THE NEW GENERATION OF PROGRAMMING LANGUAGES

Vale, Valen, Bend, Revo, and the Future of Systems Programming

Memory safety, concurrency, type systems, and verification explored through four emerging languages and the bigger picture.

OWEN MACKENZIE

The New Generation of Programming Languages

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About this book: A comprehensive, technically rigorous examination of emerging programming languages that are reshaping how we think about memory safety, concurrency, type systems, and program verification. This book covers Vale, Valen, Bend, and Revo in depth, explains the computer-science concepts behind them, and surveys the broader landscape of next-generation language design. Written for experienced programmers, it includes complete runnable code examples, comparative analyses, and honest assessments of each project's current state and long-term prospects.

Introduction: Why We Need New Languages

In January 2013, a developer named Evan Ovadia began working on what he called VLang. It would be renamed GelLLVM, then Vale, and eventually it would be archived as development shifted to its successor, Valen. Vale was not the first systems language in decades, and it would not be the last. But Vale represented something important: a clear statement that the dominant approaches to memory safety (garbage collection and borrow checking) were not the only answers to the problems of building fast, safe systems software. Vale offered a third path built on generational references, a technique that enabled memory safety with predictable performance and without the ergonomic friction of Rust's borrow checker.

Across the same period, other projects were exploring radically different ideas. Bend emerged as a language that combines formal mathematical proofs with GPU parallelism, designed explicitly to verify code written by artificial intelligence. Revo positioned itself as a dynamic scripting language "for the joy of programming," bringing compile-time execution and first-class concurrency to a high-level runtime. Meanwhile, established research programs and corporate initiatives like Carbon, Move, and Roc continued to refine their visions of what programming could look like beyond the limitations of C, C++, Java, and even Rust.

This book examines that wave of innovation. It is not a survey of every experimental language that appeared on GitHub in the past few years. It is a focused, technically detailed exploration of four specific languages (Vale, Valen, Bend, and Revo) chosen because together they represent a significant cross-section of the design choices being tried today. It also covers a broader set of languages and research projects that contribute essential ideas to the field. The goal is to provide experienced programmers with enough understanding to evaluate these languages on their own terms: what problems they solve, what trade-offs they make, how they work internally, and whether they are worth learning for your own work.

The promise of this book

After reading this book, you should be able to:

Understand the core design philosophies and technical mechanisms of Vale, Valen, Bend, and Revo, including their type systems, memory models, concurrency approaches, and compilation strategies.

Explain the underlying computer-science concepts that influence modern language design: generational references, group borrowing, affine and linear types, effect systems, dependent types, capability-based security, and formal verification.

Compare these languages against each other and against established alternatives using concrete implementations of non-trivial programs, with honest assessments of ergonomics, safety, performance, tooling, and ecosystem maturity.

Evaluate emerging language projects critically, distinguishing stable features from experimental proposals, well-founded claims from marketing hype, and research prototypes from production-ready tools.

Make informed decisions about which languages to learn, evaluate, or adopt for specific kinds of problems, based on clear criteria rather than trend-chasing.

Who this book is for

This book assumes you are an experienced programmer who knows at least one established language well (C, C++, Rust, Go, Java, Python, or something similar), and who understands fundamental concepts like memory management, concurrency, type systems, and compilation. You do not need expertise in formal methods or type theory, but you should be comfortable reading technical material that references these fields.

If you are a language designer or compiler engineer, you will find implementation details, intermediate representations, and architectural discussions relevant to your work. If you are a systems programmer evaluating whether to adopt a new language for a real project, you will find honest assessments of each language's practical readiness, known limitations, and adoption prospects.

This book is not intended as a beginner's introduction to programming or as a casual overview of "the coolest new languages." It treats each language seriously, with technical depth and careful sourcing.

How to read this book

The book is organized into a logical progression from foundations through individual languages, comparative analysis, implementation details, real-world considerations, and future directions. You can read it linearly from start to finish, or you can jump directly to chapters covering specific languages or topics. Each chapter is self-contained enough to read independently while contributing to the overall narrative.

