Garter: A Language for Teaching Python Without the Fangs

by

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Abstract

Languages used for teaching need to be easy to use, help new programmers find and correct the errors which they make in the program, and are ideally well equipped for developing actual software, to allow the student to explore outside of class with their own projects. In this work, we design and implement a subset with 'training wheels' of the dynamically-typed programming language Python [7] for use in teaching, in order to create a language for learning which better fits those criteria.

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Chapter 1

Introduction

1.1 Motivation

Modern software development has moved toward the increased usage of dynamic programming languages. These languages do not contain a complete semantic analysis phase during compilation, and instead handle and report any type errors at run-time, as incorrect code is executed. This serves as an advantage for programmers due to the ability to easily write generic code (as all code is, by default, generic over all compatible types), as well as not have to design a complete data layout before beginning to write code. This allows for projects to be written quickly and easily. In program contexts where the optimizations only available to statically typed languages are not necessary, these can be significant benefits.

Unfortunately, this dynamic execution doesn't only have run-time costs. It also affects the ease of understanding program errors, usually quite negatively. As an example, the same basic programming errors have been introduced into two programs: we will compare the error outputs of two similar incorrect problems, one written in Python, which is a dynamic language, and the other written in C [22], which is a

static language. The python programs are executed with the cpython 2.7.10 [12] interpreter, and the C programs are compiled using clang [1], with the `-Werror` flag enabled.

```
1 # Python
2 print("running")
3 x = 10
4 y = 20
5 print("x + y is", xx + y)
```

```
1 /* C */
2 #include <stdio.h>
3 int main() {
4   printf("running\n");
5   int x = 10;
6   int y = 20;
7   printf("x + y is %d\n",
8          xx + y);
9 }
```

When the python program on the left is run with cpython, the program begins executing and reaches line 5 before producing a run-time error: `NameError: name 'xx' is not defined`. In contrast, the C program fails to compile, emitting the compile-time error `error: use of undeclared identifier 'xx'`. If the python code was to refer to the incorrectly named code in an infrequent code path, the error could never be caught and reported, even with testing.

```
1 # Python
2 def add(a, b):
3     return a + b
4
5 a = 5
6 b = 10
7 c = "string"
8
9 add(a, c) # oops!
```

```
1 /* C */
2 int add(int a, int b) {
3     return a + b;
4 }
5
6 int main() {
7     int a = 5;
8     int b = 10;
9     char *c = "string";
10    add(a, c);
11 }
```

These programs, much like the earlier programs, also demonstrate a common error: passing values with incorrect types into a function. In the python code, the error is reported at run-time on line 3 - *within* the function. This function could theoretically be located within a library which a developer is using, meaning that the error is

reported at a code location which is unrelated to the actual programming error. In contrast, The strongly-typed C program reports the error on line 10, which is the call site where the actual mistake occurred.

1.2 Problem Overview

The goal of this thesis was to design, implement, and demonstrate a new teaching programming language: Garter. Garter is intended to be a language which both makes teaching programming concepts to new developers easy, and also provides a smooth path for moving away from the learning environment to implementing and solving real problems. We consider such a language to have to fit the following requirements:

1. Minimal Boilerplate: The programmer should not have to write code which they to not yet understand simply in order to get the code which they do understand to work.

2. Stepping Stone to Production: The language should act as a stepping stone to a production programming language, such that eager learners can use what they have learned in class to write more complex programs and springboard into learning a language which is used by professionals in both Scientific Programming and Application Programming.

3. Minimal Technical Trivia: When teachers use the language to teach, they should feel like they are teaching programming, rather than teaching a language. Strange edge cases and specific technical trivia about how features were designed or implemented should be eliminated.

4. Prevent Incorrect Programs: It's very easy in dynamic languages to write incorrect programs which fail at runtime with confusing error messages, often lacking important context. Programs should instead fail as fast as possible with useful error messages which guide the programmer toward writing the correct program.

1.3 Thesis Contributions

The main contributions of this thesis are as follows:

- We designed a new teaching programming language, Garter, which aims to bring together the simplicity of other teaching programming languages, like Turing, and the more modern dynamic programming language Python.
- We created a prototype implementation of Garter, based on the cpython runtime, including using the cpython IDE, IDLE, and adapting it to work with Garter code.
- We implemented a series of example programs, in Garter, demonstrating that it can be used to solve simple problems like those solved in classrooms, and showing how to migrate Turing style programs to Garter.

1.4 Thesis Outline

The remainder of this thesis is organized as follows:

Chapter 2, Background: An exploration of the other languages and tooling which exist in this space

Chapter 3, Design: A discussion of the design decisions made for the Garter language to make it fit the 4 requirements.

Chapter 4. Prototype Implementation: An exploration of the prototype implementation of Garter

Chapter 5, Conclusions and Future Work: Where Garter has succeeded and failed, as well as the path foward to a better educational programming language

Chapter 2

Background and Related Works

Garter aims to simplify and restrict the dynamic programming language Python inro a learning-friendly dialect. This is done by adding a type system, and restricting the types of programs which can be written to make writing code simpler.

There are other projects which have aimed to add a type system to a dynamic language, with varying levels of success.

The most similar project to this thesis, is the mypy project [5]. Mypy is an optional static type checker for Python, which is designed to enable Python developers with large code bases to take advantage of static typing to make better, more maintainable software. The goal of mypy is to enable as many python structures and patterns to be described with its type system, which means that it possesses a relatively complex system, which includes bidirectional type inference, generics, function types, abstract base classes, multiple inheritance and more.

This thesis proposes a language which is much simpler and smaller than that provided by mypy. The reason for this is that the most important and useful part of a learning language is its error messages. As a type system gets more complex and tries to cover all types of software which a professional programmer would try

to write, it can become unwieldy and produce unclear error messages. This thesis intentionally maintains a small type system footprint such that it can detect errors quickly, and provide useful errors, with suggestions for how the student can improve their software. Mypy also attempts to provide an easy migration path for developers with large existing python code bases: namely it is dynamic by default, and only becomes statically typed when type annotations are added. This is undesirable for a learning language, as we want the safer option to be the default option, otherwise students will accidentally write unsafe code, and not benefit from static typing and improved error detection.

Another similar project is Microsoft's Typescript project [15], [13]. Much like mypy, Typescript aims to extend the ECMAScript language [19] to have optional gradual typing. Many of the same complaints which apply to mypy also apply to Typescript: namely that it's goal is not teaching, and it ends up as a complex system in order to work for real production projects. By making covering all of the capabilities of dynamically typed languages a non-goal for this thesis, we hope to enable better error messages, and a simpler introduction to programming for students learning with it.

The Turing programming language is a teaching programming language which heavily inspired Garter's type system and decisions [20]. It has a simple nominal type system, and aims to provide good error messages. Turing is used throughout Ontario as a teaching language for new students in high school due to its simplicity. Unfortunately, Turing fails in a few areas. Firstly, its syntax no longer feels like the syntax of many modern programming languages. It's more low level than modern

programming languages, not taking advantage of modern programming language features which are popular like Garbage Collection, and can help releive new developers from thinking of details, and it doesn't follow modern programming conventions of using growable arrays, maps, and the use of objects in order to encapsulate state.

Garter aims to take inspiration from Turing's simplicity, while extending on it with a modern programming lens in order to design a language which helps new programmers write good code, while also making them familiar with Python.

Chapter 3

Design

For this thesis, we wanted to explore how we could create a better programming language for teaching new programmers. Of the requirements we identified in Section 1.2, Existing programming languages for teaching such as Turing [20] for the most part fulfil the requirements of being simple to start in, having few confusing edge cases, and restricting the types of programs which can be written to those which are correct and don't fail at runtime. Unfortunately, many of them fail when it comes to being a good stepping stone for students into producting programming languages which people in the industry use to solve real problems. It is important to reduce the barriers between the language which people learn in school and solving real-world problems, as one of the best ways to learn programming is to get engaged in trying to solve a problem you are facing, which is much easier when you have access to the libraries and resources provided to and by production programmers.

To satisfy this requirement, Garter was designed as a safe subset of the Python programming language [7]. Python is a popular programming language for modern development, ranking as the 5th most popular language on the GitHub code sharing platform in August 2015 [4]. The goal was to make the two languages so similar that

it would be trivial for an eager student to transition their knowledge from writing Garter programs into solving real problems in Python using the substantial suite of libraries and tools which Python provides.

In this chapter the design decisions which were made in establishing the Garter subset of Python are described.

3.1 Making Python Type Safe

One of the desirable properties of a teaching programming language is that it prevents new developers from writing incorrect programs, and guides them away from making simple mistakes, especially when these problems only occur at runtime, and can thus be vary hard to diagnose.

```
1 x := 5
2 s := 'x = ' + x
```

The above program is written in Garter, and would produce a validation error, reporting an `OperatorTypeMismatch`, `The operands to operator '+' (str + int), are invalid.` The equivalent program in Python would not fail until runtime, when a `TypeError` would be raised. If this code was in an infrequently traversed code path, such as a failure path, it could remain undetected, meaning that the program is subtly wrong. In the development of the Garter prototype, I often accidentally performed this very error within the error handling code, and didn't catch them until I wrote the test cases for validation errors.

In addition, we want to prevent code which, while not technically incorrect, is likely to cause problems in the future. For example, Python allows for hetrogenous arrays, consisting of values of varying types. This means it's possible to write code such as:

```
1 arr := [1, 2, 3, 4, 5, 6, 7, 8, 9]
2 arr.push(input('Enter a number: '))
```

While this code is technically correct in Python, and would execute correctly as a Python program, future code which expects the elements in `arr` to consist only numbers would fail, as one of the elements is a string. In Garter, this would produce a `ParameterTypeMismatch` validation error, as arrays are required to be homogenous, which is usually what is desired, such that individual elements can be treated uniformly.

This means that if you write code like the following in Garter, and it validates, you can always depend on it working, and there not being any strings which cause runtime failures far from the source of the problem.

```
1 sum := 0.0
2 for elt in arr:
3     sum += elt
```

To fix this problem, we adapted a simple type system based languages such as Pascal and Turing. The type system modified to use Python's basic types, such as `int`, `float`, `bool`, `str`, lists (`[T]`), dicts (`{K:V}`), functions (`R(A, R, G...)`), and user defined classes. This type system limits what values are allowed to exist in the language, such that only the common use cases, such as homogenous arrays and dictionaries, are permitted. This means that new developers will be guided away from writing code which accidentally creates one of these non-homogenous data types or variables, which is usually an error, even in real Python code.

In Garter we also decided against implementing generic or templated types. The dict and list types are instead given special status. This was because we decided that the complexities and design tradeoffs which are involved in this complex feature were unnecessary, especially for early learning. Instead, the use of the built-in types is

heavily encouraged. Some programming languages which are used in the industry, such as the Go Programming Language also lack a generics system, which helped us make this decision [2].

The possibility of merging the `int` and `float` types into a single `num` type was considered, however this would have confusing properties when it comes to array indexing, and what values are OK for using there. In Python, only `int` values can be used for indexing into an array. This behavior of treating the value `2` differently than `2.0` would be very confusing to a new programmer, so the decision was made to formalize the difference to avoid confusion and common programming errors, especially related to division of integers.

```
1 arr[2] # OK
2 arr[2.0] # Not OK
3 arr[4/2] # Not OK
4 arr[4//2] # OK
```

3.2 Objects

Data in Garter are represented by Objects.

