XL

An extensible programming language

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XL is an extensible programming language, designed to accomodate a variety of programming needs with ease.

Being *extensible* means that the language is designed to make it very easy for programmers to adapt the language to suit their needs, for example by adding new programming constructs. In XL, extending the language is a routine operation, much like adding a function or creating a class in more traditional programming languages. This extensibility is demonstrated by the fact that operations that are built-in in other programming languages, such as integer arithmetic, basic types or loops, are part of the standard library in XL.

As a consequence of this extensibility, XL is intended to be suitable for programming tasks ranging from the simplest to the most complex, from documents and application scripting, as illustrated by Tao3D, to compilers, as illustrated by the XL2 self-compiling compiler to distributed programming, as illustrated by ELFE.

> ⚠ XL is a work in progress. Even if there are some bits and pieces that happen to already work, and even if there were fully functioning releases like the XL version used in Tao3D in the past, XL is being totally reworked, and the compiler in this repository is presently not suitable for any serious programming. Examples given below may sometimes simply not work. Take it as a painful reminder that the work is far from finished, and, who knows, as an idea for a contribution. See HISTORY for how we came to the present mess. The README gives a quick overview of the language.

Chapter 1. Introduction to XL

Extensible? What does that mean for a programming language? For XL, it really means three things:

1. XL has a method to extend the language with any kind of feature, not just functions or data types, but also programming constructs, optimizations, domain-specific notations, and more. Actually, all this is done with a single operator, `is`, called the *definition operator*.
2. As a validation of the concept, most features that are built-in in other programming languages, like the `while` loop, or integer arithmetic, are *constructed* in XL. Specifically, they are provided by the standard library, using techniques that any programmer can use in their program. This, obviously, means that programmers can add their own loops, or their own machine-level data types, and even extend existing ones.
3. XL provides complete control over the program translation process. This means that libraries exist or can be written to make XL at least as good as C for low-level bit-twiddling, at least as good as C++ for generic algorithms, at least as good as Ada for tasking, at least as good as Fortran for numerical algorithms, at least as good as Java for distributed programming, and so on.

This may all seem too good to be true. This document explains how the magic happens. But first of all, one thing that really matters: XL is supposed to be *simple*. Let's start with a few well-known examples to prove this.

1.1. Two basic examples

It is practically compulsory to begin the presentation of any programming language with a "Hello World" example, immediately followed by a a recursive definition of the factorial function. Let's follow this long honored tradition.

1.1.1. Hello World

In XL, a program that prints `Hello World` on the terminal console output will look like this:

```
use XL.CONSOLE.TEXT_IO
print "Hello World"
```

The first line *imports* the `XL.CONSOLE.TEXT_IO` module. The program can then use the `print` function from that module to write the text on the terminal console.

Why do we need the `use` statement? There is a general rule in XL that you only pay for things that you use. Not all programs will use a terminal console, so the corresponding functions must be explicitly imported into a program. It is possible that some systems, like embedded systems, don't even have a terminal console. On such a system, the corresponding module would not be available, and the program would properly fail to compile.

What is more interesting, though, is the definition of `print`. That definition is discussed below, and you will see that it is quite simple, in particular when compared with similar input/output operations in languages such as C++.

1.1.2. Factorial

A program computing the factorial of numbers between 1 and 5, and then showing them on the console, can be written as follows:

```
use IO = XL.CONSOLE.TEXT_IO

0! is 1
N! is N * (N-1)!

for I in 1..5 loop
    IO.print "The factorial of ", I, " is ", I!
```

We have used an alternative form of the `use` statement, where the imported module is given a local nick-name, `IO`. This form is useful when it's important to avoid the risk of name collisions between modules. In that case, the programmer need to refer to the `print` function of the module as `IO.print`.

The definition of the factorial function shows how expressive XL is, making it possible to use the well-known notation for the factorial function. The definition consists in two parts:

- the special case of the factorial of `0` is defined as follows:

  ```
  0! is 1
  ```

- the general case is defined as follows, and involves a recursion in the form of the `(N-1)!` expression:

  ```
  N! is N * (N-1)!
  ```

That definition would not detect a problem with something like `-3!`. The second form would match, and presumably enter an infinite recursion that would exhaust available stack space. It is possible to fix that problem by indicating that the definition only works for positive numbers:

```
0!              is 1
N!  when N > 0  is N * (N-1)!
```

Writing the code that way will ensure that there is a compile-time error for code like `-3!`, because there is no definition that matches.

1.2. One operator to rule them all

XL has a single fundamental operator, `is`, called the *definition operator*. It is an infix operator with a pattern on the left and an implementation on the right. In other words, the pattern for the infix `is` is `Pattern is Implementation`, where `Pattern` is a program pattern, like `X+Y`, and `Implementation` is an implementation for that pattern, for example `Add X, Y`. This operator can also be read as *transforms into*, i.e. it transforms the code that is on the left into the code that is on the right.

This single operator can be used to define all kinds of entities.

Example 1. Simple variables or constants

```
pi              is      3.1415926
```

Example 2. Lists or data structures

```
funny_words     is      "xylophage", "zygomatic", "barfitude"
identity_matrix is
    [ [1, 0, 0],
      [0, 1, 0],
      [0, 0, 1] ]
```

Example 3. Functions

```
abs X:number    is      if X < 0 then -X else X
```

Example 4. Operators

```
X ≠ Y           is      not X = Y
```

Example 5. Specializations for particular inputs

```
0!              is      1
N!  when N > 0  is      N * (N-1)!
```

Example 6. Notations using arbitrary combinations of operators

```
A in B..C       is      A >= B and A <= C
```

Example 7. Optimizations using specializations

```
X * 1           is      X
X + 0           is      X
```

Example 8. Program structures

```
loop Body       is      Body; loop Body
```

Example 9. Types type

```
type complex    is      polar or cartesian
type cartesian  is      cartesian(re:number, im:number)
type polar      is      polar(mod:number, arg:number)
```

types in XL indicate the shape of parse trees. In other words, the `cartesian` type above will match any parse tree that takes the shape of the word `cartesian` followed by two numbers, like for example `cartesian(1,5)`.

Example 10. Higher-order functions, i.e. functions that return functions

```
adder N         is      { lambda X is N + X }
add3            is      adder 3

 // This will compute 8
 add3 5
```

The notation `lambda X`, which can also be written `\X`, is inspired by lambda calculus. It makes it possible to create patterns that match entire expressions. In other words, `X is 0` defines a name, and only the expression `X` matches that definition, whereas `\X is 0` defines a "catch-all" pattern that will match `35` or `"ABC"`. This *lambda notation* can be used to build something that behaves almost exactly like an *anonymous function* in functional languages, although the way it actually works internally is still based on pattern matching.

> The current implementations of XL special-case single-defintion contexts, and `lambda` can be omitted in that case. In a normal context, `X is Y` defines a name `X`, but it did not seem very useful to have single-definition contexts defining only a name. The above example could have been written as:
>
> ```
> adder N is (X is N + X)
> ```
>
> However, this is not consistent with the rest of the language, and `lambda` will be required in future implementations.

Example 11. Maps that associate a key to a value

```
my_map is
    0 is 4
    1 is 0
    8 is "World"
    27 is 32
    lambda N when N < 45 is N + 1

// The following is "World"
my_map 8

// The following is 32
my_map[27]

// The following is 45
my_map (44)
```

This provides a functionality roughly equivalent to `std::map` in C++. However, it's really nothing more than a regular function with a number of special cases. The compiler can optimize special kinds of mapping to provide an efficient implementation, for example if all the indexes are contiguous integers.

Example 12. Templates (C++ terminology) or generic code (Ada terminology)

```
// An (inefficient) implementation of a generic 1-based array type
type array [1] of T is
    Value : T
    1 is Value
type array [N] of T when N > 1 is
    Head  : array[N-1] of T
    Tail  : T
    lambda I when I<N is Head[I]
    lambda I when I=N is Tail

A : array[5] of integer
for I in 1..5 loop
    A[I] := I * I
```

Example 13. Variadic functions

```
min X, Y    is { Z is min Y; if X < Z then X else Z }
min X       is X

// Computes 4
min 7, 42, 20, 8, 4, 5, 30
```

In short, the single `is` operator covers all the kinds of declarations that are found in other languages, using a single, easy to read syntax.

1.3. The standard library

Each programming language offers a specific set of features, which are characteristic of that language. Most languages offer integer arithmetic, floating-point arithmetic, comparisons, boolean logic, text manipulation (often called "*strings*"), but also programming constructs such as loops, tests, and so on.

XL provides most features programmers are used to, but they are defined in the XL *standard library*, not by the compiler. The standard library is guaranteed to be present in all implementations and behave identically. However, it is written using only tools that are available to a regular developer, not just to compiler writers.

1.3.1. Usual programming features

Definitions in the standard library include common fixtures of programming that are built-in in other languages, in particular well-known programming constructs such as loops, tests, and so on.

For example, the *if statement* in XL is defined in the standard library as follows:

```
if [[true]]  then TrueClause else FalseClause   is TrueClause   ①
if [[false]] then TrueClause else FalseClause   is FalseClause
if [[true]]  then TrueClause                    is TrueClause
if [[false]] then TrueClause                    is false
```

① A value between two square brackets, as in `[[true]]` and `[[false]]`, is called a metabox. It indicates that the pattern must match the actual values in the metabox. In other words, `foo true is ...` defines a pattern with a formal parameter named `true`, whereas `foo [[true]] is ...` defines a pattern which only matches when the argument is equal to constant `true`.

Similarly, the `while` loop is defined as follows:

```
while Condition loop Body is
    if Condition then
        Body
        while Condition loop Body
```

With the definitions above, programmers can then use `if` and `while` in their programs much like they would in any other programming language, as in the following code that verifies the Syracuse conjecture:

```
while N <> 1 loop
    if N mod 2 = 0 then
        N /= 2
    else
        N := N * 3 + 1
    print N
```

1.3.2. The next natural evolutionary step

Moving features to a library is a natural evolution for programming languages. Consider for example the case of text I/O operations. They used to be built-in for early languages such as BASIC's `PRINT` or Pascal's `WriteLn`, but they moved to the library in later languages such as C with `printf`. As a result, C has a much wider variety of I/O functions. The same observation can be made on text manipulation and math functions, which were all built-in in BASIC, but all implemented as library functions in C. For tasking, Ada has built-in construct, C has the `pthread` library. And so on.

Yet, while C moved a very large number of things to libraries, it still did not go all the way. The meaning of `x+1` in C is defined strictly by the compiler. So is the meaning of `x/3`, even if some implementations that lack a hardware implementation of division have to make a call to a library function to actually implement that code.

C++ went one step further than C, allowing programmers to *overload* operators, i.e. redefine the meaning of an operation like `X+1`, but only for custom data types, and only for already existing operators. In C++, a programmer cannot *create* the *spaceship operator* `<=>` using the standard language mechanisms. It has to be implemented in the compiler. The spaceship operator has to be added to the language by compiler writers, and it takes a 35-pages article to discuss the implications. This takes time and a large effort, since all compiler writers must implement the same thing.

By contrast, all it takes in XL to implement `<=>` in a variant that always returns `-1`, `0` or `1` is the following:

```
syntax { INFIX 290 <=> }
X <=> Y     when X < Y  is -1
X <=> Y     when X = Y  is  0
X <=> Y     when X > Y  is  1
```

Similarly, C++ makes it extremely difficult to optimize away an expression like `X*0`, `X*1` or `X+0` using only standard programming techniques, whereas XL makes it extremely easy:

```
X*0     is 0
X*1     is X
X+0     is X
```

Finally, C++ also makes it very difficult to deal with expressions containing multiple operators. For example, many modern CPUs feature a form of fused multiply-add, which has benefits that include performance and precision. Yet C++ will not allow you to overload `X*Y+Z` to use this kind of operations. In XL, this is not a problem at all:

```
X*Y+Z   is FusedMultiplyAdd(X,Y,Z)
```

In other words, the XL approach represents the next logical evolutionary step for programming languages along a line already followed by highly-successful ancestors.

1.3.3. Benefits of moving features to a library

Putting basic features in the standard library, as opposed to keeping them in the compiler, has several benefits:

1. Flexibility: It is much easier to offer a large number of behaviors and to address special cases.
2. Clarity: The definition given in the library gives a very clear and machine-verifiable description of the operation.
3. Extensibility: If the library definition is not sufficient, it is possible to add what you need. It will behave exactly as what is in the library. If it proves useful enough, it may even make it to the standard library in a later iteration of the language.
4. Fixability: Built-in mechanisms, such as library versioning, make it possible to address bugs without breaking existing code, which can still use an earlier version of the library.

The XL standard library consists of a wide variety of modules. The top-level module is called `XL`, and sub-modules are categorized in a hierarchy. For example, if you need to perform computations on complex number)s, you would `use XL.MATH.COMPLEX` to load the complex numbers module

The library builtins is a list of definitions that are accessible to any XL program without any explicit `use` statement. This includes most features that you find in languages such as C, for example integer arithmetic or loops. Compiler options make it possible to load another file instead, or even to load no file at all, in which case you need to build everything from scratch.

1.3.4. The case of text input / output operations

Input/output operations (often abbreviated as I/O) are a fundamental brick in most programming languages. In general, I/O operations are somewhat complex. If you are curious, the source code for the venerable `printf` function in C is available online.

The implementation of text I/O in XL is comparatively very simple. The definition of `print` looks something like, where irrelevant implementation details were elided as ⋯:

```
write X:text            as fallible     is ... ①
write X:integer         as fallible     is ...
write X:real            as fallible     is ...
write X:character       as fallible     is ...
write [[true]]                          is write "true" ②
write [[false]]                         is write "false"
write Head, Rest                        is write Head; write Rest

print                   as fallible     is write SOME_NEWLINE_CHARACTER
print Items                             is write Items; print
```

① The fallible type is used to represent the `nil or error` type, in other words it indicates that the function either returns nothing, or returns an error.

② The `[[true]]` notation is called a metabox, and indicates that we must match the value of the expression in the metabox, in that case, `true`.

This is an example of *variadic function definition* in XL. In other words, `print` can take a variable number of arguments, much like `printf` in C. You can write multiple comma-separated items in a `print`. For example, consider the following code:

```
print "The value of X is ", X, " and the value of Y is ", Y
```

That would first call the last definition of `print` with the following binding for the variable `Items`:

```
Items   is "The value of X is ", X, " and the value of Y is ", Y`
```

This in turn is passed to `write`, and the definition that matches is `write Head, Rest` with the following bindings:

```
Head    is "The value of X is "
Rest    is X, " and the value of Y is ", Y
```

In that case, `write Head` will directly match `write X:text` and write some text on the console. On the other hand, `write Rest` will need to iterate once more through the `write Head, Rest` definition, this time with the following bindings:

```
Head    is X
Rest    is " and the value of Y is ", Y
```

The call to `write Head` will then match one of the implementations of `write`, depending on the actual type of `X`. For example, if `X` is an integer, then it will match with `write X:integer`. Then the last split occurs for `write Rest` with the following bindings:

```
Head    is " and the value of Y is "
Rest    is Y
```

For that last iteration, `write Head` will use the `write X:text` definition, and `write Rest` will use whatever definition of `write` matches the type of `Y`.

All this can be done at compile-time. The generated code can then be reused whenever the combination of argument types is the same. For example, if `X` and `Y` are `integer` values, the generated code could be used for

```
print "The sum is ", X+Y, " and the difference is ", X-Y
```

This is because the sequence of types is the same. Everything happens as if the above mechanism had created a series of additional definition that looks like:

```
print A:text, B:integer, C:text, D:integer is
    write A, B, C, D
    print

write A:text, B:integer, C:text, D:integer is
    write A
    write B, C, D

write B:integer, C:text, D:integer is
    write B
    write C, D

write C:text, D:integer is
    write C
    write  D
```

All these definitions are then available as shortcuts whenever the compiler evaluates future function calls.

The `print` function as defined above is both type-safe and extensible, unlike similar facilities found for example in the C programming language.

It is type-safe because the compiler knows the type of each argument at every step, and can check that there is a matching `write` function.

It is extensible, because additional definitions of `write` will be considered when evaluating `write Items`. For example, if you add a `complex` type similar to the one defined by the standard library, all you need for that type to become "writable" is to add a definition of `write` that looks like:

```
write Z:complex     is write "(", Z.Re, ";", Z.Im, ")"
```

Unlike the C++ `iostream` facility, the XL compiler will naturally emit less code. In particular, it will need only one function call for every call to `print`, calling the generated function for the given combination of arguments. That function will in turn call other generated functions, but the code sequence corresponding to a particular sequence of arguments will be factored out between all the call sites, minimizing code bloat.

Additionally, the approach used in XL makes it possible to offer specific features for output lines, for example to ensure that a single line is always printed contiguously even in a multi-threaded scenario. Assuming a `single_thread` facility ensuring that the code is executed by at most one thread, creating a locked `print` is nothing more than:

```
locked_print Items is
    single_thread
         print Items
```

It is extremely difficult, if not impossible, to achieve a similar effect with C++ `iostream` or, more generally, with I/O facilities that perform one call per I/O item. That's because there is no way for the compiler to identify where the "line breaks" are in your code.

1.4. Efficient translation

Despite being very high-level, XL was designed so that efficient translation to machine code was possible, if sometimes challenging. In other words, XL is designed to be able to work as a *system language*, in the same vein as C, Ada or Rust, i.e. a language that can be used to program operating systems, system libraries, compilers or other low-level applications.

For that reason, nothing in the semantics of XL mandates complex behind-the-scene activites, like garbage collection, thread safety, or even memory management. As for other aspects of the language, any such activity has to be provided by the library. You only pay for it if you actually use it. In other words, the only reason you'd ever get garbage collection in an XL program is if you explicitly need it for your own application.

This philosophy sometimes requires the XL compiler to work extra hard in order to be more than minimally efficient. Consider for example the definition of the `while` loop given above:

```
while Condition loop Body is
    if Condition then
        Body
        while Condition loop Body
```

That definition can be used in your own code as follows:

```
while N <> 1 loop
    if N mod 2 = 0 then N /= 2 else N := N * 3 + 1
```

What happens is that the compiler looks at the code, and matches against the definitions at its disposal. The `while` loop in the code matches the form `while Condition loop Body`, provided you do the following bindings:

```
Conditions is N <> 1
Body is
   if N mod 2 = 0 then N /= 2 else N := N * 3 + 1
```

The definition for the `while Condition loop Body` form is then evaluated with the above bindings, in other words, the code below then needs to be evaluated:

```
    if Condition then
        Body
        while Condition loop Body
```

Conceptually, that is extremely simple. Getting this to work well is of course a little bit complicated. In particular, the definition ends with another reference to `while`. If the compiler naively generates a *function call* to implement a form like that, executing that code would likely run out of stack space for loops with a large number of iterations. A special optimization called *tail call elimination* is required to ensure the expected behavior, namely the generation of a machine branch instruction instead of a machine call instruction.

Furthermore, the reference implementation is just that, a reference. The compiler is perfectly allowed, even encouraged, to "cheat", i.e. to recognize common idioms, and efficiently translate them. One name, `builtin`, is reserved for that purpose. For example, the definition of integer addition may look like this:

```
X:integer + Y:integer as integer    is builtin Add
```

The left part of `is` here is perfectly standard XL. It tells the compiler that an expression like `X+Y` where both `X` and `Y` have the `integer` type will result in an `integer` value (that is the meaning of `as integer`). The implementation, however, is not given. Instead, the `builtin Add` tells the compiler that it has a cheat sheet for that operations, called `Add`. How this cheat sheet is actually implemented is not specified, and depends on the compiler.

1.5. Adding complex features

Features can be added to the language that go beyond a simple notation. This can also be done in XL, although this may require a little bit of additional work. This topic cannot be covered extensively here. Instead, examples from existing implementations will provide hints of how this can happen.

1.5.1. Reactive programming in Tao3D

Reactive programming is a form of programming designed to facilitate the propagation of changes in a program. It is particularly useful to react to changes in a user interface.

Tao3D added reactive programming to XL to deal with user-interface events, like mouse movements or keyboard input. This is achieved in Tao3D using a combination of *partial re-evaluation* of programs in response to *events* sent by functions that depend on user-interface state.

For example, consider the following Tao3D program to draw the hands of a clock (see complete YouTube tutorial for more details):

```
locally
    rotate_z -6 * minutes
    rectangle 0, 100, 15, 250

locally
    rotate_z -30 * hours
    rectangle 0, 50, 15, 150

locally
    color "red"
    rotate_z -6 * seconds
    rectangle 0, 80, 10, 200
```

The `locally` function controls the scope of partial re-evaluation. Time-based functions like `minutes`, `hours` or `seconds` return the minutes, hours and seconds of the current time, respectively, but also trigger a time event each time they change. For example, the `hours` function will trigger a time event every hour.

The `locally` function controls partial re-evaluation of the code within it, and caches all drawing-related information within it in a structure called a *layout*. There is also a top-level layout for anything created outside of a `locally`.

The first time the program is evaluated, three layouts are created by the three `locally` calls, and populated with three rectangles (one of them colored in red), which were rotated along the Z axis (perpendicular to the screen) by an amount depending on time. When, say, the `seconds` value changes, a time event is sent by `seconds`, which is intercepted by the enclosing `locally`, which then re-evaluated its contents, and then sends a redraw event to the enclosing layout. The two other layouts will use the cached graphics, without re-evaluating the code under `locally`.

All this can be implemented entirely within the constraints of the normal XL evaluation rules. In other words, the language did not have to be changed in order to implement Tao3D.

1.5.2. Declarative programming in Tao3D

Tao3D also demonstrates how a single language can be used to define documents in a way that feels declarative like a declarative language, i.e._similar to HTML, but still offers the power of imperative programming like JavaScript, as well as style sheets reminiscent of CSS. In other words, Tao3D does with a single language, XL, what HTML5 does with three.

For example, an interactive slide in Tao3D would be written using code like this (note that Tao3D uses `import` instead of `use`):

```
import Slides

slide "The XL programming language",
    * "Extensible"
    * "Powerful"
    * "Simple"
```

This can easily be mis-interpreted as being a mere markup language, something similar to markdown, which is one reason why I sometimes refer to XL as an *XML without the M*.