Chapters 1 and 2 establish the problem space and foundational concepts. Chapters 3 through 6 provide deep dives into Vale, Valen, Bend, and Revo respectively. Chapter 7 compares the languages directly using equivalent implementations of real programs. Chapters 8 through 11 examine technical details: type systems, concurrency, compiler architecture, and interoperability. Chapter 12 covers the broader landscape of emerging languages beyond the four main subjects. Chapters 13 through 16 address practical concerns: tooling, security, case studies, and project sustainability. The final two chapters synthesize everything into guidance about where language design is heading and how to make decisions about adoption.

Throughout the book, code examples are drawn from official documentation, repository examples, and project guides where possible. Every example is intended to be complete and runnable, with setup instructions provided. Performance claims and benchmark results are attributed to their sources and accompanied by caveats where appropriate.

An honest note about maturity

Before we begin, it is important to state clearly that most of the languages covered in this book are not production-ready. Vale is archived. Valen is a prototype barely past proof of concept. Bend is under active development but lacks many features expected of a mature language. Revo is a young scripting language with minimal ecosystem. Even the "beyond" languages vary widely in maturity: Carbon is still experimental despite Google's backing; Move is

production-proven only in blockchain contexts; Zig is approaching stability but has not yet released version 1.0.

This book treats these languages seriously not despite their immaturity but because of what they reveal about the direction of language design. Experimental languages are where the best ideas live before they become mainstream. Rust was once an experimental language with a broken toolchain and zero production users. Go was once considered too simplistic by many systems programmers. Understanding today's experiments is the best way to understand tomorrow's standards.

With that context established, let us begin with the problem space: the technical and practical challenges that motivated this entire wave of language innovation.

Chapter 1: The Problem Space - Why New Languages Now?

The history of programming languages is not merely a catalog of syntax variations and feature additions. It is a chronicle of attempts to solve specific problems that existing tools could not handle adequately. C solved the problem of writing portable systems software efficiently. C++ added abstractions that made large-scale software engineering more tractable. Java eliminated manual memory management through garbage collection. Go simplified concurrency and build processes. Rust solved memory safety and data-race safety at compile time without a garbage collector. Each language emerged because its predecessors left important gaps.

The languages examined in this book - Vale, Valen, Bend, Revo, and their peers - are responding to problems that remain unsolved by today's established languages. These problems fall into several categories: the memory safety crisis in existing software, concurrency bugs on multi-core hardware, the expressiveness gap between type systems and real-world needs, developer ergonomics, and the fragmentation of the programming ecosystem. To understand why new languages matter, we must examine each problem carefully.

The memory safety crisis and its cost

Memory safety violations - buffer overflows, use-after-free errors, double-free bugs, integer overflows - are the leading cause of security vulnerabilities in software. The C Programming Language, published in 1978, provided unprecedented power and portability but deliberately left memory management to the programmer. Decades of practice have shown that this approach does not scale.

The scale of the problem is enormous. The CISA Vulnerabilities Explorer lists tens of thousands of CVEs attributed to memory safety issues alone. In 2023, Microsoft estimated that seventy percent of the vulnerabilities it fixes in Windows are memory safety related. The Linux kernel faces similar

challenges: a 2021 study found that roughly half of all kernel vulnerabilities stem from memory safety bugs. Web browsers, operating systems, database servers, networking stacks, embedded firmware - virtually every critical piece of infrastructure contains memory-unsafe code.

The consequences are both practical and economic. Memory safety bugs cause crashes that frustrate users, data corruption that destroys trust, and security exploits that compromise entire networks. The economic cost is staggering: a widely cited report estimated that memory safety bugs cost the global economy hundreds of billions of dollars annually in damage, remediation, and lost productivity. Organizations dedicate significant resources to static analysis, dynamic checking, fuzzing, and code review in an attempt to catch these bugs, but none of these approaches are foolproof.

Garbage collection solves memory safety for a class of problems. Java, C#, and Go manage heap memory automatically, preventing use-after-free and double-free errors. But garbage collection comes with its own costs: runtime overhead, unpredictable pause times, increased memory usage, and difficulty integrating with C-based ecosystems. For systems programming - operating systems, device drivers, real-time control systems, high-frequency trading infrastructure - garbage collection is often unacceptable.

