user interface that are more or less standard programs, like the command interpreter.

The Kernel

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- lowest level of an operating system
- executes in privileged mode
- manages all the other software
  - including other OS components
- enforces isolation and security
- provides low-level services to programs

The kernel is the lowest and arguably the most important part of an operating system. Its main distinction is that it executes in a special processor mode (often known as privileged, monitor or supervisor mode). The main tasks of the kernel are management of basic hardware resources (processor, memory) and specifically providing those resources to other software running on the computer. This includes the rest of the operating system.
Another crucial task is enforcement of isolation and security. The hardware typically provides means to isolate individual programs from each other, but it is up to the software (OS kernel) to set up those hardware facilities correctly and effectively.
Finally, the kernel often provides the lowest level of various services to the upper layers. Those are provided mainly in the form of system calls, and mainly relate (directly or indirectly) to hardware access.

System Libraries

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- form a layer above the OS kernel
- provide higher-level services
  - use kernel services behind the scenes
  - easier to use than the kernel interface
- typical example: `libc`
  - provides C functions like `printf`
  - also known as `msvcrt` on Windows

One rung above the kernel reside system libraries: among other things, they provide an interface between the kernel and higher levels of the system. The interface provided by the library to the application is also one level of abstraction above kernel services, which typically makes them easier to use.
Like all libraries, they are linked into other programs and effectively become their part: as such, library code executes with the same privileges as application code – for functionality that is not purely computational, system libraries need to communicate with other parts of the operating system: either the kernel, or other privileged components (system services, also known as daemons).

System Daemons

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- programs that run in the background
- they either directly provide services
  - but daemons are different from libraries
  - we will learn more in later lectures
- or perform maintenance or periodic tasks
- or perform tasks requested by the kernel

Daemons are long-running system programs: they take care of tasks which need to be done continuously or periodically, but at the same time do not need to reside in the kernel. This includes things like delivery of internet mail, remote access to the system (e.g. a secure shell daemon), synchronisation of the system clock (network time protocol daemon), configuration and leasing of network addresses (dynamic host control protocol daemon) and so on, printer spooling, domain

name services, parts of the network file system, hardware health monitoring, system-wide logging and others.

User Interface

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- mediates user-computer interaction
- the main shell is typically part of the OS
  - command line on UNIX or DOS
  - graphical interfaces with a desktop and windows
  - but also buttons on your microwave oven
- also building blocks for application UI
  - buttons, tabs, text rendering, OpenGL…
  - provided by system libraries and/or daemons

In most systems, application programs cannot directly drive hardware – it is therefore up to the operating system to provide an interface between the user (who operates the hardware) and the application program. This includes user inputs (like keystrokes, mouse movement, touchpad or touchscreen events and the like) and relaying the outputs of the application to the user (printing text, drawing windows on the screen, audio output, etc.).

System Utilities

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- small programs required for OS-related tasks
- e.g. system configuration
  - things like the registry editor on Windows
  - or simple text editors
- filesystem maintenance, daemon management, …
  - programs like `ls`/`dir` or `newfs` or `fdisk`
- also bigger programs, like file managers

Not all 'short-running' (i.e. non-daemon) programs are application software. There is a number of utilities which aid with the management of the operating system itself, configuration of services and of the underlying hardware and so on. Those utilities typically use the same type of interface that application software does – whether it is a command-driven interface or a graphical one.
The distinction between bundled application software and system utilities is sometimes blurry: things like the file explorer in Windows is a fairly big and complicated program, but it also serves a rather central role in day-to-day use of the system. It can be imagined, however, that someone would take a program like the Explorer and port it to a different operating system. Perhaps the effort would be non-trivial, but the program would probably not appear out of place in another GUI-based OS.
There is, however, a number of small programs with a clear-cut purpose, which are much easier to classify, like the network configuration tool `ifconfig` or the disk partitioning tool `fdisk`. Likewise with tools like `fsck` (or `chkdisk` on Windows), which are quite meaningless outside of the operating system that they came with.

Optional Components

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- bundled application software
  - web browser, media player, …
- (3rd-party) software management
- a programming environment
  - e.g. a C compiler & linker
  - C header files &c.
- source code

It is often the case that an operating system comes bundled with programs which are not an integral part of the operating system, nor are they in any way involved in its normal operation. A typical example would be a small collection of games – a tradition that dates back to the original Berkeley UNIX, if not further into the past, and has been observed by almost all general-purpose operating systems since: the Solitaire and Minesweeper games that come bundled with Windows have an almost iconic status. Of course there is other software that falls into this category: arguably, MS Paint or Windows Media Player is not in any way essential to operate Windows, nor is a web browser. On UNIX, the software that has traditionally been bundled is of a slightly different nature and stems from the different target audience (and also from a different era): a C compiler, a linker and comparatively advanced source code editors are often found distributed with UNIX-like systems. In some cases, part of those tools was in fact essential, since the user would have had to compile a kernel tailored for their computer. This has, however, not been the case for a while, but most UNIX users expect to have a C compiler available anyway. Along with a C compiler would usually come header files for system libraries and other files needed to create and build your own programs. As I said, a different era.
Finally, you may get the source code of the operating system: strictly speaking, this is not a software component, but rather a different (human-readable, instead of machine-executable) representation of the same operating system. It is quite useful if you want to learn the low-level details of how computers and operating systems work.

Part 1.2: Interfaces

Another way to look at an operating system is from the point of view of its surroundings – what kinds of interfaces are there between the operating system and other components of a computer?

Programming Interface

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- kernel provides system calls
  - ABI: Application Binary Interface
  - defined in terms of machine instructions
- system libraries provide APIs
  - Application Programming Interface
  - symbolic / high-level interfaces
  - typically defined in terms of C functions
  - system calls also available as an API

The most obvious interface of an operating system (if you are a programmer, anyway) is its API: the Application Programming Interface – as the name suggests, it is the functionality that application programs can obtain from the operating system. Most of this API is provided by system libraries – bundles of subroutines in the form of machine code that application programs (and system daemons and system utilities) can call into. Those subroutines often further communicate with the kernel, using a system-specific low-level protocol: this protocol is known as the ABI (Application Binary Interface) of the kernel. Programmers are, for the most part, not exposed to the details of the ABI. The API is typically described in terms of functions in a higher-level programming language: most often C, sometimes C++ or Objective C, rarely some other language. Programmers use those functions just like they use functions they have themselves implemented, but instead of providing definitions, the compiler translates them into calls into the corresponding machine code subroutines stored in system libraries.

Message Passing

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- APIs do not always come as C functions
- message-passing interfaces are possible
  - based on inter-process communication
  - possible even across networks
- form of API often provided by system daemons
  - may be also wrapped by C APIs

Nonetheless, C functions (or C++ or Objective C or other programming language functions) are not the only API that there is. Often, there are interfaces described in terms of inter-process communication, most often some form of message passing. Those are often interfaces that are provided by system daemons, e.g. `syslogd` (usually a UNIX domain socket) or the mail daemon (often a TCP socket).

Portability

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- some OS tasks require close HW cooperation
  - virtual memory and CPU setup
  - platform-specific device drivers
- but many do not
  - scheduling algorithms
  - memory allocation
  - all sorts of management
- porting: changing a program to run in a new environment
  - for an OS, typically new hardware

It is desirable that operating systems can run on different hardware platforms: this reduces costs in a number of ways. The best (and cheapest) code is the code that you don't need to write – using the same operating system on different hardware platforms achieves exactly this (to a degree). On the other side, this saves resources of application developers, who can target a single operating system and reach a number of different hardware devices, and also training costs – users can be migrated from one hardware platform to another without extensive retraining for new software.

While it is basically impossible to write an operating system in an entirely hardware-independent way, many of its components do not need to care about the particulars of the hardware platform. This includes even some of the core kernel components (again, to a degree). Any given thread scheduler can be often used without changes (and sometimes without any sort of additional tuning) on a different hardware platform; same goes for memory allocators, filesystem code and so on. Of course, there are also pieces that are closely tied to particular hardware: the boot sequence (which includes things like setting up the CPU and the virtual memory subsystem), device drivers (which are tied to particular devices) and so on.

Finally, when we talk about portability, porting the operating system itself is not the only concern: it is often desirable to port application programs to run on a different software stack. In general, portability is the ability of a program to be (easily) adapted to a new environment.

Hardware Platform

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- CPU instruction set (ISA)
- buses, IO controllers
  - PCI, USB, Ethernet, ...
- firmware, power management

Examples

- x86 (ISA) – PC (platform)
- ARM – Snapdragon, i.MX 6, ...
- m68k – Amiga, Atari, ...

What is a hardware platform, then? It is a loose set of hardware and firmware that is often found together, with a degree of self-compatibility over time. From a software viewpoint, the specifics of the silicon don't matter, of course, only the protocols and interfaces exposed to software.

The perhaps best-known hardware platform is the PC, dating back to the 80s IBM: it was originally built around Intel 8086 CPUs, one of two graphics adapters, a 5.25" floppy drive, and, rather importantly, BIOS – the firmware of the machine. The components have since been replaced (most of them more than once), but this was a gradual process, essentially providing continuity for the software stack to this day. Unlike most platforms, PC was atypical in one aspect: it was open, in the sense that companies outside of IBM were able to ship hardware that conformed to the same platform and hence could run the same software.

Unlike the PC, which is essentially the only platform of consequence which uses x86 CPUs, other CPU architectures make an appearance in a number of different and incompatible platforms: among the historic would be the Motorola 68000-series processors which were used in Atari and Amiga computers, Sun and NeXT workstations.

A modern day example would be the ARM CPU architecture, used mainly in mobile and other low-power devices, which appears in a number of different platforms. In this space, essentially each SoC (system on a chip) vendor has their own platform, with their own protocols, firmware and essential hardware devices.

Platform & Architecture Portability

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- an OS typically supports many platforms
  - Android on many different ARM SoC's
- quite often also different CPU ISAs
  - long tradition in UNIX-style systems
  - NetBSD runs on 15 different ISAs
  - many of them comprise 6+ different platforms
- special-purpose systems are usually less portable

Modern operating systems usually run on many different platforms, and often on multiple different CPUs (instruction sets). For instance, consider the Android OS, which runs on many different platforms (essentially each SoC vendor has their own platform) and 2 different CPU architectures (ARM and x86).

The tradition was essentially started by UNIX, which was one of the first operating systems to be written in a 'high-level' programming language – one, which could be compiled into machine code for different CPUs. Earlier operating systems were usually written in machine-specific assembly.

Code Re-Use

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- it makes a lot of sense to re-use code
- majority of OS code is HW-independent
- this was not always the case
  - pioneered by UNIX, which was written in C
  - typical OS of the time was in machine language
  - porting was basically 'writing again'

Portability is a special case of code re-use – the code is written once and then used multiple times in different contexts, be it due to changes in hardware, or other aspects of the runtime environment.

Application Portability

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- applications care more about the OS than about HW
  - apps are written in high-level languages
  - and use system libraries extensively
- it is enough to port the OS to new/different HW
  - most applications can be simply recompiled
- still a major hurdle (cf. Itanium)

In principle, most applications do not talk to the hardware directly and hence don't care much about the platform, and are written in languages which are not tied to a particular CPU architecture either. However, they do communicate with the operating system – and in many cases, this communication is a significant fraction of the code of the application.
Considering this, it should be comparatively easy to port existing applications to new hardware, given that the same operating system runs both on their 'native' platform and on the new one. It is usually more than a simple recompile, but even for complicated applications, the effort is not huge. Differences in platform hardware (as opposed to peripherals and things like screen dimensions and resolution) are largely inconsequential for Android applications, and typical UNIX programs run unmodified on dozens of platforms after a simple recompilation.
However, not all ecosystems are like that – consider the first major attempt to migrate PCs to a 64-bit architecture, the Itanium, in the early 2000s. This effort has failed, for a variety of reasons, but lack of portability of MS Windows (and of applications targeting MS Windows as their only supported OS) played an important role.

Application Portability (2)

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- same application can often run on many OSes
- especially within the POSIX family
- but same app can run on Windows, macOS, UNIX, ...
  - Java, Qt (C++)
  - web applications (HTML, JavaScript)
- many systems provide the same set of services
  - differences are mostly in programming interfaces
  - high-level libraries and languages can hide those

Besides portability of application software to new hardware, which should be essentially free (though sometimes it isn't), applications can be ported to different operating systems. Within the POSIX family, this is often a formality at a level similar to porting to new hardware – these operating systems are, from the perspective of the application, all very much alike. This is, in fact, the main reason POSIX exists in the first place.
A more involved process is porting between different operating systems which are not in the same family, say between Windows and POSIX. The APIs are very different, and on the application level, this is often completely impractical. Instead, if the ability to run 'natively' on different operating systems (outside of POSIX) is desired, applications can be written using a platform-neutral API implemented by a portable runtime, which translates its own API into calls supported by any given host operating system. Such a portable runtime is, famously, part of the Java programming language ('write once, run everywhere'). Other such runtimes, for other programming languages, exist: C++ has Qt, most high-level languages (Python, Haskell, JavaScript, ...) have one built in.

Abstraction

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- instruction sets abstract over CPU details
- compilers abstract over instruction sets
- operating systems abstract over hardware
- portable runtimes abstract over operating systems
- applications sit on top of the abstractions

While we were discussing portability, a picture of an 'abstraction tower' has emerged: each layer hides the details of the previous layers, making it possible to largely ignore them when designing on top of the tower (or stack, as it is often called). This enables portability (since the lower layers are hidden, they can be more easily replaced), but this is by far not the only reason why we build such towers.
Arguably, the main reason for abstraction is hiding complexity – something as simple as writing 'hello world' to a file on disk takes hundreds of thousands of CPU instructions, yet we can do so with a single short command. This is what abstraction gives us.

Abstraction Costs

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- more complexity
- less efficiency
- leaky abstractions

Abstraction Benefits

- easier to write and port software
- fewer constraints on HW evolution

Of course, abstraction is not free. Doing things indirectly always costs more: if we reduced the amount of abstraction, writing files would take thousands or tens of thousands of instructions, instead of hundreds of thousands. But writing even 2k instructions to write that file is 3 orders of magnitude too many to write by hand for such a simple and ubiquitous task. So we accept the overhead.
A more sneaky problem is that of leaky abstractions: we like to pretend that each abstraction layer completely seals the layers below in a manner that we can't observe them. But this is never quite true: all abstractions are leaky to a degree – exposing details of layers below. If the surface of a magnetic drive is damaged, this will cause problems all the way up in the application, even though the interface we are using – read and write bytes to a file – is supposed to shield us from such low-level issues such as a defects on a spinning platter covered in ferromagnetic dust.

Abstraction Trade-Offs

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- powerful hardware allows more abstraction
- embedded or real-time systems not so much
  - the OS is smaller & less portable
  - same for applications
  - more efficient use of resources

Clearly, there can be 'too little' abstraction (think of replacing your 3-line Python script with 25 thousand assembly instructions by hand). But there can also be too much – especially on constrained hardware, the overhead can be too great. Often the easiest way to buy efficiency is by reducing the amount of abstraction.

Part 1.3: Classification

Our last attempt at understanding what an operating system is will revolve around different types of operating systems and their differences.

General-Purpose Operating Systems

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- suitable for use in most situations
- flexible but complex and big
- run on both servers and clients
- cut down versions run on smartphones
- support variety of hardware

The most important and interesting category is 'general-purpose operating systems'. This is the one that we will mostly talk about in this course. The systems in this category are usually quite flexible (so they can cover everything that people usually use computers for) but, for the same reason, also quite complex. Often the same operating system will be able to run on both so-called 'server' computers (those mainly sitting in data centres providing services to other computers remotely) and 'client' computers – those that interact with users directly.
Likewise, the same operating system can, perhaps in a slimmed down version, run on a smartphone, or a similar size- and power-constrained device. All current major smartphone operating systems are of this type. Historically, there were a few more specialised phone operating systems, mainly because at that time, phone hardware was considerably more constrained than it is today. Nonetheless, an OS like Symbian, for instance, could conceivably be used on personal computers assuming its hardware support was extended.

Operating Systems: Examples

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- Microsoft Windows
- Apple macOS & iOS
- Google Android
- Linux
- FreeBSD, OpenBSD
- MINIX
- many, many others

There is a whole bunch of operating systems, even of general-purpose operating systems. While running the OS itself is not the primary reason for getting a computer (application software is), it does form an important part of user experience. Of course, it also interfaces with computer hardware and with application programs, and not all systems run on all computers and not all applications run on all operating systems.

Special-Purpose Operating Systems

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- embedded devices
  - limited budget
  - small, slow, power-constrained
  - hard or impossible to update
- real-time systems
  - must react to real-world events
  - often safety-critical
  - robots, autonomous cars, space probes, ...

Besides general-purpose operating systems, there are other, more constrained systems. A typical example is embedded systems, which run on very small amount of hardware (compared to modern general-purpose computers), with tight budget and with severe power constraints. In such systems, the comforts afforded by excessive abstraction are not available. This is especially true in real-time systems, which add constraints on computation time. Predictable timing is one of the things that are hardest to achieve in presence of abstraction (or in other words, precise timing of operations is one of the things that leak across abstraction boundaries).

Size and Complexity

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- operating systems are usually large and complex
- typically 100K and more lines of code
- 10+ million is quite possible
- many thousand man-years of work
- special-purpose systems are much smaller

We have mentioned earlier that general-purpose operating systems are usually large and complex. The smallest complete operating systems (if they are not merely educational toys) start around 100 thousand lines of code, but millions of lines is more typical. It is not unheard of that an operating system contains more than 10 million lines of code. These amounts clearly represent thousands of man-years of work – writing your own operating system, solo, is not very realistic.
That said, special-purpose systems are often much smaller. They usually only support far fewer hardware devices and they provide simpler and less varied services to the 'application' software.

Kernel Revisited

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- bugs in the kernel are very bad
  - system crashes, data loss
  - critical security problems
- bigger kernel means more bugs
- third-party drivers inside the kernel?

Let's recall that the kernel runs in privileged CPU mode. Any software running in this mode is pretty much all-powerful and can easily circumvent any access restrictions or security protections. It is a well-known fact that the more code you have, the more bugs there are. Since bugs in the kernel can have far-fetching and catastrophic consequences, it is imperative that there are as few as possible. Even more importantly, device drivers often need hardware access and the easiest (and sometimes only) way to achieve that is by executing in kernel (privileged) mode.
As you may also know, device drivers are often of rather questionable quality: hardware vendors often consider those an after-thought and don't pay too much attention to their software teams. If those drivers

then execute in kernel mode, this is a serious problem. Different OS vendors employ different strategies to mitigate this issue.
Accordingly, we would like to make kernels small and banish as many drivers from the kernel as we could. It is, however, not an easy (or even obviously right) thing to do. There are two main design schools when it comes to kernel 'size':

Monolithic Kernels

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- lot of code in the kernel
- less abstraction, less isolation
- faster and more efficient

Microkernels

- move as much as possible out of kernel
- more abstraction, more isolation
- slower and less efficient

The monolithic kernel is an older and in some sense simpler design. A lot of code ends up in the kernel, which is not really a problem until bugs happen. There is less abstraction involved in this design, fewer interfaces and, in general, fewer moving parts for the same amount of functionality. Those traits then translate to faster execution and more efficient resource use. Such kernels are called monolithic because everything that a traditional kernel does is performed by a single (monolithic) piece of software.
The opposite of monolithic kernels are microkernels. The kernel proper in such a system is the smallest possible subset of code that must run in privileged mode. Everything that can be banished into user mode (of the processor) is. This design provides a lot more isolation and requires more abstraction. The interfaces within different parts of the low-level OS services are more complicated. Subsystems are well isolated from each other and faults do not propagate nearly as easily. However, operating systems which use this kernel type run more slowly and use resources less efficiently.

Paradox?

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- real-time & embedded systems often use microkernels
- isolation is good for reliability
- efficiency also depends on the workload
  - throughput vs latency
- real-time does not necessarily mean fast

Finally, there is a bit of a paradox around microkernels: it is a fact that they are often used in embedded (real-time) systems – some of the most performance-critical software stacks around. However, one thing is more important than performance when it comes to embedded software: reliability. And reliability is where microkernels shine. Additionally, even in hard real-time systems, where we often consider performance to be paramount, raw speed is a bit of a red herring – what is important is latency, and even more important is an upper bound on this latency. Providing one is, however, much easier in a microkernel system, where the code base is small and much easier to reason about.

Review Questions

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1. What are the roles of an operating system?
2. What are the basic components of an OS?
3. What is an operating system kernel?
4. What are API and ABI?

Part 2: System Libraries and APIs

In this section, we will study the programming interfaces of operating systems, first in some generality, without a specific system in mind. We will then go on to deal specifically with the C-language interface of POSIX systems.

Programming Interfaces

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- kernel system call interface
- → system libraries / APIs ←
- inter-process protocols
- command-line utilities (scripting)

In most operating systems, the lowest-level interface accessible to application programs is the system call interface. It is, typically, specified in terms of a machine-language-level protocol (that is, an ABI), but usually also provided as a C API. This is the case for POSIX-mandated system calls, but also on e.g. Windows NT systems.

Lecture Overview

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1. The C Programming Language
2. System Libraries
   - what is a library?
   - header files & libraries
3. Compiler & Linker
   - object files, executables
4. File-based APIs

In this lecture, we will start by reviewing (or perhaps introducing) the C programming language. Then we will move on to the subject of libraries in general and system libraries in particular. We will look at how libraries enter the program compilation process and what other ingredients there are. Finally, we will have a closer look at a specific set of file-based programming interfaces.

Sidenote: UNIX and POSIX

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- we will mostly use those terms interchangeably
- it is a family of operating systems
  - started in late 60s / early 70s
- POSIX is a specification
  - a document describing what the OS should provide
  - including programming interfaces

We will assume POSIX unless noted otherwise

Before we begin, it should be noted that throughout this course, we will use POSIX and UNIX systems as examples. If a specific function or interface is mentioned without further qualification, it is assumed to be specified by POSIX and implemented by UNIX-like systems.

Part 2.1: The C Programming Language

The C programming language is one of the most commonly used languages in operating system implementations. It is also the subject of PB071, and at this point, you should be already familiar with its basic syntax. Likewise, you are expected to understand the concept of a function and other basic building blocks of programs. Even if you don't know the specific C syntax, the idea is very similar to any other programming language you might know.

Programming Languages

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- there are many different languages
  - C, C++, Java, C#, ...
  - Python, Perl, Ruby, ...
  - ML, Haskell, Agda, ...
- but C has a special place in most OSes

Different programming languages have different use-cases in mind, and exist at different levels of abstraction. Most languages other than C that you will meet, both at the university and in practice, are so-called high-level languages. There are quite a few language families, and there is a number of higher-level languages derived from C, like C++, Java or C#.
For the purposes of this course, we will mostly deal with plain C, and with POSIX (Bourne-style) shell, which can also be thought of as a programming language.

C: The Least Common Denominator

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- except for assembly, C is the "bare minimum"
- you can almost think of C as portable assembly
- it is very easy to call C functions
- and to use C data structures

You can use C libraries in almost every language

You could think of C as a 'portable assembler', with a few minor bells and whistles in form of the standard library. Apart from this library of basic and widely useful subroutines, C provides: abstraction from machine opcodes (with human-friendly infix operator syntax), structured control flow, and automatic local variables as its main advantages over assembly.
In particular the abstraction over the target processor and its instruction set proved to be instrumental in early operating systems, and helped establish the idea that an operating system is an entity separate from the hardware.
On top of that, C is also popular as a systems programming language because almost any program, regardless of what language it is written in, can quite easily call C functions and use C data structures.

The Language of Operating Systems

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- many (most) kernels are written in C
- this usually extends to system libraries
- and sometimes to almost the entire OS
- non-C operating systems provide C APIs

Consequently, C has essentially become a 'language of operating systems': most kernels and even the bulk of most operating systems is written in C. Each operating system (apart from perhaps a few exceptions) provides a C standard library in some form and can execute programs written in C (and more importantly, provide them with essential services).

Part 2.2: System Libraries

We have already touched the topic of system libraries last week, in the 'anatomy' section. It is now time to look at them in more detail: what they contain, how are they stored in the file system, how are they combined with programs. We will also briefly talk about system call wrappers (which mediate low-level access to kernel services – we will discuss this topic in more detail in the next lecture). Finally, we will look at a few examples of system libraries which appear in popular operating systems.

(System) Libraries

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- mainly C functions and data types
- interfaces defined in header files
- definitions provided in libraries
  - static libraries (archives): `libc.a`
  - shared (dynamic) libraries: `libc.so`
- on Windows: `msvcrt.lib` and `msvcrt.dll`
- there are (many) more besides `libc` / `msvcrt`

In this course, when we talk about libraries, we will mean C libraries specifically. Not Python or Haskell modules, which are quite different. That said, a typical C library has basically two parts, one is header files which provide a description of the interface (the API) and the compiled library code (an archive or a shared library).
The interface (as described in header files) consists of functions (for which, the types of arguments and the type of return value are given in a header file) and of data structures. The bodies of the functions (their implementation) is what makes up the compiled library code. To illustrate:

Declaration: what but not how

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```
int sum( int a, int b );
```

Definition: how is the operation done?

```
int sum( int a, int b )
{
    return a + b;
}
```

The first example on this slide is a declaration: it tells us the name of a function, its inputs and its output. The second example is called

a definition (or sometimes a body) of the function and contains the operations to be performed when the function is called.

Library Files

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- /usr/lib on most Unices
  - may be mixed with application libraries
  - especially on Linux-derived systems
  - also /usr/local/lib for user/app libraries
- on Windows: C:\Windows\System32
  - user libraries often bundled with programs

The machine code that makes up the library (i.e. the code that was generated from function definitions) resides in files. Those files are what we usually call 'libraries' and they usually live in a specific filesystem location. On most UNIX system, those locations are /usr/lib and possibly /lib for system libraries and /usr/local/lib for user or application libraries. On certain systems (especially Linux-based), user libraries are mixed with system libraries and they are all stored in /usr/lib.
On Windows, the situation is similar in that both system and application libraries are installed in a common location. Additionally, on Windows (and on macOS), shared libraries are often installed alongside the application.

Static Libraries

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- stored in libfile.a, or file.lib (Windows)
- only needed for compiling (linking) programs
- the code is copied into the executable
- the resulting executable is also called static
  - and is easier to work with for the OS
  - but also more wasteful

Static libraries are only used when building executables and are not required for normal operation of the system. Therefore, many operating systems do not install them by default – they have to be installed separately as part of the developer kit. When a static library is linked into a program, this basically entails copying the machine code from the library into the final executable.
In this scenario, after linking is performed, the library is no longer needed since the executable contains all the code required for its execution. For system libraries, this means that the code that comes from the library is present on the system in many copies, once in each program that uses the library. This is somewhat alleviated by linkers only copying the parts of the library that are actually needed by the program, but there is still substantial duplication.
The duplication arising this way does not only affect the file system, but also memory (RAM) when those programs are loaded – multiple copies of the same function will be loaded into memory when such programs are executed.

Shared (Dynamic) Libraries

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- required for running programs
- linking is done at execution time
- less code duplication
- can be upgraded separately
- but: dependency problems

The other approach to libraries is dynamic, or shared libraries. In this case, the library is required to actually run the program: the linker does not copy the machine code from the library into the executable. Instead, it only notes that the library must be loaded alongside with the program when the latter is executed.
This reduces code duplication, both on disk and in memory. It also means that the library can be updated separately from the application. This often makes updates easier, especially in case a library is used by many programs and is, for example, found to contain a security problem. In a static library, this would mean that each program that uses the library needs to be updated. A shared library can be replaced and the fixed code will be loaded alongside programs as usual.
The downside is that it is difficult to maintain binary compatibility – to ensure that programs that were built against one version of the library also work with a later version. When this is violated, as often happens, people run into dependency problems (also known as DLL hell on Windows).

Header Files

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- on UNIX: /usr/include
- contains prototypes of C functions
- and definitions of C data structures
- required to compile C and C++ programs

Like static libraries, header files are only required when building programs, but not when using them. Header files are fragments of C source code, and on UNIX systems are traditionally stored in /usr/include. User-installed header files (i.e. not those provided by system libraries) live under /usr/local/include (though again, on Linux-based systems user and system headers are often intermixed in /usr/include).

Header Example 1 (from unistd.h)

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```
int     execv(char *, char **);
pid_t   fork(void);
int     pipe(int *);
ssize_t read(int, void *, size_t);
```

(and many more prototypes)

This is an excerpt from an actual system header file, and declares a few of the functions that comprise the POSIX C API.

Header Example 2 (from sys/time.h)

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```
struct timeval
{
    time_t   tv_sec;
    long     tv_usec;
};

/* ... */

int gettimeofday(timeval *, timezone *);
int settimeofday(timeval *, timezone *);
```

This is another excerpt from an actual header – this time the snippet contains a definition of a data structure. The layout (order of fields and their types, along with hidden padding) of such structures is quite important, since that becomes part of the ABI. In other words, the definition above describes not just the high-level interface but also how bytes are laid out in memory.

The POSIX C Library

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- `libc` – the C runtime library
- contains ISO C functions
  - `printf`, `fopen`, `fread`
- and a number of POSIX functions
  - `open`, `read`, `gethostbyname`, ...
  - C wrappers for system calls

As we have already mentioned previously, it is a tradition of UNIX systems that `libc` combines the basic C library and the basic POSIX library. For the following, a particular subset of the POSIX library is going to be rather important, namely the system call wrappers. Those are C functions whose only purpose is to invoke their matching system calls.

System Calls: Numbers

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- system calls are performed at machine level
- which syscall to perform is decided by a number
  - e.g. `SYS_write` is 4 on OpenBSD
  - numbers defined by `sys/syscall.h`
  - different for each OS

At the level of the OS kernel (cue next week), system calls are represented by numbers (which are often given symbolic names like `SYS_write`, but are nonetheless just small integers and not memory addresses like with ordinary C functions). The numbers are specific to any given kernel. And of course, the `libc` must use the same numbering as the kernel.

System Calls: the `syscall` function

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- there is a C function called `syscall`
  - prototype: `int syscall( int number, ... )`
- this implements the low-level syscall sequence
- it takes a syscall number and syscall parameters
  - this is a bit like `printf`
  - first parameter decides what are the other parameters
- (more about how `syscall()` works next week)

Typically, all system calls work essentially the same: the library takes the (syscall) number and some additional data (parameters), stores them at the pre-arranged location (registers, memory) and jumps into the kernel. Since this sequence is uniform across system calls, it is possible to have a single C function which can perform any system call, given its number.
This function actually exists and is called `syscall`. It's entirely possible to perform all your syscalls using this one C function, and never call the more convenient single-purpose wrappers (see also below).

System Calls: Wrappers

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- using `syscall()` directly is inconvenient
- `libc` has a function for each system call
  - `SYS_write` → `int write( int, char *, size_t )`
  - `SYS_open` → `int open( char *, int )`
  - and so on and so forth
- those wrappers may use `syscall()` internally

To make programming a fair bit more convenient, instead of saying

```
syscall( SYS_write, fd, buffer, size );
```

we can use a function called `write`, like this:

