

#NetBSD at Scale

DESIGNING, DEPLOYING AND OPERATING
HIGH-TRAFFIC SERVER INFRASTRUCTURE



FOUNDATIONAL
ARCHITECTURE



PERFORMANCE
TUNING



HIGH
AVAILABILITY



AUTOMATION
AND DEVOPS



DISASTER
RECOVERY



SECURITY
HARDENING

— ERIC CHEN —

NetBSD at Scale

Designing, Deploying and Operating High-Traffic Server Infrastructure

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Designing, Deploying and Operating High-Traffic Server Infrastructure

This book is a production-focused guide to building reliable, secure and performant server infrastructure on NetBSD. It covers everything from foundational architecture through advanced tuning, high availability, automation and disaster recovery. The material is organized as both a structured narrative that can be read end to end and a detailed reference manual for system administrators, DevOps engineers, SREs, network engineers and security professionals deploying real workloads on NetBSD in production environments.

Introduction

When the founder of a major cloud provider once asked why anyone would choose an operating system with less than one percent market share for mission-critical infrastructure, the answer was not about market share at all. It was about predictability. About knowing exactly what a system will do under load. About code quality that has been scrutinized by decades of developers who refuse to ship anything they consider wrong.

That operating system is NetBSD.

In an era dominated by Linux distributions and cloud-managed services, NetBSD occupies a deliberate niche: it is the choice for engineers who value correctness over convenience, architecture over features and long-term maintainability over bleeding-edge novelty. Its design philosophy, “It doesn’t work unless it’s right,” is not marketing copy. It is an operating principle that shapes every layer of the system, from device drivers to userland utilities, from kernel scheduling algorithms to package management.

This book assumes you are already comfortable with Unix-like systems. You know how to read a man page, navigate shell commands, understand basic networking concepts and have likely spent time administering Linux, FreeBSD or another BSD variant. What you may not know is how NetBSD differs in practice, where its architectural decisions produce tangible operational benefits, what pitfalls are unique to the platform, and how to configure it for high-traffic production workloads that demand reliability under sustained load.

Why NetBSD for High-Traffic Workloads?

The case for NetBSD in modern infrastructure is neither sentimental nor purely ideological. It rests on concrete technical characteristics:

First, code quality. The NetBSD project applies rigorous peer review to all contributions. Every change goes through scrutiny by multiple developers before integration. This discipline produces code that is not only correct but

readable and maintainable, qualities that matter enormously when you are debugging a production issue at 3 AM or extending the system for a specialized workload.

Second, portability as an architectural virtue. NetBSD runs on more than fifty CPU architectures, from x86_64 server platforms to embedded ARM devices. This breadth is not achieved through platform-specific hacks but through a disciplined separation of machine-dependent and machine-independent code. The result is a kernel architecture where device drivers are cleanly abstracted, subsystems communicate through well-defined interfaces and the overall design favors modularity and clarity. That same architectural discipline that makes NetBSD portable also makes it easier to understand, tune and extend for server workloads.

Third, security through design rather than retrofitting. While OpenBSD has earned its reputation as the security-focused BSD, NetBSD's approach is equally principled but differently expressed. The system incorporates privilege separation in core services, kernel authorization frameworks (kauth), address space layout randomization (KASLR), Veriexec for file integrity verification, encrypted disk support via CGD and a robust packet filter (NPF). Security features are not bolted on after the fact; they emerge from the same code quality standards that govern everything else.

Fourth, the pkgsrc ecosystem. The NetBSD Packages Collection provides access to more than twenty thousand software packages through a single, consistent build framework that works across dozens of operating systems and architectures. Unlike distribution-specific package managers that diverge significantly between platforms, pkgsrc offers predictable behavior regardless of the underlying system. For production environments where reproducibility matters, this is a significant advantage.

Fifth, licensing and long-term viability. NetBSD uses the permissive two-clause BSD license across its entire codebase. This has practical consequences: organizations can integrate NetBSD components into proprietary products without copyleft obligations, vendors have built commercial distributions on top of it, and the project itself has survived more than three decades through consistent funding and community support. A technology choice for critical infrastructure must consider not just current capabilities but long-term sustainability; NetBSD's track record speaks to both.

What This Book Covers

This book progresses from foundational understanding through advanced production engineering:

Chapters one through three establish context: NetBSD's history, design philosophy, architecture internals, release model, and installation procedures. You will understand not just what NetBSD is but why it works the way it does.

Chapters four through seven cover core infrastructure services: package management with `pkgsrc`, filesystems and storage including RAIDframe and ZFS, network configuration fundamentals, and advanced networking features such as VLANs, link aggregation, firewalling with NPF, NAT, traffic shaping, and load balancing.

Chapters eight through ten address security hardening, service deployment for web and application servers plus databases and caching layers, and systematic performance tuning of kernel parameters, the TCP stack, memory management, and scheduling.

Chapters eleven through fourteen provide operational depth: monitoring and observability, high availability architecture with CARP failover clustering, automation and configuration management, virtualization options including Xen, troubleshooting methodologies, incident response procedures, and backup and disaster recovery strategies.

Chapter fifteen ties everything together with realistic reference architectures for small, medium, and large workloads, showing how requests flow through each system, where bottlenecks are likely to appear, and how to scale systematically.

Throughout the book, technical claims are grounded in official documentation, source code behavior, published research, and measured benchmarks. Where practices differ between NetBSD versions, those differences are explicitly noted. Where information is workload-dependent or uncertain, that uncertainty is stated rather than glossed over.

