The Whiley Language Specification

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Chapter 1

Introduction

This document provides a specification of the *Whiley Programming Language*. Whiley is a hybrid imperative and functional programming language designed to produce programs with fewer errors that those developed by more convention means. Whiley allows explicit specifications to be given for functions, methods and data structures, and employs a *verifying compiler* to check whether programs meet their specifications. As such, Whiley is ideally suited for use in *safety critical system*s. However, there are many benefits to be gained from using Whiley in a general setting (e.g. improved documentation, maintainability, reliability, etc). Finally, this document is *not* intended as a general introduction to the language, and the reader is referred to alternative documents for learning the language [**?**].

1.1 Background

Reliability of large software systems is a difficult problem facing software engineering, where subtle errors can have disastrous consequences. Infamous examples include: the Therac-25 disaster where a computer-operated X-ray machine gave lethal doses to patients [1]; the 1988 worm which reeked havoc on the internet by exploiting a buffer overrun [2]; the 1991 Patriot missile failure where a rounding error resulted in the missile catastrophically hitting a barracks [3]; and, the Ariane 5 rocket which exploded shortly after launch because of an integer overflow, costing the ESA an estimated $500 million [4].

The most widely used and accepted approach to improving software reliability is through extensive testing and manual code inspection. Whilst this does increase confidence, it cannot guarantee the absence of errors — which is particularly problematic in a safety-critical setting. Another successful approach is to prove the correctness of *models of software*, rather than of the software itself. For example, model checkers (e.g [5, 6, 7]) and SAT solvers (e.g. [8, 9]) have proved highly effective at checking correctness properties of finite models of software systems, including microprocessor designs [10, 11], flight-control systems [12, 13], network protocols [14, 15] and spaceflight-control systems [16]. Some model checkers (e.g. CBMC [17], Java Pathfinder [16], BLAST [18], SLAM [19]) can also be applied directly on the program code although, in such cases, either significant abstraction is performed (hence, reducing the scope) or scalability is sacrificed.

Prof. Sir Tony Hoare (ACM Turing Award Winner, FRS) proposed the creation of a *verifying compiler* as a grand challenge for computer science [20]. A verifying compiler "*uses automated mathematical and logical reasoning to check the correctness of the programs that it compiles.*" There have been numerous attempts to construct a verifying compiler system, although none has yet made it into the mainstream. Early examples include that of King [21], Deutsch [22], the Gypsy Verification Environment [23] and the Stanford Pascal Verifier [24]. More recently, the Extended Static Checker for Modula-3 [25] which became the Extended Static Checker for Java (ESC/Java) — a widely acclaimed and influential work [26]. Building on this success was JML and its associated tooling which provided a standard notation for specifying functions in Java [27]. Finally, Microsoft developed the Spec# system which is built on top of C# [28].

Both ESC/Java and Spec# build on existing object-oriented languages (i.e. Java and C#) but, as a result, suffer numerous limitations. The problem is that such languages were not designed for use with verifying compilers. Ireland, in his survey on the history of verifying compilers, noted the following [29]:

> *"The choice of programming language(s) targeted by the verifying compiler will have a significant effect on the chances of success."*

Likewise, a report on future directions in verifying compilers, put together by several researchers in this area, makes a similar comment [30]:

> *"Programming language design can reduce the cost of specification and verification by keeping the language simple, by automating more of the work, and by eliminating common errors."*

1.2 Goals

The Whiley Programming Language has been designed from scratch in conjunction with a verifying compiler. The intention of this is to provide an open framework for research in automated software verification. The initial goal is to automatically eliminate common errors, such as *null dereferences*, *array-out-of-bounds*, *divide-by-zero* and more. In the future, the intention is to consider more complex issues, such as termination, proof-carrying code and user-supplied proofs.

1.3 History

Chapter 2

Lexical Structure

2.1 Indentation

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Chapter 3

Compilation Units

3.1 Type Declarations

3.2 Constant Declarations

3.3 Function & Method Declarations

3.4 Visibility Modifiers

3.5 Packages

3.6 Imports

Chapter 4

Types

4.1 Overview

Discuss syntactic versus semantic types. Also, need to consider constrained types as well as type patterns.

```
Type  ::=
        |   TermType
        |   UnionType
        |   IntersectionType
```

```
TermType  ::=
            |   PrimitiveType
            |   TupleType
            |   RecordType
            |   ReferenceType
            |   NominalType
            |   CollectionType
            |   NegationType
            |   FunctionType
            |   MethodType
```

4.2 Primitives

```
PrimitiveType  ::=
                 |   AnyType
                 |   VoidType
                 |   NullType
                 |   BoolType
                 |   ByteType
                 |   CharType
                 |   IntType
                 |   RealType
```

4.2.1 Any Type

```
AnyType ::= any
```

Description. The type **`any`** represents the type whose variables may hold any possible value.

