

PROLOG PROGRAMMING

— FROM FUNDAMENTALS TO ADVANCED —
LOGIC PROGRAMMING

A COMPREHENSIVE GUIDE TO LOGIC PROGRAMMING
WITH **SWI-PROLOG**



START FROM THE BASICS

Facts, rules, queries, unification and backtracking



ADVANCED TOPICS

Constraints, definite clause grammars, tabling and meta-programming



AI AND SEARCH ALGORITHMS

Solve real-world problems with powerful logic techniques



TOOLS FOR SUCCESS

Debugging, testing, performance engineering and best practices



BUILD PRODUCTION APPLICATIONS

Design, implement and deploy robust, high-quality Prolog systems

```
parent(john, mary).  
parent(john, peter).  
parent(mary, alice).  
parent(peter, bob).
```

```
ancestor(X,Y) :-  
    parent(X,Y).
```

```
ancestor(X,Y) :-  
    parent(X,Z),  
    ancestor(Z,Y).
```

```
?- ancestor(john, Who).  
Who = mary ;  
Who = peter ;  
Who = alice ;  
Who = bob ;  
false.
```



EVERY CONCEPT
EXPLAINED WITH
WHAT, WHY, HOW,
WHEN, MISTAKES
AND BEST PRACTICES



ALL CODE
EXAMPLES ARE
COMPLETE AND
EXECUTABLE



FROM LEARNING
TO PROFESSIONAL
REAL-WORLD
DEVELOPMENT



SUITABLE FOR
PROGRAMMERS
NEW TO PROLOG
AND LOGIC
PROGRAMMING

DMITRI SOKOLOV

Prolog Programming: From Fundamentals to Advanced Logic Programming

A comprehensive guide to logic programming with SWI-Prolog

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A comprehensive guide to logic programming with SWI-Prolog

This book takes you from your first Prolog query through professional-level logic programming. Using SWI-Prolog as the primary implementation, it covers everything from facts, rules, and unification through constraint programming, definite clause grammars, tabling, meta-programming, AI search algorithms, debugging, testing, performance engineering, and production-quality application development. Every concept is explained with what it is, why it exists, how it works, when to use it, common mistakes, and best practices. All code examples are complete and executable. The book assumes basic programming familiarity but no prior Prolog or logic-programming experience.

Introduction

In 1972, at the University of Aix-Marseille in France, Alain Colmerauer and Philippe Roussel built something unusual: a programming language based not on step-by-step instructions, but on logical relationships. They called it Prolog, short for “programmation en logique,” or programming in logic. At the time, this was radical. Every other mainstream language asked programmers to specify how to compute an answer. Prolog asked only what the answer should satisfy.

Imagine you want to find all ancestors of a person in a family tree. In an imperative language like C or Java, you write a loop that walks up parent links, checking and collecting as you go. You manage pointers, check for nulls, handle edge cases, and carefully control the flow. The program is a recipe: do this, then that, repeat until done.

In Prolog, you say two things. First, a fact: “If X is the parent of Y, then X is an ancestor of Y.” Second, a rule: “If X is the parent of Z and Z is an ancestor of Y, then X is an ancestor of Y.” You have not written any loops. You have not specified traversal order. You have described a relationship. Then you ask Prolog to find all ancestors of someone, and Prolog searches for solutions that satisfy your rules.

This is the core idea of logic programming: you describe what is true about your problem domain using facts and rules grounded in formal logic, then you query the system to derive answers. The language handles the search.

Prolog was not designed as an academic curiosity. Colmerauer was working on natural language processing, trying to build systems that could understand French sentences. He needed a way to express grammatical relationships declaratively, so he and Roussel created Prolog around Robert Kowalski’s insight that Horn clauses from mathematical logic could be interpreted procedurally. David H. D. Warren at the University of Edinburgh then built the Warren Abstract Machine, an efficient execution model that made Prolog practical rather than just theoretically interesting.

Today, Prolog remains relevant. It is used in knowledge representation systems, expert systems, constraint solvers, compilers and parsers, bioinfor-

matics tools, natural language processing pipelines, planning systems, and rule engines embedded in larger applications. IBM Watson used Prolog for pattern matching over parse trees. Modern implementations like SWI-Prolog provide web servers, JSON support, database connectors, foreign-language interfaces, and advanced features like tabling and constraint logic programming that make it suitable for production workloads.

But Prolog is different enough from mainstream languages that picking it up requires a mindset shift. You cannot simply translate your existing imperative or object-oriented code into Prolog syntax and expect it to work well. You need to learn to think relationally: to model problems as networks of constraints and relationships rather than sequences of state changes. This book is designed to guide you through that transition systematically, from first principles to advanced techniques.

What this book covers

The book is organized into twenty chapters that build progressively on one another. Here is the roadmap.

Chapters 1 through 3 get you running immediately. You will install SWI-Prolog, start the interactive interpreter, write your first knowledge base of facts and rules, run queries, and understand how to read results. More importantly, these chapters help you develop the declarative mindset: understanding that Prolog programs describe relationships rather than procedures, and learning how this differs from imperative, object-oriented, and functional programming.