3.2.1 Value passing style

Object types can be split into two categories. The primitive types: `int`, `float`, `str`, `bool` and functions have immutable values, which means that they act as though they are passed by value.

```
1 x := 5
2 y := x
3 x = 10
4 print(y) # 5
```

In contrast, the other types, such as `[T]`, `{K: V}` and user defined types are not immutable, and act as though they are passed as a reference to a shared object.

```
1 arr := [1, 2, 3]
2 arr2 := arr
3 arr.push(4)
4 print(arr2) # [1, 2, 3, 4]
```

If a new copy of a list or dictionary is required, it can be copied with the `.copy()` method.

```
1 arr := [1, 2, 3]
2 arr2 := arr.copy()
3 arr.push(4)
4 print(arr2) # [1, 2, 3]
```

This behavior is inherited from Python, and directly mimics the behavior used in many programming languages, where simple types are immutable but complex ones are mutable and shared by reference.

3.2.2 Functions and Methods

Functions in Garter are implemented as objects, which can be passed around and have the type `R(A, R, G...)`, where `R` is the return type, and `A`, `R`, and `G` are the argument types. The following is the representation of the types of some functions

```
1 def foo(): ...                              # None()
2 def bar(x : int) -> int: ...                # int(int)
3 def baz() -> int: ...                       # int()
4 def quxx(x : int, y : int) -> int: ... # int(int, int)
```

This decision was made in order to enable teachers to teach some basic functional programming styles, which are becoming more popular in modern programming due to the popularity of web programming with languages such as JavaScript which often use callbacks and other functions as values.

Methods are represented as immutable function attributes on objects, except with the an implicit `self` argument.

```
1 class C:
2     s := 'hi'
```

```
3     def f(self): print(self.s)
4 x := C()
5 y : None() = x.f # Valid
6 y() # prints hi
```

This conforms with Python's representation of Methods, and avoids confusion around methods, especially when using them in more functional programming styles which some teachers may choose to use to teach their students.

3.3 Expressions

Expressions are based on the expression forms from Python. Like in Python, all expressions are evaluated eagerly, which both conforms with the current popular design for production languages, and simplifies reasoning about when code is executed.

3.3.1 Literals

Garter supports the following literals:

- list literals (e.g. `[1, 2, 3]`)
- dict literals (e.g. `{'a': 1, 'b': 2}`)
- numeric literals (e.g. `5`, and `5.5`)
- bool literals (`True`, and `False`)
- str literals (e.g. `'foo'`, and `"bar"`)

The list and dictionary literals especially enable much shorter code than requiring them to be built from the empty objects using mutation methods. This is especially the case for lookup tables etc.

3.3.2 Function Calls

Function calls are performed with the standard `f(x)` syntax. All functions in Garter take a fixed number of arguments of fixed types, and produce a result of a fixed type. Python's default arguments and named arguments were avoided in order to simplify writing and calling functions for new programmers.

```
1 def f(x : int): print('hi', x)
2 f(5) # prints 'hi 5'
```

Magic Functions

Garter also adapted some functions from Python which require variable count, variable type, or keyword arguments. These functions were special cased, and built-in to the language, and are present because of how important they are.

The functions which act this way are:

- `len()` - length of the argument (`str`, `[T]`, or `{K: V}`)
- conversion operators (`int()`, `str()`, `float()`) - convert the value to the written type
- `input()` - read in a line from the console, as a string. Optionally takes a prompt strin

The `print()` function-like statement (Section A.5.1), and `range()` function-like form (Section A.5.2) are also examples of special-cased functions from Python in Garter.

3.3.3 Arithmetic

Garter supports the standard binary operators (`+ - * / // % **`, mapping to the operations of addition, subtraction, multiplication, division, flooring division, modulus, and exponentiation) on both `int` and `float`.

In addition, the `+` binary operator is supported on `str` and `[T]`, representing string or list concatenation. It produces a new value with the value of the concatenation of its arguments.

`int` and `float` also support the unary `+` and `-` operators, which do nothing and negate the value respectively.

This set of operators is fairly standard in programming languages, and is copied from Python. The decision to seperate flooring division from standard division (which always produces a `float`) is based on Python 3's behavior, and also helps to prevent errors for new developers which don't understand integer division.

3.3.4 Comparison Operations

Equality with the equality operators (`==`, and `!=`) are performed by value, and supported by all types in Garter. As it is done on value, two lists or dicts with the same elements, but different identities are still equal.

```
1 arr1 := [1, 2, 3]
2 arr2 := [1, 2, 3]
3 print(arr1 == arr2) # True
4
5 dict1 := {'a': 1, 'b': 2}
6 dict2 := {'a': 1, 'b': 2}
7 print(dict1 == dict2) # True
```

This decision was made as it makes the most intuitive sense. However, there are exceptions to the comparison-is-by-value rule. Namely, user-defined classes and

functions are compared by reference.

```
1 class Foo:
2     x := 5
3 a := Foo()
4 b := Foo()
5 print(a == b) # False
6
7 def a(): print('hi')
8 def b(): print('hi')
9 print(a == b) # False
```

The other comparison operators, `<`, `>`, `<=`, and `>=` are supported on the `str`, `int`, and `float` types.

Unlike some other programming languages, comparison operations in Garter are not binary, but rather n-ary. This means that the operation `a < b < c` is not evaluated as either `(a < b) < c` or `a < (b < c)`. Instead, it is evaluated as `(a < b) and (b < c)`. This is much closer to the mathematical meaning of that statement as a constraint, and can help prevent issues when people with mathematical backgrounds try to write constraints which occur in other languages. This is important as it helps new programmers which may already be familiar with mathematical notation to adapt more quickly.

Multiple operators can be mixed together in these comparisons, meaning that the expression `a < b == c < d` is legal in Garter.

3.3.5 Attributes and Subscription

Objects often have attributes, which can be accessed using the `.` operator. This is used to access properties such as methods on built-in and user-defined types, as well as accessing and potentially modifying attributes on user-defined types.

```
1 class Foo:
2     x := 5
3 a := Foo()
4 a.x = 10
```

```
5 print('a.x =', a.x)
```

When accessing values in arrays and dictionaries, subscripting syntax is used. This involves placing the indexing value in square brackets after the value. `int` is the type used for indexing into `[T]`, while `K` is the type used for indexing into `{K: V}`. Lists in Garter are 0-indexed, which is the most common indexing strategy in use today, as well as the strategy used in Python.

```
1 x := {'a': 5}
2 y := [5, 10]
3
4 x['a'] # 5
5 y[0] # 5
```

Lists may also be sliced into over a range, using the slicing syntax (`[S:E]`). Both the values `S` and `E` are indexes, and can be omitted, defaulting to the start and end of the array respectively.

Slices can be assigned to with another array. This will update the values in the slice to be equivalent to the values from the new array, potentially shifting around values in the original array.

For more details on this syntax, see A.6.2.

3.4 Statements

3.4.1 Functions

Functions in Garter are defined with the `def` keyword. Their syntax is taken directly from Python, including the type annotation syntax. The Type annotation syntax is based off of PEP 3107 – Function Annotations [6]. We re-used this syntax as it was already part of the Python language, and thus was guaranteed not to conflict with other important features, and avoids adding new syntax as much as possible, even

though it is extremely infrequently used in Python projects.

```
def foo(x : int, y : str) -> bool:
    ...
```

Function bodies have a seperate scope, and can be nested. They can reference variables from their enclosing scope, however, they cannot assign to those variables without declaring the intention with the `global` or `nonlocal` declarations (See A.4.1).

This helps new developers avoid errors, by requiring them to clarify their intentions as to whether they want to create a local variable, or mutate an outer variable, before they use assignment statements.

The `return` statement exits a function early, and can be passed a value when the function is defined to produce a result. The `return` statement is required for functions which provide a result on all code paths.

The variable bindings created by function declarations are immutable, and cannot be re-assigned to.

3.4.2 Control Flow Statements

`for` loops in Garter loop over lists or ranges of numbers. While this is more restrictive than a traditional range statement, it tends to be more in line with the standard use of the `for` loop. (See A.5.2)

```
for x in range(10):
    # x is 0, 1, 2, 3, 4, 5, 6, 7, 8, 9. Declares x only in scope
    ...

for x in [1, 2, 3]:
    # x is 1, 2, 3. Declares x only in scope
    ...
```

Garter also supports the `while` loop, which is a basic loop. Every iteration, including the first iteration, its condition is tested. If it is `False`, then the loop

aborts, otherwise it continues (See A.5.2).

The `break` and `continue` statements can be placed within both the `for` and `while` looping construct bodies. `break` aborts the innermost loop, continuing at the next statement after the loop. `continue` causes the next item in the `for` loop to be iterated through, and re-triggers the check in a `while` loop.

Garter also supports the `if` statement. This statement, like in other languages, tests a boolean condition. If it is `True`, one branch is taken, otherwise the other branch is taken.

3.4.3 Assignments

In Garter, unlike Python, you cannot assign to a variable which has not been declared. Assignments are performed with the `x = 5` statement.

Variable declarations are performed with the `x := 5` or `x :  int = 5` statement. these declarations are lexically scoped, but are not permitted to shadow other bindings with the same name from the same function.

```
1 def foo():
2     if cond:
3         x := 5
4     else:
5         x := 10
6     return x # not OK
7     # x is defined within the if's branches, not at the root
```

```
1 def foo():
2     x := 0
3     if cond:
4         x = 5
5     else:
6         x = 10
7     return x # OK
8     # x defined in same scope as return, only assigned to in if statements
```

```
1 def foo():
2     x := 0
3     if cond:
```

```
4           x := 5 # Not OK
5           # This is an error, and catches a problem
6           # caused by probably unintentional shadowing
```

```
1 x := 0
2 def foo():
3     x := 10 # OK
4     # x is in a different function. Doesn't change global x
```

```
1 x := 0
2 def foo():
3     global x # global statement is required to change x
4     x = 10
```

Garter also supports closures, allowing functions to access variables defined in the root of an enclosing function or in the root of the program.

```
1 def foo() -> int():
2     x := 5
3     def bar() -> int:
4         return x
5     return bar
6 foo()() # 5
```

Nested functions are nice for teaching basic functional style programming which is becoming more popular due to the prevaliance of callback programming with closures in languages like JavaScript.

Accessing values which aren't in the root of a function, such as the loop iterator value from a `for` loop, is not allowed. This is because the value may not be valid by the time the function is actually called.

```
1 def foo(a : [int]) -> [int()]:
2     out : [int()] = []
3     for x in a:
4         def bar() -> int:
5             return x # Not OK
6             # x is not bound in root of function and thus cannot
7             # be seen from enclused function the value x may not
8             # have the same value as you are expecting by the time
9             # the function is done. The same variable is used
10            # for all iterations of the loop, so if this was allowed
11            # all functions would return the last value itertated
12            # through
13        out.push(bar)
14    return out
```

The declaration syntax (`x := a`) is the only syntax addition to Python. It adds no new semantic meaning to Python, having the same meaning in Python as a bare assignment statement. The meaning is only useful for the Garter validation pass.