How to Read This Book

You have three reasonable approaches:

Read it sequentially from beginning to end if you are new to NetBSD and want a comprehensive understanding before deploying anything in production. Each chapter builds on material introduced earlier.

Use it as a reference manual if you already know NetBSD basics and need specific information about configuring RAID, tuning network parameters, designing failover clusters, or hardening a firewall. The chapter and section headings are organized to support quick lookup.

Follow the implementation plan woven through later chapters if your goal is to take a concrete project from requirements gathering through production rollout. Chapters three, nine, ten, twelve, and fifteen in particular form a natural progression for deploying a real workload.

Version Targeting

This book targets NetBSD 10.x and 11.x as the primary reference versions, with NetBSD 11.0 released in July 2026 serving as the most current stable platform. Where commands or behaviors differ between versions, those differences are called out explicitly. Some material references the -current development branch to describe upcoming features, but all production recommendations are based on stable release behavior unless stated otherwise.

The NetBSD release support policy means that a major release remains supported until one month after the second succeeding major release ships. This gives you roughly two years of active support per major version when releases occur every two to three years, a reasonable window for production planning and upgrade scheduling.

A Note on Assumptions

Every recommendation in this book carries implicit assumptions about workload characteristics, hardware capabilities, network topology, and operational constraints. I will state those assumptions wherever they matter. What works for a high-traffic web serving cluster may be inappropriate for a database server with different I/O patterns. What is optimal for a bare-metal deployment may not translate to virtualized environments.

The goal is not to provide universal prescriptions but to give you the understanding and tools to make informed decisions for your specific situation.

Chapter 1: The Case for NetBSD in Production

To deploy NetBSD confidently in a high-traffic production environment, you need more than installation instructions. You need to understand where it came from, what its designers valued enough to build into its foundations, and how those design choices translate into operational characteristics that matter when your system is handling thousands of requests per second.

This chapter establishes the foundation for everything that follows. We will examine NetBSD's history not as a chronology exercise but as context for understanding why the system behaves the way it does. We will explore its design philosophy, licensing model, strengths and limitations, and arrive at a clear assessment of when NetBSD is the right choice and when it is not.

A Thirty-Year Lineage

NetBSD traces its ancestry through a lineage that includes some of the most influential operating system work in history. At its root lies the original Unix system from Bell Labs, extended and refined by the Berkeley Software Distribution project at the University of California, Berkeley throughout the 1970s and 1980s. The BSD additions, including virtual memory management, the TCP/IP networking stack, the C shell, vi, and much more, became so integral to Unix culture that they are often conflated with it.

When the US government's antitrust settlement against AT&T required the release of Unix source code in 1992, Berkeley released 4.4BSD-Lite, incorporating decades of research and development. This release formed the technical foundation for what would become the modern BSD family.

The NetBSD project itself emerged in 1993 from frustration within the 386BSD community. Four developers, Chris Demetriou, Theo de Raadt, Adam Glass, and Charles M. Hannum, grew dissatisfied with the quality and pace of patches being submitted to 386BSD. They wanted an operating system that

prioritized clean architecture, portability across platforms, and a disciplined development process over rapid feature accumulation.

The result was NetBSD 0.8, released on April 20, 1993. The name reflected its origins: a BSD created on the Internet, by developers collaborating through email and early online tools rather than within a single institution.

Since that first release, NetBSD has shipped major versions roughly every two to three years. The current stable releases are NetBSD 10.x and NetBSD 11.0 (released July 30, 2026). Each release represents not just accumulated bug fixes but deliberate architectural improvements: the introduction of UVM (a new virtual memory system) in version 1.4, the Rump kernel framework in version 5.0, NPF packet filtering in version 6.0, ZFS support in version 9.0, and continued refinement across all layers of the system.

This history matters because it established cultural norms that persist today: code review is mandatory, architectural consistency takes precedence over feature completeness, and portability is not an afterthought but a design constraint that shapes how every subsystem is implemented.

Portability as a Design Principle

NetBSD's slogan, "Of course it runs NetBSD," is more than marketing. It reflects a core architectural principle: the operating system should be portable across platforms without requiring fundamental redesign of its internal structure.

As of this writing, NetBSD provides formal releases for more than fifty CPU architectures, spanning x86, x86_64, ARM variants (including 32-bit and 64-bit), PowerPC, SPARC, Alpha, MIPS, RISC-V, VAX, Atari, Amiga, and many others. Some of these ports target mainstream server hardware; others serve embedded devices, legacy systems, or research platforms. The breadth is remarkable not because NetBSD developers port to everything but because the architecture makes porting feasible in a way that other operating systems do not.

The mechanism behind this portability is a strict separation between machine-dependent (MD) and machine-independent (MI) code. Every subsystem in the kernel is structured so that hardware-specific details are isolated behind well-defined interfaces:

- Device drivers are split into MI core logic and MD bus attachment code. An Ethernet driver like `fxp(4)` implements its protocol handling in portable

code while using platform-specific attachment routines to communicate with PCI, ISA or other buses.

- The bus architecture abstracts hardware enumeration and resource allocation through a hierarchical model where buses attach devices and devices may themselves act as buses for child devices.
- Memory management uses pmap (physical memory map) interfaces that encapsulate architecture-specific page table operations behind a consistent API.
- System calls present a uniform interface regardless of the underlying processor's calling convention or register set.

