

# Chapter 2

## Unix

*UNIX is basically a simple operating system, but you have to be a genius to understand the simplicity.* – Dennis Ritchie



### 2.1 Unix History

For many people the term “System Administrator” implies operation of Unix systems, even though the same concepts, tasks and practices apply largely to the maintenance of hosts running any operating system. In this book, we strive to describe principles that are universally applicable and not bound by a specific operating system. We will regularly use Unix as the prime example and cite its features and specific aspects because of its academic background, long history of openness, high penetration of the infrastructure marketplace, and its role as a cornerstone of the Internet.

#### 2.1.1 The Operating System

How the Unix operating system came to be and how that relates to the development of the Internet and various related technologies is fascinating; just

about every other Unix-related book already covers this topic in great detail. In this chapter, we summarize these developments with a focus on the major milestones along the road from the birth of Unix as a test platform for Ken Thompson’s “Space Travel” game running on a PDP-7 to the most widely used server operating system that nowadays also happens to power consumer desktops and laptops (in the form of Linux and Apple’s OS X), mobile devices (Apple’s iOS is OS X based and thus Unix derived; Google’s Android is a Linux flavor), TVs, commodity home routers, industry scale networking equipment, embedded devices on the Internet of Things (IoT), and virtually all supercomputers<sup>1</sup>. We will pay attention to those aspects that directly relate to or influenced technologies covered in subsequent chapters. For much more thorough and authoritative discussions of the complete history of the Unix operating system, please see [2], [3] and [5] (to name but a few).<sup>2</sup>

Let us briefly go back to the days before the Unix epoch. Unix keeps time as the number of seconds that have elapsed<sup>3</sup> since midnight UTC of January 1, 1970, also known as “POSIX time”<sup>4</sup>. The date was chosen retroactively, since “Unics” – the *Uniplexed Information and Computing Service*, as the operating system was initially called<sup>5</sup> – was created by Ken Thompson, Dennis Ritchie, Brian Kernighan, Douglas McIlroy and Joe Ossana in 1969. That is, Unix predates the *Unix epoch*!

It is interesting and a testament to the clean design to see that the basic

---

<sup>1</sup>TOP500[1], a project ranking the 500 most powerful computers in the world, listed over 89% as running a version of Linux or Unix.

<sup>2</sup>The “Unix Heritage Society” mailing list[6] is another particularly noteworthy resource in this context. It continues to be an incredible source of historical, arcane, and yet frequently and perhaps surprisingly relevant information and discussions around the history of the Unix family of operating systems. It is notable for the regular participation of many of the original developers and researchers from the early days of Unix.

<sup>3</sup>It is worth adding that this does not include leap seconds, thus making Unix time a flawed representation of what humans like to refer to as linear time. Leap seconds are inserted rather unpredictably from time to time, and Unix time has to be adjusted when that happens. Worse, *negative* leap seconds are possible, though have never been required. Just more evidence that Douglas Adams was right: “Time is an illusion, lunch time doubly so.”[7]

<sup>4</sup>This is also the reason why, for example, Spam with a “Sent” date set to 00:00:00 may, depending on your timezone offset from UTC, show up in your inbox with a date of December 31, 1969.

<sup>5</sup>The name was a pun on the “Multics” system, an alternative for which it was initially developed as.

functionality and interfaces of an operating system developed over 40 years ago have not changed all that much. The C programming language was developed in parallel by Dennis Ritchie[8], for and on Unix. Eventually, Unix itself was rewritten in C, and the programming language became such an integral part of the operating system, such a fundamental building block, that to this day no System Administrator worth their salt can avoid learning it, even though nowadays most tools running on top of Unix are written in higher-level, often interpreted languages.

The structure of the Unix file system, which we will revisit in much detail in Chapter 4, the basic commands available in the shell, the common system calls, I/O redirection, and many other features remain largely unchanged from the original design. The concept of the pipe, which defines and represents so much of the general Unix philosophy, was first implemented in 1973[10], and we still haven't figured out a better, simpler, or more scalable way for two unrelated processes to communicate with each other.

Since its parent company AT&T was prohibited from selling the operating system<sup>6</sup>, Bell Laboratories licensed it together with the complete source code to academic institutions and commercial entities. This, one might argue, ultimately led directly to the very notion of “Open Source” when the Computer Systems Research Group (CSRG) of the University of California, Berkeley, extended the operating system with their patchsets, which they called the “Berkeley Software Distribution” or BSD.

Likewise, the licensing of this “add-on” software allowed Berkeley Software Design Inc. (BSDI) to develop and sell their operating system BSD/OS. This led directly to the famous lawsuit[11] by Unix System Laboratories (USL), a wholly owned subsidiary of AT&T / Bell Labs, who did not appreciate BSDI selling their operating system via the 1-800-ITS-UNIX number. It has been argued that this lawsuit eroded some companies' confidence in the BSD family of operating systems and caused them to adopt a new Unix clone called “Linux” despite its more onerous license. Regardless of the “what if”'s involved, this part of the history is rich in lessons ranging from business logic and legal impact of software licensing to the psychological impact of version numbering and other aspects of software product release.<sup>7</sup>

---

<sup>6</sup>Under a ruling stemming from an anti-trust settlement in 1958[5], AT&T was only able to commercially sell Unix after divesting itself from Bell Labs.

<sup>7</sup>For the rather interesting details, including the full ruling of the courts as well as many discussions around its repercussions, please see the references at the end of this chapter – the legal battle and its impact on the history of computing alone could fill a book.

The different direction taken by the CSRG and the commercial entities which licensed and then sold the Unix operating system and the evolution of the code as it was merged between these branches ultimately lead to two main directions: the BSD derived family of systems and the ones tracing back to (AT&T's) Unix UNIX V, or SysV. The latter had four major releases, with System V Release 4, or SVR4, being the most successful and the basis of many other Unix versions. Multiple vendors entered the operating system marketplace and tried to distinguish themselves from their competitors via custom (and proprietary) features, which lead to significant incompatibilities between the systems (and much frustration amongst System Administrators in charge of heterogeneous environments).