3.4.4 Classes

Users in Garter are allowed to define their own types, with the `class` construct.

```
1 class C:
2     field := initialvalue
3
4     def method(self):
5         # self is implicitly avaliable here as the instance of C!
```

When a class is defined, it also declares a function with the name of the class. This function, when called, will create a new instance of that class.

```
1 x := C()
```

One of the unfortunate design decisions made in Garter because of its Python legacy is the semantics of field default values. The initial values for fields are evaluated just once when the class is defined. This can lead to confusing results when combined with list or dictionary fields, and mutation.

```
1 class C:
2     arr := []
3 x := C()
4 x.arr.push(5) # Changes value for default value for arr
5 y := C()
6 y.arr # Contains 5
```

In Python, the normal way to implement this type of logic would be to define the magic `__init__` method on the class, which is called when a new instance is created. This would mean that the `[]` literal would be evaluated each time that an instance is created.

```
1 class C:
2     def __init__(self):
3         self.arr = []
```

This syntax is highly unfortunate, requiring an understanding of constructors etc. Instead, the syntax of creating type-associated values was chosen, as it has reasonable semantics, although it sometimes creates undesirable results when used with mutable values.

There was a consideration early in the development of considering consecutive `:=` statements in classes as being an implicit `__init__` statement. This was chosen to be too different semantically from Python, and was not chosen as the option.

3.4.5 Expressions

Expressions can also just be written as a statement, and they will be evaluated for their side effects.

3.5 Programs

A program is just a series of statements. They are executed from top to bottom. Garter also supports interactive evaluation, in which partial programs are provided to the validator. Garter programs are validated in a single pass from top to bottom. Most statements are validate in order. Functions don't have their bodies typechecked until either:

1. their binding's name is referenced (for example, to be called), or

2. The end of the current program's input is reached.

This allows mutual recursion, for example:

```
1 def foo(b: bool):
2     if b:
3         print('b is true')
4     else:
```

```
5           print('b is false')
6           bar() # foo is defined before bar is defined
7
8 # if foo was called here, it would be a lookup error, but it isn't called until after
9
10 def bar():
11     foo(True)
12
13 foo(False)
```

3.6 Modules

Garter only supports a small set of basic modules provided by the base language. The currently supported modules are `random` and `turtle`. Expansion to include support for user- and teacher- defined modules are part of future work 5.2.

Another important part of teaching would be to provide a simple graphics API for teaching students, such that they can create simple games, and visualize progress. Designing such an API is, however, outside the scope of this thesis.

Chapter 4

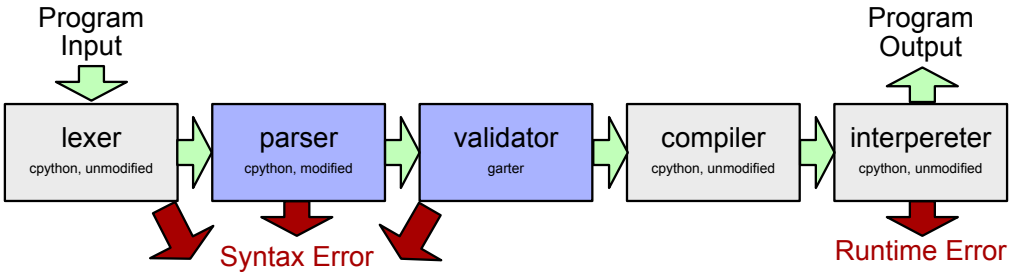
Prototype Implementation

In order to validate the claims of simplicity and feasibility, a prototype implementation of the Garter language was devised, and some example programs were written in Garter.

The prototype was built by modifying the cpython compiler [12] and tooling to support the extra functionality provided by Garter, and then adding a validation pass using the extra functionality to ensure correctness of the Garter code.

Many options were considered for how to implement this prototype, mostly focusing on Garter's similarity to Python, parsing and validating the program, and then generating finished Python logic. See Appendix D.

4.1 Program Structure



The Garter prototype implementation consisted of two major changes. Firstly, the cpython parser and AST was extended to support the `:=` and `: T =` declaration syntax. This was handled by adding an optional property on the Assignment statement which indicates whether it is a declaration, and what type was written. Types in the AST are represented as expressions, for backwards compatibility with Python's PEP 3107 – Function Annotations [6]. The parser was then modified to accept the extra syntax, and represent it correctly in the AST. The lexer, compiler, and interpereter were left unmodified, such that Python code, some of which is essential to the operation of cpython's logic, would continue to function correctly.

A validation pass was then written. This pass operates on the AST objects created by the parser, and performs the validation passes, type checking, and other restrictions which Garter enforces on code written in it compared to Python. This pass was written as a Python function in the `garter` module. For ease of integration with existing tools in the Python ecosystem, the entry point was given the same signature as Python's built-in `compile` function. It acts like `compile`, except performs the validation first.

The entry points for interacting with Python were then also modified. The IDLE

IDE provided by Python was modified such that code compilation was dispatched through Garter's `gcompile` function, rather than through the default compile framework, meaning that typechecking functions correctly. In addition, the Python `code` module was updated to also dispatch through `gcompile`, meaning that a command-line garter interpereter is also avaliable through the command `./python -m gcode`. This program acts similarially to the default Python executable. It is, however, not the default action right now in order to not break the build process. The relatively minor amount of extra work to make this the default code path is an important step.

The decision to insert the extra validation phase only when explicitly compiling garter code, rather than simply modifying the default `compile` infrastructure, was made in order to not break the rest of Python. cpython depends on large amounts of Python code internally, which would be broken by the Garter validation passes. Instead, just the major entry points for new developers were changed over, with normal Python code still being run internally.

4.2 REPL Support

One of the useful properties of Python for teaching is it's support for a Read-Eval-Print-Loop (REPL). REPLs help new programmers learn how their language will behave by getting immediate responses for the behavior of program fragments, and enabling experimentation. Some modifications had to be made to the REPL environments, such as the one found in IDLE, in order to support the validation phase needed by Garter. First, REPLs require maintaining scope and type information across compilations. This was achieved by providing callers of the `gcompile` API access to an opaque scope object which contains this information. The callers had to

be modified to retain this information across calls to the `gcompile` API.

In addition, the callers had to be modified to roll-back the changes made to the scope object if a runtime error occured during the execution of a program fragment, as a runtime error could cause new declarations to not be initialized. This required slightly more extensive changes to the call sites, however it was not too complex to re-purpose the existing infrastructure for this purpose.

Chapter 5

Conclusions and Future Work

5.1 Summary of Conclusions

Garter is a new teaching programming language, based on the Python Programming Language. It provides the developer with a safe environment in which they can learn to write programs, while familiarising themselves with Python syntax and idioms, making the transition into real programming languages used in production around the world much easier.

5.2 Limitations and Future Work

Garter unfortunately currently has many limitations, mostly due to the short time-frame in which it was designed and implemented. We hope to shore up these problems in a future version of Garter.

1. Better distribution story

   Garter's prototype implementation is not yet easy to distribute to students. Work must be done to make an implementation as easy to install as a Python

implementation, such that Garter can be used by students without having to build it from source.

2. Garter lacks a module system.

   Garter piggybacks on python, but doesn't currently support module loading, outside of a small pre-defined set of libraries. A module system to allow code modularization could be extremely useful for teachers and students, especially when dealing with larger projects.

3. Garter lacks a mechanism for exposing Python libraries to Garter code

   Occasionally a teacher may want to allow their students to perform actions which are not possible without interacting with other libraries written in Python, such as interacting with a graphics, windowing, high performance math, networking or similar library. Garter currently provides no mechanism for exposing that library other than modifying the distribution directly. Ideally a mechanism for doing this should be integrated into the language proper.

4. Garter lacks a class inheritance structure

   To enter and participate in modern programming, you often need to learn the mechanics of Object-Oriented Programming, specifically single-inheritance with interfaces. No mechanism was implemented for doing this in Garter (See A.4.2), which means that teaching of OOP concepts will have to occur in a different language. A future Garter may perform the design effort to add support for inheritance.

5. Learning Resources

Garter currently lacks the learning resources avaliable for languages such as Python and Turing. These languages have existed for longer, and thus have many more textbooks etc. written using their syntax and idioms. As Garter is close to both Python and Turing in language design, textbooks for these languages could probably be simplified into good Garter teaching material.

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Appendix A

Specification

A.1 Lexical analysis

Garter's syntax and lexical analysis are derived from the syntax and lexical rules from Python. For that reason, many parts of this section are derived directly from the Python 3 Language Reference [7].

Garter programs are described as a series of Unicode code points, and all lexical analysis is performed on the basis of these Unicode code points.

A.1.1 Logical and Physical Lines

A Garter program is formed of logical lines. The end of a logical line is represented by the `NEWLINE` token. A logical line is formed by one or more physical line, joined by explicit or implicit joins.

A physical line is a sequence of unicode code points followed by a newline sequence. This sequence is any of `\r`, `\n`, or `\r\n` where `\r` represents the ASCII Carriage Return (CR) character, and `\n` represents the ASCII Linefeed (LF) character.

A.1.2 Line joining rules

If the last character in a physical line is the backslash character (\), and the character is not part of another token (such as a string token), the current physical line is joined with the next physical line, and no `NEWLINE` token is emitted. Lines which are explicitly joined this way may not carry comments

If the end of a physical line is reached while inside a pair of parentheses (`()`), square brackets (`[]`), or curly braces ({}), the physical line is implicitly joined with the next line. Lines joined this way may carry comments.

A.1.3 Comments

A comment starts with the hash character (`#`) which is not part of a string literal, and ends at the end of a physical line. Comments are ignored by syntax, and do not cause tokens to be emitted.

A.1.4 Indentation

Leading whitespace at the beginning of a logical line is used to determine the indentation level of the line, which is used for blocks in the Garter programming language.

Whitespace measurements are done on spaces, with tabs being replaced by one to eight spaces, such that the total number of characters is a multiple of 8.

The lexical analysis uses these indentation levels to produce `INDENT` and `DEDENT` tokens, using a stack. The following excerpt from the Python reference explains the algorithm used:

Before the first line of the file is read, a single zero is pushed on the stack; this will never be popped off again. The numbers pushed on the stack will always be

strictly increasing from bottom to top. At the beginning of each logical line, the line's indentation level is compared to the top of the stack. If it is equal, nothing happens. If it is larger, it is pushed on the stack, and one INDENT token is generated. If it is smaller, it *must* be one of the numbers occurring on the stack; all numbers on the stack that are larger are popped off, and for each number popped off a DEDENT token is generated. At the end of the file, a DEDENT token is generated for each number remaining on the stack that is larger than zero.

Whitespace

Whitespace between tokens is ignored, unless it contributes to the indentation rules explained above.

A.1.5 Identifiers

Garter identifiers may be of arbitrary length, and may be formed as follows:

```
1 identifier ::= start continue*
2 start      ::= <'a'-'z', 'A'-'Z', '_'>
3 start      ::= <start, '0'-'9'>
```

Implementations may also support additional unicode characters from outside the ASCII range, following Unicode standard annex UAX-31, like Python.

As an additional restriction, names beginning and ending with two ASCII underscores (__), such as `__ADD__`, `__init__`) are reserved for implementation use, and may not be written in a Garter program.

Keywords

Keywords are a set of identifiers which cannot be used as ordinary identifiers. Unlike Identifiers, they do not produce a `NAME` token, but instead produce a token specific

to the keyword. For any keyword `Foo`, the token generated will be written as `'Foo'` in this document.

Some keywords in garter are included for compatibility with the Python programming language, while others are keywords used only within the Garter programming language.