This separation produces benefits that extend far beyond portability:

First, code clarity. When MD and MI code are cleanly separated, each piece has a well-defined responsibility. This makes the codebase easier to understand, debug and maintain, qualities that matter enormously in production environments where you may need to diagnose obscure kernel-level issues.

Second, reduced platform-specific bugs. By confining hardware-specific logic to dedicated modules, the risk of architecture-dependent errors propagating into core subsystems is minimized. A bug in the ARM port's memory management does not automatically affect x86_64 behavior.

Third, easier extensibility. Adding support for a new device or platform follows established patterns rather than requiring ad hoc modifications to core code. This consistency reduces the cognitive load on developers and maintainers.

For server infrastructure, this architectural discipline translates into predictable behavior across hardware platforms. When you deploy NetBSD on different server models or migrate between physical and virtualized environments, the fundamental operating characteristics remain consistent.

Code Quality and the “Write Once, Run Anywhere” Promise

The phrase “write once, run anywhere” has a complicated history in computing, often associated with Java's sometimes-overpromised portability guarantees. NetBSD uses similar language but with a different meaning and a much stronger track record of delivery.

NetBSD's approach to code quality is institutionalized through several mechanisms:

The peer review process requires that every change be reviewed by at least one other developer before integration. In practice, most non-trivial changes are reviewed by multiple people. Reviews focus not just on correctness but on style consistency, architectural fit, and maintainability. This process slows down development compared to systems with more permissive contribution policies but produces code that is consistently high quality.

Static analysis tools supplement human review. The project periodically runs Coverity and other code scanners across the entire source tree to identify potential bugs, memory leaks, race conditions, and security vulnerabilities. Findings are tracked and resolved systematically rather than ignored as noise.

Coding standards enforce consistency. NetBSD has detailed style guidelines covering indentation, naming conventions, comment practices, and API design. These guidelines are not arbitrary; they reflect decades of collective experience about what makes code readable and maintainable at scale. Every contributor is expected to follow them, and reviewers will reject patches that do not.

Testing infrastructure supports verification. The Automated Testing Framework (ATF) provides a standardized way to write test cases for kernel and userland components. While test coverage is not yet comprehensive across all subsystems, critical areas including networking, filesystems, and process management have substantial automated test suites.

For production administrators, these quality mechanisms produce tangible benefits:

- Fewer unexpected bugs in core functionality. A system with rigorous code review and testing catches errors before they reach production.
- More reliable documentation. When code follows consistent patterns and is well-commented, the man pages and guides that describe it tend to be accurate and complete.
- Easier long-term maintenance. Clean, consistent code is easier to understand when you need to modify it or troubleshoot issues months or years after initial deployment.

The BSD License and Ecosystem Impact

NetBSD uses a permissive two-clause BSD license for essentially all of its source code. This license grants users the right to use, modify, distribute, and sublicense the software with minimal restrictions: attribution must be retained, and warranty disclaimers included. Unlike copyleft licenses such as the GPL, it does not require derivative works to be released under the same terms.

This licensing choice has had profound effects on the computing ecosystem:

Apple's macOS and iOS are built on top of BSD-derived code, much of it originating from NetBSD and FreeBSD projects. The Darwin core that underlies Apple's operating systems incorporates networking stacks, filesystem implementations, and userland utilities whose lineage can be traced back to Berkeley and NetBSD.

Commercial vendors have used NetBSD as the foundation for proprietary products without licensing complications. Force 10 Networks built its FTOS switch operating system on NetBSD. Technologic Systems demonstrated NetBSD running on embedded hardware including a production kitchen toaster as a proof of portability concept.

The pkgsrc package collection has been adopted by other BSD projects and even Linux distributions, providing a consistent packaging experience across platforms that would be impossible under more restrictive licensing terms.

For organizations deploying NetBSD in production, the license matters in three practical ways:

First, integration flexibility. You can incorporate NetBSD components into proprietary software without triggering copyleft obligations. This is particularly relevant if your infrastructure includes custom tools or integrations that you want to keep closed source.

Second, vendor ecosystem. The permissive license encourages commercial support and derivative products. While NetBSD does not have the same level of commercial backing as some Linux distributions, vendors like Panix, TornadoVPS, and others provide hosting and support services specifically for NetBSD deployments.

Third, long-term availability. The BSD license ensures that the code remains available even if the project itself were to disappear, a consideration for

infrastructure where you cannot afford to be locked into a single entity's continuity.

Strengths for Server Workloads

Having established context, let us now examine NetBSD's specific strengths for high-traffic server environments:

Networking stack quality. The TCP/IP implementation in NetBSD is mature, well-tested, and designed with correctness as a priority. It supports IPv4 and IPv6 comprehensively, implements modern congestion control algorithms, provides robust routing capabilities through the radix tree implementation, and includes advanced features like traffic shaping (ALTQ) and stateful packet filtering (NPF). The networking code benefits from decades of refinement and contributes back to protocol standards development.

Process and memory management. NetBSD's UVM virtual memory system, introduced in version 1.4, provides sophisticated page management with support for anonymous memory objects, shared memory, copy-on-write semantics, and efficient swap handling. The Common Scheduler Framework (CSF) introduced in version 5.0 offers multiple scheduling policies including traditional multi-level feedback queue scheduling (4.4BSD), real-time FIFO and round-robin policies, and the M2 scheduler optimized for SMP systems. These subsystems are designed to handle high concurrency without priority inversion or livelock issues.

