

# SYNTAX AND SEMANTICS OF BABEL-17

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## 1. INTRODUCTION

The first question that someone who creates a new programming language will hear from others inevitably is: Why another programming language? Are there not already enough programming languages out there that you can pick from?

I always wanted a programming language

- in which I can express myself compactly and without jumping through too many hoops,
- that is easy to understand and to learn,
- in which purely functional programming is the default and not the exception,
- that supports exceptions,
- that has pattern matching,
- that has built-in support for laziness and concurrency,
- that has built-in support for purely functional lists, vectors, sets and maps,
- that seamlessly marries structured programming constructs like loops with purely functional programming,
- that supports objects, modules and data encapsulation,
- that has mature implementations for all major modern computing platforms and can (and should!) be used for real-world programming,
- that has a simple mechanized formal semantics,
- that is beautiful.

There is no such language out there. Therefore I decided to create one. When Babel-17 will have reached v1.0 then the above goals will have been achieved. The version described in this document is Babel-17 v0.3, so there is still some distance to go.

Babel-17 is not a radically new or revolutionary programming language. It picks those raisins I like out of languages like Standard ML, Scala, Alice ML, Java, Javascript, Erlang, Haskell, Lisp, Clojure and Mathematica, and tries to evolve them into a beautiful new design.

Babel-17 is a functional language. It is not a pure functional language because it contains sources of non-determinism like the ability to pick one of two values randomly. If you take these few sources of non-determinism out of the language, it becomes pure.

In Babel-17, every value has a type. These types are not checked statically, but only dynamically.

Babel-17 is also object-oriented in that many aspects of Babel-17 can be explained in terms of sending messages to objects.

The default evaluation order of Babel-17 is strict. But optional laziness is built into the heart of Babel-17, also, and so is concurrency.

Babel-17 has pattern matching and exception handling. Both are carefully integrated with each other and with the laziness and concurrency capabilities of Babel-17.

Furthermore, Babel-17 establishes the paradigm of *purely functional structured programming* via the notion of linear scope.

In this document I specify Babel-17 in a mostly informal style: formal notation is sometimes used when it supports clarity.

## 2. REFERENCE IMPLEMENTATION

At <http://babel-17.com> you will find a reference implementation of Babel-17 v0.3 that fully supports the language as described in this document. There you will also find a Netbeans plugin that has syntax and error-highlighting for Babel-17 programs. As you find your way through this document, it might be helpful to directly try out Babel-17 in Netbeans to see if the interpreter behaves as you would guess from this spec.

## 3. LEXICAL MATTERS

Babel-17 source code is always written UTF-8 encoded. If it ain't UTF-8, it ain't Babel-17.

Constructors are alphanumeric strings which can also contain underscores, and which must start with a capital letter. Identifiers are alphanumeric strings which can also contain underscores, and which must start with a non-capital letter. The distinction between two constructors or two identifiers is not sensitive to capitalization.

These are the keywords of Babel-17:

begin	end	object	with	if	then	else	elseif
while	for	do	choose	random	yield	match	case
as	val	def	in	exception	lazy	concurrent	memoize
to	downto	true	false	nil	infinity	force	this
try	catch	typedef	typeof	module	private	import	unittest
and	or	not					

Note that keywords are written always in lower case. For example, `bEGIN` is not a legal keyword, but it also isn't an identifier (because of case insensitivity). Also note that `Begin` and `BEGIN` denote the same legal constructor. When we talk about identifiers in the rest of the paper, we always mean identifiers which are not keywords.

You can write down decimal, hexadecimal, binary and octal integers in Babel-17. The following notations all denote the same integer:

```
15  0xF  0b1111  0o17
```

TABLE 1. Further Unicode Symbols

Unicode Hex Code	Display	ASCII Equivalent
2261	≡	==
2262	≠	<>
2264	≤	<=
2265	≥	>=
2237	::	::
2192	→	->
21D2	⇒	=>
2026	...	...

There is also a decimal syntax for floating point numbers in Babel-17:

15.0 1.5E1 1.5E+1 150E-1 15e0

Strings start and end with a quotation mark. Between the quotation mark, any valid UTF-8 string is allowed that does not contain newline, backslash or quotation mark characters, for example:

"hello world" "\$1, 2%" "1 <= 4! <= 5^2"

Newline, backslash and quotation mark characters can be written down in escaped form. Actually, any unicode character can be written down in its escaped form via the hexadecimal value of its codepoint:

String consisting only of a quotation mark	"\""
String consisting only of a backslash	"\\"
String consisting only of a line feed	"\n"
String consisting only of a carriage return	"\r"
String consisting only of line feed via 16-bit escaping	"\u000A"
String consisting only of line feed via 32-bit escaping	"\U0000000A"

Multi-line comments in Babel-17 are written between matching pairs of #( and )# and can span several lines. Single-line comments start with ##.

*Pragmas* start with #, just like comments. There are the following pragmas: #assert, #log, #print, #profile.

Finally, here are all ASCII special symbols that can occur in a Babel-17 program:

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

Table 1 lists all other Unicode symbols that have a meaning in Babel-17.

#### 4. OVERVIEW OF BUILT-IN TYPES

Each value in Babel-17 has a unique type. All built-in types are depicted in Table 2. Often we use the name of a type to refer to this type in this specification, but the representation of it in actual Babel-17 is given in the type column. The type of a value  $v$  can be obtained via

**typeof**  $v$

TABLE 2. Built-in Types of Babel-17

Name	Type	Description
<i>Integer</i>	<b>int</b>	the type of arbitrary size integer numbers
<i>Real</i>	<b>real</b>	the type of real numbers
<i>Boolean</i>	<b>bool</b>	the type consisting of the values <b>true</b> and <b>false</b>
<i>String</i>	<b>string</b>	the type of valid Unicode strings
<i>List</i>	<b>list</b>	the type of lists
<i>Vector</i>	<b>vect</b>	the type of vectors / tuples
<i>Set</i>	<b>set</b>	the type of sets
<i>Map</i>	<b>map</b>	the type of maps
<i>CExpr</i>	<b>cexpr</b>	the type of constructed expressions
<i>Object</i>	<b>obj</b>	the type of user-defined objects
<i>Function</i>	<b>fun</b>	the type of functions
<i>PersistentException</i>	<b>exc</b>	the type of persistent exceptions
<i>DynamicException</i>		the type of dynamic exceptions
<i>Type</i>	<b>type</b>	the type of types

## 5. OBJECTS AND FUNCTIONS

All values in Babel-17 are objects. This means that you can send messages to them. Many values in Babel-17 are functions. This means that you can apply them to an argument, yielding another value. Note that for a value to be an object, it does not need to have type **obj**, and for a value to be a function, it does not need to have type **fun**.

The result of sending message  $m$  to object  $v$  is written as

$$v . m$$

Here  $m$  is an identifier.

The result of applying function  $f$  to value  $x$  is written as

$$f x$$

Note that  $f x$  is equivalent to

$$(f.\text{apply-}) x$$

Therefore any object that responds to the `apply_` message can act as a function. In the above we could also leave out the brackets because sending messages binds stronger than function application.

Repeated function application associates to the left, therefore

$$f x y$$

is equivalent to  $(f x) y$ .

## 6. EXCEPTIONS

Exception handling in Babel-17 mimicks exception handling mechanisms like those which can be found in Java or Standard ML, while adhering at the same time to the functional paradigm.

There are two types of exceptions: *PersistentException* and *DynamicException*. The difference is that a *PersistentException* can be treated as part of any data structure,

and is passed around just like any other value, while a *DynamicException* can never be part of a data structure and has special evaluation semantics.

Exceptions in Babel-17 are not that special at all but mostly just another type of value. Let us write *PersistentException v* for a *PersistentException* with parameter *v*, and *DynamicException v* for a *DynamicException* with parameter *v*. We also write *Exception v* for an exception with parameter *v*. The parameter *v* is a *non-exceptional* value; this means that *v* can be any Babel-17 value except one of type *DynamicException*. Note that a value of type *PersistentException* is therefore non-exceptional.

