# STATELESS MCP SERVERS IN ACTION

DESIGNING, BUILDING, AND OPERATING SCALABLE MODEL CONTEXT PROTOCOL INFRASTRUCTURE


DESIGN | SECURE | DEPLOY | SCALE | OPERATE

DAVE RESSMAN

# Stateless MCP Servers in Action

## Designing, Building, and Operating Scalable Model Context Protocol Infrastructure

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# Contents

# Designing, Building, and Operating Scalable Model Context Protocol Infrastructure

About this book: The Model Context Protocol has emerged as the standard for connecting AI systems to external tools and data sources, but running MCP servers at production scale demands architectural rigor most developers have never needed. This book takes you from zero MCP knowledge to expert-level proficiency in designing, implementing, securing, deploying, and operating stateless MCP servers that can handle real-world traffic. Every chapter delivers practical guidance backed by complete, runnable code examples and production-tested patterns. By the end, you will be able to architect and maintain reliable, horizontally scalable MCP infrastructure that your organization can depend on.

# Introduction

In November 2024, Anthropic open-sourced the Model Context Protocol with a simple but ambitious goal: standardize how AI assistants connect to external tools, data sources, and systems [1]. Before MCP, every integration was bespoke. LangChain defined its own tool format. LlamaIndex used another schema. OpenAI had function calling specifications that differed again. Developers building AI applications faced an impossible choice: tie themselves to a single framework or write custom adapters for each client they wanted to support.

MCP changed that equation by introducing a universal protocol based on JSON-RPC 2.0, with well-defined message types for tool discovery, resource access, and prompt templating. Within months of its release, major players adopted the standard. OpenAI announced MCP support in its Agents SDK and Responses API. Google Cloud deployed remote MCP servers for Workspace integrations. Microsoft shipped MCP client support in Cursor and GitHub Copilot. The ecosystem grew from a curiosity into an industry standard faster than anyone anticipated [2, 3].

But protocol adoption is only the first challenge. Building an MCP server that works in development is straightforward. Building one that survives production is entirely different.

Production MCP servers face demands most developers have never encountered. They must handle hundreds or thousands of concurrent AI agents making tool calls simultaneously. Each agent expects low-latency responses because every millisecond adds to the end user's wait time. The servers must remain available during deployments, recover gracefully from infrastructure failures, resist abuse and unauthorized access, and scale elastically as traffic fluctuates throughout the day. They must do all of this while remaining compatible with any MCP-compliant client, now and in the future.

This is where stateless architecture becomes non-negotiable.

A stateless MCP server treats every request independently. It does not store session data in memory between requests. It does not rely on sticky sessions to a particular instance. Any request can be handled by any server instance at any

time, because all necessary context travels with the request itself. This design pattern is well established in traditional web services, but applying it correctly to MCP requires understanding the unique characteristics of AI-driven tool interactions: long-lived connections, streaming responses, complex capability negotiation, and the need for consistent behavior across distributed instances.

This book exists to bridge that gap. It assumes you know how to write code and deploy services, but it does not assume any prior knowledge of MCP or the specific challenges of running AI infrastructure at scale. We start from first principles: what MCP is, how the protocol actually works on the wire, and why statelessness matters for production deployments. From there, we build incrementally through implementation, security, scaling, observability, testing, and operations until you have a complete mental model for architecting MCP infrastructure that can handle real-world demands.

Every code example in this book is complete and runnable. You will not find pseudocode or "fill in the details later" placeholders. The Python implementations use the official MCP SDK v2, which supports the latest protocol specifications including the 2026-07-28 revision [4]. Configuration files are production-ready. Kubernetes manifests include proper resource limits and health checks. CI/CD pipelines integrate security scanning and automated testing. You can take these examples as starting points for your own deployments.

The book is organized into sixteen chapters plus a conclusion, arranged to build knowledge progressively. Chapters 1 through 3 establish the foundation: MCP protocol mechanics, stateless architecture principles, and the trade-offs that drive production design decisions. Chapters 4 through 9 cover implementation: building servers, choosing transports, handling authentication and authorization, managing context without server-side state, designing tools, and implementing streaming and concurrency patterns. Chapters 10 through 13 address reliability and quality: resilience engineering, caching and performance optimization, observability, and testing strategies. Chapters 14 through 16 focus on operations: cloud-native deployment with Kubernetes, multi-tenancy and interoperability, and production workflows including CI/CD, troubleshooting, and real-world case studies.

You do not need to read this book linearly if you already have experience in some areas. A backend developer comfortable with microservices might skip ahead to Chapter 4 for the MCP-specific implementation details. An AI infrastructure architect focused on deployment might jump to Chapters 14 and

15. But every chapter references concepts from earlier sections, so reading sequentially will give you the most coherent understanding of how all the pieces fit together.

By the time you finish, you will understand not only how to build a stateless MCP server, but why each architectural decision matters and what trade-offs you are accepting along the way. You will be able to evaluate different transport options for your use case, design authentication flows that meet enterprise security requirements, implement observability that actually helps during incidents, and deploy infrastructure that scales automatically without constant manual intervention. Most importantly, you will have a practical reference you can return to whenever you encounter a new challenge in MCP infrastructure.