Filesystem maturity. The FFS (Fast File System) implementation with its journaling variant via WAPBL provides reliable storage with good performance characteristics for a wide range of workloads. NetBSD also supports ZFS (from version 9.0), EXT2FS, NFS client and server, tmpfs/mfs for RAM-based filesystems, and various other filesystems through the VFS abstraction layer. The vnode interface ensures that application code does not need to be modified when switching between filesystem types.

Robust tooling. The base system includes comprehensive networking utilities (ifconfig, netstat, tcpdump, traceroute), performance monitoring tools (vmstat, iostat, top, systat), diagnostic capabilities (ddb kernel debugger, crash dump analysis), and administration utilities that are consistent with BSD traditions. These tools are well-documented through man pages and behave predictably across releases.

Security architecture. Beyond the NPF packet filter, NetBSD provides CGD for disk encryption, Veriexec for file integrity verification, kauth for kernel-level authorization decisions, privilege separation in core services like sshd, address space layout randomization (KASLR), PaX-style hardening options (MPROTECT, SEGVGUARD), and IPsec support. The security model is integrated into the system architecture rather than layered on top of it.

Operational stability. NetBSD's release cycle produces stable branches that receive bug fixes and security updates while maintaining API and ABI compatibility within a major version series. This means production systems can be updated for security without risking incompatibility with installed software or configuration files. The conservative approach to change ensures that once a system is configured correctly, it continues to work correctly over extended periods.

Honest Limitations and Trade-offs

NetBSD is not the best choice for every workload. Understanding its limitations is as important as understanding its strengths:

Smaller ecosystem. Compared to major Linux distributions or even FreeBSD, NetBSD has fewer users, fewer third-party tools written specifically for it, and less community-generated documentation. When you encounter an obscure problem, you are less likely to find someone else who has already solved it posted online. This means more time spent reading source code and official documentation rather than searching forums.

Hardware support lag. NetBSD's commitment to portability and code quality means that support for cutting-edge hardware often arrives later than on Linux or FreeBSD. Very new CPU generations, the latest network interface chips, or bleeding-edge GPUs may not have drivers available at release time. For server workloads using mainstream enterprise hardware, this is rarely a problem. For deployments requiring immediate support for brand-new components, it can be a constraint.

Package availability through pkgsrc. While pkgsrc offers more than twenty thousand packages, some software that is readily available on Linux distributions may not have a corresponding pkgsrc package or may lag behind upstream releases. The pkgsrc project prioritizes correctness and portability over currency; a package is not promoted to the main collection until it builds

and runs correctly across multiple platforms. This can mean waiting weeks or months for the latest version of a particular tool.

ZFS maturity. ZFS support in NetBSD, available since version 9.0, is functional but has known limitations. Systems with four gigabytes of RAM or less are prone to lockups due to high ARC memory consumption. Certain features including extattr wiring, efficient unlink operations, and zvol swap have open issues. For production deployments using ZFS as the primary filesystem on NetBSD, thorough testing in a staging environment is essential. The project continues to improve ZFS support but it is not yet at the same maturity level as FreeBSD's implementation.

Containerization limitations. NetBSD does not have an ecosystem comparable to Docker or Kubernetes. While Xen virtualization is well-supported and experimental jail-like isolation mechanisms are under development, container-based orchestration that has become standard practice in many organizations requires additional tooling and adaptation when using NetBSD as the host platform.

Performance optimization focus. FreeBSD has invested heavily in raw networking performance, particularly for high-throughput packet forwarding scenarios. Benchmark comparisons show FreeBSD can achieve higher packets-per-second rates on comparable hardware for certain workloads. NetBSD prioritizes correctness and architectural cleanliness over micro-optimizations; for most server applications this difference is negligible, but for specialized network appliances or extreme-performance scenarios it may matter.

Commercial support options. While commercial support exists through select vendors, the options are significantly fewer than for enterprise Linux distributions. Organizations that require guaranteed response-time SLAs or dedicated engineering support should verify that available providers meet their requirements before committing to NetBSD.

When NetBSD Is the Right Choice

Given its strengths and limitations, when is NetBSD the appropriate choice for production infrastructure?

It is an excellent fit when:

- You value code quality, architectural consistency, and long-term maintainability over having the newest features or widest hardware support.

- Your team has Unix expertise and is comfortable working with well-documented but less-popular systems.
- You need a predictable platform where behavior does not change unexpectedly between minor releases.
- Portability across different hardware architectures matters for your deployment model.
- Licensing flexibility is important for your organization's software strategy.
- You are building infrastructure that will be in place for years and want an operating system with a proven track record of stability.

Specific workload examples where NetBSD excels:

- Web serving and reverse proxy clusters where the mature networking stack and stable behavior are valuable.
- DNS infrastructure where correctness and reliability matter more than raw query-per-second maximums.
- Network appliances including firewalls, routers, and gateways leveraging NPF and routing capabilities.
- Database servers running PostgreSQL or MariaDB where process scheduling and memory management quality benefit transactional workloads.
- Mail servers where the combination of security features, stable operation, and comprehensive tooling is advantageous.
- Development and build infrastructure where pkgsrc provides reproducible package builds across platforms.
- Embedded and specialized deployments where portability to non-x86 architectures is required.

It may not be the best choice when:

- Your workload depends on software that is only available or well-supported on Linux.
- You need immediate driver support for very new hardware components.
- Container orchestration with Docker/Kubernetes is a hard requirement without adaptation work.
- Your organization requires extensive commercial support with guaranteed SLAs from multiple vendors.

