# THE DISTRIBUTED SYSTEMS HANDBOOK

Design, Implement, and Operate
Production-Grade Systems
Using Modern Engineering Practices


BUILD RELIABLE SYSTEMS FROM FIRST PRINCIPLES

DESIGN FOR FAULT TOLERANCE AND SCALE

IMPLEMENT WITH PRODUCTION-READY CODE

DEPLOY AND OPERATE WITH CONFIDENCE

TEST, MONITOR, AND IMPROVE AT SCALE

JAKE MCQUIRE

# The Distributed Systems Handbook

## Design, Implement, and Operate Production-Grade Systems Using Modern Engineering Practices

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# Contents

# Design, Implement, and Operate Production-Grade Systems Using Modern Engineering Practices

This book teaches you how to build distributed systems from first principles. Starting with fundamental concepts of networking, concurrency, and fault tolerance, we progressively construct a complete distributed platform using Go. Each chapter extends the previous one into a working system, with production-ready code that compiles and runs without omissions or placeholders. By the end, you will understand not only how distributed systems work but why they are built the way they are, and you will have the practical skills to design, implement, test, deploy, and operate your own at scale.

# Introduction: Why Distributed Systems Are Harder Than They Look

In 2011, Netflix engineers did something that would have been unthinkable in most companies a decade earlier. They wrote a program called Chaos Monkey, and they let it run in production during business hours. Its job was simple: randomly shut down servers while millions of people were streaming video [1]. The goal was not to cause an outage. The goal was to find out whether the system would survive the outage that was guaranteed to happen eventually.

This story captures everything that makes distributed systems both fascinating and difficult. They are not just bigger versions of single-machine programs. They are fundamentally different beasts, governed by their own rules, constraints, and failure modes. A program that works flawlessly on one machine can fail spectacularly when spread across ten, a hundred, or a thousand machines connected by networks that drop packets, introduce delays, and occasionally disappear entirely.

This book exists to help you understand those rules and build systems that respect them.

## What Is a Distributed System?

A distributed system is a collection of independent computers that appears to its users as a single coherent system [2]. That definition looks simple until you try to make it real. The computers are physically separate, potentially spread across different data centers or continents. They communicate over networks that are unreliable, asynchronous, and subject to arbitrary delays. They have their own clocks, which drift relative to each other. They crash, reboot, lose connectivity, and occasionally behave in ways that defy explanation.

Yet from the outside, the system should look like one machine. A user submits a request and gets a response without knowing or caring whether that request touched three servers in Virginia, two in Oregon, and a database cluster in Frankfurt. The complexity is hidden behind the abstraction.

That hiding is both the point and the problem. Distributed systems are hard because we want them to behave like single machines while being built from components that fundamentally cannot do that. We want consistency, but replication introduces conflicts. We want availability, but coordination introduces delays. We want correctness, but partial failures make it impossible to distinguish between a slow node and a dead one.

## The Fallacies That Get Us in Trouble

In the early 1990s, L. Peter Deutsch and colleagues at Sun Microsystems identified eight false assumptions that programmers commonly make when building networked systems [3]. They called them the fallacies of distributed computing:

- The network is reliable
- Latency is zero
- Bandwidth is infinite
- The network is secure
- Topology doesn't change
- There is one administrator
- Transport cost is zero
- The network is homogeneous

Every single one of these statements is false in production, and every single one tempts us to write code that works in development and breaks in the real world. A distributed system designer's job is to build software that operates correctly when all eight fallacies come true at once.

Consider latency alone. The numbers matter more than most engineers realize:

| Operation | Approximate Latency |
|---|---|
| L1 cache reference | 0.5 nanoseconds |
| L2 cache reference | 7 nanoseconds |
| Main memory access | 100 nanoseconds |
| Local network round-trip (same data center) | 0.5 milliseconds |
| Cross-region network round-trip | 50-150 milliseconds |
| Disk seek | 10 milliseconds |

A single cross-region network call takes roughly as long as one hundred thousand L1 cache accesses. A disk seek is two hundred thousand times slower than an L1 cache hit. When your code makes twenty sequential RPC calls across data centers, you are looking at seconds of latency before you have even processed any business logic [4].