Examples.

Semantics.

Notes. The **`any`** type is top in the type lattice. That is, it is the supertype of all other types.

4.2.2 Void Type

```
VoidType ::= void
```

Description. The **`void`** type represents the type whose variables cannot exist! That is, they cannot hold any possible value. Void is used to represent the return type of a function which does not return anything. However, it is also used to represent the element type of an empty list of set.

Examples.

Semantics.

Notes. The void type is a subtype of everything; that is, it is bottom in the type lattice.

4.2.3 Null Type

```
NullType ::= null
```

Description. The null type is a special type which should be used to show the absence of something. It is distinct from void, since variables can hold the special **`null`**¿ value (where as there is no special ”**`void`**” value).

Examples.

Semantics.

Notes. With all of the problems surrounding **`null`** and `NullPointerException`s in languages like Java and C, it may seem that this type should be avoided. However, it remains a very useful abstraction to have around and, in Whiley, it is treated in a completely safe manner (unlike e.g. Java).

4.2.4 Bool Type

```
BoolType ::= bool
```

Description. Represents the set of boolean values (i.e. `true` and `false`).

Examples.

Semantics.

Notes.

4.2.5 Byte Type

```
ByteType ::= byte
```

Description. Represents a sequence of 8 bits.

Examples.

Semantics.

Notes. Unlike for many languages, there is no representation associated with a byte. For example, to extract an integer value from a byte, it must be explicitly decoded according to some representation (e.g. two's compliment) using an auxillary function (e.g. `Byte.toInt()`).

4.2.6 Char Type

```
CharType ::= char
```

Description. Represents a unicode character.

Examples.

Semantics.

Notes.

4.2.7 Int Type

```
IntType ::= int
```

Description. Represents the set of (unbound) integer values.

Examples.

Semantics.

Notes. Since integer types in Whiley are unbounded, there is no equivalent to Java's `MIN_VALUE` and `MAX_VALUE` for **`int`** types.

4.2.8 Real Type

```
RealType ::= [real]
```

Description. Represents the set of (unbound) rational numbers.

Examples.

Semantics.

Notes.

4.3 Tuple Types

```
TupleType ::= [(] Type ( [,] Type )+ [)]
```

Description. A tuple type describes a compound type made up of two or more subcomponents. It is similar to a record, except that fields are effectively anonymous.

Examples.

Semantics.

Notes.

4.4 Record Types

```
RecordType ::= [{] Type Ident ( [,] Type Ident )* [ [,] [...] ] [}]
```

Description. A record is made up of a number of fields, each of which has a unique name. Each field has a corresponding type. One can think of a record as a special kind of ”fixed” map (i.e. where we know exactly which entries we have).

Examples.

Semantics.

Notes. Syntax for functions? Open versus closed records?

4.5 Reference Types

```
ReferenceType ::= & Type
```

Description. Represents a reference to an object in Whiley.

Examples.

Semantics.

Notes.

4.6 Nominal Types

```
NominalType ::= Ident
```

Description. The existential type represents the an unknown type, defined at a given position.

Examples.

Semantics.

Notes.

4.7 Collection Types

4.7.1 Set Type

```
SetType ::= { Type }
```

Description. A set type describes set values whose elements are subtypes of the element type. For example, `{1,2,3}` is an instance of set type `{int}`; however, `{1.345}` is not.

Examples.

Semantics.

Notes.

4.7.2 Map Type

```
MapType ::= { Type => Type }
```

Description. A map represents a one-many mapping from variables of one type to variables of another type. For example, the map type `{int=>real}` represents a map from integers to real values. A valid instance of this type might be `{1=>1.2,2=>3.0}`.

Examples.

Semantics.

Notes.