The following deterministic rules govern how exceptions behave with respect to sending of messages, function application, laziness and concurrency:

$$\begin{aligned}
(\text{Exception } v).m &\rightsquigarrow \text{DynamicException } v \\
(\text{DynamicException } v) \ x &\rightsquigarrow \text{DynamicException } v \\
f \ (\text{DynamicException } v) &\rightsquigarrow \text{DynamicException } v \text{ where } f \text{ is non-exceptional} \\
(\text{PersistentException } v) \ g &\rightsquigarrow \text{DynamicException } v \text{ where } g \text{ is non-exceptional} \\
\text{exception } v &\rightsquigarrow \text{DynamicException } v \\
\text{lazy } (\text{Exception } v) &\rightsquigarrow \text{PersistentException } v \\
\text{concurrent } (\text{Exception } v) &\rightsquigarrow \text{PersistentException } v \\
\text{force } v &\rightsquigarrow v \text{ for all } v, \text{ including exceptions}
\end{aligned}$$

Exceptions in Babel-17 are created with the expression **exception** *v*. Creating exceptions in Babel-17 corresponds to *raising* or *throwing* exceptions in other languages. Catching an exception can be done via **match** or via **try-catch**. Both constructs will be described later.

In the next section, we will describe the **lazy** and **concurrent** expressions of Babel-17. They are the reason why exceptions are divided into dynamic and persistent ones.

## 7. LAZINESS AND CONCURRENCY

The default evaluation mechanism of Babel-17 is strict. This basically means that the arguments of a function are evaluated before the function is applied to them. Babel-17 has two constructs to change this default behaviour.

The expression

**lazy** *e*

is not evaluated until it is actually needed. When it is needed, it evaluates to whatever *e* evaluates to, with the exception of dynamic exceptions, which are converted to persistent ones.

The expression

**concurrent** *e*

also evaluates to whatever *e* evaluates to, again with the exception of dynamic exceptions which are converted to persistent ones. This evaluation will happen concurrently.

One could think that apart from obvious different performance characteristics, the expressions **lazy** *e* and **concurrent** *e* are equivalent. This is not so. If *e* is a non-terminating expression then, even if the value of **concurrent** *e* is never needed during program execution, it might still lead to a non-terminating program execution. In other words, the behaviour of **concurrent** *e* is unspecified for non-terminating *e*.

Sometimes you want to explicitly force the evaluation of an expression. In those situations you use the expression

**force**  $e$

which evaluates to  $e$ . So semantically, **force** is just the identity function.

We mentioned before that lazy and concurrent expressions are the reason why exceptions are divided into dynamic and persistent ones. To motivate this, look at the expression

`fst (0, lazy (1 div 0))`

Here the function `fst` is supposed to be a function that takes a pair and returns the first element of this pair. So what would above expression evaluate to? Obviously, `fst` does not need to know the value of the second element of the pair as it depends only on the first element, so above expression evaluates just to 0. Now, if **lazy** was semantically just the identity function, then we would have

$$\begin{aligned} 0 &= \text{fst } (0, \text{lazy } (1 \text{ div } 0)) = \text{fst } (0, 1 \text{ div } 0) = \text{fst } (0, \text{exception } \text{DomainError}) \\ &= \text{fst } (\text{exception } \text{DomainError}) = \text{exception } \text{DomainError} \end{aligned}$$

Obviously, 0 should not be the same as an exception, and therefore **lazy** cannot be the identity function, but converts dynamic exceptions into persistent ones. For a dynamic exception  $e$  the equation

$$(0, e) = e$$

holds. For a persistent exception  $e$  this equation does not hold, and therefore the above chain of equalities is broken.

## 8. LISTS AND VECTORS

For  $n \geq 0$ , the expression

$[e_1, \dots, e_n]$

denotes a *list* of  $n$  elements.

The expression

$(e_1, \dots, e_n)$

denotes a *vector* of  $n$  elements, at least for  $n \neq 1$ . For  $n = 1$ , there is a problem with notation, though, because  $(e)$  is equivalent to  $e$ . Therefore there is the special notation  $(e,)$  for vectors which consist of only one element.

The difference between lists and vectors is that they have different performance characteristics for the possible operations on them. Lists behave like simply linked lists, and vectors behave like arrays. Note that all data structures in Babel-17 are immutable.

Another way of writing down lists is via the right-associative `::` constructor:

$h::t$

Here  $h$  denotes the *head* of the list and  $t$  its *tail*. Actually, note that the expression  $[e_1, \dots, e_n]$  is just syntactic sugar for the expression

$e_1::e_2::\dots::e_n::[]$

Dynamic exceptions cannot be part of a list but are propagated:

$(\text{DynamicException } v)::t \rightsquigarrow \text{DynamicException } v$   
 $h::(\text{DynamicException } v) \rightsquigarrow \text{DynamicException } v$  where  $h$  is non-exceptional

Note that when the tail  $t$  is not a list, we identify  $h::t$  with  $h::t::[]$ .

## 9. CEXPRs

A *CExpr* is a constructor  $c$  together with a parameter  $p$ , written  $c\ p$ . It is allowed to leave out the parameter  $p$ , which then defaults to **nil**. For example, **HELLO** is equivalent to **HELLO nil**. A constructor  $c$  cannot have a dynamic exception as its parameter, therefore we have:

$$c\ (\text{DynamicException } v) \rightsquigarrow \text{DynamicException } v$$

## 10. PATTERN MATCHING

Maybe the most powerful tool in Babel-17 is pattern matching. You use it in several places, most prominently in the **match** expression which has the following syntax:

```

match  $e$ 
  case  $p_1 \Rightarrow b_1$ 
   $\vdots$ 
  case  $p_n \Rightarrow b_n$ 
end

```

Given a value  $e$ , Babel-17 tries to match it to the patterns  $p_1, p_2, \dots$  and so on sequentially in that order. If  $p_i$  is the first pattern to match, then the result of **match** is given by the block expression  $b_i$ . If none of the pattern matches then there are two possible outcomes:

- (1) If  $e$  is a dynamic exception, then the value of the match is just  $e$ .
- (2) Otherwise the result is a dynamic exception with parameter NoMatch.

A few of the pattern constructs incorporate arbitrary value expressions. When these expressions raise exceptions, the whole pattern they are contained in is rendered non-matching.

So what does a pattern look like? Table 3 and Table 4 list all ways of building a pattern.

In this table of pattern constructions we use the  $\delta$ -pattern  $\delta$ . This pattern stands for "the rest of the entity under consideration" and can be constructed by the following rules:

- (1) The ellipsis  $\dots$  is a  $\delta$ -pattern that matches any rest.
- (2) If  $\delta$  is a  $\delta$ -pattern, and  $x$  an identifier, then  $(x \text{ as } \delta)$  is a  $\delta$ -pattern.
- (3) If  $\delta$  is a  $\delta$ -pattern, and  $e$  an expression, then  $(\delta \text{ if } e)$  is a  $\delta$ -pattern.

Note that pattern matching does not distinguish between vectors and lists. A pattern that looks like a vector can match a list, and vice versa.

Besides the **match** construct, there is also the **try** construct. While **match** can handle exceptions, most of the time it is more convenient to use **try** for this purpose. The syntax is



TABLE 3. General Patterns

Syntax	Description
-	the underscore symbol matches anything but a dynamic exception
$x$	an identifier $x$ matches anything but a dynamic exception and binds the matched expression to $x$
$(x \text{ as } p)$	matches $p$ , and binds the successfully matched value to $x$ ; the match fails if $p$ does not match or if the matched value is a dynamic exception
$z$	an integer number $z$ , like 0 or 42 or $-10$ , matches just that number $z$
$c \ p$	matches a $CExpr$ with constructor $c$ if the parameter of the $CExpr$ matches $p$ ; instead of $c \_$ you can just write $c$
$s$	a string $s$ , like "hello", matches just that string $s$
$(p)$	same as $p$
$(p \text{ if } e)$	matches any non-exceptional value that matches $p$ , but only if $e$ evaluates to <b>true</b> ; identifiers bound in $p$ can be used in $e$
$(\text{val } e)$	matches any non-exceptional value which is equivalent to $e$
$(c ! p)$	let $v$ be the value to be matched; then the match succeeds if the result $v.\text{destruct\_} c$ matches $p$
$(c !)$	short for $(c ! \_)$
$(f ? p)$	$f$ is applied to the value to be matched; the match succeeds if the result of the application matches $p$
$(f ?)$	short for $(f ? \text{true})$
$\{m_1 = p_1, \dots, m_n = p_n\}$	matches a value of type <b>obj</b> that has exactly the messages $m_1, \dots, m_n$ such that the message values match the given patterns
$\{m_1 = p_1, \dots, m_n = p_n, \delta\}$	matches a value of type <b>obj</b> that has the messages $m_1, \dots, m_n$ such that the message values match the given patterns
<b>nil</b>	matches the empty object
<b>exception</b> $p$	matches any exception such that its parameter matches $p$
$(p : t)$	matches anything that has type $t$ and matches $p$
$(p : (e))$	matches anything that matches $p$ and has the type that $e$ evaluates to
$(t \ p)$	inner-value pattern; see Section 26.2