```
write( fd, buffer size );
```

Besides being shorter to type, it is also safer: the compiler can check that we passed the right number and types of arguments. The function might internally use the equivalent `syscall()` invocation – though in practice, we prefer to sacrifice this particular bit of abstraction to save a few instructions on the comparatively hot (hot = one that is executed often) code path. That is, each syscall wrapper contains a copy of the code for entering the kernel, instead of calling `syscall`.

Portability

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- libraries provide an abstraction layer over OS internals
- they are responsible for application portability
  - along with standardised filesystem locations
  - and user-space utilities to some degree
- higher-level languages rely on system libraries

An important function of libraries is to provide a uniform API to the upper layers of the system. The designers of an operating system may decide to substantially depart from the traditional system call protocol, or even from the traditional set of system calls. However, even if the kernel looks quite non-POSIX-y, it is often still possible to provide a set of C functions that behave as POSIX specifies. This has been done more than once, most often on top of microkernels, e.g. Microsoft NT (Windows NT, XP and later) or on Mach (macOS, HURD). All those systems are capable of supporting POSIX programs without being built around a UNIX-like monolithic kernel.
Of course, the API alone is not sufficient to make POSIX programs work correctly: there are certain expectations about the filesystem (both semantics of the file system itself, but also which files exist and what they contain) and other aspects of the system.

NeXTSTEP and Objective C

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- the NeXT OS was built around Objective C
- system libraries had ObjC APIs
- in API terms, ObjC is very different from C
  - also very different from C++
  - traditional OOP features (like Smalltalk)
- this has been partly inherited into macOS
  - Objective C evolved into Swift

Not all operating systems provide (exclusively) C APIs. Historically, one of the earlier departures was the NeXT operating system, which used Objective C extensively. While the procedural part of the language is simply C, the object-oriented part is based on Smalltalk, with pervasive late binding and dynamic types.

System Libraries: UNIX

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- the math library `libm`
  - implements math functions like `sin` and `exp`
- thread library `libpthread`
- terminal access: `libcurses`
- cryptography: `libcrypto` (OpenSSL)
- the C++ standard library `libstdc++` or `libc++`

While `libc` is quite central, there are many other libraries that are part

of a UNIX system. You would find most of the above examples on most UNIX systems in some form.

System Libraries: Windows

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- `msvcrt.dll` – the ISO C functions
- `kernel32.dll` – basic OS APIs
- `gdi32.dll` – Graphics Device Interface
- `user32.dll` – standard GUI elements

System libraries look quite differently on Windows: there is no `libc`: instead, the C standard library has its own DLL (the `msvcrt`, from MicroSoft Visual C RunTime) while operating system services (the low-level kind) live in `kernel32.dll`. The other two libraries allow applications to provide a graphical user interface. The libraries mentioned here all provide C APIs, though there are also C++ and C# interfaces (which are partly wrappers around the above libraries, but not exclusively).

Documentation

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- manual pages on UNIX
  - try e.g. `man 2 write` on `aisa.fi.muni.cz`
  - section 2: system calls
  - section 3: library functions (`man 3 printf`)
- MSDN for Windows
  - <https://msdn.microsoft.com>
- you can learn a lot from those sources

Most OS vendors provide extensive documentation of their programmer's interfaces. On UNIX, this is typically part of the OS installation itself (manual pages, command `man`), while on Windows, this is a separate resource (these days accessible online, previously distributed in print or on optical media).

Part 2.3: Compiler & Linker

While compiling (and linking) programs is not core functionality of an operating system, it is quite useful to understand how these components work. Moreover, in earlier systems, a C compiler was considered a rather essential component and this tradition continues in many modern UNIX systems to this day. We will discuss different artefacts of compilation – object files, libraries and executables, as well as the process of linking object code and libraries to produce executables. We will also highlight the differences between static and shared (dynamic) libraries.

C Compiler

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- many POSIX systems ship with a C compiler
- the compiler takes a C source file as input
  - a text file with a `.c` suffix
- and produces an object file as its output
  - binary file with machine code in it
  - but cannot be directly executed

Compilers transform human-readable programs into machine-executable programs. Of course, both those forms of the program need to be stored in memory: the first is usually in the form of plain text (usually encoded as UTF-8, or in older systems as ASCII). In this form, bytes stored in the file encode human-readable letters.
On the output side, the file is binary (which is really just a catch-all term for files that are not plain text), and stores machine-friendly instructions – primitive operations that the CPU can execute. Only the compiler output cannot be directly executed yet, even though most of the instructions are in their final form.
The missing piece are addresses: numbers which describe memory locations within the program itself (they may point at instructions or at data embedded in the program). At this stage, though, neither code nor data has been assigned to particular addresses, and hence the program cannot be executed (it will need to be linked first, more on that later).

Object Files

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- contain native machine (executable) code
- along with static data
  - e.g. string literals used in the program
- possibly split into a number of sections
  - `.text`, `.rodata`, `.data` and so on
- and metadata
  - list of symbols (function names) and their addresses

The purpose of object files is to store this semi-finished machine code, along with any static data (like string literals or numeric constants) that appear in the program. All this is sorted into sections – usually one section for machine code (also called text and called `.text` in the object file), another for read-only data (e.g. string literals), called `.rodata`, another for mutable but statically-initialized variables – `.data`. Bundled with all this is metadata, which describes the content of the file (again in a machine-readable form).
One example of such metadata is a symbol table, which gives file-relative addresses of high-level functions that have been compiled into the object file. That is, the compiler will take a definition of a function that we wrote in C and emit machine code for this function. The `.text` section of an object file will consist of a number of such functions, one after another: the symbol table then tells us where each of the functions begins.

Object File Formats

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- `a.out` – earliest UNIX object format
- COFF – Common Object File Format
  - adds support for sections over `a.out`
- PE – Portable Executable (MS Windows)
- Mach-O – Mach Microkernel Executable (macOS)
- ELF – Executable and Linkable Format (all modern Unices)

There is a number of different physical layouts of object files, and each of those also carries slightly different semantics. By far the most common format used in POSIX systems is ELF. The other common formats in contemporary use are PE (used by MS operating systems) and Mach-O (used by Apple operating systems).

Archives (Static Libraries)

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- static libraries on UNIX are called archives
- this is why they get the `.a` suffix
- they are like a `zip` file full of object files
- plus a table of symbols (function names)

An archive is the simplest way to bundle multiple object files. As the name implies, it is essentially just a collection of object files stored as a single file. Each object file retains its identity and its content does not change in any way when it is bundled into an archive.

The only difference from a typical data archive (a `tar` or a `zip` archive, say) is that besides the object files themselves, the archive contains an additional metadata section – a symbol table, or rather a symbol index. If someone (typically the linker) needs to find the definition of a particular function (symbol), it can first consult this archive-wide index to find which object file provides that symbol. This makes linking more efficient, since the linker does not need to sequentially scan each object file in the archive to find the definition.

Linker

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- object files are incomplete
- they can refer to symbols that they do not define
  - the definitions can be in libraries
  - or in other object files
- a linker puts multiple object files together
  - to produce a single executable
  - or maybe a shared library

As pointed out earlier, it is the job of a linker to combine object files (and libraries) into executables. The process is fairly involved, so we will describe it across the next few slides. The input to the linker is a bunch of object files and the output is a single executable or sometimes a single shared library.
Even though archives are handled specially by the linker, object files which are given to the linker directly will always become part of the final executable. Object files provided in archives are only used if they provide symbols which are required to complete the executable.

Symbols vs Addresses

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- we use symbolic names to call functions &c.
- but the `call` machine instruction needs an address

- the executable will eventually live in memory
- data and instructions need to be given addresses
- what a linker does is assign those addresses

The main entities that come up during linking are symbols and addresses. In a program, the machine code and the data is loaded in memory, and as we know, each memory location has an address. The program in its compiled form can use addresses to refer to parts of itself. For instance, to call a subroutine, we provide its starting address to a special `call` instruction, which tells the CPU to start executing code from that address.
However, when humans write programs, they do not assign addresses to pieces of data, to functions or to individual instructions. Instead, if the program needs to refer to a part of itself, we give those parts names: those names are known as symbols. It is the shared responsibility of the compiler and the linker to assign addresses to the individual symbols, in such a way that the objects stored in memory do not conflict (overlap). If you think about it, it would be very difficult to do by hand: we usually don't know how long the machine code will be for any given function, and we would need to guess and then add gaps in case we need to add more code to a function, and so on. And we would need to remember which code lives at which address and so on. It is all very uncomfortable, and even assembly programmers usually avoid assigning addresses by hand. In fact, one of the primary roles of an assembler is to translate from symbolic to numeric addresses. But I digress.

Resolving Symbols

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- the linker processes one object file at a time
- it maintains a symbol table
  - mapping symbols (names) to addresses
  - dynamically updated as more objects are processed
- relocations are typically processed all at once at the end
- resolving symbols = finding their addresses

The linker works by maintaining an 'incomplete executable' and makes progress by merging each of the input object files into this work-in-progress file. The strategy for assigning final addresses is simple enough: there's a single output `.text` section, a single output `.data` section and so on. When an input file is processed, its own `.text` section is simply appended to the `.text` produced so far. The same process is repeated for every section.
The symbol tables of the input object files are likewise merged one by one, and the addresses adjusted as symbols are added. In addition to symbol definitions, object files contain symbol uses – those are known as relocations, and are stored in a relocation table. Relocations contain the address of the instruction that needs to be patched and the symbol the address of which is to be patched in. Like the sections themselves and the symbol table, the relocation table is built up.
The relocations are also processed by the linker: usually, this means writing the final address of a particular symbol into an as-of-yet incomplete instruction or into a variable in the data section. This is usually done once the output symbol table is complete.
The relocation and symbol tables are often discarded at the end (but may be retained in the output file in some cases – the symbol table more often than the relocation table).

Executable

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- finished image of a program to be executed
- usually in the same format as object files
- but already complete, with symbols resolved
  - but: may use shared libraries
  - in that case, some symbols remain unresolved

The output of the linker is, in the usual case, an executable. This is a file that is based on the same format as object files of the given operating system, but is complete in some sense. In static executables (those which don't use shared libraries), all references and relocations are already resolved and the program can be loaded into memory and directly executed by the CPU, without further adjustments.
It is also worth noting that the addresses that the executable uses when referring to parts of itself are virtual addresses (this is also the case with shared libraries below). We will talk more about those in a later lecture, but right now we can at least say that this means that different programs on the same operating system can use overlapping addresses for their instructions and data. This is not a problem, because virtual addresses are private to each process, and hence each copy of each executing program.

Shared Libraries

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- each shared library only needs to be in memory once
- shared libraries use symbolic names (like object files)
- there is a "mini linker" in the OS to resolve those names
  - usually known as a runtime linker
  - resolving = finding the addresses
- shared libraries can use other shared libraries
  - they can form a DAG (Directed Acyclic Graph)

The downside of static libraries is that they need to be loaded separately (often in slightly different versions) along with each program that uses them: in fact, since the linker embedded them into the program, they are quite inseparable from it.
As we have already mentioned, this is not very efficient. Instead, we can store the library code in separate executable-like files that get loaded into the address space of programs that need it. Of course, relocations in the main program that refer to symbols from shared libraries (and vice versa), and obviously also relocations in shared libraries that refer to other shared libraries, those need to be resolved. This is usually done either when the program is loaded into memory, or lazily, right before the relocation is first used.
In either case, there needs to be a program which will resolve those relocations: this is the runtime linker – it is superficially similar to the normal, compile-time linker, but in reality is quite different.

Addresses Revisited

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- when you run a program, it is loaded into memory
- parts of the program refer to other parts of the program
  - this means they need to know where it will be loaded
  - this is a responsibility of the linker
- shared libraries use position-independent code
  - works regardless of the base address it is loaded at
  - we won't go into detail on how this is achieved

We mentioned that executables and libraries use virtual addresses to refer to their own parts. However, this does not help shared libraries as much as it helps with executables. The letdown is that we want to load the same library along with multiple programs: but if the addresses used by the library are fixed, this means that the library needs to be loaded at the same start address into each program that uses that library. This quickly becomes impractical as we add more libraries into the system – no two libraries would be allowed to overlap and none of them would be allowed to overlap with any of the executables.
In practice, what we instead do is that we compile the libraries in such a way that they don't use absolute addresses to refer to parts of themselves. This often adds a little execution overhead, but makes it possible to load the library at any address range that is available in the current process. This makes the job of the runtime linker much easier.

Compiler, Linker &c.

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- the C compiler is usually called `cc`
- the linker is known as `ld`
- the archive (static library) manager is `ar`
- the runtime linker is often known as `ld.so`

On many UNIXes, the compiler and the linker are available as part of the system itself. The command names are standardized.

Part 2.4: File-Based APIs

On POSIX systems, the API for using the filesystem is a very important one, because it in fact provides access to a number of additional resources, which appear as 'abstract' (special) files in the system.

Everything is a File

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- part of the UNIX design philosophy
- directories are files
- devices are files
- pipes are files
- network connections are (almost) files

File is an abstraction: it is an object from which we can read bytes and into which we can write bytes (not all files will let us do both). In regular files, we can read and write at any offset, and if we write something we can later read that same thing (unless it was rewritten in the meantime).
Directories are somewhat like this: we can read bytes from them to find out what files are present in that directory and how to find them in the file system. We can create new entries by writing into the directory. Incidentally, this is not how things are usually done, but it's not hard to imagine it could be.
Quite a few devices (peripherals) behave this way: all kinds of hard drives (just a big bunch of bytes), printers (write some bytes to have them printed), scanners (write bytes to send commands, read bytes with the image data), audio devices (read bytes from microphones, write bytes into speakers), and so on.
Pipes are like that too: one program writes bytes, and another reads them. And network connections are more or less just pipes that work across the network.

Why is Everything a File

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- re-use the comprehensive file system API
- re-use existing file-based command-line tools
- bugs are bad → simplicity is good
- want to print? `cat file.txt > /dev/ulpt0`
  - (reality is a little more complex)

Since we already have an API to work with abstract files (because we need to work with real files anyway), it becomes reasonable to ask why not use this existing API to work with other objects that look like files. It makes sense not just at the level of C functions, but at the level of command-line programs too. In general, re-using existing mechanisms makes things more flexible, and often also simpler. Of course, there are caveats (devices often need to support operations that don't map well to reading or writing bytes, sockets are also somewhat problematic).

What is a Filesystem?

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- a set of files and directories
- usually lives on a single block device
  - but may also be virtual
- directories and files form a tree
  - directories are internal nodes
  - files are leaf nodes

While we have a decent idea of what a file is, what about a file system? Well, a file system is a collection of files and directories, typically stored

on a single block device. The directories and files form a tree (at least until symlinks come into play, at which point things start going south). Regular files are always leaf nodes in this tree.

File Paths

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- filesystems use paths to point at files
- a string with / as a directory delimiter
  - the delimiter is \ on Windows
- a leading / indicates the filesystem root
- e.g. /usr/include

Paths are how we refer to files and directories within the tree. The top-level (root) directory is named /. Each directory entry carries a name (and a link to the actual file or directory it represents) – this name can be used in the path to refer to the given entity. So with a path like /usr/include, we start at the root directory (the initial slash), then in that directory, we look for an entity called usr and when we find it, we check that it is a directory again. If that is so, we then look at its direct descendants again and look for an entity labelled include.

The File Hierarchy

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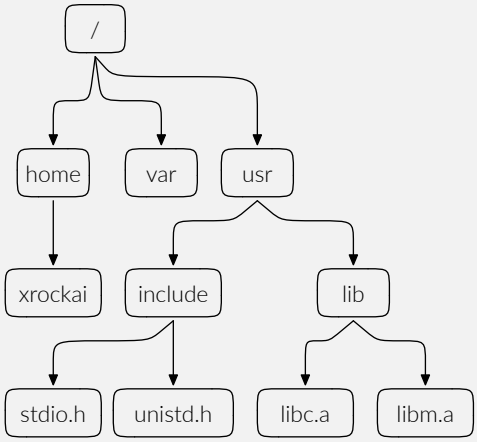

That's an example of a file system tree. You can practice looking up various paths in the tree, using the algorithm described above.

The Role of Files and Filesystems

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- very central in Plan9
- central in most UNIX systems
  - cf. Linux pseudo-filesystems
  - /proc provides info about all processes
  - /sys gives info about the kernel and devices
- somewhat reduced in Windows
- quite suppressed in Android (and more on iOS)

Different operating systems put different emphasis on the file system. We will take the way POSIX positions the file system as the baseline – in this case, the file system is quite central, in addition to regular files and directories, all sorts of special files appear in the file system and provide access to various OS facilities. However, there are also many services and APIs that are not based on the file system, including e.g. process management, memory management and so on. In many UNIX-like systems, the reliance on FS-based APIs is notched up a bit: e.g. process management is done via a virtual /proc filesystem (many different systems), or device discovery and configuration via /sys (Linux). Another level above that is Plan9, where essentially everything that can be made into a file system is made into one. Another experimental system, GNU/Hurd, has a similar ambition.

If we go the other way from POSIX, we have the native Windows APIs, which emphasise the file system much less than would be typical in POSIX. Most objects have dedicated APIs, even if they are rather file-like. However, the file system is still prominently present both in the APIs and in the user interface. Both are further suppressed by modern 'scaled-down' operating systems like Android and iOS (even if both are POSIX-compatible under the hood, 'normal' applications are not allowed to access the POSIX API, or the file system, and it is usually also hidden from users).

The Filesystem API

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- you open a file (using the open() syscall)
- you can read() and write() data
- you close() the file when you are done
- you can rename() and unlink() files
- you can use mkdir() to create directories

So how does the file system API look on POSIX systems? To work with a file, you usually need to open it first: you supply a path and some flags to tell the OS what you intend to do with the file. More on that in a short while. When you have a file open, you can read data from it and write data into it. When you are done, you use close to free up the associated resources. To work with directories, you usually don't need to open them (though you can). You can rename files (this is a directory operation) using rename, remove them from the file system hierarchy using unlink (this erases the corresponding directory entry), and you can create new directories using mkdir.

File Descriptors

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- the kernel keeps a table of open files
- the file descriptor is an index into this table
- you do everything using file descriptors
- non-Unix systems have similar concepts
  - descriptors are called handles on Windows

Remember open? When we want to work with a file, we need a way to identify that file, and paths are not super convenient in this respect: someone could rename the file we were working with, and suddenly it is gone, or worse, the file could be replaced by a different file or even a directory. Additionally, looking up a file by its path is a comparatively expensive operation: the OS has to read every directory mentioned in the path and run a lookup on it. While this information is often cached in RAM, it still takes valuable time.

When we open a file, we get back a file descriptor – this is a small integer, and using this descriptor as an index into a table, the kernel can look up all the metadata it needs (to carry out reads and writes) in constant time. The descriptor is also associated with the file directly, so if the file is moved around or even unlinked from the directory tree, the descriptor still points to the same file.

Most non-POSIX file system APIs have a similar notion (sometimes open does not return a number but a different data type, e.g. a pointer, and sometimes this value is called a handle instead of a descriptor... but the concept is more or less the same).

Regular files

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- these contain sequential data (bytes)
- may have inner structure but the OS does not care
- there is metadata attached to files
  - like when were they last modified
  - who can and who cannot access the file
- you `read()` and `write()` files

A regular file is what it appears to be. It is a sequence of bytes, stored on a persistent storage device and has metadata associated that makes it possible to locate all that data in actual disk sectors. The bytes inside the file are of no concern to the operating system. When data is read from a file, the operating system consults the file system metadata to find the particular sectors on disk that store the content. When data is overwritten, the same thing happens but those sectors are rewritten with the new data. When new data is appended, the operating system looks up some free space on the disk, then adjusts the file metadata to point at the (now taken) sectors and writes the data in there. There is some additional metadata stored alongside each file, like whom it belongs to or when it was modified.

Directories

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- a list of files and other directories
  - internal nodes of the filesystem tree
  - directories give names to files
- can be opened just like files
  - but `read()` and `write()` is not allowed
  - files are created with `open()` or `creat()`
  - directories with `mkdir()`
  - directory listing with `opendir()` and `readdir()`

A directory is a (potentially) internal node in the file hierarchy: their role is to give names to files, making them accessible via paths. Like regular files, directories are self-contained objects, but instead of raw bytes, they contain structured data: namely, a directory maps file names to other files (those can be regular files, other directories, or one of the special file types we will talk about shortly).
In principle, it would be possible to implement `read` and `write` for directories, but this would be problematic: if those functions dealt with the actual on-disk representation of a directory, user programs could easily corrupt directory entries. This is quite undesirable: instead, under normal circumstances, directories are used via paths: when we present a file path to `open`, the operating system will automatically traverse directories as needed.
Of course, user programs sometimes need to iterate through all directory entries, i.e. list all files in a given directory. To this end, POSIX provides the `opendir` function along with `readdir`, `seekdir`, `closedir` and so on. These functions provide a high-level API for interacting with directories. Nonetheless, this API is read-only: directory entries are created whenever files are created using the corresponding path, e.g. using `mkdir` or `open` with the `O_CREAT` flag.

Mounts

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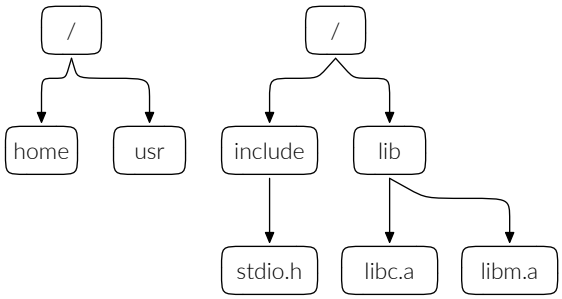
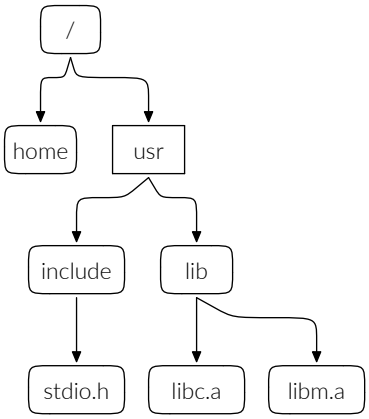
- UNIX joins all file systems into a single hierarchy
- the root of one filesystem becomes a directory in another
  - this is called a mount point
- Windows uses drive letters instead (`C:`, `D:` &c.)

A single computer (and hence, a single operating system) may have more than one hard drive available to it. In this case, it is customary that each such device contains its own file system: the question arises, how to present such multiple file systems to the user. The UNIX strategy is to present all the file systems within a single directory tree: to this end, one of the file systems is picked as a root file system: in this (and only in this) file system, the FS root directory `/` is the same as the system root directory. All other file systems are joined existing directories of other file systems at their root. Consider two file systems:



If we now mount the second file system onto the `/usr` directory of the first, we get the following unified hierarchy:



Usually, file systems are mounted onto empty directories: if `/usr` was not empty on the left (root) file system, its content would be hidden by the mount.
The other strategy is to present multiple file systems using multiple separate trees. This is the strategy implemented by the MS Windows family of operating systems: each file system is assigned a single letter, and each becomes its own, separate tree.

Pipes

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- pipes are a simple communication device
- one program can `write()` data to the pipe
- another program can `read()` that same data
- each end of the pipe gets a file descriptor
- a pipe can live in the filesystem (named pipe)

Pipes are somewhat like files in that it's possible to write data (bytes) into them, and read data from them. In most cases, the program doing the writing is a different program from the one doing the reading. Unlike a regular file, the data is not permanently stored anywhere: it disappears from the pipe as soon as it is read.
Of course, there is a buffer associated with a pipe, but it is only stored in RAM. This allows the writing process to write data even if the other end is not actively reading at the same time: the OS will buffer the write until such time it can be read.
Normally, a pipe is an anonymous device, only accessible via file descriptors. When these are closed, the device is destroyed. There is another variant of a pipe, though, called a named pipe which is given

a name in the file system. This does not mean the data is stored anywhere: a named pipe operates just like an anonymous pipe, the difference is that it can be passed to open using its a path.

Devices

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- block and character devices are (special) files
- block devices are accessed one block at a time
  - a typical block device would be a disk
  - includes USB mass storage, flash storage, etc
  - you can create a file system on a block device
- character devices are more like normal files
  - terminals, tapes, serial ports, audio devices

As we have already mentioned, many peripheral devices look like sequences of bytes, or possibly as sequences of blocks. A typical block device is addressable: the user can seek to a particular location of the device and read a chunk of data (an integer number of blocks). Unless someone writes to a particular location of the device, reading from the same address multiple times will yield the same data.
On the other hand, character devices often behave rather like pipes, in the sense that if a program writes some bytes into the device, reading the device will not yield those same bytes. Instead, character devices usually mediate communication with a peripheral that consumes bytes (which are written into the device) and/or provides some output (which is what the program gets when it reads from the device). Consider a printer: writing bytes into the printer's character device will cause those bytes to be printed (after possibly being interpreted by the printer).
Another example would be that after a scanner has been instructed to scan a document, the pixels captured by its optical sensor can be, in some form, extracted by reading from its character device. Essentially, these types of character devices behave like a pipe, but instead of another program, the other end is a hardware device (or rather its firmware).

Sockets

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- the socket API comes from early BSD Unix
- socket represents a (possible) network connection
- sockets are more complicated than normal files
  - establishing connections is hard
  - messages get lost much more often than file data
- you get a file descriptor for an open socket
- you can `read()` and `write()` to sockets

Sockets are, in some sense, a generalization of pipes. There are essentially 3 types of sockets:

1. a listening socket, which allows many clients to connect to a single server – strictly speaking, these sockets do not transport data, instead, they allow processes to establish connections,
2. a connected socket, one of which is created for each connection and which behaves essentially like a bidirectional pipe (standard pipes being unidirectional),
3. a datagram socket, which can be used to send data without establishing connections, using special send/receive API.

While the third is rather special and un-pipe-like, the first two are usually used together as a point-to-multipoint means of communication: the server listens on an address, and any client which has this address can establish communication with the server. This is quite unlike pipes, which usually need to be pre-arranged (i.e. the programs must already be aware of each other).

Socket Types

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- sockets can be internet or unix domain
  - internet sockets connect to other computers
  - Unix sockets live in the filesystem
- sockets can be stream or datagram
  - stream sockets are like files
  - you can write a continuous stream of data
  - datagram sockets can send individual messages

There are two basic address types: internet sockets, which are used for inter-machine communication (using TCP/IP), and unix domain sockets, which are used for local communication. A unix socket is like a named pipe: it has a path in the file system, and which client programs can use to establish a connection to the server.

Review Questions

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5. What is a shared (dynamic) library?
6. What does a linker do?
7. What is a symbol in an object file?
8. What is a file descriptor?

Part 3: The Kernel

This lecture is about the kernel, the lowest layer of an operating system. It will be in 5 parts:

Lecture Overview

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1. privileged mode
2. booting
3. kernel architecture
4. system calls
5. kernel-provided services

First, we will look at processor modes and how they mesh with the layering of the operating system. We will move on to the boot process, because it somewhat illustrates the relationship between the kernel and other components of the operating system, and also between the firmware and the kernel. We will look in more detail at kernel architecture: things that we already hinted at in previous lectures, and will also look at exokernels and unikernels, in addition to the architectures we already know (micro and monolithic kernels).
The fourth part will focus on system calls and their binary interface – i.e. how system calls are actually implemented at the machine level. This is closely related to the first part of the lecture about processor modes, and builds on the knowledge we gained last week about how system calls look at the C level.
Finally, we will look at what are the services that kernels provide to the rest of the operating system, what are their responsibilities and we will also look more closely at how microkernel and hybrid operating

systems work.

Reminder: Software Layering

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- → the kernel ←
- system libraries
- system services / daemons
- utilities
- application software

Part 3.1: Privileged Mode

CPU Modes

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- CPUs provide a privileged (supervisor) and a user mode
- this is the case with all modern general-purpose CPUs
  - not necessarily with micro-controllers
- x86 provides 4 distinct privilege levels
  - most systems only use ring 0 and ring 3
  - Xen paravirtualisation uses ring 1 for guest kernels

There is a number of operations that only programs running in supervisor mode can perform. This allows kernels to enforce boundaries between user programs. Sometimes, there are intermediate privilege levels, which allow finer-grained layering of the operating system. For instance, drivers can run in a less privileged level than the 'core' of the kernel, providing a level of protection for the kernel from its own device drivers. You might remember that device drivers are the most problematic part of any kernel.
In addition to device drivers, multi-layer privilege systems in CPUs can be used in certain virtualisation systems. More about this towards the end of the semester.

Privileged Mode

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- many operations are restricted in user mode
  - this is how user programs are executed
  - also most of the operating system
- software running in privileged mode can do ~anything
  - most importantly it can program the MMU
  - the kernel runs in this mode

The kernel executes in privileged mode of the processor. In this mode, the software is allowed to do anything that's possible. In particular, it can (re)program the memory management unit (MMU, see next slide). Since MMU is how program separation is implemented, code executing in privileged mode is allowed to change the memory of any program running on the computer. This explains why we want to reduce the amount of code running in supervisor (privileged) mode to a minimum. The way most operating systems operate, the kernel is the only piece of software that is allowed to run in this mode. The code in system libraries, daemons and so on, including application software, is restricted to the user mode of the processor. In this mode, the MMU cannot be programmed, and the software can only do what the MMU allows based on the instructions it got from the kernel.

Memory Management Unit

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- is a subsystem of the processor
- takes care of address translation
  - user software uses virtual addresses
  - the MMU translates them to physical addresses
- the mappings can be managed by the OS kernel

Let's have a closer look at the MMU. Its primary role is address translation. Addresses that programs refer to are virtual – they do not correspond to fixed physical locations in memory chips. Whenever you look at, say, a pointer in C code, that pointer's numeric value is an address in some virtual address space. The job of the MMU is to translate that virtual address into a physical one – which has a fixed relationship with some physical capacitor or other electronic device that remembers information.
How those addresses are mapped is programmable: the kernel can tell the MMU how the translation goes, by providing it with translation tables. We will discuss how page tables work in a short while; what is important now is that it is the job of the kernel to build them and send them to the MMU.

Paging

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- physical memory is split into frames
- virtual memory is split into pages
- pages and frames have the same size (usually 4KiB)
- frames are places, pages are the content
- page tables map between pages and frames

Before we get to virtual addresses, let's have a look at the other major use for the address translation mechanism, and that is paging. We do so, because it perhaps better illustrates how the MMU works. In this viewpoint, we split physical memory (the physical address space) into frames, which are storage areas: places where we can put data and retrieve it later. Think of them as shelves in a bookcase.
The virtual address space is then split into pages: actual pieces of data of some fixed size. Pages do not physically exist, they just represent some bits that the program needs stored. You could think of a page as a really big integer. Or you can think of pages as a bunch of books that fits into a single shelf.
The page table, then, is a catalog, or an address book of sorts. Programs attach names to pages – the books – but the hardware can only locate shelves. The job of the MMU is to take a name of the book and find the physical shelf where the book is stored. Clearly, the operating system is free to move the books around, as long as it keeps the page table – the catalog – up to date. Remaining software won't know the difference.

Swapping Pages

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- RAM used to be a scarce resource
- paging allows the OS to move pages out of RAM
  - a page (content) can be written to disk
  - and the frame can be used for another page
- not as important with contemporary hardware
- useful for memory mapping files (cf. next lecture)

If we are short on shelf space, we may want to move some books into storage. Then we can use the shelf we freed up for some other books. However, hardware can only retrieve information from shelves and therefore if a program asks for a book that is currently in storage, the operating system must arrange things so that it is moved from storage

to a shelf before the program is allowed to continue.
This process is called swapping: the OS, when pressed for memory, will evict pages from RAM onto disk or some other high-capacity (but slow) medium. It will only page them back in when they are required. In contemporary computers, memory is not very scarce and this use-case is not very important.
However, it allows another neat trick: instead of opening a file and reading it using `open` and `read` system calls, we can use so-called memory mapped files. This basically provides the content of the file as a chunk of memory that can be read or even written to, and the changes are sent back to the filesystem. We will discuss this in more detail next week.

Look Ahead: Processes

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- process is primarily defined by its address space
  - address space meaning the valid virtual addresses
- this is implemented via the MMU
- when changing processes, a different page table is loaded
  - this is called a context switch
- the page table defines what the process can see

We will deal with processes later in the course, but let me just quickly introduce the concept now, so that we can appreciate how important the MMU is for a modern operating system. Each process has its own address space which describes what addresses are valid for that process. Barring additional restrictions, the process can write to any of its valid addresses and then read back the stored value from that address.
The fact that the address space of a process is abstract and not tied to any particular physical layout of memory is quite important. Another important observation is that the address space does not need to be contiguous, and that not all physical memory has to be visible in that address space.

Memory Maps

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- different view of the same principles
- the OS maps physical memory into the process
- multiple processes can have the same RAM area mapped
  - this is called shared memory
- often, a piece of RAM is only mapped in a single process

We can look at the same thing from another point of view. Physical memory is a resource, and the operating system can 'hand out' a piece of physical memory to a process. This is done by mapping that piece of memory into the address space of the process. There is nothing that, in principle, prevents the operating system from mapping the same physical piece of RAM into multiple processes. In this case, the data is only stored once, but either process can read it using an address in its virtual address space (possibly at a different address in each process). For 'working' memory – that is both read and written by the program – it is most common that any given area of physical memory is only mapped into a single process. Instructions are, however, shared much more often: for instance a shared library is often mapped into multiple different processes. An executable itself may likewise be mapped into a number of processes if they all run the same program.

Page Tables

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- the MMU is programmed using translation tables
  - those tables are stored in RAM
  - they are usually called page tables
- and they are fully in the management of the kernel
- the kernel can ask the MMU to replace the page table
  - this is how processes are isolated from each other

The actual implementation mechanism of virtual memory is known as page tables: those are translation tables that tell the MMU which virtual address maps to which physical address. Page tables are stored in memory, just like any other data, and can be created and changed by the kernel. The kernel usually keeps a separate set of page tables for each process, and when a context switch happens, it asks the MMU to replace the active page table with a new one (the one that belongs to the process which is being activated). This is usually achieved by storing the physical address of the first level of the new page table (the page directory, in x86 terminology) in a special register.
Often, the writable physical memory referenced by the first set of page tables will be unreachable from the second set and vice versa. Even if there is overlap, it will be comparatively small (processes can request shared memory for communicating with each other). Therefore, whatever data the previous process wrote into its memory becomes completely invisible to the new process.

Kernel Protection

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- kernel memory is usually mapped into all processes
  - this improves performance on many CPUs
  - (until meltdown hit us, anyway)
- kernel pages have a special 'supervisor' flag set
  - code executing in user mode cannot touch them
  - else, user code could tamper with kernel memory

Replacing the page tables is usually a rather expensive operation and we want to avoid doing it as much as possible. We especially want to avoid it in the system call path (you probably remember system calls from last week, and we will talk about system calls in more detail later today). For this reason, it is a commonly employed trick to map the kernel into each process, but make the memory inaccessible to user-space code. Unfortunately, there have been some CPU bugs which make this less secure than we would like.

Part 3.2: Booting

The boot process is a sequence of steps which starts with the computer powered off and ends when the computer is ready to interact with the user (via the operating system).

Starting the OS

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- upon power on, the system is in a default state
  - mainly because RAM is volatile
- the entire platform needs to be initialised
  - this is first and foremost the CPU
  - and the console hardware (keyboard, monitor, ...)
  - then the rest of the devices

Computers can be turned off and on (clearly). When they are turned off, power is no longer available and dynamic RAM will, without ac-

tive refresh, quickly forget everything it held. Hence when we turn the computer on, there is nothing in RAM, the CPU is in some sort of default state and variations of the same are true of pretty much every sub-device in the computer. Except for the content of persistent storage, the computer is in the state it was when it left the factory door. The computer in this state is, to put it bluntly, not very useful.

Boot Process

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- the process starts with a built-in hardware init
- when ready, the hardware hands off to the firmware
  - this was BIOS on 16 and 32 bit systems
  - replaced with EFI on current amd64 platforms
- the firmware then loads a bootloader
- the bootloader loads the kernel

We will not get into the hardware part of the sequence. The switch is flipped, the hardware powers up and does its thing. At some point, firmware takes over and does some more things. The hardware and firmware is finally put into a state, where it can begin loading the operating system. There is usually a piece of software that the firmware loads from persistent storage, called a bootloader. This bootloader is, more or less, a part of the operating system: its purpose is to find and load the kernel (from persistent storage, usually by using firmware services to identify said storage and load data from it). It may or may not understand file systems and similar high-level things. In the simplest case, the bootloader has a list of disk blocks in which the kernel is stored, and requests those from the firmware. In modern systems, both the firmware and the bootloader are quite sophisticated, and understand complicated, high-level things (including e.g. encrypted drives).

Boot Process (cont'd)

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- the kernel then initialises device drivers
- and the root filesystem
- then it hands off to the init process
- at this point, the user space takes over

We are finally getting to familiar ground. The bootloader has loaded the kernel into RAM and jumped at a pre-arranged address inside the kernel image. The instructions stored at that address kickstart the kernel initialization sequence. The first part is usually still rather low-level: it puts the CPU and some basic peripherals (console, timers and so on) into a state in which the operating system can use them. Then it hands off control into C code, which then sets up basic data structures used by the kernel. Then the kernel starts initializing individual peripheral devices – this task is performed by individual device drivers. When peripherals are initialized, the kernel can start looking for the root filesystem – it is usually stored on one of the attached persistent storage devices (which should now be operational and available to the kernel via their device drivers).
After mounting the root filesystem, the kernel can set up an empty process and load the init program into that process, and hand over control. At this point, kernel stops behaving like a sequential program with main in it and fades into background: all action is driven by user-space processes from now on (or by hardware interrupts, but we will talk about those much later in the course).

User-mode Initialisation

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- init mounts the remaining file systems
- the init process starts up user-mode system services
- then it starts application services
- and finally the login process

We are far from done. The init process now needs to hunt down all the other file systems and mount them, start a whole bunch of system services and perhaps some application services (daemons which are not part of the operating system – things like web servers).
Once all the essential services are ready, init starts the login process, which then presents the familiar login screen, asking the user to type in their name and password. At this point, the boot process is complete, but we will have a quick look at one more step.

After Log-In

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- the login process initiates the user session
- loads desktop modules and application software
- drops the user in a (text or graphical) shell
- now you can start using the computer

When the user logs in, another initialization sequence starts: the system needs to set up a session for the user. Again, this involves some steps, but at the end, it's finally possible to interact with the computer.

CPU Init

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- this depends on both architecture and platform
- on x86, the CPU starts in 16-bit mode
- on legacy systems, BIOS & bootloader stay in this mode
- the kernel then switches to protected mode during its boot

Let's go back to start and fill in some additional details. First of all, what is the state of the CPU at boot, and why does the operating system need to do anything? This has to do with backward compatibility: a CPU usually starts up in the most-compatible mode – in case of 32b x86 processors, this is 16b mode with the MMU disabled. Since the entire platform keeps backward compatibility, the firmware keeps the CPU in this mode and it is the job of either the bootloader or the kernel itself to fix this. This is not always the case (modern 64b x86 processors still start up in 16b mode, but the firmware puts them into long mode – that is the 64b one – before handing off to the bootloader).

Bootloader

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- historically limited to tens of kilobytes of code
- the bootloader locates the kernel on disk
  - may allow the operator to choose different kernels
  - limited understanding of file systems
- then it loads the kernel image into RAM
- and hands off control to the kernel

A bootloader is a short, platform-specific program which loads the kernel from persistent storage (usually a file system on a disk) and hands off execution to the kernel. The bootloader might do some very basic hardware initialization, but most of that is done by the kernel itself in a later stage.

Modern Booting on x86

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- the bootloader nowadays runs in protected mode
  - or even the long mode on 64-bit CPUs
- the firmware understands the FAT filesystem
  - it can load files from there into memory
  - this vastly simplifies the boot process

The boot process has been considerably simplified on x86 computers in the last decade or so. Much higher-level APIs have been added to the standardized firmware interface, making the boot code considerably simpler.

Booting ARM

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- on ARM boards, there is no unified firmware interface
- U-boot is as close as one gets to unification
- the bootloader needs low-level hardware knowledge
- this makes writing bootloaders for ARM quite tedious
- current U-boot can use the EFI protocol from PCs

Unlike the x86 world, the ARM ecosystem is far less standardized and each system on a chip needs a slightly different boot process. This is extremely impractical, since there are dozens of SoC models from many different vendors, and new ones come out regularly. Fortunately, U-boot has become a de-facto standard, and while U-boot itself still needs to be adapted to each new SoC or even each board, the operating system is, nowadays, mostly insulated from the complexity.

Part 3.3: Kernel Architecture

In this section, we will look at different architectures (designs) of kernels: the main distinction we will talk about is which services and components are part of the kernel proper, and which are outside of the kernel.

Architecture Types

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- monolithic kernels (Linux, *BSD)
- microkernels (Mach, L4, QNX, NT, ...)
- hybrid kernels (macOS)
- type 1 hypervisors (Xen)
- exokernels, rump kernels

We have already mentioned the main two kernel types earlier in the course. Those types represent the extremes of mainstream kernel design: microkernels are the smallest (most exclusive) mainstream design, while monolithic kernels are the biggest (most inclusive). Systems with hybrid kernels are a natural compromise between those two extremal designs: they have 2 components, a microkernel and a so-called server, which is essentially a gutted monolithic kernel – that is, the functionality covered by the microkernel is removed.
Besides 'mainstream' kernel designs, there are a few more exotic choices. We could consider type 1 (bare metal) hypervisors to be a special type of an operating system kernel, where applications are simply virtual machines – i.e. 'normal' operating systems (more on this later in the course). Then there are exokernel operating systems, which drastically cut down on services provided to applications and unikernels which are basically libraries for running entire applications in kernel mode.

Microkernel

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- handles memory protection
- (hardware) interrupts
- task / process scheduling
- message passing

- everything else is separate

A microkernel handles only the essential services – those that cannot be reasonably done outside of the kernel (that is, outside of the privileged mode of the CPU). This obviously includes programming the MMU (i.e. management of address spaces and memory protection), handling interrupts (those switch the CPU into privileged mode, so at least the initial interrupt routine needs to be part of the kernel), thread and process switching (and typically also scheduling) and finally some form of inter-process communication mechanism (typically message passing). With those components in the kernel, almost everything else can be realized outside the kernel proper (though device drivers do need some additional low-level services from the kernel not listed here, like DMA programming and delegation of hardware interrupts).

Monolithic Kernels

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- all that a microkernel does
- plus device drivers
- file systems, volume management
- a network stack
- data encryption, ...

A monolithic kernel needs to include everything that a microkernel does (even though some of the bits have a slightly different form, at least typically: inter-process communication is present, but may be of different type, driver integration looks different). However, there are many additional responsibilities: many device drivers (those that need interrupts or DMA, or are otherwise performance-critical) are integrated into the kernel, as are file systems and volume (disk) management. A complete TCP/IP stack is almost a given. A number of additional bits and pieces might be part of the kernel, like cryptographic services (key management, disk encryption, etc.), packet filtering, a kitchen sink and so on. Of course, all that code runs in privileged mode, and as such has complete power over the operating system and the computer as a whole.

Microkernel Redux

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- we need a lot more than a microkernel provides
- in a "true" microkernel OS, there are many modules
- each device driver runs in a separate process
- the same for file systems and networking
- those modules / processes are called servers

The question that now arises is who is responsible for all the services listed on the previous slide (those that are part of a monolithic kernel, but are missing from a microkernel). In a 'true' microkernel operating system, those services are individually covered, each by a separate process (also known as a server in this context).

Hybrid Kernels

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- based around a microkernel
- and a gutted monolithic kernel

- the monolithic kernel is a big server
  - takes care of stuff not handled by the microkernel
  - easier to implement than true microkernel OS
  - strikes middle ground on performance

In a hybrid kernel, most of the services are provided by a single large server, which is somewhat isolated from the hardware. It is often the case that the server is based on a monolithic OS kernel, with the lowest-level layers removed, and replaced with calls to the microkernel as appropriate.
Hybrid kernels are both cheaper to design and theoretically perform better than 'true' (multi-server) microkernel systems.

Micro vs Mono

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- microkernels are more robust
- monolithic kernels are more efficient
  - less context switching
- what is easier to implement is debatable
  - in the short view, monolithic wins
- hybrid kernels are a compromise

The main advantage of microkernels is their robustness in face of software bugs. Since the kernel itself is small, chances of a bug in the kernel proper are much diminished compared to the relatively huge code base of a monolithic kernel. The impact of bugs outside the kernel (in servers) is considerably smaller, since those are isolated from the rest of the system and even if they provide vital services, the system can often recover from a failure by restarting the failed server.
On the other hand, monolithic kernels offer better performance, mainly through reduced context switching, which is still fairly expensive even on modern, virtualisation-capable processors. However, as monolithic kernels adopt technologies such as kernel page table isolation to improve their security properties, the performance difference becomes smaller.
Implementation-wise, monolithic kernels offer two advantages: in many cases, code can be written in direct, synchronous style, and different parts of the kernel can share data structures without additional effort. In contrast, a proper multi-server system often has to use asynchronous communication (message passing) to achieve the same goals, making the code harder to write and harder to understand. Long-term, improved modularity and isolation of components could outweigh the short-term gains in programming efficiency due to more direct programming style.

Exokernels

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- smaller than a microkernel
- much fewer abstractions
  - applications only get block storage
  - networking is much reduced
- only research systems exist

Operating systems based on microkernels still provide the full suite of services to their applications, including file systems, network stacks and so on. The difference lies in where this functionality is implemented, whether the kernel proper, or in a user-mode server. With exokernels, this is no longer true: the services provided by the operating system are severely cut down. The resulting system is somewhere between a paravirtualized computer (we will discuss this concept in more detail near the end of the course) and a 'standard' operating system. Unlike virtual machines (and unikernels), process-based application isolation is still available, and plays an important role. No production systems based on this architecture currently exist.

Type 1 Hypervisors

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- also known as bare metal or native hypervisors
- they resemble microkernel operating systems
  - or exokernels, depending on the viewpoint
- "applications" for a hypervisor are operating systems
  - hypervisor can use coarser abstractions than an OS
  - entire storage devices instead of a filesystem

A bare metal hypervisor is similar to an exokernel or a microkernel operating system (depending on a particular hypervisor and on our point of view). Typically, a hypervisor provides interfaces and resources that are traditionally implemented in hardware: block devices, network interfaces, a virtual CPU, including a virtual MMU that allows the 'applications' (i.e. the guest operating systems) to take advantage of paging.

Unikernels

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- kernels for running a single application
  - makes little sense on real hardware
  - but can be very useful on a hypervisor
- bundle applications as virtual machines
  - without the overhead of a general-purpose OS

Unikernels constitute a different strand (compared to exokernels) of minimalist operating system design. In this case, process-level multitasking and address space isolation are not part of the kernel: instead, the kernel exists to support a single application by providing (a subset of) traditional OS abstractions like a networking stack, a hierarchical file system and so on. When an application is bundled with a compatible unikernel, the result can be executed directly on a hypervisor (or an exokernel).

Exo vs Uni

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- an exokernel runs multiple applications
  - includes process-based isolation
  - but abstractions are very bare-bones
- unikernel only runs a single application
  - provides more-or-less standard services
  - e.g. standard hierarchical file system
  - socket-based network stack / API

Part 3.4: System Calls

In the remainder of this lecture, we will focus on monolithic kernels, since the more progressive designs do not use the traditional system call mechanism. In those systems, most 'system calls' are implemented through message passing, and only services provided directly by the microkernel use a mechanism that resembles system calls as described in this section.

Reminder: Kernel Protection

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- kernel executes in privileged mode of the CPU
- kernel memory is protected from user code

But: Kernel Services

- user code needs to ask kernel for services
- how do we switch the CPU into privileged mode?
- cannot be done arbitrarily (security)

The main purpose of the system call interface is to allow secure transfer of control between a user-space application and the kernel. Recall that each executes with different level of privileges (at the CPU level). A viable system call mechanism must allow the application to switch the CPU into privileged mode (so that the CPU can execute kernel code), but in a way that does not allow the application to execute its own code in this mode.

System Calls

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- hand off execution to a kernel routine
- pass arguments into the kernel
- obtain return value from the kernel
- all of this must be done safely

We would like system calls to behave more-or-less like standard subroutines (e.g. those provided by system libraries): this means that we want to pass arguments to the subroutine and obtain its return value. Like with the transfer of control flow, we need the argument passing to be safe: the user-space side of the call must not be able to read or modify kernel memory.

Trapping into the Kernel

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- there are a few possible mechanisms
- details are very architecture-specific
- in general, the kernel sets a fixed entry address
  - an instruction changes the CPU into privileged mode
  - while at the same time jumping to this address

Security from execution of arbitrary code by the application is achieved by tying the privilege escalation (i.e. the entry into the privileged CPU mode) to a simultaneous transfer of execution to a fixed address, which the application is unable to change. The exact mechanism is highly architecture-dependent, but the principle outlined here is universal.

Trap Example: x86

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- there is an `int` instruction on those CPUs
- this is called a software interrupt
  - interrupts are normally a hardware thing
  - interrupt handlers run in privileged mode
- it is also synchronous
- the handler is set in `IDT` (interrupt descriptor table)

On traditional (32 bit) x86 CPUs, the preferred method of implementing the system call trap was through software interrupts. In this case, the application uses an `int` instruction, which causes the CPU to perform a process analogous to a hardware interrupt. The two important aspects are:

1. the CPU switches into privileged mode to execute the interrupt handler,
2. reads the address to jump to from an interrupt handler table, which is a data structure stored in RAM, at an address given by a special register.

The kernel sets up the interrupt handler table in such a way that user-level code cannot change it (via standard MMU-based memory protection). The register which holds its address cannot be changed outside of privileged mode.

Software Interrupts

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- those are available on a range of CPUs
- generally not very efficient for system calls
- extra level of indirection
  - the handler address is retrieved from memory
  - a lot of CPU state needs to be saved

A similar mechanism is available on many other processor architectures. There are, however, some downsides to using this approach for system calls, the main being their poor performance. Since the mechanism piggy-backs on the hardware variety of interrupts, the CPU usually saves a lot more computation state than would be required. As an additional inconvenience, there are multiple entry-points, which must therefore be stored in RAM (instead of a register), causing additional delays when the CPU needs to read the interrupt table. Finally, arguments must be passed through memory, since registers are reset by the interrupt, again contributing to increased latency.

Aside: SW Interrupts on PCs

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- those are used even in real mode
  - legacy 16-bit mode of 80x86 CPUs
  - BIOS (firmware) routines via `int 0x10` & `0x13`
  - MS-DOS API via `int 0x21`
- and on older CPUs in 32-bit protected mode
  - Windows NT uses `int 0x2e`
  - Linux uses `int 0x80`

On the ubiquitous x86 architecture, software interrupts were the preferred mechanism to provide services to application programs until the end of the 32-bit x86 era. Interestingly, x86 CPUs since 80386 offer a mechanism that was directly intended to implement operating system services (i.e. syscalls), but it was rather complex and largely ignored by operating system programmers.

Trap Example: `amd64` / `x86_64`

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- `sysenter` and `syscall` instructions
  - and corresponding `sysexit` / `sysret`
- the entry point is stored in a machine state register
- there is only one entry point
  - unlike with software interrupts
- quite a bit faster than interrupts

When x86 switched to a 64-bit address space, many new instructions found their way into the instruction set. Among those was a simple, single-entrypoint privilege escalation instruction. This mechanism avoids most of the overhead associated with software interrupts: computation state is managed in software, allowing compilers to only save and restore a small number of registers across the system call (instead of having the CPU automatically save its entire state into memory).

Which System Call?

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- often there are many system calls
  - there are more than 300 on 64-bit Linux
  - about 400 on 32-bit Windows NT
- but there is only a handful of interrupts
  - and only one `sysenter` address

Usually, there is only a single entry point (address) shared by all system calls. However, the kernel needs to be able to figure out which service the application program requested.

Reminder: System Call Numbers

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- each system call is assigned a number
- available as `SYS_write` &c. on POSIX systems
- for the "universal" `int syscall( int sys, ... )`
- this number is passed in a CPU register

This is achieved by simply sending the syscall number as an argument in a specific CPU register. The kernel can then decide, based on this number, which kernel routine to execute on behalf of the program.

System Call Sequence

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- first, `libc` prepares the system call arguments
- and puts the system call number in the correct register
- then the CPU is switched into privileged mode
- this also transfers control to the syscall handler

The first stage of a system call is executed in user mode, and is usually implemented in `libc`.

System Call Handler

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- the handler first picks up the system call number
- and decides where to continue
- you can imagine this as a giant `switch` statement