It only contributes to the overall confusion that “Version 7 Unix”, the last version of the original “Research Unix” made available by Bell Labs’ Computing Science Research Center, was released *prior* to and became the basis of “System III”, from whence “System V” would ultimately derive.<sup>8</sup> (Linux, not being a *genetic* Unix – that is, it does not inherit nor share any code directly with the original version from Bell Labs – can be seen as a third main flavor, as it borrows semantics and features from either or both heritages. This can at times be both a source of great choice and flexibility as well as of frustration and confusion.)

### Software Versioning is Largely Arbitrary



As a wonderful illustration of the absurdity of software version numbers, consider Solaris. Internally termed “SunOS 5”, it was released as “Solaris 2” and attempted to correlate SunOS kernel versions to Solaris releases: Solaris 2.4, for example, incorporated SunOS 5.4. As other competing operating systems had higher version numbers, it appears that Sun decided to leapfrog to the “front” by dropping the major version number altogether. The release following Solaris 2.6 became Solaris 7 (incorporating SunOS 5.7).

Similarly, 4.1BSD would have been called 5BSD, but AT&T feared that would lead to confusion with its own “UNIX System V”. As a result, the BSD line started using point releases, ending with 4.4BSD.

<sup>8</sup>You can download or browse the source code and manual pages of many historical Unix versions on the website of the Unix Heritage Society[29].

I have observed similar “back matching” of OS release versions in more than one large internet company: officially supported (major) OS version numbers grow point releases that do not exist upstream, reflecting a merging of internal versions such that third-party software does not break.

Fragile as this approach is, it reflects a SysAdmin’s ability to meet conflicting needs (track OS versions without incrementing the release numbers) in a practical manner.

Throughout the eighties, a number of different versions of Unix came into existence, most notably Hewlett-Packard’s HP-UX (SysV derived; originally released in 1984), IBM’s AIX (SysV derived, but with BSD extensions; originally released in 1986), Microsoft’s Xenix (derived from “Version 7 Unix”; originally released in 1980; ownership of Xenix was later on transferred to Santa Cruz Operation (SCO), where it was ultimately succeeded by “SCO UNIX”), SGI’s IRIX (SysV derived, but with BSD extensions; originally released in 1988) and Sun Microsystems’s SunOS (BSD derived; originally released in 1982 and later on superseded by their own SysV derived Solaris).

Even though these systems were commercial, innovations from one easily flowed to the others. For example, a number of important and now ubiquitous features such as the Virtual File System (VFS) and the Network File System (NFS) were developed at Sun, which was co-founded by Bill Joy, who had been a graduate student in the CSRG at Berkeley, where he worked on various BSD releases and created a number of important tools, including the `vi(1)` editor and the `cs(1)` command-line interpreter.

Not surprisingly, the code released under the permissive BSD-License[13] was equally quickly adapted and integrated into the commercial versions. This included the Berkeley Fast File System (FFS) (also known as the Unix File System (UFS)), the BSD Sockets library and Application Programming Interface (API), and of course the DARPA sponsored integration of the TCP/IP suite (initially developed by BBN Technologies, one of the companies contracted to implement the protocols). The BSD-derived TCP/IP code finally found its way into virtually every major operating system, including Microsoft Windows.

Linux, one of the most widely used Unix versions today – technically

a “Unix-like” operating system, as it inherits from neither the SysV nor the BSD lineages – has its own unique history, invariably tied to that of the GNU Project. Developed on and inspired by MINIX, it was created in 1991 by Linus Torvalds as a “(free) operating system [...] for 386(486) AT clones”[12]. Since a kernel all by itself does not an operating system make, Linux was soon bundled with the freely available software provided by the GNU Project and, like that software, licensed under the GNU General Public License.

The GNU Project in turn was started by Richard Stallman in 1983<sup>9</sup> to provide a Unix-like operating system, and by 1991 it provided a large number of essential programs and tools (starting with the ubiquitous `emacs(1)` editor) and of course including the GNU Compiler Chain `gcc(1)`, the GNU C Library (`glibc`), as well as the GNU Core Utilities; however, it was still in need of a kernel. When Linux was released, it filled this void and GNU/Linux was born. It is interesting to note that despite the unique license this operating system was released under – in a nutshell: you get the source and are free to use and modify it, but any modifications need to be released under this same license – it has found widespread adoption by commercial entities and countless products are based on it.

Different organizations, both commercial and volunteer-based, have sprung up to provide different versions of the GNU/Linux OS. Inherently similar on a fundamental level, they tend to differ in their package manager (see Chapter 5.5 for a detailed discussion of these components), administrative tools, development process, and user interface choices. Some companies trade rapid adoption of new features available in the open source kernel for a reputation of stability and offer commercial support for their particular Linux flavor.

Even though nowadays hundreds of these Linux distributions exist, the two dominant variations in the server market tend to be those based on “Red Hat Enterprise Linux” as well as derivatives of Debian GNU/Linux. The former, a commercial product licensed to users by Red Hat, Inc., gave birth to the “Fedora” and CentOS community projects, while in 2012 Canonical Ltd.’s “Ubuntu” OS became the most widely used Debian derivative. Changes to the core components continue to be merged across all distributions, but the specific bundling of custom tools lead to different Linux flavors drifting further apart.

---

<sup>9</sup>Note that this makes the GNU project 8 years older than Linux!

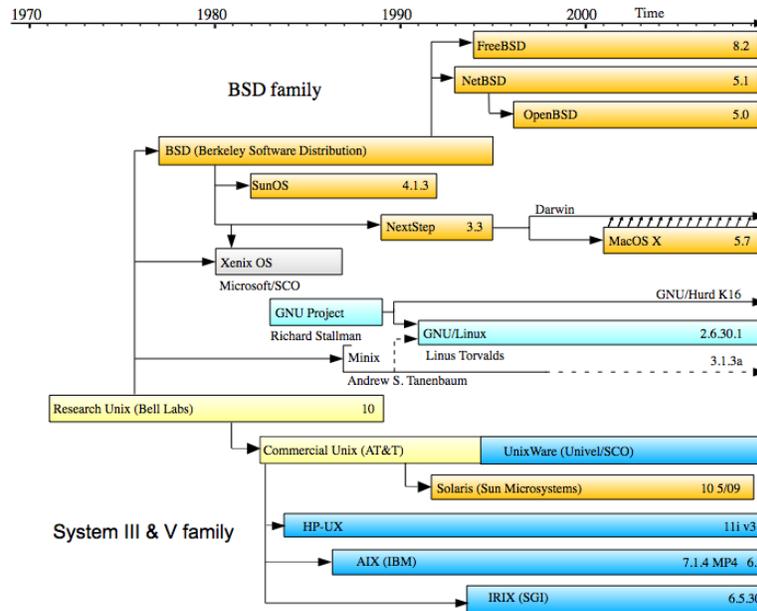


Figure 2.1: A partial Unix genealogy tree.