**try** $s_1$  $\dots$  $s_m$

TABLE 4. Collection Patterns

Syntax	Description
$[p_1, \dots, p_n]$	matches a list/vector consisting of $n \geq 0$ elements, such that element $e_i$ of the list is matched by pattern $p_i$
$(p_1, \dots, p_n)$	matches a vector/list consisting of $n = 0$ or $n \geq 2$ elements, such that element $e_i$ of the list is matched by pattern $p_i$
$[p_1, \dots, p_n, \delta]$	matches a list/vector consisting of at least $n \geq 1$ elements, such that the first $n$ elements $e_i$ of the list/vector are matched by the patterns $p_i$
$(p_1, \dots, p_n, \delta)$	matches a vector/list consisting of at least $n \geq 1$ elements, such that the first $n$ elements $e_i$ of the vector/list are matched by the patterns $p_i$
$(p, )$	matches a vector/list consisting of a single element that matches the pattern $p$ .
$(h::t)$	matches a non-empty list/vector such that $h$ matches the head of the list/vector and $t$ its tail
$\{p_1, \dots, p_n\}$	see section 17
$\{p_1, \dots, p_n, \delta\}$	see section 17
$\{q_1 \rightarrow p_1, \dots, q_n \rightarrow p_n\}$	see section 17
$\{q_1 \rightarrow p_1, \dots, q_n \rightarrow p_n, \delta\}$	see section 17
$\{->\}$	see section 17
<b>(for</b> $p_1, \dots, p_n$ <b>end)</b>	see section 24
<b>(for</b> $p_1, \dots, p_n, \delta$ <b>end)</b>	see section 24

```

catch
  case  $p_1 \Rightarrow b_1$ 
  :
  case  $p_n \Rightarrow b_n$ 
end

```

The meaning of the above is identical to the meaning of

```

match
  begin
     $s_1$ 
    ...
     $s_m$ 
  end
case (exception  $p_1$ )  $\Rightarrow b_1$ 
  :
case (exception  $p_n$ )  $\Rightarrow b_n$ 
case  $x \Rightarrow x$ 
end

```

except for the fact that the latter expression might not be legal Babel-17 because of linear scoping violations.

## 11. NON-DETERMINISM IN BABEL-17

One source of non-determinism in Babel-17 is *probabilistic* non-determinism. The expression

**random**  $n$

returns for an integer  $n > 0$  a number between 0 and  $n - 1$  such that each number between 0 and  $n - 1$  has equal chance of being returned. If  $n$  is a dynamic exception, then this exception is propagated, if  $n$  is a non-exceptional value that is not an integer  $> 0$  then the result is an exception with parameter `DomainError`.

Another source of non-determinism is choice. The expression

**choose**  $l$

takes a non-empty collection  $l$  and returns a member of the collection. The choice operator makes it possible to optimize evaluation in certain cases. For example, in

**choose** (**concurrent**  $a$ , **concurrent**  $b$ )

the evaluator could choose the member that evaluates quicker.

There is a third source of non-determinism which has its roots in the module loading mechanism (see Section 26).

Babel-17 has been designed such that if you take the above sources of non-determinism out of the language, it becomes purely functional. If in your semantics of Babel-17 you replace the concept of value by the concept of a probability distribution over values and a set of values, you might be able to view Babel-17 as a purely functional language even *including* **random** and **choose**.

## 12. BLOCK EXPRESSIONS

So far we have only looked at expressions. We briefly mentioned the term *block expressions* in the description of the **match** function, though. We will now introduce and explain block expressions.

Block expressions can be used in several places as defined by the Babel-17 grammar. For example, they can be used in a **match** expression to define the value that corresponds to a certain case. But block expressions can really be used just everywhere where a normal expression is allowed:

**begin**  
 $b$   
**end**

is a normal expression where  $b$  is a block expression. A block expression has the form

$s_1$   
 $\vdots$   
 $s_n$

TABLE 5. Legal and illegal definitions

<b>val</b> x = y	<b>def</b> x = y	<b>val</b> x = y	<b>def</b> x = y
<b>val</b> y = 0	<b>val</b> y = 0	<b>def</b> y = 0	<b>def</b> y = 0
<i>illegal</i>	<i>illegal</i>	<i>legal</i>	<i>legal</i>

where the  $s_i$  are *statements*. In a block expression both newlines and semicolons can be used to separate the statements from each other.

Statements are Babel-17's primary tool for introducing identifiers. There are several kinds of statements. Three of them will be introduced in this section.

First, there is the **val**-statement which has the following syntax:

**val**  $p = e$

Here  $p$  is a pattern and  $e$  is an expression. Its meaning is that first  $e$  gets evaluated. If this results in a dynamic exception, then the result of the block expression that the **val**-statement is part of will be that dynamic exception. Otherwise, the result of evaluating  $e$  is matched to  $p$ . If the match is successful then all identifiers bound by the match can be used in later statements of the block expression. If the match fails, then the value of the containing block expression is the dynamic exception NoMatch.

Second, there is the **def**-statement which obeys the following syntax for defining the identifier  $id$ :

**def**  $id\ arg = e$

The  $arg$  part is optional. If  $arg$  is present, then it must be a pattern. Let us call those definitions where  $arg$  is present a *function definition*, and those definitions where  $arg$  is not present a *simple definition*.

Per block expression and identifier  $id$  there can be either a single simple definition, or there can be several function definitions. If there are multiple function definitions for the same identifier in one block expression, then they are bundled in that order to form a single function.

The defining expressions in **def**-statements can recursively refer to the other identifiers defined by **def**-statements in the same block expression. This is the main difference between definitions via **def** and definitions via **val**. Only those **val**-identifiers are in scope that have been defined *previously*, but **def**-identifiers are in scope throughout the whole block expression. Table 5 exemplifies this rule.

Let us assume that a block expression contains multiple function definitions for the same identifier  $f$ :

**def**  $f\ p_1 = e_1$   
 $\vdots$   
**def**  $f\ p_n = e_n$

Then this is (almost) equivalent to

**def**  $f\ x =$   
**match**  $x$   
**case**  $p_1 => e_1$

```

      ⋮
    case  $p_n => e_n$ 
  end

```

where  $x$  is fresh for the  $p_i$  and  $e_i$ . The slight difference between the two notations is that arguments that match none of the patterns will result in a `DomainError` exception for the first notation, and in a `NoMatch` exception for the second.

While definitions only define a single entity per block and identifier, it is OK to have multiple **val**-statements for the same identifier in one block expression, for example like that:

```

val x = 1
val x = (x, x)
x

```

The above block expression evaluates to  $(1,1)$ ; later **val**-definitions overshadow earlier ones. But note that neither

```

val x = 1
def x = 1

```

nor

```

def x = 1
val x = 1

```

are legal.

Another difference between **val** and **def** is observed by the effects of non-determinism:

```

val x = random 2
(x, x)

```

will evaluate either to  $(0, 0)$  or to  $(1, 1)$ . But

```

def x = random 2
(x, x)

```

can additionally also evaluate to  $(0, 1)$  or to  $(1, 0)$  because  $x$  is evaluated each time it is used.

Let us conclude this section by describing the third kind of statement. It has the form

```

yield e

```

where  $e$  is an expression. There is also an abbreviated form of the **yield**-statement which we have already used several times in this section:

```

e

```

The semantics of the **yield**-statement is that it appends a further value to the value of the block expression it is contained in. Block expressions have a value just like all other expressions in Babel-17. It is obtained by "concatenating" all values of the **yield**-statements in a block expression. The value of

```

begin
  ...
end

```

is the empty vector  $()$ . The value of

```

begin
  yield  $a$ 
end

```

is  $a$ . The value of

```

begin
  yield  $a$ 
  yield  $b$ 
end

```

is the vector  $(a, b)$  of length 2 and so on.

In this section we have introduced the notions of block expressions and statements. Their full power will be revealed in later sections of this document.

