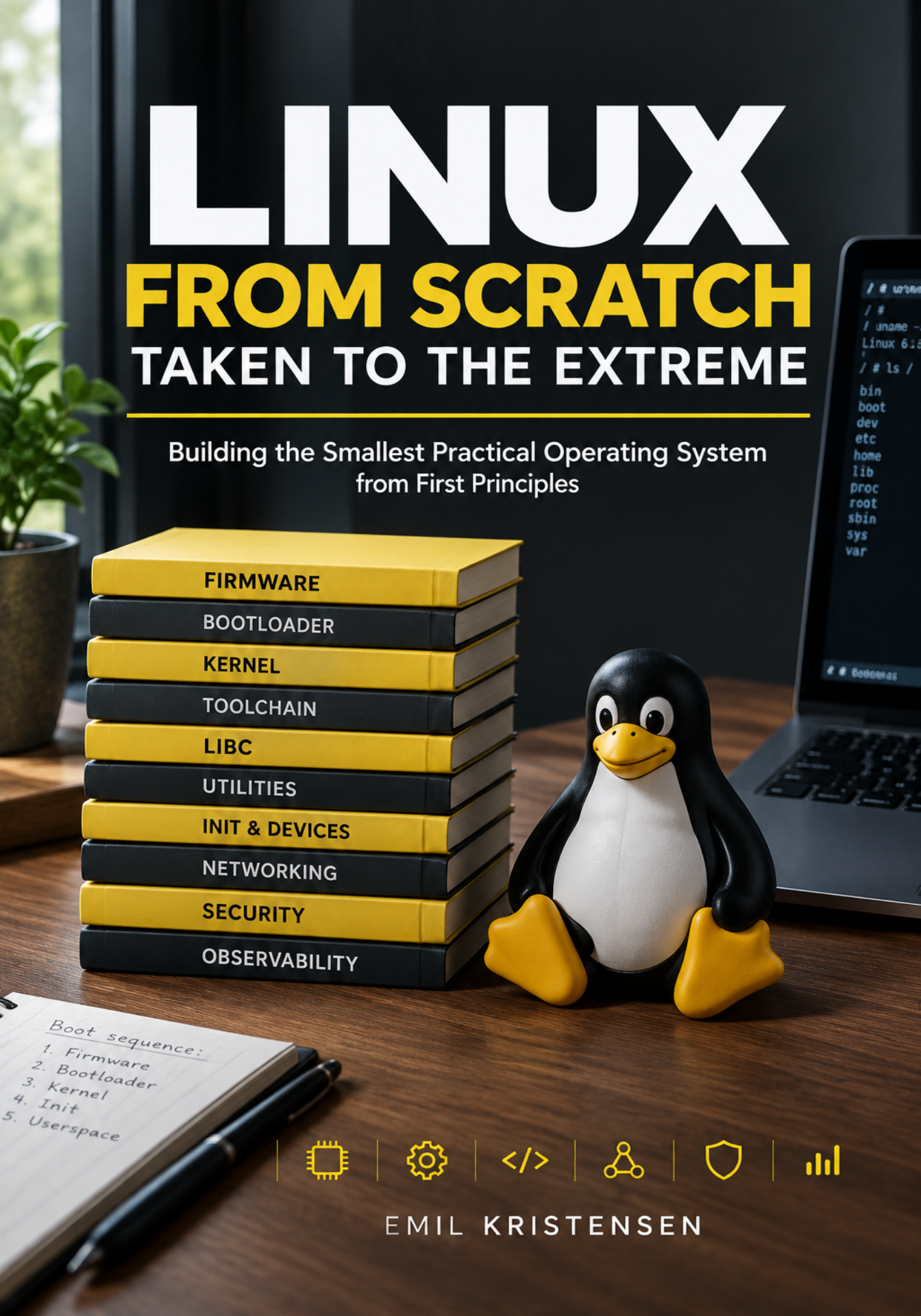
LINUX FROM SCRATCH TAKEN TO THE EXTREME

Building the Smallest Practical Operating System from First Principles



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Linux From Scratch: Taken to the Extreme