The following are the set of keywords in Garter:

```
1 False      class      finally    is         return
2 None       continue   for        lambda     try
3 True       def        from       nonlocal   while
4 and        del        global     not        with
5 as         elif       if         or         yield
6 assert     else       import     pass       print
7 break      except     in         raise      range
8 int        float      bool       str        len
```

A.1.6 Literals

String Literals

String literals takes the following form

```
1 stringliteral: (shortstring | longstring)
2 shortstring: ("'" shortstringitem* "'" |
3                '"' shortstringitem* '"')
4 longstring: ("'''" longstringitem* "'''" |
5              '"""' longstringitem* '"""')
6 shortstringitem: shortstringchar | stringescapeseq
7 longstringitem: longstringchar | stringescapeseq
8 shortstringchar: <any source character except "\\"
9                   or newline or the quote>
10 longstringchar: <any source character except "\\">
11 bytesescapeseq: "\\" <any ASCII character>
```

Escape sequences in string and bytes literals are interpreted according to rules similar to those used by Standard C. The recognized escape sequences are:

Escape Sequence	Meaning
\newline	Backslash and newline ignored
\\	Backslash (\)
\'	Single quote (')
\"	Double quote (")
\a	ASCII Bell (BEL)
\b	ASCII Backspace (BS)
\f	ASCII Formfeed (FF)
\n	ASCII Linefeed (LF)
\r	ASCII Carriage Return (CR)
\t	ASCII Horizontal Tab (TAB)
\v	ASCII Vertical Tab (VT)
\ooo	Character with octal value ooo
\xhh	Character with hex value hh
\N{name}	Character named name in the Unicode database
\uxxxx	Character with 16-bit hex value xxxx
\Uxxxxxxxx	Character with 32-bit hex value xxxxxxxx

All unrecognized escape sequences are left in the string unchanged, including leaving the backslash in the result.

Multiple consecutive string literals delimited by only whitespace are allowed, and will be concatenated into a single combined string literal. This allows writing, for example:

```
1 x := ("string␣1" "string␣2")
```

Which assigns the value `"string 1string 2"` to x.

A.1.7 Integer Literals

The following is the lexical definition for integer literals:

```
integer         ::=  decimalinteger | octinteger |
                     hexinteger | bininteger
decimalinteger  ::=  nonzerodigit digit* | "0"+
nonzerodigit    ::=  "1"..."9"
digit           ::=  "0"..."9"
octinteger      ::=  "0" ("o" | "O") octdigit+
hexinteger      ::=  "0" ("x" | "X") hexdigit+
bininteger      ::=  "0" ("b" | "B") bindigit+
octdigit        ::=  "0"..."7"
hexdigit        ::=  digit | "a"..."f" | "A"..."F"
bindigit        ::=  "0" | "1"
```

Note that decimal integer literals may not have leading `0` characters. This is to cause c-style octal literals to be an error, as otherwise they would have unexpected behavior.

A.1.8 Floating Point Literals

Floating point literals expand on integer literals to allow the definition of non-integral numbers. The following is the lexical definition:

```
floatnumber   ::=  pointfloat | exponentfloat
pointfloat    ::=  [intpart] fraction | intpart "."
exponentfloat ::=  (intpart | pointfloat) exponent
intpart       ::=  digit+
fraction      ::=  "." digit+
exponent      ::=  ("e" | "E") ["+" | "-"] digit+
```

A.1.9 Operators and Delimiters

The following are additional special operator and delimiter tokens used by Garter:

```
+       -       *       **      /       //      %
<       >       <=      >=      ==      !=      +=
-=      *=      /=      //=     %=      **=     ->
,       :       .       ;       =       (       )
[       ]       {       }
```

A.2 Data Model

Values in garter are objects. Objects have a type, which defines the type's fields, and what other operations which may be performed on it. Objects have identity, and are stored by reference in variables or fields. Assignment doesn't mutate the object inside of the variable/field, but instead replaces the reference. A variable or field is immutable if its value cannot be changed.

A.2.1 Type Subsumption

A type `T` can be said to subsume another type `Q` if a value of type `Q` can be used anywhere that a value of type `T` can be used. For example: an `int` is a more specific type than a `float`, and it would be legal to use a `int` anywhere that a `float` would be required. Thus we can say `float` subsumes `int`. In addition, we can say the inverse, that `int` is a subtype of `float`.

A.2.2 Types

```
1 type: 'int' | 'float' | 'str' | 'bool' | NAME |
2       '{' type ':' type '}' | '[' type ']' |
3       (type | 'None') '(' [typelist] ')'
4 typelist: type (',' type)* [',']
```

Numbers (`int` and `float`)

`float` is an floating point number. An object of this type may asusme the value of a double precision floating point value. `float` exposes no attributes. `float` is ordered, and can be compared with the comparison operators `<`, `>`, `<=` and `>=`.

`int` is an integer. An object of this type may assume the value of an arbitrary integer value. `int` exposes no attributes. `int` is a subtype of `float`. `int` is ordered,

and can be compared with the comparison operators `<`, `>`, `<=` and `>=`.

Strings (`str`)

`str` is a unicode string. It may assume the value of an arbitrary length sequence of unicode codepoints. `str` is ordered, and can be compared with the comparison operators `<`, `>`, `<=` and `>=`. `str` exposes the following attributes:

`join : str([str])`: The `join` attribute is a function object which concatenates the elements of the argument array, using the implicit self argument as the seperator. The `join` attribute is immutable.

Booleans (`bool`)

`bool` is a boolean. It may assume either the value `True` or `False`. `bool` exposes no attributes.

Dictionaries (`{K: V}`)

`{K: V}` is a one-to-many map from values of type `K` to values of type `V`. `K` and `V` may be arbitrary types. `{K: V}` exposes the following attributes. All attributes of `{K: V}` are immutable:

`pop : V(K, V)`: If the first parameter is a key in the map, Mutates the map, removing the key from the mapping, and returns the associated value. Otherwise, returns the second parameter.

`setdefault : V(K, V)`: If the first parameter is a key in the map, returns its associated value. Otherwise, mutates the map, inserting tke key-value pair of the parameters to the map, and returns the second parameter.

`get : V(K, V)`: If the first parameter is a key in the map, returns the associated value. Otherwise, returns the second parameter.

`clear : None()`: Mutates the map, removing all key-value pairs.

`copy : {K: V}()`: Returns a new `{K: V}`, with a shallow copy of the key-value pairs from the map.

`update : None({K: V})`: Mutates the map, adding all key-value pairs from the first parameter, overriding any existing conflicting key-value pairs.

Lists (`[T]`)

`[T]` is a list of values of type `T`. An object of this type may assume the value of an arbitrary length list of values of type `T`. `[T]` exposes the following attributes. All attributes of `[T]` are immutable:

`append : None(T)`: Mutates the list, adding the first parameter to the end of the list.

`extend : None([T])`: Mutates the list, adding the elements of the first parameter to the end of the list.

`insert : None(int, T)`: Mutates the list, adding the second parameter at the index specified by the first parameter, shifting all elements after the insertion point one element.

`remove : None(T)`: Mutates the list, removing the first element for which `it == arg` (where `it` is the element, and `arg` is the argument) evaluates to `True`.

`pop : T(int)`: Mutates the list, removing the element at the index specified by the first parameter, and returning it. Elements with indexes greater than the first parameter are shifted down one index.

`index : int(T)`: Returns the index of the first element in the list for which `it == arg` (where `it` is the element, and `arg` is the argument) evalues to `True`.

`count : int(T)`: Returns the number of elements in the list for which `it == arg` (where `it` is the element, and `arg` is the argument) evaluates to `True`.

`reverse : None()`: Mutates the list, reversing the order of its elements.

`sort : None()`: Mutates the list, sorting it in ascending order. This attribute is only avaliable on the list types `[int]`, `[float]`, and `[str]`.

Functions (`T(P, ...)`)

Function objects may have a return type (`T`), or if `None` is written instead of a type, the function returns no value. In addition, they have an arbitrary-length list of parameter types. Function objects do not expose any attributes.

User-defined Types

Users may define their own types using the `class` statement (Section A.4.2). These classes have the attributes as defined by their class definition. They are unordered, and can be compared for identity with the equality (`==` and `!=`) operator.

For more details on user-defined types, see Section A.4.2.

A.2.3 Unwritable Types

A type is said to be an unwritable type if it cannot be written using the type syntax. Values with unwritable types may not be assigned to variables or used as the type of fields, parameters, or return values. These types may only be used as the type of a temporary value within an expression. Unwritable types are the types of expressions

such as `None`, `[]` and {}.

The expression `None` has the unwritable type `__NoneType__`. This type is subsumed by all class types. Thus, the `None` value can be used in place of any class type due to subsumption rules (Section A.2.1).

The expression `[]` has the unwritable type `__EmptyListType__`. This type is subsumed by all list types. Thus, the `[]` value can be used in place of any list type due to subsumption rules (Section A.2.1). `__EmptyListType__` exposes the same methods as a normal list, except for those which require knowing the element type.

The expression {} has the unwritable type `__EmptyDictType__`. This type is subsumed by all dict types. Thus, the {} value can be used in place of any dict type due to subsumption rules (Section A.2.1). `__EmptyDictType__` exposes the same methods as a normal dict, except for those which require knowing the key/value types.

All compound list or dictionary types which have keys, values, or item types which are unwritable are also unwritable. They can be subsumed by any type for which all literal types match, and the unwritable keys, values, and/or items are subsumed by the corresponding keys, values, and/or items in the subsuming type.

A.3 Program Start Points

```
1 single_input: (NEWLINE | simple_stmt |
2                compound_stmt NEWLINE |
3                defn NEWLINE)
4 file_input: (NEWLINE | stmt)* ENDMARKER
```

A Garter input may either consist of a self-contained program, consisting of a series of newlines and statements; or a single line of interactive input coming from,

for example, a REPL.

A.4 Definitions and Scoping

```
1 defn: funcdef | classdef | vardef
```

Definitions may occur wherever a statement is permitted. They bind a value to the given name in the current scope. Binding is performed on a per-block level. Shadowing of variables from outside of the current function is permitted, but shadowing within a function is not allowed. Redeclarations are also prohibited.

When referring to a name, first a check is made to see if the variable is local. A variable is local if there is a statement declaring that variable within the current function (whether that variable is currently in scope is ignored). If the name is nonlocal, enclosing scopes are checked for local variables. If a variable with the name is not found, it is a validation time error. Once a variable is found, the variable's validity is checked. A local variable is valid if it has been declared within the current block or a direct parent. A nonlocal variable is valid if it is declared above the enclosing function definition in the root of a function or module. Other references are prohibited as they may no longer be valid when the function is called.

Variables may not be mutated if they are defined using an immutable declaration form. Nonlocal variables may not be mutated, although this may be bypassed with the `varfwd` forms described in Section A.4.1.

A.4.1 Function Definition

```
1 funcdef: ('def' NAME '(' [paramlist] ')' ['->' type] ':'
2           funcbody)
3 paramlist: param (',' param)* [',']
4 param: NAME ':' type
5
6 funcbody: (simple_stmt | NEWLINE INDENT varfwd* stmt+ DEDENT)
7 varfwd: globaldef | nonlocaldef
8 globaldef: 'global' NAME (',' NAME)*
```

```
9 nonlocaldef: 'nonlocal' NAME (',' NAME)*
```

A function definition defines a new immutable variable with the given name. It has the type of the corresponding function object, with the return type specified after the `->` token, or None if no return type is specified. The parameter types are defined as the types written after the `:` token in each parameter.