The protocol is young and evolving rapidly. New specification revisions introduce capabilities and deprecate old patterns. This book reflects the state of MCP as of mid-2026, drawing on the latest stable specifications and production deployments from organizations running MCP servers at scale [5, 6]. Some details will change as the ecosystem matures, but the architectural principles discussed here — statelessness, horizontal scalability, defense in depth, comprehensive observability — are timeless. They apply to any distributed system that must remain reliable under load, not just MCP servers.

Let us begin with understanding what MCP actually is, why it exists, and why the choice of architecture matters more for MCP servers than for most other services you might deploy.

# Chapter 1: The Model Context Protocol and Why Statelessness Matters

## The Problem MCP Solves: Fragmented AI Tooling Ecosystems

Before MCP existed, connecting an AI model to external tools required framework-specific integration work. If you built your application with LangChain, you defined tools using LangChain's BaseTool interface. Switching to LlamaIndex meant rewriting those same tools with a different schema and calling convention. Moving to OpenAI's native function calling API required yet another adaptation. Each framework had its own way of describing tool inputs and outputs, handling errors, managing authentication, and negotiating capabilities.

This fragmentation created several concrete problems for organizations building AI applications at scale. First, it locked teams into specific frameworks. Migrating between LangChain and LlamaIndex was not a simple configuration change; it required rewriting all tool integrations because the underlying protocols were incompatible [7]. Second, it prevented tool reuse. A database query tool built for one framework could not be shared with applications using another framework without creating wrapper code. Third, it complicated multi-agent architectures where different agents might use different frameworks but needed access to the same set of tools and data sources.

The situation was unsustainable. As AI adoption accelerated in 2024 and 2025, organizations found themselves maintaining dozens or hundreds of custom tool integrations across multiple frameworks. Each integration was a maintenance burden: security patches had to be applied separately, API changes required updates in multiple places, and debugging issues meant understanding the quirks of each framework's tool calling mechanism.

MCP addressed this problem by introducing a single, open protocol that any framework could implement. Instead of each framework defining its own tool interface, MCP defines a universal standard: tools are described using JSON Schema, invoked through standardized JSON-RPC methods, and discovered via a common capability negotiation process. A developer builds an MCP server once, and every MCP-compliant client can use it without modification [8].

The protocol draws inspiration from the Language Server Protocol, which solved a similar fragmentation problem for IDE tooling. Before LSP, each editor needed custom plugins to support language features like autocomplete and error checking. After LSP, any editor implementing the protocol could work with any language server. MCP applies the same pattern to AI tooling: any client implementing MCP can connect to any MCP server.

This standardization matters enormously for production deployments. When your organization runs multiple AI applications using different frameworks or model providers, MCP eliminates the need to maintain parallel sets of tool integrations. You build one MCP server for your database queries, one for your CRM system, one for internal APIs, and all your AI applications can use them through the same protocol. This reduces operational complexity, improves consistency, and makes it easier to enforce security policies across all tool access points.

## What MCP Is and What It Is Not

MCP is a protocol specification that defines how clients and servers communicate to enable AI models to access external tools and data. At its core, it specifies:

- A JSON-RPC 2.0 message format for all communication between parties [9]
- A lifecycle protocol for connection initialization, capability negotiation, and session management
- Standard method names and parameter schemas for discovering and invoking tools, reading resources, and using prompts
- Transport mechanisms for carrying messages over stdio, HTTP with Server-Sent Events, and Streamable HTTP

MCP defines three primary server capabilities that applications can expose to AI models:

Tools are executable functions that an AI model can invoke to perform actions. Examples include querying a database, calling an external API, running code in a sandboxed environment, or updating records in a CRM system. Each tool has a unique name, a description explaining its purpose, and a JSON Schema defining its input parameters [10]. The AI model decides when to call a tool based on the conversation context and the tool's description, then passes the specified parameters through MCP.

Resources are read-only data sources that provide context for AI responses. Examples include file system contents, database records, API documentation, or real-time sensor data. Resources use URI-based addressing and can be listed, read, and optionally subscribed to for change notifications [11]. Unlike tools, resources do not perform actions; they simply provide data the model can reference when generating responses.

Prompts are templated messages that help users interact with AI models in structured ways. A prompt template might define a code review workflow, a customer support response pattern, or a data analysis procedure. Prompts accept parameters that customize the template for specific use cases [12]. They are less commonly implemented than tools and resources but provide a standardized way to encode organizational knowledge about how AI should be used.

Understanding what MCP is not equally important. MCP is not an AI framework. It does not include model inference, prompt engineering utilities, memory management, or agent orchestration logic. Those responsibilities belong to the client application, which uses MCP servers as external capabilities. MCP is also not a runtime environment. It does not sandbox tool execution, manage dependencies, or provide isolated computing environments. The server implementation handles those concerns independently.

MCP does not define its own authentication or authorization system for HTTP transports. Instead, it builds on OAuth 2.1 and standard web security practices [13]. For stdio transports, it relies on the operating system's process isolation and environment variable passing. This design choice keeps the protocol focused on communication semantics while delegating security to well-established mechanisms.

Finally, MCP is not a replacement for existing API standards like REST

or gRPC. MCP servers often call REST or gRPC APIs internally as part of tool execution. MCP sits at a different layer: it standardizes how AI clients discover and invoke capabilities, regardless of the underlying implementation technology.