### 13. ANONYMOUS FUNCTIONS

So far we have seen how to define named functions in Babel-17. Sometimes we do not need a name for a certain function, for example when the code that implements this function is actually just as easy to understand as any name for the function. We already have the tools for writing such nameless, or anonymous, functions:

```

begin
  def  $\text{sqr } x = x * x$ 
   $\text{sqr}$ 
end

```

is an expression denoting the function that squares its argument. There is a shorter and equivalent way of writing down the above:

$$x \Rightarrow x * x$$

In general, the syntax is

$$p \Rightarrow e$$

where  $p$  is a pattern and  $e$  an expression. The above is equivalent to

```

begin
  def  $f \ p = e$ 
   $f$ 
end

```

where  $f$  is fresh for  $p$  and  $e$ .

There is also a syntax for anonymous functions which allows for several cases:

```

(case  $p_1 \Rightarrow b_1$ 
   $\vdots$ 
  case  $p_n \Rightarrow b_n$ )

```

is equivalent to

```

begin
  def  $f \ p_1 = \text{begin } b_1 \text{ end}$ 
   $\vdots$ 
  def  $f \ p_n = \text{begin } b_n \text{ end}$ 
end

```

```
f
end
```

where  $f$  is fresh for the  $p_i$  and  $b_i$ .

#### 14. OBJECT EXPRESSIONS

*Object expressions* have the following syntax:

```
object
  s1
  :
  sn
end
```

The  $s_i$  are statements. Those  $s_i$  that are **def** statements define the set of messages that the object responds to. If you want a def not to become a message, you state this using a **private** statement:

```
object
  private x, y
  def x = 1
  def y = 2
  def z = 3
end
```

The above object responds to the message  $z$  only.

Often you do not want to create objects from scratch but by modifying other already existing objects:

```
object + parents
  s1
  :
  sn
end
```

The expression *parents* must evaluate to either a list, a vector or a set. The members of *parents* are considered to be the parents of the newly created object, in the order induced by the collection. The idea is that the created object not only understands the messages defined by the  $s_i$ , but also the messages of the parents. Messages defined via  $s_i$  shadow messages of the parents. The messages of an earlier parent shadow the messages of a later one.

The keyword **this** can be used only in **def**-statements of an object and points to the object that the original message has been sent too.

There is also a way to denote record-like objects:

$$\{ m_1 = v_1, \dots, m_n = v_n \}$$

This is equivalent to:

```
begin
  val (w1, ..., wn) = (v1, ..., vn)
object
```

TABLE 6. Boolean Operators

<b>not a</b>	<b>a and b</b>	<b>a or b</b>
<pre> match a   case true =&gt;     false   case false =&gt;     true   case _ =&gt;     exception DomainError end </pre>	<pre> match a   case true =&gt;     match b       case true =&gt;         true       case false =&gt;         false       case _ =&gt;         exception DomainError     end   case false =&gt;     false   case _ =&gt;     exception DomainError end </pre>	<pre> match a   case false =&gt;     match b       case true =&gt;         true       case false =&gt;         false       case _ =&gt;         exception DomainError     end   case true =&gt;     true   case _ =&gt;     exception DomainError end </pre>

```

def m1 = w1
...
def mn = wn
end
end

```

The empty object is denoted by

```
nil
```

which is equivalent to

```
object end
```

## 15. BOOLEAN OPERATORS

Babel-17 provides the usual boolean operators. They are just syntactic sugar for certain **match** expressions; the exact translations are given in Table 6. Babel-17 also has **if**-expressions with the following syntax:

```

if b1 then
  e1
elseif b2 then
  e2
:
elseif bn then
  en
else
  en+1
end

```



TABLE 7. Relational Operators

Syntax	Semantics
$a < b$	$(a \sim b) < 0$
$a == b$	$(a \sim b) == 0$
$a > b$	$(a \sim b) > 0$
$a \leq b$	$(a \sim b) \leq 0$
$a \geq b$	$(a \sim b) \geq 0$
$a <> b$	$(a \sim b) <> 0$

The **elseif**-branches are optional. They can be eliminated in the obvious manner via nesting, so that we only need to give the semantics for the expression

**if**  $b$  **then**  $e_1$  **else**  $e_2$  **end**

The meaning of above expression is defined to be

```

match  $b$ 
  case true  $\Rightarrow e_1$ 
  case false  $\Rightarrow e_2$ 
  case  $\_ \Rightarrow$  exception DomainError
end

```

Actually, the **else** branch is also optional. The notation

**if**  $b$  **then**  $e$  **end**

is shorthand for

**if**  $b$  **then**  $e$  **else end**

## 16. ORDER

Babel-17 has a built-in partial order which is defined in terms of the operator  $\sim$ . The expression  $a \sim b$  returns an *Integer*; the usual relational operators are defined in Table 7. Note that  $a$  and  $b$  are unrelated iff  $a \sim b$  is less than  $-1$  or greater than  $1$ .

It is possible to chain relational operators like this:

$a \leq b \leq c > d <> e$

Intuitively, the above means

$a \leq b \ \& \ b \leq c \ \& \ c > d \ \& \ d <> e$ .

Note that we always evaluate the operands of relational operators, even chained ones, only once. For example, the precise semantics of  $a \leq b \leq c \leq d \leq e$  is

```

begin
  val  $t = a$ 
  val  $u = b$ 
   $t \leq u \ \&$ 
  begin
    val  $v = c$ 
     $u \leq v \ \&$ 
  begin

```

```

    val w = d
    v <= w & w <= e
  end
end
end

```

In the above,  $t$ ,  $u$ ,  $v$  and  $w$  are supposed to be fresh identifiers. Also note that if there are operands that are dynamic exceptions, then the result of a comparison is a dynamic exception with the same parameter as the first such operand (from left to right).

It is possible that two values  $a$  and  $b$  are not related with respect to the built-in order. In this case,  $a \sim b$  throws an *Unrelated*-exception. Taking this into account, the definition of  $a \text{ op } b$  for  $op \in \{<, >, <=, >=, ==, <>\}$  is

```

match a ~ b
case (u if u op 0) => true
case _ => false
case (exception Unrelated) => false
end

```

The built-in partial order has the following properties:

- values of type **type** are totally ordered by their name
- $a \sim b$  is equivalent to

```

match (typeof a) ~ (typeof b)
case 0 =>
  match a.compare_ b
  case u : int => u
  case e => exception CompareError e
  end
case _ => exception Unrelated
end

```

- persistent exceptions are partially ordered by their parameter
- booleans are totally ordered and **false** < **true** holds
- integers are totally ordered in the obvious way
- reals are partially ordered as described in Section 18
- strings are totally ordered via lexicographic ordering
- lists are partially ordered by the lexicographic ordering
- vectors are partially ordered by the lexicographic ordering
- constructed expressions are partially ordered by representing them by the pair consisting of constructor and parameter
- $f \neq g$  for all values  $f$  and  $g$  of type **fun**
- sets are partially ordered by first comparing their sizes, and then their elements
- maps are partially ordered by first comparing their sizes, then their keys, and then their corresponding values

## 17. SETS AND MAPS

Sets and maps are built into Babel-17. For example, the set consisting of 3, 42 and 15 can be written as

$\{42, 15, 3\}$

Sets are always sorted. The sorting order is Babel-17's built-in partial order, and every set forms a totally ordered subdomain of this partial order. Future versions of Babel-17 might allow the set order to be different from the built-in partial order. Adding or removing an element  $e$  from a set  $S$  is only well-defined when the elements of  $S$  together with  $e$  are totally ordered by the partial order of  $S$ . The same holds for testing if an element is in a set.

Maps map finitely many keys to values. For example, the map that maps 1 to 2 and 4 to 0 is written as

$\{1 \rightarrow 2, 4 \rightarrow 0\}$

The empty map is denoted by

$\{\rightarrow\}$

Maps also have always a partial order associated with them, in the current version of Babel-17 this is always Babel-17's built-in partial order. Operations on maps are only well-defined if all keys of the map together with all other involved keys are totally ordered by the associated order.

Pattern matching is available also for sets and maps. The pattern

$\{p_1, \dots, p_n\}$

matches a set that has  $n$  elements  $e_1, \dots, e_n$  such that  $p_i$  matches  $e_i$  and  $e_i < e_j$  for  $i < j$ . The pattern

$\{p_1, \dots, p_n, \delta\}$

matches a set that has  $m \geq n$  elements such that its first  $n$  elements match the patterns  $p_i$ , and the set consisting of the other  $m - n$  elements matches the  $\delta$ -pattern.