With all this back and forth between the various versions, trying to keep track of the entire genealogy of the Unix family of operating systems is no easy task. Figure 2.1 provides an incomplete and simplified visualization of the main directions; a much more complete graph of the Unix history can be seen on the “Unix Timeline” [14] – printed on letter-sized paper, the graph is over 25 feet long! Many System Administrators have covered their office walls with this reminder of the complex history of their favorite operating system.

Parallel to the development of the various Unix flavors evolved a set of standards that helped define how exactly the operating system should behave, what interfaces it should provide and what kinds of assumptions third-party software could make about the environment. These standards became to be known as the “Single UNIX Specification” (SUS, commonly referred by version, such as SUSv3) and eventually as “POSIX” (for “Portable Operating System Interface for uniX”). The SUS was used to qualify operating systems for the name “UNIX” – this certification was obtained only by a relatively small number of systems, since it was costly and required re-certification of

the system after any significant change (i.e., major OS release), something that Open Source projects, such as the BSDs certainly could not afford.

Eventually, SUSv3 and POSIX:2001 (formally known as IEEE 1003.1-2001) became more or less interchangeable; we will commonly refer to systems or interfaces as being “POSIX-compliant” (or not, as the case may be). At the time of this writing, the latest version is POSIX:2008[15], which is divided into a *Base Definition*, the *System Interfaces and Headers*, and the *Commands and Utilities*. It should be mentioned, though, that not only is “the nice thing about standards that you have so many to choose from”[16], as an old phrase coined by Andrew S. Tanenbaum goes, but also that a recommendation or requirement does not necessarily have to make sense or be realistic to be included in a standard. We will occasionally notice discrepancies between what POSIX demands and what different OS vendors chose to implement. As two entertaining examples, please refer to the section of the `fcntl(2)` manual page on e.g. a NetBSD system[17] that elaborates on the locking semantics or the fact that POSIX could be interpreted to require a `cd(1)` *executable*<sup>10</sup>.

## 2.1.2 Networking

No review of the history and basic features of the Unix operating system would be complete without a mention of the parallel evolution of the Internet. As we noted in Section 2.1.1, the development of the Unix system and that of the predecessors of what ultimately became the Internet were not only related, but became inseparably merged. The ARPANET implemented the concept of *packet switching*, allowing payload to be broken into small *datagrams* and routed along different paths; its adoption of TCP/IP[20] as its protocol suite effectively marked the beginning of the modern Internet. Even though some companies developed their own TCP/IP stack, the code included in the Berkeley Software Distribution quickly became the most widely used implementation and ultimately replaced other network protocols<sup>11</sup>.

In the early days of the Internet, the various different networks – ARPANET,

---

<sup>10</sup>If the problem of a `cd(1)` *executable* isn’t immediately obvious to you... well, see Problem 4!

<sup>11</sup>Microsoft, for example, did not include TCP/IP in their operating systems until Windows 95, allowing other companies to sell their implementations as add-on software. The move from their native NetBIOS protocol to the BSD derived TCP/IP stack helped make the latter the de-facto Internet standard protocol suite.

CSNET, MILNET, NSFNET, NSI, etc. – were connected via specific gateway hosts, and email exchanges as well as communications on the early BBSes and Usenet were performed via UUCP, the *Unix-to-Unix Copy* tools<sup>12</sup>. Once hosts were more frequently directly connected to the Internet, SMTP and NNTP became more widely used, leading to Unix servers running various so-called *dæmons* to provide network services as part of their normal operations.

But even before the advent of the Internet, Unix included networking capabilities. Through its layers of abstraction it was possible to implement support for different networking technologies and allow applications to be network protocol agnostic. In fact, some applications, such as email were available and in use prior to any traditional networking capabilities. The nature of Unix as a multiuser system lead to the development of tools, amongst them the `mail(1)` program, to allow these users to communicate efficiently with one another and across systems. We will frequently review how the nature of a scalable tool allows it to function equally well regardless of where input data comes from or what transport mechanism is used; a simple, well defined program can deliver mail on a single system while relying on a separate transport service (i.e., UUCP or SMTP) to handle connections with other systems.

Furthermore, the software implementing such services was developed on and then included in the Unix operating system. As a result, the Internet and its infrastructure were growing in parallel to the capabilities of Unix, one enabling the other to become more powerful and ubiquitous. And so today, the overwhelming majority of the systems powering the core infrastructure components of the Internet, such as, for example, the DNS root servers or most web- and mail servers, are running on a Unix variant<sup>13</sup>: the by far most popular implementation of the DNS specification is, not surprisingly, the *Berkeley Internet Name Domain (BIND)* server[21]; `sendmail`, `exim`, and `postfix` push the majority of the world’s email[22]; the `apache` web server still handles more than 45% of all HTTP traffic on active sites than any other web server[23].

---

<sup>12</sup>Every now and then you may encounter a scruffy oldtimer who insists on pointing out that their email address is something along the lines of “...!orgserver!deptserv!mybox!user”. You can trivially impress them by calling it their “bang path” and agreeing that @-based email addresses are newfangled humbug.

<sup>13</sup>As noted in the introduction, we continue to count Linux as a “Unix variant” to avoid constant repetition of the phrase “Unix or Linux”.

