COMPILATION OF A TYPED R-LIKE LANGUAGE TO WEBASSEMBLY

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Bachelor's thesis
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January 5, 2026

FACULTY
OF INFORMATION
TECHNOLOGY
CTU IN PRAGUE

Assignment of bachelor's thesis

Title:	Compilation of a typed R-like language to WebAssembly
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Supervisor:	Pierre Donat-Bouillud, Ph.D.
Study program:	Informatics
Branch / specialization:	Computer Science 2021
Department:	Department of Theoretical Computer Science
Validity:	until the end of summer semester 2026/2027

Instructions

R is an open-source programming language and software environment widely used for statistical computing and data analysis. Originally developed for statisticians, it has become the de facto standard in many scientific disciplines including bioinformatics, data analysis, finance, or data mining. In R, vectors are first-class citizens, as even 1 is represented as a vector of size 1. R is a dynamic language and is notoriously difficult to compile; it is currently only JIT-compiled in experimental projects [1]. WebAssembly [2] is an open, safe and portable compilation target for programming languages, enabling deployment in the web or locally. Currently, the R Interpreter can be compiled to WebAssembly [3] but R programs themselves cannot be.

The goal of the thesis is to define and compile a statically-typed subset of R, or R-like. It should be simple enough to be able to compile it, but expressive enough to express operations on vectors and perform statistical operations. The target architecture will be WebAssembly.

1) Research the R language and WebAssembly.
2) Define and formalize a typed subset of R. It should at least support vector operations, simple control-flow instructions, and function calls.
3) Write a compiler from this subset to WebAssembly
4) Write a runtime for the subset.
5) Evaluate the compiler and the runtime.

Electronically approved by doc. Ing. Jan Janoušek, Ph.D. on 23 June 2025 in Prague.

[1] Flückiger, O., Chari, G., Yee, M. H., Ječmen, J., Hain, J., & Vitek, J. (2020). Contextual dispatch for function specialization. Proceedings of the ACM on Programming Languages, 4(OOPSLA), 1-24.
[2] https://webassembly.org/
[3] https://github.com/r-wasm/webr

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Citation of this thesis: Baljinnyam Bilguudei. *Compilation of a typed R-like language to WebAssembly* . Bachelor's thesis. Czech Technical University in Prague, Faculty of Information Technology, 2026.

I would like to thank my supervisor, Pierre Donat-Bouillud, Ph.D for his invaluable support and patience with me throughout the work of this thesis. I also want to show my gratitude for amazing teachers at FIT, CTU, without whom, I wouldn't have learned much. I also want to thank all my friends I found in the university for making the journey unforgettable, and for my friends and my family for supporting me, especially my partner Barbora Navrátilová and, my brothers Chinguun Baljinnyam, Subeedei Purevmaa, and finally my mother Purevmaa Badii.

Declaration

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Abstract

R is a widely-used dynamic language for statistical computing, but its dynamic nature prevents efficient ahead-of-time compilation. This thesis presents the design and implementation of a compiler for a statically-typed subset of R, called Typed R, that targets WebAssembly. The defined language retains R's core characteristics, including first-class vector operations and lexical scoping, while introducing static typing to enable compilation. The compiler leverages the WebAssembly Garbage Collection proposal, which simplifies memory management and enables efficient representation of high-level language constructs. Source programs are transformed through parsing, type checking, and intermediate representation lowering to generate WebAssembly bytecode, supported by an easily extendable runtime system written in Typed R. Evaluation on representative statistical programs demonstrates the viability of compiling R-like languages to WebAssembly using modern proposals.

Keywords WebAssembly, WASM GC, Typed R, WASM bytecode, Pass-based Compiler

Abstrakt

R je široce používaný dynamický jazyk pro statistické výpočty, ale jeho dynamická povaha brání efektivní kompilaci předem. Představujeme návrh a implementaci kompilátoru pro staticky typovanou podmnožinu jazyka R, která cílí na WebAssembly. Definovaný jazyk si zachovává základní vlastnosti jazyka R, včetně prvotřídních vektorových operací a lexikálního rozsahu, a zároveň zavádí statické typování pro umožnění kompilace. Kompilátor využívá návrh WebAssembly Garbage Collection, který zjednodušuje správu paměti a umožňuje efektivní reprezentaci konstrukcí jazyků vysoké úrovně. Zdrojové programy jsou transformovány pomocí parsování, kontroly typů a mezilehlé reprezentace snižování, aby se generoval bajtkód WebAssembly, podporovaný běhovým systémem poskytujícím vektorové operace a interoperabilitu hostitelského prostředí. Vyhodnocení reprezentativních statistických programů demonstruje životaschopnost kompilace jazyků podobných jazyku R do WebAssembly s využitím moderních návrhů.

Klíčová slova WebAssembly, WASM GC, Typovaný R, WASM bytecode, kompilátor založený na průchodech

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List of abbreviations

AST	Abstract Syntax Tree
CRAN	The Comprehensive R Archive Network
FFI	Foreign function interface
GC	Garbage Collector
I/O	Input, Output
IR	Intermediate Representation
NSE	Non Standard Evaluation (R)
OOP	Object Oriented Programming
SIMD	Single Instruction, Multiple Data
WASI	WebAssembly System Interface
WASM	Web Assembly
WAT	Web Assembly Text

Chapter 1
Introduction

The R programming language is ubiquitous for statistical computing and data analysis, offering powerful abstraction for data manipulation and visualization. Inspired by S-Language, the R language has been important part for industries working with statistics and been pioneer for introducing widespread tools currently used by the community such as DataFrame.

Traditionally, R is an interpretered language that runs on most major operating systems. By interpretered language, we mean that the language source code is not translated to certain binary to be executed by processor like compiled languages. Instead interpreter is a program, usually written in low-level languages such as C, C++ or Rust, which takes the source code, does lexing and parsing to get AST and directly executes the program from its AST representation by evaluating from top node [1, 2].

Nowadays, the industry has been expanding the environments where we can run our programs. The interpreter program we discussed about, is compiled to bytecode, and then binary that the processor can execute. However, with invention of WebAssembly, we can take this interpreter and compile it to so-called WASM bytecode, and run it on web. This is exactly what webR [3] did. This way, R code we write, can seamlessly run on most browsers.

Compiling the interpreter to WASM introduces certain challenges. Since the interpreter consists of a substantial amount of code, every R program executed in the browser must include the entire interpreter compiled to WASM. This increases the overall memory footprint and can negatively impact performance, particularly in resource-constrained environments.

Thus, this thesis explores direct compilation of R-like language to WebAssembly. A subset of R with type annotations is created to make compilation possible to WASM, as it needs static typing. The thesis then explores the challenges of mapping a dynamic high-level language to WASM, and finally evaluates the performance and correctness of the compiler.

The structure of the thesis follows this premise. Chapter 2 introduces the concepts of R, WASM and previous works. Chapter 3 states the rationale for creating Typed R and introduces the language itself, both formally and informally with examples. Chapter 4 describes the building of the compiler and runtime, and lastly Chapter 5 discusses the evaluation of the compiler and the performance of the generated binary in comparison to standard R environment and WebR.

1.1 Aim

It's important to note this thesis focuses on exploring possibility and options of compiling R to WASM. Creation of type system and annotations are a vehicle to reach there and not full focus of this thesis, as there are better typing proposals [4, 5, 6]. Primarily the aim is to define a statically-typed subset of R, that is simple enough to be able to be compiled to WASM, but also expressive enough to show R's core such as mathematical operations and vectors. Then show by implementing a working and an efficient compiler for Typed R to WASM and evaluating the generation of WASM.

Chapter 2

Background

2.1 The R Programming Language

R is a domain-specific language designed for statistical computing and graphics, originally developed by Ross Ihaka and Robert Gentleman in the early 1990s as an open-source implementation of the **S** language [7]. With its CRAN package manager providing more than 20000 packages, it's a widely programming language used by industries where experimenting with data is involved, such as data analytics, data mining and bio-informatics.

R is fundamentally designed around vector operations, where everything, even scalar values, is represented as a vector. This design manifests in the language's support for **vectorization**, enabling operations to apply element-wise across data structures without explicit loops, as seen in expressions like `c(1,2,3) + c(4,5,6)` ⇒ `c(5,7,9)`. The language employs **dynamic typing** with types determined at runtime rather than through variable declarations, facilitating rapid prototyping and interactive data exploration at the cost of static verification. Combined with **lexical scoping** and closures, where functions capture their defining environment, R supports functional programming patterns that enable higher-order abstractions and metaprogramming capabilities essential for statistical computing. The language's **lazy evaluation** strategy delays argument evaluation until values are required, allowing non-standard evaluation mechanisms that support domain-specific sublanguages. To preserve referential transparency, R implements **copy-on-modify semantics**, implicitly copying objects upon modification to prevent unexpected side effects, though this approach can introduce performance overhead in memory-intensive workloads.

2.1.1 Type System

R has a dynamic type system with several foundational types, all of which are first-class objects. Unlike statically-typed languages, type information is associated with values at runtime rather than with variable declarations. R provides six atomic vector types:

- **Logical:** Boolean values `TRUE`, `FALSE`, and `NA` (missing).

  ```
  x <- TRUE
  typeof(x)      # returns "logical"
  ```

- **Integer:** Whole numbers, denoted with an `L` suffix.

  ```
  x <- 42L
  typeof(x)      # returns "integer"
  ```

- **Double:** Floating-point numbers (default numeric type).

  ```
  x <- 3.14
  typeof(x)      # returns "double"
  ```

- **Character:** Strings of text.

  ```
  x <- "hello"
  typeof(x)      # returns "character"
  ```

- **Complex:** Complex numbers with real and imaginary parts.

  ```
  x <- 2 + 3i
  typeof(x)      # returns "complex"
  ```

- **Raw:** Raw bytes (rarely used).

  ```
  x <- charToRaw("A")
  typeof(x)      # returns "raw"
  ```

  Beyond atomic vectors, R supports several composite data structures:

- **List:** Heterogeneous collections that can hold elements of different types.

  ```
  x <- list(42, "text", TRUE)
  typeof(x)      # returns "list"
  ```

- **Function:** Functions are first-class objects.

  ```
  f <- function(x) x + 1
  typeof(f)      # returns "closure"
  ```

  This means functions are treated as normal variables. It can be nested definition, passed as parameter and returned from a function.

- **Environment:** Hash-like structures for variable scoping.

  ```
  e <- new.env()
  typeof(e)      # returns "environment"
  ```

R performs implicit type coercion following a hierarchy: logical → integer → double → character. When combining types, R automatically converts to the most general type:

```
c(TRUE, 1L, 2.5, "text")  # returns character vector:
# "TRUE" "1" "2.5" "text"
```

This automatic coercion simplifies interactive use but can lead to unexpected behavior if types are not carefully managed.