Building the Smallest Practical Operating System from First Principles

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Contents

Building the Smallest Practical Operating System from First Principles

This book builds an exceptionally minimal Linux system from the ground up: firmware, bootloader, kernel, toolchain, libc, core utilities, init, device management, networking, security, and observability. Each chapter explains not only how to configure and build every component, but why it exists, what problem it solves, what the kernel expects from it, what depends on it, what happens if it is removed, and what alternatives are possible. The reference system targets x86-64 hardware or QEMU emulation, uses the Linux 6.8 LTS kernel, musl libc, and BusyBox, and is constructed with fully reproducible, copy-pasteable build scripts. By the end, you will have both a working minimal Linux system and a deep mental model of how Linux boots, executes programs, manages resources, exposes kernel functionality, and can be systematically reduced to the smallest practical configuration for any given workload.

Introduction

A modern Linux distribution ships with hundreds of megabytes of software: package managers, desktop environments, sound servers, display managers, cron daemons, log analyzers, localization data for dozens of languages, and thousands of header files for hardware you do not own. None of it is strictly necessary. The kernel needs almost nothing from userspace to be useful. The only requirement is that something runs as process ID 1, that /proc and /sys are mounted so programs can inspect the system, that /dev exists so programs can talk to hardware, and that at least one executable binary can load and run.

You can build a complete Linux system that fits in 20 megabytes. You can build one that boots in less than a second on a modest machine. You can build one that exposes almost no attack surface because there is almost nothing to attack.

This is not academic. Embedded devices run minimal Linux. Rescue environments run minimal Linux. Containers run minimal Linux. Security-conscious operations teams build minimal Linux images for their most sensitive workloads. Anyone who wants to understand what Linux actually requires, rather than what a distribution chooses to provide, benefits from constructing a system from first principles.

What This Book Does

This book takes you through the complete construction of a single reference system, from the toolchain that compiles its components to the final bootable image. The system targets x86-64 architecture and is designed to run either on real hardware or in QEMU. We use the Linux 6.8 LTS kernel for its stability and documentation quality, musl as the C library for its small footprint and clean design, and BusyBox for its ability to provide dozens of standard utilities in a single binary.

Every chapter covers one aspect of the system. Each chapter explains what that aspect is, why it exists, what alternatives exist, and what would happen if you removed it or replaced it with something different. Configuration files and

build scripts are complete and internally consistent across chapters so that the examples form one coherent working system rather than a collection of unrelated snippets.

The book assumes you already know how to use Linux. You are comfortable with the command line, you understand basic networking concepts, you have compiled software from source at least once, and you do not need hand-holding. The assumption is also that you want to understand mechanisms, not just follow instructions: why the kernel behaves the way it does, how ELF binaries get loaded, what fork and exec actually accomplish, how namespaces isolate processes, what happens at each stage of the boot sequence.

The Reference System

The reference system is designed around specific principles:

- **Correctness over cleverness**: We choose approaches that work reliably, not approaches that squeeze out the last few kilobytes at the cost of maintainability.
- **Reproducibility**: Build scripts are deterministic. The same source code and toolchain produce identical output.
- **Minimalism without fragility**: We remove what is unnecessary, but we keep error handling, logging, and observability so that when something breaks you can find out why.
- **Practical utility**: The system is not just a demonstration. It has a working shell, networking, user authentication, and the ability to run arbitrary programs.

The reference system has these characteristics when fully built:

- Kernel: Linux 6.8, configured with only the subsystems needed for QEMU x86-64 emulation, ext4 filesystem support, networking, and basic console I/O.
- Userspace: musl libc as the runtime library, BusyBox configured for a minimal set of utilities, a custom init script as the first process.
- Storage: A single ext4 root filesystem on a virtual disk, plus a compressed initramfs for early boot.

- Networking: A single virtual network interface configured with a static IP address, DNS resolution via a minimal configuration.
- Security: Kernel address space layout randomization enabled, capabilities restricted, no unnecessary services running, seccomp profiles applied where practical.

Throughout the book we will compare this reference path with alternatives. We will discuss why glibc might be chosen instead of musl in some environments, why systemd might be preferred over our minimal init script, why GRUB might be more appropriate than direct kernel boot, and why ext4 might be replaced with XFS or Btrfs for specific workloads. The goal is that you understand the tradeoffs well enough to make informed choices for your own systems.