These numbers are not abstract. They directly shape the architecture of every serious distributed system. Caching exists because memory is faster than disk, and local state is faster than remote state. Replication exists because reading from a nearby copy is faster than crossing the ocean. Async communication exists because waiting for every dependency is too slow.

## What This Book Will Do

This book takes you on a journey from fundamentals to production. We will not rely on black-box frameworks that obscure what is happening underneath. Instead, we will build each component from scratch, understand the trade-offs, and then see how industry tools solve the same problems at scale.

The progression is deliberate and cumulative:

- Chapters 1 through 3 establish foundations: distributed computing concepts, network communication, and serialization.
- Chapters 4 through 6 build the coordination layer: RPC frameworks, service discovery, leader election, and consensus.
- Chapters 7 through 9 handle data: replication, distributed logs, transactions, caching, and messaging.
- Chapters 10 through 12 focus on architecture and reliability: event-driven design, observability, resilience patterns, and chaos engineering.

- Chapters 13 through 15 cover theory, security, and operations: CAP and PACELC theorems, authentication and authorization, containerization, orchestration, and production deployment.

By the final chapter, we will have built a complete distributed platform that includes service discovery, consensus-based coordination, replicated storage, message passing, observability, and deployment tooling. Every piece of code will be functional, documented, and designed with production use in mind.

## Technology Choices

We will use Go as our implementation language. Go is an excellent choice for distributed systems work for several reasons:

- **Concurrency primitives**: Goroutines and channels provide a clean model for concurrent programming that maps naturally to distributed system patterns.
- **Networking support**: The standard library includes robust TCP, UDP, and HTTP implementations.
- **Performance**: Compiled code with low overhead, suitable for infrastructure components.
- **Industry adoption**: Kubernetes, Docker, etcd, Prometheus, and many other distributed systems tools are written in Go.
- **Simplicity**: A small language surface area means less to get wrong when building correctness-critical systems.

We will use modern tooling throughout: Go modules for dependency management, Docker for containerization, Kubernetes for orchestration, OpenTelemetry for observability, and GitHub Actions for CI/CD. Every configuration file and script will be provided so you can reproduce the results on your own machine.

## How to Read This Book

Each chapter is designed to be read sequentially and worked through actively. The theory sections explain the concepts, the implementation sections walk through code, and the design discussions justify architectural decisions. You should:

- Run the code examples as you encounter them. Modify them, break them, and fix them.
- Pay attention to the "why" behind each decision, not just the "what."
- Read the failure mode discussions carefully. Understanding how things go wrong is more important than understanding how they work correctly.
- Use the comparison tables and case studies to connect theory with real-world systems.

The book assumes basic programming knowledge: you understand variables, functions, data structures, and have written network code before. You do not need prior experience with distributed systems, and we will not assume familiarity with consensus algorithms, replication strategies, or CAP theorem until we introduce them.

## What This Book Is Not

This book is not a catalog of patterns without context. You will find books that list "circuit breaker," "bulkhead," and "saga" as bullet points with minimal explanation. Here, each pattern emerges from a concrete problem we are solving in our own system, and we will implement it ourselves rather than importing it as an abstraction.

This book is not a framework tutorial. You will not find chapters titled "How to Use Kubernetes" or "Getting Started with Kafka." Instead, you will understand the problems those tools solve well enough to use them effectively, and you will have built simplified versions of their core functionality yourself.

This book is not about exercises and quizzes. There are no review questions at the end of each chapter. The work is in reading, understanding, and running the code. If you have built the system described in this book, you do not need a quiz to prove you understand it.

## The Mindset You Need

Building distributed systems requires a particular mindset, one that differs from single-machine programming in important ways:

- **Embrace failure**: Components will fail. Networks will partition. Clocks will drift. Your job is not to prevent failures but to design systems that continue operating correctly when they occur.
- **Think in probabilities**: You cannot guarantee exact timing or ordering across machines. You work with timeouts, retries, quorums, and eventual consistency instead.
- **Prefer simplicity over cleverness**: Complex distributed algorithms are hard to get right the first time. Simple protocols that are easy to reason about are easier to debug and more likely to be correct.
- **Measure everything**: Your intuition about performance, latency, and throughput will be wrong. Instrument your system, collect data, and let measurements guide your decisions.
- **Design for observability**: If you cannot see what is happening inside your system, you cannot fix it when something goes wrong. Build logging, metrics, and tracing into every component from day one.