### 2.1.3 Open Source

Unix is an inherently open system. Developed at a renowned research institution, it was released and licensed together with the source code long before the formal idea of “Open Source” had manifested itself. As we have seen in Section 2.1, the availability of the source code made it possible for other various commercial versions to be developed by different companies, but it also allowed the development of the Berkeley Software Distribution (BSD) with its distinctly permissive licensing terms.

Having access to the source code of the operating system and all the tools in use is a foreign concept in the world of proprietary software, where the source code is guarded as a trade secret, the pillar upon which a traditional company builds its entire profit model. Within the academic world in which Unix was developed, however, access to the source code was only natural. Peer review and openness were fundamental parts of this world and the system was targeted towards engineers, hackers, advanced users who would naturally like to make changes to tools, who would want to extend the capabilities and add new features.

This wish to share one’s work with others, to allow others to take full advantage of it, and to make their own modifications took two distinct directions early on, embodied in the two open source license models that have remained dominant to this day. On the one hand, the distinctly academic BSD-License (see Listing 2.3) allowed for any use of the software whatsoever (including modification and commercial re-selling of the products) so long as credit was given where credit was due. On the other hand, the GNU General Public License (GPL), written by Richard Stallman intended to very specifically not only *grant*, but to *enforce* certain freedoms using a moral argument. This license, somewhat ironically, imposes a number of restrictions on what you can do with the source code you have received, most notably the requirement to make public under *the same* license any changes you distribute.

People have argued about the benefits of one license over the other for decades by now, and we will not attempt to resolve the dispute in this book. They represent different approaches to one’s software, perhaps a personal choice of how one wishes that it be used in the future. Suffice it to say that there is incredible software licensed using both approaches, and both models thrive to this day. A similar discussion involves the concept of cost and freedom with regards to software (“Free as in beer versus free as in speech”). Open Source software, like all software, comes at a price: a relatively small

component of the total cost of ownership is the actual purchase price, and access to the source code (which in some cases may well come under specific terms of the license with commercial and/or closed source software) is somewhat independent thereof. What’s more important – within the context of this book, anyway – is that the very concept of Open Source is embedded in the Unix philosophy and culture, and as a result System Administrators frequently *expect* to be able to analyze the source code to the applications and operating systems they run.

But not only are we *able* to inspect how a piece of software works, we *need* to. All too frequently do we encounter problems or try to analyze a system’s behaviour where the question of what on earth might be going on is answered with this advice: “Use the source, Luke!” – Unix has let us do precisely that since the beginning.<sup>14</sup>

## 2.2 Basic Unix Concepts and Features

The Unix operating system consists, somewhat simplified, of three major components: a *kernel*, which controls the hardware, schedules tasks, and interfaces with the various devices; a set of *libraries*, which provide an interface to the kernel (in the form of *system calls* that run in privileged kernel space as well as unprivileged *library functions* running in user space); and a set of *tools and applications* (often referred to as the “userland”) using these libraries to provide functionality to the end user.

Most Unix flavors use a *monolithic* kernel, but allow for dynamically loaded kernel modules.<sup>15</sup> This approach allows for a reduction of the kernel footprint and increased flexibility, as device driver support can be added or removed at runtime without requiring a reboot. The kernel, managing the system’s resources, is running in supervisor mode and exposes facilities via system calls. It is desirable to keep the number of these entry points into kernel space limited and let higher-level library functions provide added

---

<sup>14</sup>It should be mentioned that the various commercial Unix versions represent closed source systems. But not only are Open Source Unix versions nowadays much more widely in use, virtually all of the core software running *on top* of the (commercial, closed, open, or any other) OS traditionally comes with its source code.

<sup>15</sup>A discussion of *microkernels*, *unikernels*, and the various *containers* that became popular in more recent years is, unfortunately, well beyond the scope of this chapter. The broad subject matter of System Administration again forces us to focus on the general principles first.

```
$ cmd >output          # redirection of stdout to a file
$ cmd >/dev/null       # suppression of output
$ cmd >/dev/null 2>&1  # suppression of all output
$ cmd <input          # accepting input from a file
$ cmd1 | cmd2         # feeding output from cmd1 into cmd2

# Of course these redirections can be combined...
$ cmd1 2>/dev/null | cmd2 | cmd3 2>&1 | cmd4 >file 2>output
```

Listing 2.1: Simple I/O redirection in the shell

functionality executed in unprivileged mode. Therefore, most Unix versions have only a comparatively small number of system calls: as of January 2017, NetBSD, for example, had only around 482 such calls[18], with only minimal expected growth<sup>16</sup>.

Utilizing these system calls and library functions, the higher level tools and applications are able to interface with the kernel and execute on the user's behalf. These binaries then can be divided into a number of categories, such as executables essential for the basic operation of the system, tools primarily intended for use by the system administrator, and general purpose utilities. We will revisit this topic in more detail in Chapter 5.

### 2.2.1 The shell

The Unix *shell*, while in many ways nothing but a regular executable, takes a special place in the list of utilities and commands available on the system. The shell provides the primary user interface, allowing for the invocation and execution of the other tools. AT&T's Version 7 Unix included the so-called "Bourne shell" (named after Steven Bourne) installed as `/bin/sh`. In addition to the ability to invoke other commands, the shell was designed as a *command interpreter* both for interactive use as well as for *non*-interactive use. That is, it included a scripting language, allowing for complex series of commands to be executed; for example, by system startup scripts at boot time.<sup>17</sup>

---

<sup>16</sup>Revisiting an earlier draft of this chapter from January 2012 listed 472 system calls. That is, over the course of five years, only ten new system calls were added.

<sup>17</sup>It is worth noting that the early Bourne shell also included support for pipelines (invented by Douglas McIlroy and added to Unix by Ken Thompson in 1973).

Various other shells have been created since then, mostly following either the general Bourne shell syntax or that of Bill Joy's C `csh(1)` Shell. The most notable shells today include: the Almquist shell `ash(1)`, a BSD-licensed replacement for the Bourne shell, frequently installed as `/bin/sh` on these systems; the GNU Project's Bourne-again shell `bash(1)`, which is the default shell on most Linux systems and known for a large number of added features; the Korn shell `ksh(1)`, named after David Korn and which became the basis for the POSIX shell standard; the TENEX C shell `tcsh(1)`, a C shell variant developed at Carnegie Mellon University; and perhaps the Z shell `zsh(1)` another very feature rich Bourne shell variant.