## Stateful vs Stateless Servers: The Fundamental Trade-off

The distinction between stateful and stateless server architecture is fundamental to distributed systems design. A stateful server maintains information about client interactions in memory between requests. It might store session data, conversation history, authentication tokens, or partial computation results. When a client sends a new request, the server uses this stored state to provide context-aware responses.

A stateless server takes a different approach. Each request contains all information necessary for processing. The server does not rely on previously stored data about that particular client or session. If it needs persistent information, it retrieves it from external stores like databases or caches rather than maintaining it in process memory.

For traditional web applications, the choice between these models often involves trade-offs between performance and scalability. Stateful servers can respond faster because frequently accessed data is already in memory. But they are harder to scale horizontally: adding more instances requires either sticky sessions (routing each client to the same server) or complex state synchronization mechanisms.

MCP introduces unique considerations that make this trade-off particularly important. AI-driven tool interactions differ from typical web requests in several ways. First, conversations can span many tool calls over extended periods. A user might ask an AI agent to analyze data, generate a report, send it via email, and update a project management system — all as part of one logical task involving dozens of individual tool invocations. Second, some tools are inherently stateful: a code execution environment accumulates variables across calls, a database transaction spans multiple operations, or a file editing session builds on previous changes [14]. Third, MCP supports long-lived connections through SSE and Streamable HTTP transports, which might suggest stateful behavior is natural or necessary.

These characteristics tempt developers toward stateful designs. It seems convenient to store conversation context in memory, maintain active tool

sessions as server-side objects, and rely on connection persistence to keep everything organized. This approach works fine during development with a single server instance serving a handful of clients.

In production, it becomes a liability. Stateful MCP servers cannot scale horizontally without sticky sessions, which create load balancing complexity and reduce fault tolerance. If a server instance crashes, all in-progress conversations and tool sessions on that instance are lost. Deploying updates requires draining connections from each instance sequentially to avoid disrupting active sessions. Memory usage grows unbounded as more clients connect, because the server must retain state for every active session simultaneously.

Stateless architecture eliminates these problems by design. Every request carries its own context. Any server instance can handle any request at any time. Failed instances are replaced transparently without affecting other requests. Deployments proceed with zero downtime because new instances serve traffic immediately without requiring session migration. Memory usage remains predictable because each request processes independently and releases resources when complete.

The trade-off is that achieving true statelessness requires deliberate design work. You cannot simply store everything in server memory; you must externalize state to databases, caches, or client-side storage. You must structure requests so they contain all necessary context rather than relying on implicit session state. You must handle long-running operations differently, using patterns like task queues and polling instead of blocking connections.

For MCP servers specifically, this means designing tool handlers that do not assume persistent execution context between calls, implementing capability discovery as pure functions that return consistent results regardless of server state, and building connection handling that treats each message independently even over long-lived transports. The effort required is significant but necessary for any production deployment that must handle real traffic loads.

## Why Stateless Architecture Wins in Production

The argument for stateless MCP servers in production rests on five pillars: horizontal scalability, fault tolerance, operational simplicity, cost efficiency, and composability.

Horizontal scalability is the most obvious benefit. Stateful servers face a hard limit determined by individual instance capacity: memory for storing session data, CPU for processing requests, file descriptors for maintaining connections. When you hit that limit, you must either upgrade to larger instances (vertical scaling) or implement complex state-sharing mechanisms to distribute load across multiple instances. Vertical scaling has diminishing returns and expensive upper bounds. State sharing introduces latency, consistency challenges, and additional failure modes.

Stateless servers scale horizontally without these complications. Adding capacity means launching more identical instances behind a load balancer. Each new instance immediately begins serving traffic because it does not need to synchronize state with existing instances or wait for session migration [15]. This pattern aligns perfectly with modern cloud infrastructure: Kubernetes Horizontal Pod Autoscaler can add replicas automatically based on CPU utilization, request queue length, or custom metrics like active connections per second. The scaling decision is simple because each instance contributes linearly to total capacity.

Fault tolerance follows directly from horizontal scalability. In a stateful architecture, losing a server instance means losing all sessions hosted on that instance. Users experience errors, in-progress operations fail, and recovery requires reconstructing lost state from logs or backups — if that is even possible. Stateless servers handle failures transparently. When an instance fails, the load balancer stops routing traffic to it, and existing connections are redistributed to healthy instances. Because no instance holds unique session data, no user context is permanently lost [16].

Operational simplicity matters enormously for teams maintaining production systems. Stateful deployments require careful planning for every operational action. Rolling updates must drain connections from each instance before replacing it, extending deployment windows and increasing the chance of errors. Debugging issues requires correlating logs across instances while tracking which sessions ran where. Capacity planning involves estimating per-session memory usage and connection overhead to determine how many clients each instance can support.

Stateless deployments simplify all of these operations. Rolling updates proceed by gradually replacing instances without draining connections: new instances start serving traffic immediately, old instances stop receiving new requests and terminate when their current work completes [17]. Debugging

focuses on individual requests rather than session lifecycles, because each request is self-contained and traceable through standard logging. Capacity planning reduces to understanding per-request resource consumption and applying well-established formulas for sizing instance counts based on expected throughput.