Similarly, the pattern

$\{p_1 \rightarrow q_1, \dots, p_n \rightarrow q_n\}$

matches a map consisting of  $n$  key/value pairs such that the key/value pairs match the pattern pairs in order. The pattern  $\{\rightarrow\}$  matches the empty map. Map patterns can have a  $\delta$  pattern, too.

## 18. REALS AND INTERVAL ARITHMETIC

Babel-17 is radical in its treatment of floating point arithmetic: there is *only* interval arithmetic. What that means is that reals are represented in Babel-17 as closed real intervals, i.e. as pairs  $[a; b]$  where  $a$  and  $b$  are floating point numbers and  $a \leq b$ . The usual floating point numbers can then be viewed as that subset of reals for which  $a = b$  holds. For example, the notation 1.2 is just short for  $[1.2; 1.2]$ .

The general form of this interval notation is

$[a; b]$

Its value is formed by evaluating  $a$  and  $b$ , resulting in **reals**  $[a_1; a_2]$  and  $[b_1; b_2]$ , respectively, and then forming the interval  $[a_1; b_2]$  if  $a_2 \leq b_1$ . In case the evaluation does not yield reals, a *DomainError*-exception is thrown. In case  $a_2 > b_1$ , an *EmptyReal*-exception is raised.

TABLE 8. Syntactic Sugar

Sugared	Desugared
$a + b$	$a.\text{plus\_} b$
$a - b$	$a.\text{minus\_} b$
$- a$	$a.\text{uminus\_}$
$a * b$	$a.\text{times\_} b$
$a / b$	$a.\text{slash\_} b$
$a \text{ div } b$	$a.\text{div\_} b$
$a \text{ mod } b$	$a.\text{mod\_} b$
$a \wedge b$	$a.\text{pow\_} b$
$a ++ b$	$a.\text{plus\_}\_ b$
$a -- b$	$a.\text{minus\_}\_ b$
$a ** b$	$a.\text{times\_}\_ b$
$a // b$	$a.\text{slash\_}\_ b$
$a \text{ to } b$	$a.\text{to\_} b$
$a \text{ downto } b$	$a.\text{downto\_} b$
$f \ x$	$f.\text{apply\_} x$

The general rule of interval arithmetic in Babel-17 is as follows: If  $f$  is a mapping from  $\mathbb{R}^n$  to  $\mathbb{R}$ , then for its interval arithmetic implementation  $F$  the following must hold for all  $x_i \in \mathbb{R}$  and all **reals**  $y_i = [u_i; v_i]$  such that  $u_i \leq x_i \leq v_i$ :

$$f(x_1, \dots, x_n) \in F(y_1, \dots, y_n)$$

The built-in order on **reals** is defined such that

$$[a_1; a_2] \leq [b_1; b_2] \quad \text{iff} \quad a_2 < b_1 \vee (a_1 = b_1 \wedge a_2 = b_2)$$

Note that certain seemingly obvious inequalities like  $[1.0; 2.0] \leq 2.0$  do *not* hold! Also note that while  $[1.0; 2.0] < 3.0$  is true, the seemingly identical inequality  $[1.0; 2.0] < 3$  is false! This is because *Integers* and *Reals* are unrelated with respect to the built-in order.

## 19. SYNTACTIC SUGAR

One of the goals of Babel-17 is that Babel-17 code is easy to read and understand. I have found that allowing arbitrary user-specific extensions to the syntax of code is definitely not helping to achieve this goal. Nevertheless, a bare minimum of syntactic sugar is necessary to support the most basic conventions known from arithmetic; for example, one should be able to write  $3 + 5$  to denote the addition of the integer 3 and the integer 5.

The programmer can use some of this syntactic sugar when defining her own objects. For example,  $3 + 5$  is just syntactic sugar for

`3.plus_ 5`

Table 8 lists all syntactic sugar of Babel-17 that is also available to the programmer. The availability of syntactic sugar for function application means that you can let your own objects behave as if they were functions.

## 20. MEMOIZATION

Babel-17 supports *memoization*. In those places where **def**-statements can be used, **memoize**-statements can be used, also. A **memoize**-statement must always refer to **def**-statements in the same scope. Babel-17 differentiates two kinds of memoization, *strong* and *weak*. A **memoize**-statement has the following syntax:

```
memoize  $ref_1, \dots, ref_n$ 
```

The  $ref_i$  are either of the form *id* to indicate strong memoization, or of the form (*id*) to signal weak memoization. In both cases *id* refers to the **def**-statement being memoized. As an example, here is the definition of the weakly memoized fibonacci-sequence:

```
memoize (fib)
def fib 0 = 0
def fib 1 = 1
def fib n = fib (n-1) + fib (n-2)
```

The difference between weak and strong memoization is that strong memoization always remembers a value once it has been computed; weak memoization instead may choose not to remember computed results in certain situations, for example in order to free memory in low memory situations. Note that all arguments to the same memoized function must be totally ordered by the built-in partial order.

## 21. LINEAR SCOPE

We are now ready to explore the full power of block expressions and statements in Babel-17. We approach the topic of this and the following sections, *linear scope*, in an example-oriented way. A more in-depth treatment can be found in my paper *Purely Functional Structured Programming*, also available at [www.babel-17.com](http://www.babel-17.com).

First, we extend the syntax of **val**-statements such that it is legal to leave out the keyword **val** in certain situations. Whenever the situation is such that it is legal to write

$$a = \text{expr}$$

for a variable identifier *a*, we say that *a* is in *linear scope*. We call the above kind of statements *assignments*. A necessary condition for *a* to be in linear scope is for *a* to be in scope because of a previous **val**-statement or a pattern match. The idea behind linear scope is that when the program control flow has a linear structure, then we can make assignments to variables in linear scope without leaving the realm of purely functional programming.

The following two expressions are equivalent:

<b>begin</b>	<b>begin</b>
<b>val</b> x = a	<b>val</b> x = a
<b>val</b> y = b	<b>val</b> y = b
<b>val</b> x = c	x = c
d	d
<b>end</b>	<b>end</b>

So far, **val**-statements and assignments have indistinguishable semantics. The differences start to show when we look at nested block expressions:

<pre> begin   val x = 1   val y = 2   begin     val x = 3     val y = 4 * x   end   (x, y) end </pre>	<pre> begin   val x = 1   val y = 2   begin     val x = 3     y = 4 * x   end   (x, y) end </pre>	<pre> begin   val x = 1   val y = 2   begin     val x = 3     val y = 0     y = 4 * x   end   (x, y) end </pre>
evaluates to (1, 2)	evaluates to (1, 12)	evaluates to (1, 2)

The above examples show that the effect of dropping the **val** in a **val** statement is that the binding of an identifier becomes visible at that level within the linear scope where it has last been introduced via a **val** statement or via a pattern match.

Linear scope spreads along the statements and nested block expressions of a block expression. It usually does not spread into expressions. An exception are certain expressions that can also be viewed as statements. We call these expressions *control expressions*. For example, in

```

begin
  val x = 1
  x = 2
  val y = a * b
  (x, y)
end

```

the linear scope of  $x$  does not extend into the expressions  $a$  and  $b$ , because  $a * b$  is not a control expression. Therefore the above expression will always evaluate (assuming there is no exception) to a pair which has 2 as its first element. But for example in

```

begin
  val x = 1
  x = 2
  val y =
    begin
      s1
      ⋮
      sn
    end
  (x, y)
end

```

the linear scope of  $x$  extends into  $s_1$  and spreads then along the following statements. Therefore the first element of the pair that is the result of evaluating above expression depends on what happens in the  $s_i$ . Here are three example code snippets that further illustrate linear scope:

<pre> begin   val x = 1   val y =     begin       x = 2       x+x     end   (x, y) end </pre>	<pre> begin   val x = 1   val y = 3 *     begin       x = 2       x+x     end   (x, y) end </pre>	<pre> begin   val x = 1   val y = 3 *     begin       val x = 2       x+x     end   (x, y) end </pre>
evaluates to (2, 4)	illegal	evaluates to (1, 12)

These are the control expressions that exist in Babel-17:

- **begin ... end**
- **if ... end**
- **match ... end**
- **match ... end**
- **try ... catch ... end**
- **while ... end**

The last two control expressions are loops and explained in the next section. The first four have already been treated without delving too much into their statement character. We have already seen how **begin ... end** is responsible for nesting block expressions, when it is used as a statement. Just as the **begin ... end** expression may be used as a statement, you can also use all other control expressions as statements, for example:

```

begin
  val x = random 2
  if x == 0 then
    x = 100
  else
    x = 200
  end
  x + x
end

```

This expression will evaluate either to 200 or to 400.