```
switch ( sysnum )
{
   case SYS_write: return syscall_write();
   case SYS_read: return syscall_read();
   /* many more */
}
```

After the switch to privileged mode, the kernel needs to make sense of the arguments that the user program provided, and most importantly, decide which system call was requested. The code to do this in the kernel might look like the above `switch` statement.

System Call Arguments

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- each system call has different arguments
- how they are passed to the kernel is CPU-dependent
- on 32-bit x86, most of them are passed in memory
- on amd64 Linux, all arguments go into registers
  - 6 registers available for arguments

Since different system calls expect different arguments, the specific argument processing is done after the system call is dispatched based on its number. In modern systems, arguments are passed in CPU registers, but this was not possible with protocols based on software interrupts (instead, arguments would be passed through memory, usually at the top of the user-space stack).

Part 3.5: Kernel Services

Finally, we will revisit the services offered by monolithic kernels, and look at how they are realized in microkernel operating systems.

What Does a Kernel Do?

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- memory & process management
- task (thread) scheduling
- device drivers
  - SSDs, GPUs, USB, bluetooth, HID, audio, ...
- file systems
- networking

The first two points are a core responsibility of the kernel: those are rarely 'outsourced' into external services. The remaining services are a core part of an operating system, but not necessarily of a kernel. However, it is hard to imagine a modern, general-purpose operating system which would omit any of them. In traditional (monolithic) designs, they are all part of the kernel.

Additional Services

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- inter-process communication
- timers and time keeping
- process tracing, profiling
- security, sandboxing
- cryptography

A monolithic kernel may provide a number of additional services, with varying importance. Not all systems provide all the services, and the implementations can look quite different across operating systems. Out of this (incomplete) list, IPC (inter-process communication) is the only item that is quite universally present, in some form, in microkernels. Moreover, while dedicated IPC mechanisms are common in monolithic kernels, they are more important in a microkernel.

Reminder: Microkernel Systems

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- the kernel proper is very small
- it is accompanied by servers
- in "true" microkernel systems, there are many servers
  - each device, filesystem, etc. is separate
- in hybrid systems, there is one, or a few
  - a "superserver" that resembles a monolithic kernel

Recall that a microkernel is small: it only provides services that cannot be reasonably implemented outside of it. Of course, the operating system as a whole still needs to implement those services. Two basic strategies are available:

1. a single program, running in a single process, implements all the missing functionality: this program is called a superserver, and internally has an architecture that is rather similar to that of a standard monolithic kernel,
2. each service is provided by a separate, specialized program, running in its own process (and hence, address space) – this is charac-

teristic of so-called 'true' microkernel systems.

There are of course different trade-offs involved in those two basic designs. A hybrid system (i.e. one with a superserver) is easier to initially design and implement (for instance, persistent storage drivers, the block layer, and the file system all share the same address space, simplifying the implementation) and is often considerably faster, since communication between components does not involve context switches. On the other hand, a true microkernel system with services and drivers all strictly separated into individual processes is more robust, and in theory also easier to scale to large SMP systems.

Kernel Services

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- we usually don't care which server provides what
  - each system is different
  - for services, we take a monolithic view
- the services are used through system libraries
  - they abstract away many of the details
  - e.g. whether a service is a system call or an IPC call

From a user-space point of view, the specifics of kernel architecture should not matter. Applications use system libraries to talk to the kernel in either case: it is up to the libraries in question to implement the protocol for locating relevant servers and interacting with them.

User-Space Drivers in Monolithic Systems

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- not all device drivers are part of the kernel
- case in point: printer drivers
- also some USB devices (not the USB bus though)
- part of the GPU/graphics stack
  - memory and output management in kernel
  - most of OpenGL in user space

While user-space drivers are par for the course in microkernel systems, there are also certain cases where drivers in operating systems based on monolithic kernels have significant user-space components. The most common example is probably printer drivers: low-level communication with the printer (at the USB level) is mediated by the kernel, but for many printers, document processing comprises a large part of the functionality of the driver. In some cases, this involves format conversion (e.g. PCL printers) but in others, the input document is rasterised by the driver on the main CPU: instead of sending text and layout information to the printer, the driver sends pixel data, or even a stream of commands for the printing head.

The situation with GPUs is somewhat analogous: low-level access to the hardware is provided by the kernel, but again, a large part of the driver is dedicated to data manipulation: dealing with triangle meshes, textures, lighting and so on. Additionally, modern GPUs are invariably *programmable*: a shader compiler is also part of the driver, translating high-level shader programs into instruction streams that can be executed by the CPU.

We will deal with device drivers in more detail in lecture 8.

Review Questions

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9. What CPU modes are there and how are they used?
10. What is the memory management unit?
11. What is a microkernel?
12. What is a system call?

Part 4: File Systems

File systems are an integral part of general-purpose operating systems. Besides storing user data, the programs and other components that make up an operating system also reside in the file system. In this lecture, we will look at some of the inner workings of a typical POSIX-compatible file system layer.

Lecture Overview

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1. Filesystem Basics
2. The Block Layer
3. Virtual Filesystem Switch
4. The UNIX Filesystem
5. Advanced Features

We will first revisit some of the basic concepts that have been already introduced in previous lectures. Afterwards, we will look at the block layer, which exists below the file system and provides a simpler data storage abstraction. Afterward, we will have a look at VFS, a system that kernels typically use to allow multiple implementations of the on-disk structures while providing a uniform system call interface on the outside.

Afterwards, we will look at both the semantics and the on-disk organization of a typical UNIX file system. Finally, we will take a quick look at some of the more advanced features present in modern file systems (and below, in the block layer).

Part 4.1: Filesystem Basics

In this section, we will consider the basic elements of a file system, as understood by POSIX – some of the material will also repeat concepts that we have seen earlier.

What is a File System?

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- a collection of files and directories
- (mostly) hierarchical
- usually exposed to the user
- usually persistent (across reboots)
- file managers, command line, etc.

The first concern is the definition of a file system as a whole. The most abstract view is that a file system is a collection of files and directories, where files are essentially byte sequences and directories give names to files and other directories. Since directories can contain other directories, the whole structure forms a tree (with some exceptions).

File systems are usually user-visible: the user can directly access the directory hierarchy and explore both directory and file content, using tools provided by the operating system. Another typical property of

a file system is that it is persistent: rebooting the computer will not erase or alter the data stored in the file system. (Note that both these properties have exceptions: file systems can be stored on virtual devices that use RAM for storage, and those are not persistent; likewise, some operating systems do not allow the user to directly access the file system).

What is a (Regular) File?

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- a sequence of bytes
- and some basic metadata
  - owner, group, timestamp
- the OS does not care about the content
  - text, images, video, source code are all the same
  - executables are somewhat special

Since we have defined a file system as a collection of files and directories, we will need to also give a definition of a file. Again, we can give a fairly abstract definition that works: a file is an object that consists of a sequence of bytes (the data) and some additional metadata – information about the file. The content (i.e. the byte sequence) is typically not interpreted by the operating system (apart from special cases, like executable files). The metadata contains things like the identifier of the owner of the file, a few timestamps (e.g. the time of last modification) and access permissions. Please note that the file metadata does not include a name: file name is not a property of the file itself in POSIX systems.

What is a Directory?

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- a list of name → file mappings
- an associative container if you will
  - semantically, the value types are not homogeneous
  - syntactically, they are just i-nodes
- one directory = one component of a path
  - `/usr/local/bin`

The last part of the definition of a file system that we did not explain yet is a directory. Directories are maps (associative arrays, dictionaries), where the keys are names and the values are files and other directories. In fact, both files and directories are represented by the same data structure in the file system: an i-node.
We also remember that directories form a tree, and we use paths to identify individual files and directories in the file system. Each component (a section delimited by / on either side) of such a path is used as a key in a single directory.

What is an i-node?

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- an anonymous, file-like object
- could be a regular file
  - or a directory
  - or a special file
  - or a symlink

The i-node is how files and directories (and any other file system object) is represented by the POSIX file system. The i-node stores references to data blocks (more on that later) and the metadata of the file.

Files are Anonymous

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- this is the case with UNIX
  - not all file systems work like this
- there are pros and cons to this approach
  - e.g. open files can be unlinked
- names are assigned via directory entries

As we have already mentioned, files do not carry names – i.e. the i-node does not have a field which would store the name of the object. Instead, a name is given to the file by a directory entry, which ties a string (anything goes as long as there are no / characters) to an i-node. Among other things, this means that it is possible to unlink files (remove their directory entries) without erasing their data: this happens when the file is currently open. When the last process closes its last file descriptor tied to that i-node, the data is finally erased from the disk.

What Else is a Byte Sequence?

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- characters coming from a keyboard
- bytes stored on a magnetic tape
- audio data coming from a microphone
- pixels coming from a webcam
- data coming on a TCP connection

We have previously mentioned that a byte sequence is a broadly applicable abstraction. There are many things that can be treated (with a bit of generosity) as byte sequences. Most of those are not persistent in the way files are, but this is not really a problem as far as programming interfaces go.

Writing Byte Sequences

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- sending data to a printer
- playing back audio
- writing text to a terminal (emulator)
- sending data over a TCP stream

In addition to reading bytes, files (and many other things) support writing bytes, i.e. storing or otherwise processing a sequence of bytes that is sent (written) to the object in question.

Special Files

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- many things look somewhat like files
- let's exploit that and unify them with files
- recall part 2 on APIs: "everything is a file"
  - the API is the same for special and regular files
  - not the implementation though

The generality of the abstraction makes it possible (and desirable) to represent all such objects uniformly, using the file system API. However, besides using the same API, many of those objects literally appear in the file system as i-nodes with special properties. Of course, when such a file is opened, reads and writes to the file descriptor are not handled by the same kernel routines that deal with regular files. More on this in a later section, on VFS.

File System Types

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- fat16, fat32, vfat, exfat (DOS, flash media)
- ISO 9660 (CD-ROMs)
- UDF (DVD-ROM)
- NTFS (Windows NT)
- HFS+ (macOS)
- ext2, ext3, ext4 (Linux)
- ufs, ffs (BSD)

Of course, there are many different implementations of the abstract idea of a file system. While many have identical or similar semantics (in most cases those described in this lecture and codified by POSIX), this is not always the case: file systems in the FAT family, for instance, do not have the concept of an i-node and file names are an intrinsic property of the file.
While the semantics are often similar, the underlying disk format can vary rather widely: while the ext family and ufs family use a fairly traditional approach, many modern file systems, such as ZFS, btrfs or hammer are internally built on B-trees, extendible hashing or other scalable data structures, which can handle much bigger volumes with many more files than the traditional, rather naive approaches. At the same time, modern file systems provide better resilience against corruption of their data structures in the event of errors or unexpected power loss.

Multi-User Systems

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- file ownership
- file permissions
- disk quotas

Multi-user systems come with an additional set of challenges when it comes to file system implementation. It is usually desirable that files of each user are inaccessible to any other user, unless the owner of the file desires to share that particular file. Likewise, we want to be able to limit how much space each user can take up, which is usually done via disk quotas.

Ownership & Permissions

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- we assume a discretionary model
- whoever creates a file is its owner
- ownership can be transferred
- the owner decides about permissions
  - basically read, write, execute

For these reasons, the system must be able to track:

1. file system ownership, i.e. remember which file belongs to which user,
2. file permissions, i.e. what the owner of the file deems as appropriate use of their file – whether other users (and which users) can read the content of the file, or even write new data or replace existing data in the file.

Under a discretionary access model, the owner can freely decide about the permissions. There are other models, where this ability is limited (usually to improve security).

Disk Quotas

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- disks are big but not infinite
- bad things happen when the file system fills up
  - denial of service
  - programs may fail and even corrupt data
- quotas limits the amount of space per user

Besides limiting what can be done with files, the system must also be able to manage free space in the file system: since file systems are stored on some physical medium, the amount of data that can be stored is limited. Disk quotas are a mechanism by which the operating system ensures fair allocation of the space among users (or at least prevents a single user to hog all the space in the file system).

Part 4.2: The Block Layer

The block layer (of an operating system) takes care of low-level access to persistent storage devices, such as hard drives, solid-state drives and other similar devices. The file system itself then does not need to understand the details of the underlying device or the protocol by which to communicate with that device. Instead, it uses a uniform API which allows the file system to store and retrieve blocks of data. Or, in other words, a block device is an abstraction which makes file system implementation both easier (fewer details to take care of) and more universal (does not depend on the particulars of a given storage device).

Disk-Like Devices

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- disk drives provide block-level access
- read and write data in 512-byte chunks
  - or also 4K on big modern drives
- a big numbered array of blocks

A block device (i.e. a disk-like device) has the following basic operations: it can read or write a block, which is a chunk of data of a fixed size. The specific size depends on the type of device, but the usual block sizes are either 512 bytes (in older devices) or 4096 bytes in more modern hardware. The blocks are numbered and the entire device essentially 'looks' like a big array of such blocks. Reading and writing blocks means, in this context, transferring the data stored in that block to or from main memory (RAM).

Aside: Disk Addressing Schemes

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- CHS: Cylinder, Head, Sector
  - structured adressing used in (very) old drives
  - exposes information about relative seek times
  - useless with variable-length cylinders
  - 10:4:6 CHS = 1024 cylinders, 16 heads, 63 sectors
- LBA: Logical Block Addessing
  - linear, unstructured address space
  - started as 22, later 28, ... now 48 bit

Old rotational drives used an addressing scheme which reflected their physical geometry. The address consisted of 3 numbers: the cylinder (distance from the center of the platter), the head (which platter or rather which side of which platter stores the sector) and the sector number (the angle at which the sector is stored). This allowed the dri-

ver and operating system to predict operation latency: reading sectors from the same cylinder would usually be fast, reading sectors from a different cylinder would require expensive head movements (known as 'seeking').
The CHS scheme was abandoned as disk capacities increased and the address space began to run out. The replacement, known as LBA or Logical Block Addressing, uses an unstructured, flat address space (the same as main memory, but the unit of addressing is a block, not a byte).

Block-Level Access

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- disk drivers only expose linear addressing
- one block (sector) is the minimum read/write size
- many sectors can be written 'at once'
  - sequential access is faster than random
  - maximum throughput vs IOPS

Higher layers of an operating system (starting with the block layer and file system implementation) do not care about the interface between the disk driver and the disk drive itself and always use linear addressing. Within the block layer, transfers are often re-organized to maximize sequential writes (we will discuss this shortly), because most disk drives can read or write a contiguous sequence of blocks much faster than they can read them one at a time.
The sequential access regime is important when we ask about the throughput of the system (how many bytes the device can supply or store per second), while the number of blocks that it can read or write when they are randomly distributed across the entire device is known as IOPS – input/output operations per second.

Aside: Access Times

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- block devices are slow (compared to RAM)
  - RAM is slow (compared to CPU)
- we cannot treat drives as an extension of RAM
  - not even fastest modern flash storage
  - latency: HDD 3–12 ms, SSD 0.1 ms, RAM 70 ns

The entire design of the storage stack, starting with hardware buses, all they way to file systems and even application-level software, most often database systems, is strongly influenced by the slowness of block devices. Even the latest flash-based drives are many times slower than RAM (which is many times slower than CPU caches, which are still slower than the computational units in the CPU).

Block Access Cache

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- caching is used to hide latency
  - same principle between CPU and RAM
- files recently accessed are kept in RAM
  - many cache management policies exist
- implemented entirely in the OS
  - many devices implement their own caching
  - but the amount of fast memory is usually limited

You already know that CPU relies on cache memory to hide latency of RAM: data that has been recently used, or that the system suspects will be required shortly, are stored in, or prefetched into, the much faster (but much smaller) cache. This means that for data that is most often used, the CPU does not need to wait out the entire RAM latency time.
The same principle is used by operating systems to hide the latency of block devices, but in this case, the 'fast' and 'small' memory is the main memory (RAM) while the big and slow memory is the block device. Unlike CPU cache, this so-called disk cache is implemented entirely in software.
However, there is usually another layer (or two) of caching, which is done in hardware or in drive firmware and which uses dedicated hardware buffers (usually implemented as dynamic RAM or even flash storage) on the device side of the bus. This is distinct from the OS-level cache and we will ignore it from now on.

Write Buffers

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- the write equivalent of the block cache
- data is kept in RAM until it can be processed
- must synchronise with caching
  - other users may be reading the file

There is one major difference between the CPU cache and the block device cache maintained by the OS: there is a persistence mismatch between the cache (RAM) and the main storage (disk). When the system powers down, the content of the RAM is lost and along with it, any modifications which were not yet replicated from the cache onto the persistent storage device. This creates a lot of complexity, since application software (and users) expect data written to disk to stay there. This is especially important (and problematic) in systems which need to be resistant to unexpected power loss, though operating system crashes can cause the same effect even if the system is hooked up to reliable power.
For this reason, many operating systems use a split cache design: data to be written is stored in write buffers and flushed to disk as bandwidth and other resources permit. Of course, data stored in write buffers must be replicated into the read cache (or otherwise shared with it), since other processes may be reading the same blocks (usually via the file system) and should see the new content.

I/O Scheduler (Elevator)

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- reads and writes are requested by users
- access ordering is crucial on a mechanical drive
  - not as important on an SSD
  - but sequential access is still much preferred
- requests are queued (recall, disks are slow)
  - but they are not processed in FIFO order

We have already mentioned that sequential access is much faster than randomly distributed access, and that latency in rotational drives depends on physical distance between the locations where individual pieces of data are stored. Since there is usually a lot of parallelism going on in the IO subsystems (different processes reading and writing different files at the same time), it often pays to re-order the requests for IO operations.
The desired effect is that a completely random sequence of IO operations coming in from multiple processes, say 16 requests where each request is in a different physical location from the previous, is re-ordered into 4 sets of 4 operations happening in physical proximity (or even in a sequence). This reordering can easily improve overall throughput of the system (in this example situation) 3-4x, since a single batch of 4 sequential operations takes barely any extra time on top of the random-access latency incurred on the first operation in that sequence.
The reordering is more easily done with buffered writes: in this case, the block layer is free to shuffle the write queue (subject to ordering constraints imposed by the file system or perhaps by the application). However, reading is more complicated: the OS can certainly speculate what read operations will be requested next. In systems with true asynchronous IO (where the application does not block until the IO is

finished), the read queue may be longer, but still more limited than the write queue.

RAID

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- hard drives are also unreliable
  - backups help, but take a long time to restore
- RAID = Redundant Array of Inexpensive Disks
  - live-replicate same data across multiple drives
  - many different configurations
- the system stays online despite disk failures

While speed of persistent storage is a major problem, its (lack of) reliability is also rather important. While the problem of speed is tackled with caching, reliability is usually improved through redundancy: in case a component fails, other components can take over. In case of storage, that means that the data must be replicated across multiple devices, in such a way that if one of them fails, the others can still put together a complete copy of the data.
RAID is a low-level realization of this principle. RAID can be implemented in hardware or in software, the latter being more common in present-day systems. Software RAID is part of the block layer of an operating system, and is usually presented to upper layers as a single virtual device. Reading and writing to this virtual device will cause the RAID subsystem of the block layer to distribute the data across multiple physical devices. Most RAID configurations can then continue operating without data loss (and without interruption) if one of the physical devices fails.

RAID Performance

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- RAID affects the performance of the block layer
- often improved reading throughput
  - data is recombined from multiple channels
- write performance is more mixed
  - may require a fair amount of computation
  - more data needs to be written for redundancy

In a fully functioning RAID array, read performance is usually significantly enhanced: the data is collected from multiple devices in parallel, each contributing part of the overall bandwidth.
Writing is less clear-cut: depending on the RAID configuration, writes may be faster or slower than a single disk. Writing to a software RAID array also consumes additional CPU cycles, since the operating system must slice the data (and often also compute checksums).

Block-Level Encryption

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- symmetric & length-preserving
- encryption key is derived from a passphrase
- also known as "full disk encryption"
- incurs a small performance penalty
- very important for security / privacy

Another feature commonly present in modern operating systems is block-level encryption of data. This hardens the system against offline attacks: e.g. if the computer is stolen, the data remains inaccessible without the encryption key (which is usually derived from a passphrase).
Disk encryption uses symmetric crypto (usually hardware-accelerated AES) and in most implementations, the encryption is length-preserving: a single block of data results in a single block of ciphertext which is then directly stored in the corresponding physical block of the persistent storage device. For most of the software stack, this type of encryption is completely transparent. Not even the file system implementation in the operating system needs to be aware that it is stored on an encrypted device.

Storing Data in Blocks

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- splitting data into fixed-size chunks is unnatural
- there is no permission system for individual blocks
  - this is unlike virtual (paged) memory
  - it'd be really inconvenient for users
- processes are not persistent, but block storage is

We are used to working with arbitrary-sized files, but this expectation does not map very neatly onto the block device abstraction, where data is stored in fairly big chunks. Additionally, the block layer does not offer a permission system or any kind of sharing or multiplexing: there are just blocks and a process can either read or write any of them, or none at all.
While main memory is also a rather dumb array of bytes, organized into pages (which are, in fact, rather block-like), the content of this main memory is much more dynamic and much less important to the user. Part of the distinction comes down to persistence, but other than that, it is really mostly just a historical accident.

Filesystem as Resource Sharing

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- usually only 1 or few disks per computer
- many programs want to store persistent data
- file system allocates space for the data
  - which blocks belong to which file
- different programs can write to different files
  - no risk of trying to use the same block

Nonetheless, there needs to be some mechanism for sharing persistent storage among different processes (and different users). This mechanism is, of course, the file system. Among other things, it manages allocation of free space into files, and maintains persistent identities of such files.

Filesystem as Abstraction

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- allows the data to be organised into files
- enables the user to manage and review data
- files have arbitrary & dynamic size
  - blocks are transparently allocated & recycled
- structured data instead of a flat block array

Block storage is not very convenient, and in almost all cases requires additional abstractions. We can draw an analogy with main memory: the flat array of bytes exposed by the CPU is not what programmers directly use: instead, this memory is managed by a memory allocator like `malloc`, which slices it up into logical objects of varying size which can be created and destroyed as needed.
The file system plays the same role for persistent storage. However, since the file system is shared among many processes, and even directly exposed to users, it needs to be organized more rigidly and intuitively. Instead of storing numeric pointers at arbitrary locations within files (as is the case with in-memory data structures), objects within a file system are strictly separated into objects which carry pointers (structure), i.e. directories, and data-carrying objects, i.e. regular files. Since each pointer in a directory is given a name, this organizational principle gives rise to the directory hierarchy as was discussed in lecture 2.

Part 4.3: Virtual Filesystem Switch

A typical kernel must be able to accommodate a fairly large number of different file system implementations: the native file system of the operating system, of course, but at minimum also file systems that are typically used on portable media, such as USB flash drives (FAT or exFAT) or optical media (ISO 9660, UDF). It is also often desirable that non-native file systems can be mounted, such as accessing NTFS volumes on Unix systems. Finally, there are file systems which are ported to a particular operating system because of their desirable properties, such as high performance, reliability or scalability and not for compatibility reasons alone (e.g. the SGI xfs ported from IRIX to Linux, or Sun/Oracle ZFS ported from Solaris to FreeBSD).
Additionally, a number of operating systems employ various virtual file systems (such as proc on many UNIX-like systems, or sys on Linux), which also present a unified interface with the other file systems.

Virtual File System Layer

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- many different filesystems
- the OS wants to treat them all alike
- VFS provides an internal, in-kernel API
- filesystem syscalls are hooked up to VFS

Since all the different file systems provide essentially the same semantics, and need to be available via a single unified API to the outside world, the kernel would ideally also treat them all alike. This is the role of the virtual file system switch or virtual file system layer.

VFS in OOP terms

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- VFS provides an abstract class, `filesystem`
- each filesystem implementation derives `filesystem`
  - e.g. `class iso9660 : public filesystem`
- each actual file system gets an instance
  - /home, /usr, /mnt/usbflash each one
  - the kernel uses the abstract interface to talk to them

If you have encountered object-oriented programming, this paradigm should be quite familiar: there is an interface which describes a file system, from the point of view of the kernel, in the abstract. Each specific file system implements this abstract interface, but from the point of view of the API, it doesn't really matter which file system it is, since they all provide a uniform API. Unlike the block layer, this abstraction is typically not visible from outside of the kernel. Nonetheless, it is still an important abstraction.

The `filesystem` Class

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```
struct handle { /* ... */ };
struct filesystem
{
    virtual int open( const char *path ) = 0;
    virtual int read( handle file, ... ) = 0;
    /* ... */
}
```

If we consider the VFS interface as a C++ class, this is approximately how it would look like. In particular, the handle is a possibly complex data structure: the file descriptor abstraction exists between the kernel and the user-space. Within kernel, it is much less useful, since it is, among other things, process-specific. When a file system implementation needs to work with a file, what it needs is a reference to the particular i-node which represents the file (or rather to its in-memory version), and perhaps an iterator into the file: ideally one that is more efficient than a mere offset, i.e. a data structure which can, without scanning through block lists in the i-node, pinpoint specific block (or blocks) which need to be fetched from disk.

Filesystem-Specific Operations

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- open: look up the file for access
- read, write – self-explanatory
- seek: move the read/write pointer
- sync: flush data to disk
- mmap: memory-mapped IO
- select: IO readiness notification

The VFS operations partially reflect the user-level file access API, with the above-mentioned caveats. The above list is an abridged version of the VFS interface as implemented in the Linux kernel. Since VFS is internal to the kernel, it is not standardized in any way, and different kernels approach the problem differently.

Standard IO

202

- the usual way to use files
- open the file
  - operations to read and write bytes
- data has to be buffered in user space
  - and then copied to/from kernel space
- not very efficient

The standard API for input and output is based around the read and write operations. Unfortunately, these are not always efficient, since the data must be copied between the file system cache and the (private) memory of the process requesting the operation. Efficiency of read-heavy workloads can be significantly improved by using memory-mapped IO instead. This is the case whether the program needs random access to the content of a file (i.e. seeks from place to place) or whether it simply wants to process a single byte at a time.

Memory-mapped IO

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- uses virtual memory (cf. last lecture)
- treat a file as if it was swap space
- the file is mapped into process memory
  - page faults indicate that data needs to be read
  - dirty pages cause writes
- available as the mmap system call

Memory-mapped IO uses the virtual memory subsystem to reduce the amount of copying and context switching involved in IO operations. Under this scheme, file data is (at least initially) shared between the block access cache and the process.
Modification of data can be handled in two ways:

1. modifications are private, e.g. when the process simply needs to adjust the data as part of processing, but does not wish to write the changes into the original file,
2. the changes are shared, i.e. the process intends to make changes to the data and write that data into the file afterwards.

In the first case, the mapping is done in a copy-on-write regime: the pages from cache are marked read-only for the process and write at-

tempts cause the operating system to make a new copy of the data in physical memory. Future reads and writes are then redirected into this new copy. In the second case, the pages are write-through – modifications by the process affect both the cache and, eventually, also the on-disk file (when the dirty pages are flushed to disk).

Sync-ing Data

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- recall that the disk is very slow
- waiting for each write to hit disk is inefficient
- but if data is held in RAM, what if power is cut?
  - the `sync` operation ensures the data has hit disk
  - often used in database implementations

A write operation on a file is, usually, asynchronous with regards to the physical medium. That is, control returns from a `write` system call long before the data is durably stored. This means that in case of a crash or a power loss, an application may be unable to recover data that it has already written. If it is important that a write is complete before computation continues, operating systems offer a `sync` system call (or a variation, like `fsync` and `fdatasync`) which ensures that all outstanding writes are sent to the device.

Filesystem-Agnostic Operations

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- handling executables
- `fcntl` handling
- special files
- management of file descriptors
- file locks

Within the kernel, part of file-system-related functionality is independent of a particular file system implementation, and is instead implemented in other kernel modules. One example would be the code which deals with executable files: let's assume that the file system implements memory mapping of files (which itself is partially implemented in the block layer and virtual memory subsystems). When a program (stored in a regular file on some file system) is executed, the responsible module of the operating system will request a memory mapping of the file through VFS, but the remainder of the code dealing with the `exec` system call does not need any file-system-specific knowledge.

Executables

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- memory mapped (like `mmap`)
- may be paged in lazily
- executables must be immutable while running
- but can be still unlinked from the directory

There are additional provisions regarding executable files. One of them is, that they are often „paged in" lazily: this is a concept that we will explore in more detail in lecture 5. This is, however, a compromise: it means that if a given executable is 'running' – that is, if a process exists which is currently executing the program stored in said executable – the operating system must disallow any writes to the file. Otherwise, the image, which may partially reside in memory and partially on disk, may be corrupted as pages that are already in memory are combined with pages that are loaded lazily from disk.
However, since the name of the file is external to the file itself, it is not a problem for running executables to be unlinked. When the last process which uses the executable terminates, the reference count on the i-node drops to zero and the i-node is reclaimed (including any data blocks it was using).

File Locking

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- multiple programs writing the same file is bad
  - operations will come in randomly
  - the resulting file will be a mess
- file locks fix this problem
  - multiple APIs: `fcntl` vs `flock`
  - differences on networked filesystems

The kernel offers a mechanism for locking files, making it possible for multiple processes to read and write a shared file safely (i.e. without corrupting it by issuing conflicting `write` calls concurrently). In POSIX, there are historically two separate mechanisms for locking files: the `flock` call, which locks the entire file at once, and the `fcntl` call, which can lock a range of bytes within a file.
There are, unfortunately, subtle problems with these locking APIs which makes them easy to misuse, related both to the `close` system call and to network file systems. We will not go into details, but if you intend to use file locking, it is a good idea to do some research on this.

The `fcntl` Syscall

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- mostly operations relating to file descriptors
  - synchronous vs asynchronous access
  - blocking vs non-blocking
  - close on exec: more on this in a later lecture
- one of the several locking APIs

This is another bit of the file system interface that does not normally need to interact with the VFS or with a specific file system implementation. In addition to exposing an API for locking files, the `fcntl` system call mainly interacts with the file descriptor table and various file descriptor flags: for instance, it can be used to enable synchronous IO, meaning that every `write` call will only return to the caller after the data has been sent to the storage device.
Likewise, `fcntl` can be used to set blocking (default) or non-blocking mode on a file descriptor: in non-blocking mode, if a write buffer is full, the system call will not wait for space to become available: instead, it will indicate to the program that the operation cannot be completed and that it should be retried at a later point. Likewise, if there is no data available (e.g. in a pipe or in a socket), a `read` operation will return immediately indicating that this is the case, instead of waiting for more data to become available (as it would in blocking mode).
The close-on-exec flag instructs the kernel to internally perform a `close` operation on this file descriptor in the event that an `exec` call is performed while the file descriptor is still open.

Special Files

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- device nodes, pipes, sockets, ...
- only metadata for special files lives on disk
  - this includes permissions & ownership
  - type and properties of the special file
- they are just different kind of an i-node
- `open`, `read`, `write`, etc. bypass the filesystem

The special files that we have considered in lecture 2 are, likewise, mostly independent of the particular file system. The mechanics of reading and writing such files are not tied to any particular file system. The variants of those file-like objects which are linked into the file system hierarchy (named pipes, UNIX domain sockets, devices) are,

for the purpose of the file system, simply a special type of i-node, and the file system only needs to store their metadata. When such a file is opened, the file system only obtains the metadata and hands off to a different part of the kernel.

Mount Points

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- recall that there is only a single directory tree
- but there are multiple disks and filesystems
- file systems can be joined at directories
- root of one becomes a subdirectory of another

Finally, mount points are another VFS-layer feature that does not extend into individual file system implementations. In fact, arguably, the main reason for VFS to exist is that multiple different on-disk file systems can be seamlessly integrated into a single tree. The system calls which perform the joining (and un-joining, as it were) are `mount` and `unmount`, respectively.

Part 4.4: The UNIX Filesystem

In this section, we will describe, in relatively low-level terms, how the traditional UNIX file system is organized, including how things are stored on disk. We will also discuss some of the problems which are tied to organisation of data on a medium with severe penalties for non-sequential data access, and with rather inflexible read and write operations (i.e. the problems that arise because the device only provides whole-block operations).

Superblock

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- holds toplevel information about the filesystem
- locations of i-node tables
- locations of i-node and free space bitmaps
- block size, filesystem size

There is considerable amount of metadata that the file system must store on disk. It is usually impractical to allocate fixed-address regions for all this metadata, hence the locations of these metadata blocks must be stored somewhere in the file system itself. Of course, at least some metadata must have a fixed, well-known location, to bootstrap the in-memory data structures at `mount` time. This fixed part of the metadata is known as the superblock. Since it is quite essential, and changes only rarely, it is usually stored in multiple fixed locations throughout the disk, in case the primary copy is damaged.

I-Nodes

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- recall that i-node is an anonymous file
  - or a directory, or a special file
- i-nodes only have numbers
- directories tie names to i-nodes

Until now, we have treated i-nodes as an abstract concept: they simply represent an object in the file system, be it a regular file, a directory, or some kind of special file. In traditional UNIX file systems, the i-node is also an actual, physical data structure stored on disk. Since the size of the i-node is fixed, they can be stored in large arrays and indexed using numbers: these indices form the basis of the i-node numbering system.
Since i-node tables need to be consulted quite often, and the latency of random access to a traditional hard drive depends on the physical distance of the different pieces of data, the i-node array is often split into multiple chunks, each stored in a different physical location. The system then attempts to keep both references to the i-node, and data that the i-node refers to, close together.

I-Node Allocation

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- often a fixed number of i-nodes
- i-nodes are either used or free
- free i-nodes may be stored in a bitmap
- alternatives: B-trees

In case i-nodes are stored in an array, this array usually has a fixed size, which means some of the entries are unused. Since creating (and erasing) files are fairly common operations, the system must be able to quickly locate an unused i-node, and also quickly mark a previously used i-node as unused. Scanning the entire table of i-nodes to find an unused one would be very slow, since only a few i-nodes fit into a single disk sector.
A common method of speeding this up is through bitmaps: in addition to i-nodes themselves, the file system stores an array of bits, one bit per i-node. This way, even though the system still has to do a linear scan for a free i-node in the bitmap, it will do so at a rate of 512 or 4096 i-nodes per sector.
Consider this example (the sector size is 512 bytes): a file system is organized into groups, each with around 200MiB of data, and each equipped with an array of 26000 i-nodes. This works out to around 8KiB of data per i-node, which is the average expected size of a file in this file system (if it was less than that, the file system might run out of i-nodes before it runs out of data space). Each i-node is 128 bytes, hence 4 i-nodes are stored per sector and the entire i-node array thus takes up 6500 sectors (or 3.25MiB). The i-node bitmap is, on the other hand, 51 sectors (or about 25KiB).

I-Node Content

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- exact content of an i-node depends on its type
- regular file i-nodes contain a list of data blocks
  - both direct and indirect (via a data block)
- symbolic links contain the target path
- special files describe what device they represent

The arguably most important part of an i-node is the data pointers that it contains: i.e. the addresses of data blocks that hold the actual data (whether the bytes of a regular file, or the data structure which maps names to i-node numbers in case of directories).

Attaching Data to I-Nodes

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- a few direct block addresses in the i-node
  - e.g. 10 refs, 4K blocks, max. 40 kilobytes
- indirect data blocks
  - a block full of addresses of other blocks
  - one indirect block approx. 2 MiB of data
- extents: a contiguous range of blocks

A traditional approach lists each data block separately. A common optimization makes the observation, that most files are stored in a small number of contiguous spans of blocks. Those spans are called extents, and more modern file systems store, instead of a simple array of block addresses, a list of extents (i.e. in addition to a block address, they also keep a number that tells the file system how many consecutive blocks are taken up by the file system). This is, essentially, a form of

run-length encoding. The obvious downside is that finding the address of the block which contains any given offset is now a linear operation (instead of constant-time), but in a data structure that is usually much smaller (most files will only have a single-digit number of extents, as opposed to perhaps hundreds of individual data blocks).

Fragmentation

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- internal – not all blocks are fully used
  - files are of variable size, blocks are fixed
  - a 4100 byte file needs 2 blocks of 4 KiB each
  - this leads to waste of disk space
- external – free space is non-contiguous
  - happens when many files try to grow at once
  - this means new files are also fragmented

Every time structured data is stored in an unstructured array of bytes, certain trade-offs come up. One of them has to do with storage efficiency: packing data more tightly often makes many operations slower, and the required metadata more complicated.
One of the well-known problems of this type is fragmentation, of which there are two basic types. Internal fragmentation is caused by alignment: it is much more efficient to start each file at a block boundary, and hence to allocate a whole number of blocks to each file. But because files have arbitrary sizes, there is often some unused space at the end of each file. This space is overhead – it does not store any useful data. Doing things this way, though, makes file access faster. In other words, at the end of most files, there is a small fragment of disk space that cannot be used (because it is smaller than the minimum size that can be allocated for a file, i.e. one block).

External Fragmentation Problems

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- performance: can't use fast sequential IO
  - programs often read files sequentially
  - fragmentation → random IO on the device
- metadata size: can't use long extents

External fragmentation, on the other hand, does not directly waste space. In this case, as files are created and destroyed, the free space is eventually distributed across the entire file system, instead of being concentrated in a single contiguous chunk.
When creating new files, finding space for them is more work, since it has to be 'glued' from many smaller fragments. Metadata grows bigger, since average extent length goes down and hence files need more extents.
Finally, and perhaps most importantly, when free space is fragmented, so are the files that eventually make use of it. Access to these files is then less efficient, because every time there is a discontinuity in the data, the system experiences additional latency, due to non-sequential access to the underlying hard drive.

Directories

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- uses data blocks (like regular files)
- but the blocks hold name → i-node maps
- modern file systems use hashes or trees
- the format of directory data is filesystem-specific

Like regular files, directories use data blocks to store their content. However, while the content of regular files is completely arbitrary (i.e. user- or application-defined), directories are interpreted by the file system itself. The simplest format one could adopt to store directories is to simply concatenate all the (null-terminated name, i-node number) tuples after each other. Of course, this would be very inefficient. Most file systems use a more sophisticated data structure (an on-disk hash table, or a balanced tree).

File Name Lookup

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- we often need to find a file based on a path
- each component means a directory search
- directories can have many thousands entries

One of the most common operations in a file system is that of file name lookup. This operation is performed many times for each path that needs to be resolved (once for each component of the path). It is therefore very important that this can be done quickly.
While it is important that the on-disk format allows for fast lookups, even the fastest on-disk structure would be too slow: almost all operating systems employ an in-memory cache to speed up 'common' lookups (i.e. they keep a cache of directories or directory entries which have been recently used in lookups).

Old-Style Directories

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- unsorted sequential list of entries
- new entries are simply appended at the end
- unlinking can create holes
- lookup in large directories is very inefficient

As we have mentioned earlier, the simplest (but very inefficient) method of storing directories is to simply keep a linear list of directory entries (i.e. tuples which map a name to an i-node number). This causes a whole lot of problems and no serious contemporary file system uses this approach.

Hash-Based Directories

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- only need one block read on average
- often the most efficient option
- extendible hashing
  - directories can grow over time
  - gradually allocates more blocks

A common alternative is to use hash tables, which usually make name lookup very fast: the expected outcome is that, based on the hash of the name, the first sector that is fetched from the disk will contain the requested name/i-node pair, even for moderately large directories.
Of course, there are downsides, too: traversing the directory in, say, alphabetical order, will cause a random-access pattern in the underlying disk IO, since the directory is sorted on the hash, which is essentially random. Additionally, pathological directories can cause very bad behaviour, in case all (or most) directory entries hash to the same bucket.

Tree-Based Directories

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- self-balancing search trees
- optimised for block-level access
- B trees, B+ trees, B* trees
- logarithmic number of reads
  - this is worst case, unlike hashing

Another fairly common strategy is to use balanced trees, which have slightly worse average performance, but much better worst-case guar-

antees, compared to hash tables. Additionally, the entries are stored in sorted order, making certain access patterns more efficient.

Hard Links

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- multiple names can refer to the same i-node
  - names are given by directory entries
  - we call such multiple-named files hard links
  - it's usually forbidden to hard-link directories
- hard links cannot cross device boundaries
  - i-node numbers are only unique within a filesystem

An immediate consequence of how files and directories are stored in the file system is the existence of hard links. Please note that those are not special entities: they are merely a name for a situation where multiple directory entries refer to the same i-node. In this case, each of the 'hard links' is indistinguishable from all the others, and the same file simply appears in multiple places in the directory hierarchy.
Since i-nodes keep a reference count, it is usually possible to tell that the file is available under multiple different paths. Since files are only destroyed when their reference count drops to zero, removing a file from a directory (called unlinking) may or may not cause the file to be actually erased.

Soft Links (Symlinks)

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- they exist to lift the one-device limitation
- soft links to directories are allowed
  - this can cause loops in the filesystem
- the soft link i-node contains a path
  - the meaning can change when paths change
- dangling link: points to a non-existent path

Sometimes, it is useful to refer to a file not by i-node number, but by a path. This can be done by employing soft links: unlike hard links, those are actual objects, stored in the file system as a special type of i-node. When such a file is opened, the operating system will instead look up a file by the path stored in the soft link. Of course, this leads to additional problems: for instance, the target path may not exist (this is by far the most common failure mode).
If it does, an i-node of the file corresponding to the path is obtained the usual way. Unlike in standard directory entries, this new i-node may reside on a different file system.

Free Space

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- similar problem to i-node allocation
  - but regards data blocks
- goal: quickly locate data blocks to use
  - also: keep data of a single file close together
  - also: minimise external fragmentation
- usually bitmaps or B-trees

Like i-nodes, the file system needs to be able to quickly locate an empty data block, either when files and directories are created, or when when existing ones are extended. The task is slightly more complex for data blocks: for i-nodes, it is sufficient to allocate a single i-node, and placement of i-nodes relative to each other is not very important (though of course it is useful to keep related i-nodes close together).
However, many files require more than a single data block, and it is rather important that those blocks reside next to each other, if possible. To make matters worse, it is not always clear how big the file is going to be, and the file system should probably reserve some additional blocks on top of those required for the initial set of writes. Armed with a size estimate, the system then needs to find free space of that size, ideally without impinging on headroom for existing files, and ideally as a single contiguous run of blocks. Of course this may not be possible, in which case it will try to split the file into multiple chunks of free space.
Compared to the i-node case, the on-disk data structures are pretty much the same: either free block bitmaps, or balanced search trees. Most of the difference is in the inputs and algorithms.

File System Consistency

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- what happens if power is cut?
- data buffered in RAM is lost
- the IO scheduler can re-order disk writes
- the file system can become corrupt

File systems, and the data structures they employ, face a somewhat unique challenge: the changes the file system makes to its metadata can be cut off at an arbitrary point, even in the middle of an operation, most often by a power loss. Even worse, the individual writes the system has issued can be re-ordered (to improve performance), which means that there isn't a sharp cut-off point.
As an example, consider creation of a regular file: an i-node must be allocated (this means a write to the i-node bitmap), filled in (write to the i-node itself) and linked into a directory (write, or multiple writes, into the data structure of the directory). If operations are performed in this sequence and power is cut off, two things could happen:

1. the bitmap is updated, but the remaining operations are lost: in this case, the i-node is lost, unless a consistency check is performed and discovers that an unused i-node is marked as allocated in the bitmap,
2. the bitmap and the i-node itself are updated, but it is not linked to the directory hierarchy, giving essentially the same outcome, but in a form that is harder to detect during a consistency check.

In both cases, some resources are lost, which isn't good, but isn't terrible either. However, consider the case when the writes are re-ordered, and the directory update comes first. In this case, the file system has a directory entry that points to an uninitialized i-node, making a garbage file accessible to users. Depending on the content of the uninitialized i-node, bad things could happen if the file is accessed.
Fortunately, the file system can impose a partial order on the writes (i.e. guarantee that all outstanding writes are finished before it makes further changes). Using this mechanism carefully, the amount of damage to data structures can be limited, without significantly impacting performance.
The last line of defence is a dirty flag in the superblock: when a file system is mounted, the dirty flag is written to disk, and when it is unmounted, after all outstanding changes are written, it is cleared. The file system will refuse to mount if the dirty flag is already set, enforcing a consistency check.

Journalling

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- also known as an intent log
- write down what was going to happen synchronously
- fix the actual metadata based on the journal
- has a performance penalty at run-time
  - reduces downtime due to faster consistency checks
  - may also prevent data loss

A particular technique (that relies on imposing a partial order on writes) is so-called intent log, perhaps better known from relational

database systems. In this approach, the file system maintains a dedicated area on disk and before commencing any non-atomic data structure updates, writes the description of the operation (atomically) into the intent log. In this case, if the composite operation is later interrupted, the log captures the intent and can be used to undo the effects of the incomplete operation quickly. This means that in most scenarios, a full consistency check (which is usually quite expensive) is not required.

Part 4.5: Advanced Features

This section briefly introduces some additional concepts that often appear in the context of file systems. We won't have time to delve into too many details in this course, but it is important to be aware of those features.

What Else Can Filesystems Do?

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- transparent file compression
- file encryption
- block de-duplication
- snapshots
- checksums
- redundant storage

There are three rough categories of features in the above list: storage efficiency (compression, de-duplication), security (encryption) and reliability (checksums, redundant storage). The ability to make snapshots falls somewhere between efficiency and reliability, depending on the use case and implementation.

File Compression

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- use one of the standard compression algorithms
  - must be fairly general-purpose (i.e. not JPEG)
  - and of course lossless
  - e.g. `LZ77`, `LZW`, Huffman Coding, ...
- quite challenging to implement
  - the length of the file changes (unpredictably)
  - efficient random access inside the file

Of course, it's always possible to compress files at the application level, by simply using an appropriate compression program. However, the user then needs to manually decompress the file before using it and then re-compress it afterwards again. This is quite inconvenient. Of course, this could be automated, and some programs can do the (de)compression automatically when they open a file, though this is neither very common, nor very efficient.

An alternative, then, is for the file system to implement transparent file compression, that is, compress the data when it is stored on disk, but present user-space programs with uncompressed data when reading, and transparently compress newly written data before storing it.

This is not without challenges, of course. The biggest problems stem from the fact that data is never uniformly compressible, and hence, different sections of a file will compress at different ratios. This means that seeking to a specific uncompressed offset will be hard to implement. Likewise, writes in the middle of a file (which normally preserve file length) will cause the file to shrink or lengthen, making the operation much more complicated.

File Encryption

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- use symmetric encryption for individual files
  - must be transparent to upper layers (applications)
  - symmetric crypto is length-preserving
  - encrypted directories, inheritance, &c.
- a new set of challenges
  - key and passphrase management

Unlike compression, most encryption algorithms are length-preserving, making the whole affair much simpler in some sense. Nonetheless, there is an important matter of dealing with secrets which makes the code complicated in a different way. Additionally, unlike with compression, depending on the use case, the system might have to encrypt metadata as well (i.e. not just file content). This would, most importantly, cover directories: not only file names, but also the overall directory structure.

Additionally, a failure to compress a file that the user intended to be compressed is not a big problem. With encryption, such a mistake would be quite fatal.

Since block-level encryption is considerably simpler, and hence less likely to contain fatal flaws, most modern systems use it instead of file-system-level encryption as described here.

Block De-duplication

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- sometimes the same data block appears many times
  - virtual machine images are a common example
  - also containers and so on
- some file systems will identify those cases
  - internally point many files to the same block
  - copy on write to preserve illusion of separate files

There are numerous use-cases where either entire files or fragments of files are stored multiple times on a given file system. In those cases, locating duplicated blocks can lead to significant space savings. In modern file systems, it is usually not a problem to make the same data block part of multiple files. Like with other copy-on-write implementations, such shared blocks must be specifically marked as such, so that any writes that would affect them can un-share them (i.e. make a private copy).

De-duplication is somewhat expensive, since it is not easy to find identical blocks: a naive scanning comparison would take $O(n^1)$ time to find duplicated blocks (even though it only uses constant amount of memory). Of course, that is impractical, considering how $n = 10^9$ is only about 4TB of storage and $n^2 = 10^{18}$ is a very large number. Hash tables can make the operation essentially linear, though it requires on the order of 4GiB of RAM per 1TB of storage. Probabilistic algorithms and data structures can further reduce the constant factors on both time and memory.

In most cases, de-duplication is an offline process, i.e. one that is scheduled to run at some intervals, preferably during light load, since it is too resource-intensive to be performed continuously with each write (that is, online).

[1] In this setup, the DMA controller actually becomes the bus master and performs the transfer. While the effect is essentially the same, the implementation is rather different than with the DMA based on peripherals becoming bus masters that we will encounter later in the lecture.

Snapshots

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- it is convenient to be able to copy entire filesystems
  - but this is also expensive
  - snapshots provide an efficient means for this
- snapshot is a frozen image of the filesystem
  - cheap, because snapshots share storage
  - easier than de-duplication
  - again implemented as copy-on-write

If file system metadata is organized in a suitable data structure (usually a variation of B trees), it is possible to implement copy-on-write not just for data blocks, but also for this metadata. In that case, it is not very hard to provide efficient snapshots.

Taking a snapshot is, semantically, equivalent to making a copy of the entire file system while it is not mounted: that is, the copy is made atomically with regards to any concurrent writes. In yet other words, if a program overwrites two files, say A to A' and later it overwrites B to B', if a copy was taken the usual (non-atomic) way, in the copy, it could easily be the case that files A and B' are present (it is an easy exercise to work out how this could happen).

The other major advantage of a snapshot is that initially (i.e. when it does not differ very much from the live file system) it takes up very little space. Of course, as the live file system begins to diverge, more and more data blocks need to be copied upon modification, increasing the storage demands, in the worst case approaching the space requirements of a standard, full copy. Nonetheless, the time cost associated with this are amortized over the life of the snapshot. Finally, in case (read-only) snapshots are made regularly, there are permanent savings to be had from copy-on-write, since in those cases, at least some of the data will be shared between the snapshots themselves.

Checksums

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- hardware is unreliable
  - individual bytes or sectors may get corrupted
  - this may happen without the hardware noticing
- checksums may be stored along with metadata
  - and possibly also file content
  - this protects the integrity of the filesystem
- beware: not cryptographically secure

Unfortunately, storage devices are not 100% reliable, and can sometimes quietly corrupt data. That is, reading a block may yield different data than what was written to that block previously. A file system may fight this by storing checksums (e.g. CRC) along with metadata (or even along with data). This will not prevent corruption as such, but at least allows the file system to detect it early. When detected, the corrupt objects can be restored from backup: since making a backup involves reading the file system, under this scheme, such corruption should be always detected before a good copy of the affected data is lost.

Redundant Storage

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- like filesystem-level RAID
- data and metadata blocks are replicated
  - may be between multiple local block devices
  - but also across a cluster / many computers
- drastically improves fault tolerance

Finally, file systems (especially distributed file systems) may employ redundant storage for both data and metadata. Essentially this means that each data block and each metadata object is stored in multiple copies which are all kept synchronized by the file system, each copy stored on a different physical storage device. In some cases, multiple computers may be involved, improving resilience in face of failures in non-disk components (which usually knock out the entire computer).

Review Questions

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13.What is a block device?
14.What is an IO scheduler?
15.What does memory-mapped IO mean?
16.What is an i-node?

Part 5: Processes, Threads & Scheduling

In this lecture, we will look at the 2 basic resources that the computer offers, and which every program needs: CPU and memory. The main question then will be how the operating system achieves the illusion that every thread seemingly has its own processor and every process has its own memory (this is what we mean by multiplexing – turning a single physical resource into a larger set of virtual instances of the same).

Lecture Overview

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1. processes and virtual memory
2. thread scheduling
3. interrupts and clocks

There will be 3 parts. We will first look at virtual memory, and the unit of memory isolation in the operating system: a process. We will then look at CPU (processor) sharing and the unit of CPU allocation, a thread. Finally, we will look in more detail how CPU sharing is implemented in terms of hardware.

Part 5.1: Processes and Virtual Memory

Prehistory: Batch Systems

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- first computers ran one program at a time
- programs were scheduled ahead of time
- we are talking punch cards &c.
- and computers that took an entire room

The first generation of computers was strictly sequential: one program could execute at any given time, and that was that. To execute another

program, the first must have finished first.

History: Time Sharing

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- "mini" computers could run programs interactively
- teletype terminals, screens, keyboards
- multiple users at the same time
- hence, multiple programs at the same time

Computers were quite expensive at the time, and programs started to offer more interactivity. That is, a program could interact with the operator by asking questions and then waiting for inputs to be provided, for instance. Together, those two considerations made the sequential, one program at a time paradigm quite impractical.
This is the origin of time sharing systems, where a computer could execute multiple programs at seemingly the same time, by quickly switching from one program to another. As soon as this is possible, it makes sense to allow multiple users to interact with the same computer (each user through a different program).

Processes: Early View

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- process is an executing program
- there can be multiple processes
- various resources belong to a process
- each process belongs to a particular user

Since traditional programs were internally sequential, the original notion of a process encompassed both types of basic resources: memory and processor. In normal operation, a process P gets to execute on the processor for some amount of time, before it is interrupted and the system switches to executing some other process. At some later point, process P will be awaken and continue execution where it left off.

Process Resources

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- memory (address space)
- processor time
- open files (descriptors)
  - also working directory
  - also network connections

The most basic resource associated with a process is memory: this is where the program itself (the instructions) are stored, and also where its data (both static and dynamic) resides. This memory is typically private: one process cannot see the memory of another process.

Process Memory Segments

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- program text: contains instructions
- data: static and dynamic data
  - with a separate read-only section
- stack memory: execution stack
  - return addresses
  - automatic variables

The memory of a program is organized into functionally distinct segments. Traditionally, those segments were contiguous chunks of address space, but in modern operating systems, this is not quite true (and the whole idea of a segment is losing its appeal). Nonetheless, the traditional split is into program text, which contains the instructions of the program (i.e. the executable code, typically produced by a compiler), a stack which holds the C stack (i.e. the values of local variables and return addresses, along with other bookkeeping) and finally a data segment which holds, unsurprisingly, data.
In a modern system, none of those segments needs to be contiguous: the text consists of multiple mappings: one for the main program, and one for each shared library it uses. Those mappings do not need to be adjacent in the virtual address space (much less so in physical memory). Likewise, since one process can contain multiple threads (more on that later), there may be multiple stacks, again, not necessarily allocated next to each other. Finally, static (and especially read-only) data comes from executable images too, hence there might be one mapping per executable, just like with text. The dynamic data, then, is entirely unconstrained in its shape: the implementation of `malloc` in `libc` will request memory from the operating system as needed, with virtual addresses often being assigned randomly to each new region of memory.