For example, the function definition:

```
1 def foo(a: int, b: float, c: str) -> bool:
2     ....
```

Would define an immutable variable of type `bool(int, float, str)`.

When the function is invoked, the statements in the body of the function are executed sequentially.

The variable forward forms, `globaldef` and `nonlocaldef` accept names as arguments. They state that for name resolution rules, the global, or nonlocal (but in another function) variables should be treated as though they are local. This means that they may be mutated, even though they exist in an enclosing nonlocal scope.

Calls to functions are described in more detail in Section A.6.2.

The body of the function is not validated until either the end of the current input's validation phase, (either an interactive command or program file), or the validation of its first reference to the variable within the current input. This means that functions may refer to other functions or variables which have not been declared yet, as long as they are declared before the function is used.

A.4.2 Class Definition

```
1 classdef: 'class' NAME ':' class_body
2 class_body: fielddef | NEWLINE INDENT class_stmt+ DEDENT
3 class_stmt: fielddef | mthddef
4
5 fielddef: NAME ':' [type] '=' expr
```

```
6 mthddef: ('def' NAME '(' mparamlist ')' ['->' type] ':'
7           funcbody)
8 mparamlist: NAME (',' param)* [',']
```

A class definition defines a new type to the Garter type system. User-defined classes may not be referred to in a Garter program before their definition.

When the garter class definition for a type `T` is written, an immutable variable of type `T()` is defined with the name `T`. This function can be called to get a new instance of the type `T`. In addition, the initializer statements for the class are run when a class definition is executed as a statement.

If a class is declared within a function, each time that function is run the initializer statements for the class will be re-run, and will be used for new instances of that class within the given scope.

All field and method definitions declare attributes on the class type.

All class types also accept, as a possible value, the value `None`. This represents the absense of a meaningful value. Any attempt to access a field on a `None` value results in a runtime error.

Field Definitions

A field definition defines a new mutable attribute with the written type on the class type. For example, the field definition `x : int = 10` would define a mutable attribute `x` on the class type, with type `int`. Like with variable declarations, the type of the field may be inferred if the type is not written.

Method Definitions

A method definition defines a new mutable attribute with a function type on the class type. The function type will be the same as if the method definition was written as a

function definition (Section A.4.1), except that the first parameter need not be typed, and will be implicitly passed a reference to the instance of the class the function is called on.

Calls are described in more detail in Section A.6.2.

Variable Definition

```
1 vardef: NAME ':' [type] '=' expr
```

A variable definition defines a new mutable variable in the current scope. If the statement is invoked at the global scope, then it defines a new variable in the global scope. If the statement is invoked within the root of a function, it defines a new variable inside of that function's scope. The expression is then evaluated, and assigned to that variable.

If the type is not provided, it is inferred from the type of the expression. This is occasionally not possible, and a type annotation must be provided (such as with the `None` literal).

A.5 Statements

```
1 stmt: simple_stmt | compound_stmt | defn
2 simple_stmt: small_stmt (';' small_stmt)* [';'] NEWLINE
```

Control flow in Garter is controlled by statements. These statements can be categorized into two groups: the single-line small statements, and the multi-line compound statements.

Definitions are also statements, but are described in Section A.4.

A.5.1 Small Statements

```
1 small_stmt: (expr | assign_stmt | pass_stmt |
2              break_stmt | continue_stmt |
3              return_stmt | print_stmt)
```

Expr Statement

The expr statement allows for an expression to be invoked for its side effects, discarding the resulting value. Usually this is done with a function or method call. More details on expressions in Section A.6.

Assignment Statement

The basic assignment operator `lhs = rhs` assigns the value in `rhs` to `lhs`.

Compound assignment operators, `+= -= *= /= %= **= //=` perform their operation (`+ - * / % ** //` respectively), and the assign the result to `lhs`, evaluating `lhs` only once.

The `lhs` of the operator must be an assignable target. This is either a mutable variable, field, array or dictionary index, or array slice. Other expressions are not legal on the left of an assignment operator. If a field or variable is immutable (such as is the case with fields corresponding to methods, and variables corresponding to functions and classes), then it is not a legal assignable target. If a variable is nonlocal, it is also not a legal assignment target. To bypass this, the `nonlocal` and `global` forms may be used (Section A.4.1).

Pass Statement

```
1 pass_stmt: 'pass'
```

The pass statement does nothing. It exists to enable the definition of empty blocks.

Break Statement

```
1 break_stmt: 'break'
```

The break statement may only be placed lexically within the for or while statements. It causes control flow to immediately continue to the next statement after the for or while statement, not executing the remainder of the current iteration, and ignoring the normal loop exit conditions.

Continue Statement

```
1 continue_stmt: 'continue'
```

The continue statement may only be placed lexically within the for or while statements. It causes control flow to immediately continue to the next iteration of the loop, not executing the remainder of the current iteration.

Return Statement

```
1 return_stmt: 'return' [expr]
```

The return statement may only be placed lexically within a function declaration. It causes control flow to immediately exit the current function, not executing the remaining statements in the function. If the return statement is passed an expression, then it must have the same type as the return type of the function, and that value is used as the return value of the function. If the return statement is not passed an expression, then the function must not have a return type.

Print Statement

```
1 print_stmt: ('print' '(' expr (',' expr)*
2              [',' 'end' '=' expr] [','] ')')
```

Prints out the result of casting each of the arguments to a `str` to the screen. If this operation would fail, instead prints out a useful debug representation of the object. By default, each argument's representation is seperated by an ASCII space character (' '), and the print statement's output is terminated with an ASCII newline character

('\n'). This newline character can be replaced by passing the `end` 'named argument', which will instead terminate the string. The `end` named argument must be a `str`.

A.5.2 Compound Statements

```
1 compound_stmt: (if_stmt | while_stmt | for_stmt)
```

If Statement

```
1 if_stmt: ('if' expr ':' suite ('elif' expr ':' suite)*
2           ['else' ':' suite])
```

The if statement is used for conditional execution. It selects exactly one of the suites to execute by evaluating the expressions one by one until one is found to evaluate to the boolean value `True`. If all expressions evaluate to `False`, then the suite of the else clause, if present, is executed.

All of the expression arguments must be of type `bool`.

While Statement

```
1 while_stmt: 'while' expr ':' suite
```

The `while` statement is used for repeated execution while an expression evaluates to `True`. It will repeatedly test the expression, and if it is `True`, executes the suite. Whenever the expression evaluates to `False`, the loop terminates.

A `break` statement (Section A.5.1) executed in the suite terminates the loop immediately. A `continue` statement (Section A.5.1) executed in the suite skips the rest of the suite and goes back to testing the expression.

For Statement

```
1 for_stmt: ('for' NAME 'in' (expr | range) ':' suite)
2 range: 'range' '(' expr [',' expr [',' expr]] [','] ')'
```

The `for` statement is used to iterate over the elements of a list. The expression is evaluated once, and must have a `[T]` type. The suite is then executed once for

each element of the iterator, with the value bound to the name. This name binding is a local declaration, much like an the assignment declaration, however it is not valid outside of the body of the for statement (Section A.4.2.

If the `range` form is used instead of the expression, then all of the expressions must have type `int`. In the 1 argument case, the suite is executed N times, where N is the first argument, with the name bound to each integer in the range $[0, N)$. In the 2 argument case, the suite is executed $M - N$ times, where N is the first argument, and M is the second argument, with the name bound to each integer in the range $[N, M)$. In the 3 argument case, it acts much like the 2 argument case, except the step is I instead of 1, where I is the 3rd argument.

A `break` statement (Section A.5.1) executed in the suite terminates the loop immediately. A `continue` statement (Section A.5.1) executed in the suite skips the rest of the suite and proceeds to the next item in the list.

A.6 Expressions

A.6.1 Atoms

```
1 atom: ('(' expr ')' |
2         '[' [exprlist] ']' |
3         '{' [dictmaker] '}' |
4         'len' '(' expr ')' |
5         ('str' | 'int' | 'float') '(' expr ')' |
6        NAME | INTEGER | FLOATNUMBER | STRING+ |
7         'None' | 'True' | 'False')
8 exprlist: expr (',' expr)* [',']
9 dictmaker: expr ':' expr (',' expr ':' expr)* [',']
```

Atoms are the building blocks of expressions, and are the base cases for the recursive definitions of the other expressions.

Identifiers (names)

See Section A.1.5 for lexical information on identifiers. This identifier evaluates to the value of the variable with the given name in the current scope. The type of this expression is the type of the variable with the given name.

If there is no variable in the current scope with the given name, it is a validation-time error.

Literals

Literals evaluate to a literal of the given type. The `STRING` literal evaluates to a `str` object, The `INTEGER` literal evaluates to a `int` object, the `FLOAT` literal evaluates to a `float` object, the `'True'` literal evaluates to the `bool` value `True`, and the `'False'` literal evaluates to the `bool` value `False`.

The `'None'` literal evaluates to the common `None` value of user-defined types. For more information see Section A.4.2.

Parenthesized Expression

Parenthesized Expressions evaluate to the value of the contained expression, and primarially exist as a mechanism for expression precidence and operation orders.

List literals

```
1 list_literal: '[' [exprlist] ']'
2 exprlist: expr (',' expr)* [',']
```

List literals evaluate their contained expressions in order. All expressions must be of a single type `T`. They evaluate to a `[T]` value with the results of the contained expressions as the list elements.

Dictionary literals

```
1 dict_literal: '{' [dictmaker] '}'
2 dictmaker: expr ':' expr (',' expr ':' expr)* [',']
```

Dictionary literals evaluate their contained expressions in order. All expressions to the left of the colon must be of a single type `K`, while expressions to the right of the colon must be of a single type `V`. They evaluate to a `{K:V}` value with the results of the expressions to the left of the ':' as the keys, and the ones to the right as values. Duplicate keys produce a runtime error.

Len Expression

```
1 len: 'len' '(' expr ')'
```

If the expr is a `str`, produces the length of the string as an `int`. If the expr is an `[T]`, produces the number of items in the list. If the expr is an `{K: V}`, produces the number of key-value pairs in the dictionary. Otherwise, causes a validation time error.

Typecast Expressions

```
1 typecast: ('int' | 'str' | 'float') '(' expr ')'
```

The typecast expressions attempt to convert their argument to their type.

All typecast expressions only accept `int`, `float`, and `str` arguments.

The `str` typecast will convert `int` and `float` objects to their `str` representation. For example, the `int` `5` will be converted to the `str` `"5"`. It will return `str` arguments unchanged.

The `int` typecast will truncate `float` types to their closest integer representation, rounded toward `0`. It will also attempt to parse `str` types as an `int`, causing a runtime error if this fails. It will return `int` arguments unchanged.

The `float` typecast will truncate `int` types to their closest floating point representation, which may be less precise than the `int`'s original representation. It will also attempt to parse `str` types as an `float`, causing a runtime error if this fails. It will return `float` arguments unchanged.

A.6.2 Primaries

```
1 primary: fieldref | subscription | call
```

Field Reference

```
1 fieldref: primary '.' NAME
```

A field reference accesses an attribute of the given object. The type of this expression is the type of the attribute on the object. If the object lacks an attribute with the given name, it is a validation-time error.

