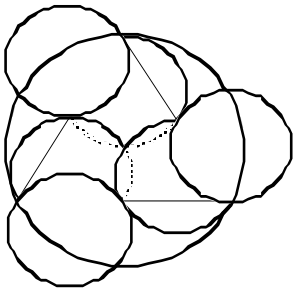

CLAIRE

Combining Logical
Assertions, Inheritance,
Relations and Entities

Introduction to the CLAIRE Programming Language Version 3.2

Yves Caseau
François Laburthe
with the help of H. Chibois, A. Demaille, S. Hadinger, F.-X. Josset, C. Le Pape, A. Linz , T. Kökeny and L. Segoufin

Table of Contents

0. INTRODUCTION

CLAIRE is a high-level functional and object-oriented language with advanced rule processing capabilities. It is intended to allow the programmer to express complex algorithms with fewer lines and in an elegant and readable manner.

To provide a high degree of expressivity, CLAIRE uses

- a rich type system including type intervals and second-order types (with static/dynamic typing),
- parametric classes and methods,
- propagation rules based on events,
- dynamic versioning that supports easy exploration of search spaces.

To achieve its goal of readability, CLAIRE uses

- set-based programming with an intuitive syntax,
- simple-minded object-oriented programming,
- truly polymorphic and parametric functional programming,
- an entity-relation approach with explicit relations, inverses and unknown values.

CLAIRE was designed for advanced applications that involve complex data modeling, rule processing and problem solving. CLAIRE was meant to be used in a C++ environment, either as a satellite (linking CLAIRE programs to C++ programs is straightforward) or as an upper layer (importing C++ programs is also easy). The key set of features that distinguishes CLAIRE from other programming languages has been dictated by our experience in solving complex optimization problems. Of particular interest are two features that distinguish CLAIRE from procedural languages such as C++ or Java:

- Versioning: CLAIRE supports versioning of a user-selected view of the entire system. The view can be made as large (for expressiveness) or as small (for efficiency) as is necessary. Versions are created linearly and can be viewed as a stack of snapshots of the system. CLAIRE supports very efficient creation/rollback of versions, which constitutes the basis for powerful backtracking, a key feature for problem solving. Unlike most logic programming languages, this type of backtracking covers any user-defined structure, not simply a set of logic variables.
- Production rules: CLAIRE supports rules that bind a CLAIRE expression (the conclusion) to the combination of an event and a logical condition. Whenever this event occurs, if the condition is verified, then the conclusion is evaluated. The emphasis on events is a natural evolution from rule-based inference engines and is well suited to the description of reactive algorithms such as constraint propagation.

CLAIRE also provides automatic memory allocation/de-allocation, which would have prevented an easy implementation as a C++ library. Also, set-oriented programming is much easier with a set-oriented language like CLAIRE than with libraries. CLAIRE is seven years old and the current version reaches a new level of maturity. The version 3.2 of CLAIRE is motivated by the introduction of Java as another target language but its main feature is the handling of typed lists and sets.

CLAIRE is a high-level language that can be used as a complete development language, since it is a general purpose language, but also as a pre-processor to C++ or Java, since a CLAIRE program can be naturally translated into a C++ program (We continue to use C++ as our target language of choice, but the reader may now substitute Java to C++ in the rest of this document). CLAIRE is a set-oriented language in the sense that sets are first-class objects, typing is based on sets and control structures for manipulating sets are parts of the language kernel. Similarly, CLAIRE makes manipulating lists easy since lists are also first-class objects. Sets and lists may be typed to provide a more robust and expressive framework. CLAIRE can also be seen as a functional programming language, with full support for lambda abstraction, where functions can be passed as parameters and returned as values, and with powerful parametric polymorphism.

CLAIRE is an object-oriented language with single inheritance. As in SMALLTALK, everything that exists in CLAIRE is an object. Each object belongs to a unique class and has a unique identity. Classes are the corner stones of the language, from which methods (procedures), slots and tables (relations) are defined. Classes belong themselves to a single inheritance hierarchy. However, classes may be grouped using set union operators, and these unions may be used in most places where a class would be used, which offers an alternative to multiple inheritance. In a way similar

to Modula-3, CLAIRE is a modular language that provides recursively embedded modules with associated namespaces. Module decomposition can either be parallel to the class organization (mimicking C++ encapsulation) or orthogonal (e.g., encapsulating one service among multiple classes).

CLAIRE is a typed language, with full inclusion polymorphism. This implies that one can use CLAIRE with a variety of type disciplines ranging from weak typing in a manner that is close to SMALLTALK up to a more rigid manner close to C++. This flexibility is useful to capture programming styles ranging from prototyping to production code development. The more typing information available, the more CLAIRE's compiler will behave like a statically typed language compiler. This is achieved with a rich type system, based on sets, that goes beyond types in C++. This type system provides functional types (second-order types) similar to ML, parametric types associated to parametric classes and many useful type constructors such as unions or intervals. Therefore, the same type system supports the naive user who simply wishes to use classes as types and the utility library developer who needs a powerful interface description language.

As the reader will notice, CLAIRE draws its inspiration from a large number of existing languages. A non-exhaustive list would include SMALLTALK for the object-oriented aspects, SETL for the set programming aspects, OPS5 for the production rules, LISP for the reflection and the functional programming aspects, ML for the polymorphism and C for the general programming philosophy. As far as its ancestors are concerned, CLAIRE is very much influenced by LORE, a language developed in the mid 80s for knowledge representation. It was also influenced by LAURE but is much smaller and does not retain the original features of LAURE such as constraints or deductive rules. CLAIRE is also closer to C in its spirit and its syntax than LAURE was.

This document is organized as follows. The first chapter is a short tutorial on the main aspects of CLAIRE. A few selected examples are used to gradually introduce the concepts of the language without worrying about completeness. These are well-formed programs that can be used to practice with the interpreter and the compiler. Our hope is that a reader familiar with other object-oriented languages should be able to start programming with CLAIRE without further reading. Chapter 2 gives a description of objects, classes and basic expressions in CLAIRE. It explains how to define a class (including a parameterized class) and how to read a slot value, call a method or do an assignment.

Chapter 3 deals with the control structures of the language. These include block and conditional structures, loops and object instantiation. It also describes the set-oriented aspects of CLAIRE and set iteration. Chapter 4 covers methods and types. It explains how to define a method, how to define and use a type. Types, being set expressions and first-class objects, can be used in many useful ways. This chapter also covers more advanced polymorphism in CLAIRE.

Chapter 5 covers the most original aspects, namely rules and versions. It introduces the notion of generalized tables and event-based rules. The rules in v3.2 are a departure from the older production rules that were part of earlier CLAIRE versions. Chapter 6 covers the remaining topics, namely input/output, modules and global variables.

In addition, three appendices are included. The first appendix focuses on the external syntax of the CLAIRE language (includes lexical conventions and a formal grammar). The second appendix is the description of the application programming interface. It is a description of the methods that are part of the standard CLAIRE system library. The last appendix is a very short description of the standard CLAIRE system (compiler & interpreter) that has been made available through ftp.

This last appendix also contains a few tips for migrating a program from earlier versions of CLAIRE.

1. TUTORIAL

1.1 Loading a Program

This first chapter is a short tutorial that introduces the major concepts gradually. It contains enough information for a reader familiar with other object-oriented language to start practicing with CLAIRE. Each aspect of the language will be detailed in a further chapter. All the examples that are shown here should be available as part of the standard CLAIRE system so that you should not need to type the longer examples.

The first step that must be mastered to practice with CLAIRE is to learn how to invoke the compiler or the interpreter. Notice that you may obtain a warning if you load CLAIRE and no file «□hit.cl□ is found in your current directory. You can ignore this message for a while, then you may use such a file to store some of your favorite settings. You are now ready to try our first program. This program simply prints the release number of the CLAIRE system that you are using.

```
main() -> printf("claire release ~A\n", release())
```

You must first save this line on a file, using your favorite text editor (e.g. emacs). Let us now assume that this one-line program is in a file *release.cl*. Using a file that ends with .cl is not mandatory but is strongly advised.

When you invoke the CLAIRE executable, you enter a loop called a top-level[1]. This loop prompts for a command with the prompt "claire>" and returns the result of the evaluation with a prompt "[..]". The number inside the brackets can be used to retrieve previous results (this is explained in the last appendix). Here we assume that you are familiar with the principle of a top-level loop; otherwise, you may start by reading the description of the CLAIRE top-level in the Appendix C. To run our program, we enter two commands at the top-level. The first one load("release") loads the file that we have written and returns **true** to say that everything went fine. The second command main() invokes the method (in CLAIRE a procedure is called a method) that is defined in this file.

```
% claire
claire> load("release")
eval[1] true
claire> main()
eval[2] claire release 3.2.0
claire> q
%
```

Each CLAIRE program is organized into blocks, which are surrounded by parentheses, and definitions such as class and method definition. Our program has only one definition of the method *main*. The declaration main() tells that this method has no parameters, the expression after the arrow -> is the definition of the method. Here it is just a printf statement, that prints its first argument (a format string) after inserting the other arguments at places indicated by the control character ~ (followed by an option character which can be A,S,I). This is similar to a C printf, except that the place where the argument *release()* must be inserted in the control string is denoted with ~S. There is no need to tell the type of the argument for printf, CLAIRE knows it already. We also learn from this example that there exist a pre-defined method *release()* that returns some version identification, and that you exit the top-level by typing q (^D also works).

In this example, *release*() is a system-defined method[2]. The list of such methods is given in the second appendix. When we load the previous program, it is interpreted (each instruction becomes a CLAIRE object that is evaluated). It can also be compiled (through the intermediate step of C++ code generation). To compile a program, one must place it into a **module**, which plays a double role of a compilation unit and namespace. The use of modules will be explained later on.

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[1] In the following we assume that CLAIRE is invoked in a workstation environment using a command shell. You must first find out how to invoke the CLAIRE system in your own environment. This should be explained in you installation documents.

[2] The release is a a string «□.X.Y□ and the version is a float X.Y, where X is the version number and Y the revision number. The release number in this book (3) should be the same as the one obtained with your system. Changes among different version numbers should not affect the correctness of this documentation.

Let us now write a second program that prints the first 11 Fibonacci numbers. We will now assume that you know how to load and execute a program, so we will only give the program file. The following example defines the *fib(n)* function, where fib(n) is the n-th Fibonacci number.

```
fib(n:integer) : integer
        -> (if (n < 2) 1 else fib(n - 1) + fib(n - 2))

main() -> (for i in (0 .. 10) printf("fib(~S) = ~S\n",i,fib(i)))
```

From this simple example, we can notice many interesting rules for writing method in CLAIRE. First, the range of a method is introduced by the "typing" character "**:**". The range is not mandatory, and the default range is *any*. Conditionals in CLAIRE use a traditional `if` construct (Section 3.3), but the iteration construct "for" is a set iteration. The expression `for x in S e(x)` evaluates the expression `e(x)` for all values `x` in the set `S`. There are many kinds of set operators in CLAIRE (Section 3.1); `(n .. m)` is the interval of integers between `n` and `m`.

Obviously, this program is very naive and is not the right way to print a long sequence of Fibonacci numbers, since the complexity of *fib(n)* is exponential. We can compute the sequence using two local variables to store the previous values of *fib(n - 1)* and *fib(n - 2)*. The next example illustrates such an idea and the use of **let**, which is used to introduce a list of local variables. Notice that they are local variables, whose scope is only the instruction after the keyword **in**. Also notice that a variable assignment uses the symbol **:=**, as in PASCAL, and the symbol **=** is left for equality.

```
main()
   ->    let n := 2, f_n-1 := 1, f_n-2 := 1 in
         (     printf("fib(0) = 1 \nfib(1) = 1\n"),
               while (n < 10)
                     let f_n := f_n-1 + f_n-2 in
                       ( printf("fib(~S) = ~S \n",n,f_n),
                             n := n + 1, f_n-2 := f_n-1, f_n-1 := f_n)  )
```

Note that we used f_n-1 and f_n-2 as variable names. Almost any character is allowed within identifiers (all characters but separators, '/', '#' and @). Hence, x+2 can be the name of an object whereas the expression denoting an addition is x + 2. Blank spaces are always mandatory to separate identifiers. Using x+2 as a variable name is not a good idea, but being able to use names such as *% that include "arithmetic" characters is quite useful.

Warning: *CLAIRE's syntax is intended to be fairly natural for C programmers, with expressions that exist both in CLAIRE and C having the same meaning. There are two important exceptions to this rule: the choice of := for assignment and = for equality,* ***and the absence of special status for characters +, *, -, etc*** *. Minor differences include the use of & and | for boolean operations and % for membership.*

A more elegant way is to use a table *fib[n]*, as in the following version of our program.

```
fib[n:integer] : integer :=  1

main()
   ->    (for i in (2 .. 10) fib[i] := fib[i - 1] + fib[i - 2],
          for i in (0 .. 10) printf("fib(~S) = ~S\n",i,fib[i]) )
```

An interesting feature of CLAIRE is that the domain of a table is not necessarily an interval of integers. It can actually be any type, which means that tables can be seen as "extended dictionaries" (Section 5.1). On the other hand, when the domain is a finite set, CLAIRE allows the user to define an "initial value" using the **:=** keyword, as for a global variable assignment. For instance, the ultimate version of our program could be written as follows (using the fact that intervals are enumerated from small to large).

```
fib[n:(0 .. 10)] : integer := (if (n < 2) 1 else fib[n - 1] + fib[n - 2])

main() ->       (for i in (0 .. 10) printf("fib(~S) = ~S\n",i,fib[i]))
```

Let us now write a file copy program. We use two system functions *getc*(p) and *putc*(p) that respectively read and write a character c on an input/output port p. A port is an object usually associated with a file from the operating system. A port is open with the system function *fopen(s1,s2)* where s1 is the name of the file (a string) and s2 is another string that controls the way the port is used (cf. Section 6.1; for instance "w" is for writing and "r" is for reading).

```
copy(f1:string,f2:string)
   -> let  p1 := fopen(f1,"r"),
                  p2 := fopen(f2,"w"),
                  c := ' ' in
          (use_as_output(p2),
           while (c != EOF) (c := getc(p1), putc(c,p2)),
           fclose(f1), fclose(f2) )
```

Let us now write a program that copies a program and automatically indents it. Printing with indentation is usually called pretty-printing, and is offered as a system method in CLAIRE: *pretty_print(x)* pretty-prints on the output port. All CLAIRE instructions are printed so that they can be read back. In the previous example, we have used two very basic read/write methods (at the character level) and thus we could have written a very similar program using C. Here we use a more powerful method called *read(p)* that reads one instruction on the port p (thus, it performs the lexical & syntactical analysis and generate the CLAIRE objects that represents instructions). Surprisingly, our new program is very similar to the previous one.

```
copy&indent(f1:string,f2:string)
   -> let  p1 := fopen(f1,"r"),
                  p2 := fopen(f2,"w"),
                  c := unknown in
          ( use_as_output(p2),
            while (c != eof)
                  pretty_print(c := read(p1)),
            fclose(p1), fclose(p2) )
```

In the next example, we will illustrate how to use modules to obtain different namespaces. All identifiers in CLAIRE belong to a namespace, represented by a module. Modules are organized into a tree, the top of which is the default *CLAIRE* module. All the previous examples have used this default namespace implicitly. Our next program is a very simplified phone directory. The public interface for that program is a set of two methods *store*(name, phone) and *dial*(name). We want all other objects and methods to be in a different namespace, so we create a new (implicit) module called phone_application. We also use comments that are defined in CLAIRE as anything that in on the same line after the character ; or after the characters // as in C++.

```
// definition of the module
begin(phone_application)

// value is a table that stores the phone #
private/value[s:string] : string

// lower returns the lower case version of a string
// (i.e. lower("aBcD") = "abcd")
lower(s:string) : string
-> let s2 := copy(s) in
        (       for i in (1 .. length(s))
                        (if (s2[i] % 'A' .. 'Z')
                                s2[i] = char!(integer!(s2[i]) - 32))
         s2)

claire/store(name:string,phone:string)
  -> (value[lower(name)] := phone)

claire/dial(name:string) : string   // returns the phone #
  -> value[lower(name)]

end(phone_application)
```

This example illustrates many important features of modules. Modules are first-class objects; the statement *begin*(x) tells CLAIRE to use the namespace associated with the module x. We may later return to the initial namespace with *end*(x). When begin(x) has been executed, any new identifier that is read will belong to the new namespace associated with x. This has an important consequence on the visibility of the identifier, since an identifier *lower* defined in a module *phone_application* is only visible (i.e. can be used) in the module *phone_application* itself or its descendents. Otherwise, the identifier must be qualified (phone_application/lower) to be used. There are two ways to escape this rule: first, an identifier can be associated to any module above the currently active module, if it is declared with the qualified form. Second, when an identifier is declared with the prefix private/, it becomes impossible to access the identifier using the qualified form. For instance, we used *private/value* to forbid the use of the table (in the CLAIRE sense) anywhere but in the descendents of the module *phone_application*.

Module organization is a key aspect of software development and should not be mixed with the code. The previous example is not the most common way to use modules. It is better to put module definitions in a project file, and to load a file inside a module's namespace using the *load(m:module)* method. For instance, we could remove the first and last lines in the previous example and put the result in the file *phone.cl*; then we write an init.cl project file as follows.

```
;; modules definitions
phone_application :: module(      part_of = claire,
                                  made_of = list("phone"))
phone_database :: module(part_of = phone_application)
```

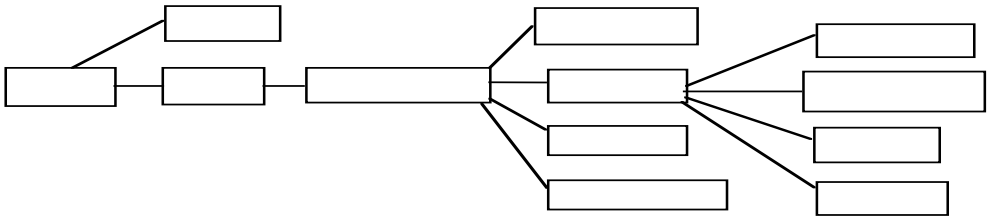
The statement *part_of = y* inside the definition of a module x says that x is a new child of the module y. We could have given any name to the project file, but calling it init.cl will make CLAIRE load it automatically when it starts. We can then call *load(phone_application)* to load the file in the *phone_application* namespace. This is achieved through the slot *made_of* that contains the list of files that we want to associate with the module (cf. Part 6)

1.2 Objects and Classes

Our next example is a small pricing software for hi-fi Audio components[3]. The goal of the program is to manage a small database of available material, to help build a system by choosing the right components (according to some constraints) and compute the price.

objectthingstereocomponentsourceamplifierspeakerheadphoneCDp

We start by defining our class hierarchy according to the following figure.



```
component <: thing(price:integer, brand:string)
amplifier <: component( power:integer, input:integer,
                                        ohms:set[{4,8}])
speaker <: component(maxpower:integer, ohm:{4,8})
headphone <: component(maxpower:integer,  ohm:{4,8})
musical_source <: component(sensitivity:integer)
CDplayer <: musical_source(laser_beams:(1 .. 3))
turntable <: musical_source()
tuner <: musical_source()
B :: thing()  C :: thing()    nodolby :: thing()
tape <: musical_source(dolby:{nodolby,B,C})
stereo <: object(    sources:set[musical_source],
                     amp:amplifier,
                     out:set[speaker U headphone],
                     warranty:boolean = false)
```

Now that we have defined the taxonomy of all the objects in our hive world, we can describe the set of all models actually carried by our store. These are defined by means of instances of those classes.

```
amp1 :: amplifier(power = 120, input = 4, ohms = {4,8},
                   price = 400, brand = "Okyonino")
amp2 :: amplifier(power = 40, input = 2, ohms = {4},
                  price = 130, brand = "Cheapy")
tuner1 :: tuner(    sensitivity = 10, price = 200, brand = "Okyonino")
tuner2 :: tuner(    sensitivity = 30, price = 80, brand = "Cheapy")
```

[3] All brands and product names are totally fictitious.

```
CD1 :: CDplayer( sensitivity = 3, price = 300,
                        laser_beams = 3, brand = "Okyonino")
CD2 :: CDplayer( sensitivity = 7, price = 180,
                        laser_beams = 2, brand = "Okyonino")
CD3 :: CDplayer( sensitivity = 15, price = 110,
                        laser_beams = 1, brand = "Cheapy")
t1 :: tape(   sensitivity = 40, price = 70,
                dolby = nodolby, brand = "Cheapy")
s1 :: speaker(      ohm = 8, maxpower = 150,
                        price = 1000, brand = "Magisound")
s2 :: speaker(      ohm = 8, maxpower = 80,
                        price = 400, brand = "Magisound")
s3 :: speaker(      ohm = 4, maxpower = 40,
                        price = 150, brand = "Cheapy")
ph :: speaker(ohms = 4, maxpower = 40, price = 50, brand = "Okyonino")
    etc ...
```

Now that we have defined some components with their technical features, we can manipulate them and define some methods. For example, we can compute the total price of a stereo as the sum of the prices of all its components. We first need an auxiliary method that computes the sum of a list of integers.

```
sum(s:list[integer]) : integer
    -> let n := 0 in (for y in s n :+ y, n)

total_price(s:stereo) : integer
        -> sum(list{x.price | x in s.sources U {s.amp} U s.out})

InventoryTotal:integer :: 0
```

Note here the use of set image (we consider the list of all *x.price* for all x in the following set: the union of *s.sources, {s.amp}* and *s.out*). Also, we introduce a global variable *InventoryTotal*, of range integer and value 0. If we want to keep some "specials" which are sets of components for which the price is less than the sum of its components, we may use a table to store them:

```
discount[s:set[component]] : integer := 0
discount[{amp1,s1}] := 1200
discount[{amp1,CD1}] := 600
```

To find the best price of a set of components, we now write a more sophisticated method that tries to identify the best subsets that are on sale. This is a good example of CLAIRE's programming style (if we assume that size(s) is small and that *discount* contains thousands of tuples).

```
[best_price(s:set[component]) : integer
  -> let p := 100000 in
        (for s2 in set[s]                                   ;; decompose s = s2 U ...
            let   x := size(s2),
                    p2 := (if (x > 1) discount[s2]
                            else if (x = 1) best_price(s2[1])
                            else 0)  in
                (if (p2 > 0) p :min (p2 + best_price(difference(s,s2)))),
         p) ]
```

Notice that we use some syntactical sugar here: p :min x is equivalent to p := (p min x). This works with any other operation (such as +).