- Raw network packet forwarding performance at millions of packets per second is the primary metric.

The decision to use NetBSD should be based on your specific requirements, team capabilities, and operational constraints rather than ideology. For many organizations running high-traffic server workloads, its combination of quality, stability, security, and licensing flexibility makes it a compelling option that deserves serious consideration alongside more mainstream alternatives.

Chapter 2: Architecture Deep Dive

Understanding how NetBSD works internally is not an academic exercise for production administrators. When you are tuning kernel parameters to handle connection storms, diagnosing why RAID reconstruction is slow, or debugging a networking issue that only appears under load, architectural knowledge transforms guesswork into systematic problem solving.

This chapter examines the internal structure of NetBSD at a level appropriate for engineers who will be operating it in production. We will cover the kernel organization, device driver model, process and scheduling subsystems, virtual memory management, networking stack design, userland architecture, and key differences from Linux and other BSD variants. The goal is not to produce kernel programmers but administrators who understand what their configuration changes affect and why certain behaviors occur.

The Kernel Structure

NetBSD uses a monolithic kernel architecture with support for loadable kernel modules. “Monolithic” means that core subsystems including process management, memory management, networking, and filesystem code run in kernel space as part of a single address space, rather than being isolated in separate microkernel services. This design choice provides low overhead for system calls and inter-subsystem communication at the cost of reduced isolation; a bug or vulnerability in any kernel component can compromise the entire system.

The kernel source tree is organized to reflect NetBSD’s portability philosophy:

- `src/sys/arch` contains machine-dependent code organized by architecture (amd64, i386, arm, etc.). Each architecture directory includes startup code, hardware-specific drivers, and assembly routines that interface directly with processor features.
- `src/sys/conf` holds configuration files and the build infrastructure for constructing kernels from configuration specifications.

- `src/sys/dev` contains device drivers organized by bus type (pci, isa, usb) and by integrated circuit family (ic). This separation allows the same core driver logic to be used across different bus attachments.
- `src/sys/kern` implements machine-independent kernel functionality including process management, scheduling, memory allocation, system call handling, and synchronization primitives.
- `src/sys/net` contains the networking stack implementation including protocol handlers for TCP, UDP, IP, ICMP, and related subsystems.
- `src/sys/netinet` and `src/sys/netinet6` hold IPv4 and IPv6 specific code respectively.
- `src/sys/ufs`, `src/sys/fs`, and related directories implement filesystem code through the VFS abstraction layer.
- `src/sys/uvm` contains the UVM virtual memory system implementation.

At runtime, the kernel is organized into several key subsystems that communicate through well-defined interfaces:

The process management subsystem tracks all running processes and their associated resources. Each process is represented by a struct proc containing execution state, open file descriptors, signal handlers, memory mappings, and accounting information. The scheduler selects which process runs on each CPU based on priority, policy, and fairness criteria.

The virtual memory subsystem (UVM) manages the mapping between virtual addresses used by processes and physical memory pages stored in RAM or swap space. It handles page faults, implements copy-on-write semantics for fork operations, manages shared memory objects, and coordinates with pagers to move data between memory and backing stores.

The VFS (Virtual File System) layer provides a uniform interface for all filesystem operations regardless of the underlying filesystem type. Applications call generic functions like open, read, write, and stat; VFS translates these into filesystem-specific operations through vnode structures that represent active files and directories.

The networking stack processes packets as they arrive from network interfaces, routes them through protocol handlers, manages connections for connection-oriented protocols, and delivers data to applications through the socket interface. The stack is organized in layers corresponding roughly to OSI model layers, with each layer implementing specific protocol functions.

The device driver subsystem communicates with hardware through a hierarchical bus attachment model where buses enumerate and manage devices, and drivers implement device-specific operations behind standardized interfaces.

Loadable kernel modules (LKMs) extend this architecture by allowing additional functionality to be compiled separately and loaded at runtime rather than being statically linked into the kernel binary. Modules are used for filesystems that may not be needed on every system, specialized network protocols, and certain device drivers. This reduces the base kernel size and allows adding functionality without rebooting, though modules must still follow kernel coding standards and share the same address space as core code.

Device Drivers and Bus Attachment

NetBSD's approach to device drivers is one of its most distinctive architectural features and a primary enabler of its portability. The design separates hardware-specific concerns from protocol logic through a hierarchical bus attachment model known as *autoconf* (automatic configuration).

At system boot, the kernel initializes buses in a top-down manner. The root bus (typically representing the motherboard or chipset) is initialized first. It then enumerates devices attached to it and for each device finds a matching driver by calling probe functions that identify hardware based on signatures, IDs, or other characteristics. When a match is found, the driver's attach function is called to initialize the device and register its capabilities with the kernel.

This process recurses through the bus hierarchy: a PCI bus driver attaches to the motherboard, then enumerates PCI devices including network cards, storage controllers, and potentially child buses like USB or SATA controllers, each of which in turn enumerate their own devices.

The key architectural principle is that drivers are split into two components:

1. **Machine-independent core logic** implements the protocol-specific behavior of a device. For example, an Ethernet driver's MI code handles packet transmission and reception at the data link layer, managing buffers, checksums, and MAC address filtering regardless of how the hardware is physically connected to the system.