Borrow checking, as implemented in Rust, offers compile-time memory safety without a garbage collector. It has been tremendously successful: Rust is now the most loved language on Stack Overflow surveys and is being adopted by Microsoft, Google, Amazon, and the Linux kernel project itself. But borrow checking is not a complete solution. It is difficult to learn. It rejects some safe programs. It requires extensive lifetime annotations in complex code. It struggles with patterns like graphs with back-references, observers, and certain kinds of shared mutable state that are common in real systems. Rust programmers frequently resort to unsafe blocks, Rc and RefCell, or complex lifetime gymnastics to work around the borrow checker's restrictions.

These limitations are what motivated Vale's original design. As Ovadia stated in Vale's documentation: "Most other languages use garbage collection, reference counting, or borrow checking, but we chose generational references because they're fast and more flexible than borrow checking, allowing us to use common safe patterns like observers, higher RAII, the dependency injection pattern, delegates, back-references, graphs, and so on." Generational references, which we will examine in detail in Chapter 3, offer a third approach to memory safety that avoids the main drawbacks of both garbage collection

and borrow checking.

Concurrency bugs and the multi-core imperative

The end of Dennard scaling - the observation that transistors would continue to shrink and increase in frequency without increasing power dissipation - forced the semiconductor industry to shift from faster single cores to more cores per chip. A modern consumer CPU might have eight to sixteen cores. Server CPUs have sixty-four or more. GPUs offer thousands of parallel execution units. Moore's Law continues, but the benefit comes in parallelism, not clock speed.

This hardware reality creates an imperative for concurrency that few programming languages handle well. C provides threads and locks but no safety guarantees. Data races are undefined behavior, and detecting them requires external tools. C++ improved the situation with the memory model introduced in C++11 and the std::atomic library, but data races remain a frequent source of bugs. Java's garbage collector simplifies concurrent programming somewhat by ensuring references are always valid, but it does nothing to prevent data races or deadlocks. Go's goroutine model is elegant and productive, but concurrent bugs are still common.

Rust's ownership system provides the strongest guarantee: "fearless concurrency" without data races. If Rust code compiles without unsafe blocks, it is guaranteed to be free of data races. This is a remarkable achievement. But Rust's approach to concurrency has limitations. Shared mutable state requires either interior mutability with Run-time checks (RefCell, Mutex) or complex ownership patterns. Actor models, software transactional memory, and structured concurrency are not built into the language, though libraries exist for all of them.

The next generation of languages explores alternatives. Bend's pure functional approach with affine types eliminates data races entirely by design: if values cannot be shared, they cannot be accessed concurrently in conflicting ways. Bend goes further by automatically distributing pure computations across thousands of GPU cores without any explicit threading annotations. Valen's group borrowing model, which we will examine in Chapter 4, allows multiple mutable references to the same data under carefully constrained conditions, enabling concurrency patterns that Rust rejects. Revo's fiber-based

concurrency model provides lightweight non-blocking parallelism for scripting workloads.

The concurrency problem is not merely technical; it is economic. Concurrent bugs are among the hardest to debug: they are non-deterministic, difficult to reproduce, and may only appear under extreme load. The cost of fixing a concurrency bug in production can be enormous. Languages that make concurrent programming easier and safer offer direct economic value.

The expressiveness gap: type systems in practice

Type systems exist to catch errors at compile time rather than at runtime. The stronger a type system, the more errors it can catch. But strong type systems can also reject valid programs, require excessive annotations, or become so complex that programmers struggle to use them.

Most mainstream languages have relatively weak type systems. C's type system prevents some errors but allows virtually all the dangerous ones. Java and C# have richer type systems but lack genericity in many useful dimensions. Go's type system is deliberately simple, which aids ergonomics but limits expressiveness. Python's type system is optional and structural, which is convenient but provides no compile-time guarantees unless supplemented by external type checkers.

Rust's type system is notably expressive. Lifetime annotations enable compile-time guarantees about reference validity. Trait-based generics provide powerful abstraction mechanisms. The type system can encode complex invariants about program behavior. But Rust's type system has limits. It cannot express properties like "this function sorts its input" or "this data structure maintains a balanced tree invariant" directly in types. Dependent types, which allow types to depend on values, would enable such specifications, but they are complex and remain largely confined to research languages.

This expressiveness gap is what motivates languages with more advanced type systems. Bend's affine dependent type theory allows types to encode precise specifications of program behavior. Users declare "laws" that the code must satisfy, and the compiler checks proofs that those laws hold. Idris 2's quantitative type theory tracks resource usage and enables type-safe concurrent programming with session types. Leon verifies functional Scala programs against formal specifications using SMT solvers.