1.3 Rules

We now want to do some reasoning about stereo systems. We start by writing down the rules for matching components with one another. We want a signal to be raised whenever one of these rules is violated. Hence we create the following exception:

```
technical_problem <: exception(s:string)
```

A rule is defined by a condition and a conclusion (using a pattern rule(*condition => conclusion*)). The condition is the combination of an event pattern and a boolean expression. The event pattern tells when the boolean expression should be checked, in case of success the conclusion is evaluated. Here are some simple rules that will raise exceptions when some technical requirements are not met.

```
compatibility1() :: rule(
        st.speaker := sp & not(sp.ohms % st.amplifier.ohms) )
        => technical_problem(s = "conflict speakers-amp"))

compatibility2() :: rule(
        st.sources :add x & size(st.sources) > st.amp.inputs
        => technical_problem(s = "too many sources"))

compatibility3() :: rule(
        st.sources :add x & exists(o in st.out | o.maxpower < st.amp.power)
        => technical_problem(s = "amp to strong for the speakers"))
```

We can now use our system (applying the rules on the small database) to look for consistent systems. For example, suppose that I want to buy speakers that fit my amp (for instance, amp1): we will try several possibilities to fill the slot *out* of my stereo and will watch whether they raise an exception or not. In order for the rule to be triggered, we need to tell which changes in the database are relevant to rule triggering. Here, modifications on the relation *out* trigger the evaluation of the concerned rules.

```
my_system :: stereo(amp = amp1)
( for sp in speaker
        try (my_system.out :add sp, break(my_system))
        catch technical_problem my_system.out :delete sp )
```

If we want to successively choose the speakers, the CD player, the tape, etc.. we cannot guarantee that if a choice does not immediately raise an exception, there will always exist a solution in the end. Thus, we need to make some hypothetical reasoning: we suppose one branch of the *choice* contains a solution, and we *backtrack* on failure. The conclusions that had been drawn during the hypothesis need to be undone. To do so, we can declare that some relations in the database are stored in a special way such that one can go back to a previous state. Such states of the database (versions) are called worlds. The methods *choice()* and *backtrack()* respectively create a new world (i.e., create a choice point) and return to the previous one. The command *store(out)* means that the graph of the relation *out* will be stored in that special way adapted to the world mechanism. In this example, we create the list of all possible (bringing no conflict according to the rules) stereos with two different musical sources.

```
store(out)

all_possible_stereos() : list[stereo]
   -> let solutions := list<stereo>() , syst:stereo := unknown in
        (for a in amplifier
              (syst.amp := a,
               for sp in speaker try
                    (choice(), syst.out := set(sp),
                    for h in headphone try
                     (      choice(), syst.out :add h,
                            for s1 in source try
                              ( choice(), syst.sources := set(s1),
                                      for s2 in {s in source | owner(s) != owner(s1)}
                                      try (choice(),
                                          syst.sources :add s2,
                                          solutions :add copy(syst) )
                                      catch any backtrack() )
                      catch any backtrack() )
                    catch any backtrack() )
              catch any backtrack()),
 solutions)
```

This method explores the tree of all possibilities for stereos and returns the list of all the valid ones.

Here is a last example of a method that returns the list of all possible stereos, classified by increasing prices. The same thing could be done with other criteria of choice.

```
price_order(s1:stereo, s2:stereo) : boolean -> (total_price(s1) <= total_price(s2))

cheapest() : list[stereo] ->
   let l := all_possible_stereos() in sort(price_order @ stereo, l) ]
```

2. OBJECTS, CLASSES AND SLOTS

2.1 Objects and Entities

A program in CLAIRE is a collection of entities (everything in CLAIRE is an entity). Some entities are pre-defined, we call them primitive entities, and some others may be created when writing a program, we call them objects. The set (a class) of all entities is called **any** and the set (a class also) of all objects is called **object**.

Primitive entities consist of integers, floats, symbols, strings, ports (streams) and functions. The most common operations on them are already built in, but you can add yours. You may also add your own entity classes using the *import* mechanism (cf. Appendix C).

Objects can be seen as "records", with named fields (called slots) and unique identifiers. Two objects are distinct even if they represent the same record. The data record structure and the associated slot names are represented by a class. An object is uniquely an instance of a class, which describes the record structure (ordered list of slots). CLAIRE comes with a collection of structures (classes) as well as with a collection of objects (instances).

Definition: *A **class** is a generator of objects, which are called its instances. Classes are organized into an inclusion hierarchy (a tree), so a class can also be seen as an extensible set of objects, which is the set of instances of the class itself and all its subclasses. A class has one unique father in the inclusion hierarchy (also called the inheritance hierarchy), called its superclass. It is a subclass of its superclass.*

Each entity in CLAIRE belongs to a special class called its *owner*, which is the smallest class to which the entity belongs. The *owner* relationship is the extension to **any** of the traditional *isa* relationship between objects and classes, which implies that for any object x, x.isa = owner(x).

Thus the focus on *entities* in CLAIRE can be summarized as follows: everything is an *entity*, but not everything is an *object.* An entity is described by its owner class, like an object, but objects are "instantiated" from their classes and new instances can be made, while entities are (virtually) already there and their associated (primitive) classes don't need to be instantiated. A corollary is that the list of instances for a primitive class is never available.

2.2 Classes

Classes are organized into a tree, each class being the subclass of another one, called its superclass. This relation of being a subclass (inheritance) corresponds to set inclusion: each class denotes a subset of its superclass. So, in order to identify instances of a class as objects of its superclass, there has to be some correspondence between the structures of both classes: all slots of a class must be present in all its subclasses. Subclasses are said to *inherit* the structure (slots) of their superclass (while refining it with other slots). The root of the class tree is the class **any** since it is the set of all entities. Formally, a class is defined by its superclass and a list of additional slots. Two types of classes can be created: those whose instances will have a name and those whose instances will be unnamed. Named objects must inherit (not directly, but they must be descendents) of the class **thing**. A named object is an object that has a name, which is a symbol that is used to designate the object and to print it. A named object is usually created with the x□ C() syntax (cf. Section 3.5) but can also be created with new(C, name).

Each slot is given as <name>:<range>=<default>. The range is a type and the optional default value is an object which type is included in <range>. The range must be defined before it is used, thus recursive class definitions use a forward definition principle (e.g., person).

```
        person <: thing                    // forward definition                                    person <:
thing(age:integer = 0, father:person)
        woman <: person                    // another forward definition
        man <: person(wife:woman)
        woman <: person(husband:man)
        child <: person(school:string)
        complex <: object(re:float,im:float)
```

A class inherits from all the slots of its superclasses, so they need not be recalled in the definition of the class. For instance, here, the class *child* contains the slots *age* and *father*, because it inherited them from *person*.

A default value is used to place in the object slot during the instantiation (creation of a new instance) if no explicit value is supplied. The default value must belong to the range and will trigger rules or inverses in the same way an explicit value would. The only exception is the "*unknown*" value, which represents the absence of value. unknown is used when no default value is given (the default *default value*). Note that the default value is a real entity that is shared by all instances and not an expression that would be evaluated for each instantiation. The proper management of default values, or their absence through unknown, is a key feature of CLAIRE.

From a set-oriented perspective, a class is the set union of all the instances of its *descendents* (itself, its subclasses, the subclasses of its subclasses, etc.). In some cases, it may be useful to "freeze" the data representation at some point: for this, two mechanisms are offered: *abstract* and *final*. First, a class *c* can be declared to have no instances with *abstract*(*c*) such as in the following:

```
abstract(person)
```

An abstract class is not an empty set, it contains the instances of its descendents. Second, a class can also be declared to have no more new descendents using *final* as follows :

```
final(colors)
```

It is a good practice to declare *final* classes that are leaves in the class hierarchy and that are not meant to receive subclasses in the future. This will enable further optimizations from the compiler. A class can be declared to instantiate *ephemeral* objects, in which case its extension (the list of its instances) is not kept. An important consequence is that ephemeral objects may be garbage collected when they are no longer used. For this behavior, the class must be declared with **ephemeral.**

```
action <: object(on:any, performed_by:object)
ephemeral(action)
```

A class definition can be executed only once, even if it is left unchanged. On the other hand, CLAIRE supports the notion of a class *forward* definition. A forward definition contains no slots and no parentheses. It simply tells the position of the class in the class hierarchy. A forward definition must be followed by a complete definition (with the same parent class !) before the class can be instantiated. Attempts to instantiate a class that has been defined only with a forward definition will produce an error. A forward definition is necessary in the case of recursive class definitions. Here is a simple example.

```
parent <: thing
child <: thing(father:parent)
parent <: thing(son:child)
```

Although the *father* of a **child** is a **parent** (in the previous example), creating an instance of **child** does not create an implicit instance of **parent** that would be stored in the *father* slot. Once an instance of child is created, it is your responsibility to fill out the relevant slots of the objects. There exists a way to perform this task automatically, using the *close* method. This method is the CLAIRE equivalent to the notion of a constructor (in a C++ or Java sense). CLAIRE does not support class constructors since its instantiation control structure may be seen as a generic constructor for all classes (cf. Section 3.5). However, there are cases when additional operations must be performed on a newly created object. To take this into account, the *close* method is called automatically when an instantiation is done if a relevant definition is found. Remember that the *close* method must always return the newly create object, since the result of the instantiation is the result of the *close* method. Here is an example that shows how to create a *parent* for each new **child** object :

```
close(x:child) -> (x.father⊡= parent(), x)
```

Slots can be mono- or multi-valued. A *multi-valued* slot contains multiple values that are represented by a list (ordered) or a set (without duplicates). CLAIRE assumes by default that a slot with range list or set is multi-valued. However, the multi-valuation is defined at the property level. This is logical, since the difference between a mono-valued and a multi-valued slot only occurs when inversion or rules are concerned, which are both defined at the property level (cf. Section 4.5). This means that CLAIRE cannot accept slots for two classes with the same name and different multi-valuation status. For instance, the following program will cause an error:

```
A <: thing(x:set[integer])      // forces CLAIRE to consider x as multi-valued
B <: thing(x:stack[integer])    // conflict: x cannot be multi-valued
```

On the other hand, it is possible to explicitly tell CLAIRE that a slot with range list or set is mono-valued, as in the following correct example:

```
  A <: thing(x:set[integer])
x.multivalued? := false     // x is from A U B  -> (set[integer] U stack[integer])
  B <: thing(x:stack[integer])
```

It is sometimes advisable to set up manually the multi-valuation status of the property before creating the slots, in order to make sure that this status cannot be forced by the creation of another class with a mono-valued slot with the same name (this could happen within a many-authors project who share a namespace). This is achieved simply by creating the property explicitly :

```
  x :: property(multivalued? = true)  // creates the property
...              // whatever happens will not change x's multi-valuation
B <: thing(x:set[integer])         // safe definition of a multi-valued slot
```

2.3 Parametric Classes

A class can be parameterized by a subset of its slots. This means that subsets of the class that are defined by the value of their parameters can be used as types. This feature is useful to describe parallel structures that only differ by a few points: parametrization helps describing the common kernel, provides a unified treatment and avoids redundancy.

A parameterized class is defined by giving the list of slot names into brackets. Parameters can be inherited slots, and include necessarily inherited parameters.

```
stack[of] <: object(of:type,content:list[any],index:integer = 0)

complex[re,im] <: object(re:float = 0.0,im:float = 0.0)
```

We shall see in Section 4 that CLAIRE includes a type system that contains parametric class selections. For instance, the set of real numbers can be defined as a subset of complex with the additional constraint that the imaginary part is 0.0. This is expressed in CLAIRE as follows:

```
complex[re:float, im:{0.0}]
```

In the previous example with stacks, parametric sub-types can be used to designate typed stacks. We can either specify the precise range of the stack (i.e., the value of the *of* parameter) or say that the range must be a sub-type of another type. For instance, the set of stacks with range integer and the set of stacks which contain integers are respectively :

```
stack[of:{integer}]  stack[of:subtype[integer]]
```

2.4 Calls and Slot Access

Calls are the basic building blocks of a CLAIRE program. A call is a polymorphic function call (a *message*) with the usual syntax : a selector followed by a list of arguments between parentheses. A call is used to invoke a method. Slot accesses follow the usual field access syntax «□.s□ where s if the name of the slot. CLAIRE uses generic objects called properties to represent the name of a *method*, used as the selector f of a function call f(...), or a *slot*, used as the selector s in a slot access x.s. In the following example, *eval* is a function and price is a property. Properties and functions are two kinds of relation.

```
eval(x), f(x,y,z), x.price, y.name
```

in previous versions of CALIRE, the syntax s(x) was also used for slot access. Thus, the current version of CLAIRE also accepts this syntax for compatibility reasons, although it is not recommended.

If a slot is read before being defined (its value being unknown), an error is raised. This only occurs if the default value is unknown. To read a slot that may not be defined, one must use the get(r:property,x:object) method.

```
John.father              // may provoke an error if John.father is unknown
get(father,john)         // may return unknown
```

When the selector is an operation, such as +,-,%,etc... (% denotes set membership) an infix syntax is allowed (with explicit precedence rules). Hence the following expressions are valid.

```
1 + 2, 1 + 2 * 3
```

Note that new operations may be defined (Section 4.5). This syntax extends to boolean operations (and:& and or:|). However, the evaluation follows the usual semantic for boolean expression (e.g., (x & y) does not evaluate y if x evaluates to false).

```
(x = 1) & ((y = 2) | (y > 2)) & (z = 3)
```

The values that are combined with and/or do not need to be boolean values (although boolean expressions always return the boolean values **true** or **false**). Following a philosophy borrowed from LISP, all values are assimilated to true, except for false, empty lists and empty sets. The special treatment for the empty lists and the empty sets (cf. Conditionals, Section 3.3) yields a simpler programming style when dealing with lists or sets. Notice that in CLAIRE 3.0, contrary to previous releases, there are many empty lists since empty lists can be typed (list<integer>(), list<string>(), … are all different).

A dynamic functional call where the selector is evaluated can be obtained using the *call* method. For instance, call(+,1,2) is equivalent to +(1,2) and call(show,x) is equivalent to show(x). The difference is that the first parameter to call can be any expression. This is the key for writing parametric methods using the inline capabilities of CLAIRE (cf. Section 4.1). This also means that using *call* is not a safe way to force dynamic binding, this should be done using the property *abstract*. An abstract property is a property that can be re-defined at any time and, therefore, relies on dynamic binding. Notice that *call* takes a variable number of arguments. A similar method named *apply* can be used to apply a property to an explicit list of arguments.

Since the use of *call* is somehow tedious, CLAIRE supports the use of variables (local or global) as selectors in a function call and re-introduce the call implicitly. For instance,

```
compose(f:function, g:function, x:any) => f(g(x))
```

is equivalent to

```
compose(f:function, g:function, x:any) => call(f, call(g,x))
```

2.5 Updates

Assigning a value to a variable is always done with the operator **:=** . This applies to local variables but also to the slots of an object. The value returned by the assignment is always the value that was assigned.

```
x.age := 10,  John.father := mary
```

When the assignment depends on the former value of the variable, an implicit syntax ":op" can be used to combine the previous value with a new one using the operation *op*. This can be done with any (built-in or user-defined) operation (an operation is a function with arity 2 that has been explicitly declared as an operation).

```
x.age :+ 1,  John.friends :add mary, x.price :min 100
```

Note that the use of :op is pure syntactical sugar: x.A :op y is equivalent to x.A := (x.A op y). The receiving expression should not, therefore, contain side-effects as in the dangerous following example A(x :+ 1) :+ 1 .

Warning: The next section describes an advanced feature and may be skipped

2.6 Reified Slots

CLAIRE supports the reification of objects' slots. This means that the value of slot, such as x.age, can be an object (with a value) that is used to represent, for instance, modal knowledge about x.age (such as in sure(x.age) = true). This is achieved through the reify declaration:

```
reify(age)
```

A reified slot must have a range which is a class that contains objects which understand the *read* and *write* methods, since the reader will substitute x.age with read(x.age) and x.age := y by write(x.age,y). Such a class is usually called a container class. Reification is the representation of each value pair age(x,y) by a container object (that can contain additional information). Here is an example that is also quite useful. We define the Store container class, which is a defeasible reference to an object, which keeps the world in which the object was last updated. Worlds are explained in Section 5.4.

```
Store[of] <: ephemeral_object(of:type, value:any, world:integer = -1)

self_print(x:Store) -> printf("store(~S)",get(value,x))

write(x:Store<X>,y:X)
-> (if (world?() > x.world)
        (put_store(value,x,y,true), put_store(world,x,world?(),true))
   else x.value := y)]

read(x:Store<X>) : type[X] => x.value
```

We can now use our container class in the following example:

```
A <: thing(x:Store<integer>, y:Store<string>)
reify(x,y)

a :: A(x = Store(integer), y = Store(string))
a.x := 1
(if (a.x > 0) a.y := "positive")
```

Notice how we can use a.x and a.y as if x and y were normal slots, and use get(x,a) and get(y,a) to access the associated container objects. We leave it as an exercise to the reader, once familiar with Section 5, to see why it may be interesting to use these Store objects to reduce the growth of the trailing stack for worlds.

3. LISTS, SETS AND INSTRUCTIONS

3.1 Lists, Sets and Tuples

CLAIRE provides two easy means of manipulating collections of objects: sets and lists. Lists are ordered, possibly heterogeneous, collections. To create a list, one must use the list(...) instruction : it admits any number of arguments and returns the list of its arguments. Each argument to the list(...) constructor is evaluated.

```
list(a,b,c,d)   list(1,2 + 3)   list()
```

Sets are collections without order and without duplicates. Sets are created similarly with the set(...) constructor :

```
set(a,b,c)   set(1,2 + 3)
```

The major novelty in CLAIRE 3.2 is the fact that lists or sets *may* be typed. This means that each bag (set or list) may have a type slot named *of*, which contains a type to which all members of the list must belong. This type is optional, as is illustrated by the previous examples, where no typing was given for the lists or sets. To designate a type for a new list or a new set, we use a slightly different syntax:

```
list<thing>(a,b,c,d)   list<integer>(1,2 + 3)   list<float>()
set<thing>(a,b,c)   set<integer>(1, 2 + 3)
```

Typing a list or a set is a way to ensure that adding new values to them will not violate typing assumptions, which could happen in earlier versions of CLAIRE. Insertion is now always a destructive operation (add(l,x) returns the list l, that has been augmented with the value x at its end).

Since typing is mandatory in order to assume type-safe updates onto a list or a set, if no type is provided, CLAIRE will forbid any future update: the list or the set is then a “read-only” structure. *This is the major novelty in CLAIRE 3.2*: there is a difference between:

```
list(a,b,c,d)   set(1,2 + 3)   list{i | i in (1 ..2)}
```

which are *read-only* structures, and

```
list<thing>(a,b)   set<integer>(1,2 + 3)  list<integer>{i | i in (1 ..2)}
```

which are structures that can be updated.

List or set types can be arbitrarily complex, to represent complex list types such as list of lists of integers (cf. Section4). However, it is recommended to use a global constant to represent a complex type that is used as a list type, as follows:

```
    MyList :: list<integer>
set<MyList>(list<integer>(1), list<integer>(2,3))
```

Constant sets are valid CLAIRE types and can be built using the following syntax:

```
{a,b,c,d}  {3, 8}
```

The expressions inside a constant set expression are not evaluated and should be primitive entities, such as integers or strings, named objects or global constants. Constant sets are constant, which means that inserting a new value is forbidden and will provoke an error.

A set can also be formed by selection. The result can either be a set with {x in a | P(x)}, or a list with list{x in a | P(x)}, when one wants to preserve the order of *a* and keep the duplicates if *a* was a list. Similarly, one may decide to create a typed or an un-typed list or set, by adding the additional type information between angular brackets. For instance, here are two samples with and without typing:

```
    {x in class | (thing % x.ancestors) }
    list{x in (0 .. 14) | x mod 2 = 0}
set<class>{x in class | (thing % x.ancestors) }
    list<integer>{x in (0 .. 14) | x mod 2 = 0}
```

When does one need to add typing information to a list or a set ? A type is needed when new insertions need to be made, for instance when the list or set is meant to be stored in an object’s slot which is itself typed.

Also, the image of a set via a function can be formed. Here again, the result can either be a set with {f(x)| x in a} or a list with list{f(x) | x in a}, when one wants to preserve the order of *a* and the duplicates.

```
{(x ^ 2) | x in (0 .. 10)}
list<integer>{size(x.slots) | x in class}
```

For example, we have the traditional average_salary method:

```
average_salary(s:set[man]) : float -> (sum(list{m.sal | m in s}) / size(s))
```

Last, two usual constructions are offered in CLAIRE to check a boolean expression universally (*forall*) or existentially (*exists*). A member of a set that satisfies a condition can be extracted (a non-deterministic choice) using the *some* construct: some(x in a | f(x)). For instance, we can write:

```
exists(x in (1 .. 10) | x > 2)                    ;; returns true
some(x in (1 .. 10) | x > 2)          ;; returns 3 in most implementations
exists(x in class | length(x.ancestors) > 10)
```

The difference between *exists* and *some* is that the first always returns a boolean, whereas the second returns one of the objects that satisfy the condition (if there exists one) and unknown otherwise. It is very often used in conjunction with **when** (cf. next section), as in the following example:

```
when x := some(x in man | rich?(x)) in
     (borrow_from(x,1000), ...)
else printf("There is no one from whom to borrow! ")
```

Conversely, the boolean expression forall(x in a | f(x)) returns true if and only if f(x) is true for all members of the set a. The two following examples returns false (because of 1):

```
forall(x in (1 .. 10) | x > 2)
forall(x in (1 .. n) | exists( y in (1 .. x) | y * y > x))
```

Definition: *A **list** is an ordered collection of objects that is organized into an extensible array, with an indexed access to its members. A list may contain duplicates, which are multiple occurrence of the same object. A **set** is a collection of objects without duplicates and without any user-defined order. The existence of a system-dependent order is language-dependent and should not be abused. The concept of **bag** in CLAIRE is the unifier between lists and sets : a collection of objects with possible duplicates and without order.*

A read-only (untyped) list can also be thought as tuples of values. For upward compatibility reasons, the expression tuple(a_1,…,a_n) is equivalent to list(a_1,…,a_n):

```
tuple(1,2,3),  tuple(1,2.0,"this is heterogeneous")
```

Since it is a read-only list, a tuple cannot be changed once it is created, neither through addition of a new member (using the method *add*) or through the exchange of a given member (using the *nth*= method). CLAIRE offers an associated data type, as explained in Section 4.2. For instance, the following expressions are true:

```
tuple(1,2,3) % tuple(integer,integer,integer)
tuple(1,2,3) % tuple(0 .. 1, 0 .. 10, 0 .. 100)
tuple(1,2.0,"this is heterogeneous") % tuple(any,any,any)
```

Typed tuples are used to return multiple values from a method (cf. Section 4.1). Because a tuple is a bag, it supports membership, iteration and indexed access operations. However, there is yet another data structure in CLAIRE for homogeneous arrays of fixed length, called *arrays*. **Arrays** are similar to lists but their size is fixed once they are created and they must be assigned a subtype (a type for the members of the array) that cannot change. Because of these strong constraints, CLAIRE can provide an implementation that is more efficient (memory usage and access time) than the implementation of bags. However, the use of arrays is considered an advanced feature of CLAIRE since everything that is done with an array may also be done with a list. Arrays are described in Section 3.7.