2. **Machine-dependent bus attachment code** handles communication between the core logic and the specific bus type. The same Ethernet chip might be accessed through PCI memory-mapped I/O on one platform and through ISA port I/O on another; the MD code provides a consistent interface to the MI code while dealing with bus-specific details like register addressing, interrupt handling, and DMA setup.

This separation is reflected in the source tree organization. A driver for the Intel 82557/82559 Ethernet chip (fxp) has:

- `src/sys/dev/ic/fxp.c` containing MI core logic
- `src/sys/dev/pci/if_fxp_pci.c` containing PCI bus attachment code
- `src/sys/dev/isa/if_fxp_isa.c` containing ISA bus attachment code

The MI code never knows or cares which bus it is running on; it uses abstraction layers like `bus_space` for register access and `bus_dma` for memory transfer operations that are implemented differently by each bus type but present a uniform API.

For production administrators, this architecture has practical implications:

- Driver availability across platforms is predictable. If a hardware component works on one NetBSD port through a well-structured driver, it is likely to work on other ports that support the same bus type without modification.
- Debugging driver issues benefits from clear separation of concerns. When a network interface misbehaves, you can often determine whether the problem lies in the chip-specific logic or the bus attachment code based on symptoms and error messages.
- Custom kernel builds can exclude unnecessary drivers safely. Since each driver is modular and self-contained, removing support for hardware you do not use reduces kernel size without affecting unrelated functionality.

Pseudo-devices are a related concept worth understanding. These are “devices” that attach to software buses rather than physical hardware and provide services like networking protocols, virtual filesystems, or system interfaces. Examples include `plog` (packet filter logging), loopback interfaces, and the NPF packet filter itself. Pseudo-devices follow the same attachment model as hardware drivers but implement their functionality in pure software.

Process Model and Scheduling

NetBSD's process model is rooted in traditional Unix design with modern enhancements for SMP systems and real-time requirements. Understanding it is essential for tuning workloads that depend on predictable CPU scheduling behavior.

Processes and LWPs. NetBSD uses a 1:1 threading model where both processes and threads are implemented as Lightweight Processes (LWPs). An LWP is the fundamental unit of scheduling; it has its own kernel stack, register state, and scheduling priority. A traditional Unix process contains exactly one LWP; a multithreaded application contains multiple LWPs sharing address space and file descriptors but scheduled independently by the kernel.

Each LWP is represented by struct `lwp` containing execution context, scheduling information, signal state, and pointers to its owning process (struct `proc`). The process structure tracks shared resources including open files, memory mappings, user credentials, and child processes.

The Common Scheduler Framework. Introduced in NetBSD 5.0, the Common Scheduler Framework (CSF) provides a standardized interface for implementing different scheduling algorithms without modifying core kernel code. CSF defines scheduling classes, categories of policies that determine how LWPs are selected to run, and allows different classes to coexist on the same system.

The traditional 4.4BSD scheduler implements multi-level feedback queue scheduling with the following characteristics:

- Priorities range from 0 to 127, where lower values indicate higher priority. Kernel threads use priorities below 50; user processes operate in the 50–127 range.
- User process priority is calculated approximately as: $p_usrpri = PUSER + (p_estcpu / 4) + 2 * p_nice$, where p_estcpu is an exponentially weighted estimate of recent CPU usage and p_nice is the user-settable nice value ranging from -20 to +20.
- The priority estimate is recalculated approximately every 40 milliseconds using a digital filter that smooths out short-term fluctuations while responding to sustained load patterns.
- Interactive processes that frequently block on I/O operations naturally accumulate lower CPU usage estimates and receive higher scheduling priority, improving responsiveness without requiring explicit configuration.

- Time slicing uses round-robin scheduling within each priority level, with quantum lengths around 0.1 seconds for user processes.

The M2 scheduler (introduced alongside CSF) is optimized for SMP systems with different design goals:

- It uses per-CPU run queues to reduce lock contention on multiprocessor systems.
- Load balancing migrates LWPs between CPUs when imbalance exceeds configurable thresholds.
- CPU affinity mechanisms preserve cache locality by preferring to keep LWPs on their current processor.
- Critical scheduling operations are designed for constant-time performance regardless of the number of runnable threads.

Real-time scheduling classes (`SCHED_FIFO` and `SCHED_RR`) provide POSIX-compliant real-time policies:

- `SCHED_FIFO` runs a LWP until it blocks, yields, or is preempted by a higher-priority LWP. No time slicing occurs within the same priority level.
- `SCHED_RR` is similar but applies round-robin time slicing among LWPs at the same priority level.
- Real-time LWPs always preempt time-sharing LWPs regardless of nice values.

For production tuning, several aspects matter:

- The `maxusers` kernel configuration parameter affects many system limits including maximum processes and file descriptors. Setting it to 64 instead of the default 32 raises maximum processes to approximately 1044 and open file descriptors to around 3404.
- Nice values can adjust relative scheduling priority for different services but should be used judiciously; extreme nice adjustments can cause starvation or unpredictable behavior under load.
- CPU affinity (settable via `schedctl`) can improve performance for cache-sensitive workloads by keeping processes on specific processors, but reduces flexibility for load balancing.
- The scheduler does not support kernel-mode preemption; once a LWP enters the kernel, it runs to completion of its kernel operation. This design simplifies locking but means long-running kernel operations can delay other processing.