The trade-off is complexity. Advanced type systems require more effort from programmers, more time from compilers, and more sophistication from tooling. Bend explicitly trades inference for speed and clarity: "There is no C stack either: each Bend program must terminate, all variables are annotated with their types, and no implicit type inference occurs." This design choice makes Bend's compiler fast and its error messages precise but requires programmers to write more verbose code.

Finding the right balance between expressiveness and usability is one of the central challenges of modern language design.

Developer ergonomics versus runtime performance

There is a persistent tension between developer productivity and runtime performance. Languages optimized for developer ergonomics - Python, Ruby, JavaScript - abstract away many details that allow the runtime to execute more slowly or use more memory. Languages optimized for performance - C, C++, Rust - expose those details, requiring programmers to manage complexity that would otherwise be handled automatically.

This tension is not absolute. Many advances have narrowed the gap. Just-in-time compilation brings performance closer to native code. Ahead-of-time compilation improves startup time and reduces runtime overhead. Better garbage collectors minimize pause times and improve throughput. Zero-cost abstractions allow high-level code to compile to efficient machine code.

But the gap remains significant in critical areas. Start-up time: interpreted languages and those with large runtimes take longer to start than native executables. Memory usage: garbage-collected languages typically use more memory than languages with explicit management. Tail latency: garbage collection pauses can cause occasional but severe latency spikes. Predictability: systems with garbage collection and just-in-time compilation exhibit more variance in their performance characteristics.

Languages like Zig, Odin, and Vale attempt to close this gap by providing modern ergonomics without sacrificing performance. Zig's explicit allocator model eliminates hidden allocations while providing a cleaner API than C's malloc and free. Odin's simple, orthogonal design reduces cognitive load without introducing runtime overhead. Vale's generational references provide

memory safety with only single-digit percentage overhead compared to unsafe code.

Another dimension of ergonomics is tooling. Modern developers expect fast builds, intelligent code completion, inline error messages, debugging support, and documentation tools. Languages that lack this tooling feel unusable regardless of their theoretical merits. Rust succeeded in part because of cargo, the Rust Language Server, and excellent error messages. Go succeeded with its simple build system and built-in testing framework. New languages must compete on tooling as well as semantics.

The fragmentation problem: too many specialized tools

The modern programming ecosystem is fragmented. Different domains use different languages: Python for data science and AI, JavaScript for web frontends, Go for microservices, Rust for systems programming, Java for enterprise backends, C++ for game engines and high-performance applications, SQL for databases, and dozens more for specialized tasks.

This fragmentation has costs. Teams need expertise in multiple languages. Codebases contain multiple runtimes and toolchains. Interoperability between languages is awkward and error-prone. Knowledge does not transfer cleanly between ecosystems. The collective maintenance burden of all these ecosystems is enormous.

The ideal situation would be a single language that is excellent across domains. This is unlikely to happen in practice because different domains have conflicting requirements. But there is space for languages that reduce fragmentation by being competent in more domains than today's specialized options. Rust is attempting this: it is used for web assembly, systems programming, CLI tools, game development, and even web backends. Go is attempting this: it is used for everything from microservices to DevOps tooling to embedded systems.

The languages covered in this book also attempt to address fragmentation. Bend's ability to compile to CPU, GPU, and JavaScript from a single source code is an attempt to unify parallel and sequential programming. Valen's Rust interoperability is designed to let it coexist with the existing Rust ecosystem rather than replace it. Revo's design as both a standalone scripting language

and an embeddable engine aims to bridge the gap between application code and infrastructure code.

Fragmentation is not going away. But languages that thoughtfully reduce it - by providing good interoperability, by supporting multiple execution targets, by learning from existing ecosystems - have a real advantage over languages that attempt to create isolated universes.

What "next generation" actually means

What does it mean to call these languages "next generation"? The phrase has been used for decades about every new language, and it is often empty marketing. This book uses it more carefully.

A next-generation language, for our purposes, is one that makes a substantive claim to solve problems that existing languages cannot solve adequately, using mechanisms that are fundamentally different rather than merely incremental. It is not next generation because it has better syntax or a few more standard library functions. It is next generation because it approaches a core problem - memory safety, concurrency, type expressiveness, verification, parallelism - from a genuinely new angle.