4.7.3 List Type

```
ListType ::= [ Type ]
```

Description. A list type describes list values whose elements are subtypes of the element type. For example, `[1,2,3]` is an instance of list type `[int]`; however, `[1.345]` is not.

Examples.

Semantics.

Notes.

4.8 Function Types

```
FunctionType ::= function ( [ Type ( , Type )* ] ) => Type
```

Description.

Examples.

Semantics.

Notes.

4.9 Method Types

```
MethodType ::= method ( [ Type ( , Type )* ] ) => Type
```

Description.

Examples.

Semantics.

Notes.

4.10 Union Types

$$\texttt{UnionType} \quad ::= \quad \texttt{IntersectionType} \left(\boxed{\texttt{|}}\ \texttt{IntersectionType} \right)^{+}$$

Description. A union type represents a type whose variables may hold values from any of its ”bounds”. For example, the union type **`null|int`** indicates a variable can either hold an integer value, or **`null`**.

Examples.

Semantics.

Notes. There must be at least two bounds for a union type to make sense.

4.11 Intersection Types

$$\texttt{IntersectionType} \quad ::= \quad \texttt{TermType} \left(\boxed{\texttt{\&}}\ \texttt{TermType} \right)^{+}$$

Description.

Examples.

Semantics.

Notes.

4.12 Negation Types

$$\text{NegationType} \quad ::= \quad \boxed{!}\ \texttt{Type}$$

Description. A negation type represents a type which accepts values *not* in a given type.

Examples.

Semantics.

Notes.

4.13 Abstract Types

4.13.1 Recursive Types

4.13.2 Effective Tuples

4.13.3 Effective Records

4.13.4 Effective Collections

4.14 Subtyping Algorithms

Discussion of soundness and completeness.

$$
\begin{array}{rcll}
\text{Expr} & ::= & Cond\ [\ (\ \boxed{\texttt{\&\&}}\ |\ \boxed{\texttt{||}}\ )\ Expr\ ] & \textit{// Expressions} \\
\text{Cond} & ::= & Append\ [\ Cop\ Expr\ ] & \textit{// Condition Expressions} \\
\text{Append} & ::= & Range\ [\ \boxed{\texttt{++}}\ Expr\ ] & \textit{// Append Expressions} \\
\text{Range} & ::= & AddSub\ [\ \boxed{\texttt{..}}\ Expr\ ] & \textit{// Range Expressions} \\
\text{AddSub} & ::= & MulDiv\ [\ (\ \boxed{\texttt{+}}\ |\ \boxed{\texttt{-}}\ )\ Expr\ ] & \textit{// Additive Expressions} \\
\text{MulDiv} & ::= & Index\ [\ (\ \boxed{\texttt{*}}\ |\ \boxed{\texttt{/}}\ |\ \boxed{\texttt{\%}}\ )\ Expr\ ] & \textit{// Multiplicative Expressions} \\
\text{Index} & ::= & ??? & \textit{// Index Expressions}
\end{array}
$$

Figure 5.1: Syntax for Binary Expressions

Chapter 5

Expressions

Expression blah blah.

5.1 Binary Expressions

Term	::=	*// Terms*	
	|	$Constant$	*// Constant expressions*
	|	$Identifier$	*// Identifier expressions*
	|	$Expr_1\ (\ \boxed{\texttt{,}}\ Expr_i\ )^+$	*// Tuple expressions*
	|	$\boxed{\texttt{(}}\ Expr\ \boxed{\texttt{)}}$	*// Bracketed expressions*
	|	$\boxed{\texttt{\|}}\ Expr\ \boxed{\texttt{\|}}$	*// Size expressions*
	|	$Identifier\ \boxed{\texttt{(}}\ [\ Expr_1\ (\ \boxed{\texttt{,}}\ Expr_i\ )^+\ ]\ \boxed{\texttt{)}}$	*// Invocation expressions*
	|	$(\ \boxed{\texttt{-}} \mid \boxed{\texttt{!}} \mid \boxed{\texttt{\~{}}} \mid \boxed{\texttt{\&}} \mid \boxed{\texttt{*}}\ )\ Expr$	*// Unary expressions*
	|	$\boxed{\texttt{new}}\ Expr$	*// Allocation expressions*
	|	$\boxed{\texttt{\{}}\ [\ Expr_1\ (\ \boxed{\texttt{,}}\ \ Expr_i\ )^*\ ]\ \boxed{\texttt{\}}}$	*// Set expressions*
	|	$\boxed{\texttt{\{}}\ [\ Expr_1\ \boxed{\texttt{=>}}\ Expr'_1\ (\ \boxed{\texttt{,}}\ \ Expr_i\ \boxed{\texttt{=>}}\ Expr'_i\ )^*\ ]\ \boxed{\texttt{\}}}$	*// Map expressions*
	|	$\boxed{\texttt{[}}\ [\ Expr_1\ (\ \boxed{\texttt{,}}\ \ Expr_i\ )^*\ ]\ \boxed{\texttt{]}}$	*// List expressions*
	|	$\boxed{\texttt{\{}}\ [\ n_1 \boxed{\texttt{:}}\ Expr_1\ (\ \boxed{\texttt{,}}\ \ n_i\ \boxed{\texttt{:}}\ Expr_i\ )^*\ ]\ \boxed{\texttt{\}}}$	*// Record expressions*