Virtual Memory Subsystem

NetBSD's virtual memory system, UVM (Unified Virtual Memory), was introduced in version 1.4 and represents a significant architectural improvement over traditional BSD VM. Designed by Charles Cranor with contributions from Matthew Green, Chuck Silvers, and others, UVM provides sophisticated page management while maintaining the clean design principles that characterize NetBSD.

Core concepts. UVM manages virtual memory through several abstractions:

- Virtual memory maps associate address ranges within a process's address space with backing objects (files, anonymous memory, device mappings). Each map entry specifies access permissions, sharing attributes, and flags controlling behavior like copy-on-write.
- Objects represent the source of data for mapped regions. File-backed objects read from filesystems; anonymous objects use swap space as backing store; device objects interface directly with hardware memory.
- Pages are fixed-size units of physical memory (typically 4KB on most architectures) that hold actual data. UVM tracks pages through several states: active (recently accessed), inactive (not recently used but still in memory), free (available for allocation), and paging (being transferred between memory and backing store).
- Pagers are object-specific handlers that move data between pages and their backing stores. The disk pager reads from filesystems; the anonymous pager manages swap space.

Lazy allocation. UVM uses lazy (demand) allocation: when a process requests virtual memory through `mmap` or `brk`, UVM reserves the address range but does not immediately allocate physical pages. Pages are allocated only when first accessed, triggering a page fault that the kernel handles by allocating memory and initializing it appropriately. This allows processes to overcommit virtual memory, requesting more than physically available, without wasting resources on memory that may never be used.

Page daemon. The page daemon runs in the kernel continuously, managing page state transitions:

- It moves pages from active to inactive lists based on access patterns and system memory pressure.
- When memory is scarce, it selects inactive pages for paging out to swap space, preferring modified (dirty) pages that have been written but not yet flushed to backing stores.
- It coordinates with pagers to perform actual I/O operations, using clustering techniques to combine multiple page transfers into larger, more efficient operations.

Swap management. NetBSD supports multiple swap devices and files configured through `/etc/fstab` with type `swap`. The kernel treats all swap areas as a single pool of backing store; individual pages are not bound to specific devices. Swap space serves three purposes:

1. Extending virtual memory beyond physical RAM by paging out inactive data.
2. Backing anonymous memory including stack, heap, and shared memory segments.
3. Supporting process swapping for systems that need to suspend entire processes to disk (rarely used in modern server environments).

For production systems, swap configuration matters:

- Servers handling high traffic should have swap space sized appropriately for workload characteristics. While active web serving does not typically require heavy swapping, unexpected memory pressure without available swap can cause out-of-memory conditions and process termination.
- Swap on fast storage (SSD/NVMe) reduces the performance penalty when paging does occur but should not be relied upon as a substitute for adequate RAM.
- The `kern.ipc.shmmaxpgs` sysctl controls maximum System V shared memory size; databases and other applications using shared memory segments may require increasing this from the default value of 8MB.

Top-down allocation. Modern NetBSD kernels allocate user process address space top-down, starting near the highest user addresses and growing downward for stack allocations while heap grows upward from lower addresses. This arrangement leaves a large gap between stack and heap that helps detect buffer overflow bugs and provides flexibility for memory mapping operations.

Networking Stack Architecture

NetBSD's networking implementation is one of its strongest subsystems, benefiting from decades of development and the same architectural discipline applied throughout the system. Understanding its structure is valuable for troubleshooting connectivity issues, tuning performance, and configuring advanced features like firewalls and load balancers.

Layered design. The stack follows a layered architecture roughly corresponding to the OSI model:

- At the lowest layer, network interface drivers (ifnet) handle hardware-specific packet transmission and reception. Drivers register with the kernel as interfaces with properties including MTU, flags, and address information.
- The link layer handles framing, MAC addresses, and protocols like ARP for IPv4 address resolution or Neighbor Discovery for IPv6.
- The IP layer (netinet/ip.c for IPv4, inet6/in6.c for IPv6) manages packet routing using the radix tree data structure for efficient longest-prefix matching, fragmentation and reassembly, TTL handling, and options processing.
- Transport protocols including TCP, UDP, SCTP, and others sit above IP, managing connections, flow control, congestion control, and reliable delivery where applicable.
- The socket interface (sys/socket.h) provides the API through which applications interact with the networking stack, abstracting protocol details behind a consistent programming model.

MBUFs. Network data is handled through mbuf (memory buffer) structures rather than direct memory copies between layers. An mbuf consists of a control header plus a data region; for larger packets, mbuf chains link multiple buffers together. This design minimizes copying as packets traverse the stack: each layer adds or removes headers in place rather than allocating new buffers.

For high-traffic systems, mbuf management is critical:

- The NMBCLUSTERS kernel option controls how many large mbuf clusters are available for packet data. Insufficient clusters cause packet drops under load.

- Automatic buffer tuning (`net.inet.tcp.recvbuf_auto` and related sysctls) adjusts socket buffer sizes based on connection characteristics, but maximum values may need manual adjustment for high-bandwidth links.

Routing. NetBSD uses a radix tree implementation for IP routing tables, providing efficient lookup performance even with large numbers of routes. The routing subsystem supports:

- Static routes configured through the `route` command or `rc.conf` scripts.
- Dynamic routing protocols including RIP (routed), OSPF (via third-party packages like Bird or FRRouting), and BGP (also via packages).
- Policy-based routing allowing traffic to be directed based on source address, interface, or other criteria.
- IPv6 routing with full support for prefix delegation and autoconfiguration.