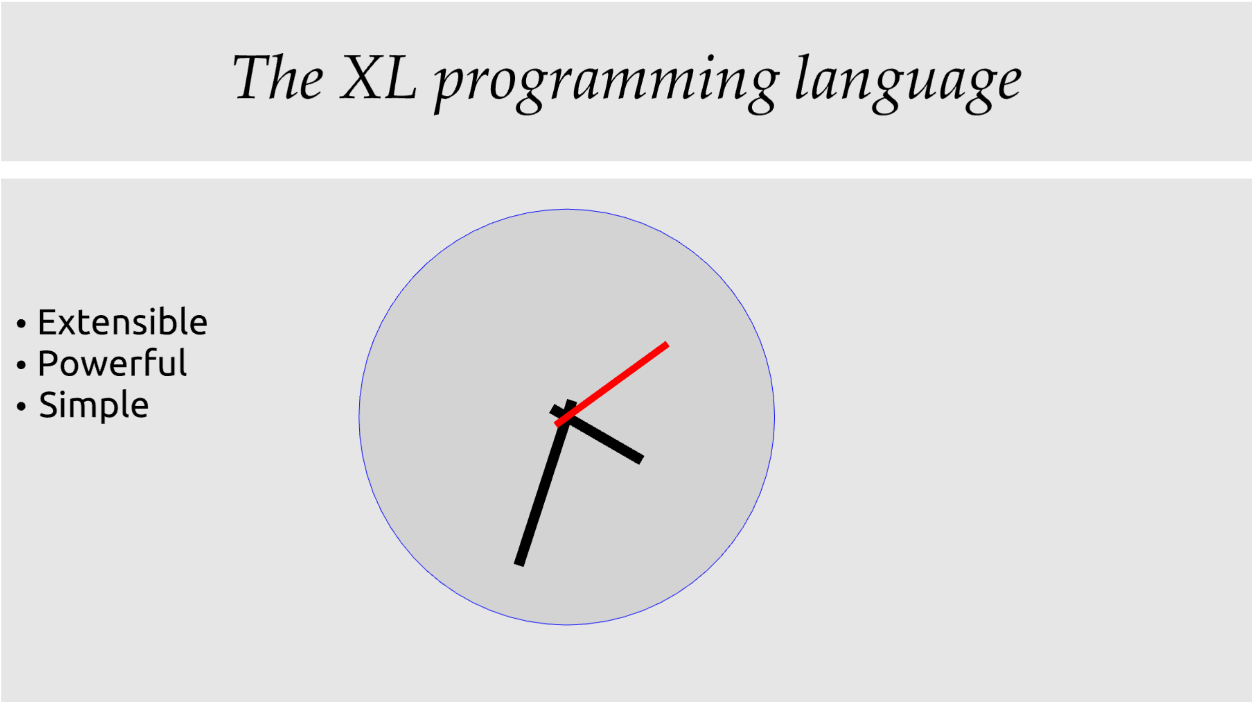
However, the true power of XL can more easily be shown by adding the clock defined previously, naming it `clock`, and then using it in the slide. This introduces the dynamic aspect that Javascript brings to HTML5.

```
import Slides

clock is
    locally
        line_color "blue"
        color "lightgray"
        circle 0, 0, 300

    locally
        rotate_z -6 * minutes
        rectangle 0, 100, 15, 250

    locally
        rotate_z -30 * hours
        rectangle 0, 50, 15, 150

    locally
        color "red"
        rotate_z -6 * seconds
        rectangle 0, 80, 10, 200

slide "The XL programming language",
    * "Extensible"
    * "Powerful"
    * "Simple"
    anchor
        translate_x 600
        clock
```

In order to illustrate how pattern matching provides a powerful method to define styles, one can add the following definition to the program in order to change the font for the titles (more specifically, to change the font for the "title" layouts of all themes and all slide masters):

```
theme_font Theme, Master, "title" is font "Palatino", 80, italic
```

The result of this program is an animated slide that looks like the following:



1.5.3. Distributed programming with ELFE

ELFE is another XL-based experiment targeting distributed programming, notably for the Internet of things. The idea was to use the homoiconic aspect of XL to evaluate parts of the program on different machines, by sending the relevant program fragments and the associated data over the wire for remote evaluation.

> ELFE is now integrated as part of XL, and the ELFE demos are stored in the demo directory of XL.

This was achieved by adding only four relatively simple XL functions:

- `tell` sends a program to another node in a "fire and forget" way, not expecting any response.
- `ask` evaluates a remote program that returns a value, and returns that value to the calling program.
- `invoke` evaluates a remote program, establishing a two-way communication with the remote that the remote can use with `reply`
- `reply` allows remote code within an `invoke` to evaluate code in its original caller's context, but with access to all the local variables declared by the remote.

Consider the following program:

```
WORKER_1 is "pi2.local"
WORKER_2 is "pi.local"

invoke WORKER_1,
   every 1.1s,
        rasp1_temp is
            ask WORKER_2,
                temperature
        send_temps rasp1_temp, temperature

   send_temps T1:real, T2:real is
       if abs(T1-T2) > 2.0 then
           reply
               show_temps T1, T2

show_temps T1:real, T2:real is
    print "Temperature on pi is ", T1, " and on pi2 ", T2, ". "
    if T1>T2 then
        print "Pi is hotter by ", T1-T2, " degrees"
    else
        print "Pi2 is hotter by ", T2-T1, " degrees"
```

This small program looks like a relatively simple control script. However, the way it runs is extremely interesting.

1. This single program actually runs on three different machines, the original controller, as well as two machines called `WORKER_1` and `WORKER_2`.
2. It still looks and feels like a single program. In particular, variables, values and function calls are passed around machines almost transparently. For example
   - the computation `T1-T2` in `send_temps` is performed on `WORKER_1`…
   - … using a value of `T1` that actually came from `WORKER_2` through the `ask` statement in `rasp1_temp`.
   - Whenever the `reply` code is executed, variable `T1` and `T2` live on `WORKER_1`…
   - … but within the `reply`, they are passed transparently as arguments in order to call `show_temps` on the controller.
3. Communication occurs primarily between `WORKER_1` and `WORKER_2`, which exchange a message every 1.1s. Communication with the controller only occurs if and when necessary. If the controller resides in Canada and the workers in Australia, this can save substantial networking costs.
4. A single `temperature` function, with an extremely simple implementation, provides an remarkably rich set of remotely-accessible features that might require a very complex API in other languages.

This last point is worth insisting on. The following program uses the same function to compute the minimum, maximum and average temperature on the remote node. Nothing was changed to the temperature API. The computations are performed efficiently by the remote node.

```
invoke "pi.local",
    min   is 100.0
    max   is 0.0
    sum   is 0.0
    count is 0

    compute_stats T:real is
        min   := min(T, min)
        max   := max(T, max)
        sum   := sum + T
        count := count + 1
        reply
            report_stats count, T, min, max, sum/count

    every 2.5s,
        compute_stats temperature

report_stats Count, T, Min, Max, Avg is
    print "Sample ", Count, " T=", T, " ",
          "Min=", Min, " Max=", Max, " Avg=", Avg
```

The definitions of `min`, `max`, `sum` and `count` would not be acceptable in the version of XL described in this document. You would need to write for example `min : real := 100` instead of `min is 100.0`, since `min is 100.0` would declare a constant.

To run the ELFE demos, you need to start an XL server on the machines called `pi.local` and `pi2.local`, using the `-remote` command-line option of XL:

```
% xl -remote
```

You can then run the program on a third machine with:

```
% xl 7-two-hops.xl
```

Like for Tao3D, the implementation of these functions is not very complicated, and more importantly, it did not require any kind of change to the basic XL evaluation rules. In other words, adding something as sophisticated as transparently distributed progrmming to XL can be done by practically any programmer, without changing the compiler.

Chapter 2. XL syntax

For programmers familiar with other programming languages, the syntax of XL may not seem very innovative at first, and that is intentional. Most programmers should be able to read and write correct XL code in a matter of minutes.

The first noticable thing is a disturbing lack of all these nice semi-random punctuation characters that have decorated programs since the dawn of computing and make most source code look like an ornate form of line noise to the uninitiated. Where are all the parentheses gone? Why this horrible lack of curly braces? How can you make sense of a program without a semi-colon to terminate or separate statements?

In reality, the difference between XL syntax and earlier programming languages is much more than skin deep. The syntax of XL is actually one of its most unique characteristics. The design of the XL syntax is essential to understand both the philosophy and implementation of the whole language.

2.1. Homoiconic representation of programs

XL is a homoiconic language, meaning that all XL programs are data and conversely. This makes it particularly easy for programs to manipulate programs, an approach sometimes referred to as *metaprogramming*. Metaprogramming is the foundation upon which the touted extensibility of XL is built.

2.1.1. Why Lisp remains so strong to this day

In that respect, XL is very much inspired by one of the earliest and most enduring high-level programming languages, Lisp. The earliest implementations of Lisp date back to 1958, yet that language remains surprisingly modern and flourishing today, unlike languages of that same era like Cobol or Fortran.

One reason for Lisp's endurance is the metaprogramming capabilities deriving from homoiconicity. If you want to add a feature to Lisp, all you need is to write a program that translates Lisp programs with the new feature into previous-generation Lisp programs. This kind of capability made it much easier to add object-oriented programming to Lisp than to languages like C: neither C++ nor Objective C were implemented as just another C library, and there was a reason for that. Unlike Lisp, these languages were not extensible.

Despite its strengths, Lisp remains confined to specific markets, in large part because to most programmers, the language remains surprisingly alien to this day, even garnering such infamous nicknames as "*Lots of Insipid and Stupid Parentheses*". As seen from a concept programming point of view, the underlying problem is that the Lisp syntax departs from the usual notations as used by human beings. For example, adding 1 and 2 is written `1+2` in XL, like in most programming languages, but `(+ 1 2)` in Lisp. In concept programming, this notational problem is called *syntactic noise*.

XL addresses this problem by putting human usability first. In that sense, it can be seen as an effort to make the power of Lisp more accessible. That being said, XL is quite a bit more than just Lisp with a new fancy and programmer-friendly syntax.

2.1.2. The XL parse tree

The XL syntax is much *simpler* than that of languages such as C, and arguably not really more complicated than the syntax of Lisp. The parser for XL is less than 800 lines of straightforward C++ code, and the scanner barely adds another 900 lines. By contrast, the C parser in GCC needs more than 20000 lines of code, which is about the size of a complete XL interpreter, and the C++ parser is over twice as much!

A key to keeping things really simple is that the XL syntax is *dynamic*. Available operators and their precedence are *configured* primarily through a syntax file. As a result, there are no hard-coded keywords or special operators in the XL compiler.

All XL programs can be represented with a very simple tree structure, called a *parse tree*. The XL parse tree contains four leaf node types (integer, real, text and name), and four inner node types (infix, prefix, postfix and block).

Leaf nodes contain values that are atomic as far as XL is concerned:

1. `integer` nodes represent integer values like `1234`, `2#1001` or `16#FFFE_FFFF`.
2. `real` nodes represent floating-point values like `1.234`, `1.5e-10` or `2#1.0001_0001#e24`.
3. `text` nodes represent text values like `"Hello world"` or `'A'`.
4. `name` node represent names like `ABC_DEF` or symbols like `<=>`.

Inner nodes contains combinations of other XL nodes:

1. `infix` nodes represent two operands separated by a name or symbol, like `A+B` or `X and Y`. Infix nodes with a "new line" name are used for separate program lines.
2. `prefix` nodes represent two nodes where the operand follows the operator, like `+A` or `sin X`.
3. `postfix` nodes represent two nodes where the operator follows the operand, like `3%` or `45km`.
4. `block` nodes represent a node surrounded by two delimiters, like `[a]`, `(a)`, `{a}`. Blocks are also used to represent indentation.

> This list of node types is what the current implementations of XL offer. Some changes may happen, notably:
>
> - Adding a "binary object" node type, which could be used to store binary data in the program. A possible syntax would be to prefix `bits` before a large integer value or file name:
>
> ```
> bits 16#FF_00_FF_00_FF_FF_00_FF_00
> bits "image.png"`
> ```
>
> - Finding a more efficient representation for large sequences of items. So far, attempts at finding such a representation came with an unacceptable cost, notably with respect to the generated code.

For example, let's consider the following code:

```
if X < 0 then
   print "The value of ", X, " is negative"
   X := -X
```

Assuming that this program is stored in a file called `program.xl`, the XL parse tree for this program can be obtained by using the following command:

```
% xl -parse program.xl -style debug -show
(infixthen
 (prefix
  if
  (infix<
   X
   0))
 (block indent
  (infix CR
   (prefix
    print
    (infix,
     "The value of "
     (infix,
      X
      " is negative"
     )))
   (infix:=
    X
    (prefix
     -
     X
    )))))
```

All of XL is built on this very simple data structure. Some choices, like having distinct `integer` and `real` node, were guided primarily by considerations beyond syntax, for example the need to be able to precisely define program evaluation or to represent distinct machine types.

Empty blocks are represented as a block with an "empty name" as a child. This is not very satisfactory. Alternatives such as representing blocks as possibly empty sequences of items have proven even more complicated, since the representation of [A,B,C] becomes ambiguous, and possibly more difficult to process in a generic way.

2.2. Syntax for XL nodes

The leaf nodes in XL all have a uniquely identifable syntax.

2.2.1. Number syntax

Numbers begin with a digit, i.e. one of `0123456789`.

A single underscore `_` character can be used to separate digits, as in `1_000_000`. The following are not valid XL numbers: `_1` (leading underscore), `2_` (trailing underscore), `3__0` (two underscores).

By default, numbers are written in base 10. Any other numerical base between 2 and 36 can be used, as well as base 64 using a special syntax. Based numbers can be written by following the base with the `#` sign. For example `8#76` is an octal representation of `62`.

For bases between 11 and 36, letters `A` through `Z` or `a` through `z` represent digit values larger than 10, so that `A` is 10, `f` is 15, `Z` is 35. Case does not matter. For example, `16#FF` and `16#ff` are two valid hexadecimal representation of `255`.

For base 64, Base64 encoding is used, and case matters. This is mostly indended for use in binary objects, i.e. after `bits`. For instance, `64#SGVsbG8h` is the base-64 encoding for the number with the same binary representation as the sequence of characters in `Hello!`.

There is an implementation-dependent limit for the maximum `integer` value. This limit cannot be less than the maximum value for a 2-complement 64-bit signed integer.

For real numbers, a dot `.` is used as decimal separator, and must separate digits. For example, `0.2` and `2.0` are valid but, unlike in C, `.2` and`2.` are not real numbers but a prefix and postifix dot respectively. Also note that the standard library denotes ranges using two dots, so `2..3` is an infix `..` with `2` and `3` as operands, representing the range between 2 and 3.

Both `integer` and `real` numbers can contain an exponent, specified by the letter `e` or `E`. If the exponent is negative, then the number is parsed as a real number. Therefore, `1e3` is integer value 1000, but `1e-3` is real value `0.001`. The exponent is always given in base 10, and it indicates an exponentiation in the given base, so that `2#1e8` is decimal value 256. For based numbers, the exponent may be preceded by a `#` sign, which is mandatory if `e` or `E` are valid digits in the base, as in `16#FF#e2` which represents decimal value 65280.

If a sign precedes a number, like `+3` or `-5.3`, it is parsed by the compiler as a prefix `+` or `-` and not as part of the number. It is possible, however, for an `integer` or `real` node to contain negative values as a result of program evaluation.

The various syntactic possibilities for XL numbers are only for convenience, and are all strictly equivalent as far as program execution is concerned. In other words, a program may not behave differently if a constant is spelled as `16#FF_FF` or as `65535`.

> One unsatisfactory aspect of XL number syntax is that it does not offer an obvious path to correctly represent "semantic" version numbers in the code. For example, a notation like `2.3.1` will parse as an infix `.` between real number `2.3` and integer `1`, making it indistinguishable from `2.30.1`.

2.2.2. Name and symbol syntax

Names in XL begin with an letter, followed by letters, symbols or digits. For example, `MyName` and `A22` are valid XL names.

A single underscore `_` can be used to separate two valid characters in a name. Therefore, `A_2` is a valid XL name, but `A__2` and `_A` are not.

> The current implementation reads its input in Unicode UTF-8 format, and makes crude attempts at accepting Unicode. This was good enough for Tao3D to deal with multi-lingual text, including in languages such as Hebrew or Arabic. However, that implementation is a bit naive with respect to filtering Unicode letters. For example, `▯_2` or `étalon` are valid XL names, and this is intentional, but `⇒A2` is presently a valid XL name, and this is considered a bug.

Case and delimiters are not significant in XL, so that `JOE_DALTON` and `JoeDalton` are treated identically.

> For historical reasons, the current implementations are quite lacking in that respect.

Symbols begin with one of the ASCII punctuation characters:

```
! # $ % & ( ) * + , - . / : ; < = > ? @ [ \ ] ^ _ ` { | } ~
```

Symbols longer than one character must be specified in the XL syntax file. For example, the XL syntax file defines a `<=` operator, but no `<=>` operator. Consequently, the sequence `1 <=> 2` will be parsed as `(1 <= (> 2))`. In order to add this operator, it is necessary to extend the syntax using a `syntax` statement.

Names and symbols are treated interchangeably by XL after the parsing phase.

2.2.3. Text syntax

Text in XL is delimited with a pair of single or double quotes. Text can contain any printable character. For example, `"Hello World"` or `'ABC'` are valid text in XL. If the delimiter is needed in the text, it can be obtained by doubling it. For example, `"He said ""Hello"""` is text containing `He said "Hello"`.

Additionally, the XL syntax file can specify delimiters for "long" text. Long text can include line-terminating characters, and only terminates when the matching delimiter is reached. By default, `<<` and `>>` are long-text delimiters, so that the following is valid text:

```
MyLongText is <<
   This is a multi-line text
   that contains several lines
>>
```

Additional separators can be configured, and can be used to define specific types of text. For example, a program that often has to manipulate HTML data could allow `HTML` and `END_HTML` as delimiters, so that you could write:

```
MyHTML is HTML
    <p>This is some HTML text here</p>
END_HTML
```

RATIONALE The reason for a built-in format for text using single or double quotes is because the syntax file is read using the standard XL parser, and it needs text tokens in some specific cases that would otherwise parse incorrectly such as block or comment delimiters.

2.2.4. Indentation and off-side rule

Indentation in XL is significant, and is parsed as a special kind of block. Individual program line are parsed as infix nodes with the first line as the left operand, and the second line as the right operand.

In other words, the two `loop` instructions below have exactly the same structure, except for the block delimiters (curly braces or indentation) and for the line-separating infix names (semi-colon or line terminator):

```
loop { Eat; Pray; Love }
loop
    Eat
    Pray
    Love
```

Indentation must use the same indentation character within a single file, either tab or space. In other words, either your whole file is indented with tabs, or it is indented with spaces, but it is a syntax error to mix both.

Indentation within a block must be consistent. For example, the following code will cause a syntax error because of the incorrect indentation of `Pray`:

```
loop
    Eat
   Pray
    Love
```

2.2.5. Operator precedence and associativity

The operators available for XL programmers are defined by the syntax file. The same rules apply for names or for symbols. The table given in this file uses keywords such as `INFIX`, `PREFIX` and `POSTFIX` to indicate if an operator is an infix, a prefix, or a postfix respectively.

The table also gives operators a precedence. For example, the following segment in the `INFIX` portion of the table indicates that `*` and `/` have higher precedence than `+` and `-`, so that `X+Y*Z` will parse as `X+(Y*Z)`:

```
        21      -> is has
        310     + -
        320     * / mod rem
```

The precedence also indicates associativity for infix operators. Even precedences indicate left associativity, as for `+` and `*` above. This means that `X * Y * Z` parses as `(X * Y) * Z`. Conversely, right-associativity is indicated by an odd precedence, as is the case for `is`. This means that `X is Y is Z` parses as `X is (Y is Z)`.

Enforcing different precedences for left and right associativity guarantees that it's impossible for operators to have the same precedence, with some being left-associative and some being right-associative, which would cause parsing ambiguities.

The syntax file uses a few special names:

- `INFIX`, `PREFIX`, `POSTFIX` and `BLOCK` introduce sections that declare the operators of the respective types.
- `COMMENT` and `TEXT` specify delimiters for comments and long text respectively.
- `SYNTAX` introduces a child syntax. It is followed by the name of a syntax file, and then by an opening and closing symbol for that syntax.
- `BINARY` specifies the names that introduce binary data. The default syntax file uses `bits`. The syntax for binary data can take one of two forms: either a very large integer constant in big-endian format, as in `bits 16#000102030405060708090A0B0C0D0E0F`, or the name of a file, as in `bits "image.png"`.
- `NEWLINE` is used to represent the infix operators that separates individual source code lines.
- `STATEMENT` is the precedence that delimits expressions from statements. Any operator with a lower precedence belongs to a statement, like `if` or `loop`. Any operator with a higher precedence belongs to an expression, like `+` or `*`.
- `DEFAULT` is the default precedence for names and symbols. It is not very important in practice.
- `FUNCTION` is the precedence for names and symbols used as a prefix when they are not explicitly listed in the file. If you write `sin X` for example, the associated precedence will be that of `FUNCTION`.

2.2.6. Delimiters

Additional sections of the syntax file define delimiters for comment, block and text. Comment and text delimiters come in pairs.

The default syntax file specifies comments that follow the C/C++ convention, i.e. comments either start with `/ and end with /` or start with `//` and end with a new line. The basic text separators (simple and double quotes) are not specified in the syntax file because they are used to parse the syntax file itself. The default syntax file adds `<<` and `>>` as separators for multi-line text..

Block separators come in pairs and have a priority. The special names `INDENT` and `UNINDENT` are used for the indentation block. The block priority is used to give the priority of the block in an expression, but also to determine if the block contains an expression or a statement.

In the default syntax file, indentation blocks and blocks delimited by curly braces `{ }` contain statements, whereas blocks delimited by parentheses `( )` or square brackets `[ ]` will contain expressions.

2.2.7. Child syntax

A syntax file can define a child syntax file, which overrides the syntax when a given name or symbol is found.

The default syntax file contains a child syntax named `C` which is activated between the `extern` name and a following semi-colon `;`. This is used to approximate C-style parsing for extern declarations, making it easier to reference C code from XL:

```
extern real sqrt(real);
```

> The so-called "C syntax" in XL is only a very crude and limited approximation of the actual C syntax, which is only intended for relatively simple function declarations.

2.2.8. Extending the syntax

The `syntax` name followed by a block can be used to alter the default syntax provided by the syntax file. Within the block, operators can be defined and their precedence given using the same rules as in the syntax file.

For example, if you want to add the spaceship operator `<=>` in your program, and give the same precedence as `⇐`, namely 290, you could write:

```
syntax
    INFIX 290 <=>
```

> Extending the syntax is intended to also work also in a module. This means that an `use` statement can alter the syntax in your source code. This is, however, rarely recommended. Also, importing a syntax extension does not presently work.

2.3. Making the syntax easy for humans

XL contains a couple of tweaks designed specifically to make code easier to read or write by humans. When the human logic is subtle, so is the XL compiler parsing…

2.3.1. Expression vs. statement

This first tweak is intended to put in XL an implicit grammatical grouping that humans apparently do. Consider for example the following:

```
print sin X, cos Y
```

Most human beings parse this as `print (sin(X),cos(Y))`, i.e. we call `print` with two values resulting from evaluating `sin X` and `cos Y`.

This is, however, not entirely logical. If `print` takes comma-separated arguments, why wouldn't `sin` also take comma-separated arguments? In other words, why doesn't this parse as `print(sin(X, cos(Y))`?

This shows that humans have a notion of *expressions* vs. *statements*. Expressions such as `sin X` have higher priority than commas and require parentheses if you want multiple arguments. By contrast, statements such as `print` have lower priority, and will take comma-separated argument lists. An indent or `{ }` block begins a statement, whereas parentheses `()` or square brackets `[]` begin an expression.

There are rare cases where the default rule will not achieve the desired objective, and you will need additional parentheses. One important such case is *expression statements*, i.e. statements that you would like to see as an expression. Consider the following two declarations:

```
debug X     is write "X=", X
expm1 X     is exp X - 1
```

The first example parses as intended, as a statement. The second one, however, is not, despite being syntactically similar. On could want to see this parse as `(exp X) -1`, but in reality, it parses as `exp (X-1)` for the same reason that the line above parses as `write ("X=", X)`.