What You Will Know After Reading

By the end of this book you will understand:

- How the firmware and bootloader hand control to the Linux kernel.
- How to configure and compile a kernel that includes only what you need.
- How ELF binaries are structured and loaded, how the dynamic linker resolves symbols, and how the kernel transitions control to userspace.
- How to build a complete toolchain from source, how cross-compilation works, and how to ensure reproducible builds.
- What the C standard library actually does, why musl is different from glibc, and when each is appropriate.
- How dynamic linking works, what the PLT and GOT are, why lazy binding exists, and when static linking is actually a better choice.
- How BusyBox packs dozens of utilities into one binary and how to configure it for your needs.
- What an initramfs is, why we need one, and how to construct a minimal one that boots the real root filesystem.
- What the first process must do, how different init systems approach service supervision, and how to write a minimal init.
- How Linux exposes hardware and kernel state through /dev, /proc, /sys, and /run.
- How filesystems are chosen, formatted, and mounted, and what the minimal directory hierarchy actually requires.

- How process creation works through fork, exec, and clone, and how signals flow through the system.
- How virtual memory is mapped, how page faults are handled, and how the page cache and slab allocator manage memory.
- How namespaces and cgroups enable containerization, and how to build the absolute minimum container environment.
- How networking is configured, how DNS resolution works, and how time synchronization is maintained.
- How kernel hardening options, capabilities, and seccomp reduce attack surface.
- How to observe system behavior through strace, ftrace, and eBPF, and how to debug boot failures.
- How to systematically reduce a working system without breaking it, and what the true minimum is for different workloads.
- How to package the system into bootable images, maintain it over time, and manage upgrades and rollback.

How to Use This Book

Read the chapters in order. Each chapter builds on concepts from earlier chapters, and the reference system accumulates components progressively. You can follow along by running the build scripts and commands on your own machine, using QEMU to test each stage. If you prefer to understand the theory before the practice, you can read through for the mental model and then return to build the system.

Some chapters are deeper than others. The chapters on ELF, dynamic linking, and kernel internals go into significant technical detail. The chapters on filesystem hierarchy and service supervision are more pragmatic. All of them share the same goal: helping you understand how Linux actually works, rather than how a distribution presents it.

If you encounter something that does not make sense, look at the specific commands or configurations presented, trace through what they do, and experiment with changing them. The best way to understand a system is to break it and see what happens.

A Note on Versions

The reference system uses Linux kernel 6.8 LTS. Kernel interfaces are stable, but details change. If you are following along with a different kernel version, pay attention to version-specific notes in the text. Similarly, musl and BusyBox evolve. The build scripts and configurations work for specific versions, but the concepts are version-independent. When in doubt, check upstream documentation.

The tools and techniques described here apply to any reasonably modern Linux kernel. Many of the kernel behaviors discussed have been stable for a decade or more. The goal is that you finish with understanding that outlasts the specific versions we happen to use.

Chapter 1: The Minimal System Problem

Why Smaller Matters

A minimal Linux system is not a parlor trick. It is a practical necessity in several domains.

Embedded systems have hard constraints on memory, storage, and power. An IoT sensor node might have 64 megabytes of RAM and 256 megabytes of flash. A standard distribution image would not fit. More important than fitting, the system must boot quickly, consume little power while idle, and expose as little as possible to the network. Each megabyte of code is a megabyte that could contain bugs or vulnerabilities.

Security-conscious deployments benefit from minimization. The principle of least privilege extends to software: if a service does not exist, it cannot be compromised. Removing unused services, unused network ports, and unused kernel modules reduces attack surface. A system with fewer components is easier to audit and easier to reason about when things go wrong.

Boot time is critical in virtualized and cloud environments. A container that starts in milliseconds instead of seconds changes the economics of scaling. The time between powering on a system and being able to run the actual workload depends on how much unnecessary work the system performs during startup.

Reproducibility and supply chain security favor smaller systems. A minimal system has fewer dependencies, and each dependency is a point where trust must be placed in someone else's code. Fewer dependencies mean fewer opportunities for supply chain attacks. Reproducible builds are easier to verify when the build graph is small.