Process Memory

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- each process has its own address space
- this means processes are isolated from each other
- requires that the CPU has an MMU
- implemented via paging (page tables)

The defining characteristic of a modern process is its address space: the virtual addresses allocated to a process is private to that process and as such invisible to any other process. The data is mostly stored in RAM, but each process only (typically) sees a small portion of the physical memory – the majority is simply not visible in its virtual address space. Behind the scenes, this separation of address spaces is built on paging, which is, in turn, provided by the MMU (memory management unit) of the CPU.

Process Switching

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- switching processes means switching page tables
- physical addresses do not change
- but the mapping of virtual addresses does
- large part of physical memory is not mapped
  - could be completely unallocated (unused)
  - or belong to other processes

In a typical time-sharing operating system (this covers pretty much every modern general-purpose OS), an illusion of virtually unlimited concurrency (the ability to run an arbitrary number of processes at the same time, regardless of the number of available CPU cores) is achieved by rapidly switching the execution from one process to the next. Or, to be more precise, execution is switched from one thread to another (which we will discuss shortly), but often, the threads will be part of different processes. In those cases, the operating system must instruct the processor to switch into the virtual address space of the new process.
Of course, in this process, the physical memory is not rearranged in any way – that would be way too expensive. Instead, the MMU is instructed to start using a different set of mapping rules (page tables) that map virtual addresses to physical addresses. Usually, the overlap between physical addresses that have been visible in the old virtual address space and those visible in the new one is minimal: as outlined earlier, the virtual address space is almost entirely private to each process.
Thus, most of the physical memory is, from the point of view of any given process, inaccessible: it is either unused, or it belongs to a different process.

Paging and TLB

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- address translation is slow
- recently-used pages are stored in a TLB
  - short for Translation Look-aside Buffer
  - very fast hardware cache
- the TLB needs to be flushed on process switch
  - this is fairly expensive (microseconds)

An important consideration is the cost associated with switching processes. On the surface, this involves a thread switch (which, as we will see later, consists of storing the content of user-accessible registers in memory and loading a new set of values from a different location in memory) and an additional register write (to load the new page table into the MMU).
Unfortunately, under the surface, that single register write causes a cascade of other effects: in particular, all modern processors use a very fast cache for storing recent address translations (i.e. which physical addresses correspond to a small set of recently-used virtual addresses), known as the TLB (translation look-aside buffer).
The TLB is required because otherwise, translating a virtual address to a physical one involves multiple round-trips into the main memory, where page tables are stored. In modern computers, each of those round-trips will take hundreds or even thousands of processor cycles – clearly, repeating this process on every address translation would make computation extremely slow.
Nonetheless, upon a process switch, the mapping of virtual addresses to physical addresses changes, and the information stored in the TLB becomes invalid, since it refers to the previous address space. The simplest remedy is simply erasing everything that is stored in the TLB. This is, in itself, a quick operation, since the TLB is implemented using very fast on-die memory. Most of the price comes from the subsequent address translations, which cannot be answered from the (now empty) TLB and must perform multiple round-trips into main memory (or, depending on cache pressure, into one of the general-purpose caches – L1, L2 or L3).
Incidentally, modern processors often use tagged TLBs, which make the entire process more efficient, but this is well outside of the scope of this course.

Threads

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- the modern unit of CPU scheduling
- each thread runs sequentially
- one process can have multiple threads
  - such threads share a single address space

While processes are the basic unit of memory management in the operating system, computation is captured by threads. Each process has at least one thread, but might have more than one. While processor time accounting is usually done at process level, execution is tied to threads, since threads is what the processor ultimately executes.

What is a Thread?

250

- thread is a sequence of instructions
  - instructions depend on results of previous instructions
- different threads run different instructions
  - as opposed to SIMD or many-core units (GPUs)
- each thread has its own stack

A thread can be thought of as an instruction stream: essentially what we imagine a traditional, sequential program to be. Within a thread, an instruction can freely use results of previous instructions (data dependencies) and make decisions (based on those results) as to which instruction to execute next (branching, or control flow). This is how a processor core executes a program (at least from the point of view of the programmer). Hence at any given time, each processor core can execute a single thread. The threads running concurrently on different cores or different CPUs can be completely unrelated (they don't even need to belong to the same process: each core has its own MMU and which can each use a different page table, and hence, each core can be executing threads in different address spaces).
Of course, this also means that each thread needs its own execution stack (i.e. the memory that stores local variables in a C program, along with return addresses and other execution-related book-keeping).

Processor Time Sharing

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- CPU time is sliced into time shares
- time shares (slices) are like memory frames
- process computation is like memory pages
- processes are allocated into time shares

Besides memory, the other main commodity in a computer is computation time. Like memory, there is a limited amount, and it needs to be distributed among multiple threads (and processes). Since different instructions take wildly different amount of time to execute, allocation of computation is based on time instead of instruction count. As a bonus, time is easier to measure.

Multiple CPUs

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- execution of a thread is sequential
- one CPU = one instruction sequence at a time
- physical limits on CPU speed → multiple cores
- more CPU cores = more throughput

With time sharing, it is possible to execute any number of threads on a single CPU core. However, physical limits in CPU design have made it, in the last decade, much easier to build processors which can execute twice as many threads (using twice as many processor cores), instead of making them execute a given number of threads twice as fast. As long as there are always enough threads ready to execute, the overall computational throughput of the system is doubled either way. Of course, this puts strain on software, which needs to be separated into more and more threads to saturate the computational power of a modern processor.

Modern View of a Process

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- in a modern view, process is an address space
- threads are the right scheduling abstraction

- process is a unit of memory management
- thread is a unit of computation
- old view: one process = one thread

To recap, there are two main abstractions that center about memory and computation. While historically, operating systems made the assumption that 1 process = 1 thread (and hence older textbooks about operating systems might follow the same design), this no longer makes sense in modern systems.
Instead, threads are the abstraction that covers computation itself (the sequence of instructions to be executed), while processes cover

memory and most other resources.

Fork

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- how do we create new processes?
- by fork-ing existing processes
- fork creates an identical copy of a process
- execution continues in both processes
  - each of them gets a different return value

Let's now look at processes from the perspective of programs (and users). The first thing to consider is how processes are created: on POSIX-like systems, this is almost exclusively through the use of the fork system call, which simply makes an identical copy of the current process. The processes are then very slightly tweaked: in one, fork returns a different value, and in the process table, one is taken to be a parent and the other to be a child. The return value of fork tells each process which of the two it is.

Lazy Fork

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- paging can make fork quite efficient
- we start by copying the page tables
- initially, all pages are marked read-only
- the processes start out sharing memory

Making a copy of an entire process would be a comparatively expensive exercise. However, like we have seen with file systems before, there are tricks (based on the copy-on-write implementation technique) which make it possible to make fork itself quite efficient. At the time of fork, the only thing that needs to be copied is the page table which is much smaller than the entire address space of the process in question.
At the same time, all pages in both copies of the page table are marked as read-only, since they are now shared by two processes, which should not have access to each other's address space. Of course, as long as they are only reading from memory, whether there are two physical copies or a single shared copy does not make a difference.

Lazy Fork: Faults

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- the shared memory becomes copy on write
- fault when either process tries to write
  - remember the memory is marked as read-only
- the OS checks if the memory is supposed to be writable
  - if yes, it makes a copy and allows the write

As soon as either of the processes attempts to issue a memory write, this will cause a fault: the pages are marked read-only in the page tables. When this happens, the processor will invoke the fault handler (which is part of the kernel) to resolve the situation. The fault handler will then consult its data structures (which may be partially embedded in the page table itself) to distinguish actual faults (i.e. the process tried to write into truly read-only memory) from copy-on-write events.
In the latter case, the page is semantically read-write, but is marked read-only because multiple processes are using a single physical copy. At this point, the fault handler will split the mapping: it will make a new physical copy of the data (i.e. it will allocate a new frame for it) and adjust the page table of the process which attempted to write, so that the offending virtual address is translated to point into this new physical copy.
Finally, the CPU is instructed to restart the offending instruction: since the page table entry is now marked as read-write (pointing to the new physical location), the instruction will execute without further impediment.

Init

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- on UNIX, fork is the only way to make a process
- but fork splits existing processes into 2
- the first process is special
- it is directly spawned by the kernel on boot

Earlier, we have claimed that fork is essentially the only way to create a new process. Of course, this cannot be entirely true, since fork may only be executed by an existing process. For this reason, there is one special process, also called `init` or `pid 1` which is directly created by the kernel upon boot. All other processes in a running system, however, descend from this original process by a sequence of forks.

Process Identifier

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- processes are assigned numeric identifiers
- also known as PID (Process ID)
- those are used in process management
- used in calls like `kill` or `setpriority`

To facilitate process management, each process is assigned a numeric identifier (known as PID, short for process identifier). Process management syscalls, then, take this number as an argument.
Traditionally, the 'namespace' of processes is global: a PID identifies a process globally (unlike, for instance, a file descriptor, which is local to each process). That is, for all users and all processes, the given number always represents the same process (until it is terminated). Please note that in container-based virtualisation, this is no longer strictly true, since different containers will get different PID namespaces even though they share the same kernel.

Process vs Executable

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- process is a dynamic entity
- executable is a static file
- an executable contains an initial memory image
  - this sets up memory layout
  - and content of the text and data segments

In previous lectures, we have touched the subject of executables: those are files which contain programs. It is very important to understand the difference between an executable (a program, so to speak, at rest) and a process (a program in the process of being executed).
An executable contains, essentially, an initial image of process memory: when a program starts executing, the kernel populates its virtual address space with data from the executable, most importantly the text segment which contains instructions, but also the static parts of the data segment. Additionally, the executable contains the (virtual) address of the entry point: this is the address of the first instruction of the program that should be executed.

Exec

260

- on UNIX, processes are created via fork
- how do we run programs though?
- exec: load a new executable into a process
  - this completely overwrites process memory
  - execution starts from the entry point
- running programs: fork + exec

However, when a process is created, its memory is not populated from an executable: instead, it is a clone of an existing process. To execute a new program, an existing process needs to call an exec system call, which then simply replaces the entire memory of the current process with the content of the executable. Only environment variables and command-line arguments (which are both stored in process memory) are copied over to the new address space.
The common 'start a new program' operation (e.g. what happens when the user runs a command in the shell) is then implemented as a fork followed by an exec in the child process.

Part 5.2: Thread Scheduling

In this section, we will look in more detail how operating systems decide which thread to run when and for how long.

What is a Scheduler?

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- scheduler has two related tasks
  - plan when to run which thread
  - actually switch threads and processes
- usually part of the kernel
  - even in micro-kernel operating systems

The scheduler is a component of the kernel which fills two basic roles: planning and thread switching (including preemption).

Switching Threads

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- threads of the same process share an address space
  - a partial context switch is needed
  - only register state has to be saved and restored
- no TLB flushing – lower overhead

To switch execution from one thread to another, within a single process, it is sufficient to store the current state of user-visible registers into memory, and load the state which corresponds to the other thread (the state of which was saved when it was last interrupted and suspended). Since the address of the (top of the) stack is stored in a register, simply replacing values in registers from a backup also has the effect of switching the active stack.
In this case, the TLB does not need to be flushed, making the switch quite efficient, even if not entirely free (there is still a small penalty due to branch prediction and speculative execution).

Fixed vs Dynamic Schedule

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- fixed schedule = all processes known in advance
  - only useful in special / embedded systems
  - can conserve resources
  - planning is not part of the OS
- most systems use dynamic scheduling
  - what to run next is decided periodically

When it comes to the schedule, that is, the plan of which thread to execute in which time slot(s), there are two basic types:

1. static schedules are computed ahead of time, for a fixed set of threads with pre-determined priorities and with their relative computational costs also known in advance,
2. dynamic schedules, in which the above information is not known.

Running on a static schedule makes the runtime scheduler particularly simple and robust. However, this approach is unsuitable for all but the simplest use cases, and is usually only found in high-assurance embedded systems.
A dynamic scheduler, on the other hand, allows threads and processes to be created in an ad-hoc manner, during execution. Likewise, the priorities of threads can be determined (and adjusted) at will. The scheduler periodically evaluates the situation and decides what to run either now, or in the very near future.

Preemptive Scheduling

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- tasks (threads) just run as if they owned the CPU
- the OS forcibly takes the CPU away from them
  - this is called preemption
- pro: a faulty program cannot block the system
- somewhat less efficient than cooperative

In most modern operating systems, the scheduler is preemptive, that is, it can suspend threads at its own discretion, without cooperation from the threads themselves. In this approach, the user-space software does not need, in principle, be aware that it is running on a time-sharing system: when a thread is preempted and later resumed, the execution continues where it left off, without any immediately detectable effect on the executing program.
A major advantage of preemptive scheduling is that uncooperative (or faulty) programs cannot endanger the system as a whole: the operating system can, at any time, decide to suspend a process, regardless of what code it executes at the time.

Cooperative Scheduling

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- threads (tasks) cooperate to share the CPU
- each thread has to explicitly yield
- this can be very efficient if designed well
- but a bad program can easily block the system

A different approach is known as cooperative scheduling. In this case, there is no preemption: the currently running thread has to yield (give up) the processor voluntarily. This makes it possible to optimize task switching, but it also means that a program which does not yield the processor will simply continue to run unimpeded.
While general-purpose operating systems no longer use cooperative scheduling globally, some programs implement so-called green threads which are scheduled cooperatively – scheduling of those threads is implemented entirely in the user-space. Usually, a large number of

such cooperative 'green' threads is dispatched onto a small number of 'real' OS threads (which are preemptively scheduled by the kernel).

Scheduling in Practice

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- cooperative on Windows 3.x for everything
- cooperative for threads on classic Mac OS
  - but preemptive for processes
- preemptive on pretty much every modern OS
  - including real-time and embedded systems

The last mainstream operating system to use cooperative scheduling at the operating system level was 'classic' Mac OS (before OS X), though it used preemptive scheduling for processes. This way, switching threads within a process could take advantage of the improved efficiency, while processes were unable to block each other. The last mainstream system with fully cooperative scheduling was MS Windows 3.11, released in 1993.

Waiting and Yielding

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- threads often need to wait for resources or events
  - they could also use software timers
- a waiting thread should not consume CPU time
- such a thread will yield the CPU
- it is put on a list and later woken up by the kernel

In most programs, it is common that a thread cannot continue its execution until some event takes place, or a resource becomes available. In this case, it is undesirable that the thread should wait actively, that is, spin in a loop that checks whether it can continue. Instead, kernels provide mechanisms which allow threads to be suspended until an event arrives, or a resource becomes available (at which point it is resumed by the kernel). This process is not completely free from overhead, but unless the wait is very short (a few dozen CPU cycles), suspending the thread will give a much better overall system throughput.

Run Queues

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- runnable (non-waiting) threads are queued
- could be priority, round-robin or other queue types
- scheduler picks threads from the run queue
- preempted threads are put back

There are two reasons why a thread is suspended, that is, it is no longer running: it's either waiting for an event (see above) or its time slot has ended and it was preempted. In the latter case, the thread is put on a run queue, which is a list of threads that are ready to run, usually sorted by a dynamic priority, which is a number that indicates how soon the thread should run, computed by the scheduler.
Whenever a thread is suspended, the scheduler picks the next thread to execute from a run queue.

Priorities

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- what share of the CPU should a thread get?
- priorities are static and dynamic
- dynamic priority is adjusted as the thread runs
  - this is done by the system / scheduler
- a static priority is assigned by the user

Not all threads are equally important, and some should take priority over others whenever they need to run. This is achieved through a combination of priorities: a static priority is assigned to each thread by the user. The static priority then feeds into the computation of a dynamic priority, which governs scheduling: while a thread is running, its dynamic priority drops and while it is suspended, its dynamic priority increases.

Fairness

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- equal (or priority-based) share per thread
- what if one process has many more threads?
- what if one user has many more processes?
- what if one user group has many more active users?

In the system that we have outlined above, scheduling is only concerned with individual threads. Such a system is clearly unfair: processes and users with many threads will get a much higher share of the CPU than processes and users with fewer threads. To mitigate this effect, most operating systems implement some form of fair scheduling.

Fair Share Scheduling

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- we can use a multi-level scheduling scheme
- CPU is sliced fairly first among user groups
- then among users
- then among processes
- and finally among threads

There are different levels on which a fair scheduler may operate: almost all systems will consider processes, while many will also consider users. In this scheme, the scheduler strives to achieve the following two goals:

1. as long as the given entity (process, user, group) has enough runnable threads, those threads get equal time when compared to any other entity with the same property (i.e. if both process A and process B have runnable threads, the total time slice of process A is equal to that of process B, assuming equal priorities),
2. resources are allocated efficiently: if an entity does not have sufficient runnable threads, the resources it cannot use are distributed among the remaining entities of the same type (i.e. if process A has 1 runnable thread, process B has 3 runnable threads and there are 4 processor cores, process B should not be hampered by process A only being able to use one of them – the system should use all 4 cores in this scenario).

Scheduling Strategies

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- first in, first served (batch systems)
- earliest deadline first (realtime)
- round robin
- fixed priority preemptive
- fair share scheduling (multi-user)

When it comes to computing a dynamic schedule, there is a number of approaches. The simplest of all is a batch scheduler, which is basically no scheduler at all: when a program is executed, it runs until it is done; afterwards, the next program is executed until termination, and so on. In real-time systems, a fairly simple scheduler is known as 'earliest deadline first': in such systems, each task comes with a deadline which tells the system when the task must be done, at the latest. In a preemp-

tive setting, then, it is an optimal strategy to first execute the task with the earliest deadline.
A naive general-purpose, preemptive scheduler is known as round robin: it runs all available threads in a fixed order, switching from one to the next as they run out of their time slice. In this system, the per-thread throughput can be prioritised (by tweaking the relative sizes of time slices of different threads), but latency can not.
A preemptive scheduler with priorities fixes the latency problem: if a high-priority thread wakes up, it will be able to run very soon (with low latency), since it can 'jump the queue', unlike in a round-robin scheduler.

Interactivity

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- throughput vs latency
- latency is more important for interactive workloads
  - think phone or desktop systems
  - but also web servers
- throughput is more important for batch systems
  - think render farms, compute grids, simulation

A scheduler will often need to make a compromise between maximising total computational throughput and minimising latency. In interactive settings, the dominant concern is latency, while in computational contexts, it's the total throughput that is usually a priority.

Reducing Latency

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- shorter time slices
- more willingness to switch tasks (more preemption)
- dynamic priorities
- priority boost for foreground processes

When optimising for low latency, the scheduler should use short time slices (so that threads that wake up do not need to wait too long for the processor to free up, even if they are not high-priority threads). Likewise, the scheduler should be willing to switch to a higher-priority thread whenever one wakes up, preempting running threads (even if they did not consume their current time slice yet).
Both decisions of course lead to more context switches, which are expensive and hence negatively affect total throughput (less total useful computation is performed in any given time, since more time is spent on overhead – both in the scheduler, but mainly in switching threads and processes).

Maximising Throughput

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- longer time slices
- reduce context switches to minimum
- cooperative multitasking

The opposite is true for high-throughput systems: the time slice should be as long as is practical, to minimize the number of context switches the CPU needs to do. Likewise, the scheduler should be unwilling to switch tasks before their current time slice runs out, pushing back threads that woke up in reaction to an event. Whenever possible, preemption should be avoided in favour of cooperation (though this is, nowadays, mainly an application-level concern).

Multi-Core Schedulers

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- traditionally one CPU, many threads
- nowadays: many threads, many CPUs (cores)
- more complicated algorithms
- more complicated & concurrent-safe data structures

In traditional designs, an operating system would only expect a single processor to be available, in which case the scheduler would be comparatively simple. However, essentially all modern computers are multi-core systems, and schedulers need to take this into account in two major ways:

1. the algorithm to decide which threads run when and on which core is much more complicated,
2. the scheduler must be able to run concurrently with itself: multiple cores must be able to decide which thread to run next in parallel, which means that the data structures used by the scheduler to keep track of threads must be concurrent-safe.

Scheduling and Caches

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- threads can move between CPU cores
  - important when a different core is idle
  - and a runnable thread is waiting for CPU
- but there is a price to pay
  - thread / process data is extensively cached
  - caches are typically not shared by all cores

It is entirely possible to suspend a thread on one core, and wake it up later on another core. Since processor cores are all identical, this does not make a semantic difference – the thread will not be able to directly detect that it has moved. However, if some of the data associated with that thread was still in the per-core part of the cache (typically at least L1, but also L2 and L3 if the core is part of a different package) this will cause a performance hit, as the new core has to re-fetch the data that was already cached by the other core.

Core Affinity

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- modern schedulers try to avoid moving threads
- threads are said to have an affinity to a core
- an extreme case is pinning
  - this altogether prevents the thread to be migrated
- practically, this practice improves throughput
  - even if nominal core utilisation may be lower

For the above reason, schedulers will try to avoid moving threads between cores. Of course, there are competing concerns: if a thread is runnable and a core other than its preferred core is idle, inefficiency creeps in: the system keeps a processor core idle while a thread is waiting to run. A realistic scheduler needs to strike a balance between those two concerns: if the preferred core is about to be freed up, it will wait, otherwise it will migrate the thread.
Of course, this will sometimes go wrong: a higher-priority thread with affinity to the same core might wake up and the original waiting thread will have to be migrated anyway. For this reason, stronger affinity will cause a drop in core utilisation, but in a well-tuned scheduler, this should not cause a drop in throughput.

NUMA Systems

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- non-uniform memory architecture
  - different memory is attached to different CPUs
  - each SMP block within a NUMA is called a node
- migrating a process to a different node is expensive
  - thread vs node ping-pong can kill performance
  - threads of one process should live on one node

In a traditional SMP (symmetric multiprocessing) system, each CPU has equal access to all RAM. However, in large computers with many CPUs, it is advantageous (from the point of view of hardware design) to violate this principle, and allow RAM to be attached locally to a single processor package. Cores from another such node then need to access this memory indirectly, adding a penalty both in terms of throughput (how many bytes per unit of time can be transferred from memory to the CPU cache) and in terms of latency (how many cycles it takes from the time data is requested to the time it is available to the processor).
A scheduler needs to take this into account: the affinity of threads (and entire processes) to a particular NUMA node is usually much stronger than the affinity of threads to individual cores within an SMP system: unlike with purely cache-related overhead, the performance hit of running on a different NUMA node is permanent: the data is not automatically migrated into a 'closer' block of memory.

Part 5.3: Interrupts and Clocks

In this section, we will look at how preemptive scheduling is actually implemented, through periodic hardware interrupts.

Interrupt

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- a way for hardware to request attention
- CPU mechanism to divert execution
- partial (CPU state only) context switch
- switch to privileged (kernel) CPU mode

Interrupts allow peripherals to request the attention of the operating system. This is a low-level CPU feature, where asserting an interrupt line (in hardware) causes the processor to stop executing instructions and execute an interrupt handler.
When an interrupt comes in, the CPU will consult a table of interrupt handlers, which is set up by the operating system. Additionally, the CPU will store its state (the values stored in registers) into memory (usually on the active stack).
Usually, only a partial context switch is done by the CPU (i.e. the page table is unaffected), but the interrupt routine will execute in privileged mode (hence it can, if it needs to, adjust page tables). In traditional designs, the kernel memory is mapped (but inaccessible from user mode) into all processes, and hence the interrupt handler can directly and immediately read and write kernel memory.
When the interrupt routine is finished, it uses a special instruction (`iret` on x86) which instructs the CPU to restore its state from the stack (which it stored upon entering the interrupt handler) and drop back into user (unprivileged) mode.

Hardware Interrupts

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- asynchronous, unlike software interrupts
- triggered via bus signals to the CPU
- IRQ = interrupt request
  - just a different name for hardware interrupts
- PIC = programmable interrupt controller

We have already talked about software interrupts earlier: interrupt handlers are quite alike in both cases (that is, for hardware and software interrupts), but there are other differences. In particular, a hardware interrupt is asynchronous: the CPU will invoke the handler regardless of the instruction that is currently being executed. Hardware-wise, interrupts are realized through bus signalling – a peripheral (or rather an interrupt controller) will send a signal down a wire to the CPU, which will react by starting its interrupt handling sequence.

Interrupt Controllers

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- PIC: simple circuit, typically with 8 input lines
  - peripherals connect to the PIC with wires
  - PIC delivers prioritised signals to the CPU
- APIC: advanced programmable interrupt controller
  - split into a shared IO APIC and per-core local APIC
  - typically 24 incoming IRQ lines
- OpenPIC, MPIC: similar to APIC, used by e.g. Freescale

An interrupt controller is essentially a hub which provides a number of interrupt lines to peripherals, and signals the CPU using a single interrupt line whenever any of the peripherals raises an interrupt. The interrupt controller of course informs the CPU which peripheral is the origin of the interrupt.

Timekeeping

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- PIT: programmable interval timer
  - crystal oscillator + divider
  - IRQ line to the CPU
- local APIC timer: built-in, per-core clock
- HPET: high-precision event timer
- RTC: real-time clock

A (programmable) timer is another traditionally discrete component that has long been integrated into the main CPU die. Its role is to keep time (historically using a quartz crystal), and raise an interrupt in regular, configurable intervals.

Timer Interrupt

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- generated by the PIT or the local APIC
- the OS can set the frequency
- a hardware interrupt happens on each tick
- this creates an opportunity for bookkeeping
- and for preemptive scheduling

Every time the configured interval expires, the timer will generate an interrupt. When this happens, the OS kernel has a chance to run, regardless of the currently executing process. Among other things, it is possible to do a context switch by doing an `iret` (or equivalent) into a different thread or process from the one that was interrupted. This is how preemptive scheduling is usually implemented.

Timer Interrupt and Scheduling

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- measure how much time the current thread took
- if it ran out of its slice, preempt it
  - pick a new thread to execute
  - perform a context switch
- checks are done on each tick
  - rescheduling is usually less frequent

The (scheduler part of) the interrupt handler for the timer interrupt quickly checks whether anything needs to be done: that is, it looks up how much time has the currently running thread left of its time slice. If it ran out, then a reschedule is in order: the handler will return into a different thread (that is, perform a context switch... if needed, this includes replacing the active page table). The slice check is done on every tick, since it is cheap. On most ticks, however, no rescheduling will take place, since a typical slice length is many ticks (and is much more expensive).

Timer Interrupt Frequency

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- typical is 100 Hz
- this means a 10 ms scheduling tick (quantum)
- 1 kHz is also possible
  - harms throughput but improves latency

The traditional timer frequency on UNIX systems is 100 Hz, or one tick every 10 milliseconds. This means that time slices available to the scheduler are multiples of 10 milliseconds. For interactive systems, the frequency can be increased, with 1 kHz being the highest commonly used setting (yielding a quantum just 1 ms long, cutting down on scheduling latency quite a bit). Of course, the CPU will spend a lot more time in the timer interrupt handler, reducing the amount of useful work it can perform, thus harming throughput.

Tickless Kernels

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- the timer interrupt wakes up the CPU
- this can be inefficient if the system is idle
- alternative: use one-off timers
  - allows the CPU to sleep longer
  - this improves power efficiency on light loads

Modern processors implement aggressive power management, shutting down parts of the CPU that are not in use. This technique is of course more efficient, if the idle circuits do not need to be woken up very often. If nothing at all is going on, then an entire core can be put to sleep. Unfortunately, the timer interrupt interferes with this somewhat: while the system is completely idle (no threads are ready to run), the processor will still need to process the interrupt, 100 times every second. This has a considerable energy cost, just to figure out that nothing needs to be done.
Instead of using a periodic timer, it's possible to configure a one-off, non-repeating timer, and when it fires, compute when the next scheduling interrupt is needed. This way, during idle times, the processor can sleep undisturbed for much longer periods of time.

Tickless Scheduling

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- quantum length becomes part of the planning
- if a core is idle, wake up on next software timer
  - synchronisation of software timers
- other interrupts are delivered as normal
  - network or disk activity
  - keyboard, mice, ...

This is done by simply doing away with the fixed scheduling quantum. The scheduler can compute when the next reschedule needs to happen, and not waste any time in the timer interrupt unless the slice is over. Sleeping threads may be blocked for any number of reasons, but the most common are waiting for events or resources – one of the events that are commonly awaited is a timer: the thread has some periodic work to do, and may ask the kernel to be woken up in a second, then do some of its work, and then sleep for another second, and so on.
If, at a given moment, all processes are sleeping, then the next timer interrupt needs to happen whenever the soonest of the threads sleeping on a timer is due to wake up. Of course, other interrupts are still delivered as usual, so if a thread is blocked waiting for data to arrive from disk or network, the respective interrupts can cause that thread to be woken up and scheduled for execution.

Other Interrupts

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- serial port
  - data is available on the port
- network hardware
  - data is available in a packet queue
- keyboards, mice
  - user pressed a key, moved the mouse
- USB devices in general

Besides the timer interrupt, there are many others that come up, and many of them indirectly affect scheduling too (usually because one of the threads was waiting for the event that the interrupt signalled).

Interrupt Routing

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- not all CPU cores need to see all interrupts
- APIC can be told how to deliver IRQs
  - the OS can route IRQs to CPU cores
- multi-core systems: IRQ load balancing
  - useful to spread out IRQ overhead
  - especially useful with high-speed networks

Finally, let us consider systems with multiple cores (probably the majority of computers nowadays) and how this affects interrupts: clearly, if a packet comes in from the network, it does not make sense to interrupt all cores: we only need a single core to execute the handler to fetch the data or otherwise deal with the event.
What is more, this does not need to be the same core every time the interrupt happens: if there are many interrupts, we would like them spread out somewhat evenly across all the cores. This is what IRQ load balancing does: it will route interrupts to cores in such a way that each core has approximately the same amount of work handling them.
Finally, since scheduling is done per-core, it is useful to have a separate timer interrupt for each core: those interrupts are of course not subject to load-balancing or other re-routing: the interrupt is, in fact, generated locally on each core (in the local APIC) and the per-core timer which generates the interrupt is programmed separately.

Review Questions

17. What is a thread and a process?
18. What is a (thread, process) scheduler?
19. What do `fork` and `exec` do?
20. What is an interrupt?

Part 6: Concurrency and Locking

This lecture will deal with the issues that arise from running multiple threads and processes at the same time, both using time-sharing of a single processor and by executing on multiple physical CPU cores.

Lecture Overview

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1. Inter-Process Communication
2. Synchronisation
3. Deadlocks

In the first part, we will explore the basic why's and how's of inter-process and inter-thread communication. This will naturally lead to questions about shared resources, and to the topic of thread synchronisation, mutual exclusion and so on. Finally, we will deal with waiting and deadlocks, which arise whenever multiple threads can wait for each other.

What is Concurrency?

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- events that can happen at the same time
- it is not important if it does, only that it can
- events can be given a happens-before partial order
- they are concurrent if unordered by happens-before

Generally speaking, an event happens-before another event when they are causally connected: the first event makes the other event possible, or directly causes it. However, just as often, events are not causally connected: they might happen in any order. We say that such events are concurrent: they can happen in either order, or they can happen, figuratively speaking, at the same time.

Why Concurrency?

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- problem decomposition
  - different tasks can be largely independent
- reflecting external concurrency
  - serving multiple clients at once
- performance and hardware limitations
  - higher throughput on multicore computers

Concurrency arises, in software systems, for a number of reasons: first, and perhaps most important, is problem decomposition: it is much easier to design a large system without explicitly ordering all possible events. A complex system will perform a large number of naturally independent – concurrent – tasks. While it would be certainly possible to impose an artificial order on such tasks, it is not a very practical approach.

Another important reason is that the concurrency came from outside: if there are external events that are concurrent, it is hard to imagine that the responses of the system would be strictly ordered: normally, the actual order of concurrent, external events cannot be predicted, and imposing an order on reactions would mean that at least some of the reactions would be unacceptably delayed.

Finally, concurrency in software allows the underlying hardware to perform better: concurrent instructions can be executed in parallel, without much concern about their relative ordering – which allows the hardware to use its limited resources more efficiently.

Parallel Hardware

298

- hardware is inherently parallel
- software is inherently sequential
- something has to give
  - hint: it's not going to be hardware

Unlike software, which usually consists of a sequence of instructions that are executed in order, hardware consists of spatially organized circuits. Most of the circuitry can operate independently of other circuits. For instance, a typical CPU will contain circuits for multiplying numbers, and other circuits for adding numbers. Those circuits are almost entirely independent, and can operate at the same time, on different pairs of numbers. If the processor is adding numbers, it could be multiplying some other numbers at the same time, without any ill effect on the process of addition happening in another part of the processor.

Of course, multi-core processors are an extreme manifestation of this: the separate cores are simply (mostly) independent copies of the same (very complicated) circuit.

Since we cannot make sequential execution much faster than it already is, the best we can hope for is leveraging concurrency to execute as many things in parallel (on parallel hardware) as we can.

Part 6.1: Inter-Process Communication

Communication is an important part of all but the most trivial software. While the mechanisms described in this section are traditionally known as inter-process communication (IPC), we will also consider cases where threads of a single process use those mechanisms (and will not use a special name, even though the communication is, in fact, intra-process in those cases).

Reminder: What is a Thread

300

- thread is a sequence of instructions
- each instruction happens-before the next
  - or: happens-before is a total order on the thread
- basic unit of scheduling

Before we go any further, we need to recall, from the last lecture, that a thread is a sequence of instructions: as such, each instruction happens before the next instruction (for the more mathematically inclined, this simply means that on the instructions of a single thread, happens-before is a linear ordering). Additionally, threads are a basic unit of scheduling: each processor core is running, at any given time, a single thread.

Reminder: What is a Process

301

- the basic unit of resource ownership
  - primarily memory, but also open files &c.
- may contain one or more threads
- processes are isolated from each other
  - IPC creates gaps in that isolation

A process, then, is a unit of resource ownership – processes own memory (virtual address spaces), open files, network connections and so on. Each process has at least one (but possibly multiple) threads, which

carry out the computation. Since each process is isolated in its own virtual address space, there is no direct way that threads from different processes can interact (communicate, synchronize). However, some degree of communication is desirable, and required: the operating system therefore provides a few primitives, which allow processes to talk to each other, creating controlled gaps in the isolation.

I/O vs Communication

302

- take standard input and output
  - imagine process A writes a file
  - later, process B reads that file
- communication happens in real time
  - between two running threads / processes
  - automatic: without user intervention

Another term that we want to delineate is that of communication: in particular, we need to differentiate it from 'offline' input and output. Technically speaking, reading a file from disk is communication, because some program wrote that file earlier. However, this is not the kind of thing that we are interested in: we are only interested in the instances that happen in real time. More formally, there should be alternation of actions from two threads, ordered by happens-before, i.e. at least one instruction of thread A is happens-before-sandwiched between instructions of thread B.

Direction

303

- bidirectional communication is typical
  - this is analogous to a conversation
- but unidirectional communication also makes sense
  - e.g. sending commands to a child process
  - do acknowledgments count as communication?

Strictly speaking, using the above definition, all communication is bidirectional. However, truly unidirectional communication is quite rare: even semantically unidirectional communication often includes an acknowledgement or other form of reply, satisfying the definition above.

Communication Example

304

- network services are a typical example
- take a web server and a web browser
- the browser sends a request for a web page
- the server responds by sending data

An intuitive, if technically complicated, example of communication would be the interaction of a web browser with a web server. In this case, the browser will use a network connection to send a request, which will be processed by the server. Finally, the server will send a reply, for which the browser is waiting: it is easy to see the causal connections: the request happens-before the reply which happens-before the browser showing the content to the user.

Files

305

- it is possible to communicate through files
- multiple processes can open the same file
- one can write data and another can process it
  - the original program picks up the results
  - typical when using programs as modules

Multiple programs (processes) can open the same file, and read or write data into it at the same time. With a little care, this can be done safely. It is not hard to imagine, then, that the two programs could use this capability for communication, as defined above: one of the programs writes some data on at a particular offset, the other program reads them and perhaps confirms this, possibly using a different mechanism.

A File-Based IPC Example

306

- files are used e.g. when you run `cc file.c`
  - it first runs a preprocessor: `cpp -o file.i file.c`
  - then the compiler proper: `cc1 -o file.o file.i`
  - and finally a linker: `ld file.o crt.o -lc`
- the intermediate files may be hidden in `/tmp`
  - and deleted when the task is completed

As an example, even if a little specific, let's recall how the compiler driver communicates with the individual compilation stages (the compilation process has been covered in the second lecture, in case you need to review it).
Each step looks the same: the driver arranges an intermediate form of the program to be written to a file, then invokes a subprocess which reads that file and writes its output into another file. Clearly, the invocation of next stage happens after the output of the previous has been written.

Directories

307

- communication by placing files or links
- typical use: a spool directory
  - clients drop files into the directory for processing
  - a server periodically picks up files from there
- used for e.g. printing and email

Another approach for communication through the file system leverages directories: a daemon sets up a directory, into which its clients can drop files. These files are then picked up and processed by the daemon, and then unlinked from the directory.
This approach is often seen in print spooling: the client program drops a file (in suitable format) that it wants printed into a spool directory, where it is picked up by the printer daemon, which arranges for the file to be printed and removed from the queue.
Email systems use an analogous process, where mail is either dropped into spool directories as part of internal processing (most mail servers are built from multiple services connected by IPC), or for pickup by individual users.

Pipes

308

- a device for moving bytes in a stream
  - note the difference from messages
- one process writes, the other reads
- the reader blocks if the pipe is empty
- the writer blocks if the pipe buffer is full

We have already talked about pipes earlier: recall that pipes move bytes from one process to another, using the standard file system API: data is sent using `write` and received using `read`.
An important consideration is that each pipe has a (finite) buffer attached to it: when the buffer is full, a process trying to `write` data will be blocked, until the other process issues a `read`, removing some of the data from the buffer. Likewise, when the buffer is empty, attempting to `read` from the pipe will block, until the other side issues a `write` that

and hence provides some data for read to return.

UNIX and Pipes

309

- pipes are used extensively in UNIX
- pipelines built via the shell's | operator
- e.g. `ls | grep hello.c`
- most useful for processing data in stages

Especially in the case of user-setup pipes (via shell pipelines), the boundary between IPC and "standard IO" is rather blurry. Programs in UNIX are often written in a style, where they read input, process it and write the result as their output. This makes them amenable for use in pipelines. While pipes are arguably "more automatic" than dropping the output in a file and running another command to process the file, there is also a degree of manual intervention. Another way to look at the difference may be that a pipe is primarily an IPC mechanism, while a file is primarily a storage mechanism.

Sockets

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- similar to, but more capable than pipes
- allows one server to talk to many clients
- each connection acts like a bidirectional pipe
- could be local but also connected via a network

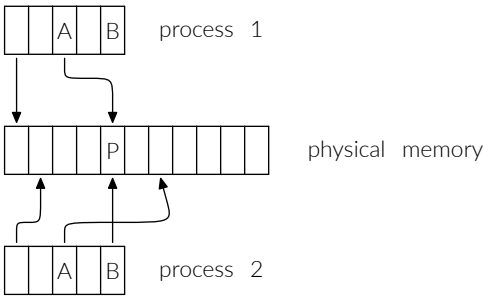
You might remember that sockets are pipe-like devices, but more powerful (and more complicated). A socket allows a single server to open communication channels to multiple clients at the same time (possibly over a network), providing a bidirectional channel between each of the clients and the server.
Additionally, sockets also come in a 'datagram' flavour, in which case they do not establish connections and do not behave like pipes at all: instead, in this mode, they can be used to send messages.

Shared Memory

311

- memory is shared when multiple threads can access it
  - happens naturally for threads of a single process
  - the primary means of inter-thread communication
- many processes can map the same physical location
  - this is the more traditional setting
  - hence also allows inter-process communication

Shared memory is, in some sense, the most straightforward communication mechanism possible: memory access is, after all, a very common operation in a program. Among threads of the same process, all memory is 'shared' in the sense that all threads can read and write all memory (since they share the same page table). Of course, in most programs, only a small, carefully delineated part of the memory is used for exchanging data between threads.
Additionally, processes can set up a piece of shared memory between them. However, since there is no shared virtual address space, each process may have the shared block of memory mapped at different virtual address (let's call the relevant virtual addresses A and B). However, there is only one block of physical memory involved: the shared memory resides at the physical address P. Inter-process shared memory is then set up in such a way, that for the first process, A translates to P and in the second process, B translates to P.



The address B may or may not be a valid address in the first process, and the same holds for A in the second process.

Message Passing

312

- communication using discrete messages
- we may or may not care about delivery order
- we can decide to tolerate message loss
- often used across a network
- can be implemented on top of sockets

While it is hard to beat the efficiency of shared memory as a communication mechanism, message passing has other advantages: first of all, it is much safer (communication through shared memory can be quite tricky to get right) and, for some use cases, considerably easier to use. Moreover, message passing can be done over networks, which makes it especially suitable for distributed systems.

Part 6.2: Synchronisation

In this section, we will deal with a specific form of communication, where no (application) data is exchanged. The purpose of synchronisation primitives is to ensure that actions of multiple threads or processes proceed in a correct order (of which, there are usually many). Our main motivation will be prevention of race conditions, which are, essentially, the wrong orderings of concurrent actions (for a suitable value of 'wrong').

Shared Variables

314

- structured view of shared memory
- typical in multi-threaded programs
- e.g. any global variable in a program
- but may also live in memory from `malloc`

Before we proceed to talk about synchronisation proper, we will have a look at a proper communication device, which we will use as an example: a shared variable is simply a named piece of shared memory, available in multiple threads under the same name.

Shared Heap Variable

315

```
void *thread( int *x ) { *x = 7; }
int main()
{
    pthread_t id;
    int *x = malloc( sizeof( int ) );
    pthread_create( &id, NULL, thread, x );
}
```

It is also possible to have anonymous shared variables, allocated dynamically on the heap. They are accessed through a pointer.

Race Condition: Example

316

- consider a shared counter, `i`
- and the following two threads

```
int i = 0;
void thread1() { i = i + 1; }
void thread2() { i = i - 1; }
```

What is the value of `i` after both finish?

Before we attempt to define a race condition, let's look at an example. In the above program, two threads modify the same shared variable: one adds, and another subtracts, one. Try to think about the possible outcomes, before you look ahead.

Race on a Variable

317

- memory access is not atomic
- take `i = i + 1` / `i = i - 1`

```
a₀ ← load i   | b₀ ← load i
a₁ ← a₀ + 1   | b₁ ← b₀ - 1
store a₁ i    | store b₁ i
```

To understand why the innocent-looking code from the previous slide fails, we need to look at a low-level description of the program (at the level of, essentially, machine instructions). Notice that each of the two statement translates into three separate instructions: load a value from memory, perform the arithmetic operation, and store the result back into memory. At this level of detail, it should be easy to see how the instructions from the two threads can be ordered to give a wrong (or at least unexpected) result, without violating the happens-before relation (remember that instructions of each thread separately are linearly ordered).

Critical Section

318

- any section of code that must not be interrupted
- the statement `x = x + 1` could be a critical section
- what is a critical section is domain-dependent
  - another example could be a bank transaction
  - or an insertion of an element into a linked list

If we want the result of the above program to be always 0, we must demand that each of the two statements is an instruction sequence that belongs to a common critical section: that is, a span of code that must not be interrupted by any instruction that belongs to the same critical section. In this case, this means that once either of the `load` instructions starts executing, the thread which did so must first get all the way to the corresponding `store` before the other thread can execute its `load`.
Critical sections do not modify the happens-before relation: the critical sections, as units, can happen in either order (they are still concurrent). However, the entirety of the critical section behaves, with regard to other instances of the same critical section, as a single atomic instruction.

Race Condition: Definition

319

- (anomalous) behaviour that depends on timing
- typically among multiple threads or processes
- an unexpected sequence of events happens
- recall that ordering is not guaranteed

We can now attempt a definition: a race condition is a behaviour which

1. depends on timing (in the sense that it depends on a specific ordering of concurrent events),
2. was not anticipated by the programmer.

With the above definition, a race condition can be benign, and the term is often used in this sense. In our study of the phenomenon, however, it is more useful to also include a third clause:

3. the behaviour is erroneous.

Race conditions often lurk in places where there is a lot of concurrency: threaded programs are a prime example (almost all instructions are concurrent with a large number of other instructions coming from other threads).
However, it is important to keep in mind, that some form of communication is necessary for a race condition to arise – concurrency alone is not sufficient. This is because completely concurrent processes cannot influence each other, and hence their behaviour cannot depend on the particular ordering of the events that are concurrent among them.

Races in a Filesystem

320

- the file system is also a shared resource
- and as such, prone to race conditions
- e.g. two threads both try to create the same file
  - what happens if they both succeed?
  - if both write data, the result will be garbled

Since file system is a resource that is shared by otherwise unrelated processes, it creates an environment prone to race conditions: there is ample concurrency, but also a lot of (sometimes accidental) communication.

Mutual Exclusion

321

- context: only one thread can access a resource at once
- ensured by a mutual exclusion device (a.k.a mutex)
- a mutex has 2 operations: `lock` and `unlock`
- `lock` may need to wait until another thread `unlocks`

Now that we have basic understanding of the problems associated with concurrency, let's look at some of the available remedies. The first, and in some sense simplest synchronisation primitive is a mutual exclusion device, designed to enforce critical sections.
It is often the case that the critical section is associated with a resource: that is, all the code between each acquisition and the corresponding release of the resource is part of a single critical section. This essentially means that one of the steps of the acquisition process is locking a mutex and, analogously, the mutex is unlocked as part of the release process associated with the resource.

Semaphore

322

- somewhat more general than a mutex
- allows multiple interchangeable instances of a resource
  - consider there are N identical printers
  - then N processes can be printing at any given time
- basically an atomic counter

Semaphores are, in a sense, a generalisation of a mutex – however, they are only useful when dealing with resources (i.e. it can only be used to guard a general critical section in the case it is exactly equivalent to a mutex). The difference between a mutex and a semaphore is that multiple threads can enter the section of code guarded by a semaphore, but the number is capped by a constant. If the constant is set to 1, then the semaphore is the same as a mutex.

Monitors

323

- a programming language device (not OS-provided)
- internally uses standard mutual exclusion
- data of the monitor is only accessible to its methods
- only one thread can enter the monitor at once

Essentially, a monitor is a fully encapsulated object (as defined in object oriented programming), with one additional restriction: each instance of a monitor has a critical section associated with it, and each of its method is, in its entirety, part of this critical section.
As long each public method leaves the object in a consistent state (which is normally required of all objects), a monitor is automatically thread-safe, that is, multiple threads can call its methods without risking race conditions.