3.2 Blocks

Parentheses can be used to group a sequence of instructions into one. In this case, the returned value is the value of the last instruction.

```
(x := 3, x := 5)
```

Parentheses can also be used to explicitly build an expression. In the case of boolean evaluation (for example in an if), any expression is considered as *true* except false, empty sets and empty lists.

```
(1 + 2) * 3    if (x = 2 & l)
```

Local variables can be introduced in a block with the **let** construct. These variables can be typed, but it is **not** mandatory (CLAIRE will use type inference to provide with a reasonable type). On the other hand, unlike languages such as C++, you always must provide an initialization value when you define a variable. A *let* instruction contains a sequence of variable definitions and, following the *in* keyword, a body (another instruction). The scope of the local variable is exactly that body and the value of the *let* instruction is the value returned by this body.

```
let x := 1, y := 3 in (z := x + y, y := 0)
```

The value of local variables can be changed with the same syntax as an update to an object: the syntax :op is allowed for all operations op.

```
x := x + 1,   x :+ 1,  x :/ 2,  x :^ 2
```

The name of a local variable can be any identifier, including the name of an existing object or variable. In that case, the new variable overrides the older definition within the scope of the let. While this may prove useful in a few cases, it should be used sparingly since it yields to code that is hard to read. A rule of thumb is to avoid mixing the name of variables and the name of properties since it often produces errors that are hard to catch (the property cannot be accessed any more once a variable with the same name is defined). The control structure *when* is a special form of *let*, which only evaluates the body if the value of the local variable (unique) is not *unknown* (otherwise, the returned value is unknown). This is convenient to use slots that are not necessarily defined as in the following example

```
when f := get(father,x) in printf("his father is ~S\n",f)
```

The default behavior when the value is unknown can be specified using the **else** keyword. The statement following the else keyword will be evaluated and its value will be returned when the value of the local variable is unknown.

```
when f := get(father,x) in printf("his father is ~S\n",f)
else printf("his father is not known at the present time \n")
```

Local variables can also be introduced as a pattern, that is a tuple of variables. In that case, the initial value must be a tuple of the right length. For instance, one could write :

```
let (x,y,z) := tuple(1,2,3) in x + y + z
```

The tuple of variable is simply introduced as a sequence of variables surrounded by two parentheses. The most common use of this form is to assign the multiple values returned by a function with range tuple, as we shall see in the next section. If we suppose that f is a method that returns a tuple with arity 2, then the two following forms are equivalent:

```
let (x1,x2) := f() in ...

let l := f(), x1 := l[1], x2 := l[2] in ...
```

Tuples of variables can also be assigned directly within a block as in the following example

```
(x1,x2) := tuple(x2,x1)
```

Although this mostly used for assigning the result of tuple-valued functions without any useless allocation, it is interesting to note that the previous example will be compiled into a nice value-exchange interaction without any allocation (the compiler is smart enough to determine that the list "list(x2,x1)" is not used as such).

The key principle of lexical variables is that they are local to the "let" in which they are defined. CLAIRE supports another similar type of block, which is called a temporary slot assignment. The idea is to change the value of a slot but only locally, within a given expression. This is done as follows:

```
let x.r := y in e
```

changes the value of r(x) to y, executes e and then restore r(x) to its previous value. It is strictly equivalent to

```
let old_v := x.r in (x.r := y, let result := e in (x.r := old_v, result)
```

CLAIRE provides automatic type inference for variables that are defined in a let so that explicit typing is not necessary in most of the cases. Here are a few rules to help you decide if you need to add an explicit type to your variable or even cast a special type for the value that is assigned to the variable :

(a) Type inference will provide a type to a Let variable **only** if they do not have one already.

(b) when you provide a type in let x:t := y, the compiler will check that the value y belong to t and will issue a warning and/or insert a run-time type-check accordingly.

(c) if you want to force the type that is infered to something smaller than what CLAIRE thinks for y, you must use a cast:

```
let x := (y as t2) in ...
```

To summarize,

- in most cases CLAIRE range inference works, so you write let x := y in ...
- you use let x:t := y to weaken the type inference, mostly because you want to put something of a different type later,
- you use let x := (y as t) to narrow the type inferred by CLAIRE.

3.3 Conditionals

if statements have the usual syntax (if <test> x else y) with implicit nestings (else if). The <test> expression is evaluated and the instruction x is evaluated if the value is different from false, nil or {} (cf. Section 2.4). Otherwise, the instruction y is evaluated, or the default value `false` is returned if no *else* part was provided.

```
if (x = 1) x := f(x,y)
else if (x > 1) x := g(x,y)
else (x := 3, f(x,y))

if (let y := 3 in x + y > 4 / x) print(x)
```

If statements must be inside a block, which means that if they are not inside a sequence surrounded by parenthesis they must be themselves surrounded by parenthesis (thus forming a block).

case is a set-based switch instruction: CLAIRE tests the branching sets one after another, executes the instruction associated with the first set that contains the object and exits the case instruction without any further testing. Hence, the default branch is associated with the set *any*. As for an *if*, the returned value is `nil` if no branch of the *case* is relevant.

```
case x ({1} x + 1, {2,3} x + 2, any x + 3)
case x (integer (x := 3, print(x)), any error("~I is no good\n",x))
```

Note that the compiler will not accept a modification of the variable that is not consistent with the branch of the case (such as case x ({1} x := 2)). The expression on which the switching is performed is usually a variable, but can be any expression. However, it should not produce any side effect since it will be evaluated many times.

3.4 Loops

CLAIRE supports two types of loops: iteration and conditional loops (*while* and *until*). Iteration is uniquely performed with the *for* statement, it can be performed on any *collection*:

```
for x in (1 .. 3) a[x] := a[x + 3]
for x in list{x in class | size(x.ancestors) >= 4} printf("~S \n",x)
```

A collection here is taken in a very general sense, i.e., an object that can be seen as a set through the enumeration method *set!*. This includes all CLAIRE types but is not restricted since this method can be defined on new user classes that inherit from the collection root. For instance, set!(n:integer) returns the subset of (0 .. 29) that is represented by the integer n taken as a bit-vector. To tell CLAIRE that her new class is a collection, the user must define it as a subclass of **collection**. If x is a *collection*, then

- for z in x
- (z % x)

are supported. Note that the method *set!* and *contain?* must be defined for a new collection (mandatory) and it is also advisable to define *iterate* and *size*.

Notice that it is possible that the expression being evaluated inside the loop modifies the set itself, such as in

```
for x in {y in S | P(y)} P(x)⊡= false
```

Because the CLAIRE compiler tries to optimize iteration using lazy evaluation, there is no guarantee about the result of the previous statement. In this case, it is necessary to use an explicit copy as follows:

```
for x in copy({y in S | P(y)}) P(x)⊡= false
```

The iteration control structure plays a major role in CLAIRE. It is possible to optimize its behavior by telling CLAIRE how to iterate a new subclass (C) of **collection**. This is done through adding a new restriction of the property *iterate* for this class C, which tells how to apply a given expression to all members of an instance of C. This may avoid the explicit construction of the equivalent set which is performed through the *set!* method. This optimization aspect is described in Section 4.6.

Conditional loops are also standard (the exiting condition is executed before each loop in a *while* and after each loop in a *until*),

```
while (x > 0) x :+ 1
until (x = 12) x :+ 1
while not(i = size(l)) (l[i] := 1, i :+ 1)
```

The value of a loop is false. However, loops can be exited with the *break*(*x*) instruction, in which case the return value is the value of *x*.

```
for x in class (if (x % subtype[integer]) break(x))
```

There is one restriction with the use of break: it cannot be used to escape from a try … catch block. This situation will provoke an error at compile-time.

3.5 Instantiation

Instantiation is the mechanism of creating a new object of a given class; instantiation is done by using the class as a selector and by giving a list of "<slot>=<value>" pairs as arguments.

```
complex(re = 0.0, im = 1.0)
person(age = 0, father = john)
```

Recall that the list of instances of a given class is only kept for non-ephemeral classes (a class is ephemeral if has been desclared as such or if it inherits from the *ephemeral_object* class). The creation of a new instance of a class yields to a function call to the method *close*. Objects with a name are represented by the class *thing*, hence descendents of *thing* (classes that inherit from thing) can be given a name with the definition operation ::. These named objects can later be accessed with their name, while objects with no name offer no handle to manipulate them after their creation outside of their block (objects with no name are usually attached to a local variable with a *let* whenever any other operation other than the creation itself is needed)

```
paul :: person(age = 10, father = peter)
```

Notice that the identifier used as the name of an object is a constant that cannot be changed. Thus, it is different from creating a global variable (cf. Section 6.4) that would contain an object as in⊡

```
aGoodGuy:person :: person(age = 10, father = peter)
```

Additionally, there is a simpler way of instantiating parameterized classes by dropping the slot names. All values of the parameter slots must be provided in the exact order that was used to declare the list of parameters. For instance, we could use :

```
complex(0.0,1.0), stack(integer)
```

The previously mentioned instantiation form only applies to a parameterized class. It is possible to instantiate a class that is given as a parameter (say, the variable v) using the *new* method. *New*(v) creates an instance of the class v and *new*(v,s) creates a named instance of the class v (assumed to be a subclass of *thing*) with the name s.

3.6 Exception Handling

Exceptions are a useful feature of software development: they are used to describe an exceptional or wrong behavior of a block. Exception can be raised, to signal this behavior and are caught by exception handlers that surround the code where the exceptional behavior happened. Exceptions are CLAIRE objects (a descendent from the

class **exception**) and can contain information in slots. The class **exception** is an “ephemeral” class, so the list of instances is not kept. In fact, raising an exception *e* is achieved by creating an instance of the class *e*. Then, the method *close* is called: the normal flow of execution is aborted and the control is passed to the previously set dynamic handler. A handler is created with the following instruction.

```
try <expression> catch <class> <expression>
```

For instance we could write

```
try 1 / x catch any (printf("1/~A does not exists",x),0)
```

A handler "try e catch c f", associated with a class c, will catch all exceptions that may occur during the evaluation of e as long as they belong to c. Otherwise the exception will be passed to the previous dynamic handler (and so on). When a handler "catches" an exception, it evaluates the "f" part and its value is returned. The last exception that was raised can be accessed directly with the *exception!()* method. Also, as noticed previously, the body of a handler cannot contain a break statement that refers to a loop defined outside the handler.

The most common exceptions are errors and there is a standard way to create an error in CLAIRE using the error(s:string,l:listargs) instruction. This instruction creates an error object that will be printed using the string s and the arguments in l, as in a printf statement (cf. Section 6). Here are a few examples.

```
error("stop here")
error("the value of price(~S) is ~S !",x,price(x))
```

Another very useful type of exception is *contradiction*. CLAIRE provides a class *contradiction* and a method contradiction!() for creating new contradictions. This is very commonly used for hypothetical reasoning with forms like (*worlds* are explained in section 5.4) :

```
try (   choice(),              ; create a new world
            ...                ; performs an update that may cause a contradiction
catch contradiction (backtrack(),  ; return to previous world
                                                    ...
```

In fact, this is such a common pattern that CLAIRE provides a special instruction, *branch*(x), which evaluates an expression inside a temporary world and returns a boolean value, while detecting possible contradiction. The statement branch(x) is equivalent to

```
try (   choice(),
            if x true else (backtrack(), false)
catch contradiction (backtrack(),  false)
```

If we want to find a value for the slot x.r among a set x.possible that does not cause a contradiction (through rule propagation) we can simply write :

```
when y := some(y in x.possible | branch(x.r = y)) in x.r := y
else contradiction!()
```

3.7 Arrays

An array can be seen as a fixed-size list, with a *member type* (the slot name is *of*), which tells the type of all the members of the array. Because of the fixed size, the compiler is able to generate faster code than when using lists, so lists should be used when the collection shrinks and grows, and an array may be used otherwise. This is especially true for arrays of floats, which are handled in a special (and efficient) way by the compiler.

Arrays are simpler than lists, and only a few operations are supported. Therefore, more complex operations such as *append* often require a cast to list (list!). An array is created explicitly with the *make_array* property :

```
   let l := make_array(10,float,0.0) in
l[1] := l[3] + l[4]
```

Note that the *of* type must be given explicitly (it can be retrieved with *member_type*(l)), as well as a default value (0.0 in the previous example). An array is printed as [0.0,0.0, …, 0.0], similarly to a list but with surrounding brackets. Operations on arrays are described in the API and include copying, casting a bag into an array (*array!*), defeasible update on arrays using *store*, and returning the length of the array with *length*. An array can also be made from a list using array!, which is necessary to create arrays that contain complex objects (such as arrays of arrays). For instance,

```
Matrix :: array!(list<float[]>{ make_array(10,float,0.0) |
                    i in (1 .. 10)})
```

is correct, while the following will not work because the internal one-dimension array will be shared for all columns.

```
Matrix :: make_array(10,float[],make_array(10,float,0.0))
```

Since they are collections, arrays can be iterated, thus all iteration structures (image, selection, ...) can be used.

4. METHODS AND TYPES

4.1 Methods

A method is the definition of a property for a given signature. A method is defined by the following pattern : a selector (the name of the property represented by the method), a list of typed parameters (the list of their types forms the domain of the method), a range expression and a body (an expression or a let statement introduced by -> or =>).

<selector>(<typed parameters>) : <range>^{opt} ->|=> <body>

```
fact(n:{0}) : integer -> 1
fact(n:integer) : integer -> (n * fact(n - 1))
print_test() : void -> print("Hello"), print("world\n")
```

Definition: *A **signature** is a Cartesian product of types that always contains the extension of the function. More precisely, a signature $A_1 \times A_2 \times \ldots \times A_n$, also represented as list(A_1,...,A_n) or $A_1 \times A_2 \times \ldots \times A_{n-1} \times A_n$, is associated to a method definition `f(...)[:` A_n `[ ...` for two purposes: it says that the definition of the **property** f is only valid for input arguments ($x_1, x_2, \ldots, x_{n-1}$) in $A_1 \times A_2 \times \ldots \times A_{n-1}$ and it says that the result of f($x_1, x_2, \ldots, x_{n-1}$) must belong to A_n. The property f is also called an overloaded function and a method m is called its **restriction** to $A_1 \times A_2 \times \ldots \times A_{n-1}$.*

This is a CLAIRE definition

If two methods have intersecting signatures and the property is called on objects in both signatures, the definition of the method with the smaller domain is taken into account. If the two domains have a non-empty intersection but are not comparable, a warning is issued and the result is implementation-dependent. The set of methods that apply for a given class or return results in another can be found conveniently with *methods*.

```
methods(integer,string)  ;; returns {date!@integer, string!@integer, make_string@integer}
```

The range declaration can only be omitted if the range is any. In particular, this is convenient when using the interpreter.

```
loadMM() -> (begin(my_module), load("f1"), load("f2"), end(my_module))
```

If the range is void (unspecified), the result cannot be used inside another expression (a type-checking error will be detected at compilation). A method's range must be declared void if it does not return a value (for instance, if its last statement is, recursively, a call to another method with range void). It is important not to mix restrictions with void range with other regular methods that do return a value, since the compiler will generate an error when compiling a call unless it can guarantee that the void methods will not be used.

CLAIRE supports methods with a variable number of arguments using the *listargs* keyword. The arguments are put in a list, which is passed to the (unique) argument of type listarg. For instance, if we define

```
[f(x:integer,y:listargs) -> x + size(y)]
```

A call f(1,2,3,4) will produce the binding x = 1 and y = list(2,3,4) and will return 4.

CLAIRE also supports functions that return multiple values using **tuples**. If you need a function that returns n values $v_1,v_2,\ldots,v_n$ of respective types $t_1,t_2,\ldots,t_n$, you simply declare its range as $tuple(t_1,t_2,\ldots,t_n)$ and return $tuple(v_1,v_2,\ldots,v_n)$ in the body of the function. For instance the following method returns the maximum value of a list and the "regret" which is the difference between the best and the second-best value.

```
[max2(l:list[integer]) : tuple(integer,integer)
-> let x1 := 1000000000, x2 := 1000000000 in
    (for y in l
      (if (y < x1) (x2 := x1, x1 := y) else if (y < x2) x2 := y),
     tuple(x1,x2)) ]
```

The tuple produced by a tuple-valued method can be used in any way, but the preferred way is to use a tuple-assignment in a let. For instance, here is how we would use the max2 method:

```
let (a,b) := max2(list{f(i) | i in (1 .. 10)}) in …
```

Each time you use a tuple-assignment for a tuple-method, the compiler uses an optimization technique to use the tuple virtually without any allocation. This makes using tuple-valued methods a safe and elegant programming technique.

The *body* of a method is either a CLAIRE expression (the most common case) or an external (C++) function. In the first case, the method can be seen as defined by a lambda abstraction. This lambda can be created directly through the following:

```
lambda[(<typed parameters>), <body> ]
```

Defining a method with an external function is the standard way to import a C/C++ function in CLAIRE. This is done with the *function!(...)* constructor, as in the following.

```
f(x:integer,y:integer) -> function!(my_version_of_f)

cos(x:float) -> function!(cos_for_claire)
```

The integration of external functions is detailed in Appendix C. It is important to notice that in CLAIRE, methods can have at most 12 parameters. Methods with 40 or more parameters that exist in some C++ libraries are very hard to maintain. It is advised to use parameter objects in this situation.

CLAIRE also provides *inline* methods, that are defined using the => keyword before the body instead of ->. An inline method behaves exactly like a regular method. The only difference is that the compiler will use in-line substitution in its generated code instead of a function call when it seems more appropriate[4]. Inline methods can be seen as polymorphic macros, and are quite powerful because of the combination of parametric function calls (using *call*(...)) and parametric iteration (using *for)*. Let us consider the two following examples, where subtype[integer] is the type of everything that represents a set of integers:

```
sum(s:subtype[integer]) : integer => let x := 0 in (for y in s x :+ y, x)

min(s:subtype[integer], f:property) : integer
   => let x := 0, empty := true in
                (for y in s
                        (if empty (x := y, empty := false)
                         else if call(f,y,x) x := y),
                 x)
```

For each call to these methods, the compiler performs the substitution and optimizes the result. For instance, the optimized code generated for sum({x.age | x in person}) and for min({x in 1 .. 10 | f(x) > 0}, >) will be

```
let x := 0 in
   (for %v in person.instances
         let y := %v.age in x :+ y, x)

let x := 0, empty := true, y := 1, max := 10 in
                (while (y <= max)
                        (if (f(y) > 0)
                                (if empty (x := y, empty := false)
                                 else if (y > x) x := y),
                         y :+ 1),
                 x)
```

Notice that, in these two cases, the construction of temporary sets is totally avoided. The combined use of inline methods and functional parameters provides an easy way to produce generic algorithms that can be instantiated as follows.

```
mymin(l:list[integer]) : integer -> min(l, my_order)
```

The code generated for the definition of mymin @ list[integer] will use a direct call to *my_order* (with static binding) and the efficient iteration pattern for lists, because *min* is an inline method. In that case, the previous definition of *min* may be seen as a pattern of algorithms.

---

[4] The condition for substitution is implementation-dependent. For instance, the compiler checks that the expression that is substituted to the input parameter is simple (no side-effects and a few machine instructions) or that there is only one occurrence of the parameter.

 CAVEAT: A recursive macro will cause an endless loop that may be painful to detect and debug.

For upward compatibility reasons (from release 1.0), CLAIRE still supports the use of external brackets around method definitions. The brackets are there to represent boxes around methods (and are pretty-printed as such with advanced printing tools). For instance, one can write:

```
[ mymin(l:list[integer]) : integer -> min(l, my_order) ]
```

Brackets have been found useful by some users because one can search for the definition of the method m by looking for occurrences of «m». They also transform a method definition into a closed syntactical unit that may be easier to manipulate (e.g., cut-and-paste).

When a new property is created, it is most often implicitly with the definition of a new method or a new slot, although a direct instantiation is possible. Each property has an extensibility status that may be one of:

- open, which means that new restrictions may be added at any time. The compiler will generate the proper code so that extensibility is guaranteed.
- undefined, which is the default status under the interpreter, means that the status may evolve to open or to closed in the future.
- closed, which means that no new restriction may be added if it provokes an inheritance conflict with an existing restriction. An inheritance conflict in CLAIRE is properly defined by the non-empty intersection of the two domains (Cartesian products) of the methods.

The compiler will automatically change the status from undefined to closed, unless the status is forced with the abstract declaration:

```
abstract(p)
```

Conversely, the final declaration:

```
final(p)
```

may be used to force the status to closed, in the interpreted mode.

4.2 Types

CLAIRE uses an extended type system that is built on top of the set of classes. Like a class, a type denotes a set of objects, but it can be much more precise than a class. Since methods are attached to types (by their signature), this allows attaching methods to complex sets of objects.

Definition: *A (data)* ***type*** *is an expression that represents a set of objects. Types offer a finer-granularity partition of the object world than classes. They are used to describe objects (range of slots), variables and methods (through their signatures). An object that belongs to a type will always belong to the set represented by the type.*

Any class (even parameterized) is a type. A parameterized class type is obtained by filtering a subset of the class parameters with other types to which the parameters must belong. For instance, we saw previously that complex[im:{0.0}] is a parametrized type that represent the real number subset of the complex number class. This also applies to typed lists or sets which use the *of* parameter. For instance, list[of:{integer}] is the set of list whose of parameter is precisely integer. Since these are common patterns, CLAIRE offers two shortcuts for parameterized type expressions. First, it accepts the expression C[p = v] as a shortcut for C[p:{v}]. Second, it accepts the expression C<X> as a shortcut for C[of = X]. This applies to any class with a type-valued parameter named of; for instance, the stack class defined in Section 2.3. Thus, stack<integer> is the set of stacks whose parameter "of" is exactly integer, whereas stack[of:subtype[integer]] is the set of stacks whose parameter (a type) is a subset of integer.

Finite constant sets of objects can also be used as types. For example, {john, jack, mary} and {1,4,9} are types. Intervals can be used as types; the only kind of intervals supported by CLAIRE 3.0 is integer intervals. Types may also formed using the two intersection (^) and union(U) operations. For example, integer U float denotes the set of numbers and (1 .. 100) ^ (-2 .. 5) denotes the intersection of both integer intervals, i.e. (1 .. 5).

Subtypes are also as type expressions. First, because types are also objects, CLAIRE introduces subtype[t] to represent the set of all type expressions that are included in t. This type can be intersected with any other type, but there are two cases which are more useful than other, namely subtypes of the list and set classes. Thus, CLAIRE uses set[t] as a shortcut for set ^ subtype[t] and list[t] as a shortcut for list ^ subtype[t]. Because of the semantics of lists, one may see that list[t] is the union of two kinds of lists:

(a) "read-only" lists (i.e., without type) that contains objects of type t,

(b) typed list from list<X>, where X is a subtype of t.

Therefore, there is a clear difference between

- list<t>, which only contains types lists, whose type parameter (of) must be exactly t.
- list[t], which contains both typed lists and un-typed lists.

Obviously, we have list<t> <= list[t].When should you use one or the other form of typed lists or sets ?

(1) use list[t] to type lists that will only be used by accessing their content. A method that uses l:list[t] in its signature will be polymorphic, but updates on l will rely on dynamic (run-time) typing.

(2) use list<t> to type lists that need to be updated. A method that uses l:list<t> in its signature will be monomorphic (i.e., will not work for l:list<t'> with t' <= t), but updates will be statically type-checked (at compile time).

Last, CLAIRE uses *tuple* and *array* types. The array type t[] represents arrays whose *member type* is t (i.e., all members of the array belong to t). Tuples are used to represent type of tuples in a very simple manner: $tuple(t_1,t_2,\ldots,t_n)$ represents the set of tuples $tuple(v_1,v_2,\ldots,v_n)$ such that $v_i \in t_i$ for all i in (1 .. n). For instance, tuple(integer, char) denotes the set of pair tuples with an integer as first element and a character as second. Also you will notice that tuple(class,any,type) belongs to itself, since class is a class and type is a type.

To summarize, here is the syntax for types expressions in CLAIRE v3.0 :

<type> ≡ <class> | <class>[<parameter>:<type>^{seq}] | {<item>^{seq}} |
(<integer> .. <integer>) |(<type> U <type>) | (<type> ^ <type>) |
set[<type>] | **list[**<type>] | <type>[] | **subtype[**<type>] |
tuple(<type>^{seq})

Classes are sorted with the inheritance order. This order can be extended to types with the same intuitive meaning that a type t_1 is a subtype of a type t_2 if the set represented by t_1 is a subset of that represented by t_2. The relation "t_1 is a subtype of a type t_2" is noted $t_1 <= t_2$. This order supports the introduction of the "subtype" constructor: subtype[t] is the type of all types that are less than t.