Chapters 4 and 5 cover the data model and unification in depth. Chapter 4 explains every type of term Prolog can represent: atoms, variables, numbers, strings, compound structures, lists, trees, and symbolic expressions. You will learn how to construct, decompose, inspect, and compare terms. Chapter 5 dives into unification, the central mechanism of Prolog execution. You will understand exactly how terms unify step by step, why they sometimes fail to unify, what the occurs check is and why most implementations omit it, and how unification differs from assignment or equality testing in other languages.

Chapters 6 through 9 explain how Prolog actually runs programs. Chapter 6 covers the execution model: SLD resolution, depth-first search, backtracking, choice points, clause order effects, goal order effects, determinism, soundness,

and completeness. This is where declarative meaning meets operational behavior, and understanding this chapter is essential for writing correct and terminating Prolog programs. Chapter 7 teaches recursive programming and list processing: the primary ways to handle repeated computation in Prolog. You will build a toolkit of patterns including membership tests, append, reverse, map, filter, fold, sorting, searching, accumulators, and termination analysis. Chapter 8 covers arithmetic carefully, explaining why arithmetic expressions are symbolic terms until explicitly evaluated, how `is/2` works, numeric comparisons, type distinctions, and why ordinary arithmetic reduces relational purity. Chapter 9 teaches control flow: conjunction, disjunction, negation as failure, if-then-else, cuts (green and red), once-like commitment, failure-driven loops, and higher-order predicates for declarative alternatives to explicit loops.

Chapters 10 through 13 introduce advanced reasoning techniques. Chapter 10 covers constraint logic programming, focusing on CLP(FD) for finite-domain constraints: how to declare relationships over integers without immediately computing values, how constraint propagation narrows domains automatically, how labeling performs search, and complete worked examples of Sudoku, N-Queens, scheduling, and optimization. Chapter 11 teaches Definite Clause Grammars: Prolog's elegant notation for parsing and generating structured text, their relationship to difference lists, recursive grammars, semantic actions, abstract syntax trees, and practical language processing applications. Chapter 12 explores meta-programming: how Prolog programs can manipulate their own code as data, using `call/N`, predicate indicators, meta-predicate declarations, term construction and inspection, meta-interpreters, and interpreters for small languages. Chapter 13 covers knowledge representation and reasoning: modeling taxonomies, inheritance-like structures, rule-based expert systems, symbolic inference, graph-based knowledge, explainable reasoning, and approaches to uncertainty.

Chapters 14 through 16 focus on AI algorithms and professional project organization. Chapter 14 implements classical search algorithms in Prolog: depth-first, breadth-first, depth-limited, iterative-deepening, best-first, A*, game trees with minimax and alpha-beta pruning, and basic planning concepts. Chapter 15 covers advanced language features: tabling for memoization and left recursion handling, attributed variables, coroutining with `freeze/2` and `when/2`, rational trees, non-backtrackable state, and delimited continuations. Chapter 16 teaches modules, libraries, and project organization: namespaces, imports, exports, predicate visibility, multifile projects, dynamic predicates, initialization code, and documentation conventions.

Chapters 17 through 20 bring everything together for production-quality development. Chapter 17 covers debugging, testing, and development workflow: tracing execution, spy points, breakpoints, common error categories, diagnosing logical bugs, writing unit tests with PLUnit, test organization, and CI integration. Chapter 18 teaches performance engineering: indexing, argument ordering, clause ordering, tail recursion, choice point reduction, data structure selection, profiling, benchmarking, and trade-offs between declarative elegance and operational efficiency. Chapter 19 covers I/O, interoperability, and integration: files, streams, text processing, command-line arguments, JSON serialization, HTTP clients and servers, database integration, foreign-language interfaces, process interaction, and concurrency. Chapter 20 synthesizes everything into professional practices: coding standards, anti-patterns and refactoring, design principles for maintainable systems, and three complete case studies: a scheduling application using constraints, a parser and interpreter using DCGs, and a rule-based recommendation system.

How to use this book

Read the chapters in order. Each chapter assumes you have understood the preceding material, and concepts are introduced before they are used. The progression is deliberate: you cannot write efficient recursive predicates without understanding unification and execution order, and you cannot understand tabling or constraint programming without grasping how ordinary Prolog search works.

Every code example is meant to be typed into SWI-Prolog and run. Do not just read the examples; execute them. Modify them. Break them. See what happens when you change clause order, remove a base case, or query with different variable patterns. The interactive REPL is your laboratory for developing intuition about how Prolog behaves.

The book uses SWI-Prolog version 10.x as the reference implementation. Where features are specific to SWI-Prolog rather than part of ISO Prolog, this is clearly noted. Portability considerations and equivalent approaches in other implementations are discussed where relevant. If you use a different Prolog system, most core material will apply, but some advanced features and library predicates may differ.

There are no exercises, quizzes, or homework assignments in this book. Instead, every major concept is illustrated with fully worked examples, step-

by-step execution traces showing variable bindings and backtracking behavior, complete case studies, and practical guidance. If you want additional practice beyond what the examples provide, the best approach is to take small problems from your own domain and try modeling them relationally in Prolog.