2.2 WebAssembly

WebAssembly is a low-level assembly-like language that is made to run in modern browser [8]. It's designed to work together with JavaScript, the language of the web environment, offering flexibility and performance. Currently most modern languages support WASM as compilation target; for example, Rust through rustc, C/C++ through Emscripten.

Practically, WebAssembly offers myriad of possibilities to developers. From Image-processing libraries in hidden behind C to desktop apps written in C#, with WASM , they can run on the web with near native-like performance. Notable examples of adoption of WASM are Figma [9], Autodesk AutoCAD Web App [10], and Google Earth [11].

Moreover, for readability, WebAssembly also has so-called Web Assembly Text Format, in short WAT. It's a form where bytecode itself is more readable, with more syntactic sugars. Let's iterate over properties of WASM and how it's structured and written in WAT format. From personal, experience WAT format really eases development and debugging process by removing friction of using different tools to analyze the bytecode. Moreover, WASM's ecosystem provides useful tools like `wasm2wat, wat2wasm, wasm-tools validate` etc, which makes development better.

Let's talk about essential characteristics of WASM. First of all, WebAssembly code is organized into modules. Modules declare imports (functions, memory, tables, globals from the host environment) and exports (making internal definitions available externally) [12]:

```
(module
  ;; Import a logging function from the host
  (import "env" "log" (func $log (param i32)))

  ;; Import memory from the host
  (import "env" "memory" (memory 1))
```

```

  ;; Internal function (not exported)
  (func $internal_add (param $a i32) (param $b i32) (result i32)
    local.get $a
    local.get $b
    i32.add
  )

  ;; Can write memory
  ;; Can create data segment

  ;; Public function that uses imports
  (func $add_and_log (param $a i32) (param $b i32) (result i32)
    local.get $a
    local.get $b
    call $internal_add    ;; call internal function
    local.get 0           ;; duplicate result for logging
    call $log             ;; log the result
  )

  ;; Export the public function
  (export "addAndLog" (func $add_and_log))
)
```

Code listing 2.1 Module demonstrating import and export mechanisms

Moreover, with goals of being fast, efficient, and portable, WebAssembly, at its heart, is a stack-based virtual machine running on the web(Possible to run on a machine through NodeJS or Wasmtime). Stack-based machine in this context is a process virtual machine that works as virtualization of computer system on top of a computer. Its workings is primarily based on interacting with the stack. For example:

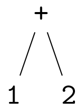


Figure 2.1 Tree representation

```
(module
  (func $compute (result i32)
    i32.const 1       ;; push constant 1 onto stack
    i32.const 2       ;; push constant 2 onto stack
    i32.add           ;; pop two values, push sum
  )
  (export "compute" (func $compute))
)
```

Code listing 2.2 A simple WebAssembly function showing stack operations

Unlike raw bytecode with goto-style jumps, WebAssembly uses structured control flow constructs: block, loop, if, and br (branch). Each construct creates a label that branches can target [12].

```
(module
  (func $max (param $a i32) (param $b i32) (result i32)
    local.get $a
    local.get $b
    i32.gt_s                    ;; signed greater-than comparison
    (if (result i32)
      (then
        local.get $a
      )
      (else
        local.get $b
      )
    )
  )
  (export "max" (func $max))
)
```

Code listing 2.3 Conditional execution using structured control flow

WebAssembly provides a contiguous, resizable array of bytes called linear memory. Memory is accessed via load/store instructions with explicit alignment and offset [12].

```
(module
  (memory 1)                    ;; declare 1 page (64KB) of memory
  (func $increment_at_zero
    i32.const 0                 ;; memory address
    i32.const 0                 ;; memory address (for load)
    i32.load                    ;; load 32-bit value from address 0
    i32.const 1                 ;; constant 1
    i32.add                     ;; increment
    i32.store                   ;; store result back to address 0
  )
  (export "memory" (memory 0))
  (export "increment" (func $increment_at_zero))
)
```

Code listing 2.4 Accessing linear memory with load and store instructions

There's still more to discuss about features and characteristics of of WASM. We can take a look at instructions, traps, data segment, element segment, tables but they are not of utmost importance for reading this thesis. The reader may look explore more in details in WASM specs[12].

2.2.1 WebAssembly Garbage Collection proposal

WASM Garbage collection proposal, in short GC, is a new proposal that tries to provide efficient support for high-level languages. Since WASM announcement, community were coming up with their own GC as a way to compile high-level languages to WASM. With GC proposal, it helps to take load off of developers who are porting their languages to WASM. In this proposal, they introduced structs and arrays, which we'll heavily use in the implementation of this thesis.

2.3 Previous works

Work related to R about compilers and interpreter has been nothing but inspiring. The R has started with what we now call Tree-Walk interpreter [7]. Then around April 2011, with release of R 2.13.0 come the bytecode compiler by Luke Tierney, which was written almost entirely in R [13]. Essentially, it's faster to compile R into some intermediate bytecode and then have it executed by VM [14]. Thus, standard R environment execution became either with AST interpreter or with Bytecode Compiler [2]. From then on all standard functions and packages in base R ws pre-compiled into bytecode. Lastly, JIT bytecode compiler became the default from R.3.4.1 [15].

On top of standard implementations, execution on different environments have also been explored. WebR [3], most notably, is a recent work that compiles the R interpreter to WebAssembly using the Emscripten compiler to run R code on the web. Though as hinted at introduction, compiling the interpreter to WASM has its tradeoffs.

In terms of type system and type annotations around the R, there has been a discussion around type system in R as well [5]. There are even implementations for type system for R [4], although it's not adopted by R community. However, the purpose of the thesis is exploring the compilation of R to WASM. In that we use type annotations, but it's important to note that we won't dig deep into type systems at all.

Chapter 3

Language Design and Type System

In this chapter, we'll design a subset of R with types and see how types and their operations could map to WASM generation.

3.1 Design Goals

Some reader at this point might be wondering why subset of R and why with types, why not just compile R to WASM. R is notoriously hard to compile to statically typed byte-code. The first reason is typing.

Let's take the following code.

```
x <- some_function()
```

WASM on the other hand is expecting variable `x` to have a type. There's `any` type in WASM. Maybe we can try mapping it to `anyref`. A reference to `any` element by the WASM GC proposal. So now we have

```
(local $x anyref) // A tagged union can be also used.
```

Then, let's have a binary operation `x + y`, where `y` is also `anyref`. Now we need to implement a generic function for plus operator that can potentially dispatch to all types of that function.

```
if x is int && y is int:
  add_int(x, y)
if x is double && y is double:
  add_double(x, y)
...
```

This code will continue for every type and its combination. We'd have to also include promotion logic inside this code. Then x is int needs `try_cast` as well. We'll need to do such generic function for every operation and functions. Some will be impossible to cover. This is essentially re-implementing the R interpreter. Thus we fixate on R that's well-typed and the type is known or inferrable at compile time.

Moreover, we will see the same issue of dynamic dispatching when R variables change types.

```r
x <- 5          # numeric
x <- "hello"    # now a string
x <- list()     # now a list
```

This bounds us to either writing generic functions or using wrappers like a tagged union, which will limit our performance and waste memory.

Moreover, R uses lazy evaluation for function arguments; they're only evaluated when actually used:

```r
f <- function(x, y) { if (x > 0) y else 0 }
f(5, expensive_computation())  # expensive_computation() never runs!
```

This requires complex bookkeeping that's hard to optimize. Then, we have one of the main challenging feature with any attempts of ahead-of-compilation. The reflection. R code can inspect and modify itself at runtime:

```r
x <- quote(a + b)   # capture unevaluated expression
eval(x)             # evaluate it later
```

Lastly, many R functions evaluate arguments in non-standard ways:

```r
subset(df, age > 30)   # 'age' isn't a variable, it's a column name!
```

This is extremely difficult to analyze statically.

In conclusion, all those issues outlined above, is not impossible to compile. However, they require complex implementation and huge performance and memory trade-offs. For these, reasons it's important for me to define the subset of R, which I can compile and limit the scope without losing R's main functionalities and purposes.

3.2 Typed R-like Language

This section presents the design of a statically-typed programming language inspired by R's syntax, which we refer to as the *Typed R-like Language*. The language maintains R's characteristic features such as the left-assignment operator (`<-`), first-class functions, and vector-oriented programming, while introducing a static type system to enable ahead-of-time compilation to WebAssembly.

Table 3.1 compares the data types supported by R and Typed R, showing which primitive and composite types are available in each language.

Language Feature (Types)	**R**	**Typed R**
Integers	✓	✓
Doubles	✓	✓
Booleans	✓	✓
Strings	✓	×
NULL/NA values	✓	×
Vectors	✓	✓
Matrices	✓	×
Lists	✓	×
Data frames	✓	×
Arrays	✓	×

Table 3.1 Comparison of language features supported by R and Typed R

Table 3.2 presents a broader comparison of language features, including type system properties, functional programming capabilities, and advanced features that distinguish Typed R from standard R.

The design philosophy emphasizes a familiar R-like syntax while ensuring type safety and efficient compilation to WebAssembly. Unlike dynamically-typed R, all type information is resolved at compile time, enabling optimized code generation and early error detection. It's also worth to mention that implementation of those features take a lot of engineering time and effort. Therefore, I have only implemented what I see as essential and most used for demonstrating the point of this thesis.

Language Feature	**R**	**Typed R**
Static typing	×	✓
First-class functions	✓	✓
Vector operations	✓	✓
Math operations	✓	✓
Control flow	✓	✓
Higher-order functions	✓	✓
Lexical scoping	✓	✓
Named arguments	✓	✓
Variable arguments (...)	✓	✓
Reflection	✓	×
Runtime type changes	✓	×
Non-standard evaluation (NSE)	✓	×
Lazy evaluation	✓	×
Copy-on-modify semantics	✓	×
Garbage collection	✓	✓
Operator overloading	✓	×
Attributes/metadata	✓	×
Method dispatch (S3/S4/R6)	✓	×

Table 3.2 Comparison of language types supported by R and Typed R

3.3 Syntax

The syntax of the Typed R-like Language closely follows R conventions with extensions for explicit type annotations. This section describes the core syntactic constructs.