The rest of this book puts that mindset into practice. Let us begin.

# Chapter 1: Foundations of Distributed Computing

Before we write a single line of networking code, we need to establish the mental model for distributed systems. This chapter covers the fundamental concepts, constraints, and patterns that will guide every design decision in the chapters ahead. We will also set up the development environment and toolchain that we will use throughout the book.

## What Is a Distributed System

We already touched on this in the introduction, but it deserves deeper examination. A distributed system is defined by three properties:

**Multiple nodes**: The system consists of two or more independent computing entities, each with its own memory, processor, and operating system. These nodes communicate exclusively through message passing over a network. There is no shared memory between nodes.

**Coherent behavior**: Despite being physically separate, the nodes work together to provide a unified service. Users and client programs interact with the system as if it were a single entity, without needing to know which node handles which request.

**No global clock**: Each node has its own local clock, and there is no mechanism to perfectly synchronize them. Events in a distributed system cannot be globally ordered with perfect precision.

These properties create challenges that do not exist in single-machine programming. Consider what happens when you call a function in your application. The call returns immediately (or blocks until it completes), and you know whether it succeeded or failed. Now consider calling a service running on another machine across the network. The call might succeed, fail, time out, or hang indefinitely. The remote service might have processed your request but lost the response. You cannot tell the difference between a slow node and a dead one without imposing an arbitrary timeout.

This uncertainty is fundamental. It is not a bug in your networking library or a configuration error. It is a property of distributed systems that you must design around.

To illustrate, consider a simple scenario: Service A sends a message to Service B and waits for a response. What can go wrong?

- The message never reaches B (network failure)
- The message reaches B but B crashes before processing it
- B processes the message and sends a response, but the response is lost
- B processes the message twice due to a retry from A
- B is so slow that A times out, retries, and ends up with duplicate work

Each of these scenarios requires different handling, and your code must be correct in all of them.

## The Fundamentals: Latency, Bandwidth, and Reliability

Three physical properties dominate distributed system design: latency, bandwidth, and reliability. Understanding their real-world values is essential for making informed architectural decisions.

**Latency** is the time it takes for a message to travel from sender to receiver. It includes processing delays, queuing delays, transmission delays, and propagation delays. The propagation delay alone is bounded by the speed of light: a signal traveling through fiber optic cable moves at approximately two-thirds the speed of light in vacuum, which means roughly five milliseconds per thousand kilometers.

Here are latency numbers that matter for distributed systems design [4]:

| Operation | Latency |
|---|---|
| CPU instruction | 0.25 nanoseconds |
| L1 cache hit | 0.5 nanoseconds |
| L2 cache hit | 7 nanoseconds |
| Main memory access | 100 nanoseconds |
| SSD read (random) | 10 microseconds |
| HDD seek | 10 milliseconds |
| Local network round-trip | 0.5 milliseconds |
| Cross-data-center round-trip | 2-10 milliseconds |
| Cross-continent round-trip | 50-150 milliseconds |

Notice the gaps between orders of magnitude. A cross-continent network call is three hundred thousand times slower than an L1 cache access. This is why caching matters, why local state matters, and why minimizing network round-trips is a primary optimization goal.

**Bandwidth** is the rate at which data can be transmitted. Modern data center networks typically provide 10-100 gigabits per second between servers, while cross-region links may be limited to megabits per second. Bandwidth constraints matter when moving large amounts of data: replicating terabytes of storage, synchronizing state across regions, or streaming video content.

**Reliability** refers to the probability that a component operates correctly over time. Individual components are unreliable: disks fail, network links drop, servers crash, and software has bugs. A single server might have 99.9 percent uptime, which sounds impressive until you realize that means roughly eight and a half hours of downtime per year. If your system depends on ten such servers and any one failure causes an outage, your effective uptime drops dramatically.