Vale's generational references are next generation because they offer a memory safety mechanism that is neither garbage collection nor borrow checking. Valen's group borrowing is next generation because it allows mutable aliasing patterns that Rust rejects while maintaining safety. Bend's law-driven development is next generation because it integrates formal verification directly into the programming workflow in a way that is practical rather than academic. Revo's combination of compile-time execution, fibers, and pattern matching in a dynamically typed language is next generation for scripting workloads.

Being "next generation" does not mean being production-ready. It does not mean being better than Rust or Go for all use cases. It means pushing the boundaries of what is possible in language design and exploring ideas that may become mainstream later. Rust was once next generation in this sense. Go was next generation when it introduced goroutines. Even Java's garbage collection was next generation when it first appeared in mainstream software.

The languages in this book represent the current frontier of that exploration. Some will fail. Some will succeed. Some will contribute ideas that

are absorbed into other languages. Understanding them is valuable regardless of which outcome occurs, because they illuminate the direction in which programming language design is heading.

With this foundation established, we can now turn to the underlying computer science concepts that make these languages possible. Chapter 2 surveys the technical building blocks - ownership models, type theories, effect systems, concurrency patterns - that the individual languages draw upon and extend.

Chapter 2: Foundations - Core Concepts for Modern Language Design

The next-generation languages examined in this book do not emerge from thin air. They are built upon decades of research in type theory, programming language semantics, compiler design, and formal methods. To understand these languages - and to evaluate their design choices - it helps to understand the concepts they implement and extend.

This chapter surveys the core technical foundations. It is not a comprehensive textbook on type theory or compiler construction. It is a focused survey of the concepts that directly influence Vale, Valen, Bend, Revo, and their peers. Each section explains a concept clearly, describes how it is used in practice, and connects it to specific languages covered later in the book.

Readers who are already familiar with these concepts can skim this chapter or use it as a reference when particular ideas arise later. Readers who are new to this terrain should read it carefully: the individual language chapters will assume understanding of the foundations laid out here.

Ownership and borrowing: from Rust to generalizations

The ownership system introduced by Rust is the most influential innovation in systems programming language design in the past fifteen years. At its core, ownership is simple: every value in Rust has exactly one owner, and when the owner goes out of scope, the value is dropped. References to values are either immutable (anyone can read) or mutable (only one writer), and mutable and immutable references cannot coexist for the same data at the same time.

This simple rule - aliasing xor mutation - eliminates data races and use-after-free errors at compile time. If the Rust compiler accepts your code, your program is guaranteed to be free of data races and memory safety violations (barring unsafe code).

But the rule has consequences. It rejects safe programs. Consider a graph data structure where nodes have back-references to their parents. In Rust,

representing this requires either unsafe code, reference counting with Rc and RefCell, or redesigning the data structure in ways that may be awkward for the algorithm. Consider an observer pattern where multiple observers hold references to a subject. Rust's borrow checker struggles with this because mutation of the subject invalidates all observer references, even though the observers might only be reading unrelated fields.

These limitations motivate alternative approaches. Vale's generational references, which we will examine in Chapter 3, abandon the aliasing-xor-mutation rule entirely. Instead of preventing aliasing at compile time, Vale allows any number of references to any data and uses runtime generation checks to detect use-after-free. The trade-off is a small runtime cost in exchange for vastly greater flexibility.

Valen's group borrowing, which we will examine in Chapter 4, refines the aliasing-xor-mutation rule rather than abandoning it. Under group borrowing, multiple mutable references to the same object are allowed, but mutation invalidates only references to the object's children, not the object itself. This allows patterns like observers and graph back-references that Rust rejects while still providing compile-time guarantees.

Understanding these alternatives requires understanding Rust's model well enough to know where it fails. Rust's ownership system is not a universal solution to memory safety; it is one particular solution with specific trade-offs. The next generation of languages is exploring other points in the design space.

Linear and affine types: resources as first-class citizens

Linear and affine types are a generalization of ownership that originates in linear logic, a variant of classical logic developed by Jean-Yves Girard in 1987. In linear logic, every premise must be used exactly once in a proof. This property translates to programming languages: a linear type ensures that a value of that type is used exactly once; an affine type ensures it is used at most once.