Call

```
1 call: primary '(' [exprlist] ')'
```

A call calls the function object with the passed arguments. The primary must evaluate to a function object, and the passed arguments must have types which correspond to the argument types of the function object.

The result type is the return type of the function object. If the function object has no return type, then this expression has no result.

This is also used to call methods, as methods are defined as immutable fields with a function object type.

Subscription

```
1 subscription: primary '[' (expr | [expr] ':' [expr]) ']'
```

If the first form of subscription is used, the primary must evaluate to a `[T]` or `{K:V}`. If the primary is a `[T]`, then the expr must be a `int`, and the expression will

yield the nth element of the list, where n is the value of the expr. If the primary is a {`K:V`}, then the expr must be a `K`, and the expression will yield the `V` which is associated with the given key.

If the second form of subscription is used, then the primary must evaluate to a `[T]`, and both expressions, if provided, must be a `int`. The first argument defaults to `0`, and the second defaults to the value of `len(primary)`. The expression yields a new list, containing the values in the list starting at the index of the first argument, and ending before the element at the index of the second argument.

Negative integer indexes on `[T]` are offset from the end of the list, so `-1` is the index of the last element in the list.

A.6.3 Comparison Operators

```
1 comparison: arith (comp_op arith)*
2 comp_op: '<'|'>'|'=='|'>='|'<='|'!='|'in'|'not' 'in'
```

These operators are not parsed as left-associative, unlike the Arithmetic Operators below. Instead, a sequence of comparison operators such as `a < b == c > d` will be resolved like `(a < b) and (b == c) and (c > d)`, except that each expression will only be evaluated once.

These operators all produce an expression of type `bool`, and will be written with only two operands. Their semantic meaning in sequence is as is written above. Their valid types will be written in place of their operands. As `int` is subsumed by `float`, it may be used whenever a `float` is required.

`float < float`: `True` if $lhs < rhs$, `False` otherwise.

`float > float`: `True` if $lhs > rhs$, `False` otherwise.

`float <= float`: `True` if $lhs \leq rhs$, `False` otherwise.

`float >= float`: `True` if $lhs \geq rhs$, `False` otherwise.

`float == float`: `True` if $lhs = rhs$, `False` otherwise.

`str == str`: `True` if lhs and rhs represent the same unicode sequence, `False` otherwise.

`bool == bool`: `True` if lhs and rhs have the same value, `False` otherwise.

`[T] == [T]`: `True` if lhs and rhs have the same number of elements, and for all elements i, `lhs[i] == rhs[i]`.

`{K: V} == {K: V}`: `True` if lhs and rhs have the same set of keys, and for each key k, `lhs[k] == rhs[k]`.

`T == T`: `True` if lhs and rhs have the same identity.

`T != T`: `True` if `T == T` is `False`, `False` otherwise.

`T in [T]`: `True` if there is an element i in rhs such that `lhs == rhs[i]`. `False` otherwise.

`K in {K: V}`: `True` if the key lhs is in rhs, `False` otherwise.

`T not in [T]`: `False` if there is an element i in rhs such that `lhs == rhs[i]`. `True` otherwise.

`K not in {K: V}`: `False` if the key lhs is in rhs, `True` otherwise.

A.6.4 Arithmetic Operators

```
1 arith: mult (('+'|'-') mult)*
2 mult: unary (('*'|'/'|'%'|'//') unary)*
3 unary: ('+'|'-') unary | power
4 power: primary ['**' unary]
```

These operators will be written with their valid types in place of their operands. Any unlisted type-operand combinations are validation-time errors. With any operators which accept `float` also accept `int` in place of their operands, unless a more specialized operator is avaliable. For example the `-` binary operator accepts any combination of `int` and `float` operators, and produces an `int` if both operands are `int`,

and a `float` otherwise, but only has two entries on this list, one for `int - int`, and one for `float - float`.

`int + int`: Returns the value $lhs + rhs$ as an `int`.

`float + float`: Returns the value $lhs + rhs$ as a `float`.

`str + str`: Returns a `str` containing the concatenation of the two strings.

`[T] + [T]`: Returns a new `[T]` containing the concatenation of the two lists.

`int - int`: Returns the value $lhs - rhs$ as an `int`.

`float - float`: Returns the value $lhs - rhs$ as a `float`.

`int * int`: Returns the value $lhs \times rhs$ as an `int`.

`float * float`: Returns the value $lhs \times rhs$ as a `float`.

`float / float`: Returns the value $\frac{lhs}{rhs}$ as a `float`.

`int % int`: Returns the remainder from the division $\frac{lhs}{rhs}$ as an `int`. The sign of this remainder will match the sign of the second operand.

`float % float`: Returns the remainder from the division $\frac{lhs}{rhs}$ as an `float`. The sign of this remainder will match the sign of the second operand.

`int // int`: Returns the value $\frac{lhs}{rhs}$, rounded down to the nearest integer as an `int`.

`float // float`: Returns the value $\frac{lhs}{rhs}$, rounded down to the nearest integer as an `float`.

`float ** float`: Returns the value lhs^{rhs}, as a `float`.

`+ int`: Returns its operand unchanged.

`+ float`: Returns its operand unchanged.

`- int`: Returns the negation of its operand.

`- float`: Returns the negation of its operand.

Unary Operators

`+`: If the operand is `int` or `float`, returns it unmodified. Other operand types cause a validation time error.

`-`: If the operand is `int` or `float`, returns its negation with the same type. Other operand types cause a validation time error.

A.6.5 Boolean Operators

```
1 or_expr: and_expr ('or' and_expr)*
2 and_expr: not_expr ('and' not_expr)*
3 not_expr: 'not' not_expr | comparison
```

Boolean Operators, unlike the other operators, do not necessarially evaluate all of their operands, they may short-circuit their execution if the value of their left operand is sufficient to compute the result.

All Boolean operators require all operands to have type `bool`.

The `or` operator evaluates its left operand. If it produces the boolean value `True`, the result is `True`. Otherwise, it evaluates its right operand, and produces its result.

The `and` operator evaluates its left operand. If it produces the boolean value `False`, the result is `False`. Otherwise, it evaluates its right operand, and produces its result.

The `not` operator evaluates its operand. If it produces the boolean value `False`, the result is `True`. Otherwise, the result is `False`.

A.6.6 If Expression

```
1 expr: or_expr ['if' or_expr 'else' expr]
```

The first and third operands must have a common type `T`. The second operand must have type `bool`.

The `if` expression evaluates its second operand. If it produces the boolean value `True`, the first operand is evaluated, and its result is produced. Otherwise, the third operand is evaluated, and its result is produced.

A.7 Built-in Functions

Garter defines only one function in the global scope at the start of the program:

`input : str()`: Reads in a line of textual input from the user, producing a `str` containing the read-in text.

`ord : int(str)`: Returns the ordinal number for the passed-in character.

Appendix B

Grammar

```
# Grammar for Garter

# Start symbols for the grammar:
#       single_input is a single interactive statement;
#       file_input is a program or sequence of commands
#       read from an input file;

# Start Symbols #
single_input: (NEWLINE | simple_stmt |
               compound_stmt NEWLINE |
               defn NEWLINE)
file_input: (NEWLINE | stmt)* ENDMARKER

# Types #
type: 'int' | 'float' | 'str' | 'bool' | NAME |
      '{' type ':' type '}' | '[' type ']' |
      (type | 'None') '(' [typelist] ')'
typelist: type (',' type)* [',']

# Statements #
stmt: simple_stmt | compound_stmt | defn
simple_stmt: small_stmt (';' small_stmt)* [';'] NEWLINE

small_stmt: (expr | assign_stmt | pass_stmt |
             break_stmt | continue_stmt |
             return_stmt | print_stmt)
assign_stmt: expr assignop expr
assignop: ('=' | '+=' | '-=' | '*=' |
           '/=' | '%=' | '**=' | '//=')
pass_stmt: 'pass'
break_stmt: 'break'
continue_stmt: 'continue'
return_stmt: 'return' [expr]
```

```
print_stmt: ('print' '(' expr (',' expr)*
             [',' 'end' '=' expr] [','] ')')

compound_stmt: (if_stmt | while_stmt | for_stmt)
if_stmt: ('if' expr ':' suite ('elif' expr ':' suite)*
          ['else' ':' suite])
while_stmt: 'while' expr ':' suite
for_stmt: ('for' NAME 'in' (expr | range) ':' suite)
range: 'range' '(' expr [',' expr [',' expr]] [','] ')'
suite: simple_stmt | NEWLINE INDENT stmt+ DEDENT

# Definitions #
defn: funcdef | classdef | vardef

# Variable Definition #
vardef: NAME ':' [type] '=' expr

# Function Definition #
funcdef: ('def' NAME '(' [paramlist] ')' ['->' type] ':'
          funcbody)
paramlist: param (',' param)* [',']
param: NAME ':' type

funcbody: (simple_stmt | NEWLINE INDENT varfwd* stmt+ DEDENT)
varfwd: globaldef | nonlocaldef
globaldef: 'global' NAME (',' NAME)*
nonlocaldef: 'nonlocal' NAME (',' NAME)*

# Class Definition #
classdef: 'class' NAME ':' class_body
class_body: fielddef | NEWLINE INDENT class_stmt+ DEDENT
class_stmt: fielddef | mthddef

fielddef: NAME ':' [type] '=' expr
mthddef: ('def' NAME '(' mparamlist ')' ['->' type] ':'
          funcbody)
mparamlist: NAME (',' param)* [',']

# Expressions #
expr: or_expr ['if' or_expr 'else' expr]
or_expr: and_expr ('or' and_expr)*
and_expr: not_expr ('and' not_expr)*
not_expr: 'not' not_expr | comparison
comparison: arith (comp_op arith)*
comp_op: '<'|'>'|'=='|'>='|'<='|'!='|'in'|'not' 'in'
arith: mult (('+'|'-') mult)*
mult: unary (('*'|'/'|'%'|'//') unary)*
unary: ('+'|'-') unary | power
power: primary ['**' unary]
primary: fieldref | subscription | call
fieldref: primary '.' NAME
```

```
85 subscription: primary '[' (expr | [expr] ':' [expr]) ']'
86 call: primary '(' [exprlist] ')'
87 atom: ('(' expr ')' |
88         '[' [exprlist] ']' |
89         '{' [dictmaker] '}' |
90        NAME | INTEGER | FLOATNUMBER | STRING+ |
91         'None' | 'True' | 'False')
92 exprlist: expr (',' expr)* [',']
93 dictmaker: expr ':' expr (',' expr ':' expr)* [',']
```

Appendix C

Error Glossary

The error messages are an important part of Garter. Garter programs will be written by inexperienced programmers, and the error messages which occur when they write incorrect programs will have to be useful and provide a mechanism for correcting their errors.

Sometimes, an error will be connected with 'notes', which are intended to provide additional information for the coder, directing them towards advice. For this reason, the error messages will occasionally be long, spanning multiple lines. To avoid scaring away developers with pages of errors, only one error should be shown at a time.

Only validation-time errors are described here.

C.1 Operator Type Mismatch

```
1 Line X, Column X
2       ....
3           ^
4 OperatorTypeMismatch:
5 The operands to operator '+' (int + str), are invalid.
```

This error appears when a user attempts to use a unary or binary operator on two types which are not supported.