Let's start with examples before diving into formalities of the language. Starting with variables, they are declared using the left-assignment operator with optional type annotations:

```
# Simple assignment with type inference
x <- 10

# Assignment with explicit type annotation
y: int <- 20

# Vector assignment
vec <- c(1, 2, 3)
```

Code listing 3.1 Variable assignment examples

After variable assignment, we have very interesting syntax for super assignment. R distinguishes between assigning a variable in the scope or outside the scope with different syntax, unlike other popular dynamic languages like Python or Javascript. In Typed R, we'll do the same.

```
outer <- function() {
    x <- 0
    inner <- function() {
        x <<- 10  # Modifies x in outer scope
    }
    inner()
    return(x)  # Returns 10
}
```

Code listing 3.2 Super-assignment example

I should also note that on Code fragment 3.2 above, Typed R looks exactly same as R. For trivial cases like this, type inference can help a lot, which we will talk in next chapter.

Moving onto functions, they are first-class values defined using the `function` keyword:

```
# Simple function with type annotations
add <- function(a: int, b: int): int {
    return(a + b)
}

# Function returning a vector
create_vector <- function(): vector<double> {
    return(c(1.0, 2.0, 3.0))
}
```

```

# Higher-order function
apply_twice <- function(f: int -> int, x: int): int {
    return(f(f(x)))
}
```

Code listing 3.3 Function definition examples in typed R

First-class value mean they are essentially same as objects like vectors. They can be passed as parameter, saved to variable, can be returned from function.

In terms of control-flow, I attempted to support everything similar as R. Starting with if-else:

```
# If statement
if (x > 0) {
    print(x)
}

# If-else statement
if (x > 0) {
    y <- 1
} else {
    y <- -1
}

# If expression (returns value)
result <- if (x > 0) { 1 } else { -1 }
```

Code listing 3.4 Conditional examples in typed R

However, in R there's syntactic sugar where `if` that return expression can be written as `if (expr) 1 else 0`, without brackets. It's not implemented in our compiler.

Moreover, like in R, two loop constructs are provided: `for` and `while`.

```
# For loop iterating over range
for (i in 1:10) {
    print(i)
}

# For loop iterating over vector
vec <- c(1, 2, 3, 4, 5)
for (x in vec) {
    print(x)
}

# While loop
i <- 1
sum <- 0
while (i <= 5) {
    sum <- sum + i
    i <- i + 1
}
```

Code listing 3.5 Loop examples

Blocks consist of zero or more statements followed by an optional tail expression. The tail expression (final expression without semicolon) determines the block's value:

```
f <- function(x: int): int {
    y <- x * 2
    z <- y + 1
    z  # Tail expression - returned automatically
}
```

Code listing 3.6 Block with tail expression

Only functions create new scopes; blocks, if-statements, and loops share their enclosing function's scope. A **closure** is a function that captures variables from its defining environment. When a function references a variable from an outer function scope, that variable remains accessible even after the outer function returns. Super-assignment (`<<-`) modifies captured variables by searching enclosing function scopes.

Example demonstrating closure:

```
make_counter <- function(start: int): () -> int {
    count <- start
    function(): int {
        count <<- count + 1
        return(count)
    }
}

counter <- make_counter(0)
print(counter())  # Prints 1
print(counter())  # Prints 2
```

Code listing 3.7 Closure example

3.3.1 Abstract Grammar

$$
\begin{aligned}
e ::= {} & x \quad \text{(variable)} \\
& \mid n \mid d \mid \texttt{true} \mid \texttt{false} \quad \text{(literals)} \\
& \mid \texttt{function}(p_1, \ldots, p_n) : \tau \ \{ \ e \ \} \quad \text{(function definition)} \\
& \mid e_1(e_2, \ldots, e_n) \quad \text{(function call)} \\
& \mid e_1(x_1{=}e_2, \ldots, x_n{=}e_n) \quad \text{(named argument call)} \\
& \mid e_1 \oplus e_2 \quad \text{(binary operation)} \\
& \mid \ominus e \quad \text{(unary operation)} \\
& \mid \texttt{c}(e_1, \ldots, e_n) \quad \text{(vector construction)} \\
& \mid e_1 : e_2 \quad \text{(range sequence)} \\
& \mid e_1[e_2] \quad \text{(vector indexing)} \\
& \mid \texttt{if} \ e_1 \ \{ \ e_2 \ \} \ \texttt{else} \ \{ \ e_3 \ \} \quad \text{(conditional)} \\
& \mid \{ \ e_1; \ \ldots; \ e_n \ \} \quad \text{(block)} \\
s ::= {} & x \leftarrow e \quad \text{(assignment)} \\
& \mid x : \tau \leftarrow e \quad \text{(typed assignment)} \\
& \mid x \ll\!\leftarrow e \quad \text{(superassignment)} \\
& \mid e \quad \text{(expression statement)} \\
& \mid \texttt{return}(e) \quad \text{(return)} \\
& \mid \texttt{for} \ (x \ \texttt{in} \ e) \ \{ \ s \ \} \quad \text{(for loop)} \\
& \mid \texttt{while} \ (e) \ \{ \ s \ \} \quad \text{(while loop)} \\
p ::= {} & x : \tau \quad \text{(required parameter)} \\
& \mid x : \tau = e \quad \text{(parameter with default)} \\
& \mid \ldots \quad \text{(varargs)}
\end{aligned}
$$

3.3.2 Lexical Elements

The language uses the following lexical tokens:

- **Keywords:** `function`, `if`, `else`, `for`, `in`, `while`, `return`
- **Type keywords:** `int`, `double`, `void`, `logical`, `vector`
- **Operators:**
  - Assignment: `<-` (assignment), `<<-` (super-assignment)
  - Arithmetic: `+`, `-`, `*`, `/`, `%%` (modulo)
  - Comparison: `==`, `!=`, `<`, `<=`, `>`, `>=`
  - Logical: `&` (and), `|` (or), `!` (not)

  - Range: `num1 : num2` (sequence generation)
  - Type annotation: `:` (in declaration context)
  - Function arrow: `->` (in type signatures)
- **Delimiters:** `(`, `)`, `{`, `}`, `[`, `]`, `,`
- **Literals:** Numeric literals, logical literals (`TRUE`, `FALSE`)
- **Identifiers:** Alphanumeric sequences starting with a letter or underscore
- **Special:** `...` (varargs placeholder)

3.4 Type System

The type system ensures type safety through static analysis while supporting type inference to maintain concise syntax and ease of development. Type inference fails for programs lacking sufficient type information, requiring explicit annotations in those cases. The type grammar defines three major categories:

$$
\begin{aligned}
\tau &::= \mathit{num} \mid \texttt{void} && \text{(base type)} \\
&\mid \tau\,\texttt{[]} && \text{(vector type)} \\
&\mid (\tau_1, \ldots, \tau_n) \to \tau && \text{(function type)} \\[1ex]
\mathit{num} &::= \texttt{int} \mid \texttt{double} \mid \texttt{bool} && \text{(numeric types)}
\end{aligned}
$$

Typed R builds upon three core numeric types that align naturally with WebAssembly's type system. The `int` type represents 32-bit signed integers, mapping directly to WebAssembly's `i32` primitive, with values ranging from -2^{31} to $2^{31} - 1$. The `double` type provides 64-bit IEEE 754 floating-point numbers, corresponding to WebAssembly's `f64`, matching R's default numeric type for statistical computations. Boolean logic uses the `logical` type with R-style literals `TRUE` and `FALSE`, represented as `i32` in WebAssembly where zero means false and non-zero means true. Finally, `void` denotes the absence of a value for functions that perform side effects without returning data.

Beyond primitive types, vectors form the core composite structure. Vectors are homogeneous arrays parameterized by element type:

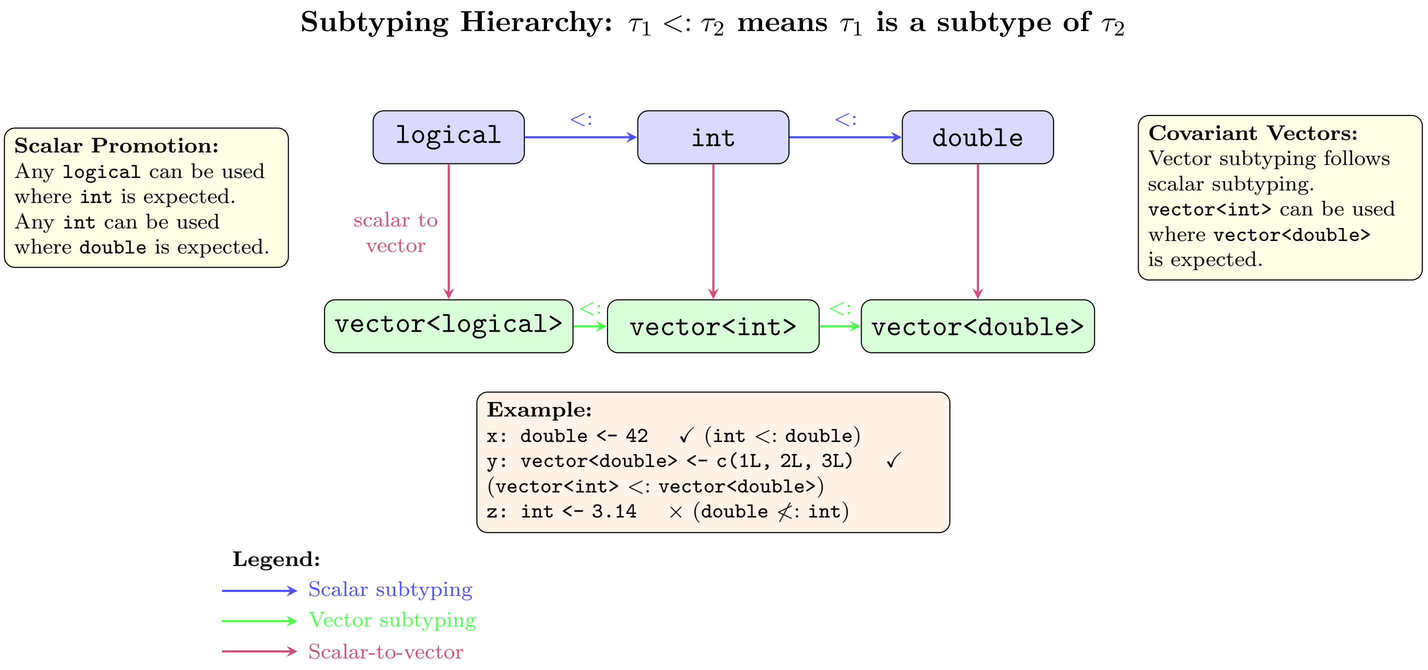
```
# Vector of integers
v1: vector<int> <- c(1, 2, 3)

# Vector of doubles
v2: vector<double> <- c(1.5, 2.5, 3.5)

# Vector operations (component-wise)
v3: vector<double> <- v2 + c(1.0, 2.0, 3.0)
```

Code listing 3.8 Vector type examples

Vectors support component-wise arithmetic operations when both operands have compatible vector types.