What you should know before starting

This book assumes you are comfortable with basic programming concepts: variables, functions or procedures, conditionals, loops, data structures like lists and trees, and the general idea of running programs in an environment. You do not need to be an expert in any particular language, but familiarity with at least one mainstream language will help when we contrast Prolog's approach with imperative, object-oriented, or functional paradigms.

No prior exposure to logic programming is required. No background in formal logic is assumed, though we will touch on first-order logic concepts at an accessible level where they illuminate how Prolog works. If you have seen predicate logic before, great; if not, the necessary foundations are introduced as needed.

Let us begin.

Chapter 1: Getting Started with Prolog

Before we can write any Prolog programs, we need a working environment. This chapter gets you from zero to running your first query. We will install SWI-Prolog, explore the interactive interpreter, load and run a small program, and establish the basic workflow you will use throughout this book.

What is Prolog and Where Did It Come From

Prolog is a logic programming language created around 1972 by Alain Colmerauer and Philippe Roussel at the University of Aix-Marseille in France. The name is an abbreviation of “programmation en logique,” French for programming in logic. The language was inspired by Robert Kowalski’s work on the procedural interpretation of Horn clauses, a restricted form of first-order logic formulas that are well-suited for computation.

The original motivation was natural language processing. Colmerauer wanted to build systems that could understand and generate French sentences, and he needed a way to express grammatical relationships declaratively rather than procedurally. Prolog emerged as the vehicle for this vision.

David H. D. Warren at the University of Edinburgh took an early Prolog interpreter and created the Warren Abstract Machine, an efficient execution model that transformed Prolog from a research prototype into a practical system. The WAM influenced virtually every subsequent Prolog implementation and remains the foundation of SWI-Prolog’s core engine.

Over the decades, Prolog has been used in expert systems, knowledge bases, computational linguistics, theorem proving, planning, bioinformatics, and many other domains. While it never achieved the mainstream adoption some enthusiasts predicted during the Fifth Generation Computer Systems project in Japan, it remains a powerful tool for problems involving symbolic reasoning, constraints, relationships, search, and language processing.

Today there are several actively maintained Prolog implementations. SWI-Prolog is the most widely used in education and research, known for its

comprehensive feature set, active development, and excellent documentation. Other notable systems include GNU Prolog (with a compiling backend), SICStus Prolog (commercial with strong performance), YAP, Stryer Prolog (WebAssembly-capable), and XSB (with built-in tabling). This book uses SWI-Prolog as the primary implementation throughout.

Choosing and Installing a Prolog System

SWI-Prolog is our choice for three reasons: it is free and open-source under the BSD-2 license, it is actively maintained with regular releases, and it provides the broadest set of features among available implementations including constraint logic programming, tabling, HTTP servers, JSON support, foreign-language interfaces, and extensive libraries. The current stable release series is version 10.x as of this writing.

Installation depends on your operating system.

Linux:

The recommended approach for most Linux users is to use your distribution's package manager or the official Ubuntu PPA. On Debian-based systems:

```
1 sudo apt-add-repository ppa:swi-prolog/stable
2 sudo apt-get update
3 sudo apt-get install swi-prolog
```

On Fedora:

```
1 sudo dnf install swig-prolog
```

On Arch Linux:

```
1 sudo pacman -S swi-prolog
```

Flatpak and Snap packages are also available if you prefer distribution-independent installations. For the absolute latest version, you can build from source using CMake, though this is typically unnecessary unless you need development features.

macOS:

The simplest approach is to use Homebrew:

```
1 brew install swi-prolog
```

Alternatively, download the macOS universal binary installer from the SWI-Prolog website and run it. This provides a graphical interface (swipl-win) in addition to the command-line interpreter.

Windows:

Download the Windows installer executable from the SWI-Prolog download page and run it. The installer adds SWI-Prolog to your system PATH, creates a Start menu entry, and optionally integrates with common text editors. After installation, you can launch Prolog from Command Prompt or PowerShell by typing `swipl`.

Verifying the installation:

Open a terminal or command prompt and type:

```
1 swipl --version
```

You should see output indicating the SWI-Prolog version, for example:

```
1 SWI-Prolog version 10.0.2 for x86_64-linux-gnu
```

If you see a version number, your installation is working. If not, check that the `swipl` executable is in your PATH and repeat the installation steps.

The Interactive REPL

Start SWI-Prolog by typing `swipl` at your system command line. You will see output like this:

```

1 SWI-Prolog version 10.0.2 for x86_64-linux-gnu
2 Welcome to SWI-Prolog (multi-threaded, 64 bits, version 10.0.2)
3
4 For help, use ?- help(Topic). or ?- apropos(Word).
5
6 ?-

```

The `?-` prompt indicates that Prolog is ready to accept queries. This interactive environment is called a REPL: read-evaluate-print loop. You type a query, Prolog evaluates it, prints the result, and returns to the prompt for the next query.