The solution is redundancy: replicate components so that the system survives individual failures. If you have three identical servers and any two can handle the load, the probability that both fail simultaneously is much lower than the probability that one fails. This principle of fault tolerance through redundancy underlies virtually every production distributed system.

## Concurrency and Parallelism

Distributed systems are inherently concurrent: multiple nodes operate simultaneously, making decisions and performing work without a global coordi-

nator. Understanding concurrency is therefore essential, and it begins with distinguishing two related but different concepts.

**Concurrency** is about dealing with many things at once. A concurrent program structures its work into independent tasks that can interleave. Concurrency does not require multiple processors: a single-threaded event loop can handle thousands of concurrent connections by switching between them as I/O operations complete.

**Parallelism** is about doing many things at once. Parallel programs execute multiple tasks simultaneously on multiple processors. Parallelism requires hardware support: multiple CPU cores or multiple machines.

Every distributed system is both concurrent and parallel. It is concurrent because each node runs its own logic independently, and it is parallel because all nodes operate at the same time. The challenge is coordinating that concurrency and parallelism without introducing bugs.

The classic problems of concurrent programming appear in amplified form in distributed systems:

- **Race conditions**: Two operations access shared state in an order that produces incorrect results. In a distributed system, the "shared state" might be a database, a cache, or any replicated data structure.
- **Deadlocks**: Two or more operations wait for each other indefinitely. Distributed deadlocks are harder to detect because there is no global view of all locks held by all processes.
- **Livelocks**: Operations continuously respond to each other without making progress. For example, two nodes might repeatedly retry an operation that fails because the other node is also retrying.
- **Starvation**: One operation never gets a chance to run because others always take priority.

Go provides excellent primitives for managing concurrency: goroutines for lightweight concurrent execution and channels for communication between goroutines. The philosophy "do not communicate by sharing memory; instead, share memory by communicating" [5] is particularly well-suited to distributed systems, where communication is the primary mechanism anyway.

## Processes, Threads, and Event Loops

Before we dive into Go's concurrency model, it helps to understand the underlying operating system concepts.

A **process** is an independent execution environment with its own memory space, file descriptors, and system resources. Processes communicate through inter-process communication mechanisms: pipes, sockets, shared memory, or message queues. The isolation between processes is strong: one process cannot directly read another process's memory.

A **thread** is a unit of execution within a process. Threads in the same process share memory and resources but have independent stacks and program counters. Thread creation and context switching are cheaper than process operations, but shared memory introduces synchronization challenges.

An **event loop** is a programming pattern for handling multiple event sources (network connections, file descriptors, timers) in a single thread. The event loop continuously checks for events, dispatches handlers, and returns to waiting. This pattern is widely used in high-performance network servers because it avoids the overhead of creating one thread per connection.

Go's goroutines combine the best aspects of these models. A goroutine is like a thread: it has its own stack and executes code independently. But goroutines are managed by the Go runtime, not the operating system, which makes them much cheaper to create and schedule. A single goroutine starts with approximately two kilobytes of stack space that grows and shrinks dynamically. You can easily run millions of goroutines on a single machine.

The Go runtime schedules goroutines onto a pool of operating system threads using a work-stealing scheduler. When a goroutine blocks on I/O, the runtime moves it off the current thread and runs other goroutines instead. This means that blocking operations do not block the entire program, and you can write concurrent code without worrying about low-level thread management.

Here is a simple example demonstrating goroutines and channels:

```
package main

import (
    "fmt"
    "sync"
)

func worker(id int, jobs <-chan int, results chan<- int, wg *sync.WaitGroup) {
    defer wg.Done()
    for j := range jobs {
        results <- j * 2
    }
}

func main() {
    const numWorkers = 3
    const numJobs = 9

    jobs := make(chan int, numJobs)
    results := make(chan int, numJobs)

    var wg sync.WaitGroup

    for w := 1; w <= numWorkers; w++ {
        wg.Add(1)
        go worker(w, jobs, results, &wg)
    }

    for j := 1; j <= numJobs; j++ {
        jobs <- j
    }
    close(jobs)

    go func() {
        wg.Wait()
        close(results)
    }()

    for r := range results {
        fmt.Println("Result:", r)
    }
}
```

This program creates three worker goroutines that read from a jobs channel, double each value, and write to a results channel. The main goroutine sends nine jobs, closes the jobs channel, waits for all workers to finish using a WaitGroup, and then collects results. This pattern scales naturally: add more workers to handle more jobs, or distribute workers across multiple machines

in a distributed system.