Function types complete the type system by encoding callable values with their parameter and return types. The simplest form, `int -> int`, describes a function accepting a single integer and producing an integer result. Multi-parameter functions extend this: `int, int -> double` takes two integers and returns a double. Higher-order functions naturally fit this notation, such as `(int -> int) -> int`, which accepts a function mapping integers to integers and returns an integer. Complex signatures like `int, (int, int -> int) -> int` combine these patterns, taking both a plain integer and a binary function as parameters. To avoid ambiguity in expressions like `int -> int -> int`, we require explicit parentheses in type annotations, ensuring each signature has exactly one interpretation.

Type promotion follows a subtyping hierarchy shown in Figure 3.1. Logical values can be used wherever integers are expected, and integers can be used wherever doubles are expected, creating the chain `logical` <: `int` <: `double`. Vectors are covariant with respect to their element types, meaning `vector<int>` can be used where `vector<double>` is expected, preserving the subtyping relationship across composite types.



Subtyping Hierarchy: $\tau_1 <: \tau_2$ **means** τ_1 **is a subtype of** τ_2

Scalar Promotion:
Any `logical` can be used where `int` is expected.
Any `int` can be used where `double` is expected.

Covariant Vectors:
Vector subtyping follows scalar subtyping.
`vector<int>` can be used where `vector<double>` is expected.

Example:
`x: double <- 42` ✓ (`int` <: `double`)
`y: vector<double> <- c(1L, 2L, 3L)` ✓ (`vector<int>` <: `vector<double>`)
`z: int <- 3.14` × (`double` $\not<:$ `int`)

Legend:
Scalar subtyping
Vector subtyping
Scalar-to-vector

Figure 3.1 Subtyping hierarchy showing scalar type promotion (`logical` <: `int` <: `double`) and covariant vector subtyping (`vector<logical>` <: `vector<int>` <: `vector<double>`). Scalar-to-vector conversions preserve the subtyping relationship, allowing implicit promotion in both scalar and vector contexts.

The language provides no user-creatable subtyping; we don't support R's

S3 system or OOP features in Typed R.

Type checking follows a bidirectional approach[16] that combines bottom-up inference and top-down checking. Bottom-up inference derives expression types from literal values and operator signatures, while top-down checking uses function return types and variable annotations to provide expected types. Unification solves type constraints to determine concrete types, incorporating the subtyping rules to enable implicit type promotion.

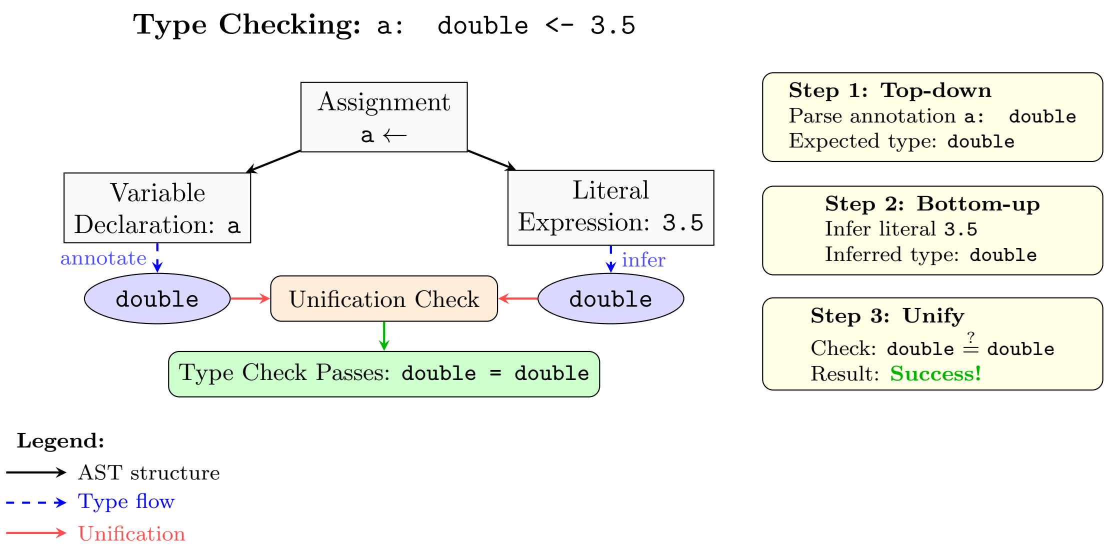


Figure 3.2 Bidirectional type checking for variable assignment. The type annotation `double` provides the expected type (top-down), while the literal `3.5` has its type inferred as `double` (bottom-up). The unification step verifies that both types match, allowing the assignment to proceed.

The basic algorithm works as follows: when type-checking an expression, if the type can be inferred from the expression itself (bottom-up), that inferred type is used. If an explicit type annotation is provided (top-down), the annotation is used as the expected type. When both are present, unification checks that the inferred type is compatible with (a subtype of) the annotated type. If neither inference nor annotation provides type information, type checking fails.

Type annotations are required for function parameters, function return types (when not inferrable from return statements), and ambiguous variable declarations. For example, in `a: double <- 3.5`, the literal `3.5` infers as `double` (bottom-up), the annotation expects `double` (top-down), and unification confirms they match (see Figure 3.2). The expression `3 + 2.5` demonstrates type promotion: `3` infers as `int` but is promoted to `double` through subtyping to match `2.5`, evaluating as `3.0 + 2.5 = 5.5`.

We do not formalize the complete type inference algorithm here, as bidirectional type inference is well-studied in programming language literature[16]. Our implementation follows standard techniques, extended with the subtyping hierarchy described in Section 3.1.

The formal type system uses inference rules with typing judgments of the form $\Gamma \vdash e : \tau$, read as "under typing context Γ, expression e has type τ." A typing context maps variable names to their types, defined as $\Gamma ::= \emptyset \mid \Gamma, x : \tau$, where $\emptyset$ is the empty context and $\Gamma, x : \tau$ extends context Γ with a binding of variable x to type τ. We write $x : \tau \in \Gamma$ when Γ contains the binding. Rules appear in natural deduction style with premises above the horizontal line and conclusions below; axioms have no premises. Our type system follows standard approaches from programming language theory [17], extended with subtyping for numeric promotion and vector operations.

Subtyping defines when one type can safely substitute for another. We write $\tau_1 <: \tau_2$ to mean "τ_1 is a subtype of τ_2" (equivalently, τ_1 can be used wherever τ_2 is expected). Every type is a subtype of itself, and the numeric promotion hierarchy establishes base cases:

$$\frac{}{\tau <: \tau}\ \textsc{S-Refl} \qquad\qquad \frac{}{\texttt{logical} <: \texttt{int}}\ \textsc{S-LogicalInt}$$

$$\frac{}{\texttt{int} <: \texttt{double}}\ \textsc{S-IntDouble}$$

S-Refl states that any type is a subtype of itself (reflexivity). S-LogicalInt allows logical values to be used as integers. S-IntDouble allows integers to be promoted to doubles, enabling mixed arithmetic like `3 + 2.5`. Subtyping is transitive, allowing chains like `logical` $<:$ `int` $<:$ `double`:

$$\frac{\tau_1 <: \tau_2 \qquad \tau_2 <: \tau_3}{\tau_1 <: \tau_3}\ \textsc{S-Trans}$$

If τ_1 can be used as τ_2, and τ_2 can be used as τ_3, then τ_1 can be used as τ_3, giving us `logical` $<:$ `double` automatically. Vectors are covariant in their element type:

$$\frac{\tau_1 <: \tau_2}{\texttt{vector}\langle\tau_1\rangle <: \texttt{vector}\langle\tau_2\rangle}\ \textsc{S-Vector}$$

When element type τ_1 is a subtype of τ_2, a vector of τ_1 can be used where a vector of τ_2 is expected. For example, `vector<int>` $<:$ `vector<double>`, so an integer vector can be passed to a function expecting a double vector. The subsumption rule connects subtyping to the type system, enabling implicit type promotion:

$$\frac{\Gamma \vdash e : \tau_1 \qquad \tau_1 <: \tau_2}{\Gamma \vdash e : \tau_2}\ \textsc{T-Sub}$$

If expression e has type τ_1 and τ_1 is a subtype of τ_2, then e can also be given type τ_2, enabling all implicit conversions. For example, if `x` has type `int`, we can use it where `double` is expected.

Literals and variables form the basic building blocks of expressions:

$$\frac{n \in \mathbb{Z}}{\Gamma \vdash n : \texttt{int}}\ \textsc{T-Int} \qquad \frac{d \in \mathbb{R}}{\Gamma \vdash d : \texttt{double}}\ \textsc{T-Double}$$

$$\frac{b \in \{\texttt{TRUE}, \texttt{FALSE}\}}{\Gamma \vdash b : \texttt{logical}}\ \textsc{T-Bool} \qquad \frac{x : \tau \in \Gamma}{\Gamma \vdash x : \tau}\ \textsc{T-Var}$$

Integer literals like `42` have type `int` (T-Int), floating-point literals like `3.14` have type `double` (T-Double), and `TRUE`/`FALSE` have type `logical` (T-Bool). Variables have whatever type the context Γ assigns them (T-Var).