Cost efficiency emerges from the combination of scalability and operational simplicity. Stateful servers require over-provisioning to handle traffic spikes: if peak load requires ten instances, you must run all ten continuously because sessions cannot be redistributed if you scale down during off-peak periods. Stateless servers can scale dynamically: running two instances during low traffic, scaling to ten during peaks, and returning to two when demand subsides. Cloud providers charge for provisioned resources, so this elasticity translates directly into cost savings [18].

Composability is the least obvious but potentially most valuable benefit. Stateless MCP servers can be combined freely in complex architectures without worrying about state coordination between them. An AI application might connect to five different MCP servers simultaneously: one for database queries, one for email operations, one for code execution, one for file storage, and one for external API integrations. Each server operates independently, scales based on its own load, and fails without affecting the others [19]. This modular design enables gradual architecture evolution: you can replace individual servers with improved implementations, add new servers for additional capabilities, or decompose monolithic servers into specialized components without disrupting the overall system.

None of these benefits come for free. Stateless design requires investing upfront in proper architecture: external data stores for persistent state, distributed caches for frequently accessed data, robust authentication and authorization mechanisms that work across instances, comprehensive observability to track requests through a distributed system, and resilient patterns for handling failures gracefully. But this investment pays dividends throughout the system's lifetime, reducing operational burden and enabling growth that would be impossible with stateful architecture.

## Book Roadmap: From Protocol to Production

This book is structured to build your knowledge progressively from protocol fundamentals through production operations. Each chapter depends on con-

cepts introduced earlier, so reading in order will give you the most coherent understanding. However, individual chapters are written as complete references that you can consult independently when working on specific aspects of your MCP infrastructure.

Chapters 1 through 3 establish the conceptual foundation. This chapter explains why MCP exists and why stateless architecture matters for production deployments. Chapter 2 provides a thorough technical reference for the MCP protocol itself: JSON-RPC mechanics, message types, capability negotiation, tool invocation patterns, and version compatibility guarantees. Chapter 3 explores stateless architecture principles in depth: how to classify different types of state, patterns for externalizing each type, idempotency requirements, and design considerations for horizontal scaling from the beginning.

Chapters 4 through 9 cover implementation details with complete, runnable code examples. Chapter 4 walks through building your first production-quality stateless MCP server using the official Python SDK: project setup, dependency management, implementing the initialization handshake, registering tools with proper metadata, and testing locally. Chapter 5 examines transport options in detail: stdio for local development, SSE for legacy integrations, and Streamable HTTP as the production standard — including complete server implementations for each. Chapter 6 addresses security comprehensively: authentication models using API keys, OAuth 2.1, and mTLS; authorization strategies for controlling tool access; input validation to prevent injection attacks; rate limiting to prevent abuse; and TLS configuration best practices.

Chapter 7 tackles the core challenge of stateless MCP servers: maintaining context across requests without server-side state. You will learn request correlation patterns, trace propagation techniques, client-side context management strategies, session identity embedding in every request, and handling long-running operations without blocking state. Chapter 8 focuses on tool design: crafting schemas that AI clients can consume effectively, static versus dynamic tool registration, parameter validation, managing tool dependencies, and versioning strategies for evolving tool APIs. Chapter 9 covers streaming responses, async programming patterns, concurrency models including event loops and worker pools, backpressure handling, and flow control for high-throughput deployments.

Chapters 10 through 13 address reliability and quality assurance. Chapter 10 explores resilience engineering: the MCP error model, retry strategies with exponential backoff and jitter, circuit breaker patterns to prevent cascading

failures, bulkhead isolation for protecting critical operations, timeout design, graceful degradation during partial failures, and dead letter queues for failed request recovery. Chapter 11 covers caching and performance optimization: distributed caching patterns using Redis, cache key design and invalidation strategies, rate limiting algorithms including token bucket and sliding window approaches, connection pooling for database and HTTP clients, profiling techniques, and performance tuning methodologies.

Chapter 12 provides a complete guide to observability: structured logging with correlation IDs, core metrics covering latency, throughput, error rates, and resource saturation, distributed tracing integration using OpenTelemetry, alert design principles for avoiding noise while catching real problems, and building operational dashboards that help during incidents. Chapter 13 addresses testing comprehensively: unit tests for tool handlers, protocol-level integration tests, end-to-end tests with real AI clients, load testing methodologies using k6 and Locust, capacity planning based on benchmark results, chaos engineering practices, and continuous quality gates in CI/CD pipelines.

Chapters 14 through 16 focus on production deployment and operations. Chapter 14 covers cloud-native deployment: containerizing MCP servers with optimized multi-stage Docker builds, Kubernetes manifests including Deployments, Services, ConfigMaps, and Horizontal Pod Autoscalers, ingress configuration for load balancing and TLS termination, service mesh integration with Istio or Linkerd, and multi-region deployment patterns for global availability. Chapter 15 addresses advanced production concerns: multi-tenant architecture with data isolation models and resource quotas, API versioning strategies for evolving MCP servers while maintaining backward compatibility, interoperability with popular AI frameworks including LangChain, LlamaIndex, and Vercel AI SDK, and migration patterns for transitioning from stateful to stateless deployments.

Chapter 16 completes the book with operational workflows: CI/CD pipelines using GitHub Actions for automated building, testing, security scanning, and deployment; canary deployment strategies using Argo Rollouts or similar tools; rollback procedures when issues arise; troubleshooting methodologies for diagnosing production incidents; debugging techniques specific to MCP infrastructure; common pitfalls and anti-patterns based on real-world experience; reference architectures for different deployment scenarios; and case studies from organizations running MCP servers at scale.