Figure 5.2: Syntax for Term Expressions

Constant	::=	*// Constants*	
	|	$(\ \boxed{\texttt{0}} \mid \boxed{\texttt{1}}\ )^+\ \boxed{\texttt{b}}$	*// Boolean constants*
	|	$(\ \boxed{\texttt{0-9}}\ )^+$	*// Integer constants*
	|	$(\ \boxed{\texttt{0-9}}\ )^+\ \boxed{\texttt{.}}\ (\ \boxed{\texttt{0-9}}\ )^+$	*// Decimal constants*
	|	$\boxed{\texttt{null}}$	*// Null constant*

Figure 5.3: Syntax for Constant Expressions

Identifier	::=	$(\ \boxed{\texttt{\_}} \mid \boxed{\texttt{a-z}} \mid \boxed{\texttt{A-Z}}\ )\ (\ \boxed{\texttt{\_}} \mid \boxed{\texttt{a-z}} \mid \boxed{\texttt{A-Z}} \mid \boxed{\texttt{0-9}}\ )^*$	*// Identifiers*

Figure 5.4: Syntax for Identifiers

Chapter 6

Statements

6.1 Assert Statement

```
AssertStmt  ::=  assert Expr
```

Description. Represents an *assert statement* of the form “**assert** e”, where e is a *boolean expression*.

Examples. The following illustrates:

```
function abs(int x) => int:
    if x < 0:
        x = -x
    assert x >= 0
    return x
```

Notes. Assertions are either *statically checked* by the verifier, or turned into *runtime checks*.

6.2 Assignment Statement

```
AssignStmt  ::=  LVal = Expr
```

Description. Represents an *assignment statement* of the form `lhs = rhs`. Here, the `rhs` is any expression, whilst the `lhs` must be an `LVal` — that is, an expression permitted on the left-side of an assignment.

Examples. The following illustrates different possible assignment statements:

```
x = y          // variable assignment
x.f = y        // field assignment
x[i] = y       // list assignment
x[i].f = y     // compound assignment
```

The last assignment here illustrates that the left-hand side of an assignment can be arbitrarily complex, involving nested assignments into lists and records.

Semantics.

Notes.

6.3 Assume Statement

AssumeStmt	::=	$\boxed{\texttt{assume}}$ Expr

Description. Represents an *assume statement* of the form "`assume e`", where `e` is a boolean expression.

Examples. The following illustrates a simple function which uses an `assume` statement to meet its postcondition:

```
function abs(int x) => int:
    assume x >= 0
    return x
```

Notes. Assumptions are *assumed* by the verifier and, since this may be unsound, are always turned into *runtime checks*.

6.4 Return Statement

ReturnStmt	::=	$\boxed{\texttt{return}}$ [Expr]

Description. Represents a *return statement* with an optional expression is referred to as the *return value*.

Examples. The following illustrates a simple function which returns the increment of its parameter `x`:

```
function f(int x) => int:
    return x + 1
```

Here, we see a simple **`return`** statement which returns an **`int`** value.

Notes. The returned expression (if there is one) must begin on the same line as the return statement itself.

6.5 Throw Statement

$$\texttt{ThrowStmt} \quad ::= \quad \boxed{\texttt{throw}}\ \texttt{Expr}$$

Description.

Examples.

Notes.