If the operator is '+', and at least one of the operands is `str`, then we can predict that the user meant to perform string concatenation, and provide a fixit note.

```
1 NOTE: Can only concatenate str and str. Consider casting the left
    argument
2 to a str for concatenation with 'str(...)'.
```

C.2 Parameter Type Mismatch

```
1 Line X, Column X
2     ....
3       ^
4 ParameterTypeMismatch:
5 The 3rd parameter to this function is invalid. Expected int, instead
    found bool.
6
7 NOTE: Function expects parameters (int, int, float)
```

This error appears when a user attempts to call a function, either internal or user-defined, with the incorrect type parameter.

The expected parameters are listed to help the user correct their logic quickly.

C.3 Parameter Count Mismatch

```
1 Line X, Column X
2     ....
3       ^
4 ParameterCountMismatch:
5 This function expects 3 parameters, instead found 4 parameters.
6
7 NOTE: Function expects parameters (int, int, float)
```

This error appears when a user attempts to call a function, either internal or user-defined, with the incorrect number of arguments.

The expected parameters are listed to help the user correct their logic quickly.

C.4 No Such Attribute

```
1 Line X, Column X
2     ....
3       ^
4 NoSuchAttribute:
```

```
5 This object of type 'str' has no attribute named 'jion'.
6
7 NOTE: 'str' has attributes: 'join'.
```

This error appears when a user attempts to access an attribute of an object which is not available. The list of available attributes is listed to help them find the attribute they ment to access.

C.5 Attribute Already Defined

```
1 Line X, Column X
2     ....
3      ^
4 AttributeAlreadyDefined:
5 This class has a duplicate definition of the attribute 'foo'.
6
7 NOTE: The previous definition of this attribute is here:
8 Line Y, Column Y
9     ....
10     ^
```

This error occurs when a user attempts to define an attribute on an object which has previously been defined. It identifies the location of the previous definition, so that the user can quickly correct the offender.

C.6 Variable Already Defined

```
1 Line X, Column X
2     ....
3      ^
4 VariableAlreadyDefined:
5 The variable 'foo' has already been defined in this scope.
6
7 NOTE: The previous definition of this variable is here:
8 Line Y, Column Y
9     ....
10     ^
```

This error occurs when a user attempts to define an variable in a scope where it has previously been defined. It identifies the location of the previous definition, so

that the user can quickly correct the offender.

C.7 Invalid Variable

```
1 Line X, Column X
2     ....
3      ^
4 InvalidVariable:
5 The variable 'foo' may not have a valid value when it is accessed here.
```

This error occurs when a user attempts to access a variable which may not be valid when it is accessed. This might happen if, for example, a function is declared in a loop, and the function attempts to access the iterator value.

C.8 Incomplete Type

```
1 Line X, Column X
2     ....
3      ^
4 IncompleteType:
5 Unable to infer the type of this value. Try annotating this declaration
    with the desired type.
```

This error occurs when the user attempts to assign an unwritable type to a variable or field. For example, the declaration `x := []`, for which the item type of the expression cannot be determined.

If it is a simple error like `x := []`, `x := {}`, or `x := None` then we also add one of these notes:

```
1 NOTE: Annotate this declaration to specify the item type of the list
2 NOTE: Annotate this declaration to specify the key and value types of
    the dict
3 NOTE: Annotate this declaration to specify the class type
```

C.9 Invalid Typecast Source

```
1 Line X, Column X
2     ....
3      ^
4 InvalidTypecastSource:
5 Cannot cast to type 'float' from type 'bool'.
```

This error occurs when a user attempts to typecast from an invalid type. It identifies both of the types.

C.10 Mismatched Branch Types

```
1 Line X, Column X
2     ....
3      ^
4 MismatchedBranchTypes:
5 The types of the branches of the if expression must match.
6 Instead found 'int' and 'bool'
```

This error occurs when an if expression with mismatched types on the then and else branches is written.

C.11 Not In Loop

```
1 Line X, Column X
2     ....
3      ^
4 NotInLoop:
5 The 'break' and 'continue' statements may only be written in loops.
```

This error occurs when the user writes a `break` or `continue` statement outside of a loop.

C.12 Return Outside Function

```
1 Line X, Column X
2     ....
3      ^
4 ReturnOutsideFunction:
5 The 'return' statement may only be written within functions.
```

This error occurs when the user writes a `return` statement outside of a function or method.

C.13 Invalid Len Argument

```
1 Line X, Column X
2     ....
3      ^
```

```
4 InvalidLenArgument:
5 The len expression only accepts lists, dicts, and strs. Instead found a
    'bool'.
```

This error occurs when an invalid argument is passed to the len magic function.

C.14 Invalid Return Type

```
1 Line X, Column X
2     ....
3      ^
4 InvalidReturnType:
5 This function must return type 'bool', instead found a 'str'.
```

This error occurs when a returns statement in a function has an invalid type.

If the function shouldn't return any type, the error will instead be:

```
1 This function doesn't return a type, instead found a 'str'.
```

If the function should return a type but there is not one written

```
1 This function must return type 'bool', instead found an argument-less
    return statement
```

C.15 Invalid Conditional

```
1 Line X, Column X
2     ....
3      ^
4 InvalidConditional:
5 The type of the conditional in an if or while must be 'bool'. Instead
    found 'int'
```

This error occurs when a non-`bool` value is used as the conditional in an `if` or `while`.

C.16 Mismatched List Type

```
1 Line X, Column X
2     ....
3      ^
4 MismatchedListType:
5 The type of elements in a list must be consisitent.
6 The first element in this list literal is 'bool', while the 3rd element
    is 'str'
```

This error occurs when a list literal is used with inconsistent item types.

C.17 Mismatched Dict Type

```
1 Line X, Column X
2     ....
3      ^
4 MismatchedDictType:
5 The type of keys and values in a dict must be consisitent.
6 The first key in this dict literal is 'bool', while the 3rd key is 'str'
```

This error occurs when a list literal is used with inconsistent key/value types.

C.18 Invalid Print Line End

```
1 Line X, Column X
2     ....
3      ^
4 InvalidPrintLineEnd:
5 The 'end' named parameter to the print statement must be 'str', instead
    found 'bool'
```

This error occurs when the `end` named parameter to the `print` function is the incorrect type.

C.19 Invalid Index Type

```
1 Line X, Column X
2     ....
3      ^
4 InvalidIndexType:
5 Only 'int' may be used to index into '[bool]'. Instead found 'float'
```

This error occurs when the incorrect type is used for indexing into `list`, `dict` or `str` types with the subscription syntax.

C.20 Unsupported Index

```
1 Line X, Column X
2     ....
3      ^
4 UnsupportedIndex:
5 Cannot index into type 'bool'.
```

This error occurs when the indexing form of the subscription syntax is used on a type which doesn't support it.

C.21 Unsupported Slice

```
1 Line X, Column X
2     ....
3      ^
4 UnsupportedSlice:
5 Cannot slice into type 'bool'.
```

This error occurs when the slicing form of the subscription syntax is used on a type which doesn't support it.

C.22 Invalid Assign Target

```
1 Line X, Column X
2     ....
3      ^
4 InvalidAssignTarget:
5 This expression is immutable, and thus cannot be assigned to.
```

This error occurs when the user attempts to assign to an expression which isn't a valid assignment target.

Appendix D

Example Programs

The following are a series of example programs written in the Garter programming language. The majority of these example programs were adapted from the series of example programs to be shown to teachers interested in using the Turing programming for education.

D.1 Hello World

This program demonstrates a minimal program in Garter. It shows the lack of boilerplate in basic Garter programs, and demonstrates the basic use of the `print` statement.

```
1 print("Hello, World!")
```

D.2 Fibonacci

This program demonstrates function definitions in Garter, recursion support and the if statement.

```
1 # Return the i-th number in the fibonacci sequence
2 def fib(n : int) -> int:
3     if n < 2:
```

```
4           return 1
5       return fib(n-2) + fib(n-1)
6
7   print(fib(5))
```

D.3 Adder

This program demonstrates user input through the `input` function-like expression, variable declaration, type coersions, and the `while` loop.

```
1  total := 0
2  while True:
3      instr := input('Enter a number (ENTER to stop): ')
4      if instr == '':
5          break
6      num := int(instr)
7      total += num
8
9  print('The total was:', total)
```

D.4 Sorter

This program demonstrates user input through the `input` function-like expression, lists, typed varaible declarations, and the `for` loop.

```
1  items : [str] = []
2  while True:
3      instr := input("Enter a string (ENTER terminates): ")
4      if instr == '':
5          break
6      items.append(instr)
7
8  items.sort()
9
10 print("Sorted:")
11 for item in items:
12     print(item)
```

D.5 Linked List

This program demonstrates a basic implementation of a linked-list structure, along with some basic implementation methods. It demonstrates class declarations, and method declarations.

```
1  class Node:
2      data := 0
3      next : Node = None
4
5  class LinkedList:
6      root : Node = None
7
8      def insert(self, value : int):
9          old := self.root
10         self.root = Node()
11         self.root.data = value
12         self.root.next = old
13
14     def contains(self, value : int) -> bool:
15         curr := self.root
16         while curr != None:
17             if value == curr.data:
18                 return True
19             curr = curr.next
20         return False
21
22     # Other LinkedList methods omitted for brevity
```

D.6 Boxes

This program demonstrates basic input, string manipulations, and the use of the `range` looping construct.

```
1  width := int(input("Enter box width: "))
2  height := int(input("Enter box height: "))
3  nacross := int(input("enter number of boxes across: "))
4  ndown := int(input("enter number of boxes down: "))
5
6  top := ""
7  middle := ""
8  bottom := ""
9  for i in range(width * nacross + 1):
10     if i % width == 0:
```

```
11          top += "␣"
12          middle += "|"
13          bottom += "|"
14      else:
15          top += "_"
16          middle += "␣"
17          bottom += "_"
18
19  print(top)
20
21  for i in range(ndown):
22      for j in range(height):
23          print(middle)
24      print(bottom)
```

D.7 Expression Parser

This program demonstrates the implementation of a trivial expression parser.

```
1  # Evaluate an input expression e of the form t { + t } where
2  #      t is of form { * p } and p is of form ( e ) or explicit real constant
3  # For example, the value of 1.5 + 3.0 * ( 0.5 + 1.5 ) "halt" is 7.5
4
5  def expn(tokens : [str]) -> float:
6      v := term(tokens)
7      while tokens[0] == "+":
8          tokens.pop(0)
9          v += term(tokens)
10     return v
11
12 def term(tokens : [str]) -> float:
13     v := primary(tokens)
14     while tokens[0] == "*":
15         tokens.pop(0)
16         v *= primary(tokens)
17     return v
18
19 def primary(tokens : [str]) -> float:
20     v := 0.0
21     if tokens[0] == "(":
22         tokens.pop(0)
23         v = expn(tokens)
24         assert tokens[0] == ")"
25     else:
26         v = float(tokens[0])
27     tokens.pop(0)
28     return v
29
```

```
30 print("This␣is␣a␣recursive␣evaluator␣for␣infix␣expressions.")
31 print("The␣only␣operators␣accepted␣are␣+␣and␣*,␣as␣well␣as␣parentheses.")
32 print("Besides␣that,␣everything␣has␣to␣be␣separated␣by␣blanks.")
33 print("Terminate␣an␣expression␣by␣anything␣handy,␣such␣as␣a␣single␣period.")
34 print("Be␣gentle,␣this␣is␣just␣a␣demo␣of␣Garter␣mutual␣recursion.")
35 print()
36
37 while True:
38     print()
39     print("Give␣an␣arithmetic␣expression,␣with␣operators␣surrounded␣by␣blanks")
40     tokens := input().split("␣")
41     answer := expn(tokens)
42     print("Answer␣is:", answer)
```

D.8 Hanoi

This program demonstrates an implementation of the tower of hanoi algorithm.

```
1 def hanoi(n : int, s : str, d : str, i : str):
2     if n == 0:
3         return
4
5     hanoi(n - 1, s, i, d)
6     print("Move␣disc", n, "from", s, "to", d)
7     hanoi(n - 1, i, d, s)
8
9 hanoi(5, "left", "right", "centre")
```

D.9 Random Number Generation

This program demonstrates the generation of a random numbers using Garter.

```
1 import random
2
3 for i in range(1000):
4     print(random.randint(0, 99))
```

Appendix E

Alternative Implementations

The first mechanism for implementing this system would be to follow in the footsteps of mypy. Mypy uses Python 3's Function Annotation syntax [6] to allow code written for mypy to also be valid python 3 code. On one hand, this is an advantage, as it means that no translation work needs to be done. Unfortunately, to make typing more explicit and reduce programmer error, we also want to add annotations to variable declarations, and other places which are not covered by the function annotation syntax. However, we will likely re-use the function annotation syntax for this thesis as a standard way to write function types and return values, as it already fits with the rest of python's syntax, and is an advanced enough feature that it is reasonable to remove from the dialect created for this thesis.