The solution is to add parentheses around the expression, i.e. to write the body as `(exp X - 1)`. Generally, when you see statements between parentheses in XL, it is to indicate that they are expression statements.

2.3.2. infix vs. prefix

Another special rule is that XL will use the presence of a space on only one side of an operator to disambiguate between an infix or a prefix. For example:

```
write -A    // write (-A)
B - A       // (B - A)
```

Chapter 3. XL program evaluation

XL defines *program execution* primarily in terms of operations on the parse tree combined with operations on an implicit *context* that stores the program state. The context itself is also described in XL in order to define the expected result of evaluation.

For efficiency, actual implementations are unlikely to store everything as an actual parse tree, although there is an *interpreter* implementation that does exactly that. A compiler is more likely to optimize representations of both code and data, as long as that optimized representation ultimately respect the semantics described using the normal form for the parse tree.

3.1. Execution phases

Executing an XL program is the result of three phases,

1. A parsing phase where program source text is converted to a parse tree,
2. A declaration phase, where all declarations are stored in the context,
3. An evaluation phase, where statements other than declarations are processed in order.

The execution phases are designed so that in a very large number of cases, it is at least conceptually possible to do both the parsing and declaration phases ahead of time, and to generate machine code that can perform the evaluation phase using only representations of code and data optimized for the specific machine running the program. It should be possible to create an efficient ahead-of-time compiler for XL. Work is currently in progress to build one.

Reasonably efficient compilers were produced for earlier generations of the language, notably as part of the Tao3D project. However, this earlier iteration of the language had a very weak type system that made advanced optimizations hard to achieve. This was actually a feature for Tao3D, which purposely disabled some optimizations in order to improve compilation speed, notably when the program structure did not change. The version of XL described in this document, however, has markedly evolved relative to what was implemented in Tao3D, with the hope that much better code quality can be achieved. This part has not been demonstrated yet.

3.1.1. Execution context

The execution of XL programs is defined by describing the evolution of a particular data structure called the *execution context*, or simply *context*, which stores all values accessible to the program at any given time.

That data structure is only intended to explain the effect of evaluating the program. It is not intended to be a model of how things are actually implemented. As a matter of fact, care was taken in the design of XL to allow standard compilation and optimization techniques to remain applicable, and to leave a lot of freedom regarding actual evaluation techniques.

In the examples below, `CONTEXT0`, `CONTEXT1`, … will denote pseudo-variables that describe the various currently visible execution contexts, following the language scoping rules. The most recent contexts will have higher numbers. In addition, `HIDDEN0`, `HIDDEN1`, … will represent pending execution contexts that are invisible to the currently executing code. These are also known as *activation records*. Entries in `HIDDEN` contexts are live, but invisible to the current code. By convention, `CONTEXT0` and `HIDDEN0` are not defined in the examples and are assumed to be inherited from earlier execution.

> By default, the context of the caller is not visible to the callee. A feature making it visible if necessary is being considered, called *caller lookup*.

3.1.2. Parsing phase

The parsing phase reads source text and turns it into a parse tree using operator spelling and precedence information given in the syntax file. This results either in a parse-time error, or in a faithful representation of the source code as a parse tree data structure that can be used for program evaluation.

Since there is almost a complete equivalence between the parse tree and the source code, the rest of the document will, for convenience, represent a parse tree using a source code form. In the rare cases where additional information is necessary for understanding, it will be provided in the form of XL comments.

Beyond the creation of the parse tree, very little actual processing happens during parsing. There are, however, a few tasks that can only be performed during parsing:

1. Filtering out comments: Comments should not have an effect on the program, so they are simply eliminated during parsing.
2. Processing `syntax` statements: This must be done during parsing, because `syntax` is designed to modify the spelling and precedence of operators, and that information is used during the parsing phase.
3. Processing `use` statements: Since imported modules can contain `syntax` statements, they must at least partially be processed during parsing. Details about `use` statements are covered in the chapter about modules.
4. Identifying words that switch to a child syntax: symbols that activate a child syntax are recognized during parsing. This is the case for example with the `extern` name in the default syntax.
5. Identifying binary data: words such as `bits` marked as introducing `BINARY` data in the syntax file are treated specially during parsing, to generate parse tree nodes representing binary data. > NOTE: this is not currently implemented.

The need to process `use` statements during parsing means that it's not possible in XL to have computed `use` statements. The name of the module must always be evaluated at compile-time.

> **RATIONALE** An alternative would have been to allow computed `use` statement, but disallow `syntax` in them. However, for convenience, `use` names look like `XL.CONSOLE.TEXT_IO` and not, say, `"xl/console/text_io.xs"`, so there is no obvious way to compute them anyway. If computed `use` statement ever become necessary, it will be easy enough to use the syntax `use "path"` for them.

Once parsing completes successfully, the parse tree can be handed to the declaration and evaluation phases. Parsing occurs for the *entire program*, including imported modules, before the other phases begin.

3.1.3. Sequences

Both declaration and evaluation phases will process *sequences*, which are one of:

- A block, in which case processing the sequence means processing the block's child

  ```
  loop { print "Hello World" }
  ```

- An infix `NEWLINE` or semi-colon `;`, in which case the left and right operands of the infix are processed in that order.

  ```
  print "One"; print "Two"
  print "Three"
  ```

- An `use` statement, which is the only statement that requires processing in all three executation phases.

  ```
  use XL.MATH.COMPLEX
  ```

- A `syntax` definition, which only plays a role during parsing is ignored during the declaration and evaluation phases.

  ```
  syntax { INFIX 290 <=> }
  ```

- An infix `is`, which is called a *definition*, an infix `:` or `as`, which are called *type annotations*, or an infix assignment operator `:=` with a `:` type annotation on the left, called a *variable initialization*. Definitions, type annotations and variable initializations are collectively called *declarations*, and are processed during the declaration phase.

```
pi is 3.1415                  // Definition of 'pi'
e as real is 2.71828          // Typed definition of 'e'
Count : integer               // Variable declaration of 'Count'
byte_size X as integer        // Function declaration of 'byte_size X'
Remaining : integer := 100    // Variable initialization of 'Remaining'
```

- Anything else, which is called a *statement* and is processed during the evaluation phase.

```
print "This is a statement"
```

For example, consider the following code:

```
pi is 3.14
circumference 5.3
circumference Radius:real is 2 * pi * Radius
```

The first and last line are representing a definition of `pi` and `circumference Radius:real` respectively. The second line is made of one statement that computes `circumference 5.3`. There are two definitions, one statement and no type annotation in this code.

Note that there is a type annotation for `Radius` in the definition on the last line, but that annotation is *local* to the definition, and consequently not part of the declarations in the top-level sequence.

In that specific case, that type annotation is a declaration of a *parameter* called `Radius`, which only accepts `real` values. Sometimes, such parameters are called *formal parameters*. A parameter will receive its value from an *argument* during the evaluation. For example the `Radius` parameter will be *bound* to argument`5.3` while evaluating the statement on the second line.

The *result* of a sequence is the value of its last statement. In our example, the result of executing the code will be the value computed by `circumference 5.3`.

3.1.4. Declaration phase

The declaration phase of the program begins as soon as the parsing phase finishes.

During the declaration phase, all declarations are stored in order in the context, so that they appear before any declaration that was already in the context. As a result, the new declarations may *shadow* existing declarations that match.

In the example above, the declaration phase would result in a context that looks something like:

```
CONTEXT1 is
    pi is 3.14
    circumference Radius:real is 2 * pi * Radius
    CONTEXT0
    HIDDEN0
```

An actual implementation is likely to store declarations is a more efficient manner. For example, an interpreter might use some hashing or some form of balanced tree. Such optimizations must preserve the order of declarations, since correct behavior during the evaluation phase depends on it.

In the case of a compiled implementation, the compiler will most likely assign machine locations to each of the declarations. When the program runs, a constant like `pi` or the definition of `circumference` may end up being represented as a machine address, and a variable such as `Radius` may be represented as a "stack location", i.e. a preallocated offset from the current stack pointer, the corresponding memory location only containing the value, i.e. the right-hand side of `:=`. Most of the type analysis can be performed at compile time, meaning that most type information is unnecessary at program run time and can be eliminated from the compiled program.

Note that since the declaration phase occurs before the execution phase, all declarations in the program will be visible during the evaluation phase. In our example, it is possible to use `circumference` before it has been declared. Definitions may therefore refer to one another in a circular way. Some other languages such as C require ``forward declarations'' in such cases, XL does not.

The parse tree on the left of `is`, `as` or `:` is called the *pattern* of the declaration. The pattern will be checked against the *form* of parse trees to be evaluated. The right operand of `:` or `as` is the type of the type annotation. The parse tree on the right of `is` is called the *body* of the definition.

3.1.5. Evaluation phase

The evaluation phase processes each statement in the order they appear in the program. For each statement, the context is looked up for matching declarations in order. There is a match if the shape of the tree being evaluated matches the pattern of the declaration. Precise pattern matching rules will be detailed below. In our example, `circumference 5.3` will not match the declaration of `pi`, but it will match the declaration of `circumference Radius:real` since the value `5.3` is indeed a real number.

When a match happens, a new context is created with *bindings* for the formal parameters to the value passed as an argument in the statement. This new context is called a *local context* and will be used to evaluate the body of the definition. For example, the local context to evaluate the body of the definition of `circumference Radius:real` would be:

```
CONTEXT2 is
    Radius:real := 5.3
    CONTEXT1
    HIDDEN1
HIDDEN1 is CONTEXT1
```

As a reminder, `Radius` is a *formal parameter*, or simply *parameter* that receives the *argument* 5.3 as a result of *binding*. The binding remains active for the duration of the evaluation of of the body of the definition. The binding, at least conceptually, contains the type annotation for the formal parameter, ensuring that all required type constraints are known and respected. For example, the context contains the `Redius:real` annotation, so that attempting `Radius := "Hello"` in the body of `circumference` would fail, because the type of `"Hello"` does not match the `real` type.

Bindings can be marked as mutable or constant. In this document, bindings made with `:=` are mutable, while binding made with `is` are constant. Since by default, an `X : T` annotation creates a mutable binding, the binding for `Radius` is made with `:=`.

Once the new context has been created, execution of the program continues with the body of the definition. In that case, that means evaluating expression `2 * pi * Radius` in the newly created local context.

After execution of the body completes, the result of that execution replaces the statement that matched the definition's pattern. In our example, `circumference 5.3` behaves like `2 * pi * Radius` in a context containing `Radius is 5.3`.

The process can then resume with the next statement if there is one. In our example, there isn't one, so the execution is complete.

3.2. Expression evaluation

Executing the body for the definition of `circumference Radius:real` involves the evaluation of expression `2 * pi * Radius`. This follows almost exactly the same process as for `circumference 5.3`, but in that case, that process needs to be repeated multiple times to complete the evaluation.

If we apply the evaluation process with `2 * pi * Radius`, assuming the declarations in the standard library, no declaration has a larger pattern like `X * Y * Z` that could match the whole expression. However, there is a definition for a multiplication between `real` numbers, with a pattern that looks like `X:real * Y:real as real`, as well as another for `integer` multiplication, with a pattern that looks like `X:integer * Y:integer`. There may be more, but we will ignore them for the rest of this discussion. The code below shows what the relevant declaration might look like (`⋯` indicates irrelevant code):

```
X:integer * Y:integer   as integer  is ...
X:real * Y:real         as real     is ...
```

The `*` operator is left-associative, so `2 * pi * Radius` parses as `(2 * pi) * Radius`. Therefore, we will be looking for a match with `X` corresponding to `2 * pi` and `Y` corresponding to `Radius`. However, that information alone is insufficient to determine if either sub-expression is `integer` or `real`. In order to be able to make that determination, immediate evaluation of the arguments is required. The evaluation process therefore repeats with sub-expression `2 * pi`, and like before, it is necessary to evaluate `pi`. This in turns gives the result `3.14` given the current context. That result replaces `pi`, so that we now must evaluate `2 * 3.14`.

The `2 * 3.14` tree does not match `X:real * Y:real` because `2` is an `integer` and not a `real`. It does not match `X:integer * Y:integer` either because `3.14` is a `real` and not an `integer`. However, the standard library provides a definition of an *implicit conversion* that looks something like this:

```
X:integer as real     is builtin IntegerToReal
```

This implicit conversion tells the compiler how to transform an `integer` value like `2` into a `real`. Implicit conversions are only considered if there is no exact match, and only one of them can be used to match a given parameter. In our case, there isn't an exact match, so the evaluation will consider the implicit conversion to get a `real` from `integer` value `2`.

The body of the implicit conversion above is therefore evaluated in a context where `X` is set to `2`:

```
CONTEXT3 is
    X:integer := 2
    CONTEXT2
    HIDDEN2
HIDDEN2 is CONTEXT2
```

The result of that implicit conversion is `2.0`. Evaluation can then resume with the `X:real * Y:real as real` definition, this time called with an argument of the correct `real` type for `X`:

```
CONTEXT4 is
    X:real := 2.0
    Y:real := 3.14
    CONTEXT2
    HIDDEN2
```

The result of the multiplication is a `real` with value `6.28`, and after evaluating `Radius`, evaluation of the second multiplication will then happen with the following context:

```
CONTEXT5 is
    X:real := 6.28 // from 2 * pi
    Y:real :=5.3  // from Radius
    CONTEXT2
    HIDDEN2
```

The result of the last multiplication is a `real` with value `33.284`. This is the result of evaluating `circumference 5.3`, and consequently the result of executing the entire program.

The standard XL library only provides implicit conversions that do not cause data loss. On most implementation, `real` has a 53-bit mantissa, which means that the implicit conversion from `integer` to `real` is actually closer to the following:

```
X:integer as real when X >= -2^53 and X < 2^53 is ...
```

3.3. Pattern matching

As we have seen above, the key to execution in XL is *pattern matching*, which is the process of finding the declarations patterns that match a given parse tree. Pattern matching is recursive, the *top-level pattern* matching only if all *sub-patterns* also match.

For example, consider the following declaration:

```
log X:real when X > 0.0 is ...
```

This will match an expression like `log 1.25` because:

1. `log 1.25` is a prefix with the name `log` on the left, just like the prefix in the pattern.
2. `1.25` matches the formal parameter `X` and has the expected `real` type, meaning that `1.25` matches the sub-pattern `X:real`.
3. The condition `X > 0.0` is true with binding `X is 1.25`

There are several kinds of patterns, each maching different kinds of expressions.

Name definitions

Top-level name patterns only match the exact same name.

Declaration	Matched by	Not matched by
`pi is 3.14`	`pi`	`ip`, `3.14`

Definitions with a top-level name pattern are called *name definitions*.

This case only applies to names, not to operators. You cannot define a `+` operator that way.

Wildcards

Name patterns that are not at the top-level can match any expression, and this does not require immediate evaluation. In that case, the expression will be bound to the name in the argument context, unless it is already bound in the current context. In that latter case, the value `New` of the new expression is compared with the already bound value `Old` by evaluating the `New=Old` expression, and the pattern only matches if that check evaluates to `true`.

Declaration	Matched by	Not matched by
`X+Y`	`2+"A"`	`2-3`, `+3`, `3+`
`N+N`	`3+3`, `A+B` when `A=B`	`3-3`, `3+4`

Such name patterns are called *wildcard parameters* because they can match any expression, or *untyped parameters* because no type checking occurs on the matched argument.

This case only applies to names, not to operators. You cannot define a `+` parameter that way.

Type annotations

When the pattern is an infix `:` or `as`, it matches an expression if the expression matches the pattern on the left of the infix, and if the type of the expression matches the type on the right of the infix.

A type annotation as a top-level pattern is a declaration:

Top-level pattern	**Matched by**	**Not matched by**
`X:integer`	`X`	`2`, `'X'`
`seconds as integer`	`seconds`	`2`, `"seconds"`

A type annotation as a sub-pattern declares a parameter:

Parameter pattern	**Matched by**	**Not matched by**
`X:integer`	`42`	`X` (unless bound to an `integer`)
`seconds as integer`	`42`	`X` (unless constant bound to an `integer`)

Such patterns are called *type annotations*, and are used to perform type checking. Normally, type annotations using `:` are used to declare the type of parameters, whereas `as` is used to declare the type of the expression being defined, as shown for the pattern on the left of `is` in the example below:

```
X:real + Y:real as real is ...
```

Function (prefix) definitions

When the pattern is a prefix, like `sin X`, the expression will match only if it is a prefix with the same name, and when the pattern on the right of the prefix matches the right operand of the expression.

Pattern	**Matched by**	**Not matched by**
`sin X`	`sin (2.27 + A)`	`cos 3.27`
`+X:real`	`+2.27`	`+"A"`, `-3.1`, `1+1`

When the prefix is a name, definitions for such patterns are called *function definitions*, and the corresponding expressions are usually called *function calls*. Otherwise, they are called *prefix definitions*.

Postfix definitions

When the pattern is a postfix, like `X%`, the expression will match only if it is a postfix with the same name, and when the pattern on the left of the postfix matches the left operand of the expression.

Pattern	Matched by	Not matched by
`X%`	`2.27%`, `"A"%`	`%3`, `3%2`
`X km`	`2.27 km`	`km 3`, `1 km 3`

Definitions for such patterns are called *postfix definitions*, and the corresponding expressions are usually called *postfix expressions*. The name or operator is sometimes called the *suffix*.

Infix definitions

When the pattern is an infix, it only matches:

- an infix expression with the same infix operator when both the left and right operands of the pattern match the corresponding left and right operands of the expression.

Pattern	Matched by	Not matched by
`X:real+Y:real`	`3.5+2.9`	`3+2`, `3.5-2.9`
`X and Y`	`N and 3`	`N or 3`

  - a name bound to an infix with the same infix operator when both the left and right operands of the pattern match the corresponding left and right operands of the bound value. In that case, the value in the name is said to be *split* to match the parameters.

Pattern	Matched by	Not matched by
`write X,Y`	`write Items` when `Items is "A","B"`	`wrote 0`, `write Items` when `Items is "A"+"B"`

    A very common idiom is to use comma `,` infix to separate multiple parameters, as in the following definition:

```
write Head, Tail is write Head; write Tail
```

This declaration will match `write 1, 2, 3` with bindings `Head is 1` and `Tail is 2,3`. In the evaluation of the body with these bindings, `write Tail` will then match the same declaration again with `Tail` being split, resulting in bindings `Head is 2` and `Tail is 3`.

\+ A definition for an infix pattern is called an *infix definition*, and the expressions are called *infix expressions*.

Conditional patterns

When a top-level pattern is an infix like `Pattern when Condition`, then the pattern matches an expression if the pattern on the left of the infix matches the expression, and if the expression on the right evaluates to `true` after bindings

Pattern	Matched by	Not matched by
`log X when X > 0`	`log 3.5`	`log(-3.5)`

Such patterns are called *conditional patterns*. They do not match if the expression evaluates to anything but `true`, notably if it evaluates to any kind of error. For example:

```
log X when X > 0 is ...
log "Logging an error"        // Will not match the definition above
```

Literal constants

When the pattern is an `integer` like `0`, a `real` like `3.5`, a `text` like `"ABC"`, it only matches an expression with the same value, as verified by evaluating the `Pattern = Value` expression, where `Pattern` is the literal constant in the pattern, and `Value` is the evaluated value of the expression. Checking that the value matches will therefore require immediate evaluation.

Pattern	Matched by	Not matched by
`0!`	`N!` when `N=0`	`N!` when `N<>0`

This case applies to sub-patterns, as was the case for `0! is 1` in the definition of factorial. It also applies to top-level patterns, which is primarily useflu in maps:

```
digits is
    0 is "Zero"
    1 is "One"
```

Metabox constants

When the pattern is a an expression between two square brackets, like `[[true]]`, it is called a *metabox*, and it only matches a value that is equal to the value computed by the metabox. This equality is checked by evaluating `Pattern = Value`, where `Pattern` is the expression in the metabox, and `Value` is the expression being tested.

Pattern	Matched by	Not matched by
`[[true]]`	`true`, `not false`	`"true"`, `1`

A metabox is used in particular when a name would be interpreted as a parameter. The two declarations below declare a short-circuit boolean `and` operator:

```
[[true]]  and X   is X
[[false]] and X   is false
```

By contrast, the two definitions would not work as intended, since they would simply declare parameters called `true` and `false`, always causing the first one to be evaluated for any `A and B` expression:

```
true  and X       is X
false and X       is false
```

Block elimination

When the pattern is a block, it matches what the block’s child would match. In other words, blocks in patterns can be used to change the relative precedence of operators in a complex expression, but play otherwise no other role in pattern matching.

Definition	Matched by	Not matched by
`(X+Y)*(X-Y) is X`$^{2-Y}$`2`	`[A+3]*[A-3]`	`(A+3)*(A-4)`

The delimiters of a block cannot be tested that way. In other words, a pattern with angle brackets can match parentheses or conversely. For example, `[A:integer]` will match `2` or `(2)` or `{2}`.

It is possible to test the delimiters of a block, but that requires a conditional pattern. For example the following code will check if its argument is delimited with parentheses:

```
has_parentheses B:block when B.opening = "(" and B.closing = ")"  is true
has_parentheses B:block                                            is false
```

In some cases, checking if an argument matches a pattern requires evaluation of the corresponding expression or sub-expression. This is called immediate evaluation. Otherwise, evaluation will be lazy.

STYLE The rules of pattern matching give a lot of freedom with respect to coding style. Several conventions are recommended and are generally followed in this document:

- When a function takes multiple parameters, they are generally represented using a comma-separated parameter list, altough in some cases, other infix operators would do just as well:

  ```
  circle CenterX:real, CenterY:real, Radius:real is ...
  ```

- When there is such a comma-separated parameter list, it is customary to surround it with parentheses when the function is intended to be used in expressions, because in such an expression context, the parentheses are necessary at the call site. For example, if `circle` is intended to create a `circle` object rather than to draw a circle, the above definition might be written as follows:

  ```
  circle CenterX:real, CenterY:real, Radius:real as circle is ...
  C : circle := circle(0.3, 2.6, 4.0)
  ```

3.3.1. Pattern matching scope values

When a pattern is a comma-separated parameter list, it can be matched to a comma-separated argument list as explained above, but it can also be matched by looking up the relevant parameter names in a scope passed as an argument.