6.6 Variable Declarations

$$\texttt{VarDecl} \quad ::= \quad \texttt{Type}\ \texttt{Ident}\ \left[\ \boxed{\texttt{=}}\ \texttt{Expr}\ \right]$$

Description. Represents a *variable declaration* which has an optional expression assignment referred to as an *variable initialiser*. If an initialiser is given, then this will be evaluated and assigned to the variable when the declaration is executed.

Examples. Some example variable declarations are:

```
int x
int y = 1
int z = x + y
```

Notes.

6.7 If Statement

$$\texttt{IfStmt}^{\ell} \quad ::= \quad \boxed{\texttt{if}}\ \texttt{Expr}\ \boxed{\texttt{:}}\ \texttt{Block}^{\gamma}\ \left(\ \boxed{\texttt{else}}\ \boxed{\texttt{if}}\ \texttt{Expr}\ \boxed{\texttt{:}}\ \texttt{Block}^{\omega_i}\ \right)^{*}$$
$$\left[\ \boxed{\texttt{else}}\ \boxed{\texttt{:}}\ \texttt{Block}^{\phi}\ \right]$$

(where $\ell < \gamma$ and $\forall i.\ell < \omega_i$ and $\ell < \phi$)

Description. Represents a classical **`if`** statement which supports chaining and an optional **`else`** branch. The expression(s) are referred to as *conditions* and must be boolean expressions. The first block is referred to as the *true branch*, whilst the optional **`else`** block is referred to as the *false branch*.

Examples. The following illustrates:

```
function max(int x, int y) => int:
    if(x > y):
        return x
    else if(x == y):
        return 0
    else:
        return y
```

Notes.

6.8 While Statement

$$\texttt{WhileStmt}^{\ell} \quad ::= \quad \boxed{\texttt{while}}\ \texttt{Expr}\ \left(\boxed{\texttt{where}}\ \texttt{Expr}\right)^{*}\ \boxed{\texttt{:}}\ \texttt{Block}^{\gamma}$$

(where $\ell < \gamma$)

Description. Represents a while statement with optional `where` clause(s) commonly referred to as *loop invariant*s.

Examples. As an example:

```
function sum([int] xs) => int:
  int r = 0
  int i = 0
  while i < |xs| where i >= 0:
    r = r + xs[i]
    i = i + 1
  return r
```

Notes. When multiple `where` clauses are given, these are combined using a conjunction. The combined invariant defines a condition which must be true on every iteration of the loop.

6.9 Do/While Statement

$$\texttt{DoWhileStmt}^{\ell} \quad ::= \quad \boxed{\texttt{do}}\ \boxed{\texttt{:}}\ \texttt{Block}^{\gamma}\ \boxed{\texttt{while}}\ \texttt{Expr}\ \left(\boxed{\texttt{where}}\ \texttt{Expr}\right)^{*}$$

(where $\ell < \gamma$)

Description.

Examples.

Notes.

6.10 For Statement

$\texttt{ForStmt}^{\ell}$ ::= $\boxed{\texttt{for}}$ VarPattern $\boxed{\texttt{in}}$ Expr ($\boxed{\texttt{where}}$ Expr)* $\boxed{\texttt{:}}$ $\texttt{Block}^{\gamma}$

(where $\ell < \gamma$)

Description.

Examples.

Notes.

6.11 Switch Statement

SwitchStmt ::=

Description.

Examples.

Notes.

6.12 Try/Catch Statement

TryCatchStmt ::=

Description.

Examples.

Notes.

Glossary

boolean expression An expression which evaluates to a value of type `bool`. 17–19, 22

expression A combination of constants, variables and operators that, when evaluated, produce a single value. Expressions in certain circumstances may have side effects. 15, 22

loop invariant A boolean expression which must hold on every iteration of a loop. 20

safety critical system A system which operates in a high-risk setting where failure can lead to loss of life, injury, significant damage or environmental harm. 3

type An descriptor for a set of values, typically used to determine the set of values a given variable or expression may hold. 22

variable declaration A statement which declares one or more variable(s) for use in a given scope. Each variable is given a *type* which limits the possible values it may hold, and may not already be declared in an enclosing scope. 19, 22

variable initialiser An optional expression used to initialise variable(s) declared as part of a variable declaration. 19

verifying compiler A compilers which employs automated mathematical and logical reasoning to check the correctness of the programs that it compiles. 3

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