Warning: The next section describes an advanced feature and may be skipped

4.3 Polymorphism

In addition to the traditional "objet-oriented" polymorphism, CLAIRE also offers two forms of parametric polymorphism, which can be skipped by a novice reader.

(1) There often exists a relation between the types of the arguments of a method. Capturing such a relation is made possible in CLAIRE through the notion of an "extended signature". For instance, if we want to define the operation "push" on a stack, we would like to check that the argument y that is being pushed on the stack s belongs to the type of(s), that we know to be a parameter of s. The value of this parameter can be introduced as a variable and reused for the typing of the remaining variables (or the range) as follows.

```
push(s:stack<X>, y:X) -> ( s.content :add y, s.index :+ 1)
```

The declaration s:stack<X> introduced X as a type variable with value `s.of`, since `stack[of]` was defined as a parameterized class. Using X in y:X simply means that y must belong to the type `s.of`. Such intermediate type variables must be free identifiers (the symbol is not used as the name of an object) and must be introduced with the following template:

<class>[p_i=v_i,...,]

The use of type variables in the signature can be compared to pattern matching. The first step is to bind the type variable. If (p = V) is used in c[...] instead of p:t, it means that we do not put any restriction on the parameter p but that we want to bind its value to V for further use. Note that this is only interesting if the value of the parameter is a type itself. Once a type variable V is defined, it can be used to form a pattern (called a <type with var> in the CLAIRE syntax in Appendix A) as follows:

<type with var> ≡ <type> | <var> | {<var>} |
tuple(<type with var>$^{seq+}$) |
<class>[□<var>:<type with var> | <var>=<var> □$^{seq+}$]

(2) The second advanced typing feature of CLAIRE is designed to capture the fine relationship between the type of the output result and the types of the input arguments. When such a relationship can be described with a CLAIRE expression $e(x_1,...,x_n)$, where x_1, ..., x_n are the types of the input parameters, CLAIRE allows to substitute `type[e]` to the range declaration. It means that the result of the evaluation of the method should belong to $e(t_1,...,t_n)$ for any types $t_1,...,t_n$ that contain the input parameters.

For instance, the identity function is known to return a result of the same type as its input argument (by definition !). Therefore, it can be described in CLAIRE as follows.

```
id(x:any) : type[x] -> x
```

In the expression that we introduce with the *type[e]* construct, we can use the types of the input variables directly through the variables themselves. For instance, in the "type[x]" definition of the id example, the "x" refers to the type of the input variable. Notice that the types of the input variables are not uniquely defined. Therefore, the user must ensure that her "prediction" e of the output type is valid for any valid types t1, ..., tn of the input arguments.

The expression e may use the extra type variables that were introduced earlier. For instance, we could define the "top" method for stacks as follows.

```
top(s:stack<X>) : type[X] -> s.content[s.index]
```

The "second-order type" e (second-order means that we type the method, which is a function on objects, with another function on types) is built using the basic CLAIRE operators on types such as U, ^ and some useful operations such as "*member*". If c is a type, *member*(c) is the minimal type that contains all possible members of c. For instance, *member*({c}) = c by definition. This is useful to describe the range of the enumeration method set!. This method returns a set, whose members belong to the input class c by definition. Thus, we know that they must belong to the type *member*(X) for any type X to whom c belongs (cf. definition of member). This translates into the following CLAIRE definition.

```
set!(c:class) : type[set[member(c)]] -> c.instances
```

For instance, if c belongs to subtype[B] then set!(c) belongs to set[B].

To summarize, here is a more precise description of the syntax for defining a method:

<function> (<v_i>:<t_i>, i □ (1 .. n)) : <range> -> <exp>

Each type t_i for the variable v_i is an "extended type" that may use type variables introduced by the previous extended types t_1, t_2 ... t_{i-1} . An extended type is defined as follows.

<et> ≡ <class> | <set> | <var> | (<et> ^ | **U** <et>) | (<obj> **..** <obj>)|
set[<et>**]** | **list[**<et>**]** | <et>**[]** | **tuple**(<et>^{seq}) |
<class>[□<var>:<et> | <var>=□<var>|<const>□□$^{seq+}$]

The <range> expression is either a regular type or a "second order type", which is a CLAIRE expression e introduced with the type[e] syntactical construct .

<range> ≡ <type> | **type[**<expression>**]**

4.4 Escaping Types

There are two ways to escape type checking in CLAIRE. The first one is casting, which means giving an explicit type to an expression. The syntax is quite explicit:

<cast> ≡ (<expression> **as** <type>)

This will tell the compiler that <expression> should be considered as having type <type>. Casting is ignored by the interpreter and should only be used as a compiler optimization. There is, however, one convenient exception to this rule, which is the casting into a list parametric type. When an untyped list is casted into a typed list, the value of its *of* parameter is actually modified by the interpreter, once the correct typing of all members has been verified. For instance, the two following expressions are equivalent:

```
list<integer>(1,2,3,4)
list(1,2,3,4) as list<integer>
```

The second type escaping mechanism is the non-polymorphic method call, where we tell what method we want to use by forcing the type of the first argument. This is equivalent to the *super* message passing facilities of many object-oriented languages.

<super> ≡ <selector>@<type>(<exp>^{seq})

The instruction f@c(...) will force CLAIRE to use the method that it would use for f(...) if the first argument was of type c (CLAIRE only checks that this first argument actually belongs to c).

A language is type-safe if the compiler can use type inference to check all type constraints (ranges) at compile-time and ensure that there will be no type checking errors at run-time. CLAIRE is not type-safe because it admits expressions for which type inference is not possible such as `read(p) + read(p)`. On the other hand, most expressions in CLAIRE may be statically type-checked and the CLAIRE compiler uses this property to generate code that is very similar to what would be produced with a C++ compiler. A major difference between CLAIRE 3.0 and earlier versions is the fact that lists may be explicitly typed, which removes the problems that could happen earlier with dynamic types. Lists and sets subtypes support inclusion polymorphism, which means that if A is a subtype of B, list[A] is a subtype of list[B]; for instance`list[(0 .. 1)] <= list[integer]`. Thus only read operations can be statically type-checked w.r.t. such type information. On the other hand, array subtypes, as well as list or set parametric subtypes, are monomorphic, since A[] is not the set of arrays which contain members of A, but the set of arrays whose member type (the *of* slot) contains the value A. Thus if A is different from B, A[] is not comparable with B[], and list<A> is not comparable with list<B>. This enables the static type-checking of read and write operations on lists. The fact that CLAIRE supports all styles of type disciplines is granted by the combination of a rich dynamic type system coupled with a powerful type inference mechanism within the compiler, and is a key feature of CLAIRE.

4.5 Selectors, Properties and Operations

As we said previously, CLAIRE supports two syntaxes for using selectors, f(...) and (.... f ....). The choice only exists when the associated methods have exactly two arguments. The ability to be used with an infix syntax is attached to the property f:.

```
f :: operation()
```

Once f has been declared as an operation, CLAIRE will check that it is used as such subsequently. Restrictions of f can then be defined with the usual syntax

```
f(x:integer, y:integer) : ...
```

Note that declaring f as an operation can only be done when no restriction of f is known. If the first appearance of f is in the declaration of a method, f is considered as a normal selector and its status cannot be changed thereafter. Each operation is an object (inherits from **property**) with a *precedence* slot that is used by the reader to produce the proper syntax tree from expressions without parentheses.

```
gcd :: operation(precedence = precedence(/))
12 + 3 gcd 4          ;; same as 12 + (3 gcd 4)
```

So far we have assumed that any method definition is allowed, provided that inheritance conflict may cause warning. Once a property is compiled, CLAIRE uses a more restrictive approach since only new methods that have an empty intersection with existing methods (for a given property) are allowed. This allows the compiler to generate efficient code. It is possible to keep the "open" status of a property when it is compiled through the *abstract* declaration.

```
abstract(f)
```

Such a statement will force CLAIRE to consider **f** as an "abstract" parameter of the program that can be changed at any time. In that case, any re-definition of f (any new method) will be allowed. When defining a property parameter, one should keep in mind that another user may redefine the behavior of the property freely in the future.

It is sometimes useful to model a system with redundant information. This can be done by considering pairs of relations inverse one of another. In this case the system maintains the soundness of the database by propagating updates on one of the relations onto the other. For example if *husband* is a relation from the class **man** onto the class **woman** and *wife* a relation from **woman** to **man**, if moreover *husband* and *wife* have been declared inverse one of another, each modification (addition or retrieval of information) on the relation husband will be propagated onto wife. For example husband(mary) := john will automatically generate the update wife(john) := mary. Syntactically, relations are declared inverses one of another with the declaration

inverse(husband) := wife

This can be done for any relation: slots and tables (cf. Section 5). Inverses introduce an important distinction between multi-valued relations and mono-valued relations. A relation is multi-valued in CLAIRE when its range is a subset of **bag** (i.e. a **set** or a **list**). In that case the slot *multivalued?* of the relation is set to true[5] and the set associated with an object x is supposed to be the set of values associated with x through the relation. Notice that other aspects of multi-valuation were covered in Section 2.2.

This has the following impact on inversion. If r and s are two mono-valued relations inverse one of another, we have the following equivalence :

$s(x) = y \Leftrightarrow r(y) = x$

In addition, the range of r needs to be included in the domain of s and conversely. The meaning of inversion is different if r is multi-valued since the inverse declaration now means :

$s(x) = y \Leftrightarrow x \in r(y)$

Two multi-valued relations can indeed be declared inverses one of another. For example, if parents and children are two relations from `person` to `set[person]` and if inverse(children) = parents, then

children(x) = {y in person | x ∈ parents(y)}

Modifications to the inverse relation are triggered by updates (with :=) and creations of objects (with filled slots). Since the explicit inverse of a relation is activated only upon modifications to the database (it is not retroactive), one should always set the declaration of an inverse as soon as the relation itself is declared, before the relation is applied on objects. This will ensure the soundness of the database. To escape the triggering of updates to inverse relations, the solution is to fill the relation with the method put instead of :=. For example, the following declaration

let john := person() in (put(wife,john,mary), john)

does the same as

john :: person(wife = mary)

without triggering the update `husband(mary) := john`.

Warning: The next section describes an advanced feature and may be skipped

4.6 Iterations

We just saw that CLAIRE will produce in-line substitution for some methods. This is especially powerful when combined with parametric function calls (using *call*(...)) taking advantage of the fact that CLAIRE is a functional language. There is another form of code substitution supported by CLAIRE that is also extremely useful, namely the iteration of set data structure.

Any object s that understands the *set!* method can be iterated over. That means that the construction *for x in s e(x)* can be used. The actual iteration over the set represented by s is done by constructing explicitly the set extension. However, there often exists a way to iterate the set structure without constructing the set extension. The simplest example is the integer interval structure that is iterated with a while loop and a counter.

---

[5] This slot can be reset to false in the rare case when the relation should actually be seen as mono-valued.

It is possible to define iteration in CLAIRE through code substitution. This is done by defining a new inline restriction of the property *iterate*, with signature (x:X,v:Variable,e:any). The principle is that CLAIRE will replace any occurrence of (`for v in x e`) by the body of the inline method as soon as the type of the expression x matches with X (v is assumed to be a free variable in the expression e). For instance, here is the definition of iterate over integer intervals:

```
iterate(x:interval[min:integer,max:integer],v:Variable,e:any)
        => let v := min(x), %max := max(x) in (while (v <= %max) (e, v :+ 1))
```

Here is a more interesting example. We can define hash tables as follows. A table is defined with a list (of size 2^n - 3, which is the largest size for which a chunk of size 2^n is allocated), which is full of "unknown" except for these objects that belong to the set. Each object is inserted at the next available place in the table, starting at a point given by the hashing function (a generic hashing function provided by CLAIRE: *hash*).

```
htable: object(   count:integer = 0,
                  index:integer = 4,
                  arg:list<any> = list<any>())
set!(x:htable) -> {y in x.arg | known?(y)}
insert(x:htable,y:any)
        -> let l := x.arg in
                (if (x.count >= length(l) / 2)
                        (x.arg := make_list(^2(x.index - 3), unknown),
                         x.index :+ 1, x.count := 0,
                         for z in {y in l | known?(y)} insert(x,z),
                         insert(x,y))
                 else let i := hash(l,y) in
                        (until (l[i] = unknown |i] = y)
                                (if (i = length(l)) i := 1 else i :+ 1),
                         if (l[i] = unknown)
                                (x.count :+ 1, l[i] := y)))
```

Note that CLAIRE provides a few other functions for hashing that would allow an even simpler, though less self-contained, solution. To iterate over such hash tables without computing set!(x) we define

```
iterate(s:htable, v:Variable, e:any)
        => (for v in s.arg (if known?(v) e))
```

Thus, CLAIRE will replace

```
let s:htable := ... in sum(s)
```

by

```
let s:htable := ... in
        (let x := 0 in
                (for v in s.arg
                        (if known?(v) x :+ v),
                 x))
```

The use of *iterate* will only be taken into account in the compiled code unless one uses *oload*, which calls the optimizer for each new method. *iterate* is a convenient way to extend the set of CLAIRE data structure that represent sets with the optimal efficiency. Notice that, for a compiled program, we could have defined *set!* as follows (this definition would be valid for any new type of set).

```
set!(s:htable) -> {x | x in s}
```

When defining a restriction of *iterate*, one must not forget the handling of values returned by a *break* statement. In most cases, the code produce by *iterate* is itself a loop (a `for` or a `while`), thus this handling is implicit. However, there may be multiples loops, or the final value may be distinct from the loop itself, in which case an explicit handling is necessary. Here is an example taken from class iteration :

```
iterate(x:class,v:Variable,e:any) : any
        => (for %v_1 in x.descendents
                let %v_2 := (for v in %v_1.instances e) in          // catch inner break
                  (if %v_2 break(%v_2)))                                  // transmit the value
```

Notice that it is always possible to introduce a loop to handle breaks if none are present; we may replace the expression e by :

```
while true (e, break(nil))
```

Last, we need to address the issue of parametric polymorphism, or how to define new kinds of type sets. The previous example of hash-sets is incomplete, because it only describes generic hash-sets that may contain any element. If we want to introduce typed hash-sets, we need to follow these three steps. First we add a type parameter to the htable class:

```
htable[of] <: object( of:type = any,  count:integer = 0, ...)
```

Second, we use a parametric signature to use the type parameter appropriately:

```
insert(x:htable<X>,y:X) -> ...
```

Last, we need to tell the compiler that an instance from `htable[X]` only contains objects from X. This is accomplished by extending the *member* function which is used by the compiler to find a valid type for all members of a given set. If x is a type, *member*(x) is a valid type for any y that will belong to a set s of type x. If T is a new type of sets, we may introduce a method *member*(x:T, t:type) that tells how to compute member(t) if t is included in T. For instance, here is a valid definition for our *htable* example:

```
member(x:htable,t:type) -> member(t @ of)
```

This last part may be difficult to grasp (do not worry, this is an advanced feature). First, recall that if t is a type and p a property, (t @ p) is a valid type for *x*.p when *x* is of type t. Suppose that we now have an expression *e*, with type *t1*, that represents a htable (thus *t1* <= *htable*). When the compiler calls *member*(t1), the previous method is invoked (x is bound to a system-dependent value that should not be used and t is bound to t1). The first step is to compute (*t1* @ of), which is a type that contains all possible values for y.of, where y is a possible result of evaluating e. Thus, *member*(*t1* @ of) is a type that contains all possible values of y, since they must belong to `y.of` by construction. This type is, therefore, used by the compiler as the type of the element variable v inside the loop generated by *iterate*.

Iteration is equally covered in the section 3.6 of the Appendix C, with the ability to optimize the iteration of specific language expressions.

5. TABLES, RULES AND HYPOTHETICAL REASONING

5.1 Tables

Named arrays, called tables, can be defined in CLAIRE with the following syntax:

<name>[var:(<integer> .. <integer>)] : <type> := <expression(var)>

The <type> is the range of the table and <expression> is an expression that is used to fill the table. This expression may either be a constant or a function of the variables of the table (i.e., an expression in which the variables appear). If the expression is a constant, it is implicitly considered as a default value, the domain of the table may thus be infinite. If the default expression is a function, then the table is filled when it is created, so the domain needs to be finite. When one wants to represent incomplete information, one should fill this spot with the value unknown. For instance, we can define

```
square[x:(0 .. 20)] : integer := (x * x)
```

Notice that the compounded expression x * x is put inside parenthesis because grammar requires a «closed» expression, as for a method (cf. Appendix A). Tables can be accessed through square brackets and can be modified with assignment expressions like for local variables.

```
square[1], square[2] := 4, square[4] :+ 5,
```

Tables have been extended in CLAIRE by allowing the use of any type instead of an integer interval for their domain. They are thus useful to model relations, when the domain of a relation is more complex than a class (in which case a slot should rather be used to model the relation). The syntax for defining such a table (i.e., an associative array) is, therefore,

<table> ≡ <name>[var:<type>] : <type> := <expression(var)>

This is a way to represent many sorts of complex relations and use them as we would with arrays. Here are some examples.

```
creator[x:class] : string := "who created that class"
maximum[x:set[0 .. 10]] : integer := (if x min(x,> @ integer) else 0)
color[x:{car,house,table}] : colors := unknown
```

We can also define two-dimensional arrays such as

```
distance[x:tuple(city,city)] : integer := 0
cost[x:tuple(1 .. 10, 1 .. 10)] : integer := 0
```

The proper way to use such a table is `distance[list(denver,miami)]` but CLAIRE also supports `distance[denver,miami]`. CLAIRE also supports a more straightforward declaration such as :

```
cost[x:(1 .. 10), y:(1 .. 10)] : integer := 0
```

As for properties, tables can have an explicit inverse, which is either a property or a table. Notice that this implies that the inverse of a property can be set to a table. However, inverses should only be used for one-dimension array. Thus the inverse management is not carried if the special two-dimension update forms such as «`cost[x,y] := 0`» are used.

5.2 Rules

A rule in CLAIRE is made by associating an event condition to an expression. The rule is attached to a set of free variables of given types: each time that an event that matches the condition becomes occurs for a given binding of the variables (i.e., association of one value to each variable), the expression will be evaluated with this binding. The interest of rules is to attach an expression not to a functional call (as with methods) but to an event, with a binding that is more flexible (many rules can be combined for one event) and more incremental.

Definition: *A **rule** is an object that binds a condition to an action, called its conclusion. Each time the condition becomes true for a set of objects because of a new event, the conclusion is executed. The condition is expressed as a logic formula on one or more free variables that represent objects to which the rule applies. The conclusion is a CLAIRE expression that uses the same free variables. An event is an update on these objects, either the change of a slot or a table value, or the instantiation of a class. A rule condition is checked if and only if an event has occurred.*

A novelty in CLAIRE 3.0 is the introduction of event logic. There are two events that can be matched precisely: the update of a slot or a table, and the instantiation of a class. CLAIRE 3.2 use expressions called event pattern to specify which kind of events the rule is associated with. For instance, the expression x.r := y is an event expression that says both that x.r = y and that the last event is actually the update of x.r from a previous value. More precisely, here are the events that are supported:

- x.r := y, where r is a slot of x.
- a[x] := y, where a is a.
- x.r :add y, where r is a multi-valued slot of x (with range bag).
- a[x] :add y, where a is a multi-valued table.

Note that an update of the type x.r :delete y (resp. a[x] :delete y), where r is a slot of x (resp. a is a table), will never be considered as an event if r is multi-valued. However, one can always replace this declaration by x.r := delete(x.r, y) which is an event, but which costs a memory allocation for the creation of the new x.r.

In addition, a new event pattern was introduced in CLAIRE 3.0 to capture the transition from an old to a new value. This is achieved with the expression x.r := (z -> y) which says that the last event is the update of x.r from z to y. For instance, here is the event expression that states that x.salary crossed the 100000 limit:

```
x.salary := (y -> z) & y < 100000 & z >= 100000
```

In CLAIRE 3.2 we introduce the notion of a "pure" event. If a property p has no restrictions, then p(x,y) represents a virtual call to p with parameters x and y. This event may be used in a rule in a way similar to x.p := y, with the difference that it does not correspond to an update. Virtual events are very generic since one of the parameter may be arbitrarily complex (a list, a set, a tuple …). The event filter associated to a virtual event is simply the expression "p(x,y)". To create such an event, one simply calls p(x,y), once a rule using such an event has been defined. As a matter of fact, the definition of a rule using p(x,y) as an event pattern will provoke the creation of a generic method p that creates the event.

Virtual event may be used for many purposes. The creation of a virtual event requires no time nor memory; thus, it is a convenient technique to capture state transition in your object system. For instance, we can create an event signaling the instantiation of a class as follows:

```
    instantiation :: property(domain = myClass, range = string)
[close(x:MyClass) -> Intantiation(x,date!(1)), x ]
    controlRule() :: rule( instantiation(x,s)
            => printd("create ~S at ~A",x,s))
```

To define a rule, we must indeed define:

- a condition, which is the combination of an event pattern and a CLAIRE Boolean expression using the same variables
- a conclusion that is preceded by =>.

Here is a classical transitive closure example:

```
r1() :: rule(
        x.friends :add y
        => for z in y.friend x.friends :add z )
```

Rules are named (for easier debugging) and can use any CLAIRE expression as a conclusion, using the event parameters as variables. Rule triggering can be traced using *trace(if_write)*, as shown in Appendix C. Notice that a rule definition in CLAIRE 3.2 has no parameters; rules with parameters require the presence of the ClaireRules library, which is no longer available.

For instance, let us define the following rule to fill the table *fib* with the Fibonacci sequence.

```
    r3() :: rule(
            y := fib[x] & x % (0 .. 100)
=> when z := get(fib,x – 1) in fib[x + 1] := y + z)
```

```
(fib[0] := 1, fib[1] := 1)
```

5.3 Hypothetical Reasoning

In addition to rules, CLAIRE also provides the ability to do some hypothetical reasoning. It is indeed possible to make hypotheses on part of the knowledge (the database of relations) of CLAIRE, and to change them whenever we come to a dead-end. This possibility to store successive versions of the database and to come back to a previous one is called the world mechanism (each version is called a world). The slots or tables x on which hypothetical reasoning will be done need to be specified with the declaration store(x). For instance,

```
store(age,friends,fib) ⊓ store(age), store(friends), store(fib)
```

Each time we ask CLAIRE to create a new world, CLAIRE saves the status of tables and slots declared with the store command. Worlds are represented with numbers, and creating a new world is done with *choice*(). Returning to the previous world is done with *backtrack()*. Returning to a previous world n is done with *backtrack(n)*. Worlds are organized into a stack (sorry, you cannot explore two worlds at the same time) so that save/restore operations are *very* fast. The current world that is being used can be found with *world?()*, which returns an integer.

Definition: *A **world** is a virtual copy of the* defeasible *part of the object database. The object database (set of slots, tables and global variables) is divided into the defeasible part and the stable part using the* ***store*** *declaration. **Defeasible** means that updates performed to a defeasible relation or variable can be undone later; r is defeasible if* store(r) *has been declared. Creating a world (* choice*) means storing the current status of the defeasible database (a delta-storage using the previous world as a reference). Returning to the previous world (*backtrack*) is just restoring the defeasible database to its previously stored state.*

In addition, you may accept the hypothetical changes that you made within a world while removing the world and keeping the changes. This is done with the *commit* and *commit=* methods. *commit()* decreases the world counter by one, while keeping the updates that were made in the current world. It can be seen as a collapse of the current world and the previous world. *commit=(n)* repeats *commit()* until the current world is *n*. Notice that this "collapse" will simply make the updates that were made in the current world (n) look like they were made in the previous world (n – 1); thus, these updates are still defeasible. A stronger version, *commit0*, is available that consider the updates made in the current world as non-defeasible (as if they belonged to the world with index 0). Thus, unless *commit* is used to return to the initial world (with index 0) – in which case commit and commit0 are equivalent - commit grows the size of the current world since it does not free the stack memory that is used to trail updates.