Condition Variables

324

- what if the monitor needs to wait for something?
- imagine a bounded queue implemented as a monitor
  - what happens if it becomes full?
  - the writer must be suspended
- condition variables have `wait` and `signal` operations

Since critical sections are often associated with communication, it may happen that code currently in a critical section cannot proceed until some other thread performs a particular action. This use case is served by another synchronisation device, known as a condition variable: the variable can be waited for, which blocks the calling thread, and signalled, which wakes up the waiting thread and allows it to proceed.

Spinlocks

325

- a spinlock is the simplest form of a mutex
- the `lock` method repeatedly tries to acquire the lock
  - this means it is taking up processor time
  - also known as busy waiting
- spinlocks contention on the same CPU is very bad
  - but can be very efficient between CPUs

A spinlock is a particularly simple implementation of the abstract mutex concept. The state of the device is a single bit, the lock operation uses an atomic compare and swap to change the bit from 0 to 1 atomically (i.e. in such a way that the operation fails in case some other thread succeeded in changing it to 1 while the operation was running), looping until it succeeds. The unlock operation simply resets the bit to 0.
There are a few upsides: the implementation is very simple, the state is very compact and the latency is as good as it gets, assuming that the contention is against another CPU core. The uncontended case is pretty much optimal.
There is, however, one serious (and in many scenarios, fatal) drawback: contention on the same CPU core has the worst possible behaviour (maximal latency and minimal throughput). Another important problem, though less severe, is that throughput strongly depends on the average length of the protected critical section: locks that are only held for a short time perform well, but longer critical sections will waste significant resources by holding up a CPU core in the busy-waiting loop.
Overall, spinlocks are useful for protecting critical sections which are short and which are guaranteed to be contended by threads running on different CPU cores. This often happens inside the kernel, but only rarely in user-space programs.

Suspending Mutexes

326

- these need cooperation from the OS scheduler
- when lock acquisition fails, the thread sleeps
  - it is put on a waiting queue in the scheduler
- unlocking the mutex will wake up the waiting thread
- needs a system call → slow compared to a spinlock

A different, much more complicated, but also much more versatile, implementation of a mutex is a suspending mutex. The main difference lies in the contended case of the lock operation: whenever there is an attempt to lock an already-locked mutex, the unlucky thread is suspended and placed on a wait queue of the scheduler. The unlock operation, of course, needs to be augmented to check if there are any threads waiting for the mutex, and if yes, wake up one of them.
The interaction with the scheduler means that both the lock and unlock operations must perform a system call, at least in some cases. Compared to atomic instructions, system calls are much more expensive, increasing the overhead of the mutex considerably.
A common implementation technique uses a combination of a spinlock and a suspending mutex: the lock operation runs a small number of loops trying to acquire the mutex, and suspends the thread if this fails. This approach combines the good behaviours of both, but is the most complicated implementation-wise, and the state of the mutex is also at least as big as that of a suspending mutex.

Condition Variables Revisited

327

- same principle as a suspending mutex
- the waiting thread goes into a wait queue
- `signal` moves the thread back to a run queue
- the busy-wait version is known as polling

The usual way to implement a condition variable is to interact with the scheduler, allowing the waiting thread to free up the CPU core it was occupying. A busy-waiting, spinlock-like alternative is possible, though not commonly used.

Barrier

328

- sometimes, parallel computation proceeds in phases
  - all threads must finish phase 1
  - before any can start phase 2
- this is achieved with a barrier
  - blocks all threads until the last one arrives
  - waiting threads are usually suspended

Another synchronisation device that we will consider is a barrier. While the devices that we have described so far can be used in scenarios with more than two threads, their behaviour is always governed by pairwise interactions.
A barrier is different: it synchronises a number of threads at a single point. Only when all the participating threads gather at the barrier are they allowed to continue.

Readers and Writers

329

- imagine a shared database
- many threads can read the database at once
- but if one is writing, no other can read nor write
- what if there are always some readers?

Let us consider another synchronisation problem, again involving more than two threads: there is a piece of data (a database if you like) that many threads need to consult, and sometimes update.
The naive solution would be to simply wrap all access to the data structure in a critical section: this is certainly correct, but wasteful, since multiple readers do not interact with each other, but still need to queue up to interact with the data.
The synchronisation device that solves the problem is called an rwlock, or read-write lock, with 3 operations: lock for reading, lock for writing and unlock. The invariant is that if the rwlock is locked for writing, it is locked by exactly one thread. Otherwise, there might be multiple threads holding a read lock (which of course prevents any write locks from being taken until the read locks are all released).

Read-Copy-Update

330

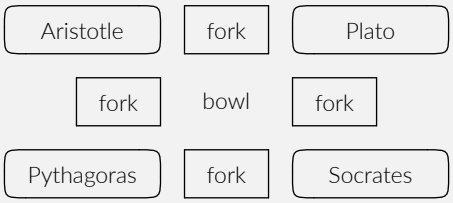
- the fastest lock is no lock
- RCU allows readers to work while updates are done
  - make a copy and update the copy
  - point new readers to the updated copy
- when is it safe to reclaim memory?

In some cases, the readers & writers scenario can be solved without taking any locks at all (not even a critical section is required). The way this works is that a writer, instead of modifying the data in place (and therefore interfering with concurrent reads), makes a copy of the data (which is a read operation, and hence can be safely performed concurrently), performs the updates in this new copy of the data, and then instructs all future readers to use this copy instead, usually by updating a pointer.

Part 6.3: Deadlocks and Starvation

Dining Philosophers

332



In the 'dining philosophers' problem, there is a bowl of food in the middle of a table, a number of philosophers seated around the table, and between each pair of philosophers, there is a single fork. To eat, each philosopher needs to use two forks at the same time. The philosophers sit and think, but when they become hungry, they pick up the forks and eat.
This scenario is used to illustrate the problem of deadlocks and starvation in concurrent systems. Can you come up with instructions for the philosophers that would ensure that each hungry philosopher gets to eat (in finite time)? Consider why simple algorithms fail.

Shared Resources

333

- hardware comes in a limited number of instances
- many devices can only do one thing at a time
- think printers, DVD writers, tape drives, ...
- we want to use the devices efficiently → sharing
- resources can be acquired and released

The most natural setting to contemplate deadlocks is one in which multiple threads (and/or processes) compete for finite resources. In this case, a resource is an abstract object, which can be acquired, used, and released. A resource cannot be used before it has been acquired, and can no longer be used after being released. The thread that has acquired (but not yet released) a resource is said to own it.

Network-based Sharing

334

- sharing is not limited to processes on one computer
- printers and scanners can be network-attached
- the entire network may need to coordinate access
  - this could lead to multi-computer deadlocks

In practice, some resources are 'remote' – made available to processes on computer A by another computer B attached to the same network. This does not make any practical difference to our consideration (other than perhaps realizing, that a single deadlock may span multiple com-

puters).

Locks as Resources

335

- we explored locks in the previous section
- locks (mutexes) are also a form of resource
  - a mutex can be acquired (locked) and released
  - a locked mutex belongs to a particular thread
- locks are proxy (stand-in) resources

In the following, we will consider locks (or even critical sections as such) to be simply a form of resource: the operations on an abstract resource neatly map to operations on an (abstract) lock.

Preemptable Resources

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- sometimes, held resources can be taken away
- this is the case with e.g. physical memory
  - a process can be swapped to disk if need be
- preemtability may also depend on context
  - maybe paging is not available

Some resources can be taken away from their owner temporarily, without causing ill effects, or at an acceptable cost (in terms of latency, loss of throughput, or resource-specific considerations, such as waste of material). A canonic example would be a page of memory: even though it is acquired by a particular process, the system might take it away without cooperation from the process, and transparently give it back whenever it is actually used (this technique is known as swapping).

Non-preemptable Resources

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- those resources cannot be (easily) taken away
- think photo printer in the middle of a page
- or a DVD burner in the middle of writing
- non-preemptable resources can cause deadlocks

Many resources are, however, practically non-preemptable; that is, once acquired by a thread or a process, they cannot be unilaterally taken away without considerable damage, e.g. killing the owning process or irreparably damaging its output through the device.

Resource Acquisition

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- a process needs to request access to a resource
- this is called an acquisition
- when the request is granted, it can use the device
- after it is done, it must release the device
  - this makes it available for other processes

Now that we have discussed resources in a bit more detail, let's just quickly revisit the protocol for their acquisition and release. In the following, we operate on the assumption that only a limited number of processes can own a particular resource at any given time (most often just one, in fact).

Waiting

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- what to do if we wish to acquire a busy resource?
- unless we don't really need it, we have to wait
- this is the same as waiting for a mutex
- the thread is moved to a wait queue

We will also assume that acquisition is blocking: if a resource is busy (owned by another process), the process will wait until it is released before continuing execution. This does not always need to be the case, but it is the most common approach.

Resource Deadlock

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- two resources, A and B
- two threads (processes), P and Q
- P acquires A, Q acquires B
- P tries to acquire B but has to wait for Q
- Q tries to acquire A but has to wait for P

Now we are finally equipped to look at (resource) deadlocks. We will look at the simplest possible case, with two threads and two resources. After the above sequence of events, there can be no further progress: without an outside intervention, both P and Q will be blocked forever. This is what we call a deadlock. Please note that it is usually the case that both acquisitions in P are concurrent with both acquisitions in Q. Of course, the above situation can be generalized to any number of threads and resources (as long as there are at least 2 of each).

Resource Deadlock Conditions

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1. mutual exclusion
2. hold and wait condition
3. non-preemtability
4. circular wait

Deadlock is only possible if all 4 are present.

A number of sound design decisions conspire to create the conditions for a deadlock to occur. It is certainly natural that a resource should only be used by a single thread at any given time – that is, after all, the nature of resources.

The hold and wait condition arises when a single thread can request multiple resources at once, performing the acquisitions in a sequence. It is hard to object here too, since it fits the linear nature of most programs – the program (or rather each thread of a program) is essentially a sequence of instructions, and each instruction is only performed after the previous has finished. Resource acquisition cannot finish while a resource is busy, and the only way to have more than a single resource is to acquire each in turn.

In some cases, non-preemptability is not even negotiable: it is a property of the resource in question. There is some maneuvering space with critical sections that cause no interaction with any external entity (resource, other threads) with the exception of their associated lock. In this case, it might be possible to roll back the effects of the critical section and attempt to restart it. This is, however, not easy to achieve.

Let us consider a static resource dependency graph, in which nodes are resources and edges indicate that a hold-and-wait condition exists between them, that is, an edge $A \rightarrow B$ is present in the graph if there is a thread which attempts to acquire B while holding A. The circular wait condition is satisfied whenever there is a cycle in this graph.

Non-Resource Deadlocks

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- not all deadlocks are due to resource contention
- imagine a message-passing system
- process A is waiting for a message
- process B sends a message to A and waits for reply
- the message is lost in transit

Quite importantly, the above four conditions only pertain to resource deadlocks: there are other types of deadlocks with a different set of conditions. This means that even if we can eliminate one of the 4 conditions, and hence prevent resource deadlocks, this does not mean, unfortunately, that our system will be deadlock-free.

Example: Pipe Deadlock

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- recall that both the reader and writer can block
- what if we create a pipe in each direction?
- process A writes data and tries to read a reply
  - it blocks because the opposite pipe is empty
- process B reads the data but waits for more → deadlock

A typical example of a non-resource deadlock has to do with pipes: remember that an empty pipe blocks on read, while a full pipe blocks on write. There is a number of ways this can go wrong, if there is more than one pipe involved. You can probably spot similarities between this type of deadlock, and the resource deadlock we have discussed at length.

Deadlocks: Do We Care?

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- deadlocks can be very hard to debug
- they can also be exceedingly rare
- we may find the risk of a deadlock acceptable
- just reboot everything if we hit a deadlock
  - also known as the ostrich algorithm

Many (probably most) deadlocks arise from race conditions, and hence will not happen very often. The so-called ostrich algorithm takes advantage of this rarity: if a deadlock happens, kill all the involved processes, or possibly just reboot the entire system. Of course, deciding that a deadlock has happened can be tricky.

Deadlock Detection

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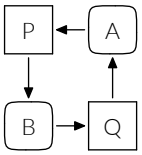
- we can at least try to detect deadlocks
- usually by checking the circular wait condition
- keep a graph of ownership vs waiting
- if there is a loop in the graph → deadlock

One way to detect deadlocks is to use a dynamic counterpart of the static circular wait condition: in this case, the dependency graph has two types of nodes: threads and resources. Edges are always between a thread T and a resource R: R → T exists if thread T currently owns resource R, and T → R exists, if thread T is waiting for the acquisition of R. If a cycle exists in this graph, the system is in a deadlock (and the threads which lie on the cycle are all blocked). Let's revisit the example with two threads, P and Q, and two resources, A and B that we saw earlier:

1. P successfully acquires A (giving rise to edge A → P)
2. likewise, Q acquires B, meaning B → Q
3. P tries to acquire B but has to wait, hence P → B
4. Q tries to acquire A but has to wait, hence Q → A

This is the resulting graph, with an obvious cycle in it:



Deadlock Recovery

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- if a preemptable resource is involved, reassign it
- otherwise, it may be possible to do a rollback
  - this needs elaborate checkpointing mechanisms
- all else failing, kill some of the processes
  - the devices may need to be re-initialised

A deadlock involving at least one preemptable resource can still happen, but unlike in the 'standard' case, it is possible to recover and continue computation without forcibly terminating any of the threads or processes involved. Instead, one of the resources is preempted, breaking the cycle and allowing the system to make progress again.
If the deadlock instead includes a restartable critical section (as outlined earlier), then this critical section can be rolled back and restarted, again allowing other threads to make progress.
Finally, if all else fails, the system can pick a victim thread on the cycle and terminate it, releasing any resources it might have been holding. Like the other cases, this allows the system to progress again.

Deadlock Avoidance

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- we can possibly deny acquisitions to avoid deadlocks
- must know the maximum resources for each process
- avoidance relies on safe states
  - worst case: all processes ask for maximum resources
  - safe means deadlocks are avoided in the worst case

In general, deadlock avoidance is an approach where the system will deny resource acquisitions if they might later lead to a deadlock. The best-known instance of deadlock avoidance is Banker's Algorithm, invented by E. Dijkstra. This algorithm applies in cases where each resource has a number of fungible instances greater than any single thread might request at once. The input to the algorithm is the maximal number of instances of a resource that can be requested by each thread. The safety invariant is this:

1. there is a thread T, such that the available resources are sufficient to satisfy its maximal resource allocation,
2. when the thread T terminates (returning all its currently allocated resources), the invariant still holds.

Any resource acquisitions which would violate this invariant are denied. The initial conditions imply that, at the outset, we are in a safe state; thus, we have demonstrated that the algorithm is correct. The algorithm assumes that nothing apart from resource acquisitions might block any of the threads. The following table illustrates the algorithm (P, Q and R are threads, the numbers are resources held / maximal allocation):

step	P	Q	R	available	action
1	0/3	0/2	0/4	5/5	P acquires 1
2	1/3	0/2	0/4	4/5	R acquires 2
3	1/3	0/2	2/4	2/5	Q acquires 1
4	1/3	1/2	2/4	1/5	P is denied 1
5	1/3	1/2	2/4	1/5	Q acquires 1
6	1/3	2/2	2/4	0/5	Q terminates
7	1/3	–	2/4	2/5	P acquires 1
8	2/3	–	2/4	1/5	

Notice that in step 4, the request by P has been denied, because there would no longer be any thread guaranteed to be able to make sufficient progress to release resources.

Deadlock Prevention

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- deadlock avoidance is typically impractical
- there are 4 conditions for deadlocks to exist
- we can try attacking those conditions
- if we can remove one of them, deadlocks are prevented

Deadlock avoidance is, unfortunately, not very practical in general-purpose operating systems: it is often the case, that a particular resource has exactly 1 instance available, and the above algorithm would then force all programs which might use the resource to run one after another. Moreover, the assumption that there are no other interactions between threads is not very realistic either.

Prevention via Spooling

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- this attacks the mutual exclusion property
- multiple programs could write to a printer
- the data is collected by a spooling daemon
- which then sends the jobs to the printer in sequence

This approach can trade a deadlock on the printer for a deadlock on disk space. However, disk space is much more likely to be preemptable in this scenario, since a job blocked by a full disk can be canceled (and erased from disk) and later retried (unlike a half-printed page).

Prevention via Reservation

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- we can also try removing hold-and-wait
- for instance, we can only allow batch acquisition
  - the process must request everything at once
  - this is usually impractical
- alternative: release and re-acquire

It is certainly conceivable that we might require that all resource acquisitions are done in batches, always requesting, as a single atomic action, all the resources required in a particular section of code. The resources may be released one at a time. If an additional resource is required while other resources are already held, the program must first release everything it holds before requesting the new batch.

Prevention via Ordering

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- this approach eliminates circular waits
- we impose a global order on resources
- a process can only acquire resources in this order
  - must release + re-acquire if the order is wrong
- it is impossible to form a cycle this way

Finally, the perhaps most practical approach within a single program (or another closed system, but not so much in an operating system) is to impose a global order on resource acquisition, which each thread must observe. This implies that the static resource dependency graph is acyclic and deadlocks cannot occur.

Livelock

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- in a deadlock, no progress can be made
- but it's not much better if processes go back and forth
  - for instance releasing and re-acquiring resources
  - they make no useful progress
  - they additionally consume resources
- this is a livelock and is just as bad as a deadlock

In a deadlock, the blocked threads are all usually suspended (not runnable). If some or all of the threads involved in a deadlock-like condition are active (busy waiting, polling or otherwise attempting an action which is bound to fail forever), we talk about a livelock: threads are executing instructions, but progress is not being made.

Starvation

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- starvation happens when a process can't make progress
- generalisation of both deadlock and livelock
- for instance, unfair scheduling on a busy system
- also recall the readers and writers problem

Finally, the most general notion is starvation, which is a condition when a thread cannot make progress, for whatever reason: it is blocked on a resource, it is denied processor time, etc. An example that is neither a deadlock nor a livelock would arise in a naive solution to the readers & writers problem from earlier: if there are sufficiently many readers so that there is always a read lock on the resource, writers will be blocked indefinitely, and hence starved.

Review Questions

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21. What is a mutex?
22. What is a deadlock?
23. What are the conditions for a deadlock to form?
24. What is a race condition?

Part 7: Device Drivers

Abstracting hardware is one of the major roles of an operating system. While we have already discussed the basic hardware resources (CPU and memory) in detail in previous lectures, so-called peripherals also play an important role. In this lecture, we will look at the interface between the operating system and the peripheral hardware (network interface cards, persistent storage, removable storage, displays, input devices and so on).

Lecture Overview

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1. Drivers, IO and Interrupts
2. System and Expansion Buses
3. Graphics
4. Persistent Storage
5. Networking and Wireless

Part 7.1: Drivers, IO and Interrupts

In the first part, we will discuss the low-level aspects of hardware interaction: how the data moves between the CPU and the peripheral, how peripherals signal events to the CPU, and how this all relates to the operating system (which is running on the CPU).

Input and Output

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- we will mostly think in terms of IO
- peripherals produce and consume data
- input – reading data produced by a device
- output – sending data to a device
- protocol – valid sequences of IO events

While peripherals can be rather complicated, we will think of them in a rather abstract, simplified way, as devices which produce and consume data. The other crucial component in our understanding of devices will be events. The valid sequences of events and the inputs and outputs tied to those events are described by a protocol.
Data transfers coupled to events (i.e. when they happen in a specific time pattern) can represent a rather wide variety of behaviours and effects. Consider a keyboard: when the user presses a key, that is an event, and is accompanied by a data transfer, which tells the system which key was pressed (or released). Likewise, when a mouse is moved, a stream of data which describe the relative motion is sent to the computer.
Other types of devices receive data instead: take a display, as an archetype of that type of device: the computer (more or less continuously) sends data which represents the pixels to show on the screen and which is in turn shown to the user.
Yet other devices accept commands (which are also of course a form of data) and again respond with data (responses to the commands). Consider a disk drive: when the system wishes to store some data, it will send a command (along with the payload, i.e. the data to be stored) and receives a confirmation. Likewise, when it wishes to retrieve some data, it sends a read command and receives a reply, which includes the data which was stored at the requested address.

What is a Driver?

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- piece of software that talks to a device
- usually quite specific / unportable
  - tied to the particular device
  - and also to the operating system
- often part of the kernel

Clearly, the input data needs to be processed and output generated. It is also rather clear that the form and content of the data will be specific to the particular device. Hence the software needs to be able to construct and understand data in the form understood by the particular device. The software in charge of this communication is known as a driver, and in the light of the above, it is rather clear that any given driver is paired off with a specific device, or a small class of devices. Or, to be more precise, the driver implements one side of the protocol (the other side is implemented by the device itself).
At first glance, there does not appear to be a good reason why a driver should be specific to a particular operating system: after all, the protocol used by the device will be the same, regardless of the operating system running on the CPU. But of course, the device-side protocol is only one part of the driver: the other part is communication with the operating system. This communication is performed using a set of interfaces that are usually specific to a given operating system (though portable drivers do exist).
The other issue that ties drivers to a specific operating system is that drivers usually need to cooperate with each other: later in the lecture, we will see that devices are connected through other devices, and the peripheral driver needs to talk to the bus driver to talk to the peripheral.

Kernel-mode Drivers

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- they are part of the kernel
- running with full kernel privileges
  - including unrestricted hardware access
- no or minimal context switching overhead
  - fast but dangerous

In some sense, the simplest type of driver is one that is part of the kernel. A driver of this type can use all CPU and hardware facilities necessary to communicate with its device directly, without going through a middleman. Since no processes are involved, it also means that the code of the driver can run without context switches whenever necessary (e.g. in response to a hardware interrupt).
This makes kernel-mode drivers particularly fast (low-overhead), but their unrestricted access to hardware and memory makes any problems in such a driver very serious. If the driver crashes, for instance, it'll usually take the entire operating system with it.

Microkernels

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- drivers are excluded from microkernels
- but the driver still needs hardware access
  - this could be a special memory region
  - it may need to react to interrupts
- in principle, everything can be done indirectly
  - but this may be quite expensive, too

While kernel-mode drivers are ubiquitous in monolithic kernel designs, they are all but banished from microkernels. Instead, each driver is a separate process and executes in user mode of the CPU.
However, many drivers require some level of direct hardware access in order to communicate with their device: most often interrupt handlers and reads/writes to a specific area of physical memory. The latter can be arranged easily enough (just map that area of memory into the driver process).
The former, however, is a problem: interrupt handlers (we will look at those in more detail shortly) always run in privileged mode and hence the driver cannot install one. Instead, the kernel will relay the interrupt to the driver process using some form of IPC, often precipitating an expensive context switch.

User-mode Drivers

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- many drivers can run completely in user space
- this improves robustness and security
  - driver bugs can't bring the entire system down
  - nor can they compromise system security
- possibly at some cost to performance

Drivers running in user mode are not exclusive to microkernels, and while they have downsides, they also have many desirable properties. Since they are isolated from the kernel, from each other and from other programs running on the system, crashes and other bugs in a driver cannot compromise the rest of the system (at least not directly, though if a peripheral is mis-programmed, it may still crash the system or make it otherwise unusable). Of course, security is also significantly improved.

Drivers in Processes

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- user-mode drivers typically run in their own process
- this means context switches
  - every time the device demands attention (interrupt)
  - every time another process wants to use the device
- the driver needs system calls to talk to the device
  - this incurs even more overhead

Let's look at the model where each driver runs in its own process. As we have already mentioned, a major problem in this model is due to additional context switches, which happen when:

1. an interrupt arrives from the hardware and some other process is executing at the time (which is almost always),
2. another process on the system tries to use the device: the request must go through the driver, which means that it needs to run, and hence its process needs to be scheduled before the request can be served.

Neither of those happen with kernel-mode drivers. Finally, to perform any privileged operation, the driver must perform a system call – while it is less expensive than a context switch, it is also significantly more expensive than a normal function call.

In-Process Drivers

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- what if a (large portion of) a driver could be a library
- best of both worlds
  - no context switch overhead for requests
  - bugs and security problems remain isolated
- often used for GPU-accelerated 3D graphics

There is an alternative model, which mitigates some of the downsides of user-mode drivers. In particular the second source of context switches can be (at least partially) eliminated by running the driver in the same process as the application which uses the device. How would this work?

The driver can come as a library and the application links to that library. Of course you would want to link the driver dynamically, so that a different driver (e.g. for a different device of the same general type) can be substituted without recompiling the application.

There are some issues that need to be resolved with regards to permissions, but in principle, an in-process (library) driver can use the same system calls that a driver running in its own process could. Effects of possible bugs or misbehaviour in the driver are limited to the particular process in which it runs. It is also common that multiple processes can use the same device, each using its own 'instance' of the driver. However, this model is not applicable when the driver needs to be protected from the application or the driver needs to perform multiplexing (i.e. it is not possible to have multiple independent instances of the driver talk to the same device, but the device needs to be nevertheless shared by multiple processes).

Port-Mapped IO

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- early CPUs had very limited address space
  - 16-bit addresses mean 64KB of memory
- peripherals got a separate address space
- special instructions for using those addresses
  - e.g. `in` and `out` on `x86` processors

Let's now look at how the CPU communicates with peripherals and how this affects drivers. Some old CPUs (most famously Intel 8086) had 2 distinct address spaces, one for memory and another for peripherals. The latter could be accessed using special-purpose instructions, which would move values between CPU registers and peripherals. In later iterations of the `x86` family, when memory protection (an MMU and privilege levels) was added, those instructions became privileged. Hence, only kernel can talk to devices which are attached to the CPU through this mechanism. But the IO instructions have been largely abandoned, and are only used with legacy devices.

Memory-mapped IO

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- devices share address space with memory
- more common in contemporary systems
- IO uses the same instructions as memory access
  - `load` and `store` on RISC, `mov` on `x86`
- allows selective user-level access (via the MMU)

The alternative to port-mapped IO is memory-mapped IO (MMIO for short), where the physical address space is shared by RAM and peripherals. Writing to some addresses (using e.g. `mov` on `x86`) will store the data in RAM, but simply changing the address will result into the data being sent to a peripheral (typically to be stored in an onboard register or memory). A specific example would be the PCI-E configuration space: each PCI-E device must expose a single page (4KiB) of MMIO address space through which it can be enumerated and configured. Unlike port-mapped IO, access to the physical memory address space is managed by the MMU (including the regions assigned to devices, not just those given to RAM). Hence it is possible to securely allow a certain process to talk to a specific device by mapping the corresponding chunk of the physical address space into the virtual address space of that process.

Programmed IO

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- input or output is driven by the CPU
- the CPU must wait until the device is ready
- would usually run at bus speed
  - 8 MHz for ISA (and hence ATA-1)
- PIO would talk to a buffer on the device

Another way to look at IO is how it is timed. Peripherals are usually orders of magnitude slower than the main CPU and the CPU must wait a significant number of cycles between, for instance, issuing commands to a given device. Commands are usually realized by writing data to the on-board registers of the device. The device periodically reads those registers and acts accordingly, perhaps writing the response into some

other register, which the CPU can then read (both input and output is done using one of the mechanisms described above: port-mapped or memory-mapped IO).
The simplest form of timing is called programmed IO or PIO. In this mode, the CPU drives the data transfer and it has to actively wait for the device (or rather the bus) to become ready after each transfer. Consider sending data to a disk: there is a RAM-based buffer in the disk controller, one that can hold at least a single physical disk sector worth of data. The CPU can transfer into this buffer at bus speed, e.g. 8MHz for ISA (admittedly a very old technology). If the CPU core runs at 32MHz, this means that it can only send data every fourth cycle. It has to spend 3 out of every 4 cycles waiting for the bus to become ready.

Interrupt-driven IO

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- peripherals are much slower than the CPU
  - polling the device is expensive
- the peripheral can signal data availability
  - and also readiness to accept more data
- this frees up CPU to do other work in the meantime

Some peripherals can only process very small amounts of data at once, and are much slower still than the bus. As an extreme example, consider a serial port configured to send 9600 bits per second. That works out to 1200 characters per second: with an on-board buffer for 60 characters, the CPU needs to fill that buffer at 20Hz, i.e. with a period of 50 milliseconds, which is of course an eternity in CPU time (almost 2 million cycles at 32MHz).
So you would perhaps use PIO to fill in that 60 character buffer (at bus speed, so 25 % efficiency, working out to 240 cycles), but actively waiting for the buffer to drain would be madness. Fortunately, the serial port hardware can be configured to cause an interrupt when the buffer becomes empty. The CPU can go about doing whatever, but the serial port driver will be woken up to fill in the next 60 bytes when needed, once every 50ms or so.
Same mechanism can be used for receiving data: the hardware will cause an interrupt once the receive buffer becomes full and needs to be read by the CPU.

Interrupt Handlers

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- also known as first-level interrupt handler
- they must run in privileged mode
  - they are part of the kernel by definition
- the low-level interrupt handler must finish quickly
  - it will mask its own interrupt to avoid re-entering
  - and schedule any long-running jobs for later (SLIH)

Upon a hardware interrupt, the CPU will drop whatever it was doing, save its current state into a designated memory area and transfer control to an interrupt handler. Or rather, one of the CPU cores will. This handler is automatically executed in privileged mode, and hence is by definition part of the kernel.
Notice that no context switch occurs: though registers are written into memory, the page table is unaffected – the interrupt handler runs in the context of whatever process was currently running at the time. This is analogous to how system calls behave.
To avoid issues with reentrancy, a first-level handler will usually mask its own interrupt (cause the CPU to temporarily ignore it). This is one of a number of reasons why the first-level handler needs to finish quickly (if an interrupt is masked for too long, this can cause data to be lost, e.g. due to buffer overruns). Hence the first-level handler will usually do the minimum required work (e.g. clear time-critical buffers) and schedule any further processing for a later time.

Second-level Handler

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- does any expensive interrupt-related processing
- can be executed by a kernel thread
  - but also by a user-mode driver
- usually not time critical (unlike first-level handler)
  - can use standard locking mechanisms

The work that was deferred by the first-level handler is picked up by a second-level handler. This handler can run in a kernel thread or even in a user-mode process. The second-level routine is usually not time critical and can synchronize with the rest of the system as needed. A second-level handler of a disk device could, for instance, call into the file system to notify it that a piece of data it has requested has arrived, which in turn could trigger a suspended `read` system call to write the data into the address space of a waiting process. The syscall then returns and the process is woken up.

Direct Memory Access

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- allows the device to directly read/write memory
- this is a huge improvement over programmed IO
- interrupts indicate buffer full/empty
- devices can read and write arbitrary physical memory
  - opens up security / reliability problems

The last mode of IO is known as DMA, or Direct Memory Access. While there is some superficial similarity with MMIO (memory-mapped IO), it is important to distinguish them. In MMIO, the CPU (and by extension, the OS) talks to the device using the memory subsystem, mapping the on-board memory or registers of that device into the physical address space of the CPU.
The situation in DMA is flipped: the CPU and the device do not talk to each other at all. Instead, physical memory attached to the CPU (i.e. the main RAM) is made accessible to the peripheral, which can then transfer data to RAM. The CPU still uses memory access instructions to fetch data that came from the device (like in MMIO) but it does not communicate with the device directly. Instead, it reads and writes into its own RAM, which just happens to contain data that the device wrote there, or will later read.
To summarise:

- both MMIO and DMA use memory access instructions on the CPU to read and write data,
- under MMIO, the main memory is not involved at all,
- under DMA, both the device and the CPU access main memory,
- under DMA, there is no direct bulk transfer of data between the CPU and the device.

The use of MMIO and DMA is not exclusive, rather to the contrary: devices often use a combination of both. In fact, MMIO can be used to configure DMA (the latter is unsuitable for configuration, but performs better for bulk data transfers).

IO-MMU

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- like the MMU, but for DMA transfers
- allows the OS to limit memory access per device
- very useful in virtualisation
- only recently found its way into consumer computers

While DMA is extremely important for devices which transfer a lot of

data (HDDs, SSDs, NICs), it has some nasty security and safety implications. Under 'traditional' DMA, the device can read and write any physical memory it wants to. For instance, it can overwrite kernel code if it so wishes. A rogue device could then very easily circumvent any software-level security. Perhaps even more importantly, a rogue driver could program the device to overwrite memory with data (and code) of the driver's choosing.
This is undesirable, especially if we want to use user-mode drivers, or if the device is not sufficiently secure.[2] The IO-MMU is a device which fixes this problem, by enforcing limits on which memory can a particular peripheral access. The IO-MMU, like the regular MMU, can only be programmed by the OS kernel (or a hypervisor, as it may be... we will learn more about those in Chapter 11). With a correctly programmed IO-MMU, DMA is safe and secure.

Part 7.2: System and Expansion Buses

The rest of the lecture will be a tour of peripherals and some of their history. Before we get to the peripherals themselves, though, we will look at buses which are used to connect peripherals to the CPU (or CPUs) and, in some cases, to RAM. While the bus itself is not a peripheral, it is common for a bus to have drivers of their own. This has two reasons:

1. all but the simplest buses have additional hardware, which mediates bus access, takes care of device configuration and enumeration, and so on, and which needs to be itself configured,
2. besides the electronics and signalling, a bus also conceptually comes with a set of protocols, which need to be implemented both by the peripherals and by their drivers; the bus driver implements those protocols: other drivers make simple function calls and the driver translates them to the required MMIO or port-mapped IO operations.

With that said, let's look at some of the historical buses which were used in PCs over time and how they evolved to the current state of the art, PCI Express.

History: ISA (Industry Standard Architecture)

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- 16-bit system expansion bus on IBM PC/AT
- programmed IO and interrupts
- a fixed number of hardware-configured interrupt lines
  - likewise for I/O port ranges
  - the HW settings then need to be typed back for SW
- parallel data and address transmission

One of the oldest expansion buses, which made an appearance with IBM PC/AT (a personal computer based on Intel 80286). The ISA bus was hooked to the CPU via IO ports (no MMIO) and provided an interrupt line to each peripheral. A limited number of DMA 'channels' were provided by a DMA controller, allowing attached peripherals (mainly storage devices) to move data to and from memory independently from the main CPU.[3]
It was not possible to enumerate the bus, much less to configure the peripherals, in software. The port ranges and IRQ lines were selected by the hardware (either hardcoded, or configurable with jumpers or switches) and had to be given to the driver by the user (i.e. it had to be 'typed back' manually).
Hardware-wise, the bus was a parallel design, synchronously transferring 16 bits across 16 wires at the same clock tick. Separate data and address lanes were used: an address could be transferred with the same clock tick as a data word.

MCA, EISA

375

- MCA: Micro Channel Architecture
  - proprietary to IBM, patent-encumbered
  - 32-bit, software-driven device configuration
  - expensive and ultimately a market failure
- EISA: Enhanced ISA
  - a 32-bit extension of ISA
  - mostly created to avoid MCA licensing costs
  - short-lived and replaced by PCI

At 8MHz and 16 bits, ISA eventually started to be a limiting factor, since both CPUs and peripherals – especially graphics adapters, but also storage devices – were getting a lot faster.

VESA Local Bus

376

- memory mapped IO & fast DMA on otherwise ISA systems
- tied to the 80486 line of Intel (and AMD) CPUs
- primarily for graphics cards
  - but also used with hard drives
- quickly fell out of use with the arrival of PCI

VESA Local Bus, or VLB, was a fairly successful effort to standardize a disparate set of home-grown buses designed to accommodate faster graphics hardware than what was possible with ISA, while avoiding the licensing costs of MCA.
The VLB essentially connected the peripheral directly to the 80486 memory bus, using an additional connector (as an extension of standard ISA). Due to incompatible memory bus design in later processors, VLB did not survive the upgrade to Pentium.

PCI: Peripheral Component Interconnect

377

- a 32-bit successor to ISA
  - 33 MHz (compared to 8 MHz for ISA)
  - later revisions at 66 MHz, PCI-X at 133 MHz
  - with support for bus-mastering and DMA
- still a shared, parallel bus
  - all devices share the same set of wires

The breakthrough in peripheral interconnects came with PCI, which provided most of the benefits of MCA while avoiding some of its problems. Perhaps the most important update was software-based configuration, but the considerable bandwidth upgrade did not hurt either. From a modern perspective, the one downside was the topology: a shared, parallel bus connecting all the devices in the system.
Parallel here means that 32 bits are transmitted with each clock cycle, along 32 separate wires. This limits achievable clock speeds due to signal delay differences along traces of different length – modern buses transmit data serially, each data wire on its own clock.

[2] Famously, any device attached to a firewire port – an external port, kind of like high-speed USB before USB 3 was a thing – can read and write any and all host memory. It is not impossibly hard to build a rogue firewire device and attach it to someone else's computer. Other connectors which expose high-speed buses may be susceptible.

[3] In this setup, the DMA controller actually becomes the bus master and performs the transfer. While the effect is essentially the same, the implementation is rather different than with the DMA based on peripherals becoming bus masters that we will encounter later in the lecture.

Bus Mastering

378

- normally, the CPU is the bus master
  - which means it initiates communication
- it's possible to have multiple masters
  - they need to agree on a conflict resolution protocol
- usually used for accessing the memory

On a shared bus, one of the devices is usually the master and is in charge of the bus and the traffic on it. Normally, this is the CPU. However, for DMA transfers (between memory and a peripheral), the CPU should not be involved, since the entire point is to free up the CPU to do other work while the transfer is going on.
To facilitate these transfers, then, the peripherals can temporarily become bus masters, directing the traffic. An arbitration protocol ensures there is at most a single master driving the bus at any given time.

DMA (Direct Memory Access)

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- the most common form of bus mastering
- the CPU tells the device what and where to write
- the device then sends data directly to RAM
  - the CPU can work on other things in the meantime
  - completion is signaled via an interrupt

In principle, it is possible for peripherals to talk to each other when one of them is the bus master. However, this is not usually done: instead, the (temporary) bus master performs a data transfer to or from the main memory.

Plug and Play

380

- the ISA system for IRQ configuration was messy
- MCA pioneered software-configured devices
- PCI further improved on MCA with "Plug and Play"
  - each PCI device has an ID it can tell the system
  - enables enumeration and automatic configuration

An important aspect of PCI (and MCA before it) was software-based configuration and enumeration of connected devices. This allows the firmware and the operating system to discover what devices are connected, load the appropriate drivers and set up the devices without user intervention.

PCI IDs and Drivers

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- PCI allows for device enumeration
- device identifiers can be paired to device drivers
- this allows the OS to load and configure its drivers
  - or even download / install drivers from a vendor

Enumeration has two components: one is a system to discover and configure the devices attached to the system. This is done by using a common, device-independent protocol which must be implemented by all PCI devices.
The other is a system for assigning a unique identifier to each peripheral, a so-called PCI ID. An operating system can then include a database of known PCI IDs and corresponding drivers for that device. Loading that driver typically makes the device available for use by the rest of the operating system, and hence by the user.

AGP: Accelerated Graphics Port

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- PCI eventually became too slow for GPUs
  - AGP is based on PCI and only improves performance
  - enumeration and configuration stays the same
- adds a dedicated point-to-point connection
- multiple transfers per clock (up to 8, for 2 GB/s)

Of course, peaking around 4 Gib/s (500 MiB/s), PCI is not the end of the story. In a clear historic pattern, graphics hardware became limited by its connection to the rest of the system (CPU and memory). Like with VLB, a dedicated graphics bus has become widespread, this time based on PCI, with essentially two modifications:

1. the bus was point-to-point (dedicated to a single peripheral), i.e. not shared with the main PCI bus in the system,
2. it allowed multiple data transfers per clock cycle – the same technique that DDR RAM uses to increase throughput without driving the clock faster.

With maximum of 8 transfers per clock, with the main clock running at 66MHz, the maximum transfer speed comes out as 16Gib/s.

PCI Express

383

- the current high-speed peripheral bus for PC
- builds on / extends conventional PCI
- point-to-point, serial data interconnect
- much improved throughput (up to ~30GB/s)

We have finally reached the present day. The modern successor to PCI moved away from synchronous parallel data transmission and from a shared bus, allowing for drastic performance increase. Even though multiple wires are used for data transfer, they are self-clocked (clock is part of the data signal) and hence asynchronous to each other. Each wire is called a 'lane' and a single peripheral can use up to 16 lanes. Low-bandwidth devices only need a single lane, saving on power requirements and manufacturing cost.
At the time of this writing, devices targeting PCIe 4.0, with 16GT (billion transactions) per second on each lane, are commonly available. This translates to a maximum per-device bandwidth of about 256Gib/s (compare to AGP at 16Gib/s) or 32GiB/s in a 16-lane configuration.
The next revision, PCIe 5.0 (final spec released in 2019) doubles the per-lane transfer rate to 32GT/s, for a per-device maximum of 64GiB/s. Software-wise, PCIe is backward-compatible with PCI, using an extended version of the PCI enumeration and configuration protocol. Additionally, PCIe allows the configuration to use MMIO instead of port-mapped IO, exposing a single 4KiB page of configuration data per endpoint (peripheral).

USB: Universal Serial Bus

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- primarily for external peripherals
  - keyboards, mice, printers, ...
  - replaced a host of legacy ports
- later revisions allow high-speed transfers
  - suitable for storage devices, cameras &c.
- device enumeration, capability negotiation

PCI brought software-driven enumeration and configuration to the permanently attached, internal peripherals (graphics hardware, storage, network interfaces, and so on). USB did the same for externally-attached devices, like keyboards, mice, printers, scanners and so on.

Earlier systems used comparatively 'dumb' buses for the same purpose. The user had to select a driver by hand and configure the driver (tell it which external port the device is attached to). With USB, the devices would identify themselves using a device-neutral protocol, just like with PCI. The host system can then load and configure the correct driver automatically. Moreover, USB supports hotplug, so this can happen whenever the user plugs in a device. Finally, the bandwidth available on USB, even in its first revision, was much higher than the earlier standards (RS-232, PS/2).
Later USB revisions considerably increased both data transmission speed and the power available to the attached peripheral. The current highest speed available to USB devices (in USB 3.2 Gen 2 mode with 2 lanes, over USB-C connectors) is 20Gib/s, exceeding the maximal transfer speeds of AGP, the fastest internal bus available in consumer hardware before PCIe.

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USB Classes

- a set of vendor-neutral protocols
- HID = human-interface device
- mass storage = disk-like devices
- audio equipment
- printing

USB comes with additional standardization, with so-called device classes. Each class constitutes a vendor-neutral protocol for a particular type of devices:

- HID (human-interface device), e.g.:
  - keyboards,
  - mice,
  - game controllers,
  - small character-based displays,
  - pretty much anything with a button.
- mass storage (persistent memory, usually with a file system):
  - flash 'pen' drives,
  - external hard drives or SSDs,
  - optical drives,
  - card readers, ...
- audio devices, e.g.:
  - headsets (headphones with a microphone),
  - sound cards,
  - active loudspeakers,
  - standalone microphones,
  - MIDI devices,
- MTP (media transfer protocol),
  - smartphones,
  - portable media players.
- printers,
- video (webcams, digital microscopes).

Essentially, none of the devices in the above list need vendor-specific drivers to operate. Instead, a single 'class' driver which implements the respective protocol can talk to any peripheral which belongs to that class. A single physical peripheral may provide multiple virtual devices, possibly in different classes (e.g. a portable recorder which can appear both as an audio device – a microphone, as well as a storage device).

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Other USB Uses

- scanners
- ethernet adapters
- usb-serial adapters
- wifi adapters (dongles)
- bluetooth

In addition to the standard device classes, there are many USB devices which do not fit one of those categories. These will use a vendor-specific protocol and will require corresponding device-specific driver.

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Bluetooth

- a wireless alternative to USB
- allows short-distance radio links with peripherals
  - input (keyboard, mice, game controllers)
  - audio (headsets, speakers)
  - data transmission (e.g. smartphone sync)
  - gadgets (watches, heartrate monitoring, GPS, ...)

While bluetooth is not a bus as such (being wireless), it behaves much like USB from the point of view of software (with additional complexity related to device pairing, security and unreliable data transmission). Many device types that can be attached via USB can also be attached with bluetooth (wireless keyboards, mice, headsets, speakers, and so on).

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ARM Buses

- ARM is typically used in System-on-a-Chip designs
- those use a proprietary bus to connect peripherals
- there is less need for enumeration
  - the entire system is baked into a single chip
- the peripherals can be pre-configured

The ARM ecosystem is somewhat different from the PC one. It is common that ARM devices are 'system on a chip' designs, where most, if not all, peripherals are part of a single chip together with CPU cores, memory controller, and interconnect (system bus). SoC vendors usually prepare operating system images or kernel builds (typically of Android) that work on their system. Software-driven enumeration and autoconfiguration is much less important and is typically not supported.
Peripherals typically included are a graphics core, an USB controller, wifi, ethernet, bluetooth controller, audio controller, NFC, storage controller (eMMC) and perhaps a few others.

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USB and PCIe on ARM

- neither USB nor PCIe are exclusive to the PC platform
- most ARM SoC's support USB devices
  - for slow and medium-speed off-SoC devices
  - e.g. used for ethernet on RPi 1
- some ARM SoC's support PCI Express
  - this allows for high-speed off-SoC peripherals

However, not all ARM processors are designed for 'sealed' devices like smartphones or smart TVs. ARM-based general-purpose hardware includes single-board computers (like Raspberry Pi, Beaglebone, ...) but also laptops (new generation of Apple hardware) and servers (Ampére

Altra). Those systems often need more connectivity and extensibility and will provide PCI Express for connecting to high-speed peripherals.

PCMCIA & PC Card

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- People Can't Memorize Computer Industry Acronyms
  - PC = Personal Computer, MC = Memory Card
  - IA = International Association
- hotplug-capable notebook expansion bus
- used for memory cards, network adapters, modems
- comes with its own set of drivers (cardbus)

Back to history: until a decade ago, it was common that laptop computers had expansion slots, a bit like traditional desktops. Of course, a standard-size expansion card has no chance of fitting in a laptop, hence special connectors and/or buses. One of the oldest was PCMCIA, with credit-card-sized (but thicker) peripherals that could be hot-plugged into a bay on the side of a laptop (i.e. the device would be hidden inside the laptop body, unlike various USB dongles with a mess of wires).