As a scripting language and due to its availability on virtually every Unix flavor, `/bin/sh` is assumed to be the lowest common denominator: a Bourne- or Bourne-compatible shell. On Linux, `bash(1)` is typically installed as both `/bin/bash` and `/bin/sh`, and it behaves (somewhat) accordingly based on how it was invoked. Unfortunately, though, its ubiquity on Linux systems has led to a shell scripts masquerading as `/bin/sh` compatible scripts that are, in fact, making use of `bash(1)` extensions or rely on `bash(1)` compatibility and syntax. This becomes frustrating to debug when trying to run such scripts on a platform with a POSIX compliant `/bin/sh`.

All Unix shells include the ability to perform I/O redirection. Each program has a set of input and output channels that allow it to communicate with other programs. Like the concept of the pipe, these streams have been part of Unix's design from early on and contribute significantly to the consistent user interface provided by all standard tools: a program accepts input from *standard input* (or `stdin`) and generates output on *standard output* (or `stdout`); error messages are printed to a separate stream, *standard error* (or `stderr`).

The shell allows the user to change what these streams are connected to; the most trivial redirections are the collection of output in a file, the suppression of output, acceptance of input from a file, and of course the connection of one program's output stream to another program's input stream via a pipe (see Listing 2.1 for Bourne-shell compatible examples).

The concept of these simple data streams being provided by the operating system was inherent in the Unix philosophy: it provided abstraction of interfaces, reduced overall complexity of all tools using these interfaces, and dictated a simple text stream as the preferred means of communication. We will have more to say on the Unix philosophy in Section 2.2.4.

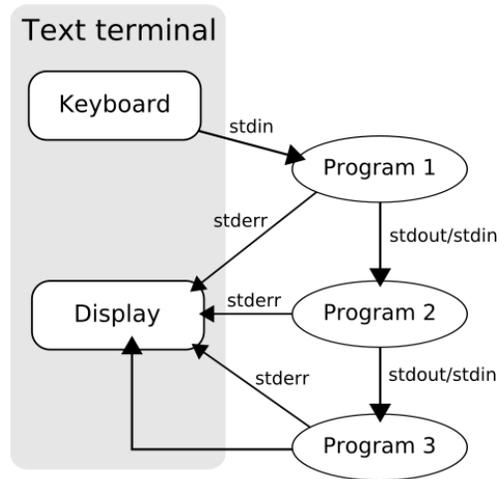


Figure 2.2: Standard streams in a simple pipeline

Finally, the unix shell provides for *job control*, a necessity for a multitasking operating system. When a user logs into the system, their *login shell* is started, serving as the primary interface between the user and the OS. After entering a command or a pipeline, the shell will create (“fork”) a new process and then execute the given programs. The standard streams are connected as illustrated in Figure 2.2. While the program or pipeline is running, the user cannot do anything else – she has to wait until the command completes and control is returned to the shell. In the mean time, all she can do is twiddle her thumbs; so much for multitasking!

To avoid this scenario, the C shell implemented a feature that was quickly incorporated in the Bourne shell, which allows users to start and control multiple concurrent processes by placing them into the *background* (by adding the `&` symbol at the end of the command or via the shell `builtin`s), bringing them to the *foreground* (via `builtin`s), suspending and continuing them (by sending possibly keyboard generated signals to the relevant process group), etc. Listing 2.2 illustrates the basic job control functionality.

```

$ cmd1 &                # send cmd1 to the background
[1] 5836                # report job number and process ID
$ cmd2 | cmd3 &        # send a process group to the background
[2] 5912
$ jobs                  # report on running jobs
[1]  Running          cmd1
[2]  Running          cmd2 | cmd3
$ fg %1                 # bring job 1 to the foreground
cmd1
^Z                       # suspend via Control+Z
[1]+ Stopped          cmd1
$ bg                    # send it back to the background
[1]+ cmd1
$                        # hit return again...
[1]+ Done             cmd1
$                        # cmd1 has completed

```

Listing 2.2: Simple job control in the shell

## 2.2.2 Manual pages and documentation

Another important feature of the Unix operating system was that it included what came to be known as the “online manual pages”<sup>18</sup>, reference documentation readily available on the running system and that went beyond just attesting to the existence of a command or feature, but instead provided actually useful information, including the correct invocation, possible options, a description of the tool’s functionality as well as any known bugs. Divided into several sections by topic, system calls are documented in section two, library functions in section three, while commands and executables are usually documented in section one for general purpose tools and section eight (on BSD, section 1M on SysV derived systems) for system administration related commands and daemons.

The standard for this documentation has always been high, reflecting the academic culture behind the operating system. Rather than treat the user as a naive consumer, Unix documentation acknowledges the fact that the target audience consists of skilled engineers who appreciate and require an accurate description of the tools at their disposal in order to make the most of them. It may not surprise you to know that the adoption of Unix within

<sup>18</sup>In Unix’s historic context, “online” initially meant that the documentation is available on the running system, not “on the Internet”.

the Bell Labs patent office, which secured funding for further development, was largely thanks to the system's abilities to typeset beautiful documents using the *roff* text formatting program<sup>19</sup>. The same tools are still used to format the manual pages.

Unix provided manual pages and documentation not just of the executables and configuration files provided by the system, but also for so-called “supplementary” documents. These comprise a number of papers that, as in the case of the Interprocess Communication (IPC) tutorials, for example, served as the de-facto reference documentation and continue to be used in countless Computer Science classes today to teach students the fundamentals of Unix IPC. Other highlights include an introduction to the GNU debugger *gdb*, the *make* tool, a *vi(1)* reference manual, an overview of the file system, and various *dæmons*. Since these documents are licensed under the permissive BSD License, they can be – and thankfully are! – included in modern Unix versions (such as e.g. NetBSD) and made available on the Internet[19].