The conclusion synthesizes key themes from the entire book, projects future directions for MCP and AI infrastructure architecture, and provides a checklist of architectural decisions you should make when designing your own stateless MCP server deployment.

Throughout the book, code examples use Python with the official MCP SDK v2 and FastAPI for HTTP transports. These choices reflect current ecosystem maturity: Python has the most complete MCP SDK implementation, and FastAPI provides excellent async support, automatic OpenAPI documentation, and strong type safety [4]. The architectural patterns discussed apply equally to implementations in other languages, and references to alternative SDKs appear where relevant.

Every chapter includes practical implementation guidance alongside theoretical discussion. You will find complete configuration files for Docker and Kubernetes, working authentication flows with OAuth 2.1 providers, production-ready logging and metrics setups, load testing scripts you can adapt for your own servers, and troubleshooting checklists for common production issues. The goal is not just to explain concepts but to give you concrete materials you can use when building real systems.

Let us move forward into the protocol itself. Chapter 2 will examine MCP's technical foundations in detail so you understand exactly how messages flow between clients and servers, what the specification requires versus recommends, and where implementation flexibility exists for your architectural choices.

# Chapter 2: MCP Protocol Fundamentals

## JSON-RPC 2.0 as the Wire Format

MCP builds all of its communication on top of JSON-RPC 2.0, a lightweight remote procedure call protocol that encodes messages as JSON objects [9]. This is a deliberate choice: JSON-RPC provides a standardized envelope for requests, responses, and notifications without imposing opinions about transport mechanisms, authentication schemes, or server architecture. The same JSON-RPC message can travel over stdio pipes, HTTP connections, WebSockets, or any custom transport that supports ordered byte streams.

Understanding JSON-RPC 2.0 is essential for building MCP servers because the protocol defines three distinct message types, each with specific semantics:

A request is a call that expects a response. It contains four fields: jsonrpc set to "2.0", method specifying the operation to perform, params providing arguments as either an object or array, and id uniquely identifying the request as either a string or integer. The server must respond to every request with either a successful result or an error, matching the original id so the client can correlate responses with outstanding requests [20].

A response contains three fields: jsonrpc set to "2.0", id matching the corresponding request, and either result containing the successful return value or error describing what went wrong. A response must never contain both result and error simultaneously – doing so violates the JSON-RPC specification and will cause undefined behavior in clients [21].

A notification is a one-way message that requires no response. It looks like a request except the id field is omitted entirely. Notifications are used for events, progress updates, and capability change announcements where the sender does not need confirmation from the receiver [22].

MCP uses all three message types extensively. Requests drive the core protocol operations: clients send initialize requests to start sessions, tools/list

requests to discover available capabilities, and tools/call requests to invoke specific functions. Responses carry results back to clients: initialization metadata, tool definitions, execution outputs, resource contents, and error information. Notifications enable server-to-client communication without requiring client requests: progress updates during long-running operations, resource change events when subscribed resources are modified, and logging messages for debugging purposes [23].

The JSON-RPC specification also defines batch messaging: a single transport message can contain an array of individual requests, notifications, or responses. MCP implementations must be able to receive and process batches even if they do not send them. This matters for production servers because some clients may optimize network efficiency by batching multiple operations together, and your server must handle these correctly without treating the batch as a single malformed request [24].

Error handling in JSON-RPC follows a structured format. Every error response includes three fields: code (an integer identifying the error type), message (a human-readable description), and data (optional additional context). The specification reserves codes from -32768 to -32000 for predefined errors like Parse Error (-32700), Invalid Request (-32600), Method Not Found (-32601), Invalid Params (-32602), and Internal Error (-32603). MCP defines its own error codes in the range -32000 to -32099 for protocol-specific failures like connection timeouts, capability mismatches, and tool execution errors [25].

For stateless server implementations, JSON-RPC's request-response model aligns naturally with stateless architecture. Each request contains all information needed for processing: the method name identifies which operation to perform, params carry all required arguments, and id provides correlation without requiring server-side session tracking. The server processes the request, generates a response, and discards any temporary state. The next request arrives independently and is handled the same way.

This model simplifies horizontal scaling enormously. Any server instance can process any request because no instance holds unique context about previous interactions. Load balancers can distribute requests using simple round-robin or least-connections algorithms without worrying about session affinity. Failed instances are replaced transparently because their loss does not orphan any in-progress conversations.

One subtlety worth noting: JSON-RPC itself is transport-agnostic, but different transports impose different constraints on message delivery ordering and reliability. Stdio provides a reliable, ordered byte stream within a single process lifetime. HTTP with SSE maintains ordering within each connection but requires careful handling when connections are dropped and re-established. Streamable HTTP adds session identifiers to maintain logical ordering across multiple HTTP requests [26]. Your stateless server design must account for these transport characteristics even though the JSON-RPC message format remains constant.

## The MCP Message Lifecycle: Initialize, Negotiate, Operate

Every MCP connection follows a three-phase lifecycle: initialization, capability negotiation, and operation. Understanding this sequence is critical because it defines when servers can and cannot process certain requests, what state must be established before normal operations begin, and how errors during each phase should be handled [27].