Languages based very closely on the semantics of other languages, such as TypeScript mentioned above, are often implemented through source-to-source compilers, or transpilers. The transpiler acts like a compiler, parsing and analyzing the code written in the dialect. However, instead of performing translation to assembly or machine code directly, transpilers emit code in the base language. For example, the

TypeScript compiler reads in TypeScript code, analyzes it, and then emits valid ECMAScript code. This has an awesome advantage of eliminating the requirement of implementing a full language implementation of the base language, as the semantics can be derived from an existing implementation of that language. We plan to use that technique for this thesis in order to avoid re-implementing much of python, and to ensure that we maintain accurate semantics.

One approach to the development of this dialect would be to take the same approach as Microsoft. The dialects transpiler would be written, much like any other compiler, from scratch using standard compiler technologies. The code generation stage would be the only difference between the transpiler and any other compiler, in that instead of generating machine code, it would be aiming to generate code in the base language which as closely maps to the original code as possible, such that errors generated by the interpreter map back accurately to the source code for debugging purposes. However, writing a complete compiler from scratch is often unnecessary as people have developed awesome tooling for implementing language dialects already.

An interesting and useful tool for defining new languages without writing a complete compiler is the Spoofax workbench [21], [9]. Spoofax is a complete tool-chain for defining the syntax and semantics of a language. Syntax is defined using the Syntax Definition Formalism (SDF3) specification format, which allows for complete language grammars to be described using a declarative formation. Semantic analysis is handled using a variety of tools, including Name Binding Language (NaBL), which handles semantic analysis of name binding, such as namespaces, declarations, and references; and Type Specification Language (TS), which allows for a declarative

definition of a language's type system. Finally, language developers translate the complete, type-checked and analyzed language into a base language, such as Java, using the Stratego Transformation Language [10], which declaratively maps AST structures in the new language to structures in an existing language, such as Java. Spoofax also provides a comprehensive testing story, with the Spoofax Testing Language (SPT) which can be used to test parsing rules, error and warnings in language productions, and transformation outputs. Finally, Stratego also uses these analyses to generate IDE tooling for the languages in question - languages built with Stratego get syntax highlighting, go to definition, and other useful tools almost for free.

The biggest, and most impressive, advantage of the Spoofax toolbox for language definition is its polish and integration with the Eclipse IDE. Languages defined in spoofax are developed in a complete development environment, which includes features such as inspection and debugging of intermediate data structures, as well as IDE integration for the generated language. The IDE integration is especially useful for a learning project, as it gives new developers the tools they need to explore and learn about their new programming language without having to memorize function and type names from libraries.

The Turing Extender Language (TXL) [16], [11] is another system for defining new languages in terms of base languages. TXLs processing is split into two distinct steps. First, in the syntactic phase, the dialect language is parsed, and an AST of the dialect language is generated. This dialect AST is then passed to the semantic phase, which describes the semantic meaning of the dialect language through a series of transformations into the base language AST. This AST is then written out, and can be compiled or executed.

Much like Spoofax, TXL is intended to be used with known syntax definitions for a base language, such as the Turing programming language. TXL supports tooling for modifying portions of a base languages syntax, allowing for dialect languages to be easily extended off of the syntactic structures of the base language. However, TXL is also capable of describing complete new languages, with completely different syntactic properties. In addition, by using multiple passes which annotate expressions with their type, it is possible for TXL to perform complex semantic type analysis. In the case of a dynamic language, a TXL definition of the base language, such as python, would be developed, followed by the addition of the typing syntactic structures in the dialect.

Much like Spoofax, and despite the use of Turing in its name, TXL is a generic framework for extending languages, and is not specific to the Turing Programming Language. With TXL it is possible to manipulate and generate code in many different programming languages.

Unlike Spoofax, TXL doesnt provide an immediate tool for integration into an IDE, but with a language like Python, an extension to the open-source IDE IDLE to transform the language before running it shouldnt be too difficult to add, and could create a very integrated experience which will be familiar when the student moves away from the statically typed subset to taking advantage of the entire language.

The Rascal meta-programming Language [24], [8] is an attempt to develop a standard language for all forms of program analysis, parsing, and code generation. It provides a single set of abstractions for creating static analyses for existing programming languages, performing automated code refactorings with understanding of the semantic meaning of the underlying code, and generating DSLs (Domain Specific

Languages) which compile to an underlying language. Like Spoofax, the programs written in Rascal can also be connected to an IDE, to provide auto-completion and features like go-to-definition to developers in the IDE, which is a very useful feature for developing a teaching language. The unified structure provides an advantage for the development of

In addition Rascal comes with parsers for existing languages, such as Java, which can allow for the easy creation of extra tooling or language features which build on top of existing language parsers, limiting the amount of development which is necessary in order to add a new feature to a programming language. This means that new features can be added to a language like Java with relative ease, by defining the new language feature in terms of features in the base language. While there are existing libraries for parsing many languages, Python is supported, which means that a new library will have to be implemented in Rascal for this project if Python is chosen as the target language, and Rascal as the transpilation framework.

If were OK with building the analysis upon other languages, we might want to take a look at the Scheme programming language [17]. The Scheme programming language takes a different approach to language extension then the approaches taken by Spoofax and TXL: namely, instead of starting from a complex language syntax and extending it, it starts with an extremely simple syntax - that of S-expressions, and defines the entire language in terms of them. In scheme, the statement ‘if‘ looks like ‘(if THEN ELSE)‘ which is identical to the appearance of a function call with two arguments ‘(func ARG1 ARG2)‘. This uniform syntax allows for very easy to use macros. Scheme defines macros like a special function type which is evaluated outside-in at compile-time. When the macro is invoked, the AST of the arguments

is provided to the macros implementation, which is then given the opportunity to emit arbitrary code as output. In addition, Scheme comes with a powerful macro-by-example system called define-syntax, which allows for syntactic patterns to be defined and matched against, along with simple syntax for defining the resulting meaning in a declarative manner. In addition, scheme macros implement hygiene, which means that they can internally use identifiers without the risk of the identifiers conflicting with identifiers found at the use-sites of the macro [18].

This is a very powerful approach, as it allows defining brand new language constructs which look nearly identical to the built-in language constructs directly within the language itself. Unfortunately, it is a relatively poor tool for defining brand new languages. While it is possible to define many new language concepts, the syntax is constrained to use s-expressions, and certain keywords are defined by the core language implementation, and cannot be re-defined by macros. Thus, schemes macro system is a very powerful system for language extension, but is incapable of defining arbitrary new languages.

However, we are not aiming to create an arbitrary new language, we are looking to extend the language with type checking. Unfortunately Scheme doesnt come with the best tools for the job here, as the program as a unit is not implicitly wrapped in a macro, which means that it is not possible in the generic case to perform full-program transformations. However, if an implicit outer macro invocation was created, it would be possible to define a macro transformation which would generate valid Scheme, and which would perform type checking. Unfortunately, however, much of the benefits of the modular scheme approach would not be able to be taken, and the macro would effectively amount to a partial compiler implementation.

In addition, Scheme has the disadvantage of, while it has a somewhat significant library collection, lacking the industry presence which we are looking for to make the language more appealing to students, and a better stepping stone to real projects. These factors make Scheme a poor choice for this project.

The Julia Programming Language [14], [3], much like in the Scheme programming language, allows programmers to manipulate the AST of Julia programs. However, unlike Scheme, Julia doesnt limit its program syntax to only take the form of s-expressions, rather the syntax takes the form of arbitrary Julia syntactic structures. The syntax for Julias macro expressions, however, are limited. Macro names must be prefixed by the @ sign, distinguishing them from native language constructs. In addition they must take one of two forms, either '@name a1 a2 ' or '@name(a1, a2,)'. Much like Schemes macros, Julias macros are hygienic, and do not pollute the call sites identifier space. The arguments which are passed to the the Julia function take the form of julia expression AST nodes.

In addition to Julias macros, Julia also supports generated functions. Generated functions are formed using the @generated macro, which annotates a function declaration. Wherever a generated function is called, the generated functions body is called, and passed the computed types of the arguments. The function is then able to generate custom logic which will be executed when the function is called at run-time. This is very similar in concept to generic functions in other languages such as C++, except instead of writing the code generation logic in a declarative system such as C++s template syntax, generated function code generation logic is instead written directly in Julia. This is extremely useful for writing complex generic functions which

need to have custom functionality based on types which would be difficult or impossible to express under a more limited system. Combined with Julias macros, this provides Julia with a very powerful meta-programming story. However, as is the case with Scheme, Julia is limited in that it is not possible to define a completely distinct language with only these constructs, as the syntactic transformations which may be performed are limited.

Julia is also a type-safe language, and has remarkably good error messages. Many of the type-checking semantics and error messages which Julia provides could be used as guides for the target behavior of whatever mechanism is chosen. Unfortunately, we do not believe that Julia does a good job of filling this role, as it lacks the libraries and production usage of other languages like Python due to its young age. However, we could see Julia potentially being used in the future for teaching programming concepts.

Another area of CS research related to program transformation is the area of Aspect Oriented Programming. In the Aspect Oriented Programming paradigm, programs are described in two parts: the main program, which describes the primary business logic, and a set of cross-cutting concerns or aspects [23]. The aspect interpreter or compiler then executes the main program, interleaving the aspect logic whenever certain pointcuts (language structures) are reached in execution. For example, an aspect may bind to method calls on a database object, causing a logging operation to take place whenever one of these calls is made. This technology can also be used by language developers which wish to make changes to the basic semantics of the target language. By binding and executing different instructions before and after pointcuts in the program using an aspect oriented interleaver, the semantics

of individual instructions can be modified without needing to change the languages structure, allowing new languages to be defined with different semantics, but the same syntax, as other languages.

This form of transformation, however, is not the type of language transformation that we need for this project. Our goal is to avoid changing the semantics of the language while providing additional analysis at compile time, which takes advantage of new syntax. For this reason, the technologies used by aspect oriented programming will be unlikely to be very useful in this project.