### Understanding the Shell



A System Administrator spends a significant amount of time in the shell, both her own login shell as well as various others. Not only does she need to run countless commands to remotely administrate various hosts, she also routinely writes small, large, complex, simple, elegant or convoluted scripts to accomplish any thinkable task. It is therefore imperative to understand how the

Unix shell works on a detailed level. It is surprising how frequently the many intricacies of I/O redirection, of job control and pipelines, of aliases and *builtins* taking precedence over commands, as well as other seemingly obscure problems manifest themselves.

If you have a background in C programming, consider writing a general purpose Unix shell from scratch – it will teach you invaluable lessons about how the system works on a very fundamental level. (If you do not have a background in C programming... develop one!)

---

<sup>19</sup>Consider that W. Richard Stevens used to typeset his famous books “Advanced Programming in the UNIX Environment” and the “TCP/IP Illustrated” series by himself using *groff(1)*.

### 2.2.3 A portable, multitasking, multiuser system

The Unix operating system was, from the very beginning, designed as a *portable, multitasking, multiuser* system. These inherent features are largely responsible for the incredible success of this over 40 year old system and each has wide-reaching consequences. Initially developed on a PDP-7 and then a PDP-11 machine, Unix was rewritten in the C programming language, which allowed it to be ported with comparatively little effort to various other machines and hardware architectures. Figure 2.3 shows a few different hardware platforms, each running a version of Unix. Prior to this, operating systems were written in assembly, and that was that – only a fool would attempt otherwise! But as a result of this bold move to stray from convention and instead to apply a fundamental design choice of abstraction of complexity, the system became inherently portable: software *for* Unix – any Unix, really – can usually be adapted to other Unix flavors with few modifications.

Now, to state that Unix is *portable* does not mean that one can trivially recompile the software without any changes – far from it! Any System Administrator can relate stories of having spent hours wrangling Makefiles, `autoconf/automake` frameworks, and hunting down header files and libraries. But in the end, it remains relatively easy to get the software to work, since all Unix systems follow (to some degree, anyway) certain standards and conventions. Consider the effort of adapting a complex piece of software from running on Linux to, say, IRIX to that from running on Windows 95 to Mac OS 9! Unix having been rewritten in the higher level C programming language, the standardization of C, as well as the POSIX guidelines really allowed a world of portable, flexible software to flourish.

The *multitasking* nature of the Unix operating system was a given, as it was intended to be a time-sharing system, allowing multiple processes to use the given resources seemingly simultaneously by means of a scheduler which initiates context switches to grant each process time on the Central Processing Unit (CPU). Allowing for multiple (simultaneous) users was just a logical consequence. Nowadays it may not seem worth mentioning, but it is worth noting that this system, conceived to allow multiple users simultaneous access was designed over 40 years ago. In comparison, Windows NT, first released in 1993, was the first of Microsoft's family of operating systems to eventually introduce multiuser capabilities, around 20 years later; Apple's Mac OS gained multiuser capabilities only with OS X in 2001.

The nature of a *multiuser* system has a number of significant implications:



Figure 2.3: Different systems and architectures running Unix. A VAX-11 by DEC (VAX), an O2 by SGI (MIPS), a Mac Mini by Apple (PowerPC), PowerEdge servers by Dell (x86).

A system that allows multiple users to simultaneously utilize the given resources is in need of a security model that allows for a distinction of access levels or privileges. The system needs to be able to distinguish between file access or resource utilization amongst users, thus requiring the concept of access permissions, process and file ownership, process priorities and the like. Controlling access to shared resources by individual users also required, effectively, a single omnipotent user to control and administer these privileges, thus necessitating the superuser or *root account* (with plenty of security implications and concerns of its own).

In order to meet these requirements, the Unix system uses a set of file permissions to restrict three different types of access – read, write and execute (or *rwX*, respectively) – to the file *owner* or *user*, members of a specific user *group*, or everybody else (i.e., *others*) on the system (*ugo*, respectively).

These permissions can be used to implement efficiently various security models, but at the same time they are simple and flexible enough to allow users to make their own choices.<sup>20</sup>

Unix has a long tradition of following the *principle of least privilege*: system services are usually run using a dedicated user account, allowing the System Administrator to separate file access and resource usage such that even if the service was compromised, harm would be minimized. This practice translates to routine tasks in system administration and standard operating procedures alike. We will revisit this concept in more detail in Chapter 11.

Processes, like files, are associated with individual users, though privilege escalation can be accomplished by means of changing the *effective user ID*. Processes also may have specific resource limitations, which the superuser can set system-wide or on a per-user or per-group basis. We will revisit the associated system calls and commands like `getrlimit(2)`, `sysctl(8)`, `ulimit(1)`, and *login classes* (see `login.conf(5)`, where available) in Chapter 14 and elsewhere.

## 2.2.4 The Unix Philosophy

The design of the Unix operating system was based on principles that not only have been proven time and again to lead to stable, scalable and robust solutions, but that have formed the basis of a specific Unix culture, a way of doing things that speaks to advanced users such as System Administrators in particular. You can find a thorough explanation of this culture in classic texts such as Kernighan and Pike’s “The UNIX Programming Environment” [4], Eric S. Raymond’s “The Art of Unix Programming” [5], or simply by searching the Internet for the term “Unix philosophy”, but it warrants summarizing due to the profound impact it has.

At its core, the Unix philosophy stipulates that tools should be kept simple and adhere to specific simple guidelines and implement an equally simple interface (namely text streams). Virtually every one of the great minds involved in the initial invention and continued development of the Unix operating system – from Douglas McIlroy to Rob Pike, from Dennis

---

<sup>20</sup>Different Unix versions have since developed support for extended file attributes including e.g. a per-file Access Control List (ACL), allowing the user to wield more fine-grained control. This is implemented on different operating systems and in different file systems, and the details and semantics differ. In the interest of simplification and focusing on the fundamental principles, we are not covering ACLs.

Ritchie to Ken Thompson – can be quoted to underline this point; they must have been on to something.