The amount of memory that is assigned to the management of the world stack is a parameter to CLAIRE, as explained in Appendix C. Defeasible updates are fairly optimized in CLAIRE, with an emphasis on minimal book-keeping to ensure better performance. Roughly speaking, CLAIRE stores a pair of pointers for each defeasible update in the world stack. There are (rare) cases where it may be interesting to record more information to avoid overloading the trailing stack. For instance, trailing information is added to the stack for each update even if the current world has not changed. This strategy is actually faster than using a more sophisticated book-keeping, but may yield a world stack overflow. The example of Store, given in Section 2.6, may be used as a template to remedy this problem.

For instance, here is a simple program that solves the n queens problem (the problem is the following: how many queens can one place on a chessboard so that none are in situation of chess, given that a queen can move vertically, horizontally and diagonally in both ways ?)

```
column[n:(1 .. 8)] : (1 .. 8) := unknown
possible[x:(1 .. 8), y:(1 .. 8)] : boolean := true
event(column), store(column, possible)

r1(x:(1 .. 8),z:(1 .. 8)) :: rule(
      column[x]⊡= z => for y in ((1 .. 8) but x) possible[y,z] := false)
r2(x:(1 .. 8),z:(1 .. 8)) :: rule(
column[x]⊡= z => let d⊡= x + z in
          for y in (1 .. min(d – 1, 8)
             possible[y,d - y] := false )
r3(x:(1 .. 8),y:(1 .. 8)) :: rule(
column[x]⊡= z => let d⊡= z – x in
          for y in (1 .. (8 – d))
             possible[y,y + d] := false)
```

```
queens(n:(0 .. 8)) : boolean
        -> (    if (n = 0) true
                else exists(p in (1 .. 8) |
                                (possible[n,p]          &
  branch( (column[n] := p, queens(n - 1)) ))))

queens(8)
```

In this program *queens*(n) returns true if it is possible to place n queens. Obviously there can be at most one queen per line, so the purpose is to find a column for each queen in each line□this is represented by the *column* table. So, we have eight levels of decision in this problem (finding a line for each of the eight queens). The search tree (these imbricated choices) is represented by the stack of the recursive calls to the method queens. At each level of the tree, each time a decision is made (an affectation to the table column), a new world is created, so that we can backtrack (go back to previous decision level) if this hypothesis (this branch of the tree) leads to a failure.

Note that the table *possible*, which tells us whether the n-th queen can be set on the p-th line, is filled by means of rules triggered by *column* (declared event) and that both *possible* and *column* are declared store so that the decisions taken in worlds that have been left are undone (this avoids to keep track of decisions taken under hypotheses that have been dismissed since).

Updates on lists can also be "stored" on worlds so that they become defeasible. Instead of using the *nth=* method, one can use the method *store*(*l,x,v,b*) that places the value v in l[x]□and stores the update if b is true. In this case, a return to a previous world will restore the previous value of l[x]. If the boolean value is always true, the shorter form *store(l,x,y)* may be used. Here is a typical use of store:

```
store(l,n,y,l[n] != y)
```

This is often necessary for tables with range list or set. For instance, consider the following :

```
A[i:(1 .. 10)] : tuple(integer,integer,integer) := list<integer>(0,0,0)
(let l := A[x] in
        (l[1] := 3, l[3]□= 3))
```

even if *store(A)* is declared, the manipulation on l will not be recorded by the world mechanism. You would need to write :

```
A[x] := list(3,A[x][2],3)
```

Using *store*, you can use the original (and more space-efficient) pattern and write:

```
(let l := A[x] in
        (store(l,1,3), store(l,3,3)))
```

There is another problem with the previous definition. The expression given as a default in a table definition is evaluated only once and the value is stored. Thus the same list<integer>(0,0,0) will be used for all A[x]. In this case, which is a default value that will support side-effects, it is better to introduce an explicit initialization of the table:

```
(for i in (1 .. 10) A[i] := list<integer>(0,0,0))
```

There are two operations that are supported in a defeasible manner: direct replacement of the i-th element of l with y (using *store*(l,i,y)) and adding a new element at the end of the list (using *store*(l,y)). All other operations, such as *nth+* or *nth-* are not defeasible. The addition of a new element is interesting because it either returns a new list or perform a defeasible side-effect. Therefore, one must also make sure that the assignment of the value of *store*(l,x) is also made in a defeasible manner (e.g., placing the value in a defeasible global variable). To perform an operation like nth+ or delete on a list in a defeasible manner, one usually needs to use an explicit copy (to protect the original list) and store the result using a defeasible update (cf. the second update in the next example)

It is also important to notice that the management of defeasible updates is done at the relation level and not the object level. Suppose that we have the following□

```
C1 <□object(a:list<any>, b:integer)
C2 <□thing(c:C1)
store(c,a)
P□: C1()
P.c□= C2(a = list<any>(1,2,3) , b = 0)          // defeasible but the C2 object remains
P.c.a□=  delete(copy(P.c.a), 2)          // this is defeasible
P.c.b□= 2                                       // not defeasible
```

The first two updates are defeasible but the third is not, because *store*(b) has not been declared. It is also possible to make a defeasible update on a regular property using *put_store*. It is worth noticing that hypothetical reasoning

6. I/O, MODULES AND SYSTEM INTERFACE

6.1 Printing

There are several ways of printing in CLAIRE. Any entity may be printed with the function *print*. When print is called for an object that does not inherit from **thing** (an object without a name), it calls the method *self_print* of which you can define new restrictions whenever you define new classes. If *self_print* was called on an object x owned by a class toto for which no applicable restriction could be found, it would print <toto>

In the case of bags (sets or lists), strings, symbols or characters, the standard method is *princ*. It formats its argument in a somewhat nicer way than print. For example

```
print("john")     gives  "john"
princ("john")     gives  john
```

Finally, there also exists a *printf* macro as in C. Its first argument is a string with possible occurrences of the control patterns ~S, ~I and ~A. The macro requires as many arguments as there are "tilde patterns" in the string, and pairs in order of appearance arguments together with tildes. These control patterns do not refer to the type of the corresponding argument but to the way you want it to be printed. The macro will call *print* for each argument associated with a ~S form, *princ* for each associated with a ~A form and will print the result of the evaluation of the argument for each ~I form. A mnemonic is A for alphanumeric, S for standard and I for instruction. Hence the command

```
printf("~S is ~A and here is what we know\n ~I",john,23,show(john) )
```

will be expanded into

```
(print(john), princ(" is "), princ(23),
   princ(" and here is what we know\n"), show(john) )
```

Output may also be directed to a file or another device instead of the screen, using a port. A port is an object bound to a physical device, a memory buffer or a file. The syntax for creating a port bound to a file is very similar to that of C. The two methods are *fopen* and *fclose*. Their use is system dependent and may vary depending on which C compiler you are using. However, *fopen* always requires a second argument: a control string most often formed of one or more of the characters 'w', 'a', 'r': 'w' allows to (over)write the file, 'a' ('a' standing for append) allows to write at the end of the file, if it is already non empty and 'r' allows to read the file. The method *fopen* returns a port. The method *use_as_output* is meant to select the port on which the output will be written. Following is an example:

```
(let p:port := fopen("agenda-1994","w") in
                ( use_as_output(p), write(agenda), fclose(p) ) )
```

A CLAIRE port is a wrapper around a stream object from the underlying language (C++ or Java). Therefore, the ontology of ports can be extended easily. In most implementations, ports are available as files, interfaces to the GUI and strings (input and output). To create a string port, you must use *port!*() to create an empty string you may write to, or *port!(s:string)* to read from a string s (cf. Appendix B).

Note that for the sake of rapidity, communications through ports are buffered, so it may happen that the effect of printing instructions is delayed until other printing instructions for this port are given. To avoid problems of synchronization between reading and writing, it is sometimes useful to ensure that the buffer of a given port is empty. This is done by the command *flush(p:port)*. *flush(p)* will perform all printing (or reading) instructions for the port p that are waiting in the associated buffer.

Two ports are created by default when you run CLAIRE: *stdin* and *stdout* . They denote respectively the standard input (the device where the interpreter needs to read) and the standard output (where the system prints the results of the evaluation of the commands). Because CLAIRE is interpreted, errors are printed on the standard output. The actual value of these ports is interface dependent.

CLAIRE also offers a simple method to redirect the output towards a string port. Two methods are needed to do this: *print_in_string* and *end_of_string*. *print_in_string()* starts redirecting all printing statements towards the string being built. *end_of_string()* returns the string formed by all the printing done between these two instructions. You can only use *print_in_string* with one output string at a time; more complex uses require the creation of multiple string ports.

Last, CLAIRE also provides a special port which is used for tracing: *trace_output*(). This port can be set directly or through the trace(_) macro (cf. Appendix C). All trace statements will be directed to this port. A *trace* statement is either obtained implicitly through tracing a method or a rule, or explicitly with the *trace* statement. the statement *trace(n, <string>, <args> ...)* is equivalent to *printf(<string>, <args> ..)* with two differences: the string is printed only if the verbosity level *verbose()* is higher than n and the output port is *trace_output()*.

To avoid confusion, the following hierarchy is suggested for verbosity levels:

1 - **error**: this message is associated with an error situation

2 - **warning**: this message is a warning which could indicate a problem

3 - **note**: this message contains useful information

4 - **debug**: this message contains additional information for debugging purposes

This hierarchy is used for the messages that the CLAIRE system sends to the user (which are all implemented with *trace*).

6.2 Reading

Ports offer the ability to direct the output to several files or devices. The same is true for reading. Ports just need to be opened in reading mode (there must be a 'r' in the control string when *fopen* is called to create a reading port). The basic function that reads the next character from a port is *getc(port)*. *getc(p)* returns the next characters read on p. When there is nothing left to be read in a port, the method returns the special character EOF. As in C, the symmetric method for printing a character on a port also exists: *putc(char,port)* writes the character c on p.

There are however higher-level primitives for reading. Files can be read one expression at a time: *read(port)* reads the next CLAIRE expression on the port *p* or, in a single step, *load(string)* reads the file associated to the string s and evaluates it. It returns *true* when no problem occurred while loading the file and *false* otherwise. A variant of this method is the method *sload(string)* which does the same thing but prints the expression read and the result of their evaluation. Another variant is the method *oload(string)* which does the same thing but substitute an optimized form to each method's body. This may hinder the inspection of the code at the toplevel, but it will increase the efficiency of the interpreter.

Files may contain comments. A comment is anything that follows a // until the end of the line. When reading, the CLAIRE reader will ignore comments (they will not be read and hence not evaluated). For instance

```
x :+ 1, //  increments x by 1
```

To insure compatibility with earlier versions, CLAIRE also recognizes lines that begin with ; as comments. Conversely, CLAIRE also support the C syntax for block comments: anything between /* and */ will be taken as a comment. Comments in CLAIRE may become active comments that behave like trace statements if they begin with [<level>] (see Appendix C, Section 2). The global variable NeedComment may be turned to true (it is false by default) to tell the reader to place any comment found before the definition of a class or a method in the *comment* slot of the associated CLAIRE object.

The second type of special instructions are immediate conditionals. An immediate conditional is defined with the same syntax as a regular conditional but with a `#if` instead of an if

```
#if <test> <expression> <else <expression> >opt
```

When the reader finds such an expression, it evaluates the test. If the value is true, then the reader behaves as if it had read the first expression, otherwise it behaves as if it had read the second expression (or nothing if there is no else). This is useful for implementing variants (such as debugging versions). For instance

```
#if debug printf("the value of x is ~S",x)
```

Note that the expression can be a block (within parentheses) which is necessary to place a definition (like a rule definition) inside a #if. Last, there exists another pre-processing directive for loading a file within a file: #include(s) loads the file as if it was included in the file in which the #include is read.

There are a few differences between CLAIRE and C++ or Java parsing that need to be underlined:

- Spaces are important since they act as a delimiter. In particular, a space cannot be inserted between a selector and its arguments in a call. Here is a simple example:

```
foo (1,2,3) // this is not correct, one must write foo(1,2,3)
```

- = is for equality and := for assignment. This is standard in pseudo-code notations because it is less ambiguous.
- characters such as +, *, -, etc. do not have a special status. This allows the user to use them in a variable name (such as x+y). However, this is not advisable since it is ambiguous for many readers. A consequence is that spaces are needed around operations within arithmetic examples such as:

```
x + (y * z)  // instead of x+y*z which is taken as (one) variable name
```

- The character '/' plays a special role for namespace (module) membership.

6.3 Modules

Organizing software into modules is a key aspect of software engineering: modules separate different features as well as different levels of abstraction for a given task. To avoid messy designs and to encourage modular programming, programs can be structured into modules, which all have their own identifiers and may hide them to other modules. A *module* is thus a namespace that can be visible or hidden for other modules. CLAIRE supports multiple namespaces, organized into a hierarchy similar to the UNIX file system. The root of the hierarchy is the module claire, which is implicit. A module is defined as a usual CLAIRE object with two important slots: *part_of* which contains the name of the father module, and a slot *uses* which gives the list of all modules that can be used inside the new module. For instance,

```
interface :: module(part_of = library, uses = list(claire))
```

defines *interface* as a new sub-module to the *library* module that uses the module claire (which implies using all the modules). All module names belong to the claire namespace (they are shared) for the sake of simplicity.

Definition: This is a CLAIRE definition

*A **module** is a CLAIRE object that represents a namespace. A **namespace** is a set of identifiers : each identifier (a symbol representing the name of an object) belongs to one unique namespace, but is visible in many namespaces. Namespaces allow the use of the same name for two different objects in two different modules. Modules are organized into a visibility hierarchy so that each symbol defined in a module m is visible in modules that are children of m .*

Identifiers always belong to the namespace in which they are created (*claire* by default). The instruction *current_module()* returns the module currently opened. To change to a new module, one may use *begin(module)* and *end(module)*. The instruction *begin(m)* makes m the current module. Each newly created identifier (symbol) will belong to the module m, until *end(m)* resumes to the original module. For instance, we may define

```
begin(interface)
window <: object(...)
end(interface)
```

This creates the identifier *interface/window*. Each identifier needs to be preceded by its module, unless it belongs to the current module or one of its descendent, or unless it is private (cf. visibility rules). We call the short form "window" the unqualified identifier and the long one "interface/window" the qualified identifier.

The visibility rules among name spaces are as follows:

- unqualified identifiers are visible if and only if they belong to a descendent of the current module,
- all qualified identifiers that are *private* are not visible,
- other qualified identifiers are visible everywhere, but the compiler will complain if their module of origin does not belong to the list of allowed modules of the current modules.

Any identifier can be made private when it is defined by prefixing it with *private/*. For instance, we could have written

```
begin(interface)
claire/window <: object(...)
private/temporary <: window(...)
end(interface)
```

The declaration *private/temporary* makes "temporary" a private identifier that cannot be accessed outside the module interface (or one of its descendents). The declaration claire/window makes window an identifier from the *claire* module (thus it is visible everywhere), which is allowed since *claire* belongs to the list of usable modules for interface.

In practice, there is almost always a set of files that we want to associate with a module, which means that we want to load into the module's namespace. CLAIRE allows an explicit representation of this through the slots *made_of* and *source*. *made_of*(m) is the list of files (described as strings) that we want to associate with the module and *source*(m) is the common directory (also described as a string). The benefits are the *load*/*sload* methods that provide automatic loading of the module's files into the right namespace and the module compiling features (cf. Appendix C). CLAIRE expects the set of file names to be different from module names, otherwise a confusion may occur at compile time.

A last important slot of a module is *uses*, a list of other modules that the new module is allowed to use. This list has two purposes, that only exist at compile time. The first one is to restrict the importation of symbols from other modules. A module is considered a legal import if it included itself in this *uses* list, or, recursively, if its father module is legal or if the module is legal for one of the modules in this list. An attempt to read a symbol m/s from a module that is not a legal import will provoke a compiler error. Second, this list is used by the compiler to find out which binaries should be included in the link script that is produced by the compiler.

The usual value is list(Reader), which is the module that contains the CLAIRE run-time environment and that supports the interpreter. It is possible to use list(Core) if the module does not require the interpreter to run, which implies, among other things, that the module contains the main@list method (cf. Appendix C).

6.4 Global Variables and Constants

CLAIRE offers the possibility to define global variables; they are named objects from the following class⊡

```
global_variable <: thing(range:type,value:any)
```

For instance, one can create the following

```
tata :: global_variable(range = integer, value = 12)
```

However, there is a shorthand notation:

```
tata:integer :: 12
```

Notice that, contrary to languages such as C++, you always must provide an initialization value when you define a global variable (it may be the unknown value). Variables can be used anywhere, following the visibility rules of their identifiers. Their value can be changed directly with the same syntax as local variables.

```
tata := 12, tata :+ 1, tata :- 10
```

The value that is assigned to a global variable must always belong to its range, with the exception of the unknown value, which is allowed. If a variable is re-defined, the new value replaces the old one, with the exception still of unknown, which does not replace the previous value. This is useful for defining flags, which are global_variables that are set from the outside (e.g., by the compiler). One could write, for instance,

```
talk:boolean :: unknown
(#if talk printf( ....
```

The value of talk may be set to false before running the program to avoid loading the *printf* statements. When the value does not change, it is simpler to just assign a value to an identifier. For instance,

```
toto :: 13
```

binds the value 13 to the identifier *toto*. This is useful to define aliases, especially when we use imported objects from other modules. For instance, if we use *Logic*/*Algebra*/*exp*, we may want to define a simpler alias with:

```
exp :: Logic/Algebra/exp
```

The value assigned to a global variable may be made part of a world definition and thus restored by backtracking using *choice*/*backtrack*. It is simply required to declare the variable as a backtrackable variable using the *store* declaration as for a relation :

```
store(tata)
(tata := 1, choice(), tata := 2, backtrack(), assert(tata = 1))
```

6.5 Conclusion

This concludes the first part of this document. You should now be able to write your first CLAIRE programs and use most original features. There is a lot to be learned from experience, so you should take advantage of the numerous public libraries that are available on the WEB. The rest of the document contains three subparts that you will find useful once you start programming with CLAIRE:

- A precise description of CLAIRE's syntax
- A description of the API methods, which are the public method in CLAIRE provided by the system.
- A user guide, which describes the features of the programming environment and give you more detailed explanation about the compiler and its options.

APPENDIX A: CLAIRE DESCRIPTION

In the following summary of the grammar, we have used the following conventions:

<a>^{seq} denotes a (possibly empty) list of <a> separated by commas
<a>$^{seq+}$ denotes a non empty list of <a> separated by commas
<a>^{opt} denotes <a> or nothing

keywords of CLAIRE are printed boldface. [and] are simply used for grouping. | is used for choices and \| is used for the CLAIRE character 'l'

A1. Lexical Conventions

a. Identifiers in the CLAIRE Language

A name expression in the CLAIRE language is called an *identifier*. It is used to designate a named object or a variable inside a CLAIRE expression. Each identifier belongs to a namespace. When it is not specified, the namespace is determined by the current reading environment, the identifier is unqualified. A qualified identifier contains its namespace as a qualification, designed by another identifier (the name of the namespace), followed by a slash '/', itself followed by the unqualified form of the identifier.

An unqualified identifier in CLAIRE is a non-empty sequence of basic characters, beginning with a non-numerical character. A basic character is any character, with the exception of '[', ']', '{', '}', '(', ')', ' ' (space), EOL (end of line), '**;**', '**"**', '**'**', '/', '**@**' and '**:**' that play a special role in the grammar. The first six are used to define expressions. Spaces and EOL are meaningless, but are not allowed inside identifiers (therefore they are separators characters). The characters '**;**', "'", '**"**', '**@**', '/' and '**:**' are reserved to the CLAIRE system. An identifier should not start with the character #. Each sequence of characters defines one unique identifier, inside a given namespace. Identifiers are used to name objects from **thing**, and unqualified identifiers are used for variables.

<ident> ≡ <unqualified identifier> | <qualified identifier>
<qualified identifier> ≡ <identifier>/<unqualified identifier>
<unqualified identifier> ≡ <'a' .. 'Z'><basic character>*
<var> ≡ <unqualified identifier>

Implementation note: in CLAIRE, the length of an unqualified identifier is limited to 50 characters.

b. Symbols

Identifiers are represented in CLAIRE with entities called symbols. Each identifier is represented by a *symbol*. A symbol is defined by a namespace (where the identifier belongs), a name (the sequence of character from the unqualified symbol) and a status. The status of a symbol is either *private* or *export* (the default status). When the status of an identifier is *private*, the reader will not recognize the qualified form from a module that is not a sub-module of that of the identifier. Therefore, the only way to read the identifier is inside its own namespace. When the status of the identifier is *export*, the qualified form gives access to the designated object, if the sharing declarations of namespaces have been properly set (Section 6.1).

Each symbol may be bound to the object that it designates. The object becomes the *value* of the symbol. The name of the object must be the symbol itself. In addition, the symbol collects another piece of useful information: the module where its value (the named object) is defined. If the symbol is defined locally (through a *private* or *export* definition), this *definition* module is the same as the owner of the symbol itself. If the symbol is shared (if it was defined as an identifier of an above module), this module is a subpart of the owner of the symbol.

CLAIRE now supports a simple syntax for creating symbols directly, in addition to the various methods provided in the API. Symbols can be entered in the same way that they are printed, by indicating the module (namespace) to which the symbol belongs and the associated string, separated by a «/».

<CLAIRE symbol> ≡ <module>/<string>

c. Characters and Strings

Characters are CLAIRE objects, which can be expressed with the following syntax:

<CLAIRE character> ≡ ' <character> '

Implementation note: A character is an ASCII representation of an 8bits integer. The ASCII value for the character 'x' may be obtained directly with #/x. The end-of-file character (ascii value -1) is stored in the global variable EOF.

Strings are objects defined as a sequence of characters. A string expression is a sequence of characters beginning and ending with '"'. Any character may appear inside the string, but the character '"'. Should this character be needed inside a string, it must be preceded by the '\' character.

< string> ≡ " □<character> - '"' □* "

The empty string, for instance, is expressed by: "". Note that the "line break" character can be either a line break (*new line*) or the special representation '\n'.

d. Integer and Floats

Numbers in CLAIRE can either be integers or floating numbers. Only the decimal representation of integers and floats is allowed. The syntax for integer is straightforward:

<integer> ≡ □□ □^{opt} <positive integer>
<positive integer> ≡ <'0' .. '9'>$^{+}$

If the integer value is too large, an overflow error is produced. The syntax for floating numbers is also very classical:

<float> ≡ <integer>.<positive integer> |
<integer>□<positive integer>□^{opt} e □+ | □ □^{opt} <positive integer>

Implementation note: in CLAIRE 3.2, integers are coded on 30 bits and floats on 64 bits.

e. Booleans and External Functions

The two boolean values of CLAIRE are **false** and **true**:

<boolean> ≡ false | true

External functions may be represented inside the CLAIRE system. An external function is defined with the following syntax:

<external_function> ≡ function!(<unqualified identifier>
□, NEW_ALLOC | UPDATE_SLOT | UPDATE_BAG □^{opt})

The identifier must be the name of a function defined elsewhere. Therefore, it is an unqualified identifier.

