



Undefined

Behavior

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A Guide to Programming's Dark Corner

Undefined Behavior

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Thomas Peuß

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Preface

Life would be much simpler if computers just did exactly what we told them to do. Unfortunately, the reality is far more complex. In the realm of software development, we frequently encounter situations where our assumptions about program behavior clash with the actual mechanics of how computers execute our code. This disconnect is perhaps most dramatically illustrated in the concept of undefined behavior.

When I first started writing this book, I asked several experienced developers what they thought about undefined behavior. The responses ranged from “it’s just when the program crashes” to “it’s something the compiler warns you about.” These answers, while not entirely incorrect, barely scratch the surface of one of programming’s most misunderstood and potentially dangerous concepts.

This book aims to demystify undefined behavior, exploring its implications from the silicon to the source code. Whether you’re a seasoned systems programmer or a developer who has just encountered their first strange compiler optimization, this book will provide you with the knowledge and tools to understand, identify, and handle unexpected behavior effectively.

Structure of This Book

The book begins with foundational concepts, exploring what undefined behavior truly is and its historical context. From there, we examine how different programming languages approach undefined behavior:

- **Core Concepts:** The first chapters cover the fundamentals of undefined behavior, its history, and theoretical understanding
- **Language-Specific Chapters:** We explore how C, C++, Python, Java, JavaScript, TypeScript, Ada, Haskell, and Rust handle (or don’t handle) undefined behavior
- **Practical Implications:** Dedicated chapters on performance, security, and embedded systems examine the real-world impact of undefined behavior

- **Mitigation Strategies:** Testing approaches and formal verification methods for detecting and preventing undefined behavior
- **Cross-Language Perspectives:** The final chapters offer a comparative analysis of undefined behavior across languages and practical guidance for migrating between language paradigms

Each chapter includes practical examples, diagnostic tools, and exercises to deepen your understanding.

Who This Book Is For

This book is designed for software developers at all levels who want to write more reliable and secure code. Whether you're:

- A student learning C, C++, or other languages with undefined behavior
- A mid-career developer troubleshooting mysterious bugs
- A systems programmer optimizing performance-critical code
- A security professional concerned with exploitable vulnerabilities

You'll find practical insights that apply directly to your work.

What You'll Gain

By reading this book, you'll develop:

- A deep understanding of undefined behavior across programming languages
- Practical skills for detecting and preventing undefined behavior
- Insights into language design tradeoffs between safety and performance
- Strategies for migrating code between languages with different safety models
- A heightened awareness of potential security vulnerabilities



Some of the examples in this book may seem counterintuitive or even impossible at first glance. That's the nature of undefined behavior – it challenges our assumptions about how programs work and forces us to think more deeply about the contracts we make with our compilers and hardware.

Whether you're working on performance-critical systems software, building web applications, or developing embedded systems, understanding undefined behavior is crucial for writing reliable, secure, and efficient code. This book will serve as your guide through this complex but fascinating aspect of programming language design and implementation.

Introduction

Imagine you're playing a game of chess, but halfway through the match, your opponent makes a move that isn't covered by the rules.

What happens next?

Does the game continue? Does it crash to a halt? Does the universe implode?

Undefined behavior is like playing chess where certain illegal moves are silently accepted during practice games, only to cause catastrophic failures during the championship match.

This is essentially what undefined behavior is in programming – it's what happens when we make a move that breaks the rules of the programming language.

Why Should You Care?

Before diving into technical details, let's address the fundamental question: why should you care about undefined behavior?

Security Implications

Undefined or unexpected behavior are at the heart of many critical security vulnerabilities. Consider these real-world examples:

- **Buffer Overflows:** The Morris Worm, one of the first computer worms, exploited buffer overflow vulnerabilities – a classic case of undefined behavior.
- **Use-After-Free:** The Chromium project regularly patches use-after-free vulnerabilities that could allow attackers to execute arbitrary code.
- **Null Pointer Dereferences:** Android's Stagefright vulnerabilities, affecting millions of devices, stemmed from undefined behavior in media processing.

- **Security Checks:** a wrong comparison operation can allow an attacker to gain access to systems.

Many developers are surprised to learn that seemingly innocuous undefined behavior can be weaponized by attackers to bypass security controls entirely.

Reliability Concerns

Code containing undefined and unexpected behavior might appear to work perfectly during development and testing, only to fail catastrophically in production. This happens because:

- Different optimization levels can change how undefined behavior manifests
- Production environments often have different memory layouts and timing characteristics
- System load can affect how undefined behavior presents itself
- Code that worked for years might suddenly break with a compiler update



Real-World Example

A major telecommunications company once spent weeks debugging a system that worked perfectly in testing but failed in production. The culprit? Undefined behavior that only manifested when the system was under heavy load.

Performance Impact

Modern compilers make significant optimization decisions based on the assumption that code doesn't contain undefined behavior:

- Aggressive loop optimizations assume no integer overflow
- Memory access optimizations assume proper alignment and valid pointers
- Function inlining decisions may change based on assumed behavior
- Vectorization opportunities depend on well-defined array access patterns



Consider this: removing a single instance of undefined behavior might force the compiler to generate additional runtime checks, potentially affecting performance throughout your entire program.