The most well-known expression of what makes Unix Unix is probably Douglas McIlroy’s summary[24], partially cited in the previous chapter:

*Write programs that do one thing and do it well. Write programs to work together. Write programs to handle text streams, because that is a universal interface.*

This is frequently succinctly described as the KISS (“Keep it simple, stupid”) principle and correlated with Richard P. Gabriel’s “Worse is Better”[25] design philosophy, according to which simplicity is to be preferred over all other attributes of software, at times even including correctness. While I do not tire of repeating precisely this advice, I believe that the existing literature tends to overlook, one major factor that helped arrive at the mantra of simplicity: deference to the user.

One of the smartest insights a program or system developer can have is that even though they are the person writing the software, they cannot foresee all possible uses of the software. They cannot know what the user will want to accomplish or in what ways she may wish to use the tool. And therein lies the crux: if I wish to enable the user to utilize the tool in any way they wish, how can I possibly keep it simple? Wouldn’t it have to end up being a general purpose tool, with countless inherent complexities as I attempt to anticipate every interface of the future? Remember, a “general purpose product is harder to design well than a special-purpose one.”[26]

This is where the Unix philosophy comes in: by imposing restrictions, it counterintuitively opens up the most flexible, the widest use. Simple tools that perform a single task and operate on a well-defined interface are less complex than software that attempts to keep state in deeply nested data structures (or, worse yet: binary objects stored in files). Our users gain the ability to use the tools for purposes we did not initially anticipate. Unix grants the user flexibility. For better or worse, Unix trusts its users to know what they’re doing and will happily let you shoot yourself in the foot.

*UNIX was not designed to stop its users from doing stupid things, as that would also stop them from doing clever things. – Doug Gwyn*

The awareness that your software might be used in ways you cannot imagine, that the user of the software might actually know better what they may wish to accomplish than the designer or implementer is what makes Unix so fascinating. Interestingly, this philosophy, this trust into the user and his or her capabilities and knowledge stands in stark contrast to that of the late Steve Jobs, who famously quipped that “people don’t know what they want until you show it to them”[27]. Apple’s products are known for their elegance and ease of use, but advanced users know that should you attempt to do something with them that the designers did not anticipate, it’s either impossible or painfully cumbersome.

The primary user interface on the Unix systems remains the command-line. This is not for a lack of other options, but a manifestation of the Unix philosophy. While it may appear more “user-friendly” to a novice to use a pointing device to select pre-determined options from a menu using a Graphical User Interface (GUI), it is anathema to efficient System Administration.

System Administrators need to be able to perform tasks remotely, quickly, and reliably unattended; execution of programs needs to be automated and scheduled, configuration be done outside of the application, and data be transformed with the myriad of available filters. As you can tell, these requirements go back to the Unix way of writing simple tools that work well together by communicating via text streams. Thanks to the consistency with which these principles are implemented across the platform, the learning curve for advanced users, while perhaps steeper than on some other systems, only needs to be climbed once. At the same time, it gets you to a higher level of efficiency quickly.

The ability to combine individual tools to build larger, more complex ones; to remotely access hundreds or thousands of systems in the same manner as one would a single system; to allow rapid development of simple prototypes constructed of growing pipelines; to be able to control access to shared resources following a simple yet flexible security model; to extend and tune the operating system itself; to be able to do all the things that the designers of the system could not have envisioned you doing – this power is what Unix confers upon the advanced user. It is why System Administrators not only prefer Unix, but actually enjoy working on this platform.

```
Copyright (c) <year>, <copyright holder>
All rights reserved.

Redistribution and use in source and binary forms, with or
without modification, are permitted provided that the
following conditions are met:

1. Redistributions of source code must retain the above
   copyright notice, this list of conditions and the
   following disclaimer.
2. Redistributions in binary form must reproduce the
   above copyright notice, this list of conditions and
   the following disclaimer in the documentation and/or
   other materials provided with the distribution.

THIS SOFTWARE IS PROVIDED BY THE COPYRIGHT HOLDERS AND
CONTRIBUTORS "AS IS" AND ANY EXPRESS OR IMPLIED
WARRANTIES, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED
WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR
PURPOSE ARE DISCLAIMED. IN NO EVENT SHALL THE COPYRIGHT
OWNER OR CONTRIBUTORS BE LIABLE FOR ANY DIRECT, INDIRECT,
INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES
(INCLUDING, BUT NOT LIMITED TO, PROCUREMENT OF SUBSTITUTE
GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR
BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY
OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR
TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY
WAY OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF
THE POSSIBILITY OF SUCH DAMAGE.

The views and conclusions contained in the software and
documentation are those of the authors and should not be
interpreted as representing official policies, either
expressed or implied, of <the project>.
```

Listing 2.3: The simplified, or 2-clause, BSD license. Nice and terse, huh? In contrast, the GNU's Not Unix (GNU) GPL clocks in at 11 full text pages.

# Problems and Exercises

## Problems

1. Research the history of the Unix operating system in more detail. Branch out into the “USL vs. BSDi” lawsuit. Follow the BSD genealogy into the Mac OS X system. Analyze the future direction of the commercial Unix versions.
2. Review the Linux, NetBSD and Solaris versioning numbers. Try to correlate specific features to specific releases across these systems (note the different Linux distributions numbers as well).
3. Review the `intro(1)` manual pages on your system (they may exist for different sections and, depending on the Unix flavor, in varying detail). From there, move on to the following manual pages, considering the multiuser implications: `chmod(1)/chown(1)`, `login(1)`, `passwd(5)`, `su(1)`, `sudo(8)`
4. Does the POSIX standard really require a `cd(1)` *executable*? If it did, what might be a problem with that? Consider the environment of a process and how a shell executes commands.
5. Play around in the Unix environment of your choice. Look at the executables found in the system’s path (`/bin`, `/usr/bin`, `/sbin`, `/usr/sbin`) – do you know what all these tools do?
6. Review your understanding of the Unix philosophy of simple tools acting as filters. Does this reflect your usage of the tools you most frequently execute? Which tools do *not* work (well) as a filter? Why?

7. Research the design decisions underlying other popular operating systems. In how far do they differ from those presented here? Do they influence or reflect the primary user base (i.e., what is cause and what is effect)? How do they affect or relate to System Administration, especially on a large scale?