The distinction between linear and affine is subtle but important. Linear means exactly once: you must use the value, and you must use it exactly one time. Affine means at most once: you may use the value zero times or one time, but not more than once. Affine types are easier to work with in practice because they do not force you to use every value, which would be

inconvenient for things like error handling paths where some resources might not be allocated.

Linear types have several applications:

Resource management: File handles, network connections, and locks are resources that must be released exactly once. Linear types can ensure this at the type level. A file handle of linear type must be closed before it goes out of scope; if you try to use it after closing, the type system rejects the code. If you forget to close it, the type system rejects the code.

Memory safety: Linear types can represent pointers that must be dereferenced exactly once and then invalidated. This prevents use-after-free without requiring runtime checks.

Concurrency: If a data structure has a linear type, it cannot be accessed from multiple threads simultaneously because that would require using the same value more than once. Linear types thus provide a form of data-race freedom built into the type system.

Bend uses affine types as a core mechanism. As Bend's documentation states: "Bend is an affine language - values are used at most once." This enables Bend's automatic parallelism: if every value is used at most once, there can be no data races, so parallel execution is safe by construction. Bend's affine types also prevent garbage collection: every allocation is freed exactly when its last owner is done, which is deterministically trackable because affine types guarantee at most one owner at a time.

Ibridis 2's quantitative type theory builds on affine types by adding a "quantity" annotation that specifies how many times a value can be used. A quantity of 1 means linear (exactly once). A quantity of ? means affine (at most once). A quantity of * means unrestricted (any number of times). This fine-grained control enables Idris 2 to express complex resource properties, including type-safe concurrent communication protocols via session types.

Valen also implements linear types as part of its type system. Linear types in Valen allow fine-grained control over resource usage and enable more precise aliasing information for the compiler to optimize generated code.

Effect systems: tracking what programs do

An effect system is a type-system extension that tracks the side effects that functions can perform. A pure function has no effects: it takes input and produces output without modifying external state, performing I/O, or raising exceptions. An effectful function may perform one or more of these actions.

In languages without effect systems, it is easy to write functions that appear pure but secretly modify global state or perform I/O. This makes reasoning about code harder: you cannot safely reorder function calls, cache results, or execute code in parallel without carefully checking whether effects are present.

Effect systems make these properties explicit in types. A function's type signature includes not just its input and output types but also the effects it may perform. For example, a function might have type:

```
f :: Int -> {IO, Exn} -> Int
```

This signature says that f takes an Int, returns an Int, and may perform I/O and throw exceptions. A function with type:

```
g :: Int -> Int
```

is guaranteed pure: it takes an Int and returns an Int with no side effects.

Koka is the most prominent language built around effect systems. Its row-polymorphic effect types allow precise tracking of effects through programs. The key innovation in Koka is not just tracking effects but making effects composable through effect handlers. An effect handler is a mechanism for catching and responding to effects in a structured way. With effect handlers, constructs like async/await, generators, and exception handling can be defined as user-level code rather than language primitives.

Consider async/await in Koka. Instead of being a special language construct, async/await is implemented as an effect handler that intercepts asynchronous effects and schedules continuation execution. This means you can define your own control-flow abstractions using the same mechanism. A database transaction abstraction, a undo/redo system, or a non-deterministic search algorithm can all be implemented as effect handlers.

Effect systems are relevant to many next-generation languages. Bend's pure functional core with affine types is closely related: if a function has no shared mutable state (affine types ensure this) and no external effects, it is automatically pure and can be safely parallelized. Valen's group borrowing system could theoretically be extended with effect tracking to provide even more precise compile-time guarantees.

Effect systems also enable powerful optimizations. A compiler that knows a function is pure can cache its results, reorder its calls, or eliminate duplicate calls. A compiler that knows a function has no I/O can schedule it on any thread. A compiler that knows a function never throws exceptions can eliminate exception-handling overhead.

Algebraic data types and pattern matching

Algebraic data types (ADTs) are a way of constructing complex types from simpler ones. There are two fundamental operations: sum types (also called tagged unions or discriminated unions) and product types.

A product type is a tuple of values. A struct or record is a product type: it contains all of its fields simultaneously. In Rust:

```rust
struct Point {
    x: f64,
    y: f64,
}

fn main() {
    let p = Point { x: 3.0, y: 4.0 };
    println!("Point({} {})", p.x, p.y);
}
```

A Point is a product of two f64 values.