For **if**-statements the **else**-branch is optional, but **match**-statements throw a `NoMatch` exception if none of the patterns matches.

## 22. RECORD UPDATES

Linear scope makes it possible to have purely functional record updates in Babel-17. Let us assume you have defined  $u$  via

```
val u = {x = 10, y = 20, z = -4}
```

and now you want to bind  $u$  to another record that differs only in the  $x$ -component. You could proceed as follows:

```
u = {x = 9, y = u.y, z = u.z}
```

but this clearly does not scale with the number of components of  $u$ . A more scalable alternative would be to write

```
u =
  object + [u]
  def x = 9
end
```

Babel-17 allows to write down the above statement in a more concise form:

```
u.x = 9
```

In general,

```
u.m = t
```

is shorthand notation for

```
u =
  begin
    val evaluated_t = t
    object + [u]
    def m = evaluated_t
  end
end
```

For the sake of completeness, there is also the much less useful notation

```
val u.m = t
```

which is short for

```
val u = { m = t }
```

## 23. WITH

By default, all yielded values of a block expression are collected into a list which collapses in the case of a single element. The programmer might want to deviate from this default and collect the yielded values differently, for example to get rid of the collapsing behavior. The **with** expression allows her to do just that. Its syntax is:

```
with c do
  b
end
```

where  $c$  is a *collector* and  $b$  is a block expression. A collector  $c$  is any object that

- responds to the message `collector_close_`,
- and returns via `c.collector_add_ x` another collector.

It is recommended that collectors also support the message **empty** to represent the empty collector that has not collected anything yet.

Lists, vectors, sets, maps and strings are built-in collectors which the programmer can use out-of-the-box; apart from that she can implement her own collectors, of course.

Here is an example where we use a set as a collector:



```

with {4} do
  yield 1
  yield 2
  yield 1
  10
end

```

Above expression evaluates to {1, 2, 4, 10}.

## 24. LOOPS

This is the syntax for the **while**-loop:

```

while c do
  b
end

```

Here *c* must evaluate to a boolean and *b* is a block expression. For example, here is how you could code the euclidean algorithm for calculating the greatest common divisor:

```

def gcd (a,b) = begin
  while b <> 0 do
    (a, b) = (b, a mod b)
  end
  a
end

```

There is also the **for**-loop. It has the following syntax:

```

for p in C do
  b
end

```

In the above *p* is a pattern, *C* is a *collection*, and *b* is a block expression. The idea is that above expression iterates through those elements of the *collection* *C* which match *p*; for each successfully matched element, *b* is executed.

An object *C* is a collection if it handles the message **iterate\_**

- by returning () if it represents the empty collection,
- or otherwise by returning (*e*, *C'*) such that *C'* is also a collection.

Here is an example of a simple **for**-loop expression:

```

begin
  val s = [10, (5, 8), 7, (3,5)]
  with {->} : for (a,b) in s do
    yield (b,a)
  end
end

```

evaluates to {8 -> 5, 5 -> 3}.

Using **for**-loops in combination with linear scope it is possible to formulate all of those *fold*-related functionals known from functional programming in a way which is easier to

parse (and remember) for most people. Let us for example look at a function that takes a list  $m$  of integers  $[a_0, \dots, a_n]$  and an integer  $x$  as arguments and returns the list

$$[q_0, \dots, q_n] \quad \text{where} \quad q_k = \sum_{i=0}^k a_i x^i$$

The implementation in Babel-17 via a loop is straightforward, efficient and even elegant:

```

m => x =>
  with [] do
    val y = 0
    val p = 1
    for a in m do
      y = y + a*p
      p = p * x
      yield y
    end
  end

```

The built-in collections that can be used with for-loops are the usual suspects: lists, vectors, sets, maps and strings. Of course you can define your own custom collections. There is even a pattern you can use for matching against an arbitrary collection:

```
(for p1, ..., pn end)
```

and the corresponding  $\delta$  pattern

```
(for p1, ..., pn,  $\delta$  end)
```

match collections with exactly  $n$  or at least  $n$  elements, respectively.

## 25. PRAGMAS

Pragmas are statements that are not really part of the program, but inserted in it for pragmatistical reasons. They are useful for testing, debugging and profiling a program. There are currently four different kinds of pragmas available:

**#log**  $e$  evaluates the expression  $e$  and logs it.

**#print**  $e$  evaluates the expression  $e$  such that it has no internal lazy or concurrent computations any more, and then logs it.

**#profile**  $e$  evaluates the expression  $e$ , gathers profiling information while doing so, and logs both.

**#assert**  $e$  evaluates the expression  $e$  and signals an error if  $e$  does not evaluate to **true**.

The Babel-17 interpreter / compiler is free to ignore pragmas, typically if instructed so by the user.

## 26. MODULES AND TYPES

Modules give Babel-17 code a static structure and improve on object expressions by providing more sophisticated encapsulation mechanisms via types. Modules are introduced with the syntax

```

module  $p_1.p_2.\dots.p_n$ 
   $s_1$ 
   $\vdots$ 
   $s_n$ 
end

```

where  $p = p_1.p_2.\dots.p_n$  is the *module path*. A condition on module paths is that all elements of a module path must be different, i.e.  $p_i \neq p_j$  for  $i \neq j$ .

The statements  $s_i$  that may appear in modules are basically those that may also appear in object expressions. Additionally, modules can contain *type definitions*; this is the topic of the next section.

Identifiers introduced via definitions become the messages that this module responds to except when hidden via **private**.

**26.1. Loading Modules.** Before a module can respond to messages, it must be loaded. A module is in one of the following three states: DOWN, LOADING or UP. There are three things that one might suspect to change the state of the module:

- A:** the module receives a message  $m$  that corresponds to a definition inside of it,
- B:** the module receives a message  $m$  that corresponds to a submodule  $p.m$ ,
- C:** the module receives an invalid message  $m$ .

Of these three things, neither B nor C change the state of the module, so we are looking now only at case A.

In the following we distinguish modules which need initialization from modules which don't. A module does not need initialization iff it consists only of the following types of statements: **def**, **typedef**, **import**, **private**, **memoize**.

If module  $p$  needs initialization and is in state DOWN, then sending it a message causes it to go to state LOADING; after  $p$  has been loaded, that is all statements of the module have been executed,  $p$  goes from state LOADING to state UP. If the module needs no initialization, the state goes directly from DOWN to UP.

If  $p$  is in state LOADING, then sending it a message will make the sender wait until  $p$  is in state UP. Note that this can lead to a deadlock situation. In case the Babel-17 runtime can detect this deadlock, a *DeadLock*-exception is thrown.

If  $p$  is already in state UP, then A does not change the state of the module.

Note that the state of a module is not directly accessible and only sometimes indirectly observable via the *DeadLock*-exception.

Here is an example that leads to a deadlock:

```

module deadlock
  def x = 10
  val a = deadlock.x + 1
  def y = a * a
end
deadlock.y

```

Note that the following example does *not* lead to a deadlock:

```

module noDeadlock
  def x = 10

```

```

    val a = x + 1
    def y = a * a
  end
noDeadlock.y

```

The most straightforward way to avoid deadlock problems is to write modules which need no initialization.

**26.2. Type Definitions.** A module may contain type definition statements. A new type  $t$  is introduced via

```
typedef t pat = expr
```

where  $t$  is an identifier,  $pat$  a pattern and  $expr$  an expression. Like a **def** statement, the above introduces a new function  $t$ . Unlike a **def** statement, it also introduces a new type  $t$ . The new function  $t$  has the property that all non-exceptional values  $v$  it returns will have type  $t$  and will consist of two components: an *inner value*, and an *outer value*. The inner value  $i$  is just the argument that was passed to  $t$ . The outer value  $o$  is the result of evaluating  $expr$  in case this evaluation does not lead to an exception. If this evaluation leads to an exception or if  $pat$  does not match, then a *TypeError*-exception is thrown.