Basic navigation:

- Type a query followed by a period `.` and press Enter to execute it.
- Press semicolon `;` after receiving an answer to ask for more solutions.
- Press Ctrl-C to interrupt a running query, then type `a` (abort) to return to the prompt.
- Type `halt.` or press Ctrl-D to exit Prolog.
- Use the up and down arrow keys to scroll through your query history.
- Tab completion is available for predicate names in many configurations.

Getting help:

SWI-Prolog includes extensive online documentation accessible from within the REPL:

```

1 ?- help.

```

This opens a browser with the reference manual. You can also search for specific predicates:

```

1 ?- help(member).
2 ?- apropos(list).

```

The `apropos` predicate searches documentation for topics containing a given word.

Loading files:

To load a Prolog source file into the interpreter, use the `consult` predicate or its shorthand `[File]`:

```
1  ?- consult('myprogram.pl').
2  % myprogram.pl compiled 0.00s, found 12 clauses
3  true.
4
5  ?- ['myprogram.pl'].
6  % myprogram.pl compiled 0.00s, found 12 clauses
7  true.
```

The square-bracket notation is idiomatic and widely used. If the file has syntax errors, Prolog reports them at load time rather than silently accepting broken code.

To reload a modified file without restarting Prolog:

```
1  ?- [myprogram].
```

Note that you can omit the `.pl` extension and quotes if the filename contains no special characters and is in the current directory. SWI-Prolog automatically searches for files with standard extensions.

Starting with a file:

You can also start Prolog with a file already loaded by passing it as a command-line argument:

```
1  swipl myprogram.pl
```

This loads the file and then presents the interactive prompt, giving you immediate access to all predicates defined in that file.

Your First Program

Let us write a tiny knowledge base and query it. Create a file named `family.pl` with the following contents:

```

1  % family.pl - A simple family knowledge base
2
3  parent(alice, bob).
4  parent(alice, carol).
5  parent(bob, dave).
6  parent(carol, eve).
7  parent(carol, frank).
8
9  male(bob).
10 male(dave).
11 male(frank).
12
13 female(alice).
14 female(carol).
15 female(eve).
16
17 father(X, Y) :- parent(X, Y), male(X).
18
19 mother(X, Y) :- parent(X, Y), female(X).
20
21 sibling(X, Y) :- parent(Z, X), parent(Z, Y), X \= Y.

```

Let us examine what we have written. The lines beginning with % are comments and are ignored by Prolog. Everything else is either a fact or a rule.

Facts are simple statements that declare something to be true. For example:

```

1  parent(alice, bob).

```

This states that Alice is a parent of Bob. The structure `parent(alice, bob)` is called a compound term: `parent` is the functor (or predicate name), and `alice` and `bob` are its arguments. The period at the end terminates the statement; forgetting this is one of the most common beginner mistakes.

Rules define relationships in terms of other relationships. For example:

```

1  father(X, Y) :- parent(X, Y), male(X).

```

Read this as: “X is a father of Y if X is a parent of Y and X is male.” The symbol `:-` means “if,” and the comma `,` means “and.” The uppercase letters X and Y are variables that stand for any values that make the rule apply.

Now load this file into Prolog:

```
1  ?- [family].
2  % family.pl compiled 0.00s, found 12 clauses
3  true.
```

The message confirms that twelve clauses (facts and rules combined) were loaded successfully. Now we can query the knowledge base.

Simple queries:

Ask whether Alice is a parent of Bob:

```
1  ?- parent(alice, bob).
2  true.
```

Prolog answers `true` because this fact appears explicitly in our file.

Ask something that is not stated:

```
1  ?- parent(dave, eve).
2  false.
```

Prolog answers `false` because it cannot derive this from the facts and rules we provided. This reflects the closed-world assumption: anything Prolog cannot prove true is assumed false. We will discuss this more in Chapter 2.

Queries with variables:

Ask who Alice's children are by using a variable:

```
1  ?- parent(alice, Child).
2  Child = bob ;
3  Child = carol.
```

Prolog first returns `Child = bob`, binding the variable to Bob. When you press semicolon, it backtracks and finds another solution: `Child = carol`. Press semicolon again and Prolog says `false`, indicating no more solutions exist.

Ask who Dave's parents are:

```
1  ?- parent(Parent, dave).  
2  Parent = bob.
```

Only Bob is listed as Dave's parent in our knowledge base.

Using derived rules:

Now query the father predicate we defined with a rule:

```
1  ?- father(X, Y).  
2  X = bob,  
3  Y = dave ;  
4  false.
```

Prolog found that Bob is a father of Dave by applying the rule: it checked that `parent(bob, dave)` holds and that `male(bob)` holds. Notice how Prolog derived this answer from existing facts rather than looking it up directly.

Query siblings:

```
1  ?- sibling(eve, Sibling).  
2  Sibling = frank.
```

Eve's only sibling in our knowledge base is Frank. The rule checks that they share a parent and are not the same person (the `X \= Y` condition ensures this).