Arithmetic operators (`+`, `-`, `*`, `/`, `%%`) follow the same typing pattern, shown here for addition:

$$\frac{\Gamma \vdash e_1 : \texttt{int} \qquad \Gamma \vdash e_2 : \texttt{int}}{\Gamma \vdash e_1 + e_2 : \texttt{int}}\ \textsc{T-AddInt}$$

$$\frac{\Gamma \vdash e_1 : \texttt{double} \qquad \Gamma \vdash e_2 : \texttt{double}}{\Gamma \vdash e_1 + e_2 : \texttt{double}}\ \textsc{T-AddDouble}$$

When both operands have the same numeric type, the result has that type. Mixed-type arithmetic like `3 + 2.5` applies subsumption to promote `3` from `int` to `double` before applying T-AddDouble. Comparison operators (`==`, `!=`, `<`, `<=`, `>`, `>=`) require both operands to have the same type after potential promotion and always produce `logical` results:

$$\frac{\Gamma \vdash e_1 : \tau \qquad \Gamma \vdash e_2 : \tau \qquad \tau \in \{\texttt{int}, \texttt{double}, \texttt{logical}\}}{\Gamma \vdash e_1 \odot e_2 : \texttt{logical}}\ \textsc{T-Compare}$$

where $\odot \in \{\texttt{==}, \texttt{!=}, \texttt{<}, \texttt{<=}, \texttt{>}, \texttt{>=}\}$. Logical AND (`&`), OR (`|`), and NOT (`!`) operate on boolean values:

$$\frac{\Gamma \vdash e_1 : \texttt{logical} \qquad \Gamma \vdash e_2 : \texttt{logical}}{\Gamma \vdash e_1 \ \texttt{\&}\ e_2 : \texttt{logical}} \ \textsc{T-And}$$

$$\frac{\Gamma \vdash e_1 : \texttt{logical} \qquad \Gamma \vdash e_2 : \texttt{logical}}{\Gamma \vdash e_1 \ \texttt{|}\ e_2 : \texttt{logical}} \ \textsc{T-Or}$$

$$\frac{\Gamma \vdash e : \texttt{logical}}{\Gamma \vdash \texttt{!}e : \texttt{logical}} \ \textsc{T-Not}$$

The `c()` function constructs vectors from elements, requiring all elements to have the same type τ after promotion:

$$\frac{\Gamma \vdash e_1 : \tau \qquad \Gamma \vdash e_2 : \tau \qquad \cdots \qquad \Gamma \vdash e_n : \tau}{\Gamma \vdash \texttt{c}(e_1, e_2, \ldots, e_n) : \texttt{vector}\langle\tau\rangle} \ \textsc{T-Vector}$$

For example, `c(1, 2, 3)` has type `vector<double>`. The colon operator creates sequences:

$$\frac{\Gamma \vdash e_1 : \tau_1 \qquad \Gamma \vdash e_2 : \tau_2 \qquad \tau_1, \tau_2 \in \{\texttt{int}, \texttt{double}\}}{\Gamma \vdash e_1 \texttt{:} e_2 : \texttt{vector}\langle\tau_1 \sqcup \tau_2\rangle} \ \textsc{T-Range}$$

where $\tau_1 \sqcup \tau_2$ denotes the **least upper bound** (join) of the two types under the subtyping relation:

$$\texttt{int} \sqcup \texttt{int} = \texttt{int} \qquad \texttt{double} \sqcup \texttt{double} = \texttt{double} \qquad \texttt{int} \sqcup \texttt{double} = \texttt{double}$$

The range `1:5` creates a sequence from 1 to 5, where the element type is the wider of the two bounds: `1L:5L` produces `vector<int>`, while `1:5` or `1L:5.0` produces `vector<double>`. Vector indexing uses bracket notation, producing a value of the element type:

$$\frac{\Gamma \vdash e_1 : \texttt{vector}\langle\tau\rangle \qquad \Gamma \vdash e_2 : \tau' \qquad \tau' \in \{\texttt{int}, \texttt{double}\}}{\Gamma \vdash e_1[e_2] : \tau} \ \textsc{T-Index}$$

The index can be an integer or double (truncated to integer at runtime), and follows R's 1-based indexing convention. Binary operators extend component-wise to vectors when both operands have the same numeric vector type:

$$\frac{\begin{array}{c}\Gamma \vdash e_1 : \texttt{vector}\langle\tau\rangle \\ \Gamma \vdash e_2 : \texttt{vector}\langle\tau\rangle \qquad \tau \in \{\texttt{int}, \texttt{double}\}\end{array}}{\Gamma \vdash e_1 \oplus e_2 : \texttt{vector}\langle\tau\rangle} \ \textsc{T-VecBinOp}$$

where $\oplus \in \{+, -, *, /, \%\%\}$. For example, `c(1,2) + c(3,4)` produces `c(4,6)`. Scalars broadcast to match vector length:

$$\frac{\Gamma \vdash e_1 : \tau \qquad \Gamma \vdash e_2 : \texttt{vector}\langle\tau\rangle \qquad \tau \in \{\texttt{int}, \texttt{double}\}}{\Gamma \vdash e_1 \oplus e_2 : \texttt{vector}\langle\tau\rangle} \text{ T-ScalarVec}$$

A scalar is implicitly replicated, so `2 * c(1,2,3)` produces `c(2,4,6)`. The symmetric case (vector $\oplus$ scalar) follows analogously.

Functions are first-class values with explicit parameter and return types. To type-check a function, we extend the context with parameter bindings and verify the body has the declared return type:

$$\frac{\Gamma, x_1 : \tau_1, \ldots, x_n : \tau_n \vdash e : \tau}{\Gamma \vdash \texttt{function}(x_1 : \tau_1, \ldots, x_n : \tau_n) : \tau\ \{\ e\ \} : (\tau_1, \ldots, \tau_n) \to \tau} \text{ T-Func}$$

The function itself has function type $(\tau_1, \ldots, \tau_n) \to \tau$. Function application checks that arguments match parameter types (with promotion via subsumption):

$$\frac{\Gamma \vdash e_0 : (\tau_1, \ldots, \tau_n) \to \tau \qquad \Gamma \vdash e_1 : \tau_1 \qquad \cdots \qquad \Gamma \vdash e_n : \tau_n}{\Gamma \vdash e_0(e_1, \ldots, e_n) : \tau} \text{ T-App}$$

The result has the function's return type. Conditional expressions require a logical condition and matching branch types:

$$\frac{\Gamma \vdash e_1 : \texttt{logical} \qquad \Gamma \vdash e_2 : \tau \qquad \Gamma \vdash e_3 : \tau}{\Gamma \vdash \texttt{if}\ (e_1)\ \{e_2\}\ \texttt{else}\ \{e_3\} : \tau} \text{ T-If}$$

Both branches must have type τ, which becomes the expression's type, enabling constructs like `x <- if (cond) { 1 } else { 2 }`. Assignment binds a value to a variable, extending the context:

$$\frac{\Gamma \vdash e : \tau}{\Gamma \vdash (x \leftarrow e) : \tau \dashv \Gamma, x : \tau} \text{ T-Assign}$$

We use $\dashv \Gamma'$ to indicate the output context after the statement. Assignment evaluates e, binds the result to x, and produces an updated context where x has type τ. The assignment itself also has type τ. Super-assignment modifies a variable in an enclosing scope:

$$\frac{x : \tau \in \Gamma_{outer} \qquad \Gamma \vdash e : \tau'}{\Gamma \vdash (x \ll\!\leftarrow e) : \tau'} \text{ T-SuperAssign}$$

where $\tau' <: \tau$ (the assigned value must be compatible with the existing binding). Super-assignment requires that x already exists in some enclosing function scope (Γ_{outer}), and the expression type must be compatible with the existing variable's type. Blocks are sequences of statements with an optional tail expression:

$$\frac{\Gamma \vdash s_1 : \tau_1 \dashv \Gamma_1 \qquad \Gamma_1 \vdash s_2 : \tau_2 \dashv \Gamma_2 \qquad \cdots \qquad \Gamma_{n-1} \vdash e : \tau}{\Gamma \vdash \{s_1; s_2; \ldots; e\} : \tau}\ \textsc{T-Block}$$

Statements are checked in sequence, with each potentially extending the context for subsequent statements. The block's type is determined by its final expression. Return statements have the type of their argument, which the type checker verifies matches the enclosing function's declared return type:

$$\frac{\Gamma \vdash e : \tau}{\Gamma \vdash \texttt{return}(e) : \tau}\ \textsc{T-Return}$$

3.5 Evaluation Model

This section describes the key runtime behaviors that affect how programs execute and how the compiler generates code.

3.5.1 Evaluation Order and Type Promotion

Expressions are evaluated left-to-right. When operands have different numeric types, the narrower type is promoted to the wider type before the operation:

- `logical` → `int`: `TRUE` becomes `1`, `FALSE` becomes `0`
- `int` → `double`: integers are converted to floating-point

For example, `TRUE + 2.5` evaluates as `1.0 + 2.5 = 3.5` (logical → int → double).

3.5.2 Vector Operations

Vector operations apply element-wise. When vectors have different element types, promotion occurs element-by-element:

$$\texttt{c}(v_1, \ldots, v_n) \oplus \texttt{c}(w_1, \ldots, w_n) = \texttt{c}(v_1 \oplus w_1, \ldots, v_n \oplus w_n)$$

When the length of the vector differs, we use recycling like in R. Essentially the vector of lower length is permutated until it has same or more length as the vector with higher length and operation is executed. For R, when the length of one vector is not divisible by the other, meaning the permutated vector will have additional elements, that won't be included in the operation, standard R environment shows a warning message. However, we don't have warning message in our compiler yet, it won't be provided.

When a scalar and vector are combined, the scalar is implicitly broadcast (replicated) to match the vector length:

$$s \oplus \texttt{c}(v_1, \ldots, v_n) = \texttt{c}(s \oplus v_1, \ldots, s \oplus v_n)$$

For example, `2 * c(1, 2, 3)` produces `c(2, 4, 6)`.

3.5.3 Function Evaluation and Closures

Functions in the typed R-like language are **closures**: they capture the environment in which they are defined. When a function is called:

1. The callee expression is evaluated to obtain a closure (function code + captured environment)
2. Arguments are evaluated left-to-right in the caller's environment
3. A new environment is created, extending the closure's captured environment with parameter bindings
4. The function body is evaluated in this new environment

It'll be discussed more in details in compiler and runtime environment in Chapter 4.

3.5.4 Built-in Functions

The language provides the following built-in functions:

Function	Type	Description
`c(e1, ..., en)`	$(\tau, \ldots, \tau) \to \texttt{vector}\langle\tau\rangle$	Creates vector from elements
`print(e)`	$\tau \to \texttt{void}$	Outputs value to stdout
`length(v)`	$\texttt{vector}\langle\tau\rangle \to \texttt{int}$	Returns vector length
`sum(v)`	$\texttt{vector}\langle\tau\rangle \to \tau$	Sums numeric vector

Table 3.3 Built-in functions and their types

Chapter 4

Compiler and Runtime

This chapter describes implementation of the compilers, highlighting important challenges and decisions made through compilation of Typed R to WASM. All implementation related to compiling and its scripts are written in Rust language. Rust is chosen for its modern features, memory safety and performance. In coming sections, we'll describe the architecture, and design decisions about the implementation of the compiler.

4.1 Compiler Architecture

Most compilers follow pass-based implementation. To make sense of the complexity, we divide compiler into so-called front-end, middle-end, and back-end. Front-end includes everything related to actually taking the code as a string and creating AST tree, and then intermediate representation. Middle-end is used for mostly language-independent optimizations on the IR. Then, finally the backend, back-end takes that IR and generates target-specific binaries or bytecode. In our case back-end would be generating the WASM code.

Conceptually, each part is composed of multiple modules shown in figure below 4.1 .