This, combined with the rules about matching blocks, makes it possible to pass arguments by name for clarity in very long parameter lists.

```
// Function to create a person, with many parameters
create_person FirstName     : text,
              LastName      : text,
              DateOfBirth   : date,
              Gender        : gender,
              Weight        : weight,
              Height        : length,
              Address       : address as person is ...

// The above function can be invoked with as scope as an argument
// Notice that since this is based on lookup, the order can be different
JohnDoe is create_person
    LastName    is "Doe"
    FirstName   is "John"
    Gender      is Male
    Weight      is 87.3kg
    Height      is 182cm
    Address     is address
        Street  is "Sesame Street"
        Number  is 42
        ZipCode is 97777
        City    is "Flooontch"
    DateOfBirth is 1902/12/05
```

This rule is a bit uncertain: the effect on readability seems desirable, but there is a bit of ad-hockery in this rule, and it's unclear that long parameter list are that useful in XL. It is also unclear that this can easily be implemented within the language as a definition for `X,Y`, which is a bit concerning. (In other words, this might be the kind of language rule that is not very natural to write in XL - To be verified…)

3.4. Overloading

There may be multiple declarations where the pattern matches a given parse tree. This is called *overloading*. For example, as we have seen above, for the multiplication expression `X*Y` we have at least `integer` and `real` candidates. This looks like:

```
X:integer * Y:integer as integer        is ...
X:real    * Y:real    as real           is ...
```

The first declaration above would be used for an expression like `2+3` and the second one for an expression like `5.5*6.4`. It is important for the evaluation to be able to distinguish them, since they may result in very different machine-level operations.

In XL, the various declarations in the context are considered in order, and the first declaration that matches is selected. A candidate declaration matches if it matches the whole shape of the tree.

> Historically, the XL2 implementation does not select the first that matches, but the *largest and most specialized* match. This is a slightly more complicated implementation, but not by far, and it has some benefits, notably with respect to making the code more robust to reorganizations. For this reason, this remains an open option. However, it is likely to be more complicated with the more dynamic semantics of XL, notably for dynamic dispatch, where the runtime cost of finding the proper candidate might be a bit too high to be practical.

For example, `X+1` can match any of the declarations patterns below:

```
X:integer + Y:integer
X:integer + 1
X:integer + Y:integer when Y > 0
X + Y
Infix:infix
```

The same `X+1` expression will not match any of the following patterns:

```
foo X
+1
X * Y
```

Knowing which candidate matches may be possible at compile-time, for example if the selection of the declaration can be done solely based on the type of the arguments and parameters. This would be the case if matching an`integer` argument against an `integer` parameter, since any value of that argument would match. In other cases, it may require run-time tests against the values in the declaration. This would be the case if matching an `integer` argument against `0`, or against `N:integer when N mod 2 = 0`.

For example, a definition of the Fibonacci sequence in XL is given below:

```
fib 0   is 0
fib 1   is 1
fib N   is (fib(N-1) + fib(N-2))
```

> Parentheses are required around the expressions statements in the last declaration in order to parse this as the addition of `fib(N-1)` and `fib(N-2)` and not as the `fib` of `(N-1)+fib(N-2)`.

When evaluating a sub-expression like `fib(N-1)`, three candidates for `fib` are available, and type information is not sufficient to eliminate any of them. The generated code will therefore have to evaluate `N-1`. Immediate evaluation is needed in order to compare the value against the candidates. If the value is `0`, the first definition will be selected. If the value is `1`, the second definition will be used. Otherwise, the third definition will be used.

A binding may contain a value that may itself need to be split in order to be tested against the formal parameters. This is used in the implementation of `print`:

```
print Items             is write Items; print
write Head, Rest        is write Head; write Rest
write Item:integer      is ...  // Implementation for integer
write Item:real         is ...  // implementation for real
```

In that case, finding the declaration matching `print "Hello", "World"` involves creating a binding like this:

```
CONTEXT1 is
    Items is "Hello", "World"
    CONTEXT0
```

When evaluating `write Items`, the various candidates for `write` include `write Head, Rest`, and this will be the one selected after splitting `Items`, causing the context to become:

```
CONTEXT2 is
    Head is "Hello"
    Rest is "World"
    CONTEXT0
    HIDDEN1 is CONTEXT1
```

3.5. Dynamic dispatch

As shown above, the declaration that is actually selected to evaluate a given parse tree may depend on the dynamic value of the arguments. In the Fibonacci example above, `fib(N-1)` may select any of the three declarations of `fib` depending on the actual value of `N`. This runtime selection of declarations based on the value of arguments is called *dynamic dispatch*.

In the case of `fib`, the selection of the correct definition is a function of an `integer` argument. This is not the only kind of test that can be made. In particular, dynamic dispatch based on the *type* of the argument is an important feature to support well-known techniques such as object-oriented programming.

Let's consider an archetypal example for object-oriented programming, the `shape` class, with derived classes such as `rectangle`, `circle`, `polygon`, and so on. Textbooks typically illustrate dynamic dispatch using a `Draw` method that features different implementations depending on the class. Dynamic dispatch selects the appropriate implementation based on the class of the `shape` object.

In XL, this can be written as follows:

```
draw R:rectangle    is ... // Implementation for rectangle
draw C:circle       is ... // Implementation for circle
draw P:polygon      is ... // Implementation for polygon
draw S:shape        is ... // Implementation for shape

draw Something      // Calls the right implementation based type of Something
```

A single dynamic dispatch may require multiple tests on different arguments. For example, the `and` binary operator can be defined (somewhat inefficiently) as follows:

```
[[false]] and [[false]]     is false
[[false]] and [[true]]      is false
[[true]]  and [[false]]     is false
[[true]]  and [[true]]      is true
```

When applied to types, this capability is sometimes called *multi-methods* in the object-oriented world. This makes the XL version of dynamic dispatch somewhat harder to optimize, but has interesting use cases. Consider for example an operator that checks if two shapes intersect. In XL, this can be written as follows:

```
X:rectangle intersects Y:rectangle  as boolean  is ... // two rectangles
X:circle    intersects Y:circle     as boolean  is ... // two circles
X:circle    intersects Y:rectangle  as boolean  is ... // rectangle & circle
X:polygon   intersects Y:polygon    as boolean  is ... // two polygons
X:shape     intersects Y:shape      as boolean  is ... // general case

if shape1 intersects shape2 then    // selects the right combination
    print "The two shapes touch"
```

Type-based dynamic dispatch is relatively similar to the notion of *virtual function* in C++, although the XL implementation is likely to be quite different. The C++ approach only allows dynamic dispatch along a single axis, based on the type of the object argument. C++ also features a special syntax, `shape.Draw()`, for calls with dynamic dispatch, which differs from the C-style syntax for function calls, `Draw(shape)`. The syntax alone makes the `intersects` example difficult to write in C++.

As another illustration of a complex dynamic dispatch not based on types, Tao3D uses theme functions that depend on the names of the slide theme, master and element, as in:

```
theme_font "Christmas", "main",       "title"   is font "Times"
theme_font "Christmas", SlideMaster,  "code"    is font "Menlo"
theme_font "Christmas", SlideMaster,  SlideItem is font "Palatino"
theme_font SlideTheme,  SlideMaster,  SlideItem is font "Arial"
```

As the example above illustrates, the XL approach to dynamic dispatch takes advantage of pattern matching to allow complex combinations of argument tests.

3.6. Immediate evaluation

In the `circumference` examples, matching `2 * pi * Radius` against the possible candidates for `X * Y` expressions required an evaluation of `2 * pi` in order to check whether it was a `real` or `integer` value.

This is called *immediate evaluation* of arguments, and is required in XL for statements, but also in the following cases:

1. When the formal parameter being checked has a type annotation, like `Radius` in our example, and when the annotation type does not match the type associated to the argument parse tree. Immediate evaluation is required in such cases in order to check if the argument type is of the expected type after evaluation. Evaluation is *not* required if the argument and the declared type for the formal parameter match, as in the following example:

   ```
   write X:infix   is  write X.left, " ", X.name, " ", X.right
   write A+3
   ```

   In that case, since `A+3` is already an `infix`, it is possible to bind it to `X` directly without evaluating it. So we will evaluate the body with binding `X:infix is A+3`.

2. When the part of the pattern being checked is a constant or a metabox. For example, this is the case in the definition of the factorial below, where the expression `(N-1)` must be evaluated in order to check if it matches the value `0` in pattern `0!`:

   ```
   0! is 1
   N! is N * (N-1)!
   ```

   This is also the case for the condition in `if-then-else` statements, to check if that condition matches either `true` or `false`:

   ```
   if [[true]]  then TrueBody else FalseBody    is TrueBody
   if [[false]] then TrueBody else FalseBody    is FalseBody
   ```

3. When the same name is used more than once for a formal parameter, as in the following optimization:

```
A - A    is 0
```

Such a definition would require the evaluation of `X` and `2 * Y` in expression `X - 2 * Y` in order to check if they are equal.

4. When a conditional clause requires the evaluation of the corresponding binding, as in the following example:

```
syracuse N when N mod 2 = 0  is N/2
syracuse N when N mod 2 = 1  is N * 3 + 1
syracuse X+5 // Must evaluate "X+5" for the conditional clause
```

Evaluation of sub-expressions is performed in the order required to test pattern matching, and from left to right, depth first. Patterns are tested in the order of declarations. Computed values for sub-expressions are memoized, meaning that they are computed at most once in a given statement.

3.7. Lazy evaluation

In the cases where immediate evaluation is not required, an argument will be bound to a formal parameter in such a way that an evaluation of the formal argument in the body of the declaration will evaluate the original expression in the original context. This is called *lazy evaluation*. The original expression will be evaluated every time the parameter is evaluated.

To understand these rules, consider the canonical definition of `while` loops:

```
while Condition loop Body is
    if Condition then
        Body
        while Condition loop Body
```

Let’s use that definition of `while` in a context where we test the Syracuse conjecture:

```
while N <> 1 loop
    if N mod 2 = 0 then
        N /= 2
    else
        N := N * 3 + 1
    print N
```

The definition of `while` given above only works because `Condition` and `Body` are evaluated multiple times. The context when evaluating the body of the definition is somewhat equivalent to the following:

```
CONTEXT1 is
    Condition is N <> 1
    Body is
        if N mod 2 = 0 then
            N /= 2
        else
            N := N * 3 + 1
        print N
    CONTEXT0
```

In the body of the while definition, Condition must be evaluated because it is tested against metabox [[true]] and [[false]] in the definition of if-then-else. In that same definition for while, Body must be evaluated because it is a statement.

The value of Body or Condition is not changed by them being evaluated. In our example, the Body and Condition passed in the recursive statement at the end of the while Condition loop Body are the same arguments that were passed to the original invokation. For the same reason, each test of N <> 1 in our example is with the latest value of N.

Lazy evaluation can also be used to implement "short circuit" boolean operators. The following code for the and operator will not evaluate Condition if its left operand is false, making this implementation of and more efficient than the one given earlier:

```
[[true]]  and Condition is Condition
[[false]] and Condition is false
```

3.8. Closures

The bindings given above for Condition and Body are somewhat simplistic. Consider what would happen if you wrote the following while loop:

```
Condition is N > 1
while Condition loop N -= 1
```

Evaluating this would lead to a "naive" binding that looks like this:

```
CONTEXT2 is
    Condition is Condition
    Body is N -= 1
    CONTEXT0
```

That would not work well, since evaluating Condition would require evaluating Condition, and indefinitely so. Something needs to be done to address this.

In reality, the bindings must look more like this:

```
CONTEXT2 is
    Condition is CONTEXT1 { Condition }
    Body is CONTEXT1 { N-= 1 }
    CONTEXT0
```

The notation `CONTEXT1 { Condition }` means that we evaluate `Condition` in context `CONTEXT1`. This one of the scoping operators, which is explained in more details below. A prefix with a context on the left and a block on the right is called a *closure*.

In the above example, we gave an arbitrary name to the closure, `CONTEXT1`, which is the same for both `Condition` and `Body`. This name is intended to underline that the *same* context is used to evaluate both. In particular, if `Body` contains a context-modifying operation like `N -= 1`, that will modify the same `N` in the same `CONTEXT1` that will later be used to evaluate `N > 1` while evaluating `Condition`.

A closure may be returned as a result of evaluation, in which case all or part of a context may need to be captured in the returned value, even after that context would otherwise normally be discarded.

For example, consider the following code defining an anonymous function:

```
adder N is { lambda X is X + N }
add3 is adder 3     // Creates a function that adds 3 to its input
add3 5              // Computes 8
```

When we evaluate `add3`, a binding `N is 3` is created in a new context that contains declaration `N is 3`. That context can simply be written as `{ N is 3 }`. A context with an additional binding for `M is "Hello"` could be written something like `{ N is 3; M is "Hello" }`.

The value returned by `adder N` is not simply `{ lambda X is X + N }`, but something like `{N is 3} { lambda X is X + N }`, i.e. a closure that captures the bindings necessary for evaluation of the body `X + N` at a later time.

This closure can correctly be evaluated even in a context where there is no longer any binding for `N`, like the global context after the finishing the evaluation of `add3`. This ensures that `add3 5` correctly evaluates as `8`, because the value `N is 3` is *captured* in the closure.

A closure looks like a prefix `CONTEXT EXPR`, where `CONTEXT` and `EXPR` are blocks, and where `CONTEXT` is a sequence of declarations. Evaluating such a closure is equivalent to evaluating `EXPR` in the current context with `CONTEXT` as a local context, i.e. with the declarations in `CONTEXT` possibly shadowing declarations in the current context.

In particular, if argument splitting is required to evaluate the expression, each of the split arguments shares the same context. Consider the `write` and `print` implementation, with the following declarations:

```
write Head, Tail        is write Head; write Tail
print Items             is write Items; print
```

When evaluating `{ X is 42 } { print "X=", X }`, `Items` will be bound with a closure that captures the `{ X is 42 }` context:

```
CONTEXT1 is
    Items is { X is 42 } { "X=", X }
```

In turn, this will lead to the evaluation of `write Items`, where `Items` is evaluated using the `{ X is 42 }` context. As a result, the bindings while evaluating `write` will be:

```
CONTEXT2 is
    Head is CONTEXT1 { "X=" }
    Tail is CONTEXT1 { X }
    CONTEXT1 is { X is 42 }
```

The whole processus ensures that, when `write` evaluates `write Tail`, it computes `X` in a context where the correct value of `X` is available, and `write Tail` will correctly write `42`.

3.9. Memoization

A sub-expression will only be computed once irrespective of the number of overload candidates considered or of the number of tests performed on the value. Once a sub-expression has been computed, the computed value is always used for testing or binding that specific sub-expression, and only that sub-expression.

For example, consider the following declarations:

```
X + 0               is Case1(X)
X + Y when Y > 25   is Case2(X, Y)
X + Y * Z           is Case3(X,Y,Z)
```

If you evaluate an expression like `A + foo B`, then `foo B` will be evaluated in order to test the first candidate, and the result will be compared against `0`. The test `Y > 25` will then be performed with the result of that evaluation, because the test concerns a sub-expression, `foo B`, which has already been evaluated.

On the other hand, if you evaluate `A + B * foo C`, then `B * foo C` will be evaluated to match against `0`. Like previously, the evaluated result will also be used to test `Y > 25`. If that test fails, the third declaration remains a candidate, because having evaluated `B * foo C` does not preclude the consideration of different sub-expressions such as `B` and `foo C`. However, if the evaluation of `B * foo C` required the evaluation of `foo C`, then that evaluated version will be used as a binding for `Z`.

RATIONALE These rules are not just optimizations. They are necessary to preserve the semantics of the language during dynamic dispatch for expressions that are not constant. For example, consider a call like `fib(random(3..10))`, which evaluates the `fib` function with a random value between `3` and `10`. Every time `random` is evaluated, it returns a different, pseudo-random value. The rules above guarantee that the *same* value will be used when testing against `0`, `1` or as a binding with `N`. Witout these rules, it would be possible for the body of the general case to be called with a value that is `0` or `1`.

3.10. Self

In a definition body, `self` refers to the input tree. A special idiom is a definition where the body is `self`, called a *self definition*. Such definitions indicates that the item being defined needs no further evaluation. For example, `true` and `false` can be defined as:

```
true    is self
false   is self
```

This means that evaluating `true` will return `true`, and evaluating `false` will return `false`, without any further evaluation. Note that you cannot write for example `true is true`, as `true` in the body is a statement, which would require further evaluation, hence an infinite recursion.

It is possible to use `self` for data structures. For example, in order to ensure that comma-separated lists are not evaluated, you can write :

```
X, Y    is self
```

Note that the following values also evaluate as themselves:

1. `integer`, `real` or `text` constants, unless an explicit declaration in the current context matches.
2. Sequences of declarations, like `{ Zero is 0; One is 1 }`, in particular the contexts captured for closures.

3.11. Nested declarations

A definition body may itself contain declarations, which are called *nested declarations*.

When the body is evaluated, a *local declaration phase* will run, followed by a *local evaluation phase*. The local declaration phase will add the local declarations at the beginning of a new context, which will be destroyed when the body evaluation terminates. The local declarations therefore shadow declarations from the enclosing context.

For example, a function that returns the number of vowels in some text can be written as follows:

```
count_vowels InputText is
    is_vowel C is
        Item in Head, Tail is Item in Head or Item in Tail
        Item in RefItem is Item = RefItem
        C in 'a', 'e', 'i', 'o', 'u', 'y', 'A', 'E', 'I', 'O', 'U', Y'

    Count : integer := 0
    for C in InputText loop
        if is_vowel C then
            Count += 1
    Count
count_vowels "Hello World" // Should return 3
```

This example is designed for illustration purpose only. It is not idiomatic XL, since the standard library provides useful tools. A better way to write it would be:

```
count_vowels InputText is count C in InputText where C in "aeiouyAEIOUY"
```

This code example defines a local helper `is_vowel C` that checks if `C` is a vowel by comparing it against a list of vowels. That local helper is not visible to the outer program. You cannot use `is_vowel X` in the outer program, since it is not present in the outer context. It is, however, visible while evaluating the body of `count_vowels T`.

Similarly, the local helper itself defines an even more local helper infix `in` in order ot evaluate the expression `C in 'a', 'e', …`.

While evaluating `count_vowels "Hello World"`, the context will look something like:

```
CONTEXT1 is
    is_vowel C is ...
    Count:integer := 0
    InputText is "Hello World"
    CONTEXT0
```

In turn, while evaluating `is_vowel Char`, the context will look somethign like:

```
CONTEXT2 is
    Item in Head, Tail is ...
    Item in RefItem is ...
    C is 'l'
    CONTEXT1
```

The context is sorted so that the innermost definitions are visible first. Also, outer declarations are visible from the body of inner ones. In the example above, the body of `is_vowel Char` could validly refer to `Count` or to `InputText`.

3.12. Scoping

A list of declarations, similar to the kind that is used in closures, is called a *map* and evaluates as itself. One of the primary uses for maps is *scoping*, in other words defining a common *scope* for the declarations that it contains. Since the declaration phase operates on entire blocks, all declarations within a scope are visible at the same time.

There are two primary operations that apply to a map:

1. *Applying* a map as a prefix to an operand, as we saw with closures, evaluates the operand in the context defined by overlaying the map definitions on top of the current context.
2. *Scoping* an expression within a map uses the infix `.` operator, where the expression on the right is evaluated in a context that consists *exclusively* of the declarations in the map on the left.

Evaluating a closure is a prime example of map application. The context is captured by the closure in a map, and the closure itself is a prefix that corresponds to the map application. Such an expression can also be created explicitly. For example, `{ X is 40; Y is 2 } { X + Y }` will evaluate as `42`, taking `X` and `Y` from the map, and taking the declaration used to evaluate `X + Y` from the current context.

Another common usage for maps is to store declarations where the patterns are constant values. For example, you can use a map called `digit_spelling` to convert a digit to its English spelling:

```
digit_spelling is
    0 is "zero"
    1 is "one"
    2 is "two"
    3 is "three"
    4 is "four"
    5 is "five"
    6 is "six"
    7 is "seven"
    8 is "eight"
    9 is "nine"
```

With this declaration, the expression `digit_spelling 3` evaluates to `"three"`. This kind of map application is called *indexing*. A suggested style choice is to make the intent more explicit using square brackets, as in `digit_spelling[4]`. This is a nod to the syntax of programming languages such as C or C++.

When the index is an expression, for example `digit_spelling[A+3]` in a context where `A is 2`, we must evaluate `A+3` in current context augmented with the declarations in `digit_spelling`. The first candidate has pattern `0`. This requires the evaluation of expression `A+3` to check if it matches the value. As indicated earlier, this evaluation will not consider constants, since it is performed to match a constant. In other words, it will match the pattern `X+Y` for `A+2`, and therefore compute the value `5`. That computed value will fail the check against pattern `0`, but because of memoization, it will then be used against the various constants in the map. As a result, `digit_spelling[A+2]` evaluates as `"five"`.

A map is not restricted to constant patterns. For example, the following map performs a more complete spelling conversion for numbers below 1000 (the notation `\N` being a shortcut for `lambda N`):

```
number_spelling is
    \N when N<10    is digit_spelling[N]
    11              is "eleven"
    12              is "twelve"
    13              is "thirteen"
    14              is "fourteen"
    15              is "fifteen"
    16              is "sixteen"
    17              is "seventeen"
    18              is "eighteen"
    19              is "nineteen"
    20              is "twenty"
    30              is "thirty"
    40              is "forty"
    50              is "fifty"
    60              is "sixty"
    70              is "seventy"
    80              is "eighty"
    90              is "ninety"
    \N when N<100   is (number_spelling[N/10*10] & " " &
                        digit_spelling[N mod 10])
    \N when N<1000  is (digit_spelling[N/100] & " hundred and " &
                        digit_spelling[N mod 100])
```

Another common idiom is to use a named map to group related declarations. This is the basis for the XL module system. For example, consider the following declaration:

```
byte_magic_constants is
    num_bits    is 8
    min_value   is 0
    max_value   is 255
```

With that declaration, `byte_magic_constants.num_bits` evaluates to `8`. A declaration like this can of course be more than a simple name:

```
magic_constants Bits is
    num_bits    is Bits
    min_value   is 0
    max_value   is 2^Bits - 1
```

In that case, `magic_constants(4).max_values` will evaluate to `15`.

This is also exactly what happens when you `use` a module. For example, with `use IO =`

`XL.CONSOLE.TEXT_IO`, a local name `IO` is created in the current context that contains the declarations in the module. As a result, `IO.write` will refer to the declaration in the module.

3.13. Named scopes

A common idiom in XL is to prefix a scope with a name, so as to better document the intent for the programmer and create patterns that are more specific, minimizing the risk of ambiguity. A scope following a name is called a *named scope*, and can be used like a regular scope, i.e. the prefix name does not play a role in the lookup.

For example, the `magic_constants` could be defined as

```
magic_constants Bits is size_constants
    num_bits    is Bits
    min_value   is 0
    max_value   is 2^Bits - 1

eight_bits is magic_constants(8)

print "The max value for 8 bits is ", eight_bits.max_value
```

This forms the basis of constructors and tagged typesin XL.

3.14. Super lookup

In a given context, `super` is a way to refer to the enclosing scope.

```
X is 42
foo X:integer is X + super.X    // super.X refers to X above
foo 3                           // Returns 45
```

3.15. Caller lookup

> This feature is only under consideration after a couple of use-cases for this kind of lookup popped up while experimenting with Tao3D, see RATIONALE.

In general, the context of the caller is invisible to the callee. For example, the following code prints `"X=Global"`.

```
outer "Argument"

X is "Global"

outer X:text is
    inner X

inner A:text is
    print "X=", X
```

While evaluating `inner`, the value `"Argument"` bound to `X` while evaluating `outer` is no longer visible. The scoping rules mean that the `X` that is being seen from within `inner` is the one defined in the global context.