This small example already demonstrates several fundamental ideas: facts declare known information, rules define relationships in terms of other relationships, queries ask questions using variables to request unknown values, and Prolog searches through facts and rules to find answers. The next chapters will unpack each of these ideas systematically.

Source Files and Project Organization

As your Prolog programs grow beyond a single file, organizing them properly becomes important. Here are the conventions used throughout this book.

File naming:

- Use the `.pl` extension for all Prolog source files.

- Choose descriptive names that reflect the module's purpose: `family.pl`, `scheduler.pl`, `parser.pl`.
- Keep filenames lowercase with underscores rather than spaces or hyphens to avoid shell and portability issues.

Directory layout:

For a small project, a single directory with all `.pl` files works fine. For larger projects, consider this structure:

```

1 my_project/
2   main.pl           % Entry point; loads other modules
3   config.pl         % Configuration data and parameters
4   knowledge_base.pl % Domain facts and rules
5   solver.pl         % Core solving or reasoning logic
6   io.pl             % Input/output and user interaction
7   tests/
8     test_knowledge.plt % Test files (more on this in Chapter 17)

```

The `main.pl` file typically loads all other modules using `use_module` directives:

```

1 :- module(main, [run/0]).
2 :- use_module(knowledge_base).
3 :- use_module(solver).
4 :- use_module(io).
5
6 run :-
7     solve_problem(Solution),
8     print_solution(Solution).

```

We will cover modules in depth in Chapter 16. For now, simple single-file programs are sufficient.

Compilation versus interpretation:

When you load a file with `[file]` or `consult(file)`, SWI-Prolog compiles it into an internal bytecode representation and stores the compiled clauses in memory. This is not pure interpretation; compilation happens automatically. For development, this gives fast reload times. For production deployment, you can create standalone executables using:

```
1 swipl -c myprogram.pl -o myprogram
```

This produces a native executable that embeds the Prolog system and your program, though it is larger than a simple script. We discuss packaging and deployment further in Chapter 20.

Running Queries and Reading Results

Understanding how to pose queries and interpret results is fundamental to using Prolog effectively. Let us go through the patterns you will encounter repeatedly.

Single-goal queries:

The simplest query asks about one relationship:

```
1 ?- parent(alice, bob).  
2 true.
```

Prolog searches for a fact or rule that matches this pattern and returns `true` if found, `false` otherwise.

Conjunctions (AND):

Combine multiple goals with comma:

```
1 ?- parent(alice, X), male(X).  
2 X = bob.
```

This asks Prolog to find all `X` such that Alice is a parent of `X` and `X` is male. Both conditions must hold.

Disjunctions (OR):

Use semicolon within a query for alternatives:

```
1 ?- parent(alice, bob) ; parent(dave, eve).  
2 true.
```

This succeeds if either condition holds. Note that semicolon has lower precedence than comma, so parentheses may be needed for clarity:

```
1  ?- (parent(alice, X), male(X)) ; female(X).
```

Queries with multiple variables:

```
1  ?- parent(Parent, Child).
2  Parent = alice,
3  Child = bob ;
4  Parent = alice,
5  Child = carol ;
6  Parent = bob,
7  Child = dave ;
8  Parent = carol,
9  Child = eve ;
10 Parent = carol,
11 Child = frank ;
12 false.
```

Prolog enumerates all parent-child pairs in our knowledge base, one at a time. Each semicolon triggers backtracking to find the next solution.

Understanding variable bindings:

When Prolog returns an answer like `X = bob`, it is telling you that for this particular solution, the variable `X` has been bound to the value `bob`. Different solutions may bind the same variable to different values. Variables in different solutions are independent; a binding from one solution does not carry over to another.

Unexpected failures:

If a query fails when you expect it to succeed, check:

1. Did you load the correct file? Verify with `current_predicate/1`:

```
1  ?- current_predicate(parent/2).
2  true.
```

2. Are your atoms spelled correctly and consistently? Prolog is case-sensitive and treats `Alice` and `alice` as different atoms.
3. Is the argument order correct? `parent(alice, bob)` is different from `parent(bob, alice)`.
4. Did you end every clause with a period? A missing period can cause clauses to merge in unexpected ways.

Infinite loops:

Some queries may appear to hang, printing nothing and accepting no input. This usually means Prolog has entered infinite recursion. Press Ctrl-C, then type a to abort. We will learn how to diagnose and fix infinite recursion in Chapter 6 when we study the execution model in detail. For now, be cautious with recursive rules that lack proper base cases or that recurse without making progress toward termination.

Summary of the workflow:

The basic development cycle in Prolog looks like this:

1. Write facts and rules in a `.pl` file.
2. Load the file into SWI-Prolog using `[file]`.
3. Pose queries at the `? -` prompt to test your knowledge base.
4. Examine the answers, checking that they match your expectations.
5. If something is wrong, edit the file, reload it with `[file].`, and query again.

This cycle is fast and interactive. Use it extensively as you learn Prolog. The REPL is not just for testing finished programs; it is a thinking tool that helps you explore how relationships compose and how rules derive new information from facts.