4.1.1 Front-end

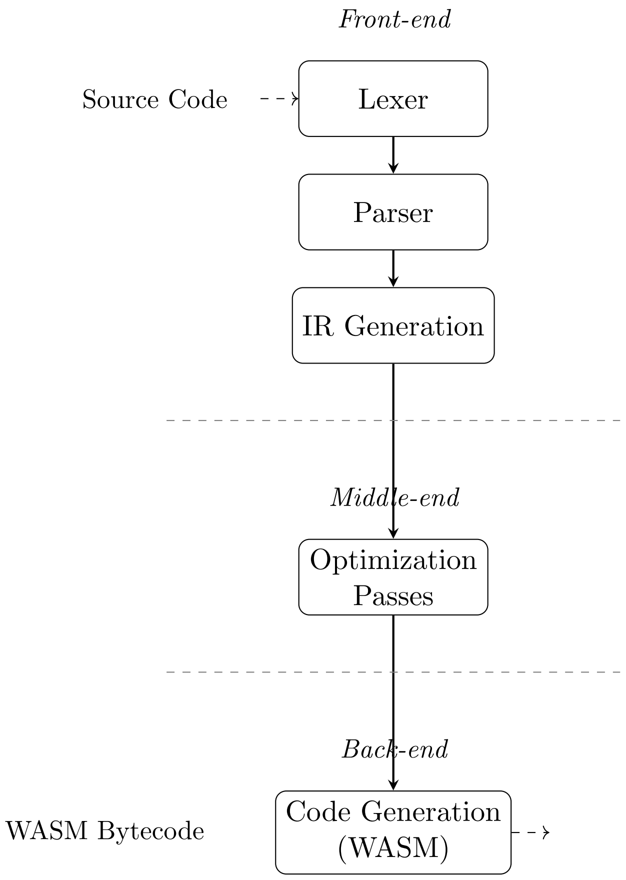
Composed of Lexer and Parser, it handles syntactic analysis and semantic analysis. Lexer takes in a source code as string, then produces so-called Tokens that programmer has defined. Those tokens are later fed into Parser, which uses the grammar to create AST tree.

4.1.2 Middle-end

This is where the optimizations happen. Or it could simply translate the IR into more efficient forms for back-end.

4.1.3 Back-end

Part that's concerned with only generating code for target architecture.



■ **Figure 4.1** Compiler pipeline architecture showing front-end, middle-end, and back-end phases

4.1.4 Compiler source code

The compiler uses multi-pass architecture. The contents of source is also available at A

4.1.4.1 Stage 1: Scanning

The lexer (`src/lexer.rs`) tokenizes source text into a stream of tokens. It recognizes R-specific operators (`<-`, `<<-`, `:`), tags built-in type names as `Token::Type`, and supports string interpolation.

4.1.4.2 Stage 2: Syntactic Analysis

The parser (`src/parser/`) constructs an untyped Abstract Syntax Tree (AST) using a recursive descent parser[18] with operator precedence. Expression parsing handles function definitions as expressions, and type annotations are parsed but not validated. The parser produces `Stmt` and `Expr` nodes defined in `src/ast.rs`.

4.1.4.3 Stage 3: Type Resolution and IR Construction

The `TypeResolver` (`src/ir/type_resolver.rs`) performs scope analysis by building a scope stack where only functions create scopes, infers types for untyped expressions, validates type annotations and operation compatibility, and produces typed IR nodes with concrete types. The IR (`src/ir/types.rs`) consists of `IRExpr` (expressions with associated `ty: Type` field), `IRStmt` (statements with type information), and built-in call resolution to `BuiltinKind` enum.

4.1.4.4 Stage 4: IR Transformation Passes

A pass manager (`src/ir/passes/manager.rs`) coordinates three transformation passes. The **Variable Collection Pass** (`variable_collection.rs`) assigns WASM local indices to all variables, tracks parameters, user variables, and compiler-generated temporaries, and populates `FunctionMetadata` for each function. The **Captured Variables Analysis** (`captured_vars.rs`) identifies variables captured from parent scopes, computes transitive captures through nested functions, and marks variables requiring reference cells for superassignment. The **Function Flattening Pass** (`function_flattening.rs`) lifts nested functions to top level, replaces them with closure construction expressions, and maintains capture lists for environment building.

4.1.4.5 Stage 5: Code Generation

The backend (`src/backend/`) generates WebAssembly where `WasmGenerator` constructs WASM module sections, registers type sections for structs, arrays, and functions, emits function code with local context tracking, and initializes memory for runtime data.

4.2 WebAssembly Code Generation

There's not many examples or implementation of a language directly compiling to WASM and it's for a good reason. Since the dawn of the programming, we've always had middle-layer or common-ground between compilers and bytecodes. Without it, we have ourselves N x M explosion. Imagine every programming language have to implement and finetune support for every architecture there is, from x86 to ARM, to WASM. To avoid this problem we have middle ground representations like bytecode, which is an intermediate, platform-independent code that can be easily compiled to different architectures. Or more commonly, LLVM[19], which a lot of languages use to compile to, helps programmers great deal. Just compile to LLVM IR generation, and use LLVM to generate any type of low-level code. This is how some static languages run in WASM. Also, JVM also built support for WASM so that JVM-based languages all can compile to WASM. Therefore, even though a lot of languages compile to WASM, they usually do it through LLVM or JVM. Even so, the aim of thesis being, compiling our typed subset of R directly to WASM, this section will focus on mappings and making typed R work in WASM.

4.2.1 Type Mapping

Types are mapped to WebAssembly value types as follows:

Source Type	WebAssembly Type
`int`	`i32`
`double`	`f64`
`logical`	`i32` (0 = false, 1 = true)
`vector<T>`	`(ref $vec_T)` (struct with data array and length)
`function`	`(ref $functype)` (typed function reference)

4.2.1.1 Vector Representation

Vectors are represented as WebAssembly GC structs:

```
(type $vec_f64 (struct
  (field $data (ref (array (mut f64))))
  (field $length (mut i32))
))
```

Code listing 4.1 Vector struct type

This representation:

- Uses WebAssembly GC arrays for efficient storage
- Stores length separately for fast access
- Allows mutable arrays for in-place updates
- Type-specialized structs for different element types (i32, f64, anyref)

Moreover, vectors can be constructed through functions embedded into runtime and built-in functions like `c, seq, rep`. WASM GC also frees of headache of book-keeping for GC.

4.2.1.2 Function References

Functions are represented using WebAssembly typed function references:

- Simple functions: Direct `(ref $functype)` where `$functype` is the function signature
- Closures: Struct containing function reference and captured environment
- Function calls use `call_ref` for indirect calls through function references

Closure representation:

```
(type $closure (struct
  (field $func (ref $functype))
  (field $env (ref $env_struct))
))
```

Code listing 4.2 Closure struct type

4.2.2 Expression Compilation

4.2.2.1 Literals

Literals compile to immediate value instructions:

- Integer literals: `i32.const n`
- Floating-point literals: `f64.const x`
- Boolean literals: `i32.const 0` (false) or `i32.const 1` (true)

As discussed earlier, R uses vectors even for scalar values. However, for Typed-R, we'll keep scalar values for better performance.

4.2.2.2 Variables

Variable references compile to local or global access:

- Local variables: `local.get $var_idx`
- Captured variables: Load from closure environment struct
- Function references: `ref.func $func_idx`

4.2.2.3 Binary Operations

Binary operations compile to corresponding WebAssembly instructions:

- Integer arithmetic: `i32.add`, `i32.sub`, `i32.mul`, `i32.div_s`, `i32.rem_s`
- Float arithmetic: `f64.add`, `f64.sub`, `f64.mul`, `f64.div`
- Integer comparison: `i32.eq`, `i32.ne`, `i32.lt_s`, `i32.le_s`, `i32.gt_s`, `i32.ge_s`
- Float comparison: `f64.eq`, `f64.ne`, `f64.lt`, `f64.le`, `f64.gt`, `f64.ge`
- Logical operations: `i32.and`, `i32.or` (with boolean normalization)

Vector operations compile to loops that apply scalar operations element-wise:

1. Allocate result vector with same length as operands
2. Loop over indices 0 to length-1
3. Extract elements from both operand vectors
4. Apply scalar operation
5. Store result in result vector

Moreover, all vector operations are written in Typed R language and it's compiled and embedded into runtime. For example:

```
system_vector_add___vec_int__vec_int <- function(a: vector<int>, b: vector<int>): vector<int> {
    n <- length(a)
    m <- length(b)

    if(n != m & n %% m != 0 & m %% n != 0) {
        stop("Vector lengths not compatible for recycling")
    }

    result_len <- max(n, m)
    result: vector<int> <- vec(length=result_len, mode="int")

    for(i in 1:result_len) {
        a_idx <- ((i - 1) %% n) + 1
        b_idx <- ((i - 1) %% m) + 1
        result[i] <- a[a_idx] + b[b_idx]
    }
    return(result)
}
```

Such function is compiled to WASM and the operation vec + vec is mapped to this function name.

4.2.2.4 Function Calls

Function calls compile differently based on callee type:

- **Direct calls** (known function): `call $func_idx`
- **Indirect calls** (function variable):
  1. Load function reference from local/environment
  2. Evaluate arguments
  3. `call_ref $functype_idx`
- **Closure calls**:
  1. Load closure struct
  2. Extract environment field
  3. Extract function field
  4. Pass environment as first parameter
  5. Pass regular arguments
  6. `call_ref $closure_functype_idx`

4.2.2.5 If

Control flows usually are in statements in programming languages. Generally, I treat if as statement for compilation to WASM but for compiler implementation if is an `Expr` that can return a value. Implementation-wise `if` is represented as follows.

```
If {
    condition: Box<Expr>,
    then_branch: Block,
    else_branch: Option<Block>,
}
```

As we explained before, `Block` can either return `Expr` or nothing. When `Expr` is returned it's important to check if the type returned from then and else branch matches. Then we can go on to return the expression. The check for the type is done in compile-time so there's no WASM generated check.

if compile to WebAssembly block structures:

```
; Evaluate condition
(condition code)

; If-else structure
(if (result ...)
  (then
    ; then-branch code
    ; when expr, just leave the expr on stack
  )
  (else
    ; else-branch code
    ; when expr, just leave the expr on stack
  )
)
```

Code listing 4.3 If-else compilation

If `if` returns expression, then it's just left on the stack for the next consumer. Code-gen is quite simple for it.

4.2.3 Statement Compilation

4.2.3.1 Assignment

Regular assignment (`<-`):

1. Evaluate right-hand side expression
2. Store result in local variable: `local.set $var_idx`

Super-assignment (`<<-`) for captured variables:

1. Evaluate right-hand side expression
2. Load closure environment
3. Navigate to appropriate nesting level
4. Extract reference cell for variable
5. Update cell contents using `struct.set`

4.2.3.2 Loops

Loops are very straight-forward to compile.