What Minimal Actually Means

Minimalism is not about making the smallest possible system at any cost. It is about building a system that is correct for its purpose, with no unnecessary

components.

There is an important distinction between required functionality and convenient functionality. Required functionality is what the kernel and userspace need to perform their basic operations: process creation, memory management, file I/O, networking, device access. Convenient functionality is what makes the system pleasant to use: a nice editor, a package manager, extensive logging, multiple shells.

A system is minimal when every component it contains is required for its intended purpose. If you can remove a component and the system still does what it is supposed to do, that component is not required. The key phrase is "supposed to do": a system that is supposed to provide an interactive shell requires more than a system that is supposed to forward network traffic.

This creates a hierarchy of minimality:

- **Absolute minimum**: The smallest system that can boot and run a program. A kernel, a single executable, nothing else. This is interesting but useless.
- **Functional minimum**: A system that can boot, run programs, manage processes, access storage and networking. This is what we will build as our baseline reference system.
- **Workload-specific minimum**: A system optimized for a particular purpose: a firewall, a web server, a container host, a rescue environment. Each adds only what is required for that workload.

Throughout this book we will explore this hierarchy. We will start with the functional minimum and then show how to extend or reduce it for specific purposes.

The Dependency Chain

Understanding minimality requires understanding dependencies. Every component in a Linux system depends on other components, and removing a dependency breaks everything that depends on it.

At the lowest level is the kernel. The kernel requires hardware or a hardware emulator. It provides the fundamental abstractions: processes, memory,

filesystems, devices, networking. Nothing in userspace can do its job without the kernel.

Above the kernel is the C library. Most userspace programs are written in C and linked against a C library that wraps kernel system calls and provides standard APIs. The choice of C library affects everything that runs on top of it. glibc is the most common choice but also the largest. musl is smaller and simpler but has different compatibility characteristics.

Above the C library are core utilities: a shell, a file manager, process management tools, networking tools. BusyBox provides most of these as a single binary. Individual GNU utilities provide more complete implementations of each tool.

Above utilities is init, the first process. Init starts other processes, mounts filesystems, handles system shutdown, and reaps zombie processes. The choice of init affects how services are managed and how the system responds to failures.

Above init are services: the actual workloads. A web server, a database, a network daemon. These depend on everything below them.

Each layer can be minimized independently, but you cannot minimize a layer without considering what depends on it. Removing a kernel feature that a userspace program relies on breaks that program. Removing a C library function that a program calls breaks that program. Removing init's ability to start services means services do not start.

The dependency chain also runs horizontally: components at the same layer depend on each other. A shell depends on being able to read configuration files from /etc. A networking daemon depends on the kernel's network stack and on being able to bind to network interfaces. DNS resolution depends on /etc/resolv.conf and on the kernel's networking capabilities.

Reference System Overview

The reference system we will build targets x86-64 architecture and is designed to run in QEMU. This choice makes the system reproducible: anyone with QEMU can boot it without special hardware. The system uses:

- **Linux kernel 6.8 LTS**: A stable, well-documented kernel with long-term support.

- **musl libc**: A lightweight C library designed for minimal systems and static linking.
- **BusyBox**: A multi-call binary providing essential Unix utilities.
- **Custom init script**: A minimal shell script that performs early boot tasks.
- **ext4 root filesystem**: A reliable, widely supported filesystem.
- **QEMU x86-64 emulation**: A reproducible execution environment.

The system will have these capabilities when complete:

- Boot in under two seconds on modern hardware.
- Provide an interactive login shell.
- Have a working network interface with DNS resolution.
- Support user authentication via /etc/passwd and /etc/shadow.
- Run arbitrary statically or dynamically linked executables.
- Support basic file operations, process management, and shell scripting.
- Log system events to a file.
- Shut down cleanly when requested.

The system will not have:

- A package manager.
- A desktop environment or graphical server.
- Sound support.
- Wireless networking.
- Encryption or secure boot.
- A database server.
- Any service not explicitly required.

This is not arbitrary. Each exclusion is deliberate: the capability is not required for the reference system's purpose, which is to demonstrate a functional minimal Linux system.