However, the `caller` context may be explicitly referenced by scoping operators. The following example will print `X=Argument`:

```
outer "Argument"

X is "Global"

outer X:text is
    inner X

inner A:text is
    print "X=", caller.X
```

RATIONALE The first use-case that was "discovered" using Tao3D was passing an implicit environment to a large number of related functions. In the case of Tao3D, that implicit environment was describing graphics attributes such as color or line width. A global variable would provide a convenient default, but a local variable with the correct name would make that default easy to override. This would play a role similar to the C++ implicit `this` pointer, with the added benefits that multiple such implicit parameters would be possible depending on usage (graphics state, window state, etc)

A second use case was also found in XL2 when looking up generic code, and plays the role of Koenig lookup in C++, i.e. make it possible to access code in the caller's context. For example, the definition corresponding to `write Head, Tail` will call `write Head`. If you want to be able to extend `write` with your own custom types, it is necessary to be able to lookup `write Head` within the caller's context as well. Whether this is really necessary or functional remains to be tested.

A reasonably efficient implementation strategy for compiled code seems possible.

3.16. Assignments and moves

The infix `:=` operator is used to perform *assignments* and returns the value being assigned. Variants such as `+=`, `-=`, `*=`, `/=` are equivalent to performing the corresponding operating and assigning the result.

```
X : integer := 0    // Initialize X to 0
X := 5              // Now X contains value 5
X += 7              // Now X contains value 12
```

The `:=` operator (and only that operator) is a *variable declaration* when its left operand is an infix `:`. This was discussed earlier, and corresponds to the first line in the example above. A variable declaration is *not* an assignment.

Seven combined operators are defined independently of the type as follows:

```
X += Y      is X := X + Y
X -= Y      is X := X - Y
X *= Y      is X := X * Y
X /= Y      is X := X / Y
X &= Y      is X := X & Y
X |= Y      is X := X | Y
X ^= Y      is X := X ^ Y
```

XL offers two additional operators, the `:+` *copy* operator and the `:<` *move* operator (which is also sometimes *cut* operator because of its shape that evokes scissors). The `:+` operator guarantees that all data is being copied, and that the new object is an independent copy of the original (hence the `+` character in it). The `:<` operator may simply move ownership of the value if that is less expensive than copying it, and invalidates the right side of the operator, which may no longer be used.

Depending on the data type, `:=` may correspond to a copy or a move. The precise details of which operator is selected and the associated rationale are detailed in the next chapter. In all cases, the previous value that was held in the left operand is destroyed by the assignment.

The `:=` operator is used to transfer arguments to parameters. This means that passing an argument in XL, like in Rust, can make the argument invalid in the caller if it is moved rather than copied. There are, however, multiple ways to pass arguments. This is all discussed in more details in the next chapter.

RATIONALE For simple types such as arithmetic types, an assignment performs a copy, which is a relatively inexpensive memmory copy between fixed-size locations. For more complicated data types, such as `spreadsheet`, `graph` or `picture`, a copy involves copying possibly megabytes of data, or complex webs of interconnected objects, which can be very expensive, and often leaves an unused copy behind. For such data types, moving data is the frequently desirable operations, for example to pass objects around as arguments, and copying data is the less frequent case. In any case, the programmer remains in charge, always having the possibility to explicitly request a copy or a move.

3.17. Functions as values

Unlike in several functional languages, when you declare a "function", you do not automatically declare a named entity or value with the function’s name.

For example, the first definition in the following code does not create any declaration for `my_function` in the context, which means that the last statement in that code will cause an error.

```
my_function X is X + 1
apply Function, Value is Function(Value)
apply my_function, 1        // Error: Nothing called 'my_function'
```

RATIONALE One reason for that choice is that overloading means a multiplicity of declarations often need to be considered for a single expression. Another reason is that declarations can have arbitrarily complex patterns. It is not obvious what name should be given to a declaration of a pattern like `A in B..C`: a "name" like `in..` does not even ``work" syntactically.

It is not clear how such a name would be called as a function either, since some of the arguments may themselves contain arbitrary parse trees, as we have seen for the definition of `print`, where the single `Items` parameter may actually be a comma-separated list of arguments that will be split when calling `write Items` and matching it to `write Head, Tail`.

If you need to perform the operation above, it is however quite easy to create a map that performs the operation. That map may be given a name or be anonymous. The following code example shows two correct ways to write such an `apply` call for a factorial definition:

```
0!                        is 1
N!                        is N * (N-1)!
apply Function, Value     is Function(Value)

// Using an anonymous map to compute 3!
apply { \N is N! }, 3

// Using a named map to compute 5!
factorial   is { \N is N! }
apply factorial, 5
```

Passing definitions like this might be seen as related to what other languages call *anonymous functions*, or sometimes *lambda function* in reference to Church's lambda calculus. The way this works, however, is markedly different internally, and is detailed in the section on scoping above.

3.18. Error handling

Code that fails will generally report it by returning an `error` value. Error values have the `error` type. For example, consider the `sqrt` (square root) function. That function is only defined for positive values.

```
sqrt X:real as real     when X >= 0     is ...
print "Square root of 2 is ", sqrt 2        // OK
print "Square root of -1 is ", sqrt(-1)     // Error
```

This program will print something similar to the following

```
Square root of 2 is 1.41421356237
Square root of -1 is Error: No form matches sqrt(-1)
```

This message is not very informative. For that reason, it is customary to add specific error messages for well-identified conditions:

```
sqrt X:real as real     when X >= 0     is ...
sqrt X:real as real     when X <  0     is error "Square root of negative real ", X
```

In that case, the output will change to something like:

```
Square root of 2 is 1.41421356237
Square root of -1 is Error: Square root of negative real -1.0
```

There are multiple ways to handle errors:

- Taking error parameters lets you explicitly deal with errors, for example to show an error message.

- Fallible types deal with cases where you expect a value or an error.
- Try-Catch will let you special-case error conditions.
- Error statements automatically propagate errors without cluttering your code with error checking conditions.

3.18.1. Taking error parameters

The simplest way to handle errors is to have a variant of the function that takes an `error` as an argument. For example, you could extend your square root function as follows:

```
sqrt X:real as real     when X >= 0     is ...
sqrt X:real as real     when X <  0     is error "Square root of negative real ", X
sqrt E:error as error                   is error "Square root of error: ", E
```

Now if you attempt to take the square root of an error, you will get a different output:

```
print "Double error is ", sqrt(sqrt(-1))
Double error is Error: Square root of error: Square root of negative real -1.0
```

As the code above illustrates, `print` and `write` are examples of functions that take an `error` parameter. In that case, these functions will print the associated error message.

3.18.2. Fallible types

Another way to handle errors is to use `fallible T` types, which hold either a `T` or an `error`. The `faillible` type (without a type argument) is the same as `fallible nil`, and is normally used for functions that are not expected to return a value, but can return an error.

`fallible T` contains four accessible fields:

- `value` is a `T` value, and can only be accessed when there was no error (otherwise, it returns… an `error`!)
- `error` is an `error` value that should only be accessed when there was an error. Otherwise, it returns `nil`.
- `good` is `true` if there was no error, and `bad` otherwise.
- `bad` is equivalent to `not good`.

The following code shows how to use a `fallible real` type to return `0.0` for the `sqrt` of a negative value:

```
sanitized_sqrt X:real as real is
    R : fallible real := sqrt X
    if R.bad then
        print "Got an error in sqrt: ", R.error
        R := 0.0
    return R.value
```

3.18.3. Try-Catch

A third way to handle errors is to use a `try Body catch Handler` form, which evaluates `Body`, and if `Body` returns an `error`, evaluates `Handler` instead. The error that was caught by `catch` is called `caught`.

With this construct, the `sanitized_sqrt` above can be written in a much shorter and more idiomatic way as follows:

```
sanitized_sqrt X:real as real is
    try
        sqrt X
    catch
        print "Got an error in sqrt: ", caught
        0.0
```

This may look like exception handling, and intentionally so. However, `error` values are not exceptions in that they don't automatically propagate across functions like C++ exceptions do. If an error happens at some level, you must deal with it at that level, if only to explicitly pass it along. This is done automatically in many cases, so that the end result may feel a little like exceptions, but conceptually, this is always an `error` value being returned, not an exception being thrown.

3.18.4. Error statements

If a statement, assignment or declaration returns an `error`, then as a special evaluation rule, that `error` valuea is immediately returned by the enclosing function. It is a type error if the interface of the enclosing function does not allow an `error` return value.

For example, in C, it is frequent to have code that looks like:

```c
Thing *read_thing_from_file(const char *filename)
{
    FILE *file = fopen(filename, "r");
    if (file == NULL)
        return NULL;
    Thing *thing = malloc(sizeof(Thing))
    if (thing == NULL)
    {
        fclose(file);
        return NULL;
    }
    thing->header = malloc(sizeof(ThingHeader));
    if (thing->header == NULL)
    {
        free(thing);
        fclose(file);
        return NULL;
    }
    size_t header_read = fread(&thing->header, 1, sizeof(ThingHeader), file);
    if (header_read != sizeof(ThingHeader))
    {
        free (thing->header);
        free (thing);
        fclose(file);
        return NULL;
    }
    if (thing->header.size < MIN_SIZE)
    {
        log_error("Header size is too small: %u", thing->header.size);
        free(thing->header);
        free(thing);
        fclose(file);
        return NULL;
    }
    // ... possibly more of the same
    fclose(file);
    return thing;
}
```

In XL, handling `error` values is implicit, so that code similar to the above can be written as follows:

```
read_thing_from_file FileName:text as fallible own thing is
    F:file := file.open(FileName)       // May error out
    H:own thing_header := read(F)       // May error out (and close F)
    if H.size < MIN_SIZE then
        // Explicitly error out with custom message
        error "Header size is too small", H.size
    T:own thing := thing(H)             // May error out, dispose H, close F
    // ... possibly more of the same
    T
```

The notation `own T` above is an owning type that dynamically allocates an object from the heap.

3.19. Interface and implementation

XL provides strong *encapsulation* by allowing a programmer to hide irrelevant details of an implementation. This is fundamental to provide a robust module system.

All values in XL expose an *interface*, which define *what* can be done with the value, and also have an *implementation* of their interface to tell the program *how* operations actually happen. The interface needs to be visible for the program to be correct, but various mechanisms may allow to hide the implementation.

For example, a variable `integer` value named `X` has the following interface:

```
X : integer
```

This is all that is really needed in order to recognize the validity and meaning of operations such as `X+X`, `2*X+1`, `X<0` or `X:=18`. The actual value of `X` does not matter. In other words, it is sufficient to have the interface above to use `X`, an implementation like the one shown below can be hidden to the users of `X`:

```
X : integer := 42
```

The same is true for functions. For example, a function checking if a value is even could expose the following interface:

```
is_odd N:integer as boolean
```

Based on this interface alone, I know that I can write code that checks if a value is even or odd:

```
for I in 1..100 loop
    if is_odd I then
        print I, " is odd"
    else
        print I, " is even"
```

It does not matter if `is_odd` is actually implemented as follows:

```
is_odd N:integer as boolean is N mod 2 <> 0
```

or maybe as folows using the bitwise `and` operator:

```
is_odd N:integer as boolean is N and 1 = 1
```

The declarations must specify the interface of the values being used, but they need not specify the implementation. A definitions of the value must be provided at some point that matches the declaration and specifies an implementation, but that definition may be in a different source file.

RATIONALE In languages such as C++, some members of a class can be made *private* or *protected*. This restricts their usage, but the compiler (and the programmer) still have knowledge of internal details of the implementation. This facilitates some low-level copmiler optimizations (most of which are obsolete or irrelevant today), but also results in a number of long-term maintenance issues. Exposing implementation details in the interface worsens the fragile base class problem, since some aspects of the implementation are public enough that they cannot be modified. In XL, the implementation can be truly hidden, and an implementation must be able to generate code that does not depend on the implementation when the situation requires it, for example if the implementation may be in a different shared library than the code using the interface.

Chapter 4. Types

XL types are a way to organize values by restricting which operations can be selected during evaluation. For example, knowing that `A` is a `real` allows expression `A+A` to match declaration pattern `X:real+Y:real`, but prevents it from matching pattern `X:integer+Y:integer`.

In XL, types are based on the *shape* of parse trees. A type identifies the tree patterns that belong to the type. The expression `type(Pattern)` returns the type for the given type declaration pattern. For example, the type for all additions where the first value is a `real` is `type(A:real+B)`.

This approach to typing means in particular that a same value can belong to *multiple* types. For example, the expression `2+3*5` belongs to `type(A+B*C)`, but also to `type(A:integer+B:integer)`, or to `infix`.

Therefore, for XL, you shouldn't talk about *the* type of a value, but rather about *a* type. However, in the presence of a type annotation, it is customary to talk about *the type* to denote the single type indicated by the annotation. For example, for `X:integer`, we will ordinarily refer to the type of `X` as being `integer`, although the value of `X`, for example `2`, may also belong to other types such as `even_integer` or `positive_integer` or `type(2)`, a type that only contains the value `2`.

4.1. Type annotations

A type can be associated to a name using a *type annotation*. For example, a type annotation such as `X:integer` indicates that the values that can be bound to the name `X` must belong to the `integer` type.

Two infix operators can be used for type annotations, `X:T` and `X as T`. Both are annotations indicating that `X` belongs to type `T`. Typical usage for these two kinds of annotations is illustrated below, indicating that the `<` operator between two `integer` values has the `boolean` type:

```
X:integer < Y:integer as boolean
```

The first difference between the two kinds of type annotations is parsing precedence. The infix `:` has precedence higher than most operators, whereas infix `as` has a very low precedence. In most declarations, an infix `:` is used to give a type to formal parameters, whereas an infix `as` is used to give a type to the whole expression. This is illustrated in the example above, where `X:integer` and `Y:integer` define the types of the two formal parameters `X` and `Y` in the pattern `X < Y`, and the `as boolean` part indicates that the result of an operation like `3 < 5` has the `boolean` type.

Another difference is mutability. If type `T` is not explicitly marked as `constant` or `variable`, `X:T` indicates that `X` is mutable, whereas `X as T` indicates that `X` is not mutable. For example, `seconds : integer` declares a *variable* named seconds, where you can store your own seconds values, whereas `seconds as integer` declares a *function* named seconds, possibly returning the number of seconds in the current time from some real-time clock.

4.2. Basic types

The XL library provides a number of standard types representing fundamental data types common in most programming languages, as well as the types used as building blocks for a parse tree.

4.2.1. Basic data types

The basic data types include `integer`, `unsigned`, `real`, `character`, `text`, `boolean`. The `boolean` type in XL matches the values `true` and `false`, but unlike languages like C, it is not a numerical type. In other words, there is no equivalence between `true` and `1` or between `false` and `0`.

4.2.2. Sized data types

Types such as `integer`, `unsigned`, `character` or `real` are optimized for the target architecture the program runs on.

For portability, XL features sized variants of these types:

- `integer` and `unsigned` for at least 8, 16, 32 and 64 bits,
- `real` for at least 32 and 64 bits,
- `character` for at least 8, 16 and 32 bits.

The size types are named by apppending the type name and the bit size, for example `integer32` or `real64`.

When the standard sizes are not sufficient, it is easy to use integer subtypes to identify precise ranges of values or precise number of bits.

4.2.3. Parse tree types

The types that are used to represent parse tree elements include `integer`, `real`, `text`, `symbol`, `infix`, `prefix`, `postfix` and `block`, as well as the `parse_tree` type, which can be any of them.

```
parse_tree is either
    I:integer
    R:real
    T:text
    S:symbol
    I:infix
    P:prefix
    P:postfix
    B:block
```

It is likely that all these types will not be visible by default, but will ultimately require a `use XL.PARSER`.

In addition, the following subtypes help identify particular syntactic structures:

- `name` is a subtype of `symbol` for syntactically valid XL names, e.g. it will accept `A_2` but not `_A2`
- `operator` is a subtype of `symbol` that accepts only syntactically valid XL operators, i.e. it will

accept `+` but not `A`.

- `paren_block`, `square_block`, `curly_block` and `indent_block` are subtypes of `block` that require specific separators.

4.3. Type declarations

Like other XL values, a type can be given a name. For example, a `complex` type made of two `real` numbers representing the real and imaginary parts can be described as follows:

```
complex is type(complex(Re:real, Im:real))
```

This declaration means that any parse tree like `complex(1.3,2.5)` will match the `complex` type.

There is a shortcut notation for declaring types, where the `type` word can be placed in the pattern instead of in the body of the definition. This is nothing more than syntactic sugar for readability. The previous example should be written as follows:

```
type complex is complex(Re:real, Im:real)
```

A declaration `type T is P` is equivalent to `T is type (P)`. This is important to remember if you write type expressions. For example:

```
// This is `type(integer)`, which only accepts the name `integer`
type int is integer

// This is `type(X:integer8)`, which accepts `integer8` values
type int8 is X:integer8

// This creates an alternate name for `unsigned`
positive is unsigned
```

4.4. Type-related concepts

A number of essential concepts are related to the type system, and will be explained more in details below:

- the lifetime of a value is the amount of time during which the value exists in the program. Lifetime is, among other things, determined by scoping.
- creation and destruction defines how values of a given type are initialized and destroyed.
- errors are special types used to indicate failure.
- mutability is the ability for an entity to change value over its lifetime.
- compactness is the property of some types to have their values represented in the machine in a compact way, i.e. a fixed-size sequence of consecutive memory storage units (most generally

bytes).

- ownership is a properties of some types to control the lifetime of the associated values or possibly some other resource such as a network connection. Non-owning types can be used to access values of an associated owning type.
- inheritance is the ability for a type to inherit all operations from another type, so that its values can safely be implicitly converted to values of that other type.
- the interface of a type is an optional scope that exposes *fields* of the type, i.e. individually accessible values. The *implementation* of the type must provide all interfaces exposed in the type's interface.
- copy, move and binding are operations used to transfer values across parts of a program.
- atomicity is the ability to perform operations in a way that allows consistent behavior across multiple threads of execution, possibly executing concurrently on different CPUs.

4.4.1. Lifetime

The lifetime of a value is the amount of time during which the value exists in the program, in other words the time between its creation and its destruction.

An entity is said to be *live* if it was created but not yet destroyed. It is said to be *dead* otherwise.

> Some entities may be live but not accessible from within the current context because they are not visible. This is the case for variables declared in the caller's context.

The lifetime information known by the compiler about entity `X` is represented as compile-time constant `lifetime X`. The lifetime values are equipped with a partial order `<`, such that the expression `lifetime X < lifetime Y` being `true` is a compiler guarantee that `Y` will always be live while `X` is live. It is possible for neither `lifetime X < lifetime Y` nor `lifetime X > lifetime Y` to be true. This `lifetime` feature is used to implement Rust-like restrictions on access types, i.e. a way to achieve memory safety at zero runtime cost.

The lifetime of XL values fall in one of the following categories:

- *Global* entities are live at least as long as they are visible. This includes builtin-enttiies, entitites declared in the top-level of the modules used by the program, and most entities created by the compiler itself. The compiler can generally assign preallocated storage to such entities, at compilation time.
- *Temporary values* hold the result of evaluation of functions. They are created in the called function, and copied or moved to the function caller. The temporary value is destroyed before the end of the statement, and possibly as early as it is no longer used. In the following example, the value of `x*3` can be destroyed as soon as the expression `x*3+5` is computed.

  ```
  f(x) is (x*3+5)/2
  ```

  Such temporary values are typically stored in registers or on the stack, although some temporary values may require heap storage that will be freed when the value is destroyed.

- *Named constants* have a lifetime that corresponds to their scope. As long as the named constant is visible, it exists. In the following example, the value of `DEGREE_TO_RADIAN`, `2 * pi / 180` exists for the duration of the `cos_degrees` function:

```
cos_degrees X is
   DEGREE_TO_RADIAN is 2 * pi / 180
   cos(X * DEGREE_TO_RADIAN)
```

  The compiler has a lot of freedom on how to implement named constants, and may use preallocated storage, functions, or immediate constants depending on the need.

- *Variables* have a lifetime that generally corresponds to their scope, but the value of their lifetime terminates each time the value is updated. In the following example, `Message` is created with value `"Hello"`, but on the second line, that value is destroyed to be replaced with value `"Hello World"`.

```
Message : text := "Hello"
Message := Message & " World"
```

  Except for global variables, variables are usually stored on the stock or in registers.

- *Dynamic values* require dynamic storage, generally in a heap. The lifetime of such values is normally controlled by the values used to access the storage. With the exception of data types used to access data not owned by the XL program (e.g. data allocated from another language), XL ownership rules ensure that dynamic values are destroyed as soon as they can no longer be accessed.

  For example, the code below creates a `string of integer`, which uses dynamically allocated storage, to hold an arbitrary large sequence of `integer` values. Thus, the `string of integer` value extends the lifetime of all values geneated in the sequence. However, it also guarantees that these values are destroyed when the `string of integer` value itself is no longer needed.

```
syracuse N:integer as string of integer is
    loop
        result := result & N
        N := if N mod 2 = 0 then N/2 else N*3+1
    until N = 1
```

  Dynamic data is normally stored on a standard heap, but XL provides hooks that make it possible to provide your own allocation for data storage.

4.4.2. Creation

Creation is the process of preparing a value for use. The XL compiler ensures that specific rules are followed to invoke creation code provided by the programmer before any other possible use of the value being created.

When you define a type, you need to specify the associate shape. For example, we defined a `complex` type as follows:

```
type complex is complex(Re:real, Im:real)
```

This means that a shape like `complex(2.3, 5.6)` is a `complex`. This also means that the *only* elementary way to create a `complex` is by creating such a shape. It is not possible to have an uninitialized element in a `complex`, since for example `complex(1.3)` would not match the shape and not have the right type.

Using the shape explicitly given for the type is called the *constructor* for the type. A constructor can never fail nor build a partial object. If an argument returns an error during evaluation, then that `error` value will not match the expected argument, except naturally if the constructor is written to accept `error` values.

Often, developers will offer alternate ways to create values of a given type. These alternate helpers are nothing else than regular definitions that return a value of the type.

For example, for the `complex` type, you may create an imaginary unit, `i`, but you need a constructor to define it. You can also recognize common expressions such as `2+3i` and turn them into constructors.

```
i   is complex(0.0, 1.0)

syntax { POSTFIX 190 i }
Re:real + Im:real i                is complex(Re, Im)      // Case 1
Re:real + Im:real * [[i]]          is complex(Re, Im)      // Case 2
Re:real + [[i]] * Im:real          is complex(Re, Im)      // Case 3
Re:real as complex                 is complex(Re, 0.0)     // Case 4
X:complex + Y:complex as complex   is ...

2 + 3i              // Calls case 1 (with explicit concersions to real)
2 + 3 * i           // Calls case 2 (with explicit conversions to real)
2 + i * 3           // Calls case 3
2 + 3i + 5.2        // Calls case 4 to convert 5.2 to complex(5.2, 0.0)
2 + 3i + 5          // Error: Two implicit conversions (exercise: fix it)
```

A type implementation may be *hidden* in a module interface, in which case the module interface should also provide some functions to create elements of the type. The following example illustrates this for a `file` interface based on Unix-style file descriptors:

```
module MY_FILE with
    type file
    open Name:text as file
    close F:file

module MY_FILE is
    type file is file(fd:integer)
    open Name:text as file is
        fd:integer := libc.open(Name, libc.O_RDONLY)
        file(fd)
    close F:inout file is
        if fd >= 0 then
            libc.close(F.fd)
            F.fd := -2
    delete F:inout file is close F    // Destruction, see below
```

RATIONALE This mechanism is similar to *elaboration* in Ada or to *constructors* in C++. It makes it possible for programmers to provide strong guarantees about the internal state of values before they can be used. This is a fundamental brick of programming techniques such as encapsulation, programming contracts or RAII.