Phase one is initialization. The client begins by sending an initialize request containing its name, version, supported protocol version, and capabilities it offers (such as sampling or root directory listing). The server responds with its own metadata: name, version, supported protocol version, and the capabilities it provides (tools, resources, prompts) [28]. This exchange establishes the foundation for the entire session.

The initialization handshake serves several purposes. It confirms both parties speak compatible versions of the protocol. It lets each side understand what the other can do before attempting operations that might not be supported. It provides metadata useful for logging and debugging when issues arise in production. For stateless servers, this phase is particularly important because it determines which capabilities must be advertised consistently across all instances.

Consider a deployment with five identical MCP server instances behind a load balancer. When a client connects to instance A and receives an initialize response advertising three tools, the client expects those same three tools to be available if subsequent requests are routed to instance B or C. If instances

advertise different capabilities during initialization, clients may call tools that some instances do not support, resulting in Method Not Found errors [29].

This requirement has architectural implications for stateless server design. Tool registration must be deterministic: every instance of your server must expose the same set of tools with identical names and schemas. You cannot register tools dynamically based on runtime conditions that differ between instances unless you implement a shared configuration mechanism that guarantees consistency across all instances simultaneously [30].

Phase two is capability negotiation. After initialization completes, the client sends an initialized notification confirming it has processed the server's capabilities and is ready to begin operations. The server may optionally respond with notifications of its own: announcing resource subscriptions available, logging startup information, or requesting additional configuration from the client [31].

This phase is brief but important for protocol compliance. The MCP specification states that servers should not process tool calls or resource reads until they have received the initialized notification. Processing requests before this point risks operating with incomplete capability information: the client might not be ready to handle certain response formats, or required configuration might not yet be established [32].

For stateless servers, this means implementing a simple connection-level flag that tracks whether initialization has completed. This flag is short-lived and per-connection rather than per-client, so it does not violate statelessness principles. When a new HTTP connection arrives or a stdio stream opens, the flag starts as false. After processing initialize and sending the response, the server waits for initialized notification before setting the flag to true. All subsequent requests check this flag and reject operations with an appropriate error if initialization has not completed [33].

Phase three is operation. Once initialization completes successfully, the connection enters its primary working state. Clients send tool calls, resource reads, prompt requests, and other operational messages. Servers respond with results or errors, optionally sending notifications for progress updates, resource changes, or log messages throughout the session [34].

This phase can last from a single request to hours of continuous interaction. MCP supports long-lived connections through SSE and Streamable HTTP transports, where clients maintain persistent connections that receive both

responses to their requests and unsolicited notifications from the server. A stateless server must handle this correctly: treating each incoming request independently while maintaining the connection for potential future messages [35].

The key insight for stateless design is that "long-lived connection" does not mean "long-lived state." The connection is a transport mechanism for delivering messages, not a container for session data. Each message on the connection is processed independently using the same logic as any other message. The server does not accumulate context about the conversation or store intermediate results between messages unless explicitly required by a specific tool's operation [36].

Connection termination can happen at any point: clients may close connections voluntarily, network failures may drop them silently, or servers may terminate them due to timeouts or resource limits. When this happens, all data associated with that specific connection (the initialization flag, any in-flight request processing) is discarded. The next connection from the same client begins fresh with a new initialization handshake [37].

This behavior has implications for tool design. Tools that perform multi-step operations cannot rely on a single persistent connection to maintain state between steps. Instead, they must either complete all work within a single tool call (potentially taking significant time but returning a complete result), or use external mechanisms like task queues and polling endpoints where clients check operation status using request IDs rather than connection identity [38].

## Server Capabilities and Client Discovery

MCP's capability model provides a standardized way for servers to advertise what they can do and for clients to discover available functionality dynamically. This model is fundamental to MCP's design philosophy: build tools once, let any compatible client find and use them automatically [39].

During initialization, the server includes a capabilities object in its response listing all features it supports. The specification defines three primary capability categories:

The tools capability indicates the server exposes executable functions that AI models can invoke. When present, clients know they can send tools/list requests to discover available tools and tools/call requests to execute them

[40]. Tools must have unique names within a server, JSON Schema definitions for their parameters, and clear descriptions explaining their purpose.

The resources capability signals the server provides read-only data sources addressable by URI. Clients can send resources/list to enumerate available resources, resources/read to retrieve specific content, and optionally subscribe to change notifications using resources/subscribe [41]. Resources support templating through resource templates, which define parameterized patterns for generating resource URIs dynamically.

The prompts capability announces the server offers templated message workflows. Clients use prompts/list to discover available prompts and prompts/get to retrieve specific prompt templates with their parameters filled in [42]. Prompts are less commonly implemented than tools and resources but provide a standardized mechanism for encoding organizational knowledge about AI interaction patterns.

Each capability can include additional metadata. The tools capability might specify whether the server supports tool annotations or structured output schemas. The resources capability might indicate support for subscription-based change notifications or specific content types [43]. This metadata helps clients make informed decisions about how to interact with the server and what features they can rely on.

For stateless servers, capability advertisement must be consistent and deterministic. Every instance of your server must report identical capabilities during initialization, because clients may connect to different instances at different times and expect uniform behavior [44]. This means tool registration, resource definitions, and prompt configurations cannot depend on per-instance runtime conditions unless those conditions are synchronized across all instances through a shared configuration mechanism.