In the next chapter, we step back to examine the conceptual foundations of logic programming: what makes Prolog different from other paradigms, how it relates to formal logic, and why the declarative mindset matters for writing effective Prolog programs.

Chapter 2: The Declarative Mindset

The single most important skill for learning Prolog is not memorizing syntax or built-in predicates; it is learning to think differently about problems. If you approach Prolog as “another language in which I express my existing imperative algorithms,” you will write code that works but feels awkward, and you will miss the power of the paradigm. This chapter explains what logic programming is fundamentally about, how it differs from other paradigms, and why understanding these differences matters for writing programs that are correct, maintainable, and genuinely idiomatic.

Imperative Versus Declarative Programming

Programming languages fall along a spectrum from imperative to declarative, distinguished by what the programmer specifies.

In an **imperative language** like C, Java, or Python, you write a sequence of instructions that tell the computer how to transform state step by step. You manage variables, loops, conditionals, and data structures explicitly. The program is a recipe: start here, do this, check that, repeat until done, produce the result. The focus is on control flow: the order in which operations execute.

In a **declarative language** like Prolog, SQL, or Haskell to varying degrees, you describe what you want without specifying how to compute it. You state constraints, relationships, or transformations, and the system figures out the execution strategy. The focus is on specification: what conditions must hold for a correct answer.

Consider finding all prime numbers up to 100.

An imperative approach in Python might look like this:

```

1 primes = []
2 for n in range(2, 101):
3     is_prime = True
4     for d in range(2, int(n**0.5) + 1):
5         if n % d == 0:
6             is_prime = False
7             break
8     if is_prime:
9         primes.append(n)

```

You manage a list, iterate with loops, maintain a flag variable, compute square roots, and control the flow explicitly.

A declarative approach in Prolog states what a prime number is:

```

1 prime(N) :-
2     N > 1,
3     \+ has_proper_divisor(N).
4
5 has_proper_divisor(N) :-
6     between(2, N-1, D),
7     N mod D == 0.

```

This reads almost like a mathematical definition: N is prime if it is greater than one and has no proper divisor. There are no loops, no flags, no explicit iteration control. You describe the property that primes satisfy, and Prolog searches for numbers that have this property.

The distinction matters because it changes how you design programs. Imperative programming asks: “What steps do I take to compute the answer?” Declarative programming asks: “What conditions must the answer satisfy?” The latter question often leads to simpler, more direct code for problems involving relationships, constraints, search, or symbolic manipulation.

However, declarative does not mean magic. Prolog still executes by searching through possibilities using concrete algorithms. Understanding both what your program declares and how it searches is essential. We explore this tension throughout the book.

Relations, Not Functions

In most mainstream languages, computation is organized around functions: inputs are transformed into outputs. A function takes arguments, performs

some computation, and returns a result. The direction of data flow is fixed: from inputs to output.

Prolog is organized around **relations**: statements about how values are connected. A relation holds or does not hold for given arguments. There is no fixed distinction between inputs and outputs; any argument can be specified or left as a variable to be determined.

Consider the mathematical relationship $x + y = z$. In an imperative language, you typically implement this as a function that takes x and y and returns z :

```
1 def add(x, y):
2     return x + y
```

You cannot ask “what two numbers add to make 10?” by calling `add(?, ?, 10)`. The direction is fixed.

In Prolog with constraint logic programming (which we cover in Chapter 10), you can express addition as a relation:

```
1 ?- use_module(library(clpfd)).
2 true.
3 ?- X #= Y + Z.
4 X #= Y+Z.
5 ?- X #= Y + Z, X = 10.
6 X = 10,
7 Y in inf..9,
8 Y #= 10-Z,
9 Z in inf..sup ;
10 ...
```

You can specify any subset of the variables and solve for the rest. This multi-directional capability is one of Prolog’s most powerful features, though ordinary arithmetic with `is/2` does not provide it (we discuss this limitation in Chapter 8).

Even without constraints, relational thinking applies to how you design predicates. The predicate `parent(alice, bob)` states a relationship between Alice and Bob. You can query it in multiple directions:

```
1 ?- parent(alice, Child).    % Who are Alice's children?
2 ?- parent(Parent, bob).    % Who are Bob's parents?
3 ?- parent(X, Y).           % What parent-child relationships exist?
```

The same predicate serves all three questions because it describes a relationship, not a one-way computation. When designing your own predicates, ask: “What relationship am I describing?” rather than “What function am I implementing?” This shift often leads to more flexible and reusable code.

That said, not every Prolog predicate is fully relational in practice. Many built-in predicates like `is/2` or `write/1` have fixed modes due to their operational nature. Understanding which predicates are genuinely multi-directional and which are not is part of becoming proficient. We discuss this throughout the book.

First-Order Logic Foundations

Prolog is grounded in first-order logic, also known as predicate logic. You do not need a formal logic background to use Prolog effectively, but understanding the basic connection helps explain why Prolog behaves the way it does.

Propositions and predicates:

In propositional logic, you reason about statements that are either true or false: “It is raining,” “The light is on.” These are atomic propositions with no internal structure.