4.4.3. Destruction

When the lifetime of a value `V` terminates, the statement `delete V` automatically evaluates. Declared entites are destroyed in the reverse order of their declaration. A `delete X:T` definition is called a *destructor* for type `T`. It often has an inout parameter for the value to destroy, in order to be able to modify its argument, i.e. a destructor often has a signature like `delete X:inout T`.

There is a built-in default definition of that statement that has no effect and matches any value:

```
delete Anything is nil
```

There may be multiple destructors that match a given expression. When this happens, normal lookup rules happen. This means that, unlike languages like C++, a programmer can deliberately override the destruction of an object, and remains in control of the destruction process.

RATIONALE In XL, multiple patterns can match a given value. It might seem desirable to call all the patterns that match, but not only would it introduce a special-case lookup, it would also be extremely dangerous in a number of easily identified cases. As an illustration, consider the following code:

```
delete F:inout file when F.fd < 0  is ... // Case 1
delete F:inout file                is ... // Case 2
```

Clearly, the intent of the programmer is to special-case the destruction of `file` values that have an invalid file descriptor, for example as a result of an error condition from the C `open` call (which returns `-1` on error).

It is possible to create local destructor definitions. When such a local definition exists, it is possible for it to override a more general definition. The general definition can be accessed using super lookup.

```
show_destructors is
    delete Something is
        print "Deleted", Something
        super.delete Something
    X is 42
    Y is 57.2
    X + Y
```

This should output something similar to the following:

```
Deleted 42.0
Deleted 57.2
Deleted 42
```

The first value being output is the temporary value created by the necessary implicit conversion of `X` from `integer` to `real`. Note that additional temporary values may appear depending on the optimizations performed by the compiler. The value returned by the function should not be destroyed, since it's passed to the caller.

Any destruction code must be able to be called multiple times with the same value, if only because you cannot prevent a programmer from writing:

```
delete Value
```

In that case, `Value` will be destroyed twice, once by the explicit `delete`, and a second time when `Value` goes out of scope. There is obviously no limit on the number of destructions that an object may go through.

```
for I in 1..LARGE_NUMBER loop
    delete Value
```

Also, remember that assigning to a value implicitly destroys the target of the assignment.

4.4.4. Errors

Errors in XL are represented by values with the `error` type (or any type that can be implicitly converted to `error`, in other words, any value that inherits from error). The error type has a constructor that takes a simple error message, or a simple message and a payload:

```
type error is either
    error Message:text
    error Message:text, Payload
```

A function that may fail will often have a `T or error` return value. There is a specific shortcut for that, `fallible T`:

```
fallible T:type is T or error
```

For example, a logarithm returns an error for non-positive values, so that the signature of the `log` functions is:

```
log X:real as fallible real     is ... // May return real or error
```

If possible, error detection should be pushed to the interface of the function. For the `log` function, it is known to fail only for negative or null values, so that a better interface would be:

```
log X:real as real  when X > 0.0    is ... // Always return a real
log X:real as error                 is ... // Always return an error
```

A benefit of writing code this way is that the compiler can more easily figure out that the following code is correct and does not require any kind of error handling:

```
if X > 0.0 then
    print "Log(", X, ") is ", log X
```

RATIONALE By returning an `error` for failure conditions, XL forces the programmer to deal with errors. They cannot simply be ignored like C return values or C++ exceptions can be. Errors that may possibly return from a function are a fundamental part of its type, and error handling is not optional.

A number of types derive from the base `error` type to feature additional properties:

- A `compile_error` helps the compiler emit better diagnostic for situations which would lead to an invalid program.

  ```
  // Emit a specific diagnostic when writing a real into an integer
  X:integer := Y:real       is compile_error "Possible truncation"
  ```

- A `range_error` indicates that a given value is out of range. The default message provided is supplemented with information comparing the value with the expected range.

```
T:text[A:integer] as character or range_error is
    if A < 0 or A >= length T then
        range_error "Text index is out of bounds", A, T
    else
        P : memory_address[character] := memory_address(T.first)
        P += A
        *P
```

- A `logic_error` indicates an unexpected condition in the program, and can be returned by `assert`, `require` and `ensure`.

```
if X > 0 then
    print "X is positive"
else if X < 0 then
    print "X is negative"
else
    logic_error "I never considered that case"
```

4.4.5. Mutability

A value is said to be *mutable* if it can change during its lifetime. A value that is not mutable is said to be *constant*. A mutable named entity is called a *variable*. An immutable named entity is called a *named constant*.

The `X:T` type annotations indicates that `X` is a mutable value of type `T`, unless type `T` is explicitly marked as constant. When `X` is a name, the annotation declares that `X` is a variable. The `X as T` type annotation indicates that `X` is a constant value of type `T`, unless type `T` is explicitly marked as variable. When `X` is a name, this may declare either a named constant or a function without parameters, depending on the shape of the body.

```
StartupMessage : text := "Hello World"  // Variable
Answer as integer is 42                 // Named constant
```

A mutable value can be initialized or modified using the `:=` operator, which is called an *assignment*. There are a number of derived operators, such as `+=`, that combine a frequent arithmetic operation and an assignment.

```
X : integer := 42       // Initialize with value 42
X := X or 1             // Binary or, X is now 43
X -= 1                  // Subtract 1 from X, now 42
```

Some entities may give access to individual inner values. For example, a `text` value is conceptually made of a number of individual `character` values that can be accessed individually. This is true irrespective of how `text` is represented. In addition, a slice of a `text` value is itself a `text` value. The mutability of a `text` value obviously has an effect on the mutability of accessed elements in the `text`.

The following example shows how `text` values can be mutated directly (1), using a computed assignment (2), by changing a slice (3) or by changing an individual element (4).

```
Greeting : text := "Hello"               // Variable text
Person as text is "John"                 // Constant text
Greeting := Greeting & " " & Person      // (1) Greeting now "Hello John"
Greeting &= "!"                          // (2) Greeting now "Hello John!"
Greeting[0..4] := "Good m0rning"         // (3) Greeting now "Good m0rning John!"
Greeting[6] := 'o'                       // (4) Greeting now "Good morning John!"
```

None of these operations would be valid on a constant text such as `Person` in the code above. For example, `Person[3]:='a'` is invalid, since `Person` is a constant value.

In the case (3) above, modifying a `text` value through an access type can change its length. This is possible because `Greeting[0..4]` is not an independent value, but an access type, specifically a `slice`, which keeps track of both the `text` (`Greeting` here) and the index range (`0..4` in that case), with a `:=` operator that modifies the accessed `text` value.

A constant value does not change over its lifetime, but it may change over the lifetime of the program. More precisely, the lifetime of a constant is at most as long as the lifetime of the values it is computed from. For example, in the following code, the constant `K` has a different value for every interation of the loop, but the constant `L` has the same value for all iterations of `I`

```
for J in 1..5 loop
    for I in 1..5 loop
        K is 2*I + 1
        L is 2*J + 1
        print "I=", I, " K=", K, " L=", L
```

RATIONALE There is no syntactic difference between a constant and a function without parameters. An implementation should be free to implement a constant as a function if this is more effective, or to use smarter strategies when appropriate.

4.4.6. Compactness

Some data types can be represented by a fixed number of contiguous memory locations. This is the case for example of `integer` or `real`: all `integer` values take the same number of bytes. Such data types are called *compact*.

On the other hand, a `text` value can be of any length, and may therefore require a variable number of bytes to represent values such as `"Hi"` and `"There once was a time where text was represented in languages such as Pascal by fixed-size character array with a byte representing the length. This meant that you could not process text that was longer than, say, 255 characters. More modern languages have lifted this restriction."`. These values are said to be *scattered*.

Scattered types are always built by *interpreting* compact types. For example, a representation for text could be made of two values, the memory address of the first character, and the size of the text. This is not the only possible representation, of course, but any representation require interpreting fixed-size memory locations and giving them a logical structure.

Although this is not always the case, the assignment for compact types generally does a copy, while the assignment for scattered types typically does a move.

4.4.7. Ownership

Computers offer a number of resources: memory, files, locks, network connexions, devices, sensors, actuators, and so on. A common problem with such resources is to control their *ownership*. In other words, who is responsible for a given resource at any given time.

In XL, like in languages like Rust or C++, ownership is largely determined by the type system, and relies heavily on the guarantees it provides, in particular with respect to creation and destruction. In C++, the mechanism is called RAII, which stands for *Resource Acquisition is Initialization*. The central idea is that ownership of a resource is an invariant during the lifetime of a value. In other words, the value gets ownership of the resource during construction, and releases this ownership during destruction. This was illustrated in the `file` type of the module `MY_FILE` given earlier.

Types designed to own the associated value are called *owner types*. There is normally at most one live owner at any given time for each controlled resource, that acquired the resource at construction time, and will release it at destruction time. It may be possible to release the owned resource early using `delete Value`.

The standard library provides a number of types intended to own common classes of resources, including:

- An `array`, a `buffer` and a `string` all own a contiguous sequence of items of the same type.
  - An `array` has a fixed size during its lifetime and allocates items directly, e.g. on the execution stack.
  - A `buffer` has a fixed size during its lifteime, and allocates items dynamically, typically from a heap.
  - A `string` has a variable size during its lifetime, and consequently may move items around in memory as a result of specific operations.
- A `text` owns a variable number of `character` items, being equivalent to `string of character`.
- A `file` owns an open file.
- A `mutex` owns execution by a single thread while it's live.
- A `timer` owns a resource that can be used to measure time and schedule execution.
- A `thread` owns an execution thread and the associated call stack.
- A `task` owns an operation to perform that can be dispatched to one of the available threads of execution.
- A `process` owns an operating system process, including its threads and address space.
- A `context` captures an execution context.

- An `own` value owns a single item allocated in dynamic storage, or the value `nil`.

4.4.8. Access

Not all types are intended to be owner types. Many types delegate ownership to another type. Such types are called *access types*. When an access type is destroyed, the resources that it accesses are *not* disposed of, since the access type does not own the value. A value of the acces type merely provides *access* to a particular value of the associated owner type.

For example, if `T` is a `text` value and if `A` and `B` are `integer` values, then `T[A..B]` is a particular kind of access value called a *slice*, which denotes the fragment of text between `0`-based positions `A` and `B`. By construction, slice `T[A..B]` can only access `T`, not any other `text` value. Similarly, it is easy to implement bound checks on `A` and `B` to make sure that no operation ever accesses any `character` value outside of `T`. As a result, this access value is perfectly safe to use.

Access types generalize *pointers* or *references* found in other languages, because they can describe a much wider class of access patterns. A pointer can only access a single element, whereas access types have no such restriction, as the `T[A..B]` example demonstrates. Access types can also enforce much stricter ownership rules than mere pointers.

> The C language worked around the limitation that pointers access a single element by abusing so-called "pointer arithmetic", in particular to implement arrays. In C, `A[I]` is merely a shortcut for `*(A+I)`. This means that `3[buffer]` is a valid way in C to access the third element of `buffer`, and that there are scenarios where `ptr[-1]` also makes sense as a way to access the element that precedes `ptr`. Unfortunately, this hack, which may have been cute when machines had 32K of memory, is now the root cause of a whole class of programming errors known as *buffer overflows*, which contribute in no small part to the well-deserved reputation of C as being a language that offers no memory safety whatsoever.

The standard library provides a number of types intended to access common owner types, including:

- A `slice` can be used to access range of items in contiguous sequences, including `array`, `buffer` or `string` (and therefore `text`, which is `string of character`).
- A `reader` or a `writer` can be used to access a `file` either for reading or writing.
- A `lock` takes a `mutex` to prevent multiple threads from executing a given piece of code.
- Several types such as `timing`, `dispatch`, `timeout` or `rendezvous` will combine `timer`, `thread`, `task` and `context` values.
- A `ref` is a reference to a live `own` value.
- The `in`, `out` and `inout` type expressions can sometimes be equivalent to an access types if that is the most efficient way to pass an argument around. However, this is mostly invisible to the programmer.
- A `memory_address` references a specific address in memory, and is the closest there is in XL to a raw C pointer. It is purposely verbose and cumbersome to use, so as to discourage its use when not absolutely necessary.

4.4.9. Inheritance

A type is said to *inherit* another type, called its *base type*, if it can use all its operations. The type is then said to *derive* from the base type. In XL, this is achieved simply by providing an *implicit conversion* between the derived type and the base type:

```
Derived:derived as base is ...
```

As a consequence of this approach, a type can derive from any number of other types, a feature sometimes called multiple inheritance. There is also no need for the base and derived type to share any specific data representation, although this is often done in practice. For example, there is an implicit conversion from `integer16` to `integer32`, altough the machine representation is different.

4.4.10. Subtypes

A type can be given additional constraints, which define a *subtype*. A subtype can always be converted to the type it was derived from, and therefore derives from that type in the inheritance sense. A subtype machine representation may differ from the type it derives from.

For example, from the `integer` type, one can construct a `month` type that matches only `integer` values between `1` and `12` using a regular conditional pattern as follows:

```
month is type(X:integer when X >= 1 and X <= 12)
```

4.4.10.1. Range subtypes

Subtyping to select a range is common enough that there is a shortcut for it. For any type with an order, subtypes can be created with the `range` infix operator:

```
T:type range Low:T..High:T      is type(X:T when X in Low..High)
```

With this definition, the `month` type can be defines simply as follows:

```
month is integer range 1..12
```

4.4.10.2. Size subtypes

The infix `bits` operator creates a subtype with the specified number of bits. It applies to `real`, `integer` and `character` types.

For example, the `integer8` type can be defined as:

```
integer8 is integer bits 8
```

This implicitly implies a `range` that depends on the type being subtyped. For example, for `integer` and `unsigned`, the range would be defined as follows:

```
[[integer]]  bits N:unsigned    is integer  range -2^(N-1)..2^(N-1)-1
[[unsigned]] bits N:unsigned    is unsigned range  0..2^N-1
```

> The `bits` subtypes are intended to specify the bit size of the machine representation. The requested size may be rounded up to a more convenient or more efficient machine representation. For example, on a 32-bit machine, `integer bits 22` might be more efficiently represented as a 32-bit value in registers and as 3 bytes, i.e. 24 bits, in memory.

4.4.10.3. Real subtypes

The `real` type can be subtype with a `range` and a `bits` size, as well as with additional constraints more specific to the `real` type:

- a `digits` count specifies the number of accurate decimal digits. For example, `real digits 3` is represents values with at least 3 significant digits.
- a `quantum` followed by a literal real value specifies a representation that should be representable exactly. For example, on a machine using IEEE-754, the value `0.01` cannot be represented accurately but `real quantum 0.01` will accurately represent it. > NOTE: Converting to a `real` will lose that accuracy.
- an `exponent` specifies the maximum decimal exponent. For example, `real exponent 100` will ensure that values up to `1.0e100` can be represented.
- a `base` specifies the base for the internal representation. Only bases `2`, `10` and `16` are allowed. Base `2` requires a binary floating-point representation. Base `10` requires a decimal floating-point representation. Base `16` requires an hexadecimal floating-point representation on historical platforms that support it.

A `real` subtype is represented as a *fixed point* representation if one of the following conditions is true:

- The `exponent` is specified as `0`
- The `range` is small enough to be representable entirely with the same exponent
- A `quantum` is specified and no `exponent` is specified.

For example, the `hundredth` type defined below could be represented internally by `integer` values between `0` and `100`, and converted to `real` by multiplying this value by the given `quantum` value.

```
hundredth is real range 0.0..1.0 quantum 0.01
```

4.4.10.4. Character and text subtypes

The `character` and `text` can be subtyped with the `range` and, for `character`, the `bits` operators.

In addition, they both can be subtyped with the following infix operators:

- The `encoding` operator specifies the encoding used for the text, for example `text encoding UTF8` or `character encoding ASCII`.
- The `locale` operator specifies the locale for the text, for example `text locale fr_FR` will select a French locale.
- The `collation` operator specifies collating order. For example, to have `text` values that sort following German rules, you would use `text collate de_DE`

4.4.11. Interface

The interface of a type can specifiy a scope for values that match the type, using the syntax `type T with I`, where `I` is a scope containing the publicly available declarations. These declarations are called *fields* of the type when they denote mutable values, and *members* of the type if they are constant.

The code below defines a `picture` type that exposes `width`, `height` and `data` fields, as well as a `size` member that is used to compute the size of the `data` buffer.

```
type picture with
    width  : unsigned
    height : unsigned
    data   : buffer[size] of unsigned8
    size as unsigned
```

Note that only knowing the interface of a type does not allow values of the type to be created. Typically, the interface of a function making it possible to create values will also be provided. In the rest of the discussion for the `picture` type, we will also assume that there is a `create_picture` function with the following interface:

```
picture(width:unsigned, height:unsigned) as picture
```

A type interface can announce that the declared type will derive from one or several other types using the `like` infix:

```
type derived like base1, base2, base3 with
    additional : field
```

An interface may consist of only announcing the inheritance, or of not announcing anything at all:

```
type derived like base      // All we know is that it derives from base
type totally_abstract       // All we know is that the type exists
```

4.4.11.1. Information hiding

The interface does not reveal any information on the actual shape of the parse tree for `picture` values. In other words, it does not specify how the `picture` type is actually implemented. A type that has a name but no implementation, like `picture` above, is called a *tag type*. A tag type can only match values that were *tagged* with the same type using some explicit type annotation.

The type interface above remains sufficient to validate code like the following definition of `is_square`:

```
is_square P:picture is P.width = P.height
```

In that code, `P` is properly tagged as having the `picture` type, and even if we have no idea how that type is implemented, we can still use `P.width` and deduce that it's an `integer` value based on the type interface alone.

4.4.11.2. Anonymous scope implementation

The simplest way to implement fields is to create a type that has a structure exposing declarations that directly match the interface. For the `picture` type, this could be the following code:

```
type picture is
    width   : unsigned
    height  : unsigned
    data    : buffer[size] of unsigned8
    size is width * height
```

Remember that this is equivalent to:

```
picture is type
    width   : unsigned
    height  : unsigned
    data    : buffer[size] of unsigned8
    size is width * height
```

This implementation of the `picture` type is a pattern that matches values that have the exact same structure, such as:

```
my_picture is
    1024
    768
    my_buffer
```

For better readability, the pattern can also match a scope

```
another_picture is
    width  is 1024
    height is 768
    buffer is another_buffer
```

4.4.11.3. Named scope implementation

In general, you want the pattern to be more specific, so it is customary to add a prefix that matches the type name and add infix `,` operators separating the values, therefore creating a constructor.

```
type picture is picture
    width   : unsigned,         // Notice the comma
    height  : unsigned,         // Here too
    data    : buffer[size] of unsigned8
    size is width * height

my_picture is picture(1024, 768, my_buffer)

another_picture is picture
    width  is 256
    height is 256
    data   is another_buffer
```

4.4.11.4. Indirect implementation

However, the implementation is often entirely different, and merely needs to *expose* the interface in some way. This is called an *indirect implementation* of the interface.

For example, the `picture` type can be implemented by *delegating* the implementation to another value that provides the required information. For the sake of illustration, we will imagine that we use a `bitmap` type defined as follows:

```
type bitmap with
    width  : unsigned16
    height : unsigned16
    buf    : array[width, height] of unsigned8
```

This means that the implementation of the `picture` type must perform some adjustments in order to delegate the work to the underlying `bitmap` value.

```
type picture is picture
    Bitmap:bitmap
    buffer:optional[buffer[size] of unsigned8]

(P:picture).width   is P.Image.width
(P:picture).height  is P.Image.height
(P:picture).buffer  is P.Image.buffer
```

4.4.12. Copy

The assignment operator is written `A := B` in XL. For compact types, this is normally equivalent to `A :+ B`, which is guaranteed to be a *copy*.

4.4.13. Move

4.4.14. Binding

4.4.14.1. `in` arguments

4.4.14.2. `out` arguments

4.4.14.3. `inout` arguments

4.4.15. Atomicity

4.5. Type expressions

A type declaration is like any other XL declaration. It can have parameters, including parameters with the `type` type, and such declarations can then be used to build *type expressions*.

For example, the following code extends our previous `complex` type to take an argument that indicates the representation for `real` numbers, and uses that first declaration to declare two types, `complex` and `complex32`, the latter using `real32` as a representation type for real numbers:

```
type complex[real:type] is complex(Re:real, Im:real)
type complex is complex[real]
type complex32 is complex[real32]
```

Type expressions play for XL the role that "class templates" play in C++, or "generic types" in Ada. By convention, the formal parameters or arguments of type expressions are placed between square brackets, as in `complex[real]`, although there is no requirement for this. In practice, exceptions are frequent, notably for types using operator-like notations, like `pointer to T`.

4.6. Standard type expressions

A number of type expressions are provided by the standard library. The most common and useful ones are:

- `nil` is a type that contains a single value, `nil`, which evaluates to itself. That is generally used to represent an absence of value.
- `T1 or T2` is a type for values that belong to `T1` or to `T2`. It is similar to what other languages may call union types. For example, `integer or real` will match both `integer` and `real` values. Operations on `T1 or T2` will cause dynamic dispatch depending on the actual value being considered. For example, consider:

```
double X:(integer or real) is X + X
double 1      // returns 2 as an integer
double 3.5    // returns 7.0 as a real
```

- `T1 and T2` is a type for values that belong to both `T1` and `T2`. For example, `number and totally_ordered` will match totally ordered numbers, i.e. it will not match `"ABC"` (`totally_ordered`, but not a `number`) nor will it match `ieee754(2.5)` (`number`, but not `totally_ordered`).
- `another T` is a new type that is identical to `T`, allowing overloading. For example, `type distance is another real` will create another `real` type, allowing you to forbid multiplication, and preventing errors such as adding a `distance` to a `real`.

```
type distance is another real
X:distance * Y:distance is compile_error "Cannot multiply distances"
X:real as distance is compile_error "Implicit distance from real"
syntax { POSTFIX 400 m cm mm km }
X:real m  is distance(X)
X:real cm is distance(X * 0.01)
X:real mm is distance(X * 0.001)
X:real km is distance(X * 1000.0)

D:distance is 3.2km
D + D     // OK: inherit X:distance+Y:distance from X:real+Y:real
D + 1.0   // Error: Implicit distance from real
D * D     // Error: Cannot multiply distances
```

> The code above is incomplete, since `distance` would inherit `X:integer as real`, so that `D+1` would be accepted.

- `optional T` is a shortcut for `T or nil`. This is useful for functions like `find` that return an optional value, and where not finding something is not an error but an expected result. > NOTE: Compilers should perform specific optimizations such as > representing the value with a pointer and reserving the null > pointer for value `nil`.
- `fallible T` is a shortcut for `T or error`, and should be used for functions that may fail. Unlike

nil, an error carries a payload that gives information about the error, and can be used to generate an error message.