Implementation note: in most implementations of CLAIRE, external functions can only be used for a function call when the CLAIRE program has been compiled and linked to the definition of the external function.

f. Spaces, Lines and Comments

Spaces and end_of_lines are not meaningful in CLAIRE. However they play a role of separator:

<separator> ≡ | | [|] | { | } | (|) | : | " | ' | ; |
@ | SPACE | EOL | /

Comments may be placed after a '//' on any line of text. Whatever is between a '//' or a ';' and a EOL character is considered as a comment and ignored. Also, the C syntax for block (multiple lines) is supported:

<comment> ≡ //'<character - EOL>* EOL |
;'<character - EOL>* EOL |
/* □<character> | *<character - />□* □□□ */

Comments that use ';' are provided for upward compatibility reasons. However, CLAIRE comments defined with //, as in C++, have a special status since they are passed into the code generated by the compiler (for those comments that are defined between blocks). Thus, it may be useful to use «□ld-fashioned□» comments when this behavior is not desirable.

Named objects (also called things) are also designated entities, since they can be designated by their names. The following convention is used in this syntax description for any class C:

<*C*> ≡ <x:identifier, where x is the name of a member of class *C*>

This convention will be used for <class>, <property> and <table>.

The set of designated entities is, therefore, defined by:

<designated entity> ≡ <thing> | <integer> | <float> |
<boolean> | <external function> |
<CLAIRE character> | <string>

A2. Grammar

Here is a summary of the grammar. A program (or the transcript of an interpreted session) is a list of blocks. Blocks are made of definitions delimited by square brackets and of expressions, either called <exp>, when they need not to be surrounded by parentheses or <fragment> when they do.

<program> ≡ <block>$^{seq+}$

<block> ≡ (<fragment>) | <definition> | <declaration call>

<fragment> ≡ □<statement | <conditional> □^{seq}

<statement> ≡ **for** <var def> **in** <exp> <statement> |
while <exp> <statement> |
until <exp> <statement> |
let □<var def> **:=** <comp-exp> □$^{seq+}$ **in** <statement> |
when <var def> **:=** <comp-exp> **in** <statement> |
case <exp> (□<type> <statement> □$^{seq+}$) |
try <statement> **catch** <type> <statement> |
branch(<statement>) |
<comp-exp> | <update>

<definition> ≡ <ident> **::** <exp> |
<var def> **::** <exp> |
<ident>(□<var>**:**<type with var> □^{seq}) **:** <range>
□**->** | => □ <body> |
<ident>[<var def>] **:** <type> **:=** <fragment> |
<ident>□[<var>$^{seq+}$]□^{opt} **<:** <class>
□(□<property> **:** <type> □**=** <exp> □^{opt} □$^{seq+}$) □^{opt} |

<ident>(<var def> [, <var def>]^opt) :: **rule**(
<rulecondition> [**=>** <fragment>]^opt)

<conditional> ≡ **if** <exp> <statement> [**else** <conditional> | <statement>]^opt

<body> ≡ <exp> | **let** [<var def> **:=** <comp-exp>]^seq+ **in** (<exp>)

<update> ≡ [<var> | <property>(<exp>) | <table>**[**<exp>^seq+**]**]
:<operation> <comp-exp>

The basic building block for a CLAIRE instruction is an expression. The grammar considers different kinds of expressions:

<comp-exp> ≡ <exp> | <exp> **as** <type> | <comp-exp> <operation> <comp-exp>

<exp> ≡ <ident> | <set exp> | <fragment> |
<call> | <slot> | **break**(<exp>) |
<table>**[** <exp>**]** | <class>([<property> **=** <exp>]^seq) |
lambda**[** [<var>**:**<type with var>]^seq, <exp>**]**

<set exp> ≡ **set**<memtype>^opt(<comp-exp>^seq+) |
list<memtype>^opt (<comp-exp>^seq+) |
{ <const>^seq+ } | <type> |
list<memtype>^opt { <var> **in** <exp> [**|** <statement>] } |
[**set**<memtype>]^opt { <var> **in** <exp> [**|** <statement>] } |
list<memtype>^opt { <exp> [**|** <var> **in** <exp>] } |
[**set**<memtype>]^opt { <exp> [**|** <var> **in** <exp>] } |
forall(<var> **in** <exp> [**|** <statement>]) |
some(<var> **in** <exp> [**|** <statement>]) |
exists(<var> **in** <exp> [**|** <statement>])

<memtype> ≡ '<'<type>'>'

<call> ≡ <function> [**@** <type>]^opt(<comp-exp>^seq)

<slot> ≡ <exp> . <property>

In CLAIRE, function calls are limited to 12 parameters at most. The binary operators (as, :=, | (OR), &(AND), and the <operation> objects) are grouped according the their precedence value (stored as a slot and user-modifiable). Operators with lower precedence values are applied first. Here is the default preference values for CLAIRE binary operators:

as	**:**	**0**
^	**:**	**9**
add, delete, @, %, meet, inherit?, join, <<, >>, and, or, cons, /+, /, *, mod, but	**:**	**10**
+, - , min, max	**:**	**20**
..	**:**	**30**
**U, **	**:**	**50**
=, !=, <, >, <=, >=, less?	**:**	**60**
:=	**:**	**100**
&	**:**	**1000**
|	**:**	**1010**

The typing system is the following

<var def> ≡ <var>**:**<type>

<type> ≡ <class> | <class>**[**□<var> : <type> □$^{seq+}$**]** | <class><memtype> |
set[<type>**]** | **list[**<type>**]** | **subtype[**<type>**]** | {<const>$^{seq+}$ } |
tuple(<type>$^{seq+}$) | (<comp-type>)

<comp-type> ≡ <type> **U** <type> | <type> **^** <type> | <const> **..** <const>

<const> ≡ <integer> | <float> | <named object> | <string> | <char> |

Typing also includes second-order typing which has special syntactical conventions□

<type with var> ≡ <var> | <type> | {<var>} |
tuple(<type with var>$^{seq+}$) |
<class>**[** □<var>:<type with var> | <var> = □<var>|<const>□□$^{seq+}$**]**

<range> ≡ <type> | **type[**<exp>**]**

The condition language used for rules (to describe the event and the boolean condition to which a rule is attached) is defined as follows.

<rule condition> ≡ <event pattern> □**&** <exp>□^{opt}
<event patter> ≡ <rel-exp> := <var> |
<rel-exp> := (<var> -> <var>) |
<property>(<var>,<var>)

<rel-exp> ≡ <var>.<property> | <table>[<var>]

APPENDIX B: CLAIRE'S API

This section contains the list of all methods and (visible) slots in CLAIRE. For each method we give the signature of the restrictions, the modules where they are defined and a brief description of their use. Methods that have a unified semantic and multiple implementations (e.g., self_print) may be abstracted into a single method.

This section also distinguishes methods that belong to "Diet Claire". The suffix **DIET_** is added to the module information. This is important since only diet methods can be used in programs that will be compiled with "light" compilers (cf. Appendix C – 3.7).

^ **Kernel -** DIET_ **method**

x:integer ^ y:integer → integer
x:float ^ y:float → float
x:list ^ y:integer → list
x:set ^ y:set → set

(x ^ y) returns x^y when x and y are numbers. If x is an integer, then y must be a positive integer, otherwise an error is raised.

(l ^ y) skips the y first members of the list l. If the integer y is bigger than the length of the list l, the result is the empty list, otherwise it is the sublist starting at the y+1 position in l (up to the end).

(s_1 ^ s_2) returns the *intersection* of the two sets s_1 and s_2 that is the set of entities that belong to both s_1 and s_2.

Other internal restrictions of the property ^ exist, where ^ denotes the intersection (it is used for the type lattice)

^2 **Core** **method**

^2(x:integer) → integer

^2(x) returns 2^x

% **Kernel** **method**

x:any % y:class → boolean
x:any % y:collection → boolean

(x % y) returns (x ∈ y) for any entity x and any abstract set y. An abstract set is an object that represents a set, which is a type or a list. Note that membership to a static type is actually "diet".

***** **Kernel -** DIET_ **method**

x:integer * y:integer → integer
x:float * y:float → float

(x * y) returns x × y when x and y are numbers. If x is an integer, then y must also be an integer, otherwise an error is raised (explicit conversion is supported with float!).

The operation * defines a commutative monoid, with associated divisibility operator divide? and associated division /.

/ **Kernel -** DIET_ **method**

x:integer / y:integer → integer
x:float / y:float → float

(x / y) returns x / y when x and y are numbers. If x is an integer, then y must also be an integer, otherwise an error is raised (explicit conversion is supported with float!).

+ **Kernel -** DIET_ **method**

x:integer + y:integer → integer
x:float + y:float → float

(x + y) returns x + y when x and y are numbers. If x is an integer, then y must be an integer, otherwise an error is raised (explicit conversion is supported with float!).

The operation + defines a group structure, with associated inverse -.

- **Kernel -** DIET_ **method**

x:integer - y:integer → integer
x:float - y:float → float
-(x:integer) → integer
-(x:float) → float

(x - y) returns x + y when x and y are numbers. -(x) returns the opposite of x.

/+ **Kernel -** DIET_ **method**

x:list /+ y:list → list
x:string /+ y:string → string
x:symbol /+ y:(string U symbol) → symbol

(x /+ y) returns the *concatenation* of x and y (represents the *append* operation). Concatenation is an associative operation that applies to strings, lists and symbols. It is not represented with + because it is not commutative. When two symbols are concatenated, the resulting symbol belongs to the namespace (module) of the first symbol, thus the second symbol is simply used as a string. By extension, a symbol can be concatenated directly with a string.

.. , - - **Kernel** **method**

.. x:integer .. y:integer → Type
-- x:integer .. y:integer → Interval

(x .. y) returns the interval {z | x ≤ z ≤ y}. Intervals are only supported for integers, in CLAIRE v3.0. Notice that (3 .. 1) returns the empty set, which is a type. The new method (x – y) is an explicit interval constructor (it produces an error if the first argument is larger than the second).The result is an object from the class *Interval*, which is a type.

=, != **Kernel -** DIET_ **method**

x:any = y:any → boolean
x:any != y:any → boolean

(x = y) returns true if x is equal to y and nil otherwise. Equality is defined in Section 2: equality is defined as identity for all entities except strings, lists and sets. For lists, sets and strings, equality is defined recursively as follows: x and y are equal if they are of same size *n* and if x[i] is equal to y[i] for all *i* in (1 .. *n*).

(x != y) is simply the negation of (x = y).

=type? **Core** **method**

=type?(x:any, y:any) → boolean

returns true if x and y denote the same type. For example =type?(boolean, {true, false}) returns true because final(boolean) was declared after the two instances true and false were created, so the system knows that no other instances of boolean may ever be created in the future. This equality is stronger than set equality in the sense that the system answers true if it knows that the set equality will hold ever after.

<=, >=, <, > **Kernel -** DIET_ **method**

x:integer <= y:integer → boolean
x:float <= y:float → boolean
x:char <= y:char → boolean
x:string <= y:string → boolean
x:type <= y:type → boolean
x:X < y:X → boolean for X = integer, float, char and string
x:X > y:X → boolean for X = integer, float, char and string
x:X >= y:X → boolean for X = integer, float, char and string

The basic order property is <=. It is defined on integers and floats with the obvious meaning. On characters, it is the ASCII order, and on strings it is the lexicographic order induced by the ASCII order on characters. The order on types is the inclusion: ((x <= y) if all members of type x are necessarily members of type y).

(x < y), (x > y) and (x >= y) are only defined for numbers, char and strings with the usual meaning.

<< , >> **Kernel -** DIET_ **method**

l:list << n:integer → list

x:integer << n:integer → integer

x:integer >> n:integer → integer

(l << n) left-shifts the list l by n units, which means that the n first members of the list are removed. This is a method with a side-effect since the returned value is the original list, which has been modified. (x <<n) and (x >> n) are the result of shifting the integer x seen as a bitvector respectively to the left and to the right by n positions.

@ — Core — method

p:property @ t:type → entity
p:property @ l:list[type] → entity
t:type @ p:parameter → type

(p @ t) returns the restriction of p that applies to arguments of type t. When no restrictions applies, the value nil is returned. If more than one restriction applies, the value unknown is returned. Notice that the form p@t (without blank spaces) is used to print the restriction and also in the control structure `<property>@<class>(...)`.

(p @ list(t1,..tn)) is similar and returns the restriction of p that applies to arguments in t1 ×… × tn.

(t @ p) returns the type that is inferred for x.p when x is an object of type t and p a parameter (read-only property).

abstract — Core — method

abstract(c:class) → void

abstract(p:property) → void

abstract(c) forbids the class c to have any instance. abstract(p) defines p as an extensible property. This is used by the compiler to preserve the ability to add new restrictions to p in the future that would change its semantics on existing classes. By default, a property is extensible until it is compiled. A corollary is that function calls that use extensible properties are compiled using late binding.

active? — Compile — slot

compiler.active? → boolean

This boolean is set to true when the compiler is active (i.e., compiling CLAIRE code into C++ code). This is useful to introduce variants between the compiled and interpreted code (such as different sizes). Note that there is another flag, loading?, to see if a file is loaded by the compiler.

add — Kernel - DIET_ — method

add(s:set,x:any) → set
add(l:list,x:any) → list
add(p:relation,x:object,y:any) → any

add(s,x) adds x to the set s. The returned value is the set s ∪ {x}. This method may modify the set s but not necessarily. When x is a list, add(l,x) inserts x at the end of l. The returned value is also the list obtained by appending (x) to l, and l may be modified as a result but not necessarily. The pseudo-destructive behavior of *add* is similar to that of *add**, which is described below.

add(p,x,y) is equivalent to *p(x) :add y* (This form is interesting when one wants to write such an expression for a variable p)

add* — Kernel - DIET_ — method

add*(l1:list, l2:list) → list

add(l1,l2)* returns the concatenated list l1 . l2, but it is destructive: it uses l1 as the data structure on which to perform the concatenation. Hence, the original l1 is no longer available after the method add* has been called.

and — Kernel - DIET_ — method

and(x□nteger,y□nteger) → integer

and(x,y) returns the bitwise intersection of two integers (seen as bitvectors).

apply — Core — method

apply(p:property, l:list) → any

apply(f:external_function, ls:list[class], lx:list) → any

apply(la:lambda, lx:list) → any

apply(m:method, lx:list) → any

apply(p,l) is equivalent to a function call where the selector is p and the argument list is l. For instance, apply(+,list(1,2)) = (1 + 2) = call(+,1,2).

apply(f,ls,l) applies the function f to the argument list l, where ls is the list of sort of the arguments and the result (i.e. length(ls) = length(l) + 1). For instance, if f is the external function that defines + @ integer, apply(f,list(integer,integer,integer),list(1,2)) = 1 + 2.

apply(la,lx) applies the lambda expression to the argument list. *apply(m,lx)* applies the method to the argument list.

array! — Kernel - DIET_ — method

array!(x:list,t:type) → type[t[]]

creates a copy of the list x that is represented as an array. The member type must be given as a parameter t and an error will occur if a member of the list does not belong to t..

arg1 / arg2 — Kernel — method

arg1(x:Interval) → any
arg2(x:Interval) → any

These slots contain respectively the minimal and maximal element of a CLAIRE interval..

begin — Kernel — method

begin(m:module) → void

sets the current namespace to m (a module).

but — Core — method

but(s:any,x:any) → any

Returns the set of members of s that are different from x.

car, cdr — Kernel - DIET_ — method

car(l:list) → type[member(l)]
cdr(l:list) → type[l]

These two classical LISP methods return the head of the list , e.g. l[1] (for car) and its tail, e.g. the list l starting at its second element (for cdr).

call — Kernel — method

call(p:property, l:listargs) → any

call(x:lambda, l:listargs) → any

call(X,x_1,x_2 ,...,x_n) is equivalent to apply(X,list(x_1,x_2 ,...,x_n)).

cast! — Kernel — method

cast!(s:bag,t:type) → bag

cast(s,t) sets the member type of the bag s to t

char! — Kernel - DIET_ — method

char!(n:integer) → char

char!(n) returns the character which ASCII code is n.

class! — Core — method

class!(x:any) → class

class!(x) returns the intersection of all classes y such that x <= y (Such an intersection always exists since classes are organized in a lattice). Hence, if c is a class class!(c)=c.

close — Core — method

close(m:module) → module
close(c:class) → class

close(e:exception) → any
close(v:global_variable) → global_variable

The method close is called each time an object is created. It is executed and returns the created object. It can sometimes be very helpful to define new restrictions, they will be automatically called when an instance is created. Exceptions are a special case: raising an exception is done internally by creating an instance of exception. The method close is responsible for looking for the innermost handler, etc.

cons — Kernel - DIET_ — method

cons(x:any, l:list) → list

This traditional method appends x at the beginning of l and returns the constructed list.

contradiction!() — Kernel - DIET_ — method

contradiction!() → void

This method creates a contradiction, which is an instance of the class *contradiction*. It is equivalent to *contradiction*() but is more efficient and should be preferred.

copy — Kernel - DIET_ — method

copy(x:object) → object
copy(s:bag) → bag
copy(a:array) → array
copy(s:string) → string

copy(x) returns a duplicate of the object x. It is not recursive : the slots of the copied object are shared with that of the original one. Similarly, the copy of a bag (a set or a list) returns a fresh set or list with the same elements and the copy of a string is ... a copy of the string.

current_module — Kernel — method

current_module() → module

current_module() returns the module which is currently open.

date! — Kernel — method

date!(i:integer) → string

date!(i) returns the date, using the integer parameter i to indicate whether the full date is needed or only the day or the time. For instance

```
date!(0) = "Thu Mar  9 08:04:22 2000"
date!(1) = "Thu Mar  9 2000"
date!(2) = "08:04:22"
```

delete — Kernel - DIET_ — method

delete(p:relation, x:object, y:any) → any
delete(s:bag, x:any) → bag

delete(s,x) returns s if x is not in s and the list (resp. set) s without the first (resp. only) occurrence of x otherwise. *delete(p,x,y)* is equivalent to *p(x) :delete y*. This is a destructive method in the sense that it modifies its input argument. The proper way to use delete, therefore, is either destructive (*l :delete x*) or non-destructive (*delete(copy(l),x)*).

descendents — Core — slot

descendents(x:class) → set[class]

For a class c, c.*descendents* is the set all classes that are under c in the hierarchy (transitive closure of the subclass relation).

difference — Kernel — method

difference(s:set, t:set) → set

difference(s,t) returns the difference set s - t, that is the set of all elements of s which are not elements of t.

domain — Core — slot

domain(r:restriction) → list
domain(r:relation) → any

A restriction is either a slot or a method. If r is a slot, domain(r) is the class on which r is defined. If r is a method, r.*domain* is the list formed by the types of the parameters required by the method. For a relation r, r.*domain* is the type on which r is defined.

end_of_string — Kernel - DIET_ — method

end_of_string() → string

end_of_string() returns the string containing everything that has been printed since the last call to print_in_string().

erase — Kernel - DIET_ — method

erase(a:table) → any

erase(r:property,x:any) → any

erase(a) removes all value pairs contained in the table. This means that, on one hand, the value a[x] becomes unknown for each object x, and also that any references to an object from the table's domain or an associated value is lost, which may be useful to allow for complete garbage collection.

erase(p,x) removes the value associated to x with the property p. The default value, or the unknown value, is placed in the slot x.p, and the inverse if updated (if any).

exception! — Kernel — method

exception!() → exception

exception!() returns the last exception that was raised.

exit — Kernel - DIET_ — method

exit(n:integer) → void

exit(n) stops CLAIRE running and returns to the hosting system the value n. What can happen next is platform-dependent.

factor? — Kernel — method

factor?(x:integer, y:integer) → boolean

factor?(x,y) returns true if x is a multiple of y.

fcall — Core — method

fcall(f:external_function, s1:class, x:any, s:class) → any
fcall(f:external_function, s1:class, x:any, s2:class, y:any, s:class) → any
fcall(f:external_function, s1:class, x:any, s2:class, y:any,
s3:class,z□lass,s□lass) → any

fcall provide an easy interface with external (C++) functions. *fcall*(f,s1,x,s) applies an external function to an argument of sort s1. The sort of the returned value must be passed as an argument (cf. Appendix C). . *fcall*(f,s1,x,s2,y,s) is the equivalent method in the two-arguments case.

final — Core — method

final (c:class) → void

final (p:property) → void

final(c) forbids the user to create any subclass of the class c. If c is a constant class, this is taken as a "diet" compiling directive.

final(p) change the extensibility status of the property p (represented with the slot open) so that the property p becomes closed, which means that a new restriction may no longer be added if it causes an inheritance conflict.

finite? — Core — method

finite?(t:type) → boolean

finite?(t) returns true if the type t represents a finite set. Set iteration (with the for loop) can only be done over finite sets

float! — Kernel - DIET_ — method

float!(x:integer) → float

float!(x:string) → float

transforms an integer or a string into a float.

flush — Kernel - DIET_ — method

flush(p:port) → void

Communications with ports are buffered, so it can happen that some messages wait in a queue for others to come, before being actually sent to their destination port. *flush(p)* for input and output ports and empties the buffer associated with p, by physically sending the print messages to their destination.

fopen, fclose — Kernel - DIET_ — method

fopen(s1:string,s2:string) → port
fclose(p:port) → any

fopen returns a port that is handle on the file or external device associated with it. The first string argument is the name of the file, the second is a combination of several control characters, among which 'r' allows reading the file, 'w' (over)writing the file and 'a' appending what will be write at the end of the file. Other possibilities may be offered, depending on the underlying possibilities. Such other possibilities are platform-dependent.

format — Kernel - DIET_ — method

format(string,list) → any

This method does the same thing as printf, except that there are always two arguments, thus the arguments must be replaced by an explicit list.

formula — Core — slot

formula(m:method) → lambda **Core**
formula(d:demon) → lambda **Core**

formula gives the formula associated with the method/demon.

funcall — Core — slot

funcall(m:method, x:any) → any

funcall(m:method, x:any, y:any) → any

funcall(m:method, x:any, y:any, z:any) → any

funcall provide an easy interface with external (C++) functions. *funcall*(f,s1,x,s) applies an external function to an argument of sort s1. The sort of the returned value must be passed as an argument (cf. Appendix C). *funcall*(f,s1,x,s2,y,s) is the equivalent method in the two-arguments case, and *funcall*(f,s1,x,s2,y,s3,y, s) is the equivalent method in the three-arguments case. Notice that the LAST argument is the sort of the result, and that giving an erroneous sort argument will likely produce a fatal error.

funcall also applies a method or a lambda to one or two arguments.

gc — Kernel — method

gc() → any

gc() forces a garbage collection to take place

gensym — Kernel - DIET_ — method

gensym() → symbol
gensym(s:string) → symbol

gensym() generates randomly a new symbol. *gensym(s)* generates randomly a new symbol that begin with s.

get — Kernel - DIET_ — method

get(p:property + slot, x:object) → any **Core**
get(a:table, x:any) → integer **Core**
get(s:string, c:char) → integer **Core**
get(l:list, x:any) → integer **Core**
get(m:module) → integer **Core**

get(p,x) is equivalent to *p(x)*, but without any verification on *unknown*. So does *get(a,x)* for a table.*get(s,x)* returns i such that s[i]=x (if no such i exists, 0 is returned). So does *get(l,x)* for a list. *get(m)* is equivalent for a module m to *(load(m), open(m))*

get_module — Core, Optimize — method

get_module(s:symbol) → module **Core**
get_module(x:thing) → module **Optimize**

get_module returns the module where the identifier s was created.

get_value — Kernel — method

get_value(s:string) → any

get_value(m:module, s:string) → any

returns the object whose name corresponds to the string; if a module argument is passed, the associated symbol is sought in the module's namespace, otherwise the module claire is used by default. To find the value associated to a string within the current module, simply use get_value(module!(),s).

getc — Kernel - DIET_ — method

getc(p:port) → char

getc(p) returns the next character read on port p.

getenv — Kernel — method

getenv(s:string) → string

getenv(s) returns the value of the environment variable s if it exists (an error occurs otherwise since an attempt is made to create a string from the NULL value that is returned by the environment).

hash — Kernel - DIET_ — method

hash(l:list,x:any) → integer

hash(l,x) returns an integer between 1 and length(l) that is obtained through generic hashing. To obtain the best dispersion, one may use a list of size 2^i-3. This function can be used to implement hash tables in CLAIRE; it is the basis of the table implementation.