First-order logic adds predicates: functions from objects to truth values. Instead of a single proposition “Alice is happy,” you have a predicate `happy(X)` that can be applied to any individual: `happy(alice)`, `happy(bob)`. Predicates with multiple arguments express relationships: `parent(X, Y)` means `X` is a parent of `Y`.

This is exactly how Prolog facts are structured. A fact like `parent(alice, bob)` declares that the proposition `parent(alice, bob)` is true.

Quantifiers:

First-order logic has two quantifiers. The universal quantifier (for all) and the existential quantifier (there exists).

In Prolog, variables in queries are implicitly existentially quantified. When you write:

```
1 ?- parent(alice, X).
```

You are asking: “Does there exist an X such that Alice is a parent of X?” Prolog finds values of X that make this true.

Variables in rule bodies are implicitly universally quantified within the scope of the rule. The rule:

```
1 grandparent(X, Z) :- parent(X, Y), parent(Y, Z).
```

means: “For all X, Y, and Z, if X is a parent of Y and Y is a parent of Z, then X is a grandparent of Z.” This universal reading is what makes rules general rather than specific to particular individuals.

Logical connectives:

Prolog uses logical connectives familiar from first-order logic:

- Conjunction (AND): written as comma `,` in Prolog. `A, B` means both A and B must hold.
- Disjunction (OR): written as semicolon `;`. `A ; B` means at least one of A or B holds.
- Implication (IF-THEN): written as `:-` in rules. `Head :- Body` means “if Body holds, then Head holds.”
- Negation: written as `\+`. We discuss its precise semantics in Chapter 9.

These connectives let you build complex logical expressions from simpler ones, and Prolog’s execution engine searches for assignments to variables that make these expressions true.

Horn Clauses and Logical Implication

Prolog is not based on full first-order logic; it uses a restricted subset called **Horn clauses**. This restriction is what makes automated reasoning computationally feasible.

A **clause** in logic is a disjunction of literals (atomic formulas or their negations). For example: $\neg\text{parent}(X, Y) \vee \text{grandparent}(X, Z) \vee \neg\text{parent}(Y, Z)$ is a clause stating that at least one of these literals must be true.

A **Horn clause** is a clause with at most one positive literal. This simple restriction has profound consequences:

- A Horn clause with exactly one positive literal is called a **definite clause**. It can be written as an implication: if all the negative literals' arguments are true, then the positive literal is true. In Prolog syntax: `Head :- Body1, Body2, . . .`.
- A Horn clause with no negative literals is a **fact**: a single positive literal that is unconditionally true. In Prolog: `Head.`
- A Horn clause with no positive literals is a **goal clause**: a query asking whether the negation of all its literals can be derived. In Prolog queries, this appears as a conjunction of goals to prove.

Every Prolog program consists entirely of definite clauses (facts and rules). Every Prolog query is a goal clause. This structure is why Prolog programs are sometimes called “logic programs”: they are literally sets of logical formulas in Horn clause form.

The restriction to Horn clauses trades expressive power for computational tractability. You cannot directly express arbitrary disjunctions in the head of a rule (you cannot say “X is either a bird or a fish” as a single rule head), and you cannot express universal quantification in the negative direction as freely as in full first-order logic. But within these constraints, Horn clauses are Turing-complete: any computable function can be expressed using them.

Understanding that Prolog works with Horn clauses explains several things: why rules have exactly one head, why rule bodies use conjunction, why queries work the way they do, and why certain logical patterns require workarounds in Prolog rather than direct expression.

Closed-World Assumption

One of the most important conceptual differences between Prolog and mathematical logic is the **closed-world assumption**.

In classical first-order logic, if you cannot prove a statement true, it does not follow that the statement is false. It might simply be unknown. This is called the open-world assumption: lack of evidence for truth is not evidence for falsehood.

Prolog uses the closed-world assumption: anything that cannot be proven true from the given facts and rules is assumed to be false. If you ask Prolog whether `parent(dave, eve)` holds and it answers `false`, this does not mean

“I have proved this is false.” It means “I cannot derive this from what you told me, so I assume it is false.”

This assumption is practical for programming. Databases use it extensively: if a customer record does not exist in the database, we treat that as “the customer does not exist” for operational purposes, even though in reality we might simply lack information. Prolog inherits this pragmatic stance.

The closed-world assumption has important consequences:

1. **Completeness of knowledge matters.** If your program relies on negation (asking whether something is NOT the case), you must ensure that all relevant positive facts are present. Missing facts can cause negated queries to succeed incorrectly. We discuss this carefully in Chapter 9 when covering negation as failure.
2. **Negation is not classical logical negation.** The predicate `\+ Goal` succeeds when Prolog cannot prove `Goal`, which under the closed-world assumption is treated as `Goal` being false. But if new facts are added later that would prove `Goal`, the earlier negative conclusion was based on incomplete information, not logical refutation.
3. **Design implication:** When modeling a domain in Prolog, be explicit about what you know. If something important can be absent rather than false, you may need to represent that explicitly rather than relying on absence of facts.