Measuring Minimality

To claim that a system is minimal, we must be able to measure it. Several metrics are useful:

- **Disk image size**: The total size of the bootable image. This measures how much storage the system requires.
- **Memory footprint**: The amount of RAM used at idle. This measures how much memory the system consumes when not doing useful work.
- **Boot time**: The time from power-on to a usable state. This measures how fast the system becomes operational.
- **Binary size**: The size of individual executables. This measures the overhead of each component.
- **Component count**: The number of distinct software packages. This measures complexity.
- **Attack surface**: The number of network services, kernel modules, and privilege escalation paths. This measures security exposure.

We will track these metrics throughout the book. The goal is not to minimize every metric simultaneously (that is impossible; reducing boot time may increase memory usage, for example) but to show how choices affect these metrics and how to trade off between them based on your requirements.

The reference system targets these approximate metrics:

- Disk image size: 20-50 MB for the complete bootable image.
- Memory footprint: 30-80 MB at idle with a shell running.
- Boot time: Under two seconds on a modern x86-64 machine.
- Binary count: Fewer than 50 distinct binaries, with BusyBox providing most of them.

These numbers are achievable without heroic effort. The key is understanding what is actually required and building only that.

Chapter 2: Reference Architecture and Build Environment

Choosing a Platform

We target x86-64 (also known as AMD64) as the reference architecture. This is a deliberate choice, not the only possible one.

ARM is now ubiquitous in embedded systems and mobile devices. If this book were focused exclusively on embedded targets, ARM would be the natural choice. But x86-64 has advantages for learning and development: virtually every developer has access to x86-64 hardware, the architecture is well-documented, QEMU provides excellent emulation support, and most documentation and examples assume x86-64. The concepts we cover apply equally to ARM and RISC-V, but the specific configuration values and some kernel options differ.

For hardware, we use QEMU (Quick Emulator) as the primary execution platform. QEMU emulates x86-64 systems at the instruction level, allowing us to boot and test our kernel and userspace without physical hardware. The advantages are:

- **Reproducibility**: Anyone with QEMU can replicate the exact environment.
- **Isolation**: A QEMU instance does not affect the host system.
- **Debugging**: QEMU provides serial console output, debugging interfaces, and the ability to pause execution.
- **Flexibility**: We can test different hardware configurations by changing QEMU command-line parameters.

QEMU is available on virtually every Linux distribution. Install it with your distribution's package manager: `apt install qemu-system-x86` on Debian-based systems, `dnf install qemu-system-x86` on Fedora, `pacman -S qemu-full` on Arch Linux.

The specific QEMU machine type we use is the standard PC (i440FX chipset) with a virtio-blk virtual disk and a virtio-net virtual network interface. This combination provides reasonable performance and compatibility. Later chapters will show the exact QEMU command lines used.

The Build Host

The build host is the machine where we compile the kernel, toolchain, and userspace components. The build host does not need to match the target architecture because we will be building a native toolchain for x86-64 (assuming the build host is also x86-64).

Minimum requirements for the build host:

- 8 GB of RAM (16 GB recommended). Kernel and toolchain compilation are memory-intensive.
- 20 GB of free disk space (50 GB recommended). Source code, build artifacts, and disk images add up.
- A recent Linux distribution (Debian 12+, Ubuntu 22.04+, Fedora 38+, or equivalent).
- Standard development tools: make, git, bzip2, xz-utils, gawk, flex, bison, gcc (for building the toolchain), and their dependencies.

The exact distribution does not matter as long as it can run the tools we need. What matters is that the build environment is consistent and reproducible.

Build Isolation with Docker

To ensure reproducibility and avoid polluting the host system, we run builds inside a Docker container. The container provides:

- A clean environment with known packages and versions.
- Isolation from the host system's configuration and installed software.
- The ability to rebuild from scratch easily.