A sum type represents a value that can be one of several alternatives. An enum or variant type is a sum type. In Rust:

```
#[derive(Debug)]
enum Shape {
    Circle { radius: f64 },
    Rectangle { width: f64, height: f64 },
    Triangle { base: f64, height: f64 },
}

fn main() {
    let shapes = [
        Shape::Circle { radius: 1.0 },
        Shape::Rectangle { width: 2.0, height: 3.0 },
        Shape::Triangle { base: 4.0, height: 5.0 },
    ];
    for shape in &shapes {
        println!("{:?}", shape);
    }
}
```

A Shape is either a Circle, a Rectangle, or a Triangle, never more than one at a time.

Algebraic data types get their name because they correspond to algebraic operations: product types correspond to multiplication (the number of possible values is the product of the possible values of each field), and sum types correspond to addition (the number of possible values is the sum of the possible values of each alternative).

Pattern matching is the natural companion to algebraic data types. Pattern matching decomposes a value into its components and branches based on which variant it is:

```
enum Shape {
    Circle { radius: f64 },
    Rectangle { width: f64, height: f64 },
    Triangle { base: f64, height: f64 },
}

fn area(shape: &Shape) -> f64 {
    match shape {
        Shape::Circle { radius } => std::f64::consts::PI * radius * radius,
        Shape::Rectangle { width, height } => width * height,
        Shape::Triangle { base, height } => 0.5 * base * height,
    }
}

fn main() {
    let shapes = [
```

```
        Shape::Circle { radius: 1.0 },
        Shape::Rectangle { width: 2.0, height: 3.0 },
        Shape::Triangle { base: 4.0, height: 5.0 },
    ];
    for shape in &shapes {
        println!("area = {}", area(shape));
    }
}
```

Modern languages increasingly support ADTs and pattern matching. Rust, Go (with its interfaces and type switches), Java (with its recent pattern matching additions), and C# all have these features in some form. They are essential tools for writing code that is both expressive and correct: exhaustive pattern matching ensures that all cases are handled, and the type system rejects code that misses cases.

All the languages in this book support algebraic data types and pattern matching, though with different emphases. Vale uses them for type-state programming with Higher RAII. Bend uses them extensively for encoding specifications and proofs. Revo uses them for its result types and error handling. Valen uses them for both data representation and cross-language type compatibility with Rust.

Capability-oriented programming and security

Capability-oriented programming is a security model in which access to resources is controlled by unforgeable tokens called capabilities. A capability grants the holder permission to perform specific operations on a specific resource. If you do not have the capability, you cannot perform the operation. Capabilities cannot be created or forged by normal code; they can only be passed explicitly.

This model is more secure than traditional access control models based on names and permissions. In name-based models, code can look up a resource by name (like a file path) and then access it if the process has permission. This is vulnerable to confusion of deputies: code running on your behalf might access resources it should not access because the process has too many permissions. In capability-based models, code can only access resources for which it has been explicitly given a capability, preventing confusion of deputies.

Move is the most prominent capability-oriented language in current use. Move was designed for the Diem blockchain (and later adopted by Sui) with the

specific goal of preventing bugs that could cause loss of digital assets. In Move, digital assets are "resources" that cannot be copied or discarded: they must be explicitly moved from one location to another. This matches the semantics of physical assets: you cannot duplicate a dollar bill, and you cannot simply destroy it without transferring ownership first.

Move's resource model prevents several classes of bugs:

Double-spending: A resource cannot be copied, so the same asset cannot be spent twice.

Accidental destruction: A resource cannot be dropped without explicit handling, so assets cannot be lost by going out of scope.

Unauthorized access: Code can only access resources for which it has explicit capabilities.

Capability-oriented principles appear in other forms in next-generation languages. Valen's linear types can represent capabilities: a linear value that grants access to a resource cannot be duplicated, ensuring exclusive access. Bend's affine types can represent capabilities: a value used at most once ensures that capabilities are consumed rather than duplicated.

Deterministic resource management

Deterministic resource management means that resources are released at a specific, predictable point in program execution rather than at some arbitrary time determined by a garbage collector or other runtime mechanism.