ExpressCard

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- an expansion card standard like PCMCIA / PC Card
- based on PCIe and USB
  - can mostly re-use drivers for those standards
- not in wide use anymore
  - last update was in 2009, introducing USB 3 support
  - the industry association disbanded the same year

ExpressCard is a more modern version of the same idea and a similar form factor, with USB and PCIe in the backend. Modern laptops, however, no longer offer this functionality and the association responsible for ExpressCard was disbanded over a decade ago.

miniPCIe, mSATA, M.2

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- those are physical interfaces, not special buses
- they provide some mix of PCIe, SATA and USB
  - also other protocols like I^4C, SMBus, ...
- used mainly for compact SSDs and wireless
  - also GPS, NFC, bluetooth, ...

What does survive are connectors for internal devices in a small form factor: mainly for SSDs, but also for wifi adapters, bluetooth and similar modules. These are common in laptops and mini-ITX (small desktop) systems. Depending on the particular connector standard (and variant), it will provide a variety of bus connections, including PCIe (up to 4 lanes) and USB.

Part 7.3: Graphics and GPUs

Graphics hardware was always a very important part of both home computers and professional workstations. Often, it is also the most demanding peripheral in those applications, and the most complex.

Graphics Cards

394

- initially just a device to drive displays
- reads pixels from memory and provides display signal
  - basically a DAC with a clock
  - the memory can be part of the graphics card
- evolved acceleration capabilities

Originally, a graphics card would simply contain some fast static memory (frame buffer), a clock and a digital-to-analog converter (DAC), which would drive a CRT display (cathode ray tube). The displays of the era worked by pointing an electron gun (using electromagnets) at individual pixels in rapid succession while modulating the voltage between the cathode and anode (essentially a conductive coating of the inside of the screen) to attain corresponding brightness on each pixel.
The graphics card would generate the signal driving this modulation, in step with the advancing electron gun. The memory of the graphics card would contain digital information about the brightness of each pixel. Typical refresh rates would be in the 30-120 Hz range for the entire screen. For a VGA screen (640 columns, 480 rows) at 70 Hz, this works out to about 20 MHz (20 million pixels per second). The three component colours are transmitted in parallel.

Graphics Accelerator

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- allows common operations to be done in hardware
- like drawing lines or filled polygons
- the pixels are computed directly in video RAM
- this can save considerable CPU time

Composing a picture to be displayed on screen can take a lot of computation and/or memory traffic. If some of those operations are performed by dedicated hardware instead of the main CPU, this can drastically improve performance, since the CPU is free to do other things while the graphics hardware asynchronously performs the simple, repetitive tasks. There are two main classes of operations that can be easily accelerated using dedicated hardware:

- rasterization of geometric shapes such as lines, rectangles, polygons or curves (vector graphics) – those are used in, for instance, graphical user interfaces and in vector drawing programs or 2D computer-aided design systems,
- bulk pixel operations, such as flood fill or bit blitting[5] mainly used in raster graphics (e.g. video games).

Since essentially each pixel (or at best a small block of pixels) needs at least one memory write, and for a CPU, memory writes are expensive (lots of waiting for slow memory), such operations are especially wasteful on the CPU. Even worse if data (textures, sprites) need to be read from memory and written back elsewhere, perhaps after performing a simple operation on the pixels.

[5] A memory copy with some additional logic: it operates on pixels (instead of bytes) in various formats (e.g. 2 or 8 pixels per byte) and can deal with transparent pixels which are skipped (allows drawing non-rectangular shapes over an existing background).

3D Graphics

396

- rendering 3D scenes is computationally intensive
- CPU-based, software-only rendering is possible
  - texture-less in early flight simulators
  - bitmap textures since '95 / '96 (Descent, Quake)
- CAD workstations had 3D accelerators (OpenGL '92)

While 2D graphics takes a lot of resources (at least in terms of the capabilities of older hardware), it is essentially free compared to 3D graphics, where computing each output pixel can take hundreds of operations, some of which are geometric and others which are raster-based. Hence, the potential for hardware acceleration of 3D graphics is considerably higher than with 2D graphics, but the hardware to do so is much more complicated.

GPU (Graphics Processing Unit)

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- a term coined by Sony in '94 (the GPU in PlayStation)
- originally a purpose-built hardware renderer
  - based on polygonal meshes and Z buffering
- increasingly more flexible and programmable
- on-board RAM, high-speed connection to system RAM

First GPUs were essentially hardware built for rasterization of 3D geometry, supplied as a polygonal (triangular) mesh with textures attached to the faces. The hardware would then compute visibility and lighting to produce a raster image to be displayed on screen. The CPU would prepare the geometry for each frame which the GPU would then render and display.
Each generation of GPUs brings more flexibility and programmability, allowing for acceleration of lots of different effects without hard-coding them in hardware. Contemporary GPUs are essentially fully programmable general-purpose vector processors, with registers, memory, control flow and so on.

GPU Drivers

398

- split into a number of components
- graphics output / frame buffer access
- memory management is often done in kernel
- geometry, textures &c. are prepared in-process
- front end API: OpenGL, Direct3D, Vulkan, ...

A typical GPU driver is split into a number of components, some of which reside in the kernel (frame buffer setup, memory management) while the more complex parts are libraries linked into client applications (geometry and texture processing, shader compilation).

Shaders

399

- current GPUs are computation devices
- the GPU has its own machine code for shaders
- the GPU driver contains a shader compiler
  - either all the way from a high level language (HLSL)
  - or starting with an intermediate code (SPIR)

Since modern GPUs are really just vector processors in disguise, they run programs in their own machine code. The driver then compiles higher-level programs which are part of the software (e.g. a computer game or a 3D game engine) into the hardware-specific machine language. While the output is very device-specific, the input (which is what the application gives to the driver) is mostly standardized, with two main options being HLSL (High-Level Shader Language) and SPIR (Standard Portable Intermediate Representation).

Mode Setting

400

- deals with screen configuration and resolution
- including support for e.g. multiple displays
- usually also supports primitive (SW-only) framebuffer
- often in-kernel, with minimum user-level support

While there is a lot of bells and whistles on a modern GPU, there are some boring tasks which did not really change in the last 2-3 decades, like display configuration. It's common that current computers can attach multiple displays, and each needs to be given a resolution, color depth, refresh rate &c., together known as a graphics 'mode'. This is the task of the 'mode setting' part of a graphics driver.

Graphics Servers

401

- multiple apps cannot all drive the graphics card
  - the graphics hardware needs to be shared
  - one option is a graphics server
- provides an IPC-based drawing and/or windowing API
- performs painting on behalf of the applications

While not a driver itself, graphics servers form an important part of the graphics stack (on systems which use one). The problem here is that only one program can meaningfully draw on any given screen, but we usually want to show the output of more than a single program. One option is a graphics server, which hands out regions (rectangular windows, typically) into which programs can paint using its API.

Compositors

402

- a more direct way to share graphics cards
- each application gets its own buffer to paint into
- painting is mostly done by a (context-switched) GPU
- the individual buffers are then composed onto screen
  - composition is also hardware-accelerated

The other common approach is to use a compositor, which differs crucially from a graphics server in one thing: how the individual applications paint their content. In a graphics server, there is a painting API which the program calls to display shapes and pixmaps on screen. With a compositor, each program gets an off-screen buffer (pixmap) into which they can paint by directly interacting with the driver of the graphics hardware. The compositor then combines those buffers into a single picture which is shown to the user (again by making appropriate calls into the graphics driver). In typical usage, each window corresponds to a single buffer.

GP-GPU

403

- general-purpose GPU (CUDA, OpenCL, ...)
- used for computation instead of just graphics
- basically a return of vector processors
- close to CPUs but not part of normal OS scheduling

As we have mentioned earlier, contemporary GPUs are really general-purpose vector processors and can be used for purely computational tasks that have nothing to do with graphics (machine learning is a

popular application, but anything that benefits from massive SIMD is a good candidate).

Part 7.4: Persistent Storage

In this section, we will look at bulk storage devices – those that usually carry file systems and which retain the stored data while offline (disconnected from power).

Drivers

405

- split into adapter, bus and device drivers
- often a single driver per device type
  - at least for disk drives and CD-ROMs
- bus enumeration and configuration
- data addressing and data transfers

Storage devices have traditionally had their own dedicated, specialized bus. The host side of this bus is implemented by an adapter (controller) which is connected to a system bus (PCI, PCIe) on one side and to the storage bus on the other. Individual storage devices are then connected to this dedicated bus.
This hardware structure essentially dictates the driver structure: the bus is usually standardized and comes with a set of protocols, just like system buses that we discussed earlier do. However, for any given bus, there might be many different adapter models made by different vendors. In some cases, they use a common protocol, but in other cases, device-specific drivers are required to configure them.
Like with USB, on any given storage bus, there is considerable standardization among the storage devices themselves (endpoints), and a single 'class' driver is sufficient (a HDD driver, a CD-ROM driver, a tape unit driver, ...).

IDE / ATA

406

- Integrated Drive Electronics
  - disk controller becomes part of the disk
  - standardised as ATA-1 (AT Attachment ...)
- based on the ISA bus, but with cables
- later adapted for non-disk use via ATAPI

One of the oldest standardized storage buses was IDE (vendor name, later standardized as ATA). This is essentially an ISA bus with cabling, hence the adapter, if connected to the host ISA bus, was especially simple. However, later revisions of the ATA (now known as Parallel ATA) spec diverged from ISA due to much higher speeds that were eventually required. The ATA family of buses did not switch to use PCI internally and the storage bus and system bus evolved separately, even if along similar lines.

ATA Enumeration

407

- each ATA interface can attach only 2 drives
  - the drives are HW-configured as master/slave
  - this makes enumeration quite simple
- multiple ATA interfaces were standard
- no need for specific HDD drivers

Since most implementations offer exactly 4 connectors (2 interfaces, each capable of connecting 2 drives), enumeration is not much of an issue. Each interface has a standard set of IO ports (for port-mapped IO). The system uses those ports to send 2 `IDENTIFY` commands on each interface, one for the master and the other to the slave device. This completes the enumeration.

PIO vs DMA

408

- original IDE could only use programmed IO
- this eventually became a serious bottleneck
- later ATA revisions include DMA modes
  - up to 160MB/s with highest DMA modes
  - compare 1900MB/s for SATA 3.2

SATA

409

- serial, point-to-point replacement for ATA
- hardware-level incompatible to (parallel) ATA
  - but SATA inherited the ATA command set
  - legacy mode lets PATA drivers talk to SATA drives
- hot-swap capable – replace drives in a running system

Like other interfaces, storage systems made a transition to serial data links. For ATA, the result is known as SATA or Serial ATA. The newer standard retains software-level backward compatibility with Parallel ATA: if the controller is in 'legacy mode', it will emulate a PATA host controller and work with legacy PATA drivers. However, this PATA-compatible mode necessarily hides new features (ability to connect more drives, hotswap, native command queuing).

AHCI (Advanced Host Controller Interface)

410

- vendor-neutral interface to SATA controllers
  - in theory only a single 'AHCI' driver is needed
- an alternative to 'legacy mode'
- NCQ = Native Command Queuing
  - allows the drive to re-order requests
  - another layer of IO scheduling

Most SATA host controllers implement the AHCI standard and hence don't need device-specific drivers. Running the controller in AHCI mode is required to make use of new SATA technologies, such as NCQ (native command queuing) and hotswap. While attempts were made to add command queuing to PATA, those were ultimately unsuccessful, due to insufficient DMA capabilities of the old ISA-based system (with a 3rd-party DMA controller). Since SATA drives perform DMA themselves, NCQ has much better performance.

ATA and SATA Drivers

411

- the host controller (adapter) is mostly vendor-neutral
- the bus driver will expose the ATA command set
  - including support for command queuing
- device driver uses the bus driver to talk to devices
- partially re-uses SCSI drivers for ATAPI &c.

SCSI (Small Computer System Interface)

412

- originated with minicomputers in the 80's
- more complicated and capable than ATA
  - ATAPI basically encapsulates SCSI over ATA
- device enumeration, including aggregates
  - e.g. entire enclosures with many drives
- also allows CD-ROM, tapes, scanners (!)

A different storage bus, called SCSI, has been in parallel use with ATA, mainly targeting servers and high-end hardware in general. The overall structure is the same as with ATA: there is an adapter (called HBA – host bus adapter – in SCSI jargon), a bus with a set of protocols, and an array of storage devices attached to the storage bus.
Unlike Parallel ATA, the SCSI bus can attach many more devices and those devices can have additional internal structure (e.g. it's possible to attach a SATA RAID controller with a dozen disks as a single 'composite' SCSI endpoint). For this reason, it has advanced software-based enumeration and configuration capabilities: the HBA will 'scan' the storage bus to discover devices and report them to the operating system. SCSI also commonly supports hotplugging devices (i.e. attaching and detaching devices while the system is running). Also unlike ATA, external SCSI connectors and cabling are common.
Like ATA (and like system buses) SCSI used a parallel design for a long time, but modern versions use high-speed serial links instead. The technology is known as SAS, Serial-Attached SCSI. SAS can optionally use a SATA-compatible connector (and SAS adapters with such connectors will work with SATA drives, but not vice versa).

SCSI Drivers

413

- split into: a host bus adapter (HBA) driver
- a generic SCSI bus and command component
  - often re-used in both ATAPI and USB storage
- and per-device or per-class drivers
  - optical drives, tapes, CD/DVD-ROM
  - standard disk and SSD drives

While SCSI hardware is somewhat uncommon, the protocols it uses are in widespread use. Both SATA and USB storage devices use SCSI as their command protocols. Additionally, Fibre Channel (FC, a storage-area network technology) and InfiniBand (IB, a high-speed, low-latency interconnect) offer SCSI implementations. This essentially means that the same 'class' driver can be used for storage devices attached to SATA, USB, SAS, FC, IB or ethernet (via iSCSI, see below), with an appropriate glue layer.

iSCSI

414

- basically SCSI over TCP/IP
- entirely software-based
- allows standard computers to serve as block storage
- takes advantage of fast cheap ethernet
- re-uses most of the SCSI driver stack

The SCSI protocol can be also encapsulated in TCP/IP and transported using, for instance, ethernet. This approach allows SCSI endpoints to be implemented in software: instead of specialized hardware, a RAID enclosure (a box with many disks combined into one or a few logical drives using RAID) can be implemented as a commodity x86 server with an ethernet connection. This is sufficient for many use cases, while being significantly cheaper than 'native' storage-area networks (fibre channel, infiniband), or even standard externally-connected SAS.

NVMe: Non-Volatile Memory Express

415

- a fairly simple protocol for PCIe-attached storage
- optimised for SSD-based devices
  - much bigger and more command queues than AHCI
  - better / faster interrupt handling
- stresses concurrency in the kernel block layer

A 'return to the roots' technology: what ATA was to ISA, NVMe is to PCIe. Essentially a protocol on top of PCIe interconnect, re-using PCIe enumeration and configuration. The protocol calls for rather massive command queues, taking advantage of the correspondingly massive parallelism in the SSD hardware. NVMe storage is usually very fast and the block layer, originally designed for much slower devices, may struggle to keep up.

USB Mass Storage

416

- an USB device class (vendor-neutral protocol)
  - one driver for the entire class
- typically USB flash drives, but also external disks
- USB 2 is not suitable for high-speed storage
  - USB 3 introduced UAS = USB-Attached SCSI

As mentioned earlier, storage devices can be also directly attached to USB.

Tape Drives

417

- unlike disk drives, only allow sequential access
- needs support for media ejection, rewinding
- can be attached with SCSI, SATA, USB
- parts of the driver will be bus-neutral
- mainly for data backup, capacities 6-15TB

While disk-like devices (HDDs, SSDs, RAID enclosures) are by far the most important, there are other storage devices worth mentioning. Data centers will often use tape drives for backups, since they offer excellent data density, low price per gigabyte stored and good durability. From an OS standpoint, tapes are special since they can only be accessed sequentially, and it doesn't make sense to put a traditional file system on them. Instead, specialized programs are used to prepare data for writing on a tape, e.g. tar (short for Tape ARchive).

Optical Drives

418

- mainly used as a read-only distribution medium
- laser-facilitated reading of a rotating disc
- can be again attached to SCSI, SATA or USB
- conceived for audio playback → very slow seek

Another somewhat special class of storage devices are optical drives: CD-ROM, DVD-ROM, Blu-ray. While random access is possible, it is very slow even compared to HDDs. Optical drives are more suitable for streaming (mainly audio and video) or content distribution. Unlike tapes, (read-only) file systems are commonly used on optical media (ISO 9660 for CD-ROM, UDF for DVD and Blu-ray).

Optical Disk Writers (Burners)

419

- behaves more like a printer for optical disks
- drivers are often done in user space
- attached by one of the standard disk buses
- special programs required to burn disks
  - alternative: packet-writing drivers

Part 7.5: Networking and Wireless

The last category of devices that we will discuss in this lecture are network interface cards. Please note that this is only an overview of network hardware that can be attached to a general-purpose computer – networking in general will be discussed in the next lecture.

Networking

421

- networks allow multiple computers to exchange data
  - this could be files, streams or messages
- there are wired and wireless networks
- we will only deal with the lowest layers for now
- NIC = Network Interface Card

Network hardware allows computers to directly communicate with each other, using some sort of interconnect, either wired or wireless. A computer connects to the network using a network interface card, typically a PCIe device with an external connector (e.g. RJ 45 for metallic ethernet), or an antenna (for wireless tech). A computer network as a whole resembles a bus of the kind we have discussed in the first part of the lecture, though with some crucial differences.

Ethernet

422

- specifies the physical medium
- on-wire format and collision resolution
- in modern setups, mostly point-to-point links
  - using active packet switching devices
- transmits data in frames (low-level packets)

Like with system buses, networks have evolved away from shared media (token ring, coaxial 10MiB ethernet, twisted-pair ethernet with passive hubs). Modern networks use dedicated point-to-point links, with packet-switching hardware at hubs where a number of point-to-point links meet. Ethernet 'packets' are called frames and are transmitted as a single unit. Each frame has some metadata (sender, recipient, size) and of course carries some data (payload).

Addressing

423

- at this level, only local addressing
  - at most a single LAN segment
- uses baked-in MAC addresses
  - MAC = Media Access Control
- addresses belong to interfaces, not computers

Lowest-level addressing only works within a single ethernet segment (broadcast domain). All computers know the MAC addresses of all other computers that they wish to talk to (or rather of their network interface cards). In old shared-medium networks, the frame would be transmitted on the shared medium and picked up by the intended recipient based on the target address. In a packet-switched network, the switch will keep a mapping of MAC addresses to physical ports, and only retransmit frames on the port to which the intended recipient is attached.

Transmit Queue

424

- packets are picked up from memory
- the OS prepares packets into the transmit queue
- the device picks them up asynchronously
- similar to how SATA queues commands and data

When the OS wants to send packets (frames) over the network, they are appended to a transmit queue (also known as Tx queue) where the hardware picks them up and transmits them over its physical connection. The queue works approximately like this:

1. each queue (there can be more than one) has a pair of registers accessible through MMIO, one for the head pointer and another for a tail pointer,
2. the pointers hold addresses into a ring buffer of a fixed size, stored in the main memory, accessed through DMA; each item in the ring is, again, a pointer, along with a size, and describes a memory buffer holding a single frame (packet),
3. the head and tail pointer split the ring into two parts, one that belongs to the NIC and one that belongs to the software,
4. the operating system (via the driver) controls the tail pointer in the device register:
   a. to send a packet, it will create a buffer and store the packet data in that buffer,
   b. it will fill in the first cell in the OS-controlled part of the ring with the address and size of this buffer,
   c. it will shift the tail pointer, handing over the newly filled-in cell to the NIC,
5. the network card controls the head pointer: whenever it processes a packet, it'll shift the head pointer so that the processed buffer is now in the OS-controlled part of the ring.

As outlined in the first part of the lecture, events related to the transmit ring can be signalled via interrupts.

Receive Queue

425

- data is also queued in the other direction
- the NIC copies packets into a receive queue
- it invokes an interrupt to tell the OS about new items
  - the NIC may batch multiple packets per interrupt
- if the queue is not cleared quickly → packet loss

The receive (Rx) queue works analogously. Interrupts signal newly appended items. The OS is in charge of allocating buffers for packets: handing off a buffer to the NIC on the Rx queue means that the NIC is free to overwrite the buffer with packet data. After it does so, the Rx ring cell is handed back to the OS.
In the common case, all frame (packet) buffers must be large enough to hold a biggest possible frame (known as an MTU = Maximal Transfer Unit), though at least some NICs can split incoming packets over multiple Rx cells if they don't fit in a single buffer.
If an Rx ring fills up while packets continue to arrive on the interface, packets will be lost (hence the OS must clear the Rx ring sufficiently quickly). The packets don't need to be processed immediately: the OS is free to allocate new buffers and put those on the ring, instead of re-using existing buffers. The filled buffers can be processed and reclaimed later.

Multi-Queue Adapters

426

- fast adapters can saturate a CPU
  - e.g. 10GbE cards, or multi-port GbE
- these NICs can manage multiple Rx and Tx queues
  - each queue gets its own interrupt
  - different queues → possibly different CPU cores

Contemporary network adapters can send and receive packets so quickly that a single CPU core cannot keep up (since there is typically a lot of work to be done for each packet as it bubbles up through the network stack and into user space).
Those same adapters can be configured to use multiple Tx and Rx queues (rings), each with their own head/tail registers and interrupt. It is up to the OS to configure these queues – a typical setup would use a single Tx/Rx pair per CPU core.
For transmission, the NIC simply interleaves packets from all the queues, since the OS decides which queue to use for sending a particular packet. It'll typically just use the one associated with the CPU core performing the operation.
For reception, the story is slightly more complicated, since the NIC has to decide which queue to use. The NIC can be configured to filter or hash (parts of) incoming packets and use an Rx queue based on the result. The goal is to keep related packets in the same queue (improves locality) but also to keep all queues busy (improves load balancing).

Checksum and TCP Offloading

427

- more advanced adapters can offload certain features
- e.g. computation of mandatory packet checksums
- but also TCP-related features
- needs both driver support and TCP/IP stack support

To speed up packet processing, some per-packet tasks can be performed in hardware. Computing and verifying checksums is the most common task performed by hardware: packet headers often contain a checksum to detect data corruption. Those checksums can usually be computed in hardware very quickly and it's a waste of CPU cycles to do it in software. Hence, when a packet is stored in the Tx queue, the checksum fields are left blank and the hardware will fill them in before transmitting the packet (this applies to higher-level protocol checksums, e.g. TCP; ethernet frame checksums are always computed in hardware).

While by far the simplest, checksum offloading is not the only task that can be done in hardware; some others include:

- cryptography (IPsec) offloading: authentication headers, payload encryption and decryption,
- large send, receive segment coalescing: segmentation and reassembly of large TCP packets (i.e. those that don't fit in a single IP packet),
- UDP segmentation (splitting up UDP packets which do not fit into the MTU of the NIC).

WiFi

428

- wireless network interface – 'wireless ethernet'
- shared medium – electromagnetic waves in air
- (almost) mandatory encryption
  - otherwise easy to eavesdrop or even actively attack
- a very complex protocol (relative to hardware standards)
  - assisted by firmware running on the adapter

Compared to relative simplicity of wired networks, WiFi is extremely complicated due to the nature of its medium, which is shared, noisy, easily eavesdropped and generally unreliable. Devices which connect to WiFi networks are often portable and need to maintain connectivity as they move about, switching between access points or even networks.
Due to pervasive encryption, clients and access points need to authenticate each other and establish session key pairs. Authentication is required because otherwise an active attacker could trick a client into connecting to their device and become a 'man in the middle', rendering the encryption ineffective. Since authentication is required anyway, it often doubles as an access control measure.
Aspects of WiFi-related protocols are implemented in hardware, firmware (software running on the adapter) and software (running on the main CPU).

Review Questions

429

25. What is memory-mapped IO and DMA?
26. What is a system bus?
27. What is a graphics accelerator?
28. What is a NIC receive queue?

Part 8: Network Stack

In this lecture, we will look at networking from the point of view of the operating system. We will mainly focus on the internet stack: that is TCP/IP and related protocols and host name resolution. We will also look at network file systems (i.e. file systems which are stored by one computer on a network, but can be used by multiple other computers on the same network).

Lecture Overview

431

1. Networking Intro
2. The TCP/IP Stack
3. Using Networks
4. Network File Systems

We will first do a quick recap of networking terminology and of the basic concepts in general terms. Afterwards we will look at the TCP/IP stack more specifically, and how it matches the more general notions introduced earlier. The next part of the lecture will focus on network-related application programming interfaces. Finally, we will look at file system sharing in a network environment.

Part 8.1: Networking Intro

In this section, we will mostly deal with familiar network-related concepts, so that we have sufficient context down the line, when we delve into a bit more detail and into OS-level specifics.

Host and Domain Names

433

- hostname = human readable computer name
- hierarchical system, little endian: `www.fi.muni.cz`
- FQDN = fully-qualified domain name
- the local suffix may be omitted (`ping aisa`)

The first thing we need to understand is how to identify computers within a network. The primary means to do this is via hostnames: human-readable names, which come in two flavours: the name of the computer itself, and a fully-qualified name, which includes the name of the network to which the computer is connected, so to speak.

Network Addresses

434

- address = machine-friendly and numeric
- IPv4 address: 4 octets (bytes): `192.168.1.1`
  - the octets are ordered MSB-first (big endian)
- IPv6 address: 16 octets
- Ethernet (MAC): 6 octets, `c8:5b:76:bd:6e:0b`

While humans prefer to refer to computers using human-readable names, those are not suitable for actual communication. Instead, when computers need to refer to other computers, they use numeric addresses (just like with memory locations or disk sectors). Depending on the protocol, the size and structure of the address may be different: traditional IPv4 uses 4 octets, while the addresses in the newer IPv6 use up 16 (128 bits). One other type of address that you can commonly encounter is MAC (from media access control), which is best known from the Ethernet protocol.

Network Types

435

- LAN = Local Area Network
  - Ethernet: wired, up to 10Gb/s
  - WiFi (802.11): wireless, up to 1Gb/s
- WAN = Wide Area Network (the internet)
  - PSTN, xDSL, PPPoE
  - GSM, 2G (GPRS, EDGE), 3G (UMTS), 4G (LTE)
  - also LAN technologies – Ethernet, WiFi

Networks are broadly categorized into two types: local area, spanning an office, a household, maybe a building. LAN is usually a single broadcast domain, which means, roughly speaking, that each computer can directly reach any other computer attached to the same LAN. The most common technologies (layers 1 and 2) used in LANs are the wired ethernet (the most common variety running at 1Gb/s, less common but still mainstream at versions at 10Gb/s) and the wireless WiFi (formally known as IEEE 802.11).
Wide-area networks, on the other hand, span large distances and connect a large number of computers. The canonic WAN is the internet, or the network of an ISP (internet service provider). Wide area networks often use a different set of low-level technologies.

Networking Layers

436

1. Link (Ethernet, WiFi)
2. Internet / Network (IP)
3. Transport (TCP, UDP, ...)
4. Application (HTTP, SMTP, ...)

The standard model of networking (known as Open Systems Interconnection, or OSI for short) splits the stack into 7 layers, but TCP/IP-centric view of networking often only distinguishes 4, as outlined above. The link layer roughly corresponds to OSI layers 1 (physical) and 2 (data), the internet layer is OSI layer 3, the transport layer is OSI layer 4 and the rest (OSI layers 5 through 7) is lumped under the application layer.
We will follow the simplified TCP/IP model, but whenever we refer to layers by number, those are the OSI numbers, as is customary (specifically, IP is layer 3 and TCP is layer 4).

Networking and Operating Systems

437

- a network stack is a standard part of an OS
- large part of the stack lives in the kernel
  - although this only applies to monolithic kernels
  - microkernels use user-space networking
- another chunk is in system libraries & utilities

For the last two decades or so, networking has been a standard service provided by general-purpose operating systems. In systems with a monolithic kernel, a significant part of the network stack (everything up to and including the transport layer) is part of the kernel and is exposed to user programs via the sockets API.
Additional application-layer functionality is usually available in system libraries: most importantly domain name resolution (DNS) and encryption (TLS, short for transport-layer security, which is confusingly enough an application-layer technology).

Kernel-Side Networking

438

- device drivers for networking hardware
- network and transport protocol layers
- routing and packet filtering (firewalls)
- networking-related system calls (sockets)
- network file systems (SMB, NFS)

The link layer is generally covered by device drivers and the client and server sides of TCP/IP are exposed via the socket API. There are additional components in TCP/IP networks, though: some of them, like routing and packet filtering can be often done in software, and if this is the case, they are usually implemented in the kernel. Bridging and switching (which belong to the link layer) can be done in software too, but is rarely practical. However, many operating systems implement one or both to better support virtualisation.
A few application-layer network services may be implemented in the kernel too, most notably network file systems, but sometimes also other protocols (e.g. kernel-level HTTP acceleration).

System Libraries

439

- the socket and related APIs
- host name resolution (a DNS client)
- encryption and data authentication (SSL, TLS)
- certificate handling and validation

Strictly speaking, the socket API is the domain of system libraries (though in most monolithic kernels, the C functions will map 1:1 to system calls; however, in microkernels, the networking stack is split differently and system libraries are likely to pick up a bigger share of the work).
Since nearly all network-related programs need to be able to resolve hostnames (translate the human-readable name to an IP address), this service is usually provided by system libraries. Likewise, encryption is

ubiquitous in the modern internet, and most operating systems provide an SSL/TLS stack, including certificate management.

System Utilities & Services

440

- network configuration (`ifconfig`, `dhclient`, `dhcpd`)
- route management (`route`, `bgpd`)
- diagnostics (`ping`, `traceroute`)
- packet logging and inspection (`tcpdump`)
- other network services (`ntpd`, `sshd`, `inetd`)

The last component of the network stack is located in system utilities and services (daemons). Those are concerned with configuration (including assigning addresses to interfaces and autoconfiguration, e.g. DHCP or SLAAC) and route management (especially important for software-based routers and multi-homed systems).
A suite of diagnostic tools is also usually present, at very least the `ping` and `traceroute` programs which are useful for checking connectivity, perhaps tools like `tcpdump` which allow the operator to inspect packets arriving at an interface.

Networking Aspects

441

- packet format
  - what are the units of communication
- addressing
  - how are the sender and recipient named
- packet delivery
  - how a message is delivered

When looking at a network protocol, there are three main aspects to consider: the first is, what constitutes the unit of communication, i.e. how the packets look, what information they carry and so on. The second is addressing: how are target computers and/or programs designated. Finally, packet delivery is concerned with how messages are delivered from one address to another: this could involve routing and/or address translation (e.g. between link addresses and IP addresses).

Protocol Nesting

442

- protocols run on top of each other
- this is why it is called a network stack
- higher levels make use of the lower levels
  - HTTP uses abstractions provided by TCP
  - TCP uses abstractions provided by IP

Since we are talking about a protocol stack, it is important to understand how the individual layers of the stack interact with each other. Each of the above aspects cuts through the stack slightly differently – we will discuss each in a bit more detail in the following few slides.

Packet Nesting

443

- higher-level packets are just data to the lower level
- an Ethernet frame can carry an IP packet in it
- the IP packet can carry a TCP packet
- the TCP packet can carry (a fragment of) an HTTP request

When we consider packet structure, it is most natural to start with the bottom layers: the packets of the higher layers are simply data for the lower layer. The overall packet structure looks like a matryoshka: an ethernet frame is wrapped around an IP packet is wrapped around an UDP packet and so on.
From the point of view of the upper layers, packet size is an important consideration: when packet-oriented protocols are nested in other packet-oriented protocols, it is useful if they can match their packet sizes (most protocols have a limit on packet size). With the size limitations in mind, in the view 'from top', a packet is handed down to the lower layer as data, the upper layer being oblivious to the additional framing (headers) that the lower layer adds.

Stacked Delivery

444

- delivery is, in the abstract, point-to-point
  - routing is mostly hidden from upper layers
  - the upper layer requests delivery to an address
- lower-layer protocols are usually packet-oriented
  - packet size mismatches can cause fragmentation
- a packet can pass through different low-level domains

When it comes to delivery, the relationships between layers are perhaps the most complicated. In this case, the view from top to bottom is the most appropriate, since lower layers provide delivery as a service to the upper layer.
Since the delivery on the internet layer (OSI layers 3 and up) is usually much wider in scope than that of the link layer, it is quite common that a single IP packet will traverse a number of link-layer domains.

Layers vs Addressing

445

- not as straightforward as packet nesting
  - address relationships are tricky
- special protocols exist to translate addresses
  - DNS for hostname vs IP address mapping
  - ARP for IP vs MAC address mapping

Finally, since (packet, data) delivery is a service provided by the lower layers to the upper layers, the upper layer must understand and provide correct lower-level addresses. The easiest way to look at this aspect is pairwise: the link layer and the internet layer obviously need to interact, usually through a special protocol which executes on the link layer, but logically belongs to the internet layer, since it deals with IP addresses.
Situation between the internet and transport layers is much simpler: the address at the transport layer simply contains the internet layer address as a field (e.g. a TCP address is an IP address + a port number). Finally, the relationship between the application layer and the transport layer is analogous (but not entirely the same) to the internet/link situation. The application layer primarily uses host names to identify computers, and uses a special protocol, known as DNS, which operates using transport-layer addresses, but otherwise belongs to the application layer.

ARP (Address Resolution Protocol)

446

- finds the MAC that corresponds to an IP
- required to allow packet delivery
  - IP uses the link layer to deliver its packets
  - the link layer must be given a MAC address
- the OS builds a map of IP $\rightarrow$ MAC translations

The address resolution protocol, which straddles the link/internet boundary, enables the internet layer to deliver its packets using the services of the link layer. Of course, to request link-layer delivery of a packet, a link address is required, but the IP packet only contains an

IP address. The ARP protocol is used to find link addresses of IP nodes which exist in the local network (this includes routers, which operate on the internet layer – in other words, packets destined to leave the local network are sent to a router, using the router's IP address, which is translated into a link-layer address using ARP as usual).

Ethernet

447

- link-level communication protocol
- largely implemented in hardware
- the OS uses a well-defined interface
  - packet receive and submit
  - using MAC addresses (ARP is part of the OS)

Perhaps the most common link layer protocol is ethernet. Most of the protocol is implemented directly in hardware and the operating system simply uses an unified interface exposed by device drivers to send and receive ethernet frames.

Packet Switching

448

- shared media are inefficient due to collisions
- ethernet is typically packet switched
  - a switch is usually a hardware device
  - but also in software (usually for virtualisation)
  - physical connections form a star topology

High-speed networks are almost exclusively packet switched, that is, a node sends packets (frames) to a switch, which has a number of physical ports and keeps track of which MAC addresses are reachable on which physical ports. When a frame arrives to a switch, the recipient MAC address is extracted, and the packet is forwarded to the physical port(s) which are associated to that MAC address.

Bridging

449

- bridges operate at the link layer (layer 2)
- a bridge is a two-port device
  - each port is connected to a different LAN
  - the bridge joins the LANs by forwarding frames
- can be done in hardware or software
  - `brctl` on Linux, `ifconfig` on OpenBSD

Bridges are analogous to switches, with one major difference: the expectation for a switch is that there are many physical ports, but each has only one MAC address attached to it (with perhaps the exception of a special 'uplink' port). A bridge, on the other hand, is optimized for the case of two physical ports, but each side will have many MAC addresses associated with it.

Tunneling

450

- tunnels are virtual layer 2 or 3 devices
- they encapsulate traffic using a higher-level protocol
- tunneling can implement Virtual Private Networks
  - a software bridge can operate over an UDP tunnel
  - the tunnel is usually encrypted

Tunnelling is a technique which allows lower-layer traffic to be nested in the application layer of an existing network. The typical use case is to tie physically distant computers into a single broadcast (link layer) or routing (internet layer) domain.

In this case, there are two instances of the network stack: the VPN software implements an application layer protocol running in the outer stack, while also acting as a link-layer interface (or an internet-layer subnet) that is bridged (routed) as if it was just another physical interface.

PPP (Point-to-Point Protocol)

451

- a link-layer protocol for 2-node networks
- available over many physical connections
  - phone lines, cellular connections, DSL, Ethernet
  - often used to connect endpoints to the ISP
- supported by most operating systems
  - split between the kernel and system utilities

The point-to-point protocol is another somewhat important and ubiquitous example of a link-layer protocol and is usually found on connections between LANs, or between a LAN and a WAN.

Wireless

452

- WiFi is mostly like (slow, unreliable) Ethernet
- needs encryption since anyone can listen
- also authentication to prevent rogue connections
  - PSK (pre-shared key), EAP / 802.11x
- encryption needs key management

Finally, WiFi is, from the point of view of the rest of the stack, essentially a slow, unreliable version of ethernet, though internally, the protocol is much more complicated.

Part 8.2: The TCP/IP Stack

In this section, we will look at the TCP/IP stack proper, and we will also discuss DNS in a bit more detail.

IP (Internet Protocol)

454

- uses 4 byte (v4) or 16 byte (v6) addresses
  - split into network and host parts
- it is a packet-based protocol
- is a best-effort protocol
  - packets may get lost, reordered or corrupted

IP is a low-overhead, packet-oriented protocol in wide use across the internet and most local area networks (whether they are attached to the internet or not). Quite importantly, its low-overhead nature means that it does not guarantee delivery, nor the integrity of the data it transports.

IP Networks

455

- IP networks roughly correspond to LANs
  - hosts on the same network are located with ARP
  - remote networks are reached via routers
- a netmask splits the address into network/host parts
- IP typically runs on top of Ethernet or PPP

Within a single IP network, delivery is handled by the link layer – the local network being identified by a common address prefix (the length of this prefix is part of the network configuration, and is known as the netmask).

Routing

456

- routers forward packets between networks
- somewhat like bridges but layer 3
- routers act as normal LAN endpoints
  - but represent entire remote IP networks
  - or even the entire internet

Packets for recipients outside the local network (i.e. those which do not share the network part of the address with the local host) are routed: a layer 3 device, analogous to a layer 2 switch, forwards the packet to one of its interfaces (into another link-layer domain). The routing tables are, however, much more complex than the information maintained by a switch, and their maintenance across the internet is outside the scope of this subject.

ICMP: Internet Control Message Protocol

457

- control messages (packets)
  - destination host/network unreachable
  - time to live exceeded
  - fragmentation required
- diagnostic packets, e.g. the `ping` command
  - `echo request` and `echo reply`
  - combine with TTL for `traceroute`

ICMP is the 'service protocol' used for diagnostics, error reporting and network management. The role of ICMP was substantially extended with the introduction of IPv6 (e.g. to include automatic network configuration, via router advertisements and router solicitation packet types). ICMP does not directly provide any services to the application layer.

Services and TCP/UDP Port Numbers

458

- networks are generally used to provide services
  - each computer can host multiple
- different services can run on different ports
- port is a 16-bit number and some are given names
  - port 25 is SMTP, port 80 is HTTP, ...

As we have briefly mentioned earlier, transport-layer addresses have two components: the IP address of the destination computer and a port number, which designates a particular service or application running on the destination node.

TCP: Transmission Control Protocol

459

- a stream-oriented protocol on top of IP
- works like a pipe (transfers a byte sequence)
  - must respect delivery order
  - and also re-transmit lost packets
- must establish connections

The two main transport protocols in the TCP/IP protocol family are TCP and UDP, with the former being more common and also considerably more complicated. Since TCP is stream-oriented and reliable, it needs to implement the logic to slice a byte stream into individual packets (for delivery using IP, which is packet-oriented), consistency checks (packet checksums) and retransmission logic (in case IP packets carrying TCP data are lost).

TCP Connections

460

- the endpoints must establish a connection first
- each connection serves as a separate data stream
- a connection is bidirectional
- TCP uses a 3-way handshake: SYN, SYN/ACK, ACK

To provide stream semantics to the user, TCP must implement a mechanism which creates the illusion of a byte stream on top of a packet-based foundation. This mechanism is known as a connection, and essentially consists of some state shared by the two endpoints. To establish this shared state, TCP uses a 3-way handshake.

Sequence Numbers

461

- TCP packets carry sequence numbers
- these numbers are used to re-assemble the stream
  - IP packets can arrive out of order
- they are also used to acknowledge reception
  - and subsequently to manage re-transmission

Sequence numbers are part of the connection state, and allow the byte stream to be reassembled in the correct order, even if IP packets carrying the stream get reordered during delivery.

Packet Loss and Re-transmission

462

- packets can get lost for a variety of reasons
  - a link goes down for an extended period of time
  - buffer overruns on routing equipment
- TCP sends acknowledgments for received packets
  - the ACKs use sequence numbers to identify packets

Besides packet reordering, TCP also needs to deal with packet loss: an event where an IP packet is sent, but vanishes without trace enroute to its destination. A lost packet is detected as a gap in sequence numbers. However, it is the sender which must learn about a lost packet, so that it can be retransmitted: for this reason, the recipient of the packet must acknowledge its receipt, by sending a packet back (or more often, by piggybacking the acknowledgement on a data packet that it would send anyway), carrying the sequence numbers of packets that have been received.
If an acknowledgement is not received within certain time (dynamically adjusted) from the sending of the original packet, the packet is sent again (retransmitted).

UDP: User (Unreliable) Datagram Protocol

463

- TCP comes with non-trivial overhead
  - and its guarantees are not always required
- UDP is a much simpler protocol
  - a very thin wrapper around IP
  - with minimal overhead on top of IP

Not all applications need the comparatively strong guarantees that TCP provides, or conversely, cannot tolerate the additional latency introduced by the algorithms that TCP employs to ensure reliable, in-order delivery. For those cases, UDP presents a very light-weight layer on top of IP, essentially only adding the port number to the addresses, and a 16-bit checksum to the packet header (which is, in its entirety, only 64 bits long).

Firewalls

464

- the name comes from building construction
  - a fire-proof barrier between parts of a building
- the idea is to separate networks from each other
  - making attacks harder from the outside
  - limiting damage in case of compromise

Firewall is a device which separates two networks from each other, typically by acting as the (only) router between them, but also examining the packets and dropping or rejecting them if they appear malicious, or attempt to use services that are not supposed to be visible externally. Often, one of these networks is the internet. Sometimes, the other network is just a single computer.

Packet Filtering

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- packet filtering is an implementation of a firewall
- can be done on a router or at an endpoint
- dedicated routers + packet filters are more secure
  - a single such firewall protects the entire network
  - less opportunity for mis-configuration

Like with other services, it usually pays off to centralize (within a single network) the responsibility for packet filtering, reducing the administrative burden and the space for misconfigured nodes to endanger the entire network. Of course, it is reasonable to run local firewalls on each node, as a second line of defence.

Packet Filter Operation

466

- packet filters operate on a set of rules
  - the rules are generally operator-provided
- each incoming packet is classified using the rules
- and then dispatched accordingly
  - may be forwarded, dropped, rejected or edited

A packet filter is, essentially, a finite state machine (perhaps with a bit of memory for connection tracking, in which case it is a stateful packet filter) which examines each packet and decides what action to take on it. The specific classification rules are usually provided by the network administrator; in simple cases, they match on source and destination IP addresses and port numbers, and on the connection status (which is remembered by the packet filter), for TCP packets.
After they are classified, the packets can be forwarded to their destination (as a standard router would), quietly dropped, rejected (sending an ICMP notification to the sender) or adjusted before being sent along (most commonly for network address translation, or NAT, the details of which are out of scope of this subject).

Packet Filter Examples

467

- packet filters are often part of the kernel
- the rule parser is a system utility
  - it loads rules from a configuration file
  - and sets up the kernel-side filter
- there are multiple implementations
  - `iptables`, `nftables` in Linux
  - `pf` in OpenBSD, `ipfw` in FreeBSD

There are usually two components to a packet filter: one is a system utility which reads a human-readable description of the rules, and based on those, compiles an efficient matcher for use in the kernel component which does the actual classification.

Name Resolution

468

- users do not want to remember numeric addresses
  - phone numbers are bad enough
- host names are used instead
- can be stored in a file, e.g. `/etc/hosts`
  - not very practical for more than 3 computers
  - but there are millions of computers on the internet

In the last part of this section, let's have a look at hostname resolution and the DNS protocol. What we need is a directory (a yellow pages sort of thing), but one that can be efficiently updated (many updates are done every hour) and also efficiently queried by computers on the network. The system must be scalable enough to handle many millions of names.

DNS: Domain Name System

469

- hierarchical protocol for name resolution
  - runs on top of TCP or UDP
- domain names are split into parts using dots
  - each domain knows whom to ask for the next bit
  - the name database is effectively distributed

Essentially, at the internet scale, we need some sort of a distributed system (i.e. a distributed database). Unlike relational databases though, delays in update propagation are acceptable, making the design simpler. The name space of host names is organized hierarchically, and the structure of DNS follows this organisation: going from right to left, starting with the top-level domain (a single dot, often left out), one of the DNS servers for that domain is consulted about the name immediately to the left, usually resulting in the address of another DNS server which can get us more information. The process is repeated until the entire name is resolved, usually resulting in an IP address of the host.

DNS Recursion

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- take `www.fi.muni.cz.` as an example domain
- resolution starts from the right at root servers
  - the root servers refer us to the `cz.` servers
  - the `cz.` servers refer us to `muni.cz`
  - finally `muni.cz.` tells us about `fi.muni.cz`

The process described above is called recursion and is usually performed by a special type of DNS server, which performs the recursion on behalf of its clients and caches the results for subsequent queries. This also means that it can, most of the time, start from the middle, since the name servers of the one or two topmost domains are most likely in the cache.