Here is the Dockerfile for our build environment:

```
FROM debian:12

RUN apt-get update && apt-get install -y \
    build-essential \
    git \
    wget \
    bzip2 \
    xz-utils \
    zlib1g-dev \
    libncurses-dev \
    flex \
    bison \
    libssl-dev \
    bc \
    cpio \
    file \
    rsync \
    qemu-system-x86 \
    && rm -rf /var/lib/apt/lists/*

WORKDIR /build
```

Build and run the container with:

```
docker build -t lfs-extreme .
docker run -it --rm --name lfs-extreme lfs-extreme
```

The container mounts a working directory at /build where all source code, build artifacts, and output images will reside. You can bind-mount a directory from the host to persist data:

```
docker run -it --rm -v $(pwd)/workspace:/build lfs-extreme
```

If you prefer not to use Docker, you can build directly on the host. The commands are the same; you just skip the containerization step. The trade-off is that the host system may have configuration or package versions that affect reproducibility.

Directory Layout and Build Scripts

The build directory uses a structured layout that separates source code, build artifacts, and final output:

```
/build/
├── src/                    # Downloaded source code
│   ├── linux-6.8.tar.xz
│   ├── musl-1.2.5.tar.gz
│   ├── busybox-1.36.1.tar.bz2
│   ├── binutils-2.43.tar.gz
│   └── gcc-14.2.0.tar.gz
├── build/                  # Build directories (out-of-tree)
│   ├── kernel/
│   ├── musl/
│   ├── busybox/
│   ├── binutils/
│   └── gcc/
├── toolchain/              # Built toolchain (cross-compiler)
│   └── x86_64-lfs-linux-gnu/
├── rootfs/                 # Target root filesystem tree
│   ├── bin/
│   ├── etc/
│   ├── lib/
│   ├── sbin/
│   ├── proc/
│   ├── sys/
│   ├── dev/
│   ├── run/
│   ├── tmp/
│   ├── var/
│   └── usr/
├── initramfs/              # Initramfs source tree
│   ├── bin/
│   ├── dev/
│   ├── etc/
│   ├── proc/
│   ├── sys/
│   └── init
├── output/                 # Final output images
│   ├── bzImage
│   ├── initramfs.cpio.gz
│   └── disk.img
└── scripts/                # Build automation scripts
    ├── build-all.sh
    ├── build-toolchain.sh
    ├── build-kernel.sh
    ├── build-userspace.sh
    └── run-qemu.sh
```

This layout follows standard practices:

- Source code stays in src/ and is never modified in-place.
- Builds occur in build/ in separate directories for each component.

- The target root filesystem is assembled in rootfs/ and packaged into disk.img.
- The initramfs has its own tree, which is packaged separately.
- All automation is in scripts/, making the build process transparent and repeatable.

Here is the master build script, scripts/build-all.sh:

```
#!/bin/bash
set -euo pipefail

SCRIPT_DIR="$(cd "$(dirname "$0")" && pwd)"
BUILD_DIR="$(dirname "$SCRIPT_DIR")"

echo "=== Linux From Scratch: Taken to the Extreme ==="
echo "Build directory: $BUILD_DIR"
echo ""

# Step 1: Build toolchain (if not already built)
if [ ! -d "$BUILD_DIR/toolchain/x86_64-lfs-linux-gnu" ]; then
    echo ">>> Building toolchain..."
    "$SCRIPT_DIR/build-toolchain.sh" || exit 1
else
    echo ">>> Toolchain already built, skipping..."
fi

# Step 2: Build kernel
echo ">>> Building kernel..."
"$SCRIPT_DIR/build-kernel.sh" || exit 1

# Step 3: Build userspace (BusyBox and utilities)
echo ">>> Building userspace..."
"$SCRIPT_DIR/build-userspace.sh" || exit 1

# Step 4: Assemble root filesystem
echo ">>> Assembling root filesystem..."
mkdir -p "$BUILD_DIR/rootfs"/{bin,sbin,etc,lib,proc,sys,dev,run,tmp,var/usr}

# Step 5: Build initramfs
echo ">>> Building initramfs..."
find "$BUILD_DIR/initramfs" -print0 | cpio --null -ov --format=newc | gzip -9 >
↪  "$BUILD_DIR/output/initramfs.cpio.gz"

echo ">>> Build complete."
echo "Kernel: $BUILD_DIR/output/bzImage"
echo "Initramfs: $BUILD_DIR/output/initramfs.cpio.gz"
```

Each individual build script is covered in detail in the relevant chapter. The master script simply orchestrates the build in the correct order.