## Failure Modes in Distributed Systems

Understanding how things fail is at least as important as understanding how they work. Distributed systems face a wide variety of failure modes, and designing for them requires knowing what to expect.

**Crash failures**: A node stops responding entirely. It may have crashed due to a hardware fault, an operating system panic, or a software bug. From the perspective of other nodes, a crash looks like silence: no responses, no heartbeats, nothing. The node may recover later, possibly with lost state.

**Omission failures**: A node fails to perform an action it should have taken. It might drop a message, fail to send a response, or forget to update its state. Omission failures are particularly insidious because the node appears to be running normally while silently doing the wrong thing.

**Timing failures**: A node responds, but too slowly. The response arrives after the caller has given up and moved on. Timing failures blur the line between success and failure: did the operation complete but the response get lost, or did it never complete at all?

**Byzantine failures**: A node behaves arbitrarily or maliciously. It might send conflicting information to different nodes, fabricate data, or collude with other faulty nodes. Byzantine failures are the hardest to handle because you cannot assume any particular behavior from the faulty node. Most distributed systems assume non-Byzantine failures (crash and omission) because Byzantine fault tolerance requires significantly more overhead.

**Network failures**: The network itself fails in various ways. Links go down, routers fail, packets get dropped or duplicated, messages arrive out of order, and latency spikes unpredictably. Network partitions divide the system into isolated groups that cannot communicate with each other.

The key insight is that you cannot reliably distinguish between some of these failure modes. If a node does not respond, it might have crashed, it might be slow, or the network might be broken. Your code must handle all possibilities correctly.

This leads to an important design principle: **timeouts are necessary but dangerous**. A timeout lets you make progress when a response does not arrive,

but it introduces uncertainty about whether the timed-out operation actually completed. If you retry an operation that already succeeded, you might end up with duplicate work. Handling this requires idempotency: operations that produce the same result when executed multiple times.

## Setting Up Your Development Environment

Now let us set up the development environment we will use throughout this book. We will install Go, configure our project structure, and establish the tooling for building, testing, and running distributed systems.

**Prerequisites**: You need a machine running Linux, macOS, or Windows (with WSL2 recommended for Windows). All code examples are tested on Linux and macOS; Windows support is provided through WSL2.

**Step 1: Install Go**

Download and install Go version 1.22 or later from https://go.dev/dl/. Verify the installation:

```
go version
```

You should see output like `go version go1.22.0 linux/amd64`.

Add Go's bin directory to your PATH if it is not already included. On most installations, this is done automatically.

**Step 2: Create the project structure**

We will build our distributed system incrementally in a single repository. Each chapter adds new components while preserving previous ones. Create the project directory:

```
mkdir -p ~/distsys
cd ~/distsys
go mod init github.com/yourusername/distsys
```

Create the following directory structure:

```
mkdir -p cmd/{server,client,registry,consensus,cache,broker}
mkdir -p internal/{config,network,rpc,discovery,consensus,storage,messaging,observability,resilience,security}
mkdir -p pkg/{protocol,codec}
mkdir -p test/{integration,e2e,chaos}
mkdir -p deploy/{docker,kubernetes,cicd}
```

This structure separates concerns clearly:

- `cmd/` contains executable entry points for each component
- `internal/` contains private packages used only within this project
- `pkg/` contains public packages that could be reused by other projects
- `test/` contains test suites at different levels
- `deploy/` contains deployment configurations

**Step 3: Install development tools**

We will use several tools throughout the book. Install them now:

```
# Docker for containerization
# Follow instructions at https://docs.docker.com/get-docker/

# Go testing and benchmarking tools (included with Go)
go install golang.org/x/tools/cmd/goimports@latest
go install honnef.co/go/tools/cmd/staticcheck@latest
go install github.com/vektra/mockery/v2@latest

# For later chapters: Kubernetes tools
# kubectl: https://kubernetes.io/docs/tasks/tools/
# Helm: https://helm.sh/docs/intro/install/
```

**Step 4: Create the base configuration package**

Every component in our system needs configuration. Let us create a reusable configuration package that supports loading from environment variables, command-line flags, and configuration files.