DNS Recursion Example

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```
$ dig www.fi.muni.cz. A +trace
.                   IN NS j.root-servers.net.
cz.                 IN NS b.ns.nic.cz.
muni.cz.        IN NS ns.muni.cz.
fi.muni.cz.     IN NS aisa.fi.muni.cz.
www.fi.muni.cz. IN A 147.251.48.1
```

To observe recursion in practice (and perform other diagnostics on DNS), we can use the `dig` tool, which is part of the ISC (Internet Software Consortium) suite of DNS-related tools.

DNS Record Types

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- `A` is for (IP) Address
- `AAAA` is for an IPv6 Address
- `CNAME` is for an alias
- `MX` is for mail servers
- and many more

Besides `NS` records, which tell the system whom to ask for further information, there are many types of DNS records, each carrying different type of information about the name in question. Besides IPv4 and IPv6 addresses, there are free-form TXT records (which are used, for instance, by spam filtering systems to learn about authorized mail servers for a domain), SRV records for service discovery in local networks, and so on.

Part 8.3: Using Networks

In this section, we will briefly look at the socket API which allows applications to use and provide network services (on POSIX operating systems, that is) and at a couple examples of application-level network services.

Sockets Reminder

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- the socket API comes from early BSD Unix
- socket represents a (possible) network connection
- you get a file descriptor for an open socket
- you can `read()` and `write()` to sockets
  - but also `sendmsg()` and `recvmsg()`
  - and `sendto()` and `recvfrom()`

Remember that socket is a file-like object, accessible through a file descriptor. On connected stream sockets, programs can use the usual `read` and `write` system calls, with semantics akin to pipes. While these are also possible on datagram sockets, a different API is often preferred, one of the reasons being that with `read`, it is impossible to distinguish datagrams coming from different sources.
The system calls `sendto`, `recvfrom` allow the program to specify (or learn, in case of `recvfrom`) the address of the recipient (sender) of the packet.

Socket Types

475

- sockets can be internet or unix domain
  - internet sockets work across networks
- stream sockets are like files
  - you can write a continuous stream of data
  - usually implemented using TCP
- datagram sockets send individual messages
  - usually implemented using UDP

Communication on IP networks is done using internet sockets (with `domain` set to `AF_INET` or `AF_INET6`). If the socket is a stream socket (its `type` is `SOCK_STREAM`) the communication is executed using TCP (stream-type sockets must be explicitly connected by a call to the `connect` or `accept` system call, which in case of internet sockets perform the TCP handshake).
Datagram sockets (`type` set to `SOCK_DGRAM`) may be optionally 'connected', though this only sets up a default destination for datagrams to be sent to. Communication is performed using UDP.

Creating Sockets

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- a socket is created using the `socket()` function
- it can be turned into a server using `listen()`
  - individual connections are established with `accept()`
- or into a client using `connect()`

All types of sockets are created using the `socket` system call, and specialize into server and client sockets based on the subsequent API calls performed on them. A server socket is obtained through `listen` and `bind`, while a client socket is obtained using `connect`. The server then repeatedly calls `accept` which returns a new file descriptor which then represents the TCP connection.

Resolver API

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- `libc` contains a resolver
  - available as `gethostbyname` (and `getaddrinfo`)
  - also `gethostbyaddr` for reverse lookups
- can look in many different places
  - most systems support at least `/etc/hosts`
  - and DNS-based lookups

The socket API only deals with numeric IP addresses. If an application needs to be able to connect to computers using their host names, it needs to use the resolver API which, behind the scenes, uses the appropriate database or protocol to find the corresponding IP addresses. The exact sequence of steps depends on system configuration, but usually the resolver consults the `/etc/hosts` file and a recursive DNS server (the IP address of which is again part of system configuration).

Network Services

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- servers listen on a socket for incoming connections
  - a client actively establishes a connection to a server
- the network simply transfers data between them
- interpretation of the data is a layer 7 issue
  - could be commands, file transfers, ...

Most network services operate in a client-server regime, on top of TCP: a server passively awaits connections on a particular transport-layer

address (i.e. an IP address coupled with a port number). The client, on the other hand, actively connects to a listening server, establishing a bidirectional channel (the TCP connection) between them. From that point on, the network stack simply transfers data across that channel. The data usually conforms to some application-level protocol (SMTP, HTTP, ...) though it does not need to be standardized or well-known.

Network Service Examples

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- (secure) remote shell – sshd
- the internet email suite
  - MTA = Mail Transfer Agent, speaks SMTP
  - SMTP = Simple Mail-Transfer Protocol
- the world wide web
  - web servers provide content (files)
  - clients and servers speak HTTP and HTTPS

Client Software

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- the ssh command uses the SSH protocol
  - a very useful system utility on virtually all UNIXes
- web browser is the client for world wide web
  - browsers are complex application programs
  - some of them bigger than even operating systems
- email client is also known as a MUA (Mail User Agent)

Part 8.4: Network File Systems

We have learned earlier that file systems are an important, ubiquitous abstraction. It is only natural to allow a file system to be accessed remotely (from another computer) using the API that is used for local access, making the 'network' part almost entirely transparent to the program.

Why Network Filesystems?

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- copying files back and forth is impractical
  - and also error-prone (which is the latest version?)
- how about storing data in a central location
- and sharing it with all the computers on the LAN

Perhaps the most compelling case for network file systems arises from the need to make workstations (desktop computers) at an institution fungible: that is, allow any user to log in onto any of the available workstations and immediately have all their data and settings at hand.

NAS (Network-Attached Storage)

483

- a (small) computer dedicated to storing files
- usually running a cut down operating system
  - often based on Linux or FreeBSD
- provides file access to the network
- sometimes additional app-level services
  - e.g. photo management, media streaming, ...

Another use case comes from the desire to store data which is shared by multiple users on a central device, where it is easy to back up and accessible from all computers (and hence by all users, even when some of the other computers are powered down).

NFS (Network File System)

484

- the traditional UNIX networked filesystem
- hooked quite deep into the kernel
  - assumes generally reliable network (LAN)
- filesystems are exported for use over NFS
- the client side mounts the NFS-exported volume

NFS is one of the first implementations of a network file system. It is based, essentially, on hooking up the VFS interface and exporting it over a remote procedure call interface to other kernels on the network. To create an NFS share, the local file system must be exported on the would-be NFS server; afterwards, it can be mounted by clients, making the share part of their local file system hierarchy.

NFS History

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- originated in Sun Microsystems in the 80s
- v2 implemented in System V, DOS, ...
- v3 appeared in '95 and is still in use
- v4 arrives in 2000, improving security

Network file system is a rather old technology (nearly 40 years old), but it has seen significant evolution over the first 20 or so years, with version 4 mainly addressing security concerns.

VFS Reminder

486

- implementation mechanism for multiple FS types
- an object-oriented approach
  - `open`: look up the file for access
  - `read`, `write` – self-explanatory
  - `rename`: rename a file or directory

Recall, from lecture 4, that VFS (virtual file system switch) is a mechanism inside the kernel that allows multiple file system implementations to present a unified interface to the rest of the kernel. NFS takes advantage of this existing interface and makes it available over the network. Of course, unlike VFS itself, the semantics of the NFS functions is standardized across implementations (NFS clients and servers are mostly compatible across different UNIX-like operating systems).

RPC (Remote Procedure Call)

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- any protocol for calling functions on remote hosts
  - ONC-RPC = Open Network Computing RPC
  - NFS is based on ONC-RPC (also known as Sun RPC)
- NFS basically runs VFS operations using RPC
  - easy to implement on UNIX-like systems

The way the NFS interface is exposed to the network is via a remote procedure call mechanism, which essentially takes a procedure call (the name of the function, along with the arguments that it should be called with), packs them into a byte string and sends it over the network to another computer, which then actually performs the call and sends the result back. The protocol has a mechanism to send data buffers, in addition to primitive values (integers).

Port Mapper

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- ONC-RPC is executed over TCP or UDP
  - but it is more dynamic wrt. available services
- TCP/UDP port numbers are assigned on demand
- `portmap` translates from RPC services to port numbers
  - the port mapper itself listens on port 111

In modern systems, ONC-RPC is implemented exclusively on top of the TCP/IP stack. Since the protocol can expose multiple services on each machine, the need arises to translate between those RPC services and TCP/UDP port numbers. In most cases, an RPC service called 'portmapper' takes care of this need, itself running on a fixed port (number 111).

The NFS Daemon

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- also known as `nfsd`
- provides NFS access to a local file system
- can run as a system service
- or it can be part of the kernel
  - this is more typical for performance reasons

Given an RPC stack, NFS is provided by an `nfsd`, which registers itself as a service with the RPC stack. The daemon can be a proper, user-space daemon, but it can also be part of the kernel (running as a kernel thread).

SMB (Server Message Block)

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- a network file system from Microsoft
- available in Windows since version 3.1 (1992)
  - originally ran on top of NetBIOS
  - later versions used TCP/IP
- SMB1 accumulated a lot of cruft and complexity

SMB is a completely different implementation of a network transparency layer for file systems. Like NFS, it is not tied to a particular on-disk format. SMB saw many incremental changes with each new Microsoft operating system that came along, while at the same time it was kept backward compatible, so that older operating systems could interoperate, both as clients and as servers. This made the protocol extremely complicated, making further extensions impractical.

SMB 2.0

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- simpler than SMB1 due to fewer retrofits and compat
- better performance and security
- support for symbolic links
- available since Windows Vista (2006)

Microsoft designed a new protocol for networked filesystems in their Windows Vista operating system, under the name SMB 2.0. Like NFSv4 a few years earlier, SMB 2 addressed many of the security weaknesses of its predecessor, while also improving performance and extending the protocol to support new file system features, such as symlinks.

Review Questions

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29.What is ARP (Address Resolution Protocol)?
30.What is IP (Internet Protocol)?
31.What is TCP (Transmission Control Protocol)?
32.What is DNS (Domain Name Service)?

Part 9: Shells & User Interfaces

This lecture will focus on human-computer interaction and the role of an operating system in this area. We will look at both text-based interaction modes (mainly command-line interfaces, i.e. shells) and at graphical interfaces, driven by a pointing device (mouse, trackpad) or a touch screen.

Lecture Overview

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1. Command Interpreters
2. The Command Line
3. Graphical Interfaces

The first part will focus on shell as a simple programming language, while in the second we will briefly look at terminals (or rather terminal emulators), interactive use of shell and at other text-mode programs. Finally, the third part will be about graphical interfaces and how they are built.

Part 9.1: Command Interpreters

Historically, shells play a dual role in most operating systems. Command-driven interaction is probably the easiest to implement, and was hence what computers and operating systems initially used. As soon as interactive terminals became available, that is (we will skip batch-mode systems today).
Any command interpreter has one interesting property though: you can make a transcript of a sequence of commands to achieve more complex tasks than any individual command can perform. This works without any involvement from the command interpreter itself: you can simply write them down on a piece of paper, and type them back later.
Now of course it would be much more convenient, if the computer could read the commands one by one from a file and execute them, as if you were typing them. This is the origin of shell scripts.

Shell

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- programming language centered on OS interaction
- rudimentary control flow
- untyped, text-centered variables
- dubious error handling

Of course, in your hardcopy or handwritten notes, you could include additional remarks and instructions, like only run this command if the previous one succeeded, or repeat this command 3 times, or repeat this command until such and such thing happens. Wouldn't it be wonderful, though, if you could include such annotations in the transcript that the computer reads and performs?
But of course, we have just invented control flow. And quite obviously this is exactly what shells came to implement. The other 'obvious' invention is placeholders in commands, to be replaced by appropriate values at execution time. For instance, you write down, in your paper notebook, a sequence of commands to update a list of users stored in a text file: you would presumably use a placeholder for the name of the file you are currently working with. And when you type the commands back, replace every occurrence of this placeholder with the real filename in question. But why, you have just invented variables!
Another thing that sort of carries over from these paper-based scripts into the executable sort is error handling… or rather the lack thereof. It so happens that you wouldn't bother instructing yourself that you should stop and investigate if one of the commands from your notebook fails unexpectedly.

Interactive Shells

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- almost all shells have an interactive mode
- the user inputs a single statement on keyboard
- when confirmed, it is immediately executed
- this forms the basis of command-line interfaces

Before we go on about control flow and variables, let us remind ourselves that most shells are interactive in nature. In this interactive mode, the user enters a single 'statement' (a single line) and confirms it, after which it is immediately executed. Most often this is a single command, but it can be a sequence, a loop or any other construct allowed by the language: there is no distinction in the kinds of syntax available in shell scripts and the interactive command line. This makes it possible to write short scripts (so-called 'one-liners') directly on the command line, to automate simple tasks, without bothering to write the program down. Learning to do it is well worth the investment, as it can save considerable time in day-to-day work.

Shell Scripts

498

- a shell script is an (executable) file
- in simplest form, it is a sequence of commands
  - each command goes on a separate line
  - executing a script is about the same as typing it
- but can use structured programming constructs

In contrast to interactive command execution, a shell script is a file with a list of statements in it, executed sequentially. Of course, as discussed above, basic control flow is available to alter this sequential execution, if needed. Variables can be used to substitute in parts of commands that change from one invocation of the script to the next.

Shell Upsides

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- very easy to write simple scripts
- first choice for simple automation
- often useful to save repetitive typing
- definitely not good for big programs

So how does shell compare as a programming language? First of all, it can be very productive and very easy to use, especially in scenarios where you are not programming as such, but really just automating simple tasks that you would otherwise do manually, by typing in commands.
However, try to create anything bigger and the limitations become significant: larger programs cannot just drop dead whenever something fails, nor can they ignore errors left and right (the two basic strategies available in scripts). The lack of structured data, a type system, and general 'programming hygiene' makes larger scripts fragile and hard to maintain. The next logical step is then a dedicated 'scripting' language, like Perl or Python, which make a compromise between the naivety (and simplicity) of shell and the structure and rigour of heavyweight programming languages like C++ or Java.

Bourne Shell

500

- a specific language in the 'shell' family
- the first shell with consistent programming support
  - available since 1976
- compatible shells are still widely used today
  - best known implementation is bash
  - /bin/sh is mandated by POSIX

The Bourne shell was created in 1976 and essentially codified the dual nature of shells as both interactive and programmable. We still use its basic model (and syntax) today. There are many Bourne-compatible shells, many of them descended from the Korn shell (ksh, which we will discuss shortly).
You may have heard of bash: the name stands for Bourne Again Shell[6] and it is probably the most famous shell that there is (to the extent that some people believe it is the only shell).

C Shell

501

- also known as csh, first released in 1978
- more C-like syntax than sh (Bourne Shell)
  - but not really very C-like at all
- improved interactive mode (over sh from '76)
- also still used today (mainly via tcsh)

Historically, the second well-known UNIX shell was the C shell[7] – it made improvements in interactive use, many of which were adopted into other shells, among others:

- command history (ability to recall already executed commands),
- aliases (user-defined shortcuts for often-used commands),
- command and filename completion (via tcsh),
- interactive job control.

The tcsh branch is a variant of csh with additional features, maintained alongside the original csh since early 80's. It is still distributed with many operating systems (and is, for instance, the default root shell on FreeBSD).

Korn Shell

502

- also known as ksh, released in 1983
- middle ground between sh and csh
- basis of the POSIX.2 requirements
- a number of implementations exist

[6] Because bad puns should be a human right.
[7] What is it with computer people and bad puns?

In essence a fusion of sh (the Bourne shell) and csh/tcsh (mainly as a source of improved user interaction; the scripting syntax remained faithful to sh). The original was based on sh source code, with many features added. This is the shell that POSIX uses as a model for /bin/sh.

Commands

503

- typically a name of an executable
  - may also be control flow or a built-in
- the executable is looked up in the filesystem
- the shell does a fork + exec
  - this means new process for each command
  - process creation is fairly expensive

The most typical command is simply a name of a program, perhaps followed by arguments (which are not interpreted by the shell, they are simply passed to the program as a form of input).
Commands in this form are performed, conceptually, as follows (details may differ in actual implementations, e.g. point 2 may be done as part of point 4):

1. check that the program given is not the name of a builtin command or a construct (if so, it is processed differently)
2. the name of the program is taken to be a name of an executable file – a list of directories (given by PATH, which will be explained later) is searched to see if an executable file with a given name exists,
3. the shell performs a fork system call to create a new process (see lecture 3),
4. the child process uses exec to start executing the executable located in 2, passing in any command line arguments,
5. the main shell process does a wait (i.e. it suspends until the executed program terminates).

This means that each command involves quite a lot of work, which is not a problem for interactive use, or reasonably-sized shell scripts. Executing many thousands of commands, especially if the commands themselves run quickly, may get a little slow though.

Built-in Commands

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- cd change the working directory
- export for setting up environment
- echo print a message
- exec replace the shell process (no fork)

Some commands of the form program [arguments] are interpreted specially by the shell (i.e. they will not use the above fork + exec process). There are basically two separate reasons why this is done:

1. efficiency – some commands are used often, especially in scripts, and creating new processes all the time is expensive – this is purely an optimisation, and is the case of built-in commands like echo or test,
2. functionality – some effects cannot be (easily, reasonably) done by a child process, mainly because changes need to be done to the main shell process: usually, only the main process can do such changes – this is the case of cd (changes the 'current working directory' of the main process), export (changes the environment of the main process, see also below) or exec (performs an exec without a fork, destroying the shell).

Variables / Parameters

505

- variable names are made of letters and digits
- using variables is indicated with $
- setting variables does not use the $
- all variables are global (except subshells)

```
variable="some text"
echo $variable
```

Earlier, we have mentioned an idea of 'placeholders', in the context of scripts written down in notepads. Shells take that idea, quite literally, and turn it into what we call variables (at least in most programming languages; the 'official' terminology in shell is parameters – rather in line with the idea of a placeholder).
Essentially, the shell maintains a mapping of names to values, where names are strings made of letters and digits and the values are arbitrary strings. To create or update a mapping, the following command is used:

```
variable="some text"
```

The quotes are not required unless there are spaces in the value. Whitespace around = is not allowed (writing variable = value is interpreted as the command variable with arguments = and value).

Parameter Expansion / Variable Substitution

506

- variables are substituted as text
- $foo is simply replaced with the content of foo
- arithmetic is not well supported in most shells
  - or any expression syntax, e.g. relational operators
  - consider the POSIX syntax z=$((x + y))

Variables (parameters) can be used more or less anywhere in any command, including as the command name. This is achieved by writing a dollar sign, $, followed by the name of the variable (parameter), like this:

```
echo $variable
```

The command will print some text. The substitution is done in a purely textual manner (the process is also known as parameter expansion). After substitution, everything about variables is 'forgotten' in the sense that whether any part of the text came from a substitution or was present from the start makes no difference and cannot be detected. This may lead to surprises if the value of a variable contains whitespace (we will discuss this later).
Coming from normal programming languages, a user may be tempted to write something like $a + $b in a shell. This will not work: if a=7 and b=3, the above 'expression' will be interpreted as the command 7 with arguments + and 3. To perform arithmetic in a shell script, the expression must be enclosed in $((…)) – to make it a little less painful, variables inside $((…)) do not need to be prefixed with $.
They are still substituted as text though:

```
a=3+1; echo $a = $((a))
```

will print 3+1 = 4 (and not e.g. an error because a is not a number).[8] However, substitutions within $((…)) without dollar signs are bracketed – in particular,

[8] Depending on the implementation, a=3+b; b=7; echo $((a)) may or may not work (in the sense that it'll print 10).

```
a=3+1; b=7; echo $((a * b))
```

will print 28, since it is expanded as `$(((3+1) * 7))`. This is not the case for `$` substitutions:

```
a=3+1; b=7; echo $(($a * $b))
```

will print 10.

Command Substitution

507

- basically like parameter substitution
- written as `` `command` `` or `$(command)`
  - first executes the command
  - and captures its standard output
  - then replaces `$(command)` with the output

Sometimes, it is desirable to compute a piece of a command, most commonly by running another program. This can be done using `$( … )`, e.g. `cat $(ls)`:

1. first, `ls` is executed as a shell command (since it is a name of a program, it will be fork'd and exec'd as normal),
2. the output of `ls` (the list of files in current directory, e.g. `foo.txt bar.txt`) is captured into a buffer,
3. the content of the buffer is substituted into the original command, i.e. `cat foo.txt bar.txt`,
4. the command is executed as normal.

Like with parameter substitution, there are whitespace related caveats (see below).

Quoting

508

- whitespace is an argument separator in shell
- multi-word arguments must be quoted
- quotes can be double quotes `"x"` or single `'x'`
  - double quotes allow variable substitution

Quoting and Substitution

509

- whitespace from variable substitution must be quoted
  - `foo="hello world"`
  - `ls $foo` is different than `ls "$foo"`
- bad quoting is a very common source of bugs
- consider also filenames with spaces in them

An important feature of parameter (variable) substitution is that it is done before argument splitting. Hence, values which contain whitespace may be interpreted, after substitution, as multiple arguments. Sometimes, this is desirable, but quite often it is not. Consider `cat $file`, clearly the author expects `$file` to be substituted for a single filename. However, if the value is `foo bar`, the command will be expanded to `cat foo bar` and execute the program `cat` with arguments `foo` and `bar`. Quoting can be used to prevent this from happening.
Consider the example on the slide above: the first command, `ls $foo` will expand into `ls hello world` and execute with:

```
argv[ 0 ] = "ls"
argv[ 1 ] = "hello"
argv[ 2 ] = "world"
```

In effect, like with the `cat` example, it will be looking for two separate files. The latter, `ls "$foo"`, will be executed as:
argv[0] = "ls" argv[1] = "hello world"

Special Variables

510

- `$?` is the result of last command
- `$$` is the PID of the current shell
- `$1` through `$9` are positional parameters
  - `$#` is the number of parameters
- `$0` is the name of the shell – `argv[0]`

Besides variables (parameters) that the users set themselves, the shell provides a few 'special' variables which contain useful information. Positional parameters refer to the command-line arguments given to the currently executing shell script.
Here are a few more variables:

- `$@` expands to all positional parameters, with special behaviour when double-quoted (each parameter is quoted separately),
- `$*` same, but without the special quoting behaviour,
- `$!` the PID of the last 'background process' (created with the `&` operator which will be discussed later),
- `$-` shell options.

Environment

511

- is like shell variables but not the same
- the environment is passed to all executed programs
  - a child cannot modify environment of its parent
- variables are moved into the environment by `export`
- environment variables often act as settings

POSIX has a concept of environment variables, which are independent of any shell: they are passed around from process to process, both across `fork` and across `exec`. However, since `fork` makes a new copy of the entire environment, changes in those variables can only be passed down (to new child processes), never up (to parent processes), or to already-running processes in general.
Despite being formally independent of shell, environment variables have similar semantics: their names are alphanumeric strings and their content is arbitrary text. To further add to the confusion, shells treat environment variables in the same way they treat their 'internal' variables (parameters). If `FOO` is an environment variable, a shell will replace `$FOO` by its value, and executing `FOO=bar` as a shell command will change its value in the main shell process (and hence all of its future child processes).

Important Environment Variables

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- `$PATH` tells the system where to find programs
- `$HOME` is the home directory of the current user
- `$EDITOR` and `$VISUAL` set which text editor to use
- `$EMAIL` is the email address of the current user
- `$PWD` is the current working directory

By convention, environment variables are named in all-uppercase. There are a few 'well-known' variables which affect the behaviour of various programs: the `PATH` variable gives a list of directories in which to look for executables (when executing commands in a shell, but also when invoking programs by name from other programs). The `HOME` variable tells programs where to store per-user files (both data and configuration), and so on. Some are set by the system when creating the user session (`HOME`, `LOGNAME`), others are set by the shell (`PWD`), some are normally configured by the system administrator (but can be changed by users), like `PATH`, yet others are configured by the user (`EDITOR`, `EMAIL`).

Globbing

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- patterns for quickly listing multiple files
- e.g. `ls *.c` shows all files ending in `.c`
- `*` matches any number of characters
- `?` matches one arbitrary character
- works on entire paths – `ls src/*/*.c`

Let us get back to shell and its syntax. Since files are ubiquitous and many commands expect file names as arguments, shells provide special constructs for working with them. One of those is globbing, where a single pattern can replace a possibly long list of file names (and hence saves a lot of tedious typing).
Glob expansion is done by the shell itself, i.e. the program receives individual file names as arguments, not the glob. Quotes (both single and double) prevent glob expansion (useful to pass strings which contain `*` or `?` as arguments). Unquoted strings with any of the glob 'metacharacters' is treated (and expanded) as a glob, including in results of parameter expansion (substitution).

Conditionals

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- allows conditional execution of commands
- `if cond; then cmd1; else cmd2; fi`
- also `elif cond2; then cmd3; fi`
- `cond` is also a command (the exit code is used)

The most basic of all control flow constructs is conditional execution, where a command is executed or skipped based on the outcome of a previous command. Shells use the traditional `if` keyword, optionally followed by `elif` and `else` clauses.
Unlike most programming languages, `cond` is not an expression, but a regular command. If the command 'succeeds' (terminates with exit code 0), this is interpreted as 'true' and the `then` branch is taken. Otherwise, the `elif` branches are evaluated in turn (if present) and if none succeed, the `else` branch (again, if present) is executed.

`test` (evaluating boolean expressions)

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- originally an external program, also known as `[`
  - nowadays built-in in most shells
  - works around lack of expressions in shell
- evaluates its arguments and returns `true` or `false`
  - can be used with `if` and `while` constructs

While the condition of an `if` statement (command) is a command, it would be often convenient to be able to specify expressions which relate variables to each other, or which check for presence of files. To this end, POSIX specifies a special program called `test` (actually built into most shells).
The `test` command receives arguments like any other command, evaluates them to obtain a boolean value and sets its exit code based on this value, so that `if test …; then …` behaves as expected.

`test` Examples

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- `test file1 -nt file2` → 'nt' = newer than
- `test 32 -gt 14` → 'gt' = greater than
- `test foo = bar` → string equality
- combines with variable substitution (`test $y = x`)

There are 3 classes of predicates provided by `test`:

1. existence and properties of files,
2. integer comparisons, and
3. string comparisons.

The latter two mimic what 'normal' programming languages provide (albeit with odd syntax). The first makes it easy and convenient to write commands that execute only if a particular file exists (or is missing), a very common task in shell programming.

Loops

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- `while cond; do cmd; done`
  - `cond` is a command, like in `if`
- `for i in 1 2 3 4; do cmd; done`
  - allows globs: `for f in *.c; do cmd; done`
  - also command substitution
  - `for f in $(seq 1 10); do cmd; done`

After conditional execution, loops are the next most fundamental construct. Again, like in general-purpose programming languages, loops allow shell scripts to repeat a sequence of commands, either:

1. until a particular command fails (a `while` loop, the command in question often being `test`, though of course it can be any command),
2. once for each value in a list, often of file names (which can be in turn constructed by using globs).

Another common form of the `for` loop uses command substitution (command expansion) to generate the list. An oft-used helper in this context is (sadly, non-standard) `seq` utility, which generates sequences of numbers. A similar (and likewise non-standard) utility called `jot` is available on BSD systems.

Case Analysis

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- selects a command based on pattern matching
- `case $x in *.c) cc $x;; *) ls $x;; esac`
  - yes, `case` really uses unbalanced parens
  - the `;;` indicates end of a case

A slightly more advanced control flow construct is case analysis, which allows the use of glob-like pattern matching on arbitrary strings (i.e. not just filenames). The string to match against is given after `case`, and is usually a result of parameter or command expansion. Note that the patterns after the `in` clause of the `case` statement are not glob-expanded into a list of filenames.

Command Chaining

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- `;` (semicolon): run two commands in sequence
- `&&` run the second command if the first succeeded
- `||` run the second command if the first failed
- e.g. compile and run: `cc file.c && ./a.out`

While the straightforward command chaining operator `;` (semicolon) is perhaps too banal to call control flow, there are a few similar operators that are more interesting. The first set is the boolean combinators `&&` and `||` which essentially function like a short-hand syntax for `if` statements. Since commands combined with `&&` and `||` are again commands, these can appear in the condition clause of an `if` or a `while` statement. However, they are also useful standalone, and also in interactive mode. Especially `&&` can be used to type a sequence of commands that stops on the first failure, significantly cutting down on interaction latency (where the user waits for each command to complete, and after each command, the computer waits for the user to type in the next com-

mand).

Pipes

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- shells can run pipelines of commands
- `cmd1 | cmd2 | cmd3`
  - all commands are run in parallel
  - output of `cmd1` becomes input of `cmd2`
  - output of `cmd2` is processed by `cmd3`