QEMU Setup and Validation

QEMU is our test environment. Before building anything complex, we must verify that QEMU works correctly on our build host.

First, install QEMU if not already installed. In the Docker container, this is done by the Dockerfile. On a host system:

```
# Debian/Ubuntu
sudo apt-get install qemu-system-x86

# Fedora/RHEL
sudo dnf install qemu-system-x86

# Arch Linux
sudo pacman -S qemu-full
```

Verify the installation:

```
qemu-system-x86_64 --version
```

The output should show a QEMU version 8.0 or later. Older versions work but may lack features we use later.

We use QEMU in non-graphics mode with a serial console, which is the standard approach for minimal systems:

```
qemu-system-x86_64 \
    -m 512M \
    -cpu host \
    -enable-kvm \
    -nographic \
    -serial stdio \
    -device virtio-blk-pci,drive=drive0 \
    -drive id=drive0,file=disk.img,format=raw
```

The parameters mean:

- `-m 512M`: Allocate 512 MB of RAM. Our system will not need this much, but 512 MB is a reasonable starting point.
- `-cpu host`: Use the host CPU model. This provides the best performance but may not work on all systems. Use `-cpu qemu64` for maximum compatibility.
- `-enable-kvm`: Use kernel-based virtualization for near-native performance. If KVM is not available, remove this flag.
- `-nographic`: Disable graphical output. All I/O goes through the serial console.
- `-serial stdio`: Redirect the serial console to standard input/output. Combined with -nographic, this means you interact with the guest through your terminal.
- `-device virtio-blk-pci,drive=drive0`: Add a virtio block device for fast disk I/O.
- `-drive id=drive0,file=disk.img,format=raw`: Attach the disk image as a raw disk.

To exit QEMU, press Ctrl+A then X. During development, you will also find Ctrl+A C useful, which toggles between the guest console and the QEMU monitor.

For kernel development and testing, we often use QEMU's direct kernel boot feature, which loads the kernel directly without a bootloader:

```
qemu-system-x86_64 \
    -m 512M \
    -cpu host \
    -enable-kvm \
    -nographic \
    -serial stdio \
    -kernel bzImage \
    -append "console=ttyS0 root=/dev/vda init=/bin/sh" \
    -drive file=disk.img,format=raw,if=virtio
```

The `-kernel` flag tells QEMU to load the specified kernel image directly. The `-append` flag passes kernel command-line parameters. This bypasses any bootloader entirely, which is useful for rapid kernel iteration.

The Target Specification

What should the finished reference system be able to do? Here are the acceptance criteria:

Boot and initialization:

- Boot successfully in QEMU x86-64 emulation.
- Mount the root filesystem, /proc, /sys, /dev, and /run.
- Start init as PID 1.
- Reach a usable state within two seconds on modern hardware.

Shell and user interface:

- Provide an interactive shell login.
- Support basic shell operations: file navigation, text editing, process management.
- Display a boot message or login prompt.

User authentication:

- Support root login via console.
- Support at least one non-root user.
- Use /etc/passwd and /etc/shadow for credential storage.

File operations:

- Read, write, create, and delete files and directories.
- Support standard file permissions and ownership.
- Provide basic text processing utilities: cat, grep, sed, awk.

Process management:

- Create and manage processes via fork and exec.
- Support signal handling.
- Provide ps and kill utilities.

Networking:

- Bring up a network interface.
- Configure an IP address.
- Resolve hostnames via DNS.
- Support ping and basic TCP connectivity.

Logging:

- Log system events to /var/log/messages or equivalent.
- Provide dmesg output.

Shutdown:

- Shut down cleanly via poweroff or reboot commands.
- Unmount filesystems in correct order.

Extensibility:

- Support running arbitrary statically linked executables.
- Support running dynamically linked executables (with appropriate libraries).
- Provide /etc directories for configuration files.

The system should not include anything beyond what is required to satisfy these criteria. If a feature is not in this list and not required to implement something on this list, it does not belong in the reference system.

Later chapters will walk through building each piece that satisfies these criteria, explaining what it is, why it is needed, and how it fits into the whole.

Chapter 3: Firmware and the Boot Journey

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Power-On and Firmware

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