The closed-world assumption is one reason Prolog programs feel different from mathematical specifications. You are not just stating truths; you are constructing a complete enough description of your domain that absence of derivability meaningfully implies falsehood for the purposes of your application.

Declarative Versus Procedural Interpretation

Every Prolog clause has two interpretations, and understanding both is essential for writing programs that are logically correct and operationally efficient.

The declarative interpretation reads a clause as a logical statement about relationships, ignoring execution order entirely. The rule:

```
1 ancestor(X, Y) :- parent(X, Y).  
2 ancestor(X, Y) :- parent(X, Z), ancestor(Z, Y).
```

declaratively means: “X is an ancestor of Y if X is a parent of Y, or if there exists some Z such that X is a parent of Z and Z is an ancestor of Y.” This is a precise mathematical definition of the ancestor relationship, independent of how it might be computed.

The procedural interpretation reads the same clause as execution instructions. To prove `ancestor(X, Y)`, Prolog first tries to prove `parent(X, Y)`. If that fails, it tries to find some Z such that `parent(X, Z)` holds and then recursively proves `ancestor(Z, Y)`. The order of rules matters: the parent rule is tried before the recursive rule. The order of goals in the recursive rule matters: `parent(X, Z)` is evaluated before `ancestor(Z, Y)`.

For many simple programs, the two interpretations align nicely: the procedurally efficient reading matches the logically natural reading. But they can diverge in important ways:

1. **Termination:** A logically correct definition may not terminate under Prolog’s depth-first search strategy if rules or goals are ordered poorly. We will see concrete examples in Chapter 6.
2. **Efficiency:** Two declaratively equivalent programs (defining the same relationships) can have vastly different performance characteristics depending on rule order, goal order, and argument structure.
3. **Completeness:** Due to infinite search spaces and depth-first search, Prolog may fail to find answers that logically exist. A program can be sound (never returning incorrect answers) without being complete (finding all correct answers).

The art of Prolog programming involves designing programs where the declarative interpretation captures the intended logic cleanly while the procedural interpretation executes efficiently and terminates correctly. You start with the declarative meaning: what relationship are you defining? Then you refine the procedural aspects: in what order should rules be tried, in what order should subgoals be evaluated, how can indexing help, when is a cut appropriate?

This dual perspective recurs throughout the book. Every time we introduce a feature or pattern, we examine both what it means logically and how it

behaves operationally. Keeping both interpretations in mind prevents many common mistakes: writing rules that are logically correct but loop forever, using cuts that improve speed but change meaning, designing predicates that work for one query pattern but fail for another direction of use.

Common Misconceptions from Imperative Backgrounds

Programmers coming from imperative languages often carry assumptions that lead to confusion when first encountering Prolog. Here are the most common ones.

“Variables hold values that change over time.”

In Prolog, variables are logical placeholders, not storage locations. When a variable is bound to a value during unification, that binding persists for the current proof attempt but can be undone during backtracking. Variables do not have their values reassigned; they either are unbound (logical variables) or are bound to specific terms. This difference is fundamental and affects how you structure computations. We explore it in detail in Chapters 4 and 5.

“I need to write loops to process lists.”

Prolog has no traditional loop constructs like `for`, `while`, or `do-while`. Repetition is expressed through recursion: a predicate calls itself with progressively simpler arguments until reaching a base case. This feels unnatural at first to imperative programmers but becomes second nature quickly. Chapter 7 covers recursive patterns extensively.

“A predicate is like a function that returns a value.”

Prolog predicates do not return values; they succeed or fail, possibly binding variables in the process. Information flows through all arguments bidirectionally (in principle), not just from inputs to an output. This relational view enables powerful patterns but requires thinking differently about how data moves through your program.

“If my logic is correct, Prolog will find the answer.”

Logical correctness is necessary but not sufficient. Due to Prolog’s depth-first search strategy and sensitivity to clause/goal ordering, a logically sound program may loop forever or miss answers. You must design with termination and search behavior in mind. Chapter 6 explains why.

“I can translate my existing algorithm directly into Prolog.”

Direct translation usually produces code that works but is unidiomatic and misses Prolog’s strengths. Instead of translating algorithms, reframe the problem: what relationships and constraints define a solution? Let Prolog’s search mechanism do the work of exploring possibilities rather than encoding exploration explicitly. This reframing is the core skill this book develops.

Summary

This chapter has laid the conceptual groundwork for understanding Prolog as more than syntax and built-in predicates. The key ideas are:

- Prolog is a declarative language where you specify what must be true rather than how to compute it.
- Programs describe relationships between values, not functions from inputs to outputs.
- The language is grounded in first-order logic and specifically in Horn clauses.
- The closed-world assumption treats unprovability as falsehood, which affects how negation works.
- Every clause has both a declarative meaning (what it states logically) and a procedural interpretation (how it executes), and both matter.
- Imperative programming habits often conflict with idiomatic Prolog; success requires learning to think relationally.

The next chapter returns to concrete programming: facts, rules, and queries in detail, with systematic coverage of syntax, structure, and the basic patterns you will use in every Prolog program.

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