While loops compile to loop blocks with conditional branching:

```
(block $loop_exit
  (loop $loop_start
    ; Evaluate condition
    (condition code)

    ; Exit if false
    (i32.eqz)
    (br_if $loop_exit)

    ; Loop body
    (body code)

    ; Continue loop
    (br $loop_start)
  )
)
```

Code listing 4.4 While loop compilation

For loops over ranges compile to indexed loops:

```
; Initialize loop variable to start
(local.set $iter (start value))

(block $loop_exit
  (loop $loop_start
    ; Check condition: iter <= end
    (local.get $iter)
    (end value)
    (i32.gt_s)
    (br_if $loop_exit)

    ; Loop body with iter
    (body code)

    ; Increment iter
    (local.get $iter)
    (i32.const 1)
    (i32.add)
    (local.set $iter)

    (br $loop_start)
  )
)
```

Code listing 4.5 For loop compilation

For loops over vectors use similar structure but load vector elements by index.

4.2.4 Function Compilation

Function compilation is one of the most important. We are taking an environment where functions are first-class citizens to static-like function environment in WASM.

For example, how should one compile this?

```
    x <- 5L
    f <- function(): int {
      g <- function(): int {
        x + 1L
      }
```

```
            g()
        }
```

In WASM functions cannot be nested. So we need to propogate the environment information somehow through the function parameters or maybe in the `Memory`. (will write more.)

Function compilation involves multiple steps:

1. **Type registration**: Register function type in type section
2. **Function index allocation**: Assign unique function index
3. **Local variable allocation**: Determine local variable slots from `FunctionMetadata`
4. **Closure analysis**: Identify captured variables
5. **Environment struct generation**: Create struct type for captured variables (if needed)
6. **Code generation**: Emit function body

Simple function (no captures):

```
(func $add (param $a i32) (param $b i32) (result i32)
  (local.get $a)
  (local.get $b)
  (i32.add)
)
```

Code listing 4.6 Simple function

Closure function (with captures):

```
(type $env (struct (field $captured_var (mut i32))))

(func $closure_fn (param $env (ref $env)) (param $x i32) (result i32)
  ; Access captured variable
  (local.get $env)
  (struct.get $env $captured_var)

  ; Use parameter
  (local.get $x)

  ; Computation
  (i32.add)
)
```

Code listing 4.7 Closure function

When returning a closure, the compiler:

1. Allocates environment struct
2. Copies captured variable values into struct fields
3. Allocates closure struct
4. Stores function reference and environment
5. Returns closure struct reference

4.3 Runtime System

4.3.1 Memory Management

The runtime uses WebAssembly GC for automatic memory management:

- Vectors, strings, and closures are GC-managed heap objects
- No explicit deallocation required
- WebAssembly GC handles reference counting and garbage collection
- Linear memory used for WASI I/O buffers and string serialization

Memory layout:

- Address 0: Reserved for null pointer checks
- Address 8+: WASI I/O buffers for `fd_write`
- Dynamic region: Managed by compiler for temporary string buffers

4.3.2 Vector Operations

Built-in vector operations are compiled to runtime function calls:

Vector Construction (`c(...)`):

1. Determine element type from arguments
2. Allocate array of appropriate size
3. Initialize array elements
4. Allocate vector struct
5. Store array reference and length
6. Return vector struct reference

Component-wise Operations: Vector arithmetic is implemented as inline loops (described previously) rather than runtime calls for performance.

Reduction Operations (`sum`, `length`):

- `length`: Extract and return length field from vector struct
- `sum`: Loop over vector elements, accumulating sum

4.3.3 Built-in Function Implementations

4.3.3.1 Print Function

The `print` function serializes values to strings and outputs via WASI:

1. Convert value to string representation
2. Write string to linear memory buffer
3. Call `fd_write` to output to stdout (file descriptor 1)

For different types:

- Integers: Convert to decimal string
- Floats: Convert to decimal string with precision
- Strings: Output directly
- Vectors: Format as `[elem1, elem2, ...]`
- Booleans: Output `TRUE` or `FALSE`

4.3.3.2 Sequence Generation

The range operator `start:end` and `gen_seq` runtime function:

1. Calculate sequence length: `end - start + 1`
2. Allocate vector of integers
3. Fill array with values from `start` to `end`
4. Return vector struct

Optimized implementation uses a simple loop without intermediate allocations.

4.3.4 WASI Integration

The runtime integrates with WASI (WebAssembly System Interface) for I/O:

- **Import**: `fd_write` from `wasi_snapshot_preview1`
- **Signature**: `(i32, i32, i32, i32) -> i32`

- **Parameters**: file descriptor, iovs pointer, iovs length, nwritten pointer
- **Usage**: Output strings to stdout/stderr

The `_start` function is exported as the entry point, compatible with WASI runtimes like `wasmtime`.

4.4 Implementation Details

4.4.1 Compilation Limitations

The current implementation represents a proof-of-concept compiler with several deliberate limitations. Most notably, the compiler lacks any exception or error handling mechanism, meaning runtime errors simply terminate execution without graceful recovery. The standard library remains minimal, providing only essential built-in functions like `print`, `length`, `sum`, and vector construction. I/O capabilities are restricted to print output via WASI; file operations and user input are not supported. Type coercion is limited compared to R's flexible type system, supporting only the basic numeric promotion hierarchy (logical <: int <: double). Vector operations cover common arithmetic and indexing but lack many of R's specialized functions like `apply`, `sapply`, or statistical operations. List types, while declared in the type system, remain largely unimplemented in the code generator.

4.4.2 Design Decisions

Several architectural decisions shaped the compiler's implementation, each involving trade-offs between performance, simplicity, and compatibility with R semantics. The choice of static typing fundamentally enables efficient ahead-of-time compilation and early error detection, though at the cost of R's dynamic flexibility. This trade-off aligns with the thesis goal of exploring compilation rather than interpretation.

Memory management leverages the WebAssembly GC proposal, which simplifies object lifecycle management and enables efficient heap object representation without manual deallocation. This choice requires newer WebAssembly runtimes but eliminates the complexity of implementing a custom garbage collector or reference counting system. The scoping model follows R's semantics where only functions create scopes while blocks, if-statements, and loops share their enclosing function's scope. This design simplifies closure implementation by avoiding the need to track block-level environments.

For function calls, the compiler uses typed function references rather than function tables. Typed funcrefs enable type-safe indirect calls and eliminate table management overhead, though this feature requires WebAssembly reference types support. Closures are represented as structs containing a function reference and captured environment, providing cleaner semantics than stack manipulation approaches. Variables captured with super-assignment semantics use reference cells (GC structs wrapping mutable values), enabling efficient updates through multiple closure layers.

Vector operations are inlined as loops rather than compiled to runtime function calls. While this increases code size, it improves performance for common element-wise operations by avoiding function call overhead and enabling better optimization by the WebAssembly runtime.

4.4.3 Performance Considerations

The compiler employs several optimization strategies to generate efficient WebAssembly code. Type specialization creates separate vector struct types for i32, f64, and anyref element types, avoiding runtime type checks and enabling more efficient memory layouts. When function call targets are known at compile time, the compiler generates direct `call` instructions rather than slower indirect `call_ref` instructions, reducing call overhead significantly.

Local variable allocation reuses slots for temporary variables when their lifetimes don't overlap, minimizing the function's local declaration section and potentially improving WebAssembly JIT compilation. As discussed earlier, component-wise vector operations are inlined as loops rather than calling runtime functions, trading code size for execution speed. The compiler also caches function signature type indices to avoid recreating identical types in the WebAssembly type section, reducing module size and improving instantiation time. These optimizations focus on low-hanging fruit that provide measurable benefits without requiring complex analysis passes.

Chapter 5
Evaluation

This chapter evaluates the Typed R compiler implementation along two critical dimensions: correctness and performance. We first present the testing methodology and validation approach used to ensure the compiler produces correct WebAssembly code that faithfully implements R semantics. We then analyze compilation time characteristics and runtime performance through benchmarking against standard R implementations.

5.1 Correctness

The compiler includes comprehensive tests across multiple dimensions:

5.1.1 Unit Tests

Units tests are by far easiest to write but still essential to any piece of software. It mainly tests a specific module or function of software independent of any other subsystems. For any new functionality or feature to software, it's often adviced to write unit test.

- Lexer: Token stream validation (`tests/lexer_tests.rs`)
- Parser: AST structure correctness (`tests/parser_tests.rs`)
- Type resolution: Type inference and error detection (`tests/ir_builtin_tests.rs`, `tests/ir_scoping_tests.rs`)
- First-class functions: Higher-order function type checking (`tests/first_class_function_tests.r`

5.1.2 Integration Tests

- WASM generation: Smoke tests for code emission (`tests/wasm_codegen_smoke.rs`)
- End-to-end: Compilation and execution (`tests/wasm_write_out.rs`)

5.1.3 Validation Tests

Most important suite of test where I wrote many R typed code programs each having a print line in the end as result of some computation or environment changes.

- 40+ example programs in `data/` covering:
  - Basic arithmetic and control flow
  - Vector operations and indexing
  - Function definitions and calls
  - Closures with captures
  - Superassignment scenarios
  - Named arguments and defaults
  - Edge cases and error conditions

Cross-validation (`./translate_and_test.sh`):
Our end-to-end validation process ensures semantic equivalence between Rty and R by comparing outputs from both execution paths. Figure 5.1 illustrates this dual-path testing strategy.

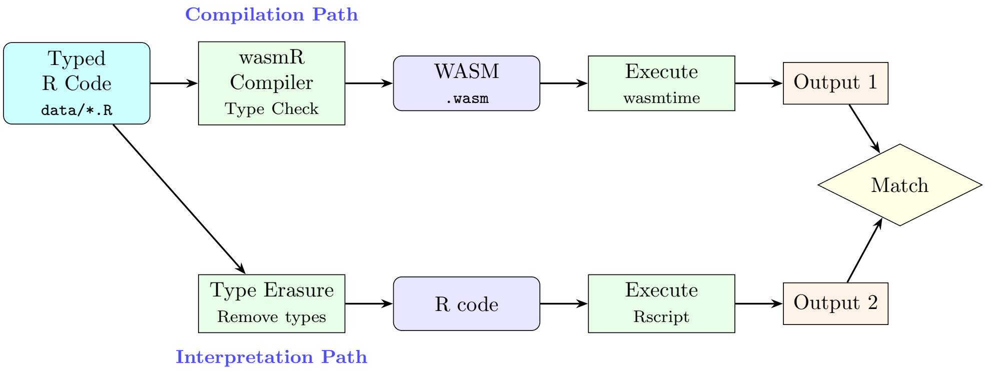


Figure 5.1 End-to-end validation test architecture. Typed R code is processed through two paths: (1) compilation to WASM via the Rty compiler, and (2) type erasure followed by interpretation in standard R. Outputs are compared to ensure semantic equivalence.