- array[N] of T defines a 0-based array containing N elements of type T. The value of N need not be a constant. Another variant, array[A..B] of T, allows arrays where the index is between values A and B, which can be any enumerated type. For example, array['A'..'Z'] of boolean provides 26 boolean values, indexed by an alphabetic letter.
- string of T is a variable size sequence of values with the same type T. The size of a string can change over its lifetime. A text may be represented as a string of character.
- either Patterns is a type that matches one of the patterns given. It can be used in particular for what would be called "enumerations" in a language like C, but is richer, much like Rust enumerations

```
type complex is either
    cartesian(Re:real, Im:real)
    polar(Mod:real, Arg:real)
```

- variable T or var T is a mutable version of type T, whereas constant T is a non-mutable version of type T. Only mutable values can be changed using the := operator or their variants. > NOTE: By default, formal parameters are mutable, since > they are generally specified with something like X:integer, but > modifications apply to the binding in the current evaluation > context, therefore not modifying the corresponding argument.
- in T, out T and inout T are types design to optimize parameter passing in a safe way. They indicate how you intend data to flow between the caller and the callee. These types also may have uses in data structures.
- T in ValueList is a subtype of T that only accepts values in the given comma-separated ValueList. For types that have a total order, ValueList elements can also include ranges written as A..B. For example, integer in 1..5,9,12..20 is a type that only accept integer values 1 through 5, or 9, or 12 through 20. Similarly, text in "One", "Two", "Three", "Four" is a type that only accepts the given text strings.

These are only some common examples of type expressions. There is nothing that prevents you from adding many others.

The case of in T, out T and inout T are examples of what will be called *ownership controlling types*, i.e. types that are dedicated to controlling who owns what data. More details are provided in the section on ownership below.

4.6.1. Copy or Move

4.6.2. Variant types

```
type picture with
    width  : unsigned
    height : unsigned
    format : either { RGB; GRAY }
    data   : buffer
    size is width * height
    type grayscale is fixed_point range 0.0..1.0 bits 8
    type buffer is buffer[1..size] of pixel

    type pixel is pixel[format]
    type pixel[RGB] is rgb(red   : grayscale,
                           green : grayscale,
                           blue  : grayscale)
    type pixel[GRAY] is gray(gray: grayscale)
```

copy-controlling types, which cause a copy when the value is initialized, when it goes out of scope, or in both cases. They are mostly used for function parameters, although they can also be used in data structures. `increment X:inout integer is X := X+1; print_A print_A is print "A=", A A:integer := 45 increment A // Can print either "A=45" or "A=46" depending on copy or ref` > NOTE: The language makes no guarantee that the copies happen > *only* when the value is created or destroyed. Typically, `inout T` > will perform copies only for small objects, and use references for > larger ones if the lifetime of the bound value allows it. The > compilers determines which approach is more efficient in an > architecture-dependent way.

The `copy_in T`, `copy_out T` and `copy_inout T` are types that guarantee that copy will occur.

- `ref T` is a reference to the entity being bound, meaning that any change to the `ref T` value will actually modify the bound value. The lifetime of the bound value must dominate the lifetime of the `ref T` value. Mutability for the reference is the same as mutability for the

  ```
  // Increment in place
  increment X:ref integer is X := X+1; print_A
  print_A is print "A=", A
  A:integer := 45
  increment A   // Guaranteed to print "A=46", X is the same as A
  ```

4.7. Type hierarchy

4.7.1. MOSTLY JUNK BELOW, IGNORE (IDEAS SCRATCHPAD)

The difference matters in particular in the interface of a type, as declared by `with`. The non-mutable declarations using `as` are considered as belonging only to the type, whereas mutable declarations using `:` are considered as belonging to values of the type. As a result, much like C++ class member declarations, "functions" or "methods" are interpreted as belonging to the type, whereas "values" or "members" belong to type instances.

For example, consider a `person` type declaration like the following:

type person with Name : text Greeting as text

This means that the `Name` belongs to each value of the `person` type, but that the `Greeting` belongs to the `person` type, not to individual `person` instances. If `P` is a `person`, then `P.Name` depends on the individual person, but `P.Greeting` is the same as `person.Citizenship`.

Inversely, if a declaration takes a value of the type as its first argument (usually called `Self`), then the value can be passed using the dot field notation. For example, consider:

type person with FirstName : text LastName : text FullName Self:person as text

In that case, it is possible to write `P.FullName` which will be a shortcut for `person.FullName P`.

A given piece of code can belong to multiple types. For example, code like `2 + 3` could belong to an `addition` type defined as `addition is type A+B`, but also be considered an `infix` type before evaluation, or an `integer` after evaluation using the declarations in the `ARITHMETIC` module.

A subtype is a type whose values all belong to its supertype. A subtype can therefore be used wherever the supertype can. Several type constructors create subtypes with various restrictions. For example, `constant integer` is a subtype of `integer` where values cannot be mutated, whereas `integer range 1..5` is a subtype of integer where values have to be between 1 and 5.

A derived type is a type built by adding more capabilities to a base type. Therefore, the derived type is a subtype of the base type. For example, `integer` is a derived type of `number`, adding a specific representation of values, which implies that `integer` values can be used for any operation that accepts the `number` type.

The TYPE module offers a number of type constructors, notably the most basic one, `type Pattern`, which returns a type matching the pattern. For example, `type complex(Re:real, Im:real)` would match the vaue `complex(2.0, 3.5)`. This is XL's equivalent of struct in C.

Types are first-class citizen in XL: they can be stored in variables, passed around, and so on. The compiler will determine if a specific use of a type variable should be treated like "template code" to use C++ terminology, or if there is a better way to implement it.

For example, consider an allocation of memory for type `T`:

```
Allocate[T:type] as pointer[T]
```

The compiler is free to implement this as a generic function, similar to a C++ template, or as a function taking some pointer to type data, using for example `T.ByteSize` to allocate memory.

A type has an *interface* and an *implementation*. An interface is described using the `with` operator, whereas an implementation is given using the `is` operator. The compiler checks that the implementation matches the interface, but there are many ways to implement the interface.

Consider for example the following interface: type complex with Re : real Im : real Modulus : real Argument : real

This does not imply anything about the actual representation of complex numbers. It only implies that if `Z` is a complex number, it is possible to read and write all four fields.

A valid implementation of this type could be storing data in cartesian form and performing computation when reading or writing Modulus and Arguments. It could also switch back and forth between polar and cartesian form based on actual field accesses, and have an implementation that looks like: type complex is either cartesian Re:real, Im:real polar Modulus:real, Argument:real The latter is closer to how the type is actually implemented in the standard library */

use BITWISE, MEMORY, TEXT, BOOLEAN

type type with // ——————————————————————————- // A `type` is used to identify a set of values // ——————————————————————————- // Simple types like `integer` or `array[1..5] of real` occupy a known // amount of space in memory. They are defined by consecutive bits and bytes. // // Reference and pointer types are represented by a machine pointer. // For example, an `access integer` will be a simple pointer to an integer. // In that case, the pointer type's `Indirect` field points to the type // being pointed to, `integer` in the above example. // // If the actual type of the object is only known at runtime, as would // be the case for `any integer`, then the value pointer is followed // by a type pointer, and `DynamicType` is a pointer to that dynamic type. // For example, if you pass a `M:mammal` value as `A:any animal`, then // `(any animal).Indirect = animal` and `(any animal).DynamicType` is // `any animal`. The value `A` is made of two pointers, the first one // being a pointer to `M`, the second one being a pointer to `mammal` // // If the actual size of the object is only known at runtime, as would be would point to a type where `DynamicSize` is itself the size type. // In that case, the size type is what the base pointer points to, // For example, a small string with less than 255 byte-sized elements // could be represented with `DynamicSize` pointing to `unsigned8`. // // The fields `Mutable` and `Constant` indicate if the type was explicitly // made mutable or constant.

Chapter 5. Compiled XL

5.1. Compiled representations

Code and any data can also have one or several *compiled forms*. The compiled forms are generally very implementation-dependent, varying with the machine you run the program on as well as with the compiler technology being used.

Types also determine properties such as the size and binary representation of values. For example, on most machines, `integer` will be represented as a 64-bit 2-complement binary value, and `real` using the IEEE-754 64-bit representation.

5.2. Data

5.3. Lifetime

5.4. Closures

5.5. Caller lookup

Whenever code contains `caller.X`, an implicit `X` argument is added to the enclosing function, wich needs to be passed by all callers.

For example, the following code:

```
example X:integer as integer is X + caller.Base
Base : integer := 25
example 3
```

is transformed into:

```
example X:integer, Base:integer as integer is X + Base
Base : integer := 25
example 3, Base
```

5.6. Compact vs. Packed

Chapter 6. Basic operations

Chapter 7. Modules

Chapter 8.

Chapter 9. History of XL

The status of the current XL compiler is a bit messy. There is a rationale to this madness. I attempt to give it here.

There is also a blog version if you prefer reading on the web (but it's not exactly identical). In both cases, the article is a bit long, but it's worth understanding how XL evolved, and why the XL compiler is still work in progress.

9.1. It started as an experimental language

Initially, XL was called LX, "Langage experimental" in French, or as you guessed it, an experimental language. Well, the very first codename for it was "WASHB" (What Ada Should Have Been). But that did not sound very nice. I started working on it in the early 1990s, after a training period working on the Alsys Ada compiler.

What did I dislike about Ada? I never liked magic in a language. To me, keywords demonstrate a weakness in the language, since they indicated something that you could not build in the library using the language itself. Ada had plenty of keywords and magic constructs. Modern XL has no keyword whatsoever, and it's a Good Thing ™.

Let me elaborate a bit on some specific frustrations with Ada:

- Tasks in Ada were built-in language constructs. This was inflexible. Developers were already hitting limits of the Ada-83 tasking model. My desire was to put any tasking facility in a library, while retaining an Ada-style syntax and semantics.
- Similarly, arrays were defined by the language. I wanted to build them (or, at least, describe their interface) using standard language features such as generics. Remember that this was years before the STL made it to C++, but I was thinking along similar lines. Use cases I had in mind included:
    - interfacing with languages that had different array layouts such as Fortran and C,
    - using an array-style interface to access on-disk records. Back then, `mmap` was unavailable on most platforms,
    - smart pointers that would also work with on-disk data structures,
    - text handling data structures (often called "strings") that did not expose the underlying implementation (e.g. "pointer to char" or "character array"), …
- Ada text I/O facilities were uncomfortable. But at that time, there was no good choice. You had to pick your poison:
    - In Pascal, `WriteLn` could take as many arguments as you needed and was type safe, but it was a magic procedure, that you could not write yourself using the standard language features, nor extend or modify to suit your needs.
    - Ada I/O functions only took one argument at a time, which made writing the simplest I/O statement quite tedious relative to C or Pascal.
    - C's `printf` statement had multiple arguments, but was neither type safe nor extensible, and

the formatting string was horrid.

- I also did not like Ada pragmas, which I found too ad-hoc, with a verbose syntax. I saw pragmas as indicative that some kind of generic "language extension" facility was needed, although it took me a while to turn that idea into a reality.

I don’t have much left of that era, but that first compiler was relatively classical, generating 68K assembly language. I reached the point where the compiler could correctly compile a "Hello World" style program using an I/O library written in the language. I was doing that work at home on Atari-ST class machines, but also gave demos to my HP colleagues running XL code on VME 68030 boards.

From memory, some of the objectives of the language at the time included:

- Giving up on superfluous syntactic markers such as terminating semi-colon.
- Using generics to write standard library component such as arrays or I/O facilities.
- Making the compiler an integral part of the language, which led to…
- Having a normalised abstract syntax tree, and…
- Considering "pragmas" as a way to invoke compiler extensions. Pragmas in XL were written using the `{pragma}` notation, which would indirectly invoke some arbitrary code through a table.

Thus, via pragmas, the language became extensible. That led me to…

9.2. LX, an extensible language

I wanted to have a relatively simple way to extend the language. Hence, circa 1992, the project was renamed from "experimental" to "extensible", and it has kept that name since then.

One example of thing I wanted to be able to do was to put tasking in a library in a way that would "feel" similar to Ada tasking, with the declaration of task objects, rendez-vous points that looked like procedures with parameter passing, and so on.

I figured that my `{annotations}` would be a neat way to do this, if only I made the parse tree public, in the sense that it would become a public API. The idea was that putting `{annotation}` before a piece of code would cause the compiler to pass the parse tree to whatever function was associated with `annotation` in a table of annotation processors. That table, when pointing to procedures written in XL, would make writing new language extensions really easy. Or so I thought.

Ultimately, I would make it work. If you are curious, you can see the grand-child of that idea in the `translation` statements under `xl2/`. But that was way beyond what I had initially envisionned, and the approach in the first XL compiler did not quite work. I will explain why soon below.

The first experiment I ran with this, which became a staple of XL since then, was the `{derivation}` annotation. It should have been `{differentiation}`, but at that time, my English was quite crappy, and in French, the word for "differentiation" is `` `derivation". The idea is that if you prefixed some code, like a function, with a `{derivation} `` annotation, the parse tree for that function would be passed to the `derivation` pragma handler, and that would replace expressions that looked like differential expressions with their expanded value. For example, `{derivation} d(X+sin(X))/dX` would generate code that looked like `1 + cos(X)`.

If you are curious what this may look like, there are still tests in the XL2 test suite using a very similar feature and syntax.

9.3. LX, meet Xroma

That initial development period for LX lasted between 1990, the year of my training period at Alsys, and 1998, when I jointed the HP California Language Lab in Cupertino (CLL). I moved to the United States to work on the HP C++ compiler and, I expected, my own programming language. That nice plan did not happen exactly as planned, though…

One of the very first things I did after arriving in the US was to translate the language name to English. So LX turned into XL. This was a massive rename in my source code, but everything else remained the same.

As soon as I joined the CLL, I started talking about my language and the ideas within. One CLL engineer who immediately "got it" is Daveed Vandevoorde. Daveed immediately understood what I was doing, in large part because he was thinkering along the same lines. He pointed out that my approach had a name: meta-programming, i.e. programs that deal with programs. I was doing meta-programming without knowing about the word, and I felt really stupid at the time, convinced that everybody in the compilers community knew about that technique but me.

Daveed was very excited about my work, because he was himself working on his own pet language named Xroma (pronounced like Chroma). At the time, Xroma was, I believe, not as far along as XL, since Daveed had not really worked on a compiler. However, it had annotations similar to my pragmas, and some kind of public representation for the abstract syntax tree as well.

Also, the Xroma name was quite Xool, along with all the puns we could build using a capital-X pronounced as "K" (Xolor, Xameleon, Xode, …) or not (Xform, Xelerate, …) As a side note, I later called "Xmogrification" the VM context switch in HPVM, probably in part as a residual effect of the Xroma naming conventions.

In any case, Daveed and I joined forces. The combined effort was named Xroma. I came up with the early version of the lightbulb logo still currently used for XL, using FrameMaker drawing tools, of all things. Daveed later did a nice 3D rendering of the same using the Persistence of Vision ray tracer. I don’t recall when the current logo was redesigned.

9.4. XL moves to the off-side rule

Another major visual change that happened around that time was switching to the off-side rule, i.e. using indentation to mark the syntax. Python, which made this approach popular, was at the time a really young language (release 1.0 was in early 1994).

Alain Miniussi, who made a brief stint at the CLL, convinced me to give up the Ada-style `begin` and `end` keywords, using an solid argumentation that was more or less along the lines of `` `I like your language, but there’s no way I will use a language with `begin `` and `end` ever again''. Those were the times where many had lived the transition of Pascal to C, some still wondering how C won.

I was initially quite skeptical, and reluctantly tried an indentation-based syntax on a fragment of the XL standard library. As soon as I tried it, however, the benefits immediately became apparent. It was totally consistent with a core tenet of concept programming that I was in the process of developing (see below), namely that the code should look like your concepts. Enforcing indentation made sure that the code did look like what it meant.

It took some effort to convert existing code, but I've never looked back since then. Based on the time when Alain Miniussi was at the CLL, I believe this happened around 1999.

9.5. Concept programming

The discussions around our respective languages, including the meta-programming egg-face moment, led me to solidify the theoretical underpinning of what I was doing with XL. My ideas actually did go quite a bit beyond mere meta-programming, which was really only a technique being used, but not the end goal. I called my approach *Concept Programming*. I tried to explain what it is about in this presentation. Concept programming is the theoretical foundation for XL.

Concept programming deals with the way we transform concepts that reside in our brain into code that resides in the computer. That conversion is lossy, and concept programming explores various techniques to limit the losses. It introduces pseudo-metrics inspired by signal processing such as syntactic noise, semantic noise, bandwidth and signal/noise ratio. These tools, as simple as they were, powerfully demonstrated limitations of existing languages and techniques.

Since then, Concept Programming has consistently guided what I am doing with XL. Note that Concept Programming in the XL sense has little do do with C++ concepts (although there may be a connection, see blog referenced above for details).

9.6. Mozart and Moka: Adding Java support to XL

At the time, Java was all the rage, and dealing with multiple languages within a compiler was seen as a good idea. GCC being renamed from ``GNU C Compiler'' to the "GNU Compiler Collection" is an example of this trend.

So with Daveed, we had started working on what we called a ``universal program database'', which was basically a way to store and access program data independently of the language being used. In other words, we were trying to create an API that would make it possible to manipulate programs in a portable way, whether the program was written in C, C++ or Java. That proved somewhat complicated in practice.

Worse, Daveed Vandevoord left the HP CLL to join the Edison Design Group, where he's still working to this date. Xroma instantly lost quite a bit of traction within the CLL. Also, Daveed wanted to keep the Xroma name for his own experiments. So we agreed to rename "my" side of the project as "Mozart". For various reasons, including a debate regarding ownership of the XL code under California law, the project was open-sourced. The web site still exists to this day, but is not quite functional since CVS support was de-commissioned from SourceForge.

Part of the work was to define a complete description of the source code that could be used for different language. Like for Xroma, we stayed on bad puns and convoluted ideas for naming. In Mozart that representation was called `Coda`. It included individual source elements called `Notes` and the serialized representation was called a `Tune`. Transformation on Notes, i.e. the operations of compiler plug-ins, were done by `Performer` instances. A couple of years later, I would realize that this made the code totally obfuscated for the non-initiated, and I vowed to never make that mistake again.

Mozart included Moka, a Java to Java compiler using Mozart as its intermediate representation. I published an article in Dr Dobb's journal, a popular developers journal at the time.

But my heart was never with Java anymore than with C++, as evidenced by the much more extensive documentation about XL on the Mozart web site. As a language, Java had very little interest for me. My management at HP had no interest in supporting my pet language, and that was one of the many reasons for me to leave the CLL to start working on virtualization and initiate what would become HPVM.

9.7. Innovations in 2000-vintage XL

By that time, XL was already quite far away from the original Ada, even if it was still a statically typed, ahead-of-time language. Here are some of the key features that went quite a bit beyond Ada:

- The syntax was quite clean, with very few unnecessary characters. There were no semi-colons at the end of statement, and parentheses were not necessary in function or procedure calls, for example. The off-side rule I talked about earlier allowed me to get rid of any `begin` or `end` keyword, without resorting to C-style curly braces to delimit blocks.
- Pragmas extended the language by invoking arbitrary compiler plug-ins. I suspect that attributes in C++11 are distant (and less powerful) descendants of this kind of annotation, if only because their syntax matches my recollection of the annotation syntax in Xroma, and because Daveed has been a regular and innovative contributor to the C++ standard for two decades…
- Expression reduction was a generalisation of operator overloading that works with expressions of any complexity, and could be used to name types. To this day, expression reduction still has no real equivalent in any other language that I know of, although expression templates can be used in C++ to achieve similar effect in a very convoluted and less powerful way. Expression templates will not allow you to add operators, for example. In other words, you can redefine what `X+Y*Z` means, but you cannot create `X in Y..Z` in C++.
- True generic types were a way to make generic programming much easier by declaring generic types that behaved like regular types. Validated generic types extended the idea by adding a validation to the type, and they also have no real equivalent in other languages that I am aware of, although C++ concepts bring a similar kind of validation to C++ templates.
- Type-safe variable argument lists made it possible to write type-safe variadic functions. They solved the `WriteLn` problem I referred to earlier, i.e. they made it possible to write a function in a library that behaved exactly like the Pascal `WriteLn`. I see them as a distant ancestor of variadic templates in C++11, although like for concepts, it is hard to tell if variadic templates are a later reinvention of the idea, or if something of my e-mails influenced members of the C++ committee.
- A powerful standard library was in the making. Not quite there yet, but the key foundations were there, and I felt it was mostly a matter of spending the time writing it. My implementation of complex numbers, for example, was 70% faster than C++ on simple examples, because it

allowed everything to be in registers instead of memory. There were a few things that I believe also date from that era, like getting rid of any trace of a main function, top-level statements being executed as in most scripting languages.

9.8. XL0 and XL2: Reinventing the parse tree

One thing did not work well with Mozart, however, and it was the parse tree representation. That representation, called `Notes`, was quite complicated. It was some kind of object-oriented representation with many classes. For example, there was a class for `IfThenElse` statements, a `Declaration` class, and so on.

This was all very complicated and fragile, and made it extremely difficult to write thin tools (i.e. compiler plug-ins acting on small sections of code), in particular thin tools that respected subtle semantic differences between languages. By 2003, I was really hitting a wall with XL development, and that was mostly because I was also trying to support the Java language which I did not like much.

One of the final nails in the Mozart coffin was a meeting with Alan Kay, of Smalltalk fame, during an HP technical conference. Kay was an HP Fellow at the time. I tried to show him how my language was solving some of the issues he had talked about during his presentation. He did not even bother looking. He simply asked: *"Does your language self-compile?"*. When I answered that the compiler was written in C++, Alan Kay replied that he was not interested.

That gave me a desire to consider a true bootstrap of XL. That meant rewriting the compiler from scratch. But at that time, I had already decided that the internal parse tree representation needed to be changed. So that became my topic of interest.

The new implementation was called XL2, not just as a version number, but because I was seeing things as a three-layer construction:

- `XL0` was just a very simple parse tree format with only eight node types. I sometimes refer to that level of XL as ``*XML without the M*'', i.e. an extensble language without markup.
- `XL1` was the core language evaluation rules, not taking any library into account.
- `XL2` was the full language, including its standard library. At the time, the goal was to reconstruct a language that would be as close as possible at the version of XL written using the Mozart framework.

This language is still available today, and while it's not been maintained in quite a while, it seems to still pass most of its test suite. More importantly, the `XL0` format has remained essentially unchanged since then.

The XL0 parse tree format is something that I believe makes XL absolutely unique among high-level programming languages. It is designed so that code that can look and feel like an Ada derivative can be represented and manipulated in a very simple way, much like Lisp lists are used to represent all Lisp programs. XL0, however, is not some minor addition on top of S-expressions, but rather the definition of an alternative of S-expressions designed to match the way humans parse code.

The parse tree format consists of only eight node types, four leaf node types (integer, real, text and symbol), four inner node types (infix, prefix, postfix and block).