Id — Kernel — method

Id(x:any) → type[x]

Id(x) returns x. Id has a special behavior when compiled which makes it useful. The argument is evaluated before being compiled. The intended use is with global variables: the compiler uses the actual value of the variable instead of a reference to the global variable. This is very convenient to introduce parameters that are defined outside the module that is being compiled.

This is also used to tell the compiler that an iteration should make explicit use of all iterations rules that may apply to some subclasses of the set expression that is being iterated.

inherit? — Core — method

inherit?(c1:class, c2:class) → boolean

inherit?(c1,c2) returns (c2 % ancestors(c1))

instances **Kernel** **slot**

instances(c:class) → type[set[c]]

returns the set of all instances of c, created up to now (if c has not been declared ephemeral).

integer! **Kernel -** DIET_ **method**

integer!(s:string) → integer
integer!(f:float) → integer
integer!(c:char) → integer
integer!(l:set[(0 .. 29)]) → integer
integer!(s:symbol) → integer

integer!(s) returns the integer denoted by the string s if s is a string formed by a sign and a succession of digits, *integer!(f)* returns the lower integer approximation of f, *integer!(c)* returns the ASCII code of c and *integer!(l)* returns the integer represented by the bitvector l, i.e. the sum of all 2^i for i in l. Last, *integer(s)* returns a unique index associated to a symbol s.

interface **Kernel -** DIET_ **method**

interface(p:property) → void

interface(c:class, p1:property, p2: property, …) → void

interface(c:Union, p1:property, p2: property, …) → void

This new method (in CLAIRE 3.1) is used to associate the interface status to a property or a set of properties. Within a class (through the use of intertface(c,p1,…)), this means that a member method will be generated for the C++ class associated to c. Note that this definition requires the presence of a method pi @ C for each property pi. In a stand-alone fashion (using interface(p)), it means that p is meant to be a uniform property for which dynamic calls should be optimized. In CLAIRE 3.1, a union (c1 U c2 … U c_n) can be used instead of a class, which is an elegant way to factor the interface declaration for c1, … c_n.

inverse **Kernel -** DIET_ **slot**

inverse(r:relation) → relation

r.*inverse* contains the inverse relation of r. If the range of r inherits from bag then r is considered multi-valued by default (cf. Section 4.5). If r and its inverse are mono-valued then if r(x) = y then inverse(r)(y) = x. If they are multi-valued, then inverse(r)(y) returns the set (resp. list) of all x such that (y % r(x)).

invert **Core** **method**

invert(r:relation,x:any) → any

invert(r,x) return $r^{-1}(x)$ assuming that r has an inverse.

isa **Core** **slot**

isa(x:object) → class

returns the class of which x is an instance.

kill, kill! **Kernel** **method**

kill(x:object) → any **Kernel**
kill(x:class) → any **Kernel**
kill!(x:any) → any **Kernel**

kill is used to remove an object from the database of the language. *kill* does it properly, removing the object from all the relation network but without deallocating. *kill!* is more brutal and deallocates without any checking.

known? **Kernel** **method**

known?(p:relation, x:object) → boolean
known?(x:any) → boolean

known?(p,x) is equivalent to *get(p,x) != unknown* . The general method known? simply returns true whenever the object exists in the database.

last **Kernel -** DIET_ **method**

last(l:list) → type[member(l)]

last(l) returns *l[length(l)]*

length — Kernel - DIET_ — method

length(l:bag) → integer
length(a:array) → integer
length(l:string) → integer

returns the length of an array, a bag or a string. The length of a list is not its *size* ! The following is true: length(set!(l)) = size(l) = size(set!(l)).

list! — Kernel - DIET_ — method

list!(a:array) → type[member_type(a)[]]
list!(s:set) → type[list[member(s)]]

For any array or set x, *list!(s)* transforms x into a list. If x is a set, the order of the elements in the list can be anything.

load, sload, oload, eload — Reader — method

load(s:string) → any
sload(s:string) → any
oload(s:string) → any
eload(s:string) → any
load(m:module) → any
sload(m:module) → any
oload(m:module) → any

These methods load a file (or the files associated to a module). The difference between them is that *load(s)* reads and evaluates all the instructions found in the file named s, whereas *sload(s)* reads, prints, evaluates and prints the results of the evaluation of all the instructions found in the file named s. *oload(s)* is similar to *load(s)* but also optimizes the methods that are newly defined by substituting an optimized version of the lambda abstraction. *eload(s)* is similar to *load(s)* but assumes that the file only contains expressions (such as f(1,2)). This is convenient for loading data input files using a functional format.

loading? — Compile — slot

compiler.loading? → boolean

This boolean is set to true when the compiler is loading a file before compiling it. This is useful to introduce variants between the compiled and interpreted code (see also the *active*? flag)

log — Kernel - DIET_ — method

log(x:float) → float

computes log(x) – base *e*.

made_of — Kernel — slot

made_of(m:module) → list[string]

m.*made_of* contains the list of files that contain the code of the module.

make_array — Kernel - DIET_ — method

make_array(n:integer,t:type,x:any) → type[x[]]

returns an array of length n filled with x. The parameter t is the member_type of the array, thus x must belong to t, as well as any future value that will be put in the array. Note that x is shared for all members of the array, which cause a problem if updates can be performed (for instance if x is iyts

make_list — Kernel - DIET_ — method

make_list(n:integer,x:any) → type[list[x]]

returns a list of length n filled with x (e.g., make_list(3,0) = list<any>(0,0,0)). This is a typed list with member type any, thus it can be updated.

make_string — Kernel - DIET_ — method

make_string(i:integer, c:char) → string
make_string(s:symbol) → string
make_string(l:list) → string

make_string(i,c) returns a string of length i filled with the character c.

make_string(s) returns a string denoting the same identifier. If s is given in the qualified form (module/identifer), than the result will contain the name of the module ("module/identifier").

make_string(l) creates a string from the list of its characters.

mem — Kernel — method

mem() → list[integer]
mem(c:class) → integer

mem returns a list of 4 integers (a,b,c,d) where

a is the number of cells used by chunks (objects and lists of size > 5)
b is the number of cells used by small objects and lists
c is the number of cells used by imported objects
d is the number of cells used by symbols.

The method *stat()* pretty prints this information. *mem(c)* returns the number of cells used for one class (and its instances).

member — Core — method

member(x:type) → type

member(x) returns the type of all instances of type x, assuming that x is a CLAIRE type which contains objects y such that other objects z can belong to. If this is the case, member(x) is a valid type for all such z, otherwise the returned value is the empty set. For instance, if x is list[integer], all instances of x are lists that contain integers, and all members of these lists are integers. Therefore, member(list[integer]) is integer.

member_type — Kernel — method

member_type(x:array) → type

member_type(x) returns the type of all members of the array x. Therefore, member(a) = member_type(a) for an array a.

methods — Reader — method

methods(d:class,r:class) → set[method]

methods(d,r) returns the set of methods with a range included in r and a domain which is a tuple which first component is included in d.

min / max — Core — method

min(m:method[domain:tuple(X,X), range:boolean],
l:set[X] U list[X]) → type[X]

min(x:integer,y:integer) → integer
max(x:integer,y:integer) → integer

given an order function (m(x,y) returns true if x <= y) and a bag, this function returns the minimum of the bag, according to this order. min/max on integer returns the smallest/largest of two integers.

mod — Kernel - DIET_ — method

mod(x:integer, y:integer) → integer

mod(x,y) is the rest of the Euclidean division of x by y.

module! — Core, Optimize — method

module!(r:restriction) → module

module! returns the module where the method r was created.

new — Core — method

new(c:class) → any
new(c:class, s:symbol) → thing

new is the generic instantiation method. *new(c)* creates an object of class c (It is equivalent to c()). *new(c,s)* creates an object of class c with name s.

not — Kernel - DIET_ — method

not(x:any) → boolean

not(x) returns false for all x except false, the empty set and the empty list.

nth, nth=, nth+, nth- — Kernel - DIET_ — method

nth(a:table, x:any) → any — **Kernel**
nth(x:integer, i:integer) → boolean — **Kernel**
nth(l:bag, i:integer) → any — **Kernel**
nth(a:array, i:integer) → any — **Kernel**
nth(s:string, i:integer) → char — **Kernel**
nth=(a:table, x:any, y:any) → any — **Kernel**
nth=(a:array, x:any, y:any) → any — **Kernel**
nth=(l:list, i:integer, x:any) → any — **Kernel**
nth=(s:string, i:integer, x:char) → char — **Kernel**
nth+(l:list, i:integer, x:any) → bag — **Kernel**
nth-(l:list, i:integer) → bag — **Kernel**
nth_put(l:string, i:integer, x:any) → bag — **Kernel**
nth_get(l:string, i:integer) → bag — **Kernel**

nth is used for accessing elements of structured data: nth(l,i) is the i^{th} element of the bag l, nth(s,i) is the i^{th} character of the string s. For tables, nth(a,x) is equivalent to a[x], even when x is not an integer. Finally, nth also deals with the bitvector representation of integers: nth(x,i) returns true if the i^{th} digit of x in base 2 is 1.

nth= is used for changing an element at a certain place to a certain value. In all the restrictions *nth=(s,i,x)* means: change the i^{th} value of s to x.

There exists two other ways of modifying the values in such data structures: *nth+* and *nth-*. *nth+* uses the same syntax as *nth=* : *nth+(l,i,x)* returns a list (that may be l) where x has been inserted in the i^{th} position. By extension, *i* may be *length(l) + 1*, in which case *x* is inserted at the end of *l*.

nth- is used for removing an element. *nth-(s,i)* returns a value that differs from s only in that the i^{th} place has been erased.

Strings in CLAIRE can be used as buffers (arrays of characters) using the methods *nth_get* and *nth_put* that do not perform bound checking. The string does not need to be terminated by a null character and any position may be accessed. This use of strings may provoke severe errors since there are no bound checks, thus it should be used scarcely and with a lot of care.

occurrence — Language — method

occurrence(exp:any, x:variable) → integer

returns the number of times when the variable x appears in exp

open — Core — slot

open(c:class) → integer

open(r:relation) → integer

x.open is a slot that tells the extensibility level of the class or relation x..

or — Kernel - DIET_ — method

or(x:integer,y:integer) → integer

or(x,y) returns the bitwise union of two integers (seen as bitvectors).

owner — Kernel — method

owner(x:any) → class

owner(x) returns the class from which the object is an instance. It x is an object, then *owner(x) = isa(x)* = the unique class *c* such that *x % instances(c)*.

parts, part_of, — Kernel — slot

parts(m:module) → list
part_of(m:module) → module

m.part_of contains the module to which m belongs. parts is the inverse of part_of : parts(m) is the set of submodules of m (in the module hierarchy).

port! — Kernel - DIET_ — method

port!() → port
port!(s:string) → port

creates a port that is bound to a string. The first method creates an empty string port that is used for writing. The value of the string associated with the port may be retrieved with the method string!(p:port). The second method transforms an existing string into a port that can be read. This is useful to read an expression stored in a string, although the simpler method read(s:string) is most often enough for the task.

pretty_print — Language — method

pretty_print(x:any) → void

performs the pretty_printing of x. For example, you can pretty print CLAIRE code: if <inst> is a CLAIRE instruction *pretty_print*(`<inst>) will print it nicely indented (the backquote here is to prevent the instruction from begin evaluated).

princ, print — Kernel - DIET_ — method

princ(x:integer) → void
princ(x:string) → void
princ(x:char) → void
princ(x:symbol) → void
princ(x:bag) → void
print(x:any) → void

print(x) prints the entity x (x can be anything). princ(x:integer) is equivalent to print(x). If x is a string / char / symbol/ bag, print(x) prints x without the " / ' / '/ separator.

print_in_string — Kernel - DIET_ — method

print_in_string() → void

print-in-string() opens a new output port that will be stored as a string. The user is given access to the string at the end of the transcription, when the call to *end_of_string()* returns this string.

put — Kernel - DIET_ — method

put(p:property, x:object, y:any) → any
put(a:table, x:object, y:any) → any
put(s:slot, x:object, y:any) → any
put(s:symbol,x:any) → any

put(p,x,y) is equivalent to *p(x) := y* but does not trigger the rules associated to r or the inverse of r. Besides, this operation is performed without any type-checking. The method *put* is often used in conjunction with *propagate*. *put(s,x)* binds the symbol s to the object x.

put_store — Kernel - DIET_ — method

put_store(r1: relation, x:any, v:any,b:boolean) → void

put_store(r,x,v,b) is equivalent to put(r,x,v) but also stores this update in the current world if b is true. The difference with the use of the statement store(p) is that put_store allows the user to control precisely which update should be backtracked.

putc — Kernel - DIET_ — method

putc(c:char, p:port) → void

putc(c,p) sends c to the output port p.

random, random! — Kernel - DIET_ — method

random(n:integer) → integer

random!(n:integer) → void

random(n) returns an integer in (0 .. n-1), supposedly with uniform probability. *random(n)* resets the seed for the random number generation process.

range — Kernel, Language — method

range(r:restriction) → any — **Kernel**
range(r:relation) → any — **Kernel**
range(v:global_variable) → any — **Kernel**
range(v:Variable) → any — **Language**

For a relation or a restriction r, *range(r)* returns the allowed type for the values taken by r over its domain. For a variable v, *range(v)* is the allowed type for the value of v.

read — Kernel, Reader — method

read(p:property, x:object) → any — **Kernel**
read(p:port) → any — **Reader**
read(s:string) → any — **Reader**

read(p,x) is strictly equivalent to p(x): it reads the value and raises an exception if it is unknown. *read(p)* and *read(s)* both read an expression from the input port *p* or the string *s*.

read_in_string — Reader — method

read_in_string(r:meta_reader, s:string) → void

considers s as the new stream of input. **meta_reader** is the class of the object *reader*.

release — Core — method

release() → string

returns a release number of your CLAIRE system (<release>.<version>.<revision>).

restrictions — Kernel — method

restrictions(p:property) → list[restriction]

returns the list of all restrictions of the property. A property is something a priori defined for all entities. A restriction is an actual definition of this property for a given class (or type).

safe — Optimize — method

safe(x:any) → any

safe(x) is semantically equivalent to x and is ignored by the interpreter (x = safe(x)). On the other hand, this tells the compiler that the expression x must be compiled with the safe setting of the optimizing options. This is useful when a complete program requires high optimization settings for performance reasons but you still want to ensure that (say) overflow errors will be detected. A typical use would be

```
try safe( x * y) catch error MAXINT
```

to implement a bounded multiplication that can be placed in an optimized module.

self_print — Kernel - DIET_ — method

self_print(x:any) → any

this is the standard method for printing unnamed objects (objects that are not in thing). It is called by default by printf on objects.

set! — Core — method

set!(s:collection) → set
set!(x:integer) → set[(0 .. 29)]

set!(s) returns an enumeration of the collection s. The result is, by definition, a set that contains exactly the members of s. An error occur if s is not finite, which can be tested with finite?(x).

set!(x) returns a set that contains all integers i such that $(x / 2^i) \bmod 2 = 1$. This method considers x as the bitvector representation of a subset of (0 .. 29). The inverse is integer!.

shell — Kernel — method

shell(s:string) → any

Passes the command s to the operating system (the shell).

show — Reader — method

show(x:any) → any

The method *show* prints all the information it can possibly find about the object it has been called on: the value of all its slots are displayed. This method is called by the debugger.

shrink — Kernel - DIET_ — method

shrink(x:list,n:integer) → list
shrink(x:string,n:integer) → string

The method *shrink* truncates the list or the string so that its length becomes n. This is a true side-effect and the value returned is always the same as the input. As a consequence, shrink(l,0) returns an empty list that is different from the canonical empty list nil.

size — Core — method

size(l:bag) → integer
size(x:any) → integer

size(l) gives the number of elements in l. If x is an abstract set (a type, a class, ...) then size(x) denotes the number of elements of type x. If the set is infinite, an exception will be raised. Note that the size of a list is not its length because of possible duplicates.

slots — Kernel — method

slots(c:class) → any

slots(c) returns the list of all slots that c may have

sort — Core — method

sort(m:method, l:list) → type[l] **Core**

The method sort has two arguments: an order method m such that m(x,y) = true if x <= y and a list of objects to be sorted in ascending order (according to m). The method returns the sorted list. The method is usually designated using @, as in sort(< @ integer, list(1,2,8,3,4,3)).

sqrt — Kernel — method

sqrt(x:float) → float

returns the square root of x. Returns an irrelevant value when x is strictly negative.

stat — Kernel — method

stat() → void

stat() pretty prints the result given by mem(): it prints the memory situation of the CLAIRE system: the number of used cells and the number of remaining cells for each type of cell (chunk, small object, imported object, symbol). If the verbosity is more than 5, stat() produces a more detailed report about the way memory is used in CLAIRE.

store — Kernel - DIET_ — method

store(r1: relation, r2:relation ...) → void
store(v: global_variable) → void
store(a:array,n:integer,v:any,b:boolean) → void
store(l:list,n:integer,v:any,b:boolean) → void

store(r1,r2,...) declares the relations (properties or tables) as defeasible (using the world mechanism). If x is an array or a list, *store(x,n,v,b)* is equivalent to x[n]⊡= v but also stores this update in the current world if b is true. As a syntactical convenience, the argument b may be omitted if it is true. Note that there is a similar method for properties

called *put_store*. *store(v)* can be used to declare a global_variable v as defeasible (notice that only one argument is allowed).

string! — Kernel - DIET_ — method

string!(s:symbol) → string
string!(n:integer) → string
string!(x:float) → string

string! converts a symbol, an integer or a float into a string. For example *string*!(toto) returns "toto" and *string*!(12) returns "12". Unlike *make_string*, it returns the unqualified form (*string*!(Francois/agenda) = "agenda", whereas *make_string*(Francois/agenda) = "Francois/agenda").

substitution — Language — method

substitution(exp:any, v:Variable, f:any) → any

substitution(exp,v,f) returns exp where any occurrence of the free variable v is substituted by f. Hence, if *occurrences*(exp,v) = 0 then *substitution*(exp,v,f) returns exp for any f.

substring — Kernel - DIET_ — method

substring(s:string, i:integer, j:integer) → string
substring(s1:string, s2:string, b:boolean) → integer

substring(s,i,j) returns the substring of s starting at the i^{th} character and ending at the j^{th}. For example, *substring*("CLAIRE",3,4) returns "AI". If i is negative, the empty string is returned and if j is out of bounds (j > *length*(s)), then the system takes j=*length*(s). *substring*(s1,s2,b) returns i if s2 is a subsequence of s1, starting at s1's i^{th} character. The boolean b is there to allow case-sensitiveness or not (identify 'a' and 'A' or not). When s2 cannot be identified with any subsequence of s1, the returned value is 0.

symbol! — Kernel - DIET_ — method

symbol!(s:string) → symbol
symbol!(s:string, m:module) → symbol

symbol!(s) returns the symbol associated to s in the *claire* module. For example, *symbol*!("toto") returns claire/«toto». *symbol*!(s,m) returns the symbol associated to s in the module m.

time_get, time_set, time_show, time_read — Kernel - DIET_ — method

time_get() → integer
time_read() → integer
time_set() → void
time_show() → void

time_set() starts a clock, *time_get*() stops it and returns an integer proportional to the elapsed time. Several such counters can be embedded since they are stored in a stack. *time_show*() pretty prints the result from *time_get*(). *time_read*() can be used to read the value of the time counter without stopping it.

type! — Language — method

type!(x:any) → any

returns the smallest type greater than x (with respect to the inclusion order on the type lattice), that is the intersection of all types greater or equal to x.

U — Core — method

U(s1:set, s2:set) → set
U(s:set, x:any) → any
U(x:any, y:any) → any

U(s1,s2) returns the union of the two sets. Otherwise, U returns a type which is the union of its two arguments. This constructor helps building types from elementary types.

uniform? — Core — method

uniform?(p:property) → boolean

Tells if a property is uniform, that is contains only methods as restrictions, with the same types for arguments and ranges. Note that interface properties should be uniform, as well as all properties that are used dynamically in a "diet" program.

use_as_output — Kernel - DIET_ — method

use_as_output(p:port) → port

uses_as_output(p) changes the value of the current output (the port where all print instructions will be sent) to p. It returns the previous port that was used as output which can thus be saved and possibly restored later.

vars — Kernel — slot

system.vars → list[string]

system.*vars* contains the list of arguments passed on the shell command line (list of strings).

verbose — Kernel - DIET_ — slot

system.verbose → integer

verbose(system) (also *verbose*()) is the verbosity level that can be changed. Note that trace(i:integer) sets this slot to i.

version — Kernel — slot

system.version → float

compiler.version → float

the version if a float number (<version>.<revision>) that is part of the release number.

world?, commit,choice, backtrack — Kernel - DIET_ — method

world?() → integer
choice() → void
backtrack() → void
backtrack(n:integer) → void
commit() → void
backtrack0() → void
commit(n:integer) → void

These methods concern the version mechanism and should be used for hypothetical reasoning: each world corresponds to a state of the database. The slots s that are kept in the database are those for which store(s) has been declared. These worlds are organized into a stack, each world indexed by an integer (starting form 0). *world*?() returns the index of the current world; *choice*() creates a new world and steps into it; *backtrack*() pops the current world and returns to the previous one; *backtrack*(n) returns to the world numbered with n, and pops all the intermediary worlds. The last three methods have a different behavior since they are used to return to a previous world *without* forgetting what was asserted in the current world. The method *commit*() returns to the previous world but carries the updates that were made within the current world; these updates now belong to the previous world and another call to *backtrack*() would undo them. On the other hand, *backtrack0*() also return to the previous world, but the updates from the current world are permanently confirmed, as if they would belong to the world with index 0, which cannot be undone. Last, *commit*(n) returns to the world numbered with n through successive applications of *commit*().

write — Core — method

write(p:property, x:object, y:any) → any

This method is used to store a value in a slot of an object. *write*(p,x,y) is equivalent to p(x) := y.