The point of all this is that the value  $v$  behaves just like its outer value  $o$ , i.e.  $v$  responds to the same messages as  $o$ , and does so in the same way. Nevertheless, the type of  $v$  is  $t$ , whatever the type of  $o$  might be. This means that you can implement the behavior of  $v$  by choosing an appropriate  $o$  which accesses the hidden encapsulated state  $i$ . This hidden state can also be accessed in the module in which the type has been defined via the *inner-value pattern* ( $t\ p$ ) which matches  $v$  if it has type  $t$  and its inner value  $i$  matches  $p$ .

Let's look at a first type definition example:

```

module cards
  typedef rank i =
    match i
      case 14 => Ace
      case 13 => King
      case 12 => Queen
      case 11 => Jack
      case x if 2 <= x <= 10 => Number x
    end
end

```

In the above we define the type *cards.rank*. We can create a value of this type like this:

```
val k = cards.rank 13
```

The expression `(:cards.rank)` evaluates to the type *cards.rank*, therefore

```
(typeof k) == (:cards.rank)
```

evaluates to **true**.

Note that there is no other way to create a value of type *cards.rank* than via the *rank* function in the module *cards*. If you want to access the inner value of a value of type *cards.rank*, you can do so *within* the module *cards* via the inner-value pattern:

```

module cards
  typedef rank ...
  ...
  def rank2num(rank n) = n
  ...
end

```

Now you can access the inner value of a rank even outside of the *cards* module by calling the *rank2num* function we just defined. The following evaluates to **true**:

```
cards.rank2num (cards.rank 14) == 14
```

You can use the fact that a rank value behaves like its outer value to do pattern matching on rank values:

```

def rank2str(r : rank) =
  match r
    case (Ace !) => "ace"
    case (King !) => "king"
    case (Queen !) => "queen"
    case (Number ! n) => "number"+n
  end

```

It is possible to distribute the definition of a type *t* over several statements:

```

typedef t pat1 = expr1
  ⋮
typedef t patn = exprn

```

So an alternative way of defining the rank type would have been:

```

module cards
  typedef rank 14 = Ace
  typedef rank 13 = King
  typedef rank 12 = Queen
  typedef rank 11 = Jack
  typedef rank (n if 2 <= n <= 10) = Number n
end

```

As a shortcut notation, several typedef clauses belonging to the same type *t* can be combined into a single one by separating the different cases by commas:

```

module cards
  typedef rank 14 = Ace, 13 = King, 12 = Queen, 11 = Jack,
    (n if 2 <= n <= 10) = Number n
end

```

Another shortcut notation allows you to write instead of

```
typedef t (x as p) = x
```

just

```
typedef t p
```

Finally, it is possible to identify a type with the module it is defined in by using the same name for the type and the module. For example:

```

module util.orderedSet
  typedef orderedSet ...
  ...
end

```

This defines the module *util.orderedSet* and the type *util.orderedSet.orderedSet*. Because of our convention of identifying modules and types that have the same name, you can refer to the type *util.orderedSet.orderedSet* also just by *util.orderedSet*. In particular, the following evaluates to **true**:

```
(: util.orderedSet.orderedSet) == (:util.orderedSet)
```

This is all there is to defining your own types in Babel-17. In the following we list a few common type definition patterns: *simple enumerations*, *algebraic datatypes*, and *abstract datatypes*.

**26.3. Simple Enumerations.** It is easy to define a type that is just an enumeration:

```

module cards
  typedef suit Spades, Clubs, Diamonds, Hearts
end

```

We may choose to represent our rank type rather as an enumeration, too:

```

module cards
  typedef rank Ace, King, Queen, Jack, Number (n if 2 <= n <= 10)
end

```

**26.4. Algebraic Datatypes.** For enumeration types, the inner value is always equal to the outer value. This property is also shared by the more complex algebraic datatypes which are typically recursively defined:

```

module cards
  typedef bintree Leaf _, Branch ( _ : bintree, _ : bintree )
end

```

**26.5. Abstract Datatypes.** The type definition facility of Babel-17 is powerful enough to allow you to define your own abstract datatypes. Currently there is no type in Babel-17 for representing sets that are ordered by a given (i.e., not necessarily the built-in) order. So let's define our own. To keep it simple, we use lists to internally represent sets:

```

module util.orderedSet

  private orderedSet, ins

  typedef orderedSet (leq, list) = nil

  def insert (orderedSet (leq, list), y) = (orderedSet (leq, ins (leq, list, y)))

  def toList (orderedSet (leq, list)) = list

```

```

def ins (leq, [], y) = [y]
def ins (leq, x::xs, y) =
  if leq (y, x) then
    if leq (x, y) then x::xs else y::x::xs end
  else
    x::(ins (leq, xs, y))
  end
end

```

From outside the module, the only way to create values of type *orderedSet* is by calling *empty* and *insert*. The only way to inspect the elements of an *orderedSet* is via *toList*.

**26.6. Type Conversions.** It often makes sense to convert a value of one type into a value of another type. Probably the most prominent example of this is converting an *Integer* to a *Real* and rounding a *Real* to an *Integer*.

Because type conversions are so ubiquitous, there is special notation for it in Babel-17. To convert a value *v* canonically to a value of type *t*, the notation

```
v :> t
```

is used. If *t* is a value of type **type**, you can write

```
v :> (t)
```

to express the conversion operation.

Your own object can implement conversion to a type *t* via

```

object
...
def this : t = ...
...
end

```

In case your object cannot convert to *t*, it should throw a *CannotConvert*-exception.

You can annotate your *def*-statements with a *return type t*, for example:

```
def myfun pat : t = expr
```

This is just another notation for

```
def myfun pat = (expr :> t)
```

**26.7. Import.** A module can be accessed from anywhere via its module path. For example will

```

module hello.world
  def x = 2
end
hello.world.x

```

result in the value 2.

To avoid typing long module paths you can *import* them:

```

import hello.world.x
(x, x, x)

```

will evaluate to (2, 2, 2).

You can also import types this way:

```
import util.orderedSet.orderedSet
def e : orderedSet = util.orderedSet.empty
```

Alternatively, to make the above statement even shorter, import *both* the type and its enclosing module:

```
import util.orderedSet
def e : orderedSet = orderedSet.empty
```

Of course, you can also just import all members of the module instead:

```
import util.orderedSet._
def e : orderedSet = empty
```

You can also rename imports, for example:

```
import util.orderedSet => set
def e : set = set.empty
```

You can combine several imports into a single one:

```
import util.orderedSet.{empty, insert => orderedInsert}
def e : set = set.empty
```

or import everything from a module *except* certain names:

```
import util.orderedSet.{-empty}
def e : set = set.empty
```

All imports must be grouped together at the beginning of a block, and later **import**-statements in this group take earlier **import**-statements in this group (and outside this group, of course) into account.

**26.8. Abstract Datatypes, Continued.** We have seen previously how to define our own abstract datatype *orderedSet*. This is already fine, but we would like *orderedSet* to integrate more tightly with how things work in Babel-17. In particular,

- (1) ordered sets should be comparable in a way that makes sense; right now, the expression

```
insert (empty leq, 1) == insert (empty leq, 2)
```

evaluates to **true** because both values have outer value **nil**,

- (2) instead of `insert (r, x)` we just want to write `r + x`,
- (3) instead of `toList r` we want to write `r :> list`,
- (4) we want to be able to traverse the set via

```
for x in r do ... end
```

- (5) and we want to be able to write

```
with empty leq do
  yield a
  yield b
  yield c
end
```



for the set consisting of the elements  $a$ ,  $b$  and  $c$ .

We can achieve all that by replacing the line

```
typedef orderedSet (leq, list) = nil
```

with the following code:

```
typedef orderedSet (leq, list) =
  object

    ## (1)
    def compare_ (orderedSet (leq2, list2)) = list ~ list2

    ## (2)
    def plus_ x = insert (this, x)

    ## (3)
    def this : list = list

    ## (4)
    def iterate_ =
      match list
      case [] => ()
      case (x::xs) => (x, orderedSet (leq, xs))
    end

    ## (5)
    def collector_close_ = this
    def collector_add_ x = this + x
    def empty = orderedSet (leq, [])

end
```

## 27. UNIT TESTS

Unit testing has become a corner stone of most popular software development methodologies. Therefore Babel-17 provides language support for unit testing in form of the unittest keyword. This keyword can be used in two forms.