Consider a scenario where tools are registered dynamically based on database queries or external API responses. If instance A's database contains different data than instance B's database at the moment of initialization, they might advertise different tool sets. Clients connecting to instance A would discover tools unavailable on instance B, leading to confusing errors when requests are load-balanced between instances [45].

The solution is one of three approaches: first, define all capabilities statically in code or configuration files that are identical across all instances. This is the simplest and most reliable approach for most deployments. Second, use

a shared external configuration store (like Consul, etcd, or a database) that all instances query during initialization, ensuring they read the same capability definitions [46]. Third, implement capability caching with invalidation: each instance caches capabilities from an external source, refreshes periodically, and uses versioning to detect when cached data is stale.

Client discovery happens through tools/list requests after initialization completes. The client sends this request with no parameters, and the server responds with a list of Tool objects, each containing name, description, inputSchema (the JSON Schema for valid parameters), and optionally outputSchema and annotations [47]. This response allows clients to build their understanding of available functionality without hardcoding tool definitions.

For production servers, tools/list is called frequently: every time a new client connects, potentially multiple times during a session if the server supports dynamic tool registration, and whenever clients need to refresh their capability cache. This makes it an important performance consideration. The response should be generated efficiently, ideally from in-memory data structures populated at startup rather than computed on each request [48].

Stateless servers handle tools/list trivially: every instance maintains its own copy of the tool registry (loaded from static configuration or a shared external source), and each tools/list request simply returns this pre-built list. No coordination between instances is required because all instances serve identical data. The response time depends only on serialization overhead, not on database queries or cross-instance communication [49].

Capability negotiation also extends to protocol versioning. During initialization, both client and server specify their supported protocol versions. If no compatible version exists, the connection terminates with an error. When a compatible version is found, all subsequent communication uses that negotiated version's semantics [50]. For stateless servers, this means supporting multiple protocol versions simultaneously if needed: the version negotiated during initialization determines how each request on that connection is interpreted, but different connections may use different versions without conflict.

## Tools, Resources, Prompts, and Templates

Tools are the primary mechanism through which MCP servers expose functionality to AI models. Understanding tool semantics in detail is essential

for designing tools that work reliably in production, especially when serving multiple clients across distributed server instances [51].

A tool definition consists of four core components: name, description, input schema, and optionally output schema. The name uniquely identifies the tool within a server and must follow JSON-RPC method naming conventions (alphanumeric characters, underscores, forward slashes for namespacing). The description explains what the tool does in natural language – this text is shown to the AI model when it decides whether to call the tool, so clarity matters enormously [52].

The input schema uses JSON Schema to define valid parameter types and constraints. This schema serves dual purposes: it documents the tool's interface for both humans and AI models, and it provides machine-readable validation rules that servers enforce before executing tool logic. A well-designed input schema specifies required versus optional parameters, type constraints (string, number, boolean, array, object), enum values when applicable, minimum and maximum bounds for numeric types, pattern matching for strings, and nested object structures for complex inputs [53].

Consider a database query tool. Its input schema might define a required table parameter as a string limited to an enum of allowed table names, an optional filter parameter as an object with specific field definitions, and an optional limit parameter as an integer between 1 and 1000. This schema prevents the tool from accepting arbitrary SQL strings (which would be a security risk) while providing enough flexibility for useful queries [54].

The output schema, when present, defines the structure of successful results using JSON Schema. This helps AI models understand what data to expect from a tool call and how to use it in subsequent reasoning or actions. Not all tools require output schemas: some return simple text responses that do not benefit from structured typing [55].

Tool execution happens through tools/call requests containing the tool name and arguments matching its input schema. The server validates arguments against the schema before executing the tool logic. If validation fails, it returns an Invalid Params error without invoking the tool handler. If validation succeeds, the handler runs and returns either a successful result or an execution error [56].

For stateless servers, tool handlers must be designed as pure functions with respect to server-side state: they may read from external data stores

(databases, caches, file systems) and perform side effects in those stores, but they should not rely on in-memory state that persists between requests. Each tools/call request contains all information needed for execution: the tool name identifies which handler to invoke, arguments provide all required inputs, and any additional context (authentication tokens, tenant identifiers, trace IDs) travels in HTTP headers or request metadata [57].

This design constraint affects how you implement tools that naturally seem stateful. A code execution tool might appear to need persistent environment state between calls: variables defined in one call should be available in the next. For a stateless server, this requires externalizing the execution environment: using containerized runtimes with persistent storage, maintaining execution contexts in a distributed cache keyed by session identifiers, or accepting that each call starts fresh and requiring clients to pass necessary context explicitly [58].

Resources provide read-only data access through URI-based addressing. A resource definition includes a URI identifying the data source, a name for display purposes, a description explaining its contents, an optional MIME type indicating content format, and optionally upsertable flags indicating whether the resource can be modified [59]. Resources are discovered through resources/list requests and accessed through resources/read requests specifying the target URI.

Resource templates extend this model by defining parameterized patterns for generating resource URIs dynamically. A template might define a pattern like /users/{user_id}/profile where user_id is a required parameter. Clients use resources/templates/list to discover available templates, then construct specific URIs by filling in parameters [60]. This approach avoids requiring servers to enumerate potentially millions of individual resources while still providing structured access to parameterized data.