Create `internal/config/config.go`:

```
package config

import (
    "encoding/json"
    "fmt"
    "os"
    "time"
)

// ServerConfig holds configuration for a network server.
type ServerConfig struct {
    Host              string        `json:"host"`
    Port              int           `json:"port"`
    ReadTimeout       time.Duration `json:"read_timeout"`
    WriteTimeout      time.Duration `json:"write_timeout"`
    IdleTimeout       time.Duration `json:"idle_timeout"`
    MaxConnections    int           `json:"max_connections"`
    GracefulShutdown  time.Duration `json:"graceful_shutdown"`
}

// DefaultServerConfig returns a ServerConfig with sensible defaults.
func DefaultServerConfig() ServerConfig {
    return ServerConfig{
        Host:              "0.0.0.0",
        Port:              8080,
        ReadTimeout:       5 * time.Second,
        WriteTimeout:      10 * time.Second,
        IdleTimeout:       60 * time.Second,
        MaxConnections:    10000,
        GracefulShutdown:  30 * time.Second,
    }
}

// LogConfig holds configuration for logging.
type LogConfig struct {
    Level   string `json:"level"`
    Format  string `json:"format"` // "json" or "text"
    Output  string `json:"output"` // "stdout", "stderr", or file path
}

// DefaultLogConfig returns a LogConfig with sensible defaults.
func DefaultLogConfig() LogConfig {
    return LogConfig{
        Level:  "info",
        Format: "json",
        Output: "stdout",
    }
}

// AppConfig holds the complete application configuration.
```

```
type AppConfig struct {
    Server ServerConfig `json:"server"`
    Log    LogConfig    `json:"log"`
    Name   string       `json:"name"`
    ID     string       `json:"id"`
}

// LoadConfig loads configuration from a file, environment variables, and
↪  defaults.
// Environment variables override file values, and both override defaults.
func LoadConfig(file string) (AppConfig, error) {
    cfg := AppConfig{
        Server: DefaultServerConfig(),
        Log:    DefaultLogConfig(),
        Name:   "distsys-service",
        ID:     generateID(),
    }

    // Load from file if provided
    if file != "" {
        data, err := os.ReadFile(file)
        if err != nil {
            return cfg, fmt.Errorf("reading config file: %w", err)
        }

        if err := json.Unmarshal(data, &cfg); err != nil {
            return cfg, fmt.Errorf("parsing config file: %w", err)
        }
    }

    // Override with environment variables
    if v := os.Getenv("DISTSYS_HOST"); v != "" {
        cfg.Server.Host = v
    }
    if v := os.Getenv("DISTSYS_PORT"); v != "" {
        var port int
        fmt.Sscanf(v, "%d", &port)
        cfg.Server.Port = port
    }
    if v := os.Getenv("DISTSYS_LOG_LEVEL"); v != "" {
        cfg.Log.Level = v
    }
    if v := os.Getenv("DISTSYS_NAME"); v != "" {
        cfg.Name = v
    }

    return cfg, nil
}

// generateID creates a unique identifier for this service instance.
```

```
func generateID() string {
    hostname, _ := os.Hostname()
    pid := os.Getpid()
    return fmt.Sprintf("%s-%d", hostname, pid)
}
```