First, it can be used as part of the name of a module, for example like in

```
module util.orderedSet.unittest

import util.orderedSet._

def leq (a, b) = a <= b
def geq (a, b) = a >= b

#assert insert (insert (empty leq, 3), 1) :> list == [1, 3]
#assert insert (insert (empty geq, 3), 1) :> list == [3, 1]
```

**end**

Second, it can be used to separate a module definition into two parts:

```

module util.orderedSet

typedef orderedSet ...

...

unittest

def leq (a, b) = a <= b
def geq (a, b) = a >= b

#assert insert (insert (empty leq, 3), 1) :> list == [1, 3]
#assert insert (insert (empty geq, 3), 1) :> list == [3, 1]

end

```

The meaning of the above is

```

module util.orderedSet

typedef orderedSet ...

...

def unittest =
  begin

    def leq (a, b) = a <= b
    def geq (a, b) = a >= b

    #assert insert (insert (empty leq, 3), 1) :> list == [1, 3]
    #assert insert (insert (empty geq, 3), 1) :> list == [3, 1]

  end

end

```

except for the fact that this is not legal Babel-17.

The idea is that Babel-17 can run in two modes. In *production mode*, all unit tests are ignored. In *unit testing mode*, you can run your unit tests. Usually in production mode, you would switch off assertions, and in unit testing mode you would turn them on, but that is up to you.

An important detail is that production code is separated from unit testing code, i.e. while unit testing code can import other unit testing code and production code, production code can only import other production code. For example,

```

module mystuff

  import util.orderSet.unittest => test

  test ()

end

```

is not legal Babel-17, because the production code module *mystuff* cannot import the unit testing function *util.orderSet.unittest*. On the other hand, the following is valid Babel-17:

```

module mystuff.unittest

  import util.orderSet.unittest => test

  test ()

end

```

## 28. STANDARD LIBRARY

The standard library is an important part of the language definition of Babel-17.

The standard library of Babel-17 lives in the module *babel17.standard*. All public elements of this module are automatically and implicitly imported.

The messages implemented by the built-in types of the standard library can be grouped as follows:

- `compare_`,
- collector related messages (Section 23),
- collection related messages (Section 24),
- messages that convert between different types,
- those messages that are listed as syntactic sugar in Table 8,
- messages specific to the type.

As a convention, all messages that are normally only used via some sort of syntactic sugar end with an underscore in their name.

**28.1. `compare_`.** The role of the `compare_` message has been explained in Section 16. There we have also described the canonical orderings of the built-in types.

**28.2. Collections and Collectors.** The built-in types that can be used as collectors and collections are: List, Vector, Set, Map and String. In the case of maps, the elements of the collection are pairs (vectors of length 2) where the first element of the pair represents the key, and the second element the value the key is mapped to. For strings, the elements of the collection are strings of length 1, consisting of a single Unicode code point.

TABLE 9. Additional messages for collection/collector  $c$ 

Message	Description
$c.\text{isEmpty}$	checks if $c$ is an empty collection
$c.\text{empty}$	an empty collection that has the same type as $c$
$c.\text{size}$	the size of collection $c$
$c + x$	adds $x$ as member to collection $c$
$c ++ d$	adds all members of $d$ as members to $c$
$c - x$	removes from $c$ all members that are equal to $x$
$c -- d$	removes from $c$ all members that are equal to an element in $d$
$c ** d$	removes from $c$ all members that are not equal to an element in $d$
$c.\text{head}$	the first element of $c$
$c.\text{tail}$	all elements of $c$ except the first one
$c.\text{atIndex } i$	the $i$ -th element of $c$
$c.\text{indexOf } x$	the lowest $i$ such that $c.\text{atIndex } i == x$
$c.\text{contains } x$	checks if $c$ contains $x$
$c.\text{take } n$	forms a collection out of the first $n$ elements of $c$
$c.\text{drop } n$	forms a collection by dropping the first $n$ elements of $c$
$c/f$	maps the function $f$ over all elements of $c$
$(c * f) a_0$	folds $f$ over $c$ via $a_{i+1} = f(c_i, a_i)$
$c \hat{=} f$	filters $c$ by boolean-valued function $f$
$c // f$	map created by all key/value pairs $(x, f(x))$ where $x$ runs through the elements of $c$ ; later pairs overwrite earlier pairs

TABLE 10. Type Conversions

Destination Type	Source Types
Integer	Boolean, String, Real
Real	Integer, String
Boolean	Integer, String
String	Integer, Real, Boolean
List	Vector, Set, Map
Vector	List, Set, Map
Set	List, Vector, Map
Map	List, Vector, Set

All built-in collection/collector types implement the messages described in Table 9.

**28.3. Type Conversions.** Many built-in types have conversions defined between them. Table 10 lists all of them. Note that Babel-17 does no automatic type conversion.

In the rest of this section we enumerate for each built-in type all messages that are supported by this type. Collector and collection messages are excluded from this enumeration.

TABLE 11. List/Vector-specific messages

$l\ i$	same as $l.\text{atIndex } i$
$-l$	reverses $l$

TABLE 12. Map-specific Messages

$c.\text{contains } x$	checks if $c$ contains $x$
$c.\text{containsKey } k$	checks if $c$ contains $(k, v)$ for some $v$
$m + (k, v)$	map created from the map $m$ by associating $k$ with $v$
$m - k$	map created from the map $m$ by removing the key $k$
$m ++ n$	map created from the map $m$ by adding the key/value pairs that are elements of $n$
$m -- n$	map created from $m$ by removing all keys that are elements of $n$
$m ** n$	map created from $m$ by removing all keys that are not elements of $n$
$m\ k$	returns the value $v$ associated with $k$ in $m$ , or returns a dynamic exception with parameter <b>DomainError</b> if no such value exists
$m\ //\ f$	map created by applying the function $f$ to the key/value pairs $(k, v)$ of $m$ , yielding key/value pairs $(k, f(k, v))$

28.4. **Integer.** Integers can be arbitrarily large and support the usual operations ( $+$ , binary and unary  $-$ ,  $*$ ,  $\wedge$ , **div**, **mod**). Division and modulo are Euclidean.

The expression  $a\ \text{to } b$  denotes the list of values  $a, a + 1, \dots, b$ . The expression  $a\ \text{downto } b$  denotes the list of values  $a, a - 1, \dots, b$ .

28.5. **Reals.** Reals are intervals bounded by floating point numbers. For more information on them see Section 18.

28.6. **String.** Implements no messages specific for strings. The semantics of the `indexOf` and `contains` messages is extended with respect to the usual collection semantics to not only search for strings of length 1, but arbitrarily long strings.

28.7. **List and Vector.** Those messages specific to lists and vectors are listed in Table 11.

28.8. **Set.** There are no messages specific to sets except that for a set  $s$  the expression  $s\ x$  is equivalent to  $s.\text{contains } x$  and therefore tests if  $x$  is an element of  $s$ .

28.9. **Map.** The messages specific to maps are listed in Table 12. Note that the operators  $-$ ,  $--$ ,  $**$  and  $//$  deviate in their semantics from the usual collection semantics, but that the operators  $+$  and  $++$  *do* behave according to the usual collection semantics.

28.10. **Object.** Custom objects respond exactly to the set of messages defined in their body, with one exception: if the custom object implements all four of these messages:

- `collector_add_`
- `collector_close_`

- `empty`
- `collector.iterate_`

then the custom object automatically inherits standard implementations for all messages listed in Table 9 and for the three type conversions to `list`, `vector` and `set`. These standard implementations are shadowed by actual implementations the custom object might provide.

## 29. WHAT'S NEXT?

Where will Babel-17 go from here? There are two dimensions along which Babel-17 has to grow in order to find adoption.

**Maturity and breadth of implementations** While there will probably always be a reference implementation of Babel-17 that strives for simplicity and clarity and sacrifices performance to achieve this, Babel-17 will need quality implementations on major computing platforms like JavaVM, Android, iOS and HTML 5. A lot of the infrastructure of these implementations can be shared, so once there is a speedy implementation of Babel-17 running for example on the Java Virtual Machine, the other implementations should follow more quickly. For example, there are many many opportunities for both static and particularly dynamic optimizations of the standard library implementation.

**Development of the language** Babel-17 is a dynamically typed purely functional programming language with a module system that has powerful encapsulation mechanisms. Some way of dealing with state, user interfaces, and communication with the outside world will be added to future versions of Babel-17.