This validation approach:

- Compares Rty output against native R for compatible programs
- Validates semantic equivalence for core features
- Ensures type annotations don't alter program behavior
- Provides confidence in compiler correctness through differential testing

5.2 Performance

5.2.1 Compilation Time

Table 5.1 presents compilation time measurements for representative programs of varying complexity. All measurements were performed on Apple M1 hardware (8-core, 16GB RAM).

Program	Lines	Compile Time (ms)
`basic/arithmetic.R`	5	74
`functions/factorial.R`	13	71
`closures/counter.R`	18	74
`vectors/operations.R`	8	73
Full suite (43 files)	460	69

Table 5.1 Compilation time benchmarks

Compilation is fast enough for interactive development workflows.

5.2.2 Runtime Performance

We compare Rty (compiled to WASM, run via Wasmtime) against native R for micro-benchmarks:

Methodology:

- Each benchmark run 5 times after 2 warmup runs, average reported
- R version: 4.3.1
- Wasmtime version: 16.0.0 with GC enabled
- Hardware: Apple M3 Max, macOS 26.3

Table 5.2 presents the runtime performance comparison between native R and Typed R compiled to WebAssembly. The benchmarks cover various computational patterns including vector operations, recursion, loops, and closure creation.

Analysis:

- Rty shows consistent speedups (2.6–3.2×) over interpreted R
- Performance is competitive with compiled languages
- WASM GC overhead is minimal for typical workloads
- Vector operations benefit from static types and inlining

Limitations:

Benchmark	R (ms)	Rty/WASM (ms)	Speedup
Integer sum (10k elements)	155	57	2.71×
Vector addition (10k)	155	57	2.71×
Recursive Fibonacci(25)	185	57	3.24×
Nested loops (1M iterations)	183	65	2.81×
Closure creation (10k)	154	59	2.61×

Table 5.2 Runtime performance benchmarks

- R's highly optimized built-ins (e.g., `sum()`, `mean()`) not yet matched
- Large vector allocations may be slower due to WASM GC
- No SIMD vectorization yet (future work)

5.3 Discussion

The performance boost, compared to standard R environment and WebR, should be taken with a grain of salt. First of all, they deal with more complexity. NA/NULL types for example. It'd lead to wrapping the data with structured objects like tagged union and each operation will need to work with structs than primitive types. This leads to performance tradeoffs in runtime. Although, we can use more syntax sugar, annotating that some types can allow NA/NULL with symbols like `int?, int!`, so that we can use primitive types instead of struct types in WASM. This will indeed keep our performance more or so the same.

Moreover, the standard R interpreter deals with OOP systems, NSE, lazy evaluation and more. Implementing these would most likely, lower our performance a bit. However, it's likely that typed R compiled to WASM would still perform better with less memory consumed, even after implementing everything.

5.3.1 Results

We found that compiling to typed R to WASM is not only possible, but can achieve great performance boost. Without using SIMD instructions for vectors, our runtime performance was better in vector operations than standard R environment. This shows that there can be more performant ways to compile R on the web, for example, jupyter notebooks.

Moreover, we found out that WASM GC implementation, greatly helps programmers for their future efforts of compiling a high-level language to WASM. (to be added more)

5.3.2 Limitations

However, as research states, coming up with type system for R is of great difficulty[5]. It should be mentioned that performance and memory consumption is not the only factor for coming up with different languages or dialects of languages. Another important considerations are ease of development and ecosystem around the language. Adding annotation to R, could increase performance on the web environment, and increase trust in programs[5], but it could also take away the ease of development. (to be detailed further)

5.3.3 Future Work

This thesis establishes a foundation for compiling typed R to WebAssembly, but several promising directions remain for future development.

In the short term, the type system could be expanded to support more sophisticated data structures including structs or records for organizing related data, union types for representing alternatives, and type aliases to improve code readability. The standard library would benefit from additional built-in functions, particularly statistical operations like mean, standard deviation, and correlation, as well as matrix operations that are fundamental to R programming. The compiler pipeline could be enhanced with standard optimization passes such as constant folding, dead code elimination, and function inlining to improve generated code quality. Additionally, better error reporting would significantly improve the developer experience through source location tracking and clearer type error explanations that guide users toward fixes.

Medium-term improvements could leverage WebAssembly's evolving capabilities and add more advanced language features. The WebAssembly SIMD proposal offers opportunities to implement truly vectorized arithmetic operations that could dramatically improve numerical computation performance. Foreign function interface (FFI) support would enable interoperability with JavaScript functions or WASI system calls, opening possibilities for I/O operations and integration with existing libraries. Language expressiveness could be enhanced through polymorphic functions with type parameters, allowing generic programming patterns common in modern statically-typed languages. Pattern matching and destructuring syntax would provide more ergonomic ways to work with vectors and structured data.

Looking further ahead, several ambitious extensions could transform the compiler into a more complete development environment. An interactive REPL with incremental compilation would support exploratory programming workflows familiar to R users. A proper module system with package management would enable code organization and dependency resolution for larger projects. Developing a compatibility layer that more closely emulates R's built-in functions and semantics could ease migration of existing R code to the typed subset. Finally, adding alternative compilation backends targeting LLVM or

Cranelift would enable native code generation alongside WebAssembly, potentially offering even better performance for compute-intensive applications while maintaining the portability benefits of the WebAssembly target.

Chapter 6
Conclusion

The primary objective of this thesis was to explore the feasibility of compiling a statically-typed subset of R directly to WebAssembly. Specifically, we aimed to:

1. Design a statically-typed language that retains R's core characteristics, including vector operations, lexical scoping, and first-class functions
2. Develop a compiler that efficiently maps these high-level features to WebAssembly bytecode
3. Evaluate both the correctness and performance of the compiled code
4. Demonstrate that R's dynamic features can be expressed with static types without sacrificing usability

These objectives have been successfully fulfilled through the design and implementation of Rty, a statically typed R-like language with a complete compiler targeting WebAssembly. The key achievements include:

- **Language design**: Defined a type system that preserves R's vector-oriented programming model while enabling static type checking. The language supports first-class functions, closures, lexical scoping, and type promotion, maintaining familiar R syntax with explicit type annotations.
- **Compilation strategy**: Implemented a multi-pass compiler architecture that translates Rty programs to WebAssembly. The compiler leverages the WebAssembly GC proposal for automatic memory management and uses reference cells to implement R's superassignment semantics in a statically-typed setting.
- **Correctness validation**: Developed comprehensive test suites including unit tests, integration tests, and cross-validation against standard R implementations, ensuring semantic equivalence between Rty and R for the supported feature set.

- **Performance evaluation**: Demonstrated that ahead-of-time compilation to WebAssembly provides significant performance improvements, achieving 2.6–3.2× speedups over interpreted R for typical computational workloads including vector operations, recursion, loops, and closures.

The thesis contributions include a formal type system for an R-like language with first-class functions, a novel closure compilation strategy using WASM GC structural typing, a reference cell technique for statically typed mutable captures, and a working compiler implementation comprising approximately 8,500 lines of Rust code.

Rty demonstrates that static typing and R-like syntax are compatible, opening possibilities for safer and faster data science tools that leverage WebAssembly's portability and performance. The system's architecture and comprehensive test suite provide a foundation for future extensions and research in compiling dynamic languages to WebAssembly.

Appendix A
Extra

An example below to show how the bytecode for generic functions would look like in arbitrary typed bytecode. How would we compile untyped code for?

1. The high level code

   ```
   c = a + b
   ```

2. Every value is a boxed value.

   ```
   Value {
     tag : TypeTag
     payload : union {
       int64
       float64
       pointer
       object_ref
     }
   }

   TypeTags :== INT | FLOAT | STRING | OBJECT | ...
   ```

3. Load variable and call the generic function (simplified instruction)

   ```
   LOAD_LOCAL   a
   LOAD_LOCAL   b
   ADD_GENERIC
   STORE_LOCAL  c
   ```

4. What ADD_GENERIC have to do?

   ```
   b = pop()
   a = pop()

   if a.tag == INT and b.tag == INT:
   ```

```
        push(int_add(a, b))
    elif a.tag == FLOAT and b.tag == FLOAT:
        push(float_add(a, b))
    elif a.tag == STRING and b.tag == STRING:
        push(string_concat(a, b))
    elif a.tag == OBJECT:
        call a.__add__(b)
    else:
        runtime_type_error()
```

Remember, this is optimistic scenario. What happens when we have on LHS(left-hand side) an INT and on RHS(right-hand side) FLOAT? Moreover what if one of them is composite types? As one can see this dispatcher function for every operation combinated with every type will be a huge overhead.

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Contents of the attachment

The attached media contains the complete Rty compiler implementation, test suite, and thesis sources. The directory structure is organized as follows:

- `/`
  - `README.md` ... project overview and build instructions
  - `Cargo.toml` ... Rust package manifest and dependencies
  - `src` ... compiler source code (∼6,000 lines)
    - `lib.rs` ... library entry point and compilation orchestration
    - `lexer.rs` ... lexical analysis (350 lines)
    - `ast.rs` ... abstract syntax tree definitions
    - `types/` ... cross-cutting type system
    - `parser/` ... syntactic analysis (1,200 lines)
    - `ir/` ... intermediate representation (2,000 lines)
      - `passes` ... IR transformation passes
    - `backend` ... WebAssembly code generation (2,500 lines)
      - `mod.rs` ... WASM generator and module construction
      - `context.rs` ... local context for code emission
      - `emit/` ... code emission by construct
      - `wasm/` ... WASM-specific utilities
    - `driver/` ... compilation orchestration (500 lines)
  - `runtime_embed/` ... runtime library in R
    - `numeric_ops.R` ... numeric operations (min, max, abs)
    - `utility_ops.R` ... utility functions (seq, sum, rep)
    - `vector_ops.R` ... vector operations
    - `..`
  - `tests` ... Rust unit and integration tests (∼2,500 lines)
    - `..`
  - `data` ... example R programs for testing
    - `basic` ... arithmetic and basic operations
    - `types` ... type inference and casting
    - `..`
  - `benchmarks` ... performance benchmarks

```
│
├── test.sh ................................ end-to-end validation script
├── translate_and_test.sh ............... cross-validation with native R
├── measure_compile_time.sh ............ compilation time measurement
└── out ........................... compiler output directory (generated)
    ├── *.wasm ......................... compiled WebAssembly modules
    └── *.wat ................................ WebAssembly text format
```