Interrupt handling and netisr. Modern NetBSD kernels use network interrupt steering (`netisr`) to distribute network processing across multiple CPUs in SMP systems. When a packet arrives, the interrupt handler places it on a per-CPU queue; dedicated kernel threads process packets from these queues rather than doing all work in the interrupt context. This design reduces interrupt latency and improves parallelism for high-throughput interfaces.

NPF packet filter. NetBSD's native packet filter (NPF), introduced in version 6.0, is a high-performance, modular layer 3 filtering system that supports IPv4, IPv6, stateful inspection, NAT, IP tables, and traffic normalization. NPF replaced the older `pf` implementation which has been deprecated. NPF uses bytecode compilation with JIT optimization for rule evaluation, providing efficient filtering even with complex rule sets. Configuration is through `/etc/mpf.conf` using a syntax that supports variables, tables, groups, rules, and NAT mappings.

Userland Design Philosophy

NetBSD's userland, the collection of programs, libraries, and utilities that run outside the kernel, follows design principles consistent with the rest of the system: correctness, portability, and clean architecture.

The C library. NetBSD ships its own implementation of `libc` rather than relying on third-party libraries like `glibc`. This provides several advantages:

- Tight integration with kernel interfaces without compatibility layers.
- Consistent behavior across all NetBSD ports since the same codebase is used everywhere.
- Easier maintenance and security auditing since the library is part of the core project rather than an external dependency.

The libc implementation follows POSIX standards closely while providing BSD-specific extensions where useful. System call wrappers in libc translate application calls into kernel traps using architecture-specific mechanisms but presenting a uniform API to applications.

Standard utilities. The base system includes a comprehensive set of command-line tools following Unix traditions: shell (sh, ksh), text processing (sed, awk, grep, sort), file management (cp, mv, rm, find), networking utilities (ifconfig, ping, netstat, traceroute, tcpdump), and administrative tools (ps, top, vmstat, iostat). These utilities are generally compatible with other BSD systems and POSIX standards while occasionally providing NetBSD-specific extensions.

Init system. NetBSD uses a traditional SysV-style initialization system driven by /etc/rc.conf and scripts in /etc/rc.d/. Services are enabled or disabled through variables in rc.conf (sshd=YES, ntpd=YES, etc.) and started in a defined order during boot. This approach is straightforward, well-documented, and reliable compared to more complex modern init systems, though it lacks some features like dependency-based parallel startup that systemd provides.

Privilege separation. Many core services implement privilege separation architectures where components requiring root access are isolated from components handling untrusted input. The sshd daemon is a prominent example: an unprivileged child process handles protocol parsing and user interaction while a privileged parent manages authentication and key operations through a controlled communication channel. This design limits the damage that vulnerabilities in protocol-handling code can cause.

How It Differs from Linux and Other BSDs

Understanding how NetBSD compares to alternatives helps administrators coming from other platforms adapt their mental models and avoid assumptions that do not carry over.

Versus Linux:

- **Kernel architecture:** Linux is monolithic with extensive use of loadable modules; NetBSD is also monolithic but with stricter separation between MD and MI code and less reliance on modules for core functionality.
- **Device model:** Linux uses the device tree and sysfs for hardware abstraction; NetBSD uses its autoconf bus attachment hierarchy. The conceptual models differ significantly.
- **Networking:** Linux networking configuration typically uses iproute2 tools (ip, ss) and iptables/nftables for filtering; NetBSD uses BSD-style ifconfig/netstat and NPF for packet filtering.
- **Package management:** Linux distributions use diverse package managers (apt, yum, pacman, etc.) with different philosophies; NetBSD uses pkgsrc consistently across all ports.
- **Init system:** Modern Linux largely uses systemd; NetBSD uses traditional rc.d scripts.
- **Licensing:** Linux uses GPL; NetBSD uses the permissive BSD license.

Versus FreeBSD:

- **Hardware focus:** FreeBSD optimizes for x86/x86_64 platforms with extensive tuning for those architectures; NetBSD maintains equal attention to all supported platforms, which can mean slower adoption of new x86 hardware features but more consistent behavior across diverse systems.
- **ZFS integration:** FreeBSD has deep, mature ZFS integration as a primary filesystem option; NetBSD's ZFS support is functional but less mature with known limitations on memory-constrained systems.
- **Networking performance:** FreeBSD has invested heavily in raw networking throughput optimizations; NetBSD prioritizes correctness and clean design over micro-optimizations, resulting in slightly lower peak packet forwarding rates in some benchmarks.
- **Package ecosystem:** FreeBSD ports offers more packages generally kept more current; pkgsrc emphasizes portability across operating systems, sometimes at the cost of currency on any single platform.

Versus OpenBSD:

- **Security approach:** OpenBSD conducts continuous proactive code audits specifically targeting security vulnerabilities and has introduced many security innovations (pledge, unveil, etc.); NetBSD relies on rigorous code review and quality standards rather than dedicated security auditing campaigns, resulting in a secure but differently-hardened system.

- Feature set: OpenBSD tends to ship only software developed or heavily modified by the project itself; NetBSD includes a broader range of functionality through pkgsrc and base system packages.
- pf vs NPF: OpenBSD created and continues to develop pf as its primary packet filter; NetBSD deprecated pf in favor of NPF, which has different configuration syntax and some architectural differences.

These differences are not value judgments but trade-offs reflecting each project's priorities and history. For production workloads, the choice among them depends on specific requirements around hardware support, performance characteristics, ecosystem compatibility, and operational preferences.

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