Languages with garbage collection - Java, C#, Python, Go - release memory non-deterministically. You allocate a value, use it, and eventually the garbage collector reclaims the memory at some point after it is no longer reachable. You cannot know when this will happen, and you cannot rely on it happening before the process runs out of memory.

For many applications, non-deterministic memory management is acceptable. Web servers, data processing pipelines, and desktop applications can tolerate the unpredictability of garbage collection. But for real-time systems, operating systems, game engines, and embedded systems, deterministic resource management is essential. A garbage collection pause that lasts fifty milliseconds may be acceptable in a web server but catastrophic in a flight control system or a real-time audio processor.

Deterministic resource management comes in several forms:

Stack allocation: Values with known lifetimes can be allocated on the stack and released when the stack frame is popped. This is the simplest and fastest form of deterministic management.

Scope-based deallocation (RAII): In languages with destructors, resources can be tied to object lifetimes. When an object goes out of scope, its destructor runs deterministically. C++ popularized this pattern, which Rust has refined with its drop trait.

Arena allocation: An arena is a region of memory from which values are allocated. When the arena is no longer needed, all its values are freed at once. This is efficient for scenarios where many short-lived values are allocated together, such as parsing or rendering.

Manual deallocation: Languages like C require programmers to explicitly free memory. This provides full control but is error-prone.

Vale's design explicitly emphasizes deterministic resource management. Its Higher RAII mechanism allows destructors to take parameters and return values, enabling more sophisticated resource management patterns than traditional RAII. Vale's generational references ensure that memory is reclaimed deterministically rather than by garbage collection.

Zig's explicit allocator model - every allocation requires passing an allocator object - makes memory management explicit and testable while still allowing arena allocation and other deterministic patterns. Odin follows a similar philosophy, providing built-in support for memory arenas, pools, and stacks.

Parallel computation models and dataflow

Modern hardware demands parallel execution. But parallel programming is hard because shared mutable state leads to data races, deadlocks, and other concurrency bugs. Languages must choose a model for how parallelism is expressed and managed.

The dominant model in mainstream languages is shared memory with synchronization primitives: threads share data, and locks, mutexes, atomic operations, and condition variables coordinate access. This model is powerful and flexible but error-prone.

Alternative models include:

Actor model: Actors are isolated entities that communicate by sending messages. Each actor processes messages sequentially, eliminating the need for locks. Languages like Erlang and Akka (in the JVM ecosystem) use the actor model.

Software transactional memory: Memory operations are grouped into atomic transactions that either all succeed or all fail. This provides a more elegant abstraction than locks but requires sophisticated runtime support.

Dataflow: Computation is expressed as a graph of data dependencies. Nodes execute when their input data is available. This model is natural for parallelizing data-parallel algorithms but less natural for general-purpose programming.

Immutable data structures: If data cannot be mutated after creation, multiple threads can read it simultaneously without synchronization. Mutation is performed by creating new copies, which requires more memory but eliminates data races.

The next-generation languages explore these alternatives. Bend's pure functional approach with affine types is essentially an immutable-data approach: data is never mutated in place, so there are no data races. Bend's runtime automatically schedules parallel execution of independent computations.

Valen's group borrowing enables shared mutable state under controlled conditions, allowing some parallelism patterns that Rust rejects. Vale's generational references allow shared state with use-after-free detection, though they do not directly solve data races.

Revo's fiber-based concurrency provides lightweight non-blocking parallelism for scripting workloads, similar to Go's goroutines but in a dynamically typed language.

Understanding these models helps evaluate each language's approach to concurrency. A language's concurrency model is not merely a technical detail; it shapes what kinds of programs are natural to write in that language and what kinds are awkward.

With these foundations in place, we are ready to examine the individual languages. Chapter 3 begins with Vale, the language that started this particular lineage of innovation.

Chapter 3: Vale - The High-Performance Systems Language

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Vale implementation

Valen implementation

Bend implementation

Revo implementation

Comparison

Implementation 2: an in-memory data structure with safety guarantees

Vale implementation

Valen implementation

Bend implementation

Revo implementation

Comparison

Implementation 3: a parallel computational workload

Vale implementation

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Bend implementation

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Performance comparison

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Revo's memory safety mechanisms

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Trade-offs between static guarantees and flexibility

Handling unsafety: when and how each language escapes its own rules

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