## Exercises

1. Using the programming language of your choice, write a simple interactive shell capable of executing programs on the user's behalf. Try to use it as your shell. Were you aware of the limitations before you did this? Were you aware of the complexity of even basic features?
  - (a) Compare your shell to some of the existing implementations. What features are missing from your shell? How difficult do you think would it be to implement them?
  - (b) Add additional features to your shell, such as support for input/output redirection, pipelines, expansion of environment variables or job control. (Note: this is a *significant* project, but you will learn a great deal about the Unix operating system in the process.)
  - (c) Research and review the concept of a *restricted shell*. Would writing such a shell be *more* or *less* effort to do?

## Bibliography

- [1] TOP500; on the Internet at <https://www.top500.org/statistics/list/> (visited January 16, 2017)
- [2] *The Creation of the UNIX Operating System*, on the Internet at <http://www.bell-labs.com/history/unix/> (visited January 7, 2012)
- [3] Dennis M. Ritchie, 'The Evolution of the Unix Time-sharing System', published in *AT&T Bell Laboratories Technical Journal*, "Computing Science and Systems: The UNIX System," 63 No. 6 Part 2, October 1984; also available via the Internet Archive at e.g. <https://web.archive.org/web/20150408054606/http://cm.bell-labs.com/cm/cs/who/dmr/hist.html> (visited January 17, 2017)
- [4] Brian W. Kernighan, Rob Pike, *The UNIX Programming Environment*, Prentice Hall, 1984
- [5] Eric Steven Raymond, *The Art of Unix Programming*, Addison-Wesley Professional, September 2003; also available on the Internet at <http://catb.org/~esr/writings/taoup/> (visited January 7, 2012)
- [6] The Unix Heritage Society Mailing List, <http://minnie.tuhs.org/mailman/listinfo/tuhs>
- [7] Douglas Adams, *The Hitchhiker's Guide to the Galaxy*, Pan Books, 1979
- [8] Brian W. Kernighan, Dennis M. Ritchie, *The C Programming Language*, Prentice Hall, 1988
- [9] Dennis M. Ritchie, 'Advice from Doug Mcilroy'; now only found on the Internet Archive at <https://web.archive.org/web/20150205024833/http://cm.bell-labs.com/cm/cs/who/dmr/mdmpipe.html>
- [10] Douglas McIlroy, *A Research UNIX Reader: Annotated Excerpts from the Programmer's Manual, 1971-1986*; on the Internet at <http://www.cs.dartmouth.edu/~doug/reader.pdf>
- [11] 'USL vs. BSDI documents', only available on the Internet Archive via e.g. <https://web.archive.org/web/20150205025251/http://cm.bell-labs.com/cm/cs/who/dmr/bsdi/bsdisuit.html> (visited January 18, 2017)

- [12] 'What would you like to see most in minix?', Linus Torvalds, posting to the `comp.os.minix` newsgroup on Usenet, on the Internet at <https://groups.google.com/group/comp.os.minix/msg/b813d52cbc5a044b> (visited January 16, 2012)
- [13] *BSD Licenses* on Wikipedia at [https://en.wikipedia.org/wiki/BSD\\_licenses](https://en.wikipedia.org/wiki/BSD_licenses) (visited January 18, 2017)
- [14] Éric Lévénez, *Unix History*, on the Internet at <http://www.levenez.com/unix/> (visited January 5, 2012)
- [15] The IEEE and The Open Group, "The Open Group Base Specifications Issue 7, IEEE Std 1003.1, 2016 Edition" on the Internet at <http://pubs.opengroup.org/onlinepubs/9699919799/> (visited January 17, 2017)
- [16] Andrew S. Tanenbaum, in 'Computer Networks', Prentice Hall, 2004
- [17] `fcntl(2)`, NetBSD System Calls Manual, on the Internet at <http://netbsd.gw.com/cgi-bin/man-cgi?fcntl++NetBSD-current> (visited January 18, 2017)
- [18] NetBSD system call name/number "master" file, on the Internet at <http://cvsweb.netbsd.org/bsdweb.cgi/src/sys/kern/syscalls.master?rev=HEAD> (visited January 18, 2017)
- [19] 4.4 Berkeley Software Distribution Documentation, on the Internet at <http://www.netbsd.org/docs/bsd/lite2/> (visited January 28, 2012)
- [20] Vinton G. Cerf, Robert E. Kahn, "A Protocol for Packet Network Intercommunication", IEEE Transactions on Communications 22 (5); also available on the Internet at <http://ece.ut.ac.ir/Classpages/F84/PrincipleofNetworkDesign/Papers/CK74.pdf> (visited January 28, 2012)
- [21] DNS server survey, 2004; on the Internet at <http://mydns.bboy.net/survey/> (visited February 4, 2012)
- [22] Mail (MX) Server Survey, August 1st, 2007, showed over 60% of SMTP traffic to originate from a Sendmail, Exim, or Postfix installation; on the Internet at [http://www.securityspace.com/s\\_survey/data/man.200707/mxsurvey.html](http://www.securityspace.com/s_survey/data/man.200707/mxsurvey.html) (visited February 4, 2012)

- [23] January 2017 Web Server Survey, on the Internet at <https://news.netcraft.com/archives/2017/01/12/january-2017-web-server-survey.html> (visited January 18, 2017)
- [24] M. D. McIlroy, E. N. Pinson, and B. A. Tague *Unix Time-Sharing System Forward*, The Bell System Technical Journal. Bell Laboratories, 1978
- [25] Richard P. Gabriel, “Worse is Better”, on the Internet at <http://dreamsongs.com/RiseOfWorseIsBetter.html.html> (visited February 5, 2012)
- [26] Frederick P. Brooks, Jr., *The Design of Design*, Addison-Wesley Professional, 2010
- [27] Steven P. Jobs, as quoted in BusinessWeek (25 May 1998)
- [28] Peter H. Salus, *A Quarter Century of UNIX*, Addison-Wesley Professional, 1994
- [29] The Unix Heritage Society, *The Unix Archive*, on the Internet at <http://www.tuhs.org/Archive/README> (visited April 11, 2012)