Create `internal/config/config_test.go`:

```
package config

import (
    "os"
    "testing"
    "time"
)

func TestDefaultServerConfig(t *testing.T) {
    cfg := DefaultServerConfig()

    if cfg.Host != "0.0.0.0" {
        t.Errorf("expected host 0.0.0.0, got %s", cfg.Host)
    }
    if cfg.Port != 8080 {
        t.Errorf("expected port 8080, got %d", cfg.Port)
    }
    if cfg.ReadTimeout != 5*time.Second {
        t.Errorf("expected read timeout 5s, got %v", cfg.ReadTimeout)
    }
    if cfg.MaxConnections != 10000 {
        t.Errorf("expected max connections 10000, got %d", cfg.MaxConnections)
    }
}

func TestDefaultLogConfig(t *testing.T) {
    cfg := DefaultLogConfig()

    if cfg.Level != "info" {
        t.Errorf("expected level info, got %s", cfg.Level)
    }
    if cfg.Format != "json" {
        t.Errorf("expected format json, got %s", cfg.Format)
    }
}

func TestLoadConfigFromEnv(t *testing.T) {
    os.Setenv("DISTSYS_HOST", "127.0.0.1")
    os.Setenv("DISTSYS_LOG_LEVEL", "debug")
    defer func() {
        os.Unsetenv("DISTSYS_HOST")
```

```
        os.Unsetenv("DISTSYS_LOG_LEVEL")
    }()

    cfg, err := LoadConfig("")
    if err != nil {
        t.Fatalf("LoadConfig failed: %v", err)
    }

    if cfg.Server.Host != "127.0.0.1" {
        t.Errorf("expected host 127.0.0.1, got %s", cfg.Server.Host)
    }
    if cfg.Log.Level != "debug" {
        t.Errorf("expected level debug, got %s", cfg.Log.Level)
    }
}

func TestLoadConfigFromFile(t *testing.T) {
    content := `{
        "server": {"host": "0.0.0.0", "port": 9090},
        "log": {"level": "warn"},
        "name": "test-service"
    }`

    tmpfile, err := os.CreateTemp("", "config-*.json")
    if err != nil {
        t.Fatalf("creating temp file: %v", err)
    }
    defer os.Remove(tmpfile.Name())

    if _, err := tmpfile.WriteString(content); err != nil {
        t.Fatalf("writing config: %v", err)
    }
    tmpfile.Close()

    cfg, err := LoadConfig(tmpfile.Name())
    if err != nil {
        t.Fatalf("LoadConfig failed: %v", err)
    }

    if cfg.Server.Port != 9090 {
        t.Errorf("expected port 9090, got %d", cfg.Server.Port)
    }
    if cfg.Log.Level != "warn" {
        t.Errorf("expected level warn, got %s", cfg.Log.Level)
    }
    if cfg.Name != "test-service" {
        t.Errorf("expected name test-service, got %s", cfg.Name)
    }
}

```

```
func TestLoadConfigEnvOverridesFile(t *testing.T) {
    content := `{"server": {"port": 9090}, "log": {"level": "warn"}}`

    tmpfile, err := os.CreateTemp("", "config-*.json")
    if err != nil {
        t.Fatalf("creating temp file: %v", err)
    }
    defer os.Remove(tmpfile.Name())

    if _, err := tmpfile.WriteString(content); err != nil {
        t.Fatalf("writing config: %v", err)
    }
    tmpfile.Close()

    os.Setenv("DISTSYS_LOG_LEVEL", "debug")
    defer os.Unsetenv("DISTSYS_LOG_LEVEL")

    cfg, err := LoadConfig(tmpfile.Name())
    if err != nil {
        t.Fatalf("LoadConfig failed: %v", err)
    }

    if cfg.Log.Level != "debug" {
        t.Errorf("expected env override debug, got %s", cfg.Log.Level)
    }
}
```

**Step 5: Verify the setup**

Run the tests to verify everything is working:

```
cd ~/distsys
go test ./internal/config/... -v
```

You should see all tests passing. Run static analysis:

```
staticcheck ./...
```

This completes our development environment setup. We now have a project structure, configuration system, and tooling ready for building distributed systems. In the next chapter, we will start with network communication: implementing TCP and UDP servers and clients that form the foundation of all inter-process communication in our platform.

# Chapter 2: Network Communication from the Ground Up

This content is not available in the sample book. The book can be purchased on Leanpub at https://leanpub.com/thedistributedsystemshandbook.

## Understanding TCP and UDP

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## DNS-Based Discovery Patterns

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## Handling Conflicts and Write Skew

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