```
echo hello world | sed -e s,hello,goodbye,
```

Perhaps the most powerful feature of shells are pipes, which offer a very flexible and powerful (even if very simple) way to combine multiple commands. The pipe operator causes both commands to be executed in parallel, and anything that the first program writes to its standard output is sent to the second program on its standard input. POSIX specifies a considerable number of utility programs specifically designed to work well in such pipelines, and many more are available as vendor-specific extensions or in 3rd-party software packages.

Functions

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- you can also define functions in shell
- mostly a light-weight alternative to scripts
  - no need to `export` variables
  - but cannot be invoked by non-shell programs
- functions can also set variables

Recall that the environment is only passed down, never back up. This means that a shell script setting a variable will not affect the parent shell. However, in functions (and when scripts are invoked using `.`), variables can be set and the effect of such changes is visible in the script that invoked the function.

Part 9.2: The Command Line

While in some sense, the interactive aspects of shells are much more immediately important to users, they are not as theoretically interesting. You can learn more about the interactive shell by simply using it and discovering its features as you go and as you find them useful. That said, we will do a quick tour of the basic features most contemporary shells provide to make interactive use comfortable and efficient.

Interactive Shell

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- the shell displays a prompt and waits
- the user types in a command and hits enter
- the command is executed immediately
- output is printed to the terminal

The interactive mode is characterised by a prompt–response cycle, where the shell prompts the user for a command, the user types in a command, confirms it, and the shell executes it in response to the confirmation. The standard output and standard error output (descriptors 1 and 2) and the standard input (descriptor 0) are connected to the terminal, i.e. to the display and the keyboard of the user.

Command Completion

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- most shells let you use TAB to auto-complete
  - works at least for command names and file names
  - but "smart completion" is common
- interactive history: hit 'up' to recall a command
  - also interactive history search, e.g. `^R` in `bash`

During interactive use, a significant portion of time is spent typing in commands. Hence, shells try quite hard to reduce the effort needed to input these commands. One of the early, and very efficient, features in this direction is 'tab completion', where:

1. the user types in a portion of a command name or a file name and hits tab,
2. the shell looks up all possible commands or file names with the given prefix,
3. if there is only one option, it completes the name, otherwise it offers a list, which the user may cycle through, or type in more letters to make the prefix unique.

This saves time in two different ways: first, it is often faster to hit tab than to type in the remaining characters, and second, the user does not need to type in an extra command to list files, or find the exact name of the command.

Besides command names and file names, many shells offer 'smart completion' which can complete arguments in a context-sensitive way, i.e. depending on the prefix of the command being written. For instance, typing `ifc^I ^I` (the TAB character is sometimes spelled as `^I`) might complete first the command to `ifconfig` (for configuring network interfaces) and then offer a list of devices available in the particular computer.

The other major feature which saves typing is interactive history: when the user types a command, that command is saved in a 'history file'. The last few commands can be easily recalled by simply hitting the up arrow, while it's also possible to interactively search the history using keywords. The logic is, that for a longer command, editing the existing command can be much faster than typing it out again in its entirety.

Prompt

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- the string printed when shell expects a command
- controlled by the `PS1` environment variable
- usually shows your username and the hostname
- or working directory, battery status, time, weather, ...

An important tool that helps the user orient themselves is the prompt, which primarily serves to indicate that the shell is ready to accept a command.

The secondary function of the prompt is to give the user some basic information: usually, the host name of the computer (it is very easy to use shells remotely), the login they are working under, and the current working directory are present. What is printed can be customized, and many shells can run arbitrary commands to compute the prompt to print. In that case, the prompt can include anything that fits on the line, including the current time, battery status, the exit code of the last command, the current weather, the active `git` branch, current CPU or memory utilization, and so on and so forth.

Job Control

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- only one program can run in the foreground (terminal)
- but a running program can be suspended (`C-z`)
- and resumed in background (`bg`) or in foreground (`fg`)
- use `&` to run a command in background: `./spambot &`

While job control is not essential on modern systems, it can be occasionally useful. The original motivation was that typically, user only had a single terminal with a single screen, and hence could only be running a single command at a time: the shell would be unavailable until the program terminated (since the standard IO of the program would be connected to the terminal).
To improve the situation, shells allow programs to be executed in background, and continue interacting with the user while the program runs. Job control then allows the user to recall background programs into foreground, suspend the foreground program, and so on. Today, it's usually not a problem to open as many terminals as the user wants.

Terminal

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- can print text and read text from a keyboard
- normally everything is printed on the last line
- the text could contain escape (control) sequences
  - for printing colourful text or clearing the screen
  - also for printing text at a specific coordinate

The terminal itself is a key part of the interaction, though it is not part of the shell itself. Instead, shell uses terminal to do its input and output, like any other text-oriented program. While terminals used to be hardware devices, these days it's much more common to use 'terminal emulators', programs which behave like a traditional hardware terminal, but simply draw the content of the screen into a window.
In normal use of a terminal, older text scrolls upwards: this is the mode used with a typical shell. Moreover, this scrollback behaviour is automatic in the terminal. However, full-screen terminal applications (which use coordinate-based printing) will not use the capability. This is usually achieved by printing special 'escape sequences' to the terminal, which are not printed as literal text, but instead encode instructions for the terminal, like moving the cursor around, or printing coloured text.

Full-Screen Terminal Apps

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- applications can use the entire terminal screen
- a library abstracts away the low-level control sequences
  - the library is called `ncurses` for `new curses`
  - different terminals use different control sequences

Terminals are 'character cell' devices: the screen is divided into a non-overlapping grid of cells and each cell can display a single character or symbol. Terminals typically allow applications to disable automatic scrolling and then put characters anywhere on the screen: these capabilities make it possible to use the screen in an application-specific way.
For instance, a text editor can display a section of the file being edited, and allow the user to move both up and down in the file, as they see fit. Clearly, such usage does not fit the model, where text is only printed on the last line and scrolls up automatically when the line fills or a newline is printed.
Historically, different terminals used different escape sequences for the same (or related) feature. The features were also subtly different from vendor to vendor and even between different terminal models. For this reason, a library called `ncurses` translates high-level commands (put a red 'a' at given coordinates) into the low-level sequences based on the terminal the application is currently using.

UNIX Text Editors

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- `sed` – stream editor, non-interactive
- `ed` – line oriented, interactive
- `vi` – visual, screen oriented
- `ex` – line-oriented mode of `vi`

A typical example of a full-screen terminal program is a text editor. However, this was not always so: the first commonly used 'screen oriented' text editor was `vi`.[9] An earlier editor, `ed`, was command-based, and to see a portion of the file, the user would have to type in a command to that effect.

TUI: Text User Interface

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- special characters exist to draw frames and separators
- the program draws a 2D interface on a terminal
- these types of interfaces can be quite comfortable
- they are often easier to program than GUIs
- very low bandwidth requirements for remote use

Using a special character set (and a special font), it is possible to draw simple graphics (rectangular frames) on the terminal. Full-screen programs which make use of such features are halfway to GUIs, and often offer menus, forms with text fields, checkboxes or buttons, dialog windows and other elements commonly seen in graphical programs.

Part 9.3: Graphical Interfaces

Of course, modern operating systems[10] offer graphical user interfaces, based on a grid of millions of tiny pixels, instead of large character cells. Besides keyboard for entering text, pointing devices (mice, touchpads, touchscreens, ...) are ubiquitous. Pixel-based display devices can display arbitrary pictures, though user interfaces traditionally stick with simple, rectangular shapes.

Windowing Systems

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- each application runs in its own window
  - or possibly multiple windows
- multiple applications can be shown on screen
- windows can be moved around, resized &c.
  - facilitated by frames around window content
  - generally known as window management

The central paradigm of earlier GUI systems was that of a window, invented at Xerox PARC 70s and adopted into mainstream systems by the likes of Apple, Microsoft and Sun in the 80s.
The system can display multiple applications at a time, each restricted to a window: a rectangular area of the screen that can be moved around, resized and that can overlap with other applications.

[9] There are a couple screen-oriented editors which predate `vi`, though none of them survived the specific hardware and operating system they were written for. On the other hand, `vi` clones are still in common use today.

[10] At least those that offer some level of support for running on general-purpose end-user devices like desktops, laptops, tablets or smartphones.

Window-less Systems

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- especially popular on smaller screens
- applications take the entire screen
  - give or take status or control widgets
- task switching via a dedicated screen

While window-based systems dominated the computing world in the 90s and early 2000s, this started to change in 2007, with the arrival of the first iPhone. While of course it wasn't the first smartphone or the first small-screen device, it had an outsized impact on the computing landscape. The small screen of the iPhone made windowing impractical and essentially revived the 'one application at a time' mode of operation.
Of course, the underlying operating system was fully capable of multitasking, and the computer did run a number of background tasks. The user interface provides ways to interact with those tasks (e.g. notifications) that give aspects of both single- and multi-tasking environments. The paradigm is now in common use on tablet computers and smartphones of all major manufacturers.

A GUI Stack

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- graphics card driver, mode setting
- drawing/painting (usually hardware-accelerated)
- multiplexing (e.g. using windows)
- widgets: buttons, labels, lists, ...
- layout: what goes where on the screen

Displaying a character cell grid is a fairly simple affair: each letter and symbol that can be displayed is given a bitmap with the size of the grid cell. The picture on the screen is then glued from a non-overlapping grid of these small rectangular bitmaps.
On the other hand, the graphical stack is much more complex. While arguably the underlying concept: small colored rectangles (pixels) are clearly simpler than character cells, the process of building useful pictures out of them is a lot more involved.

Well-known GUI Stacks

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- Windows
- macOS, iOS
- X11
- Wayland
- Android

Portability

536

- GUI 'toolkits' make portability easy
  - Qt, GTK, Swing, HTML5+CSS, ...
  - many of them run on all major platforms
- code portability is not the only issue
  - GUIs come with look and feel guidelines
  - portable applications may fail to fit

Different GUI stacks provide different APIs, different abstractions and different capabilities. Since software portability is also desired in GUI applications, programmers often use a toolkit, which sits on top of the GUI stack and puts a uniform abstraction on top of it. This way, the application can run on different GUI stacks with a simple rebuild. However, there is a price: toolkits can get very complicated (hundreds of thousands of lines of code, in the case of the web stack currently running into many millions).

Text Rendering

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- a surprisingly complex task
- unlike terminals, GUIs use variable pitch fonts
  - brings up issues like kerning
  - hard to predict pixel width of a line
- bad interaction with printing (cf. WYSIWIG)

Bitmap Fonts

538

- characters are represented as pixel arrays
  - usually just black and white
- traditionally pixel-drawn by hand
  - very time consuming (many letters, sizes, variants)
- the result is sharp but jagged (not smooth)

Outline Fonts

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- Type1, TrueType – based on splines
- they can be scaled to arbitrary pixel sizes
- same font can be used for screen and for print
- rasterisation is usually done in software

Hinting, Anti-Aliasing

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- screens are low resolution devices
  - typical HD displays have DPI around 100
  - laser printers have DPI of 300 or more
- hinting: deform outlines to better fit a pixel grid
- anti-aliasing: smooth outlines using grayscale

X11 (X Window System)

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- a traditional UNIX windowing system
- provides a C API (`xlib`)
- built-in network transparency (socket-based)
- core protocol version 11 from 1987

X11 Architecture

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- X server provides graphics and input
- X client is an application that uses X
- a window manager is a (special) client
- a compositor is another special client

Remote Displays

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- application is running on computer A
- the display is not the console of A
  - could be a dedicated graphical terminal
  - could be another computer on a LAN
  - or even across the internet

Remote Display Protocols

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- one approach is pushing pixels
  - VNC (Virtual Network Computing)
- X11 uses a custom drawing protocol
- others use high-level abstractions
  - NeWS (PostScript-based)
  - HTML5 + JavaScript

VNC (Virtual Network Computing)

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- sends compressed pixel data over the wire
  - can leverage regularities in pixel data
  - can send incremental updates
- and input events in the other direction
- no support for peripherals or file sync

Basically the only virtue of VNC is simplicity. Security is an afterthought and not super-compatible across implementations. It is mainly designed for low-bandwidth, high-latency networks (i.e. the Internet).

RDP (Remote Desktop Protocol)

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- more sophisticated than VNC (but proprietary)
- can also send drawing commands over the wire
  - like X11, but using DirectX drawing
  - also allows remote OpenGL
- support for audio, remote USB &c.

RDP is primarily based on the pixel-pushing paradigm, but there is a number of extensions that allow sending high-level rendering commands for local, hardware-accelerated processing. In some setups, this includes remote accelerated OpenGL and/or Direct3D.

SPICE

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- Simple Protocol for Independent Computing Env.
- open protocol somewhere between VNC and RDP
- can send OpenGL (but only over a local socket)
- two-way audio, USB, clipboard integration
- still mainly based on pushing (compressed) pixels

Remote Desktop Security

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- the user needs to be authenticated over network
  - passwords are easy, biometric data less so
- the data stream should be encrypted
  - not part of the X11 or NeWS protocols
  - or even HTTP by default (used for HTML5/JS)

For instance, RDP in Windows 10 does not support fingerprint logins (it was supported on earlier versions, but was disabled due to security flaws).

Review Questions

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33.What is a shell?
34.What does variable substitution mean?
35.What is an environment variable?
36.What belongs into the GUI stack?

Part 10: Access Control

This lecture will focus on basic security considerations in an operating system, with focus on file systems, which are typically the most visible instance of access control in an OS.

Lecture Overview

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1. Multi-User Systems
2. File Systems
3. Sub-user Granularity

We will first look at the motivation and implementation of users, the basic unit of ownership and access control in an operating system. We will also look at some consequences and some applications of multi-user computing, and discuss how access control is implemented and enforced. In the second part, we will focus on the canonical case study in access control: file systems. Finally, the last part will explore what happens when per-user access control is not sufficient and we need a more granular permission system.

Part 10.1: Multi-User Systems

Multi-user systems had been the norm until the rise of personal computers circa mid-80s: earlier computers were too expensive and too bulky to be allocated to a single person. Instead, earlier systems used some form of multi-tenancy, whether implemented administratively (batch systems) or by the operating system (interactive, terminal-based computers).

Users

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- originally a proxy for people
- currently a more general abstraction
- user is the unit of ownership
- many permissions are user-centered

The concept of a user has evolved from the need to keep separate accounts for distinct people (the eponymous users of the system). In modern systems, a user continues to be an abstraction that includes accounts for individual humans, but also covers other needs. Essentially, user is a unit of ownership, and of access control.

Computer Sharing

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- computer is a (often costly) resource
- efficiency of use is a concern
  - a single user rarely exploits a computer fully
- data sharing makes access control a necessity

While efficient resource usage is what drove multi-tenancy of computer systems, it is the global shared file system that drove the requirement for access control: users do not necessarily wish to trust all other users of the system with access to their files.

Ownership

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- various objects in an OS can be owned
  - primarily files and processes
- the owner is typically whoever created the object
  - though ownership can be transferred
  - restrictions usually apply

The standard model of access control in operating systems revolves around ownership of objects. Generally speaking, ownership of an object confers both rights (to manipulate the object) and obligations (owned objects count towards quotas). Depending on circumstances, object ownership may be transferred, either by the original owner, or by system administrators.

Process Ownership

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- each process belongs to some user
- the process acts on behalf of the user
  - the process gets the same privilege as its owner
  - this both constrains and empowers the process
- processes are active participants

The perhaps most important ownership relationship is between users and their processes. This is because processes execute code on behalf of the user, and all actions a user takes on a system are mediated by some process or another. In this sense, processes act on behalf of their owner and the actions they perform are subject to any restrictions which apply to the user in question.

File Ownership

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- each file also belongs to some user
- this gives rights to the user (or rather their processes)
  - they can read and write the file
  - they can change permissions or ownership
- files are passive participants

Like processes, files are objects which are subject to ownership. However, unlike processes, files are passive: they do not perform any actions. Hence in this case, ownership simply gives the owner certain rights to perform actions on the file (most importantly change access control rights pertaining to that file).

Access Control Models

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- owners usually decide who can access their objects
  - this is known as discretionary access control
- in high-security environments, this is not allowed
  - known as mandatory access control
  - a central authority decides the policy

There are two main approaches to access control: the common discretionary model, where owners decide who can interact with their files (or other objects, as applicable) and mandatory, in which users are not trusted with matters of security, and decisions about access control are placed in the hands of a central authority.
In both cases, the operating system grants (or denies) access to object based on an access control policy: however, only in the latter case this policy can be thought of as a coherent, self-contained document (as opposed to a collection of rules decided by a number of uncoordinated users).

(Virtual) System Users

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- users are a useful ownership abstraction
- various system services get their own 'fake' users
- this allows them to own files and processes
- and also limit their access to the rest of the OS

Users have turned out to be a really useful abstraction. It is common practice that services (whether system- or application-level) run under special users of their own. This means that these service can own files and other resources, and run processes under their own identity. Additionally, it means that those services can be restricted using the same mechanisms that apply to 'normal' users.

Principle of Least Privilege

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- entities should have minimum privilege required
  - applies to software components
  - but also to human users of the system
- this limits the scope of mistakes
  - and also of security compromises

The principle of least privilege is an important maxim for designing secure systems: it tells us that, regardless of the subject and object combination, permissions should only be granted where there is genuine need for the subject to manipulate the particular object. The rationale is that mistakes happen, and when they do, we would rather limit their scope (and hence damage): mistakes cannot endanger objects which are inaccessible to the culprit.

Privilege Separation

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- different parts of a system need different privilege
- least privilege dictates splitting the system
  - components are isolated from each other
  - they are given only the rights they need
- components communicate using very simple IPC

An important corollary of the principle of least privilege is the design pattern known as privilege separation. Systems which follow it are split into a number of independent components, each serving a small, well-defined and security-wise self-contained function. Each of these modules can be then isolated in their own little sandbox and communicate with the rest of the system through narrowly defined interfaces (usually built on some form of inter-process communication).

Process Separation

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- recall that each process runs in its own address space
  - shared memory must be explicitly requested
- each user has a view of the filesystem
  - a lot more is shared by default in the filesystem
  - especially the namespace (directory hierarchy)

There is not much need for access control of memory: each process has their own and cannot see the memory of any other process (with small, controlled exceptions created through mutual consent of the two processes).
The file system is, however, very different: there is a global, shared namespace that is visible to all users and all processes. Moreover, many of the objects (files) are meant to be shared, in a rather ad-hoc fashion, either through 'well-known' paths (this being the case with many

system files) or through passing paths around. Importantly, paths are not any sort of access token and in almost all circumstances, withholding a path does not prevent access to the object (paths can be easily discovered).

Access Control Policy

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- there are 3 pieces of information
  - the subject (user)
  - the action/verb (what is to be done)
  - the object (the file or other resource)
- there are many ways to encode this information

We have mentioned earlier, that the totality of the rules that decide which actions are allowed, and which disallowed, is known as an access control policy. In the abstract, it is a rulebook which answers questions of the form 'Is (subject) allowed to perform (action) on (object)?' There are clearly many different ways in which this rulebook can be encoded: we will look at some of the most common strategies later.

Access Rights Subjects

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- in a typical OS those are (possibly virtual) users
  - sub-user units are possible (e.g. programs)
  - roles and groups could also be subjects
- the subject must be named (names, identifiers)
  - easy on a single system, hard in a network

The most common access control subject (at least when it comes to access policy specification), are, as was already hinted at, users, whether 'real' (those that stand in for people) or virtual (which stand for services).
In most circumstances, it must be possible to name the subjects, so that it's possible to refer to them in rules. Sometimes, however, rules can be directly attached to subjects, in which case there is no need for these subjects to have stable identifiers attached.

Access Rights Actions (Verbs)

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- the available 'verbs' (actions) depend on object type
- a typical object would be a file
  - files can be read, written, executed
  - directories can be searched or listed or changed
- network connections can be established &c.

The particular choice of actions depends on the object type: each such type has a fixed list of actions, which correspond to operations, or variants of operations, that the operating system offers through its interfaces.
The actions may be affected by the policy directly or indirectly – for instance, the read permission on a file is not enforced at the time a `read` call is performed: instead, it is checked at the time of `open`, with the provision that `read` can be only used on file descriptors that are open for reading. That is, the program is required to indicate, at the time of `open`, whether it wishes to read from the file.

Access Rights Objects

566

- anything that can be manipulated by programs
  - although not everything is subject to access control
- could be files, directories, sockets, shared memory, ...
- object names depend on their type
  - file paths, i-node numbers, IP addresses, ...

Like subjects, objects need to have names unless the pieces of policy relevant to them are directly attached to the objects themselves. However, in case of objects, this direct attachment is much more common: it is rather typical that an i-node embeds permission information.

Subjects in POSIX

567

- there are 2 types of subjects: users and groups
- each user can belong to multiple groups
- users are split into normal users and `root`
  - `root` is also known as the super-user

In POSIX systems, there are two basic types of subjects that can appear in the access control policy: users and groups. Since POSIX only covers access control for the file system, objects do not need to be named: their permissions are attached to the i-node.
A special user, known as `root`, represents the system administrator (also known as the super-user). This account is not subject to permission checking. Additionally, there is a number of actions (usually not attached to particular objects) which only the `root` user can perform (e.g. reboot the computer).

User and Group Identifiers

568

- users and groups are represented as numbers
  - this improves efficiency of many operations
  - the numbers are called `uid` and `gid`
- those numbers are valid on a single computer
  - or at most, a local network

In the access control policy, users and groups are identified by numbers (each user and each group getting a small, locally unique integer). Since these identifiers have a fixed size, they can be stored very compactly in i-nodes, and can be also very efficiently compared, both of which have been historically important considerations. Besides efficiency, the numeric identifiers also make the layout of data structures which carry them simpler, reducing scope for bugs.

User Management

569

- the system needs a database of users
- in a network, user identities often need to be shared
- could be as simple as a text file
  - `/etc/passwd` and `/etc/group` on UNIX systems
- or as complex as a distributed database

The user database serves two basic roles: it tells the system which users are authorized to access the system (more on this later), and it maps between human-readable user names and the numeric identifiers that the system uses internally.
In local networks, it is often desirable that all computers have the same idea about who the users are, and that they use the same mapping between their names and id's. LDAP and Active Directory are popular

choices for centralised network-level user databases.

Changing Identities

570

- each process belongs to a particular user
- ownership is inherited across `fork()`
- super-user processes can use `setuid()`
- `exec()` can sometimes change a process owner

Recall that all processes are created using the `fork` system call, with the exception of `init`. When a process forks, the child process inherits the ownership of the parent, that is, it belongs to the same user as the parent does (whose ownership is not affected by `fork`).
However, if a process is owned by the super-user, it can change its owner by using the `setuid` system call. Additionally, `exec` can sometimes change the owner of the process, via the so-called `setuid` bit (not to be confused with the system call of the same name). The `init` process is owned by the super-user.

Login

571

- a super-user process manages user logins
- the user types in their name and password
  - the `login` program authenticates the user
  - then calls `setuid()` to change the process owner
  - and uses `exec()` to start a shell for the user

You may recall that at the end of the boot process, a `login` process is executed to allow users to authenticate themselves and start a session. The traditional implementation of `login` first asks the user for their user name and password, which it checks against the user database. If the credentials match, the `login` program sets up the basic environment, changes the owner of the process to the user who just authenticated themselves and executes their preferred shell (as configured in the user database).

User Authentication

572

- the user needs to authenticate themselves
- passwords are the most commonly used method
  - the system needs to recognize the right password
  - user should be able to change their password
- biometric methods are also quite popular

By far, the most common method of authenticating users (that is, ascertaining that they are who they claim they are) is by asking for a secret – a password or a passphrase. The idea is that only the legitimate owner of the account in question knows this secret.
In an ideal case, the system does not store the password itself (in case the password database is compromised), but stores instead information that can be used to check that a password that the user typed in is correct. The usual way this is done is via (salted) cryptographic hash functions.
Besides passwords, other authentication methods exist, most notably cryptographic tokens and biometrics.

Remote Login

573

- authentication over network is more complicated
- passwords are easiest, but not easy
  - encryption is needed to safely transmit passwords
  - along with computer authentication
- 2-factor authentication is a popular improvement

While password is simply short string that can be quite easily sent across a network, there are caveats. First, the network itself is often insecure, and the password could be snooped by an attacker. This means we need to use cryptography to transmit the password, or otherwise prove its knowledge.
The other problem is, in case we send an encrypted password, that the computer at the other end may not be the one we expect (i.e. it could belong to an attacker).
Since the user is not required to be physically present to attempt authenticating, this significantly increases the risk of attacks, making strong passwords much more important. Besides strong passwords, security can be improved by 2-factor authentication (more on this shortly).

Computer Authentication

574

- how to ensure we send the password to the right party?
  - an attacker could impersonate our remote computer
- usually via asymmetric cryptography
  - a private key can be used to sign messages
  - the server signs a challenge to establish its identity

When interacting with a remote computer (via a network), it is rather important to ensure that we communicate with the computer that we intended to. While the most immediate concern is sending passwords, of course this is not the only concern: accidentally uploading secret data to the wrong computer would be as bad, if not worse.
A common approach, then, is that each computer gets a unique private key, while its public counterpart (or at least its fingerprint) is distributed to other computers. When connecting, the client can generate a random challenge, and ask the remote computer to sign it using the secret key associated to the computer that we intended to contact, in order to prove its identity. Unless the target computer itself has been compromised, an attacker will be unable to produce a valid signature and will be foiled.

2-factor Authentication

575

- 2 different types of authentication
  - harder to spoof both at the same time
- there are a few factors to pick from
  - something the user knows (password)
  - something the user has (keys, tokens)
  - what the user is (biometric)

Two-factor (or multi-factor) authentication is popular for remote authentication (as outlined earlier), since networks make attacks much cheaper and more frequent. In this case, the first factor is usually a password, and the second factor is a cryptographic token – a small device (often in the form of a keychain) which generates a unique sequence of codes, one of which the user transcribes to prove ownership of the token. Remote biometric authentication is somewhat less practical (though not impossible).
Of course, two-factor authentication can be used locally too, in which

case biometrics become considerably more attractive. Cryptographic tokens or smart cards are also common, though in the local case, they usually communicate with the computer directly, instead of relying on the user to copy a code.

Enforcement: Hardware

576

- all enforcement begins with the hardware
  - the CPU provides a privileged mode for the kernel
  - DMA memory and IO instructions are protected
- the MMU allows the kernel to isolate processes
  - and protect its own integrity

Now that we have an access control policy and we have established the identity of the user, there is one last thing that needs to be addressed, and that is enforcement of the policy. Of course, an access control policy is useless if it can be circumvented.
The ability of an operating system to enforce security stems from hardware facilities: software alone cannot sufficiently constrain other software running on the same computer. The main tool that allows the kernel to enforce its security policy is the MMU (and the fact that only the kernel can program it) and its control over interrupt handlers.

Enforcement: Kernel

577

- kernel uses hardware facilities to implement security
  - it stands between resources and processes
  - access is mediated through system calls
- file systems are part of the kernel
- user and group abstractions are part of the kernel

Hardware resources are controlled by the kernel: memory via the MMU, processors via the timer interrupt, memory-mapped peripherals again through the MMU and through the interrupt handler table. Since user programs cannot directly access physical resources, any interaction with them must go through the kernel (via system calls), presenting an opportunity for the kernel to check the requested actions against the policy.

Enforcement: System Calls

578

- the kernel acts as an arbitrator
- a process is trapped in its own address space
- processes use system calls to access resources
  - kernel can decide what to allow
  - based on its access control model and policy

When a system call is executed, the kernel knows the owner of that process, and also any objects involved in the system call. Armed with this knowledge, it can easily consult the access control policy to decide whether the requested action is allowed, and if it is not, return an error to the process, instead of performing the action.

Enforcement: Service APIs

579

- userland processes can enforce access control
  - usually system services which provide IPC API
- e.g. via the `getpeereid()` system call
  - tells the caller which user is connected to a socket
  - user-level access control relies on kernel facilities

Just as the kernel sits on resources that user programs cannot directly access, the same can principle can be applied in userspace programs, especially services.
Probably the most illustrative example is a relational database: the database engine runs under a dedicated (virtual) user and stores its data in a collection of files. The permissions on those files are set such that only the owner can read or write them – hence, the kernel will disallow any other process from interacting with those files directly.
Nonetheless, the database system can selectively allow other programs to interact with the data it stores: the programs connect to a database server using a UNIX socket. At this point, the database can ask the operating system to provide the user identifier under which the client is running (using `getpeereid`).
Since the server can directly access the files which store the data, and hence can, on the behalf of the client, execute queries and return the results. It can, however, also disallow certain queries based on its own access control policy and the user id of the client.

Part 10.2: File Systems

File Access Rights

581

- file systems are a case study in access control
- all modern file systems maintain permissions
  - the only extant exception is FAT (USB sticks)
- different systems adopt different representation

Representation

582

- file systems are usually object-centric
  - permissions are attached to individual objects
  - easily answers “who can access this file”?
- there is a fixed set of verbs
  - those may be different for files and directories
  - different systems allow different verbs

The UNIX Model

583

- each file and directory has a single owner
- plus a single owning group
  - not limited to those the owner belongs to
- ownership and permissions are attached to i-nodes

Access vs Ownership

584

- POSIX ties ownership and access rights
- only 3 subjects can be named on a file
  - the owner (user)
  - the owning group
  - anyone else

Access Verbs in POSIX File Systems

585

- read: read a file, list a directory
- write: write a file, link/unlink i-nodes to a directory
- execute: `exec` a program, enter the directory
- execute as owner (group): `setuid`/`setgid`

Permission Bits

- basic UNIX permissions can be encoded in 9 bits
- 3 bits per 3 subject designations
  - first comes the owner, then group, then others
  - written as e.g. `rwxr-x--` or `0750`
- plus two numbers for the owner/group identifiers

Changing File Ownership

- the owner and `root` can change file owners
- `chown` and `chgrp` system utilities
- or via the C API
  - `chown()`, `fchown()`, `fchownat()`, `lchown()`
  - same set for `chgrp`

Changing File Permissions

- again available to the owner and to `root`
- `chmod` is the user space utility
  - either numeric argument: `chmod 644 file.txt`
  - or symbolic: `chmod +x script.sh`
- and the corresponding system call (numeric-only)

`setuid` and `setgid`

- special permissions on executable files
- they allow `exec` to also change the process owner
- often used for granting extra privileges
  - e.g. the `mount` command runs as the super-user

Sticky Directories

- file creation and deletion is a directory permission
  - this is problematic for shared directories
  - in particular the system `/tmp` directory
- in a sticky directory, different rules apply
  - new files can be created as usual
  - only the owner can unlink a file from the directory

Access Control Lists

- ACL is a list of ACE's (access control elements)
  - each ACE is a subject + verb pair
  - it can name an arbitrary user
- ACL is attached to an object (file, directory)
- more flexible than the traditional UNIX system

ACLs and POSIX

- part of POSIX.1e (security extensions)
- most POSIX systems implement ACLs
  - this does not supersede UNIX permission bits
  - instead, they are interpreted as part of the ACL
- file system support is not universal (but widespread)

Device Files

- UNIX represents devices as special i-nodes
  - this makes them subject to normal access control
- the particular device is described in the i-node
  - only a super-user can create device nodes
  - users could otherwise gain access to any device

Sockets and Pipes

- named sockets and pipes are just i-nodes
  - also subject to standard file permissions
- especially useful with sockets
  - a service sets up a named socket in the file system
  - file permissions decide who can talk to the service

Special Attributes

- flags that allow additional restrictions on file use
  - e.g. immutable files (cannot be changed by anyone)
  - append-only files (for logfile integrity protection)
  - compression, copy-on-write controls
- non-standard (Linux `chattr`, BSD `chflags`)

Network File System

- NFS 3.0 simply transmits numeric `uid` and `gid`
  - the numbering needs to be synchronised
  - can be done via a central user database
- NFS 4.0 uses per-user authentication
  - the user authenticates to the server directly
  - filesystem `uid` and `gid` values are mapped

File System Quotas

- storage space is limited, shared by users
  - files take up storage space
  - file ownership is also a liability
- quotas set up limits space use by users
  - exhausted quota can lead to denial of access

Removable Media

598

- access control at file system level makes no sense
  - other computers may choose to ignore permissions
  - user names or id's would not make sense anyway
- option 1: encryption (for denying reads)
- option 2: hardware-level controls
  - usually read-only vs read-write on the entire medium

The `chroot` System Call

599

- each process in UNIX has its own root directory
  - for most, this coincides with the system root
- the root directory can be changed using `chroot()`
- can be useful to limit file system access
  - e.g. in privilege separation scenarios

Uses of `chroot`

600

- `chroot` alone is not a security mechanism
  - a super-user process can get out easily
  - but not easy for a normal user process
- also useful for diagnostic purposes
- and as lightweight alternative to virtualisation

Part 10.3: Sub-User Granularity

In this section, we will explore a few cases where a more precise notion of an access control subject is required or useful.

Users are Not Enough

602

- users are not always the right abstraction
  - creating users is relatively expensive
  - only a super-user can create new users
- you may want to include programs as subjects
  - or rather, the combination user + program

One of the main drawbacks of the user-centric security paradigm is heavyweight and requires super-user privileges. Moreover, normal users cannot easily constrain processes under auxiliary users (only via a `setuid` helper, which must again be configured by the `root` user).
A natural extension of the concept of an access control subject is to include the currently running program in the description – allowing the policy to say things like `/home/xuser/mail` can be accessed by thunderbird (a mail client) running under the account of `xuser`, but not by firefox (a web browser) running under the same account.

Naming Programs

603

- users have user names, but how about programs?
- option 1: cryptographic signatures
  - portable across computers but complex
  - establishes identity based on the program itself
- option 2: i-node of the executable
  - simple, local, identity based on location

Unfortunately, attaching policy rules to programs is much harder than it is for files or users, since their identity is rather elusive. There might be any number of programs called thunderbird, some of which may be different versions or builds of the same software, but some might just claim to be thunderbird to get to one's email.
A fairly good, if complicated, solution is to embed a cryptographic signature into executables, stating the rough equivalent of 'this program is Firefox, signed by Mozilla'. Assuming we trust Mozilla (we probably do since we run their software), we can refer to 'Firefox by Mozilla' in our access control policy. A variation of this approach is used by mobile operating systems, like Android and iOS.
The other option, much simpler, is to add a note like 'this program is Firefox' to the i-node of the executable. This approach is used by systems like SELinux (where the note is realized as a security label).

Program as a Subject

604

- program: passive (file) vs active (processes)
  - only a process can be a subject
  - but program identity is attached to the file
- rights of a process depend on its program
  - `exec()` will change privileges

Now that we have managed to delineate what is a program and how to identify it, a new problem pops up: in both cases, we have attached the identity to a file, but it actually belongs to a process. However, processes being much more dynamic than files, assigning identifiers to them is even less practical. In this case, we can use the same trick that was used for `setuid` programs: the `exec` system call can examine the binary and adjust the privileges of the process accordingly.

Mandatory Access Control

605

- delegates permission control to a central authority
- often coupled with security labels
  - classifies subjects (users, processes)
  - and also objects (files, sockets, programs)
- the owner cannot change object permissions

Security labels are, in some sense, a generalisation of user groups. They can be attached to both objects and subjects, and `exec` will update the labels attached to a process based on the labels attached to the executable (file).
Under mandatory access control, the users are not allowed to change permissions on objects. However, in practical systems, both modes are usually combined: discretionary permissions are attached to files as usual, and applied to an action whenever the mandatory rules alone would have allowed it.

Capabilities

606

- not all verbs (actions) need to take objects
- e.g. shutting down the computer (there is only one)
- mounting file systems (they can't be always named)
- listening on ports with number less than 1024

The term 'capabilities' is often used to mean one of two forms of access control policy rules:

1. where the object is a singleton, i.e. there is only a single object for the given action, or
2. where it is impractical to name the objects or to attach permission information to them.

Dismantling the root User

607

- the traditional root user is all-powerful
  - "all or nothing" is often unsatisfactory
  - violates the principle of least privilege
- many special properties of root are capabilities
  - root then becomes the user with all capabilities
  - other users can get selective privileges

In many cases, the simple split between root and normal users (which, incidentally, mirrors the split between the kernel and user programs) is inadequate. There are three principal ways to address this:

1. setuid programs can extend some of the special root-only privileges to normal users (e.g. mount, passwd),
2. the system of capabilities adds the option of allowing certain users to perform some of the restricted operations,
3. the user-level approach mentioned at the end of section 1, where the service runs under root (e.g. PolicyKit).

Security and Execution

608

- security hinges on what is allowed to execute
- arbitrary code execution are the worst exploits
  - this allows unauthorized execution of code
  - same effect as impersonating the user
  - almost as bad as stolen credentials

Control over which code can execute (and with what privileges) is at the center of all access control restrictions. If a program can be tricked into executing code supplied by an attacker, all the privileges that the program had are automatically available to the attacker as well.

Untrusted Input

609

- programs often process data from dubious sources
  - think image viewers, audio & video players
  - archive extraction, font rendering, ...
- bugs in programs can be exploited
  - the program can be tricked into executing data

The most common way programs can be hijacked in this manner is through improper processing of untrusted inputs, that is, content coming from untrustworthy sources. If unexpected input data can derail program execution, this opens the door for an attacker to take control of the program.
The payload (the code that the attacker wants executed) is usually supplied as part of the input, and hence is normally treated as data by the program. However, in presence of certain bug, the program can be tricked into executing (or interpreting) this data as code.

Process as a Subject

610

- some privileges can be tied to a particular process
  - those only apply during the lifetime of the process
  - often restrictions rather than privileges
  - this is how privilege dropping is done
- restrictions are inherited across fork()

Programs (or parts of programs running in a separate process) can ask the operating system to remove some of their privileges (like file system access, network access, and so on). There are many ways to do this, though they are not very portable (i.e. they depend on non-POSIX features of particular operating systems, e.g. Linux user namespaces, seccomp, FreeBSD Capsicum, OpenBSD pledge and unveil and so on). One of the few portable approaches, known as privilege drop, is essentially a subset of privilege separation: a special user is created for the particular process and the process, after having done any privileged initialization operations that it needed to do, uses setuid and perhaps chroot to lock itself down.

Sandboxing

611

- tries to limit damage from code execution exploits
- the program drops all privileges it can
  - this is done before it touches any of the input
  - the attacker is stuck with the reduced privileges
  - this can often prevent a successful attack

Sandboxing is a collection of techniques (including some of the above) that tries to minimize the impact of a successful exploit against a program. Sandboxing can be voluntary (the program sets up its own sandbox) and involuntary (see also next slide).

Untrusted Code

612

- traditionally, you would only execute trusted code
  - often based on reputation or other external factors
  - this does not scale to a large number of vendors
- it is common to execute untrusted, even dubious code
  - this can be okay with sufficient sandboxing

Running code from questionable sources is always risky, but is essentially guaranteed to result in a compromise unless precautions are taken. However, since the modern web is full of executable code, we simply resort to locking it down as much as we can and hope for the best.

API-Level Access Control

613

- capability system for user-level resources
  - things like contact lists, calendars, bookmarks
  - objects not provided directly by the kernel
- enforcement e.g. via a virtual machine
  - not applicable to execution of native code
  - alternative: an IPC-based API

Selectively granting permissions to programs through user-level permission systems is also possible for non-root users. There are two commonly employed methods:

1. a (program-level) virtual machine, like the JVM or the javascript virtual machines built into web browsers, which enforce that the program only talks to the system through restricted APIs,
2. a strict sandbox with the only access to the system provided by a daemon running on the outside of the sandbox (e.g. snap and flatpak, to a degree).

Both approaches can be combined, with a common technique locking a VM using OS-level sandboxing to defend against security bugs in the VM itself.

Android/iOS Permissions

614

- applications from a store are semi-trusted
- typically single-user computers/devices
- permissions are attached to apps instead of users
- partially virtual users, partially API-level

On Android, for instance, each application gets its own virtual user with very limited permissions and interaction with the system is done almost exclusively through high-level APIs. These APIs then perform permission checks, possibly prompting the user for confirmation as needed.

Review Questions

615

37. What is a user?
38. What is the principle of least privilege?
39. What is an access control object?
40. What is a sandbox?

Part 11: Virtualisation & Containers

This lecture will focus on running multiple operating systems on the same physical computer. Until now, we have always assumed that the operating system (in particular the kernel) has direct control over physical resources. This week, we will see that this does not always need to be the case (in fact, it is increasingly rare in production systems). Instead, we will see that multiple operating systems may share a single computer in a manner similar to how multiple applications (processes) co-exist within an operating system.
We will also explore a compromise approach, known as containers, where only the user-space parts of the operating system are duplicated and isolated from each other, while the kernel remains shared and retains direct control of the underlying machine.

Lecture Overview

617

1. Hypervisors
2. Containers
3. Management

The lecture is split into 3 parts: first part will introduce full-blown virtualisation and the concept of a hypervisor, while the second part will discuss containers. Finally, we will look at a few topics which are common to both systems, and in some sense are also relevant when managing networks of physical computers.

Part 11.1: Hypervisors

In the domain of hardware-accelerated virtualisation, a hypervisor is the part of the VM software that is roughly equivalent to an operating system kernel.

What is a Hypervisor

619

- also known as a Virtual Machine Monitor
- allows execution of multiple operating systems
- like a kernel that runs kernels
- improves hardware utilisation

While hypervisor itself behaves a bit like a kernel, standing as it does between the hardware and the virtualised operating systems, the virtualised operating systems running on top are, in a sense, like processes (including their kernels). In particular, they are isolated in physical memory (by using either regular MMU and a bit of software magic, or using an MMU capable of second-level translation) and they time-share on the available processors.

Motivation

620

- OS-level sharing is tricky
  - user isolation is often insufficient
  - only `root` can install software
- the hypervisor/OS interface is simple
  - compared to OS-application interfaces

Virtualised operating systems allow a degree of autonomy that is not usually possible when multiple users share a single operating system. This is partially due to the simplicity of the interface between the hypervisor and the operating system: there are no file systems, in fact no communication between the operating systems (other than through standard networking), no user management and so on. Virtual machines simply bundle up some resources and make them available to the operating system.

Virtualisation in General

621

- many resources are "virtualised"
  - physical memory by the MMU
  - peripherals by the OS
- makes resource management easier
- enables isolation of components

Operating systems (or computers, if you prefer) are of course not the only thing that can be (or is) virtualised. If you think about it, a lot of operating system itself is built around some sort of virtualisation: virtual memory, file systems, network stack, device drivers – they all, in some sense, virtualise hardware resources. This in turn makes it possible for multiple programs, and multiple users, to share those resources safely and fairly.

Hypervisor Types

622

- type 1: bare metal
  - standalone, microkernel-like
- type 2: hosted
  - runs on top of normal OS
  - usually need kernel support

There are two basic types of hypervisors, based on how the overall system is layered. In type 1, the hypervisor is at the bottom of the stack (just above hardware), and is responsible for management of the basic resources (a bit like a simple microkernel): processor and RAM (scheduling and memory management, respectively).
On the other hand, type 2 hypervisors run on top of an operating

system and reuse its scheduler and memory management: the virtual machines appear as actual processes of the host system.

Type 1 (Bare Metal)

623

- IBM z/VM
- (Citrix) Xen
- Microsoft Hyper-V
- VMWare ESX

Type 2 (Hosted)

624

- VMWare (Workstation, Player)
- Oracle VirtualBox
- Linux KVM
- FreeBSD bhyve
- OpenBSD vmm

History

625

- started with mainframe computers
- IBM CP/CMS: 1968
- IBM VM/370: 1972
- IBM z/VM: 2000

The first foray into running multiple operating systems on the same hardware was made by IBM in the late 60s and was made, on big iron, a rather standard feature soon after.

Desktop Virtualisation

626

- x86 hardware lacks virtual supervisor mode
- software-only solutions viable since late 90s
  - Bochs: 1994
  - VMWare Workstation: 1999
  - QEMU: 2003

Small (personal) computers, for a long time, did not offer any OS virtualisation capabilities. Performance of PC processors became sufficient to do PC-on-PC emulation in mid-90s, but the performance penalty was initially huge and was only suitable to run legacy software (which was designed for much slower hardware).

Paravirtualisation

627

- introduced as VMI in 2005 by VMWare
- alternative approach in Xen in 2006
- relies on modification of the guest OS
- near-native speed without HW support

A decade later, VMWare has made a breakthrough in software-based virtualisation technology, by inventing paravirtualisation: this required modifications to the guest operating system, but by the time, open-source operating systems were gaining a foothold – and porting open-source systems to a paravirtualising hypervisor was not too hard.

The Virtual x86 Revolution

628

- 2005: virtualisation extensions on x86
- 2008: MMU virtualisation
- unmodified guest at near-native speed
- most software-only solutions became obsolete

Around the same time, vendors of desktop CPUs started to incorporate virtualization extensions, which in turn made it unnecessary to modify the guest operating system (at least in principle). By 2008, mainstream desktop processors offered MMU virtualisation, further simplifying x86 hypervisor design (and making it more efficient at the same time).

Paravirtual Devices

629

- special drivers for virtualised devices
  - block storage, network, console
  - random number generator
- faster and simpler than emulation
  - orthogonal to CPU/MMU virtualisation

However, paravirtualisation made a quick and dramatic comeback: while virtualisation of CPU and memory was, for the most part, handled by the hardware itself, a hardware-based approach is not economical for virtualisation of peripherals.
Additionally, paravirtualised peripherals do not need changes in the guest operating system: all that is required is a quite regular device driver that targets the respective protocol. The virtual peripherals offered by the host system then simply appear as regular devices through an appropriate device driver running in the guest.

Virtual Computers

630

- usually known as Virtual Machines
- everything in the computer is virtual
  - either via hardware (VT-x, EPT)
  - or software (QEMU, `virtio`, ...)
- much easier to manage than actual hardware

The entire system running under a virtualised operating system is known as a virtual machine (or, sometimes, a virtual computer), not to be confused with program-level VMs like the Java Virtual Machine.

Essential Resources

631

- the CPU and RAM
- persistent (block) storage
- network connection
- a console device

A typical virtual machine will offer at least a processor, memory, block storage (on which the operating system will store a file system), a network connection and a console for management. While other peripherals are possible, they are not very common, at least not on servers.

CPU Sharing

632

- same principle as normal processes
- there is a scheduler in the hypervisor
  - simpler, with different trade-offs
- privileged instructions are trapped

Most instructions (specifically those available to user-space programs) are simply executed without additional overhead by the host CPU, without direct involvement of the hypervisor. However, the hypervisor does manage the virtualised MMU. However, just as importantly, when the CPU encounters certain types of privileged instructions, it will invoke the hypervisor to perform the required actions in software.

RAM Sharing

633

- very similar to standard paging
- software (shadow paging)
- or hardware (second-level translation)
- fixed amount of RAM for each VM

Like CPU virtualisation, memory sharing is built on the same basic principles that standard operating systems use to isolate processes from each other. Memory is sliced into pages and the MMU does the heavy lifting of address translation.

Shadow Page Tables

634

- the guest system cannot access the MMU
- set up shadow table, invisible to the guest
- guest page tables are sync'd to the sPT by VMM
- the gPT can be made read-only to cause traps

The trap can then synchronise the gPT with the sPT, which are translated versions of each other. The 'physical' addresses stored in the gPT are virtual addresses of the hypervisor. The sPT stores real physical addresses, since it is used by the real MMU.

Second-Level Translation

635

- hardware-assisted MMU virtualisation
- adds guest-physical to host-physical layer
- greatly simplifies the VMM
- also much faster than shadow page tables

Shadow page tables cause a lot of overhead, trapping every change of the guest page table into the hypervisor. Unfortunately, page tables are rearranged by the guest operating system rather often (on real hardware, this is comparatively cheap).
However, modern processors offer another level of translation, which is inaccessible to the guest operating system. Since the MMU is aware of virtualisation, the guest can directly modify its page tables, without compromising isolation of VMs from each other (and from the hypervisor).

Network Sharing

636

- usually a paravirtualised NIC
  - transports frames between guest and host
  - usually connected to a SW bridge in the host
  - alternatives: routing, NAT
- a single physical NIC is used by everyone

In contemporary virtualisation solutions, networking uses a paravirtual NIC (network interface card) which is connected to an Ethernet tunnel pseudo-device in the host system (essentially a virtual network interface card that handles Ethernet frames). The frames sent on the paravirtual device appear on the virtual NIC in the host and vice versa. The pseudo-device is then either software-bridged to the hardware NIC (and hence to the outside ethernet), or alternatively, routing (layer 3) is set up between the pseudo-device and the hardware NIC.

Virtual Block Devices

637

- usually also paravirtualised
- often backed by normal files
  - maybe in a special format
  - e.g. based on copy-on-write
- but can be a real block device

Like networking, block storage is typically based on paravirtualisation. In this case, the host side of the device is either backed by a regular file in the file system of the host, or sometimes it is backed by a block device on the same (often virtualised, e.g. through LVM/device-mapper or similar technology, but sometimes backed directly by a hardware block device).

Special Resources

638

- mainly useful in desktop systems
- GPU / graphics hardware
- audio equipment
- printers, scanners, ...

Now that we have covered the essentials, let's briefly look at other classes of hardware. However, with the possible exception of compute GPUs, peripherals are only useful on desktop systems, which are a tiny market compared to server virtualisation.

PCI Passthrough

639

- an anti-virtualisation technology
- based on an IO-MMU (VT-d, AMD-Vi)
- a virtual OS can touch real hardware
  - only one OS at a time, of course

Let's first mention a very generic, but very un-virtualisation method of giving hardware access to a virtual machine, that is, exposing a PCI device to the guest operating system directly, via IO-MMU-mapped memory. An IO-MMU must be involved, because otherwise the guest OS could direct the hardware to overwrite physical memory that belongs to the host, or to another VM running on the same system. With that covered, though, there is nothing that stops the host system from handing over control of specific PCI endpoints to a guest (of course, the host system must not attempt to communicate with those devices though its own drivers, else chaos would ensue).

GPUs and Virtualisation

640

- can be assigned (via VT-d) to a single OS
- or time-shared using native drivers (GVT-g)
- paravirtualised
- shared by other means (X11, SPICE, RDP)

Of course, since a GPU is attached through PCI, it can be shared using the IO-MMU (VT-d) approach described above. However, modern GPUs all support time-sharing (i.e. they allow contexts to be suspended and resumed, just like threads and processes on a CPU). For this to work, the hypervisor (or the host OS) must provide drivers for the GPU in question, so that it can mediate access to individual VMs.
Another solution, is paravirtualisation: the guest uses a vendor-neutral protocol to send a command stream to the driver running in the hypervisor, which in turn does the multiplexing. The guest system still needs the userspace part of the GPU driver to generate the command stream and to compile shaders.
Finally, existing network graphics protocols can be, of course, used between a guest and the host, though they are never quite as efficient as one of the specialised options.

Peripherals

641

- useful either via passthrough
  - audio, webcams, ...
- or standard sharing technology
  - network printers & scanners
  - networked audio servers

Finally, there is a wide array of peripherals that can be attached to a PC. Some of them, like printers and scanners, and in some cases (or rather, in some operating systems) audio hardware, can be shared over standard networks, and hence also between guests and the host over a virtual network. For this type of peripherals, there is either no loss in performance (printers, scanners) or possibly a small increase in latency (this mainly affects audio devices).

Peripheral Passthrough

642

- virtual PCI, USB or SATA bus
- forwarding to a real device
  - e.g. a single USB stick
  - or a single SATA drive

Of course, network-based sharing is not always practical. Fortunately, most peripherals attach to the host system through a handful of standard buses, which are not hard to either pass through, or paravirtualise. The devices then appear as endpoints on the virtual bus of the requisite type exposed to the guest operating system.

Suspend & Resume

643

- the VM can be quite easily stopped
- the RAM of a stopped VM can be copied
  - e.g. to a file in the host filesystem
  - along with registers and other state
- and also later loaded and resumed

An important feature available in most virtualisation solutions is the ability to suspend the execution of a VM and store its state in a file (i.e. create an image of the running virtualised OS). Of course this is only useful if the image can later be loaded and resumed 'as if nothing happened'.
On the outside, this looks rather like what happens when a laptop's lid is closed: the computer stops (in this case to save energy) and when it is opened again, continues where it left off. An important difference here is that in a VM, the guest operating system does not need to cooperate, or even be aware of the suspend/resume operation.

Migration Basics

644

- the stored state can be sent over network
- and resumed on a different host
- as long as the virtual environment is same
- this is known as paused migration

Of course, if an image can be stored in a file, it can just as well be sent over a network. Resuming an image on a different host is called a 'paused' migration, since the VM is paused for the duration of the network transfer: depending on the size of the image, this can be long enough to time out TCP connections or application-level protocols. Of course, even if this does not happen, there will be a noticeable lag for any interactive use of such a system.
Of course, the operation is predicated on the requirement that the supporting environment on the outside of the VM is sufficiently compatible between the hosts: in particular, the backing storage for virtualised block storage, and the virtual networking infrastructure need to match.

Live Migration

645

- uses asynchronous memory snapshots
- host copies pages and marks them read-only
- the snapshot is sent as it is constructed
- changed pages are sent at the end

Live migration is an improvement over paused migration above in that it does not cause noticeable lag and does not endanger TCP or other stateful connections that use timeouts to detect broken connections.
The main idea that enables live migration is that the VM can continue to run as normal while its memory is being copied, with the provision that any subsequent writes must be tracked by the hypervisor: this is achieved through the standard 'copy-on-write' trick, where pages are marked read-only right before they are copied, and the hypervisor traps faults. As appropriate, it allows the write to proceed, but also marks the page as dirty. When the initial sweep is finished, another pass is made but this time only through dirty pages, marking them as clean.

Live Migration Handoff

646

- the VM is then paused
- registers and last few pages are sent
- the VM is resumed at the remote end
- usually within a few milliseconds

When the number of dirty pages is sufficiently small at the end of an iteration, the VM is paused, the remaining dirty pages and the CPU context are copied over and the VM is immediately resumed. Since the last transfer is only a few hundred kilobytes, the switchover latency is almost negligible.

Memory Ballooning

647

- how to deallocate "physical" memory?
  - i.e. return it to the hypervisor
- this is often desirable in virtualisation
- needs a special host/guest interface

One final consideration is that the hypervisor allocates memory to the guest VMs on demand, but normally, operating systems don't have a concept of 'deallocating' physical memory that they are not actively using. In these circumstances, if the VM sees a spike in memory use, this memory will be indefinitely locked by that VM, even though it has no use for it.
A commonly employed solution is a so-called 'memory ballooning driver' which runs on the guest side and returns unmapped 'physical' (from the point of view of the guest) memory to the host operating system. The memory is unmapped on the host side (i.e. the content of the memory is lost to the guest) and later mapped again if the demand arises.

Part 11.2: Containers

While hardware-accelerated virtualisation is rather efficient when it comes to CPU overhead, there are other costs associated. Some of them can be mitigated by clever tricks (like memory ballooning, TRIM, copy-on-write disk images, etc.) but others are harder to eliminate. When maximal resource utilization is a requirement, containers can often outperform full virtualisation, without significantly compromising other aspects, like maintainability, isolation, or security.

What are Containers?

649

- OS-level virtualisation
  - e.g. virtualised network stack
  - or restricted file system access
- not a complete virtual computer
- turbocharged processes

Containers use virtualisation (in the broad sense of the word) already built into the operating system, mainly based on processes. This is augmented with additional separation, where groups of processes can share, for instance, a network stack which is separate from the network stack available to a different set of processes. While both stacks use the same hardware, they have separate IP addresses, separate routing tables, and so on. Likewise, access to the file system is partitioned (e.g. with `chroot`), the user mapping is separated, as are process tables.

Why Containers

650

- virtual machines take a while to boot
- each VM needs its own kernel
  - this adds up if you need many VMs
- easier to share memory efficiently
- easier to cut down the OS image

There are two main selling points of containers:

1. so-called 'provisioning speed' – the time it takes from 'I want a fresh system' to having one booted,
2. more efficient resource use.

Both are in large part enabled by sharing a kernel between the containers: in the first case, there is no need to initialize (boot) a new kernel, which saves non-negligible amount of time. For the second point, this is even more important: within a single kernel, containers can share files (e.g. through common mounts) and processes across containers can still share memory – especially executable images and shared libraries that are backed by common files. Achieving the same effect with virtual machines is quite impossible.

Kernel Sharing

651

- multiple containers share a single kernel
- but not user tables, process tables, ...
- the kernel must explicitly support this
- another level of isolation (process, user, container)

Of course, since a single kernel serves multiple containers, the kernel in question must support an additional isolation level (on top of processes and users), where separate containers have also separate process tables and so on.

Boot Time

652

- a light virtual machine takes a second or two
- a container can take under 50ms
- but VMs can be suspended and resumed
- but dormant VMs take up a lot more space

Even discounting issues like preparation of disk images, on boot time alone, a container can be 20 times faster than a conventional virtual machine (discounting exokernels and similar tiny operating systems).

`chroot`

653

- the mother of all container systems
- not very sophisticated or secure
- but allows multiple OS images under 1 kernel
- everything else is shared

The `chroot` system call can be (ab)used to run multiple OS images (the user-space parts thereof, to be more specific) under a single kernel. However, since everything besides the file system is fully shared, we cannot really speak about containers yet.

`chroot`-based 'Containers'

654

- process tables, network, etc. are shared
- the superuser must also be shared
- containers have their own view of the filesystem
  - including system libraries and utilities

Since the process tables, networking and other important services are shared across the images, there is a lot of interference. For instance, it is impossible to run two independent web servers from two different `chroot` pseudo-containers, since only one can bind to the (shared) port 80 (or 443 if you are feeling modern).
Another implication is that the role of the super-user in the container is not contained: the `root` on the inside can easily become `root` on the outside.

BSD Jails

655

- an evolution of the `chroot` container
- adds user and process table separation
- and a virtualised network stack
  - each jail can get its own IP address
- `root` in the jail has limited power

The jail mechanism on FreeBSD is an evolution of `chroot` that adds what is missing: separation users, process tables and network stacks. The jail also limits what the 'inside' `root` can do (and prevents them from gaining privileges outside the jail). It is one of the oldest open-source containerisation solutions.

Linux VServer

656

- like BSD jails but on Linux
  - FreeBSD jail 2000, VServer 2001
- not part of the mainline kernel
- jailed `root` user is partially isolated

Similar work was done on the Linux kernel a year later, but was not accepted into the official version of the kernel and was long distributed as a set of third-party patches.

Namespaces

657

- visibility compartments in the Linux kernel
- virtualizes common OS resources
  - the filesystem hierarchy (including mounts)
  - process tables
  - networking (IP address)

The solution that was eventually added to official Linux kernels is based around namespaces which handle each aspect of containerisation separately: when a new process is created (with a `fork`-like system call, called `clone`), the parent can specify which aspects are to be shared with the parent, and which are to be separated.

`cgroups`

658

- controls HW resource allocation in Linux
- a CPU group is a fair scheduling unit
- a memory group sets limits on memory use
- mostly orthogonal to namespaces

The other important component in Linux containers are 'control groups' which limit resource usage of a process sub-tree (which can coincide with the process sub-tree that belongs to a single container). This allows containers to be isolated not only with respect to their access to OS-level objects, but also with respect to resource consumption.

LXC

659

- mainline Linux way to do containers
- based on namespaces and `cgroups`
- relative newcomer (2008, 7 years after vserver)
- feature set similar to VServer, OpenVZ &c.

LXC is a suite of user-space tools for management of containers based on Linux namespaces and control groups. Since version 1.0 (circa 2014), LXC also offers separation of the in-container super user, and also unprivileged containers which can be created and managed by regular users (limitations apply).

User-Mode Linux

660

- halfway between a container and a virtual machine
- an early fully paravirtualised system
- a Linux kernel runs as a process on another Linux
- integrated in Linux 2.6 in 2003

Ports of kernels 'to themselves' so to speak: a regime where the kernel runs as an ordinary user-space process on top of a different configuration the same kernel, are somewhere between containers and full virtual machines. They rely quite heavily on paravirtualisation techniques, although in a rather unusual fashion: since the kernel is a standard process, it can directly access the POSIX API of the host operating system, for instance directly sharing the host file system.

DragonFlyBSD Virtual Kernels

661

- very similar to User-Mode Linux
- part of DFlyBSD since 2007
- uses standard `libc`, unlike UML
- paravirtual ethernet, storage and console

Another example of the same approach is known as 'virtual kernels' in DragonFlyBSD. In this case, the user-mode port of kernel even uses the standard `libc`, just like any other program. Unfortunately, no direct access to the host file system is possible, making this approach closer to standard VMs.

User Mode Kernels

662

- easier to retrofit securely
  - uses existing security mechanisms
  - for the host, mostly a standard process
- the kernel needs to be ported though
  - analogous to a new hardware platform

When it comes to implementation effort, user-mode kernels are simpler than containers, and offer better host-side security, since they appear as regular processes, without special status.

Migration

663

- not widely supported, unlike in hypervisors
- process state is much harder to serialise
  - file descriptors, network connections &c.
- somewhat mitigated by fast shutdown/boot time

One major drawback of both containers and user-mode kernels is lack of support for suspend and resume, and hence for migration. In both cases, this comes down to the much more complex state of a process, as opposed to a virtual machine, though the issue is considerably more serious for containers (the user-mode kernel is often just a single process on the host, whereas processes in containers are, in fact, real host-side processes).

Part 11.3: Management

Disk Images

665

- disk image is the embodiment of the VM
- the virtual OS needs to be installed
- the image can be a simple file
- or a dedicated block device on the host

Snapshots

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- making a copy of the image = snapshot
- can be done more efficiently: copy on write
- alternative to OS installation
  - make copies of the freshly installed image
  - and run updates after cloning the image

Duplication

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- each image will have a copy of the system
- copy-on-write snapshots can help
  - most of the base system will not change
  - regression as images are updated separately
- block-level de-duplication is expensive

File Systems

668

- disk images contain entire file systems
- the virtual disk is of (apparently) fixed size
- sparse images: unwritten area is not stored
- initially only filesystem metadata is allocated

Overcommit

669

- the host can allocate more resources than it has
- this works as long as not many VMs reach limits
- enabled by sparse images and CoW snapshots
- also applies to available RAM

Thin Provisioning

670

- the act of obtaining resources on demand
- the host system can be extended as needed
  - to keep pace with growing guest demands
- alternatively, VMs can be migrated out
- improves resource utilisation

Configuration

671

- each OS has its own configuration files
- same methods apply as for physical networks
  - software configuration management
- bundled services are deployed to VMs

Bundling vs Sharing

672

- bundling makes deployment easier
- the bundled components have known behaviour
- but updates are much trickier
- this also prevents resource sharing

Security

673

- hypervisors have a decent track record
  - security here means protection of host from guest
  - breaking out is still possible sometimes
- containers are more of a mixed bag
  - many hooks are needed into the kernel

Updates

674

- each system needs to be updated separately
  - this also applies to containers
- blocks coming from a common ancestor are shared
  - but updating images means loss of sharing

Container vs VM Updates

675

- de-duplication may be easier in containers
  - shared file system – e.g. link farming
- kernel updates: containers and type 2 hypervisors
  - can be mitigated by live migration
- type 1 hypervisors need less downtime

Docker

676

- automated container image management
- mainly a service deployment tool
- containers share a single Linux kernel
  - the kernel itself can run in a VM
- rides on a wave of bundling resurgence

The Cloud

677

- public virtualisation infrastructure
- “someone else’s computer”
- the guests are not secure against the host
  - entire memory is exposed, including secret keys
  - host compromise is fatal
- the host is mostly secure from the guests

Review Questions

678

41What is a hypervisor?
42What is paravirtualisation?
43How are VMs suspended and migrated?
44What is a container?

Part 12: Special-Purpose Operating Systems

In this lecture, we will take a look at special-purpose operating system (as opposed to general-purpose systems, which were the focus of much of the course). Those systems will lack some (and sometimes many) of the characteristics that we took for granted until now.
TBD.

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Review Questions

45Question 1
46Question 2
47Question 3
48Question 4