- `Integer` represents integer numbers, like `123` or `16#FFFF_FFFF`. As the latter example shows, the XL syntax includes support for based numbers and digit grouping.
- `Real` represents floating-point numbers, like `123.456` or `2#1.001_001#e-3`. Like for `Integer`, XL supports based floating-point numbers and digit grouping.
- `Text` represents textual constants like `"Hello"` or `'A'`.
- `Name` represents names like `ABC` or symbols like `⇐`.
- `Infix` represents operations where a name is between two operands, like `A+B` or `A and B`.
- `Prefix` represents operations where an operator precedes its operand, like `sin X` or `-4`.
- `Postfix` represents operations where an operator follows its operand, like `3 km` or `5%`.
- `Block` represents operations where an operand is surrounded by two names, like `[A]`, `(3)` or `{write}`.

Individual program lines are seen as the leaves of an infix "newline" operator. There are no keywords at all, the precedence of all operators being given dynamically by a syntax file.

9.9. Bootstrapping XL

The initial translator converts a simplified form of XL into C++ using a very basic transcoding that involves practically no semantic analysis. The limited XL2 acceptable as input for this translation phase is only used in the bootstrap compiler. It already looks a bit like the final XL2, but error checking and syntax analysis are practically nonexistent.

The bootstrap compiler can then be used to translate the native XL compiler. The native compiler performs much more extended semantic checks, for example to deal with generics or to implement a true module system. It emits code using a configurable "byte-code" that is converted to a variety of runtime languages. For example, the C bytecode file will generate a C program, turning the native compiler into a transcoder from XL to C.

That native compiler can translate itself, which leads to a true bootstrap where the actual compiler is written in XL, even if a C compiler is still used for the final machine code generation. Using a Java or Ada runtime, it would theoretically be possible to use a Java or Ada compiler for final code generation.

The XL2 compiler advanced to the point where it could pass a fairly large number of complex tests, including practically all the things that I wanted to address in Ada:

- Pragmas implemented as compiler plug-ins.
- Expression reduction generalising operator overloading.
- An I/O library that was as usable as in Pascal, but written in the language and user-extensible.
- A language powerful enough to define its own arrays or pointers, while keeping them exactly as usable as built-in types.

9.10. XL2 compiler plugins

XL2 has full support for compiler plug-ins, in a way similar to what had been done with Mozart. However, plug-ins were much simpler to develop and maintain, since they had to deal with a very simple parse tree structure.

For example, the differentiation plugin implements symbolic differentiation for common functions. It is tested here. The generated code after applying the plugin would look like this. The plugin itself is quite simple. It simply applies basic mathematical rules on parse trees. For example, to perform symbolic differentiation on multiplications, the code looks like this:

```
function Differentiate (expr : PT.tree; dv : text) return PT.tree is
    translate expr
        when ('X' * 'Y') then
            dX : PT.tree := Differentiate(X, dv)
            dY : PT.tree := Differentiate(Y, dv)
            return parse_tree('dX' * 'Y' + 'X' * 'dY')
```

Meta-programming became almost entirely transparent here. The `translate` statement, itself provided by a compiler plug-in (see below), matches the input tree against a number of shapes. When the tree looks like `X*Y`, the code behind the matching `then` is evaluated. That code reconstructs a new parse tree using the `parse_tree` function.

Also notice the symmetric use of quotes in the `when` clause and in the `parse_tree` function, in both cases to represent variables as opposed to names in the parse tree. Writing `parse_tree(X)` generates a parse tree with the name `X` in it, whereas `parse_tree('X')` generates a parse tree from the `X` variable in the source code (which must be a parse tree itself).

9.11. XL2 internal use of plugins: the `translation` extension

The compiler uses this plug-in mechanism quite extensively internally. A particularly important compiler extension provides the `translation` and `translate` instructions. Both were used extensively to rewrite XL0 parse trees easily.

We saw above an example of `translate`, which translated a specific tree given as input. It simply acted as a way to compare a parse tree against a number of forms, evaluating the code corresponding to the first match.

The `translation` declaration is even more interesting, in that it is a non-local function declaration. All the `translation X` from all modules are accumulated in a single `X` function. Functions corresponding to `translation X` and `translation Y` will be used to represent distinct phases in the compiler, and can be used a regular functions taking a tree as input and returning the modified tree.

This approach made it possible to distribute `translation XLDeclaration` statements throughout the compiler, dealing with declaration of various entities, with matching `translation XLSemantics` took care of the later semantics analysis phase.

Writing code this way made it quite easy to maintain the compiler over time. It also showed how concept programming addressed what is sometimes called aspect-oriented programming. This was yet another proof of the "extensible" nature of the language.

9.12. Switching to dynamic code generation

One issue I had with the original XL2 approach is that it was strictly a static compiler. The bytecode files made it possible to generate practically any language as output. I considered generating LLVM bitcode, but thought that it would be more interesting to use an XL0 input instead. One reason to do that was to be able to pass XL0 trees around in memory without having to re-parse them. Hence XLR, the XL runtime, was born. This happened around 2009.

For various reasons, I wanted XLR to be dynamic, and I wanted it to be purely functional. My motivations were:

- a long-time interest in functional languages.
- a desire to check that the XL0 representation could also comfortably represent a functional languages, as a proof of how general XL0 was.
- an intuition that sophisticated type inference, Haskell-style, could make programs both shorter and more solid than the declarative type systems of Ada.

While exploring functional languages, I came across Pure, and that was the second big inspiration for XL. Pure prompted me to use LLVM as a final code generator, and to keep XLR extremely simple.

9.13. Translating using only tree rewrites

I sometimes describe XLR as a language with a single operator, `is`, which reads as *transforms into*. Thus, `X is 0` declares that `X` has value `0`.

Until very recently, that operator was spelled using an arrow, as `→`, which I thought expressed the *transforms into* quite well. Around 2018, I decided that this was unreadable for the novice, and switched to using `is` as this *definition operator*. This `→` operator is still what you will find for example on the Tao3D web site.

This notation can be used to declare basic operators:

```
x:integer - y:integer as integer    is opcode Sub
```

It makes a declaration of `writeln` even shorter than it was in XL2:

```
write x:text as boolean              is C xl_write_text
write x:integer as boolean           is C xl_write_integer
write x:real as boolean              is C xl_write_real
write x:character as boolean         is C xl_write_character
write A, B                           is write A; write B
writeln as boolean                   is C xl_write_cr
writeln X as boolean                 is write X; writeln
```

More interestingly, even if-then-else can be described that way:

```
if true  then TrueBody else FalseBody   is TrueBody
if false then TrueBody else FalseBody   is FalseBody
if true  then TrueBody                  is TrueBody
if false then TrueBody                  is false
```

> the above code now requires a metabox for `true` in the version of XL described in this document, i.e._`true` must be replaced with `[[true]]` in order to avoid being interpreted as a formal parameter.

Similarly for basic loops, provided your translation mechanism implements tail recursion properly:

```
while Condition loop Body is
    if Condition then
        Body
    while Condition loop Body

until Condition loop Body is while not Condition loop Body

loop Body is Body; loop Body

for Var in Low..High loop Body is
    Var := Low
    while Var < High loop
        Body
        Var := Var + 1
```

> The fact that such structures can be implemented in the library does not mean that they have to. It is simply a proof that basic amenities can be constructed that way, and to provide a reference definition of the expected behaviour.

9.14. Tao3D, interactive 3D graphics with XL

When I decided to leave HP, I thought that XLR was flexible enough to be used as a dynamic document language. I quickly whipped together a prototype using XLR to drive an OpenGL 3D rendering engine. That proved quite interesting.

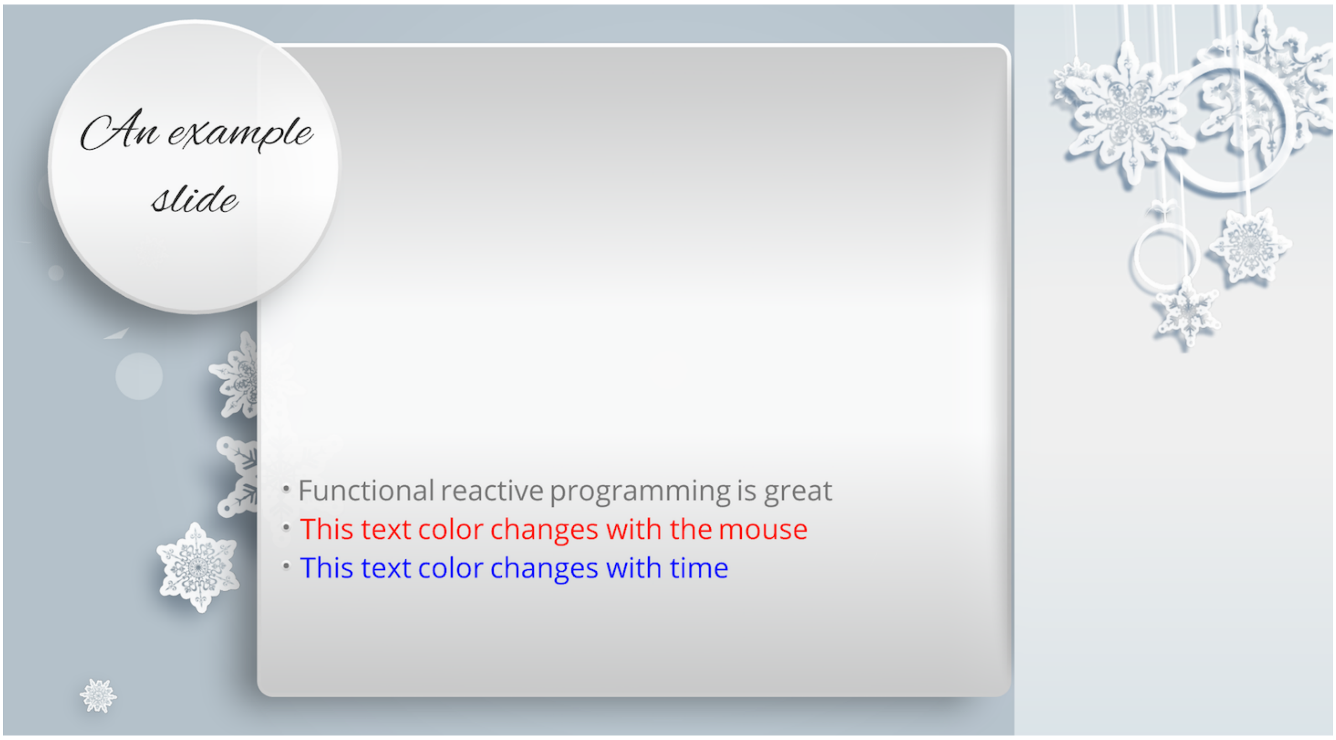
Over time, that prototype morphed into Tao3D. As far as the XLR language itself is concerned, there wasn't as much evolution as previously. A few significant changes related to usability popped up after actively using the language:

- Implicit conversions of integer to real were not in the original XLR, but it was quite annoying in practice when providing object coordinates.
- The XL version in Tao3D also became sensitive to spacing around operators, so as to distinguish `Write -A` from `X - Y`. Earlier versions forced you to use parentheses in the first case, as in `Write (-A)`, which was quite against the ideas of concept programming that your code must match your ideas.
- The more important change was the integration in the language of reactivity to transparently deal with events such as mouse, keyboard or time. Thus, the Tao3D language a fully functional-reactive language, without changing the core translation technology at all.

Precisely because the changes were so minor, Tao3D largely proved the point that XL was really extensible. For example, a `slide` function (that takes code as its second argument) makes it easy to describe a great-looking bullet points slide:

```
import WhiteChristmasTheme
theme "WhiteChristmas"

slide "An example slide",
    * "Functional reactive programming is great"
    color_hsv mouse_x, 100%, 100%
    * "This text color changes with the mouse"
    color_hsv time * 20, 100%, 100%
    * "This text color changes with time"
```

and get an animated slide that looks like this:



The same technique goes well beyond mere bullet points:

image:images/tao3d-slide.jpg

Tao3D developed a relatively large set of specialised modules, dealing with things such as stereoscopy or lens flares. As a product, however, it was never very successful, and Taodyne shut down in 2015, even if the open-source version lives on.

Unfortunately, Tao3D was built on a relatively weak implementation of XL, where the type system in particular was not well thought out (it was really a hack that only supported parse tree types). This made a few things really awkward. Notably, all values are passed by reference, which was mostly an implementation hack to enable the user-interface to "retrofit" values into the code when you move shapes on the screen. Unfortunately, this made the language brittle, and forced many modules to rely on poor hacks when updating values. To make a long story short, `X := Y` in Tao3D is a joke, and I'm rightfully ashamed of it.

9.15. ELFE, distributed programming with XL

ELFE was another experiment with XL, that took advantage of XL's extensibility to explore yet another application domain, namely distributed software, with an eye on the Internet of Things. The idea was to take advantage of the existence of the XL0 standard parse tree to communicate programs and data across machines.

An ELFE program looks as as if it was running on a single machine, but actively exchanges program segments and their associated data between distant nodes (in modern XL, `→` below would read `is`):

```
invoke "pi2.local",
   every 1.1s,
        rasp1_temp ->
            ask "pi.local",
                temperature
        send_temps rasp1_temp, temperature

   send_temps T1:real, T2:real ->
       if abs(T1-T2) > 2.0 then
           reply
               show_temps T1, T2

show_temps T1:real, T2:real ->
    write "Temperature on pi is ", T1, " and on pi2 ", T2, ". "
    if T1>T2 then
        writeln "Pi is hotter by ", T1-T2, " degrees"
    else
        writeln "Pi2 is hotter by ", T2-T1, " degrees"
```

ELFE only adds a very small number of features to the standard XL, which are simply regular XL functions implemented in C++:

- The `ask` statement sends a program, and returns the result of evaluating that program as if it has been evaluated locally. It works like a remote function call.

- An `invoke` statement sends a program to a remote node. It's a ``fire and forget'' operation, but leaves a reply channel open while it's executing.
- Finally, the `reply` statement allows a remote node to respond to whoever `invoke`'d it, by evaluating one of the available functions in the caller's context.

A few very simple ELFE demos illustrate these remote-control capabilities. For example, it's easy to monitor temperature on two remote sensor nodes, and to ask them to report if their temperatures differ by more than some specified amount. The code is very short and looks like this:

```
invoke "pi2.local",
   every 1.1s,
        rasp1_temp ->
            ask "pi.local",
                temperature
        send_temps rasp1_temp, temperature

   send_temps T1:real, T2:real ->
       if abs(T1-T2) > 2.0 then
           reply
               show_temps T1, T2

show_temps T1:real, T2:real ->
    write "Temperature on pi is ", T1, " and on pi2 ", T2, ". "
    if T1>T2 then
        writeln "Pi is hotter by ", T1-T2, " degrees"
    else
        writeln "Pi2 is hotter by ", T2-T1, " degrees"
```

ELFE was designed to run with a small memory footprint, so it provides a complete interpreter that does not require any LLVM. As the names in the example above suggest, it was tested on Raspberry Pi. On the other hand, the LLVM support in that "branch" of the XL family tree fell into a bad state of disrepair.

9.16. XL gets a type system

Until that point, XL lacked a real type system. What was there was mostly quick-and-dirty solutions for the most basic type checks. Over a Christmas vacation, I spent quite a bit of time thinking about what a good type system would be for XL. I was notably stumped by what the type of `if-then-else` statements should be.

The illumination came when I realized that I was blocked in my thinking by the false constraint that each value had to have a single type. Instead, the type system that seems natural in XL is that a type indicates the shape of a parse tree. For example, `integer` is the type of integer constants in the code, `real` the type of real constants, and `type(X+Y)` would be the type of all additions.

Obviously, that means that in XL, a value can belong to multiple types. `2+3*5` belongs to `type(X+Y)`, to `type(X:integer+Y:integer)` or to `infix`. This makes the XL type system extremely powerful. For example. a type for even numbers is `type(X:integer when X mod 2 = 0)`.

ELFE also gave me a chance to implement a relatively crude version of this idea and validate that it's basically sane. Bringing that idea to the optimizing compiler was an entirely different affair, though, and is still ongoing.

9.17. The LLVM catastrophy

For a while, there were multiple subtly distinct variants of XL which all shared the same XL0, but had very different run-time constraints.

- Tao3D had the most advanced library, and a lot of code written for it. But that code often depends on undesirable behaviours in the language, such as implicit by reference argument passing.
- ELFE had the most advanced type system of all XLR variants, being able to perform overloading based on the shape of parse trees, and having a rather complete set of control structures implemented in the library. It also has an interesting modular structure, and a rather full-featured interpreter.
- XLR has the most advanced type inference system, allowing it to produce machine-level instructions for simple cases to get performance that was on a par with C. Unfortunately, due to lack of time, it fell behind with respect to LLVM support, LLVM not being particularly careful about release-to-release source compatibility. And the type inference was never solid enough to retrofit it in Tao3D, which still uses a much simpler code generation.
- XL2 was the only self-compiling variant of XL ever written, and still had by far the most sophisticated handling of generics and most advanced library. But it has been left aside for a few years. As an imperative language, it is more verbose and feels heavier to program. Yet it is not obsolete, as the discussion above demonstrates. Its type system, with its support for generics or validation, is much more robust than whatever was ever implemented in all XLR variants. It would need quite a bit of love to make it really usable, for example improving the standard library and actually connect XLR as a bytecode back-end as initially envisioned.

In addition to this divergence, another problem arose externally to the XL project. The LLVM library, while immensely useful, proved a nightmare to use, because they purposely don't care about source cdoe compatibility between releases. XLR was initially coded against LLVM 2.5, and the majority of Tao3D development occured in the LLVM 2.7 time frame.

Around release 3.5, LLVM started switching to a completely different code generation model. Being able to support that new model proved extremely challenging, in particular for something as complex as Tao3D. The problem is not unique to Tao3D: the LLVM pipe in the Mesa project has similar issues. But in Tao3D, it was made much worse precisely because Tao3D uses both OpenGL and XL, and the Mesa implementation of OpenGL commonly used on Linux also uses LLVM. If the variants of LLVM used by the XL runtime and by OpenGL don't match, mysterious crashes are almost guaranteed.

From 2015 to 2018, all development of XL and Tao3D was practically stuck on this problem. It did not help that my job during that time was especially challenging time-wise. In practice, the development of Tao3D and XLR was put on hold for a while.

9.18. Repairing and reconverging

A project that lasted several months, called `bigmerge` allowed me to repair a lot of the issues:

- The XL2 compiler was brought back into the main tree
- The ELFE interpreter was merged with the main tree, and its modular approach (designed to allow the use of XL as an extension language) was incorporated in XL. As a result, ELFE is dead, but it lives on in the main XL tree. XL was also turned into a library, with a very small front-end calling that library to evaluate the code.
- The switch from `→` to `is` as the definition operator was implemented.
- The LLVM "Compatibility Restoration Adaptive Protocol" (LLVM-CRAP) component of XL was completely redesigned, giving up pre-3.5 versions of LLVM, but supporting all the recent ones (from 3.7 to 9.0).
- The Tao3D branch of the compiler was forward-ported to this updated compiler, under the name `FastCompiler`. That work is not complete, howver, because some of the changes required by the two previous steps are incompatible with the way Tao3D was interfacing with XL.

This is the current state of the XL tree you are looking at. Not pretty, but still much better than two years ago.

9.19. Language redefinition

During all that time, the language definition had been a very vaguely defined TeXMacs document. This document had fallen somewhat behind with respect to the actual language implementation or design. Notably, the type system was quickly retrofitted in the document. Also, the TexMacs document was monolithic, and not easy to convert to a web format.

So after a while, I decided to rewrite the documentation in markdown. This led me to crystalize decisions about a few things that have annoyed me in the previous definition, in particular:

- The ambiguity about formal parameters in patterns, exhibited by the definition of `if-then-else`. The XL language had long defined `if-then-else` as follows:

  ```
  if true  then TrueClause      is TrueClause
  if false then TrueClause      is false
  ```

  There is an obvious problem in that definition. Why should `true` be treated like a constant while `TrueClause` a formal parameter?

  The solution proposed so far so far was that if a name already existed in the context, then we were talking about this name. In other words, `true` was supposed to be defined elsewhere and not `TrueClause`.

  This also dealt with patterns such as `A - A is 0`. However, the cost was very high. In particular, a formal parameter name could not be any name used in the enclosing context, which was a true nuisance in practice.

More recently, I came across another problem, which was how to properly insert a computed value like the square root of two in a pattern? I came up with an idea inspired parameters in `translate` statements in XL2, which I called a "metabox". The notation `[[X]]` in a pattern will evaluate `X`. To match the square root of 2, you would insert the metabox `[[sqrt 2]]`. To match `true` instead of defining a name `true`, you would insert `[[true]]` instead of `true`.

Downside: fix all the places in the documentation that had it backwards.

- The addition of opaque binary data in parse trees, for example to put an image from a PNG file in an XL program. I had long been thinking about a syntax like `binary "image.png"` It should also be possible to declare arbitrary binary data inline, as in `binary 16#FFFF_0000_FFFF_0000_FF00_00FF_FF00_00FF`.
- Adding a `lambda` syntax for anonymous functions. Earlier versions of XL would use a catch-all pattern like `(X is X + 1)` to define a lambda function, so that `(X is X + 1) 3` would be `4`. That pattern was only recognized in some specific contexts, and in other contexts, this would be a definition of a variable named `X`. It is now mandatory to add `lambda` for a catch-all pattern, as in `lambda X is X + 1`, but then this works in any context.

9.20. Future work

The work that remains to make XL usable again (in the sense of being as stable as it was for Tao3D in the 2010-2015 period) includes:

- Complete the work on an Haskell-style type inference system, in order to make the "O3" compiler work well.
- Repair the Tao3D interface in order to be able to run Tao3D again with modern LLVM and OpenGL variants.
- Re-connect the XL2 front-end for those who prefer an imperative programming style, ideally connecting it to XLR as a runtime.
- Sufficient library-level support to make the language usable for real projects.
- Bootstrapping XLR as a native compiler, to validate that the XLR-level language is good enough for a compiler. Some of the preparatory work for this is happening in the `native` directory.
- Implement a Rust-style borrow checker, ideally entirely from the library, and see if it makes it possible to get rid of the garbage collector. That would be especially nice for Tao3D, where GC pause, while generally quite small, are annoying.
- Some reworking of XL0, notably to make it easier to add terminal node types. An example of use case is version numnbers like `1.0.1`, which are hard to deal with currently. The distinction between `Integer` and `Real` is indispensable for evaluation, but it may not be indispensable at parse time.
- Replace blocks with arrays. Currently, blocks without a content, such as `( )` or `{ }`, have a blank name inside, which I find ugly. It would make more sense to consider them as arrays with zero length. Furthermore, blocks are often used to hold sequences, for example sequences of instructions. It would be easier to deal with a block containing a sequence of instructions than with the current block containing an instruction or a chain of infix nodes.
- Adding a "binary object" node type, which could be used to either describe data or load it from

files. I have been considering a syntax like:

```
binary 16#0001_0002_0003_0004_0005_0006_0007_0008_0009
binary "image.jpg"
```

It is unclear if I will be able to do that while at the same time working on my job at Red Hat and on various other little projects such as `make-it-quick` or `recorder` (which are themselves off-shoots of XL development).

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