Development and Debugging Costs

Undefined behavior can significantly impact development costs:

- Debugging becomes much more challenging when behavior isn't consistent
- Testing needs to cover multiple platforms and configurations
- Code reviews must carefully consider potential undefined behavior
- Documentation needs to explicitly warn about potential pitfalls



Cost Impact Example

A financial institution discovered that 30% of their debugging time was spent investigating issues that ultimately traced back to undefined behavior in their codebase.

Undefined vs. Unexpected behavior

Now that we understand why this topic matters, let's clarify the difference between two commonly confused terms: undefined and unexpected behavior.

What is Undefined Behavior?

In the most formal sense, undefined behavior refers to conditions that occur when a program enters a state that is not specified by the programming language standard. The application essentially throws up its hands and says, “all bets are off.”

Figure 1. Undefined behavior in C example

```
1  #include <stdio.h>
2
3  int main() {
4      int array[5] = {1, 2, 3, 4, 5}; // Array with 5 elements (indexes 0-4)
5
6      // Accessing beyond array bounds - undefined behavior
7      printf("Sixth element: %d\n", array[5]);
8
9      // Even worse - writing beyond array bounds
10     array[10] = 42;
11
12     return 0;
13 }
```

This code attempts to access and modify memory outside the allocated array, which is undefined behavior. The code might work (reading beyond the size of the array) or crash (because some compilers implement safeguards against this program error). The former is more scary than the latter in my opinion.



Key Effects of Undefined Behavior

- The program might crash
- It might produce incorrect results
- It might *appear* to work perfectly
- It might format your hard drive
- It might do any or all of these things intermittently

What is Unexpected behavior?

Unexpected behavior on the other hand is fully deterministic. Your application is behaving other than you expect but it follows language rules and specifica-

tions. Unexpected behavior is only affecting the specific operation you want to use and does not affect the rest of the application.

Figure 2. Unexpected behavior in Javascript example

```

1  // JavaScript equality and type coercion disasters
2  console.log([] == '');           // true
3  console.log([] == 0);            // true
4  console.log('' == 0);            // true
5  console.log('' == '0');          // false
6  console.log(0 == '0');           // true
7
8  // The truly shocking ones
9  console.log(null == undefined);  // true
10 console.log([10] == 10);          // true
11 console.log('10' == 10);          // true
12 console.log(true == 1);           // true
13 console.log(true == '1');         // true
14 console.log(false == '0');        // true
15
16 // The absolute disaster
17 console.log('' == false);          // true
18 console.log('0' == false);        // true
19 console.log(0 == false);           // true
20
21 // But this is false!
22 console.log('false' == false);     // false

```

These seemingly impossible equivalences occur because JavaScript silently converts types before comparison. The empty array becomes an empty string, which then becomes zero—creating a chain of “equal” values that are fundamentally different. This isn’t merely confusing—it’s dangerous. What makes this behavior particularly treacherous is that it violates the basic mathematical principle of transitivity in equality, undermining our ability to reason logically about our code.¹ But this code can be debugged, tested and fixed systematically. That’s the main difference between undefined and unexpected behavior: it is deterministic.

Comparison Table: Undefined vs. Unexpected Behavior

¹This is why experienced JavaScript developers always use the strict equality operator === which doesn’t perform type coercion and prevents these dangerous equivalences. Another solution is to use Typescript. We come to this in a later chapter.

Aspect	Undefined Behavior	Unexpected Behavior
Definition	Not specified by language standard	Specified but counterintuitive
Predictability	Completely unpredictable	Deterministic but surprising
Scope of impact	Can affect entire program	Limited to specific operation
Debugging difficulty	Extremely difficult	Challenging but systematic
Fix complexity	Often requires fundamental changes	Usually fixable with proper knowledge
Example languages	C, C++	JavaScript, PHP
Primary dangers	Security vulnerabilities, crashes	Logic errors, data corruption
Detection by tools	Static analyzers, sanitizers	Linters, type checkers



Key Effects of Unexpected behavior

- Is a program behaving differently than intended
- Still follows language rules and specifications
- Has deterministic and well-defined outcomes
- Only affects the specific operation in question

Portability Challenges

Code that relies on specific manifestations of undefined behavior creates significant portability issues:

- **Different Architectures:** What works on x86 might fail on ARM due to different memory models
- **Operating Systems:** Behavior that’s consistent on Linux might be completely different on Windows

- **Compiler Variations:** GCC and Clang might handle the same undefined behavior differently
- **Future Compatibility:** Code that works today might break with future compiler versions



Warning

Never assume that undefined behavior will manifest consistently across different platforms or environments. What appears to work reliably on your development machine might fail spectacularly elsewhere.

Legal and Compliance Implications

In certain industries, undefined behavior can have serious legal consequences:

- **Safety-Critical Systems:** Undefined behavior in medical devices or automotive systems could lead to loss of life
- **Financial Systems:** Trading systems with undefined behavior might cause significant financial losses
- **Regulatory Compliance:** Some industries require certification that code is free of undefined behavior

Understanding undefined behavior isn't just an academic exercise - it's a crucial skill for anyone serious about developing reliable, secure, and maintainable software. The consequences of ignoring it can range from subtle bugs to catastrophic failures.

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Undefined Behavior

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Stagefright

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Step 2: Craft Malicious Input

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Step 3: Control Execution Flow

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Behavior Comparison Across Languages

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Tools for Detecting Undefined Behavior

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