For stateless servers, resource reads are straightforward: each request specifies the resource URI or template with parameters, the server retrieves the data from its source (database, file system, external API), and returns it in the response. No session state is required because the URI fully identifies what data to return [61].

Prompts provide templated message workflows that guide AI interactions. A prompt definition includes a name, description, and parameters specifying customizable inputs. Clients retrieve prompts through prompts/get requests,

receiving rendered templates with parameters filled in according to their specifications [62]. Prompts are less commonly implemented than tools and resources but offer value for encoding standard interaction patterns: code review workflows, customer support procedures, data analysis methodologies, or compliance checklists.

For stateless servers, prompt retrieval is a pure function: given a prompt name and parameters, return the rendered template. No server-side state is involved because templates are defined statically or loaded from external configuration [63].

Templates across all three capability types (tools, resources, prompts) share a common principle: they define patterns that generate concrete instances dynamically rather than requiring explicit enumeration of every possible item. This approach scales well for production servers dealing with large datasets or dynamic configurations. A stateless server can support millions of resource URIs through templates without maintaining any per-resource state in memory [64].

## Protocol Versioning and Compatibility Guarantees

The MCP specification evolves over time, introducing new capabilities, modifying existing behaviors, and occasionally deprecating old features. Understanding versioning semantics is essential for building production servers that remain compatible with evolving clients while supporting gradual updates across distributed deployments [65].

MCP uses date-based version identifiers: 2024-11-05 was the initial release, followed by revisions like 2025-03-26, 2025-06-18, 2025-11-25, and 2026-07-28 [66]. Each version identifier represents a specific snapshot of the specification with defined compatibility guarantees. The current stable specification as of mid-2026 is the 2026-07-28 revision, which introduces refinements to authorization flows, streaming semantics, and error handling compared to earlier versions [67].

During initialization, both client and server declare their supported protocol versions. The negotiation process selects the highest version both parties support. If no overlap exists, the connection fails with a clear error explaining the incompatibility [68]. This mechanism allows gradual ecosystem evolution: newer clients can take advantage of latest features when connecting to updated

servers, while older clients continue working with servers supporting their required versions.

For stateless server deployments, version negotiation has important implications for rollout strategy. When deploying an updated server that supports a new protocol version, you do not need to update all instances simultaneously. New instances support the newer version while old instances continue supporting previous versions. Clients negotiate during initialization and connect to whichever instance they reach, using whatever version both sides support [69].

This rolling upgrade capability is one of the practical benefits of MCP's versioning design. You can deploy updates gradually: first a small percentage of instances with new capabilities, then incrementally increasing the ratio while monitoring for issues, then completing the rollout when confidence is high. If problems arise, you can roll back individual instances without disrupting clients connected to remaining old-version instances [70].

The MCP specification maintains backward compatibility within major version ranges. Features added in newer versions are optional: servers supporting older versions simply do not advertise new capabilities during initialization, and clients gracefully handle missing features by falling back to supported alternatives [71]. Breaking changes — modifications that invalidate existing client behavior — are rare and accompanied by extended deprecation periods giving implementers time to adapt.

However, some specification revisions have introduced notable changes that affect server implementations. The transition from SSE-based HTTP transport (2024-11-05) to Streamable HTTP (2025-03-26) represents the most significant architectural shift [72]. Servers built for the older SSE model required two endpoints: a GET endpoint for receiving server-to-client events and a POST endpoint for client-to-server requests. The Streamable HTTP model consolidates these into a single endpoint using content negotiation through Accept headers, simplifying deployment and improving compatibility with standard HTTP infrastructure [73].

Servers targeting production deployments in 2026 should support the Streamable HTTP transport as their primary HTTP mechanism while optionally maintaining SSE support for legacy clients. The official Python SDK v2 supports both transports and handles version negotiation automatically when configured correctly [4].

Another important change: OAuth 2.1 authorization became mandatory for internet-accessible MCP servers starting with the November 2025 specification revision [74]. Earlier versions allowed simpler authentication mechanisms like static API keys for HTTP transports, but production deployments now must implement proper OAuth flows including PKCE for public clients, Protected Resource Metadata publication, and audience token validation. Servers deployed before this change should plan migration to compliant authorization implementations [75].

For stateless servers, protocol versioning interacts with the consistency requirements discussed earlier. All instances in a deployment should ideally support the same set of protocol versions to avoid subtle behavioral differences when clients connect to different instances. If mixed-version deployments are necessary during rollouts, ensure that capability advertisement remains consistent: an instance supporting both old and new versions should advertise only capabilities that all instances in the pool support, or use version-specific capability negotiation to prevent clients from discovering features unavailable on some instances [76].

The official MCP SDKs abstract much of this complexity by handling version negotiation automatically. When you create a server using the Python SDK and declare your tools, resources, and prompts through the SDK's API, it generates appropriate initialization responses based on the negotiated protocol version [4]. This reduces the risk of manual implementation errors but does not eliminate the need to understand version semantics: when specification changes affect how tools behave or how transports work, you must update both your SDK dependencies and potentially your tool implementations to remain compliant [77].

With the protocol fundamentals established, we can now move into architectural principles. Chapter 3 will explore stateless architecture in depth: what true statelessness means for MCP servers, how to classify and externalize different types of state, patterns for ensuring idempotency, and design considerations that enable horizontal scaling from day one.

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