APPENDIX C: USER GUIDE

1. CLAIRE

When you run CLAIRE, you enter a *toplevel* loop. A prompt `claire>` allows you to give commands one at a time. An expression is entered, followed by <enter> on the Macintosh version or <return> on the UNIX or NT version. The expression is evaluated and the result of the evaluation is printed out after an `eval[n]>` prompt where n starts from 0 and gets incremented by one on each evaluation. This counter is there to help you keep track of your session. To quit, you can type ^D, q (for quit) or exit(1).

```
claire> 2 + 2
eval[0]> 4
```

The value returned at the level n can also be retrieved later using the array EVAL. EVAL[n] contains the value returned by `eval[n]>`, modulo the size of this array. To prevent the evaluation of an instruction, one may use the backquote character (`) in a way similar to LISP's quote.

```
claire> `(2 + 2)
eval[1]> 2 + 2
```

Formally, the expression entered at the toplevel can be any <fragment>, to avoid painful parenthesis. To prevent ambiguities, the newline character is taken as a separator inside compounded expressions (cf. Appendix A, <comp-exp>). This restriction is only true at the top-level and not inside a file. It prevents from writing

```
claire> 1 + 2
          + 3
```

but not

```
claire> 1 + 2 +
          3
```

The CLAIRE system takes care of its memory space and triggers a garbage collection whenever needed. If CLAIRE is invoked from a shell, it can accept parameters according to the following syntax:

```
claire      [-s <int> <int>][opt]
            [-n | -v <integer> | -f <file> | -m <module> | -l <lib>][*]
            [-S <flag>][*] [-D | -O [opt] [-p [opt] [-safe [opt]
  [-od <dir> [opt] [-ld <dir> [opt] [-env <os> [opt]
            [ [ [-cm | -cc | -cl | -cj [<module>] | -cx <file> [ [-o <file>][opt] [opt]
```

Note that `claire -?` will produce a summary of all the options and their meaning.

The -s option allows changing the size of the memory zone allocated for CLAIRE. The first number is a logarithmic increment[6] for the static zone (bags, objects, symbols), the second number is a logarithmic increment for the dynamic zone (the stacks). For instance, -s 0 0 provides the smallest possible memory configuration and -s 1 1 multiplies the size of each memory zone by 2. The method *stat()* is useful to find out if you need more memory for your application. A good sign is the presence of numerous garbage collection messages. The option –s 0 0, which is useless since it does not change the memory parameters, has a new side effect since the 2.4 release: it reduces the size of the evaluation stack to 1000, so that it can be used to debug endless loops.

Whenever CLAIRE starts, it looks for the *init.cl* file in the current directory. This file is loaded before any other action is started.

The parameters after CLAIRE will be used as if they were entered from a shell. The loading of the init.cl file can be prevented with the -n option. The -v (for verbose) option will set the value of verbose() to the integer parameter and thus produce more or fewer messages.

---

[6] A logarithmic increment n means that the size is multiplied by 2^n .

The options -f and -m are used to load files and modules into CLAIRE. The argument <file> is a name of a file (e.g. `-f test` is equivalent to `load("test")`) . The argument <module> is the name of a module that is either part of the CLAIRE system or defined in the *init.cl* file (`-m test` is equivalent to `get(test)`) . The option –l X is used to tell CLAIRE that the library X.lib should be linked with the output executable (usually this library contains the external C++ functions that are used in the CLAIRE source).

The option -S is used to set the value of a global_variable <flag> to false. This option can be used in conjunction with #if if to implement different versions of a same program in a unique file. The options –od and –ld are used to designate respectively the output and the library directory (i.e., where the code generated by CLAIRE will be produced and where CLAIRE should find the libraries (*.lib) for linking).

There are four options that invoke the CLAIRE compiler: -cx, -cl, -cm and -cc. They are used to compile respectively a (configuration) file or a module (3modes). The -o option may be used to give a new name to the executable that is generated (if any). The options -O and -D are used respectively to increase the optimization or the debugging level (cf. Section 3). The option –safe resets the optimizing level to 2, which is safe for most applications.

The -cc option is the lightest compiling strategy for a module: `claire -cc m` will produce a C++ file for each CLAIRE file in m.made_of. It does not produce a makefile or system file, and assumes that the user want to keep a complete control over the generation of the executable. A more friendly option is `–cl`, which adds a linking step so that all generated C++ files are compiled and linked into a library m.lib (the name of the library can be redefined with –o or by using the *external* slot of the module).

The easier way to use the compiler is the -cm option which produces an executable from a module. It is similar to -cl, but in addition it produces a system file for the module that is being compiled and a makefile which is executed by CLAIRE, producing an executable that includes the interpreter. For most users, `claire –cm` is the only option that they need to know.

Last, when `claire -cx test` is invoked, the compiler takes a CLAIRE configuration file (test), produces an equivalent C++ file and another C++ file called the system file. The first file is named <file>.cp (here test.cp) and the second file is named <out>-s.cp (here test-s.cp). They are both placed in the directory source(compiler) (cf. Section 3). The name <out> is <file> by default and is changed with the -o option. The generated files are compiled and linked directly by CLAIRE. This is done by producing a makefile <out>.mk that links the generated binaries with the necessary CLAIRE modules. The option –cx is used to generate multi-module executable and is aimed at serious CLAIRE developers. A configuration file is a file that contains only methods without any type-checking ambiguity.

If the environment does not provide a shell, compiling becomes a more complex task. One can use the *compile* method that is presented in section 3 to generate C or C++ files from CLAIRE files or modules. In addition the method *compile* must be used to generate the system file that contains the start up procedures. These files need to be compiled and linked explicitly using the users' choice of programming environment.

The option –p tells the compiler to generate code that is instrumented for the CLAIRE profiler. This profiler is one of the many CLAIRE libraries that are available in the public domain, such as CLAIRE SCHEDULE (constraints for scheduling problems), ECLAIR (finite-domain constraint solver), HTML (generating HTML documents from CLAIRE) or microGUI (for building very simple user interfaces).

In addition, the option –cj invokes, when available, the Java Light compiler (cf. Section 3.7). The light compiler compiles a module into *.java files, one for each class plus one for the module.

Migration from CLAIRE 1.0:

Programs from CLAIRE 1.0 are no longer supported. They should be migrated to CLAIRE 2.x first using the tips described in the associated user manual.

Changes from CLAIRE 2.0 to CLAIRE 3.0

- Lists and sets are strongly typed – this is THE major change. Because we do no longer rely on dynamic typing, the following is no longer true (in 3.0, but actually true in 3.2):

```
list(1,2,4) % list[integer]
```

Thus, migrating from 2.x to 3.0 is not an easy task. The proposed method is to get rid of all subtypes of the form list[x] or set[x] and replace them with parametric types list<x> and set<x> for slots and global variables, and with list of set for dynamic bag that are used within methods. This should be reasonably straightforward, although the updating of a slot or a variable that has a strong type now requires a value that is strongly typed as well. The second step is to

re-introduce further typing for lists or sets that are used within methods, but this can be done progressively, as it is mostly an optimization.

- Tuples are no longer lists, they are an independent subtype of bag. This should not cause any problems, unless you were using list methods on tuple – a really poor idea.
- The external representation of floats uses the native "double" type. This should be totally transparent to you, unless you wrote C++ functions to implement some of your methods.
- A number of features that were of little use have been removed:
  1. queries
  2. interfaces (the word takes a new meaning in v3.1 and onwards)

Changes from CLAIRE 3.0 to CLAIRE 3.1

Here are the main changes in the 3.1 release:

- The interface(p) declaration is introduced to support much faster dynamic method calls
- The interface(c,p1,p2,…) declaration is introduced to support the generation of C++ methods with member methods
- The method PRshow(..) is introduced to give easy access to the profiling capabilities of CLAIRE
- The optimizing pattern "for x in Id(s) e(x)" is introduced.

Changes from CLAIRE 3.1 to CLAIRE 3.2

CLAIRE 3.2 is an interesting evolution of CLAIRE 3.0, since it actually makes the transition from 2.5 much easier. The key change is the fact that types list[t] may apply to untyped list. Therefore, a CLAIRE 2.5 code fragment becomes valid and safe in 3.2, unless it performs updates on such a list. The major difference, from a migration point of view, is the fact that updates on untyped list are no longer allowed. The list of changes from 3.1 is as follows.

- Lists now exist in two flavors: read-only untyped lists and typed lists, which support (safe) updates.
- Propagation rules have been simplified dramatically. They are now reduced to simple event-propagation rules, but they are a standard feature of the CLAIRE language, as opposed to an external library, which was the case for version 3.0.
- The debugger now checks the range of the method for each call, a long awaited feature !

History of feature upgrades in CLAIRE 2.x

Here are the main changes in the 2.1 release:

- external functions must be characterized by three status flags instead of a boolean, in the function! Constructor
- string buffers can be used with *nth_get* and *nth_put*.
- Spying can be bound to entering into a given method (*spy*(p))
- Id(x) forces the evaluation of x before compilation (useful to define global_variables)
- Dynamic modules (with *begin* and *end*).
- Interfaces are introduced (global_constant that represent unions) as a bridge towards Java.

Here are the main changes in the 2.2 release:

- the reified properties (*reify*(p))
- tracing and spying can be activated after a given number of call evaluation, using a call counter.
- Rule modes *exists*, *set* and *break* have been introduced for a better control of the meaning of "existential" variables in logical rules.
- x.p or p[x] are allowed as assertions in the logic if p is of range boolean.

Here are the main changes in the 2.3 release:

- the *stop* statement (cf. later)
- the profiler option –p
- the check_range method

Here are the main changes in the 2.4 release:

- the array class.
- the optimized compilation of float expressions

Here are the main changes in the 2.5 release:

- a new set of options for the shell compiler and the withdrawal of the –cf option.
- A few new methods (look in the API for date!, time_read, vars, safe)
- The removal of dynamic namespaces
- The CLSMALL installation option is now provided for users that do not require large class hierarchies.
- Forward class declarations have stricter rules

Avoiding common mistakes:

Here are a few unwise programming practices that occur naturally:

- Using a global variable to store a complex set expression that will only be used in an iteration. Compare:

```
let s := {x in S | P(x)} in
  for y in s f(y)
```

With

```
for y in {x in S | P(x)} f(y)
```

the second approach is better because the compiler will not build the intermediate selection set if it is just built to be iterated.

- Declare the range of a slot as C ∪ {unknown}, as in

```
Person <: thing(age: (integer U {unknown}))
```

This is perfectly correct, but declaring the range as integer will be more efficient, because the compiler has been tuned to deal with the unknown value. Notice that one can reset the value to unknown with the method *erase*(p,x).

- Using a class of non-ephemeral objects when the set extension is not needed. The default for CLAIRE is to maintain the set extension of any class C, which supports the convenience of "for x in C …". However, this has a cost and it prevents the garbage collection of unused objects. If you plan to instantiate thousands or millions of objects from C, chances are that you want to declare it as ephemeral.
- Using the {f(x) | x in S} where a list{f(x) | x in S} is sufficient. The first form implies a duplicate elimination after the collection process.
- Using the same name for a module and a file, which causes a problem at compile time.
- Using a complex expression with make_list or make_array, where the expected behavior is to get multiple evaluations of the expression whereas CLAIRE shares the same result. For instance,

```
make_list(10,myObject())     // does NOT create a list with 10 different objects
A :: make_array(10,list[],list{i | i in (1 .. 10)})          // A[1] and A[2] are the same list !
```

2. The Environment

CLAIRE provides a few simple but powerful tools for software development: interactive debugger, stepper and inspector. All three of them are contained in the Kernel library and have the same structure of top level loops.

CLAIRE provides a powerful tool to trace programs. Trace statements are either explicit or implicit. To create an explicit trace statement, one uses the instruction

```
trace(level:integer,pattern:string,l:listargs)
```

which is equivalent to a format(pattern,l) onto the port trace_output() if verbose() is more than *level*. . Explicit trace statements are very useful while debugging. They may often be seen as "active comments" that describe the structure of an algorithm. For instance, we may use

```
trace(DEBUG, "start cycle exploration from node ~S\n",x)
```

Such a statement behaves like a "printf" if the verbosity level is less than the value of the global variable DEBUG, and is inactive otherwise. The goal is to be able to selectively turn on and off pieces of the debugging printing statements. By changing the value of the DEBUG variable, we can control the status of all trace statements that use this variable as their verbosity level.

It would be nice if we could separate visually these tracing statements from the rest of the code, especially since too many trace statements can quickly reduce the readability of the original algorithm. To achieve this goal, CLAIRE provides the notion of extended comments. An extended comment is a comment that starts with //[..], and which is treated like an explicit trace statement. For instance, the previous trace statement would be written as

```
//[DEBUG] start cycle exploration from node ~S // x
```

More precisely, an extended comment can only be used inside a block (i.e., within parentheses). The verbosity level is the string contained between the two brackets after //, the rest of the line is the concatenation of the pattern string and the argument list, separated with another "//", unless the list is empty. The last character should be a comma if a comma would be required after a trace statement in a similar position (i.e., if the trace statement is not the last statement of the block). Here is a simple example :

```
let x := 1 in
   ( //[1] start the loop with ~S // x,
     while (x < 10)
           (if g(x) x:= f(x,x) else x:+ 1,
            //[2] examine ~S // x
))
```

Implicit trace statements are produced by tracing methods or rules. The instruction `trace(m:property)` will produce two trace statements at the beginning and the end of each restriction of m (method). For instance, here what we could get by tracing the function *fib*.

```
1:=> fib(3)
2:=>> fib(2)
3:=>>> fib(1)
[3]>>> 1
3:=>>> fib(0)
[3]>>> 1
[2]>> 1
2:=>> fib(1)
[2]>> 1
[1]> 3
```

The level associated with the method's trace statement is the current level of verbose(). At any time, the trace statements can be deactivated with *untrace(m:method)*. The other way to generate trace statements is to activate the trace generation of the rule compiler with *trace(if_write)*. Whenever *trace(if_write)* is active, the code generated by the rule compiler will be instrumented with trace statements. Therefore, a statement will be printed as soon as the rule is triggered. One can play with *trace(if_write)* and *untrace(if_write)* to selectively instrument some rules and not the others, and later to activate/deactivate the trace statements that have been generated.

Note: implicit tracing requires the debugger to be activated, using the *debug*() command. The statements *debug*() and *step*() are designed to be entered at the top-level and not placed within methods.

The output_port can be set with trace(p:port) or trace(s:string) which creates an implicit port fopen(s,"w"). In addition, trace(...) can be used for two special functions. trace(m:module) activates a compiled module, which means that its compiled methods can be traced exactly like interpreted method. This will only happen if the module was

compiled with the -D option (cf. Section 3). trace(spy) activates the *spy* property if the method spy @ void has been defined previously. This means that spy() is invoked after each method call. This will slow down execution quite a lot but is extremely useful to detect which method has caused an undesired situation. Suppose for instance that the value r(X) must always be lower than 10. After the execution of your program, you find that r(X) = 12. If you try

```
spy() -> assert(r(X) <= 10)
trace(spy)
```

and run your program, it will stop exactly after the "wrong" method call that violated your assumption. *assert*(X) is a convenient macro which is equivalent to (if not(X) error(...)). The error message indicates in which file/line the error occurred. assert() statements are not compiled unless the debug mode of the compiler is active, or unless safety(compiler) = 0. Thus, assert statements should be used freely in a CLAIRE program since they are known to have a very positive effect on code safety and reliability.

Spy may become a burden from a execution time point of view, so the statement `spy(p1, p2, ...)` tells CLAIRE that the `spy()` call should only be executed during the evaluation of a function call f(...) where f is one of the properties p1, p2, ... Note that this instance of the spy method takes a variable number of arguments, that all must be properties. A typical use is when you want to find a bug in a part of your program that is executed long after its start, say in the result printing stage. By declaring `spy(printResult)`, the spy() method will only be called once the program has entered the printResult method.

The *debugger* is a toplevel loop that allows the user to inspect the stack of function calls. The debugger is invoked each time an error occurs, or by an explicit call through a *breakpoint()* statement. First, the debugger must be activated with the *debug()* method which works as a toggle (activate/deactivate). Then, whenever an error occurs, the debug toplevel presents the `debug>` prompt. In addition to being a standard read-eval-print toplevel (thus any CLAIRE expression can be evaluated), the following additional methods are supported:

`where(n:integer)`	shows the n last function calls in the stack. For each call, only the selector (the property) and the value of the arguments are shown
`block(n:integer)`	shown the n last function calls with the explicit method that was called, all the local variables (including the input) parameters and their current values.
`dn(n:integer)`	moves the current top of the stack down by n levels
`up(n:integer)`	moves the top of the stack up by n levels

For instance, here what we could get

```
f(n:integer) -> let y := n - 1 in (1 / n + f(y))
debug()
f(2)
---------------------- Debug ----------------------------
Integer arithmetic: division/modulo of 1 by 0
debug> where(10)
debug[1] > 1 / 0
debug[2] > f(0)
debug[3] > f(1)
debug[4] > f(2)
debug> block(10)
debug[1] > 1 / 0
debug[2] > f@integer(x = 0, y = -1)
debug[3] > f@integer(x = 1, y = 0)
debug[4] > f@integer(x = 2, y = 1)
```

The debugger only shows method calls that occur in interpreted code or in compiled code from an active module. As for trace statements, an active module needs to be compiled with the -D option first and activated with the *trace(m)* statement. For a compiled method, the *block(n)* instruction will only show the module where the method is defined.

The debugger can be invoked explicitly with the *breakpoint*() statement, which allows the user to inspect the stack of calls and the values of the local variables at the time the breakpoint is set. Once the inspection is completed, the execution resumes normally (as opposed to the usual error handling case). The debugger prompt allows the user to evaluate any expression, thus to inspect the current state of any objects. However, note that this is a eval(read) loop

with no implicit printing (to keep the dialog short) thus you need to input queries that cause explicit printing such as show(class) or print(1 + 2). To exit the breakpoint top-level loop, one must enter 'q'.

This library also provides a stepper. The method *step()* invokes the stepper, which will be active for the next message evaluation. The stepper can also be turned on after a given method p is evaluated, with the command step(p). Once it is triggered, the stepper stops at each function call, shows the name of the method and the value of the arguments and offers the following menu:

[s,i,o,q,t,b,x]

s:step	the stepper will evaluate the function
i:in	the stepper enters the function and stops at the first function call
o:out	the stepper exits the function
q:quit	the stepper stops (but may restart if there are other calls to active methods)
t:trace	the stepper starts tracing the function
b:breakpoint	you enter a breakpoint toplevel, to inspect the current state of objects.
x:exit	you exit the stepper by raising an exception. You come back to the interpreter prompt.

Finally, an inspector is also available for browsing CLAIRE objects. It is turned on by the method inspect. Calling *inspect*(x) will give information about x (the same information that the method show would give, that is the list of all slots and their values) and make you enter another toplevel loop with an `inspect>` prompt.

Each information about the inspected object is numbered. Typing in a number will make the inspector focus on the corresponding slot of the object.

- If the inspected object is x, typing the property p will drive the inspector to the object p(x)
- Typing in the name of an object will focus the inspector on that object
- Typing up will return to the previously inspected entity.
- Typing q will have you quit the inspector.

Tracing, stepping and using the spy methods are powerful tools for debugging and understanding a program. However, most often they yield too much information because we are only interested in a short part of the program, which is executed after quite a while. CLAIRE provides a function call counter and the ability to activate tracing, spying or stepping only after a given number of calls have been processed. The call counter is reset to 0 each time a new expression is evaluated at the top level.

- trace(where) activates the call counter. Each implicit trace contains the counter value (between brackets)
- trace(x,y) sets the verbosity level to x after processing y calls.
- trace(spy,y) activates the spy method only after processing y calls.
- step(y) activates the stepper only after processing y calls.

Finally, CLAIRE provides the ability to stop when the interpreter enters a given property with a given list of arguments. This is useful to find out why a given method was invoked (using the debugger). Remember that to stop for any set of arguments you may use step(p).

stop(p:property,a1:any, …, an:any)	tells the interpreter to stop when the call p(a1,..,an) is evaluated.
stop(p)	cancels all stopping statements about p.

The CLAIRE compiler supports a **profiling** option "-p" that generates a code that gathers some useful performance measurements for each properties. This option is mostly designed to be used in combination with a profiling tool, but it can be used independently as follows. First, one compile the module using the –p option. Second, one runs the module as always. Last, before exiting the top-level, one may get simple-minded performance reports

with PRshow() and PRshow(p:property). These two methods, that are defined in the Reader module, respectively apply to the ten most important properties (run-time-wise) or to the property p.

3. The Compiler

3.1 Compiler Architecture

The CLAIRE compiler is based on a reflective architecture, where everything is represented by objects, with associated methods that may be redefined or extended. It is organized into three separate components:

- The **Optimizer**, which is represented by the Optimize module. The optimizer transforms a CLAIRE instruction into an equivalent but faster, optimized, instruction.
- The generic code producer, which is part of the **Generate** module, and which contains a set of generic methods that produce target code (C++ but also C or Java) by pretty-printing optimized instructions;
- The target-specific code producer, which is represented by an object PRODUCER from a specific meta-class that is dependent on the target language. Producer objects are intended to be inter-changeable, so that generating Java code, for instance is achieved by defining a java_producer object. The Generate module also contains the definition of the default C++ producer.

Thus, one can summarize CLAIRE compiling as follows. The first step is a source-to-source transformation that is done at the object level, using CLAIRE's reflective nature. This is the most complex part of the compiler (the Optimize module). The second step is the generation of C-like code, which is simply obtained by an adequate "pretty-printing" of the objects that represent the optimized instructions. The last step is only applied when this pretty printing is different from one target language to another. This "ideal architecture" is actually implemented for the major part of the CLAIRE language, in the sense that it is indeed enough to re-define a small CLAIRE file to generate code for a new target language. The public-domain "jlight" module is precisely the definition of the java code-producer. However, some of the CLAIRE constructs are too complex and require more re-engineering of the compiler. This yields the important notion of Diet CLAIRE (cf. Section 3.7), which is the simple fragment that can be easily compiled into most target architectures.

3.2 C++ Code Generation

The CLAIRE compiler generates C++ files from a CLAIRE file (or a set of files associated with a module). For a given file f.cl, it will produce a code file f.cp (or f.cc) and a header file f.h. In the case of a module m, it will produce a unique header file m.h and multiple code files. Each code file contains a list of C++ functions for each method in the file, plus one large method that contains the C++ code for generating the CLAIRE objects that are defined in f.cl. In addition to a few compiler-generated comments lines, the comments lines that begin with // in the CLAIRE source file are also included in the C++ generated file.

The interface file contains the C++ classes generated for each CLAIRE class, the function prototypes for each compiled method, and the extern definition of all the generated identifiers (see later). In addition, the compiler can also be used to generate a "system file", which name is f-s.c, where f is the output parameter. This system file is either produced implicitly by using the -cm or –cx options of the compiler.

The system file contains code for building all the modules and loading them in the right order. Its key generated function is run_claire() which must be invoked by the main() function of your program (this is done automatically with the main.c file that is used with the -cm or -cf option). If you decide to write your own main() function, you must remember to call run_claire before using any CLAIRE objects. The *mainm.c* file that the CLAIRE compiler uses for the -cm and -cf option is straightforward. It contains a very simple toplevel and provides only two features: it loads the start.cl file before entering the toplevel (if it exists) and it accepts the "-s a b" option as shell parameters to change dynamically the size of the memory allocated to your program.

CLAIRE provides a way to include C++ directly into the generated code. The method *externC* has one argument (a string) and no effect when interpreted. On the other hand, a call to externC is compiled into its string argument. The compiler assumes that no value is returned (type void). If the value of the C++ expression must be returned, then its type (i.e., its sort that is a CLAIRE class) must be given as the second argument. For instance, to define a bitwise and operation we may use

```
bit&(x:integer,y:integer) : integer -> externC("(x & y)",integer)
```

3.3 What the Compiler Produces

Reading or using the C++ generated code is very easy as soon as you have a vague idea of what is produced by the compiler (here we assume that you have already read Section 6.5). The first output of the compiler is a set of class definition that is placed in the header file. Each CLAIRE class that is an object sort (i.e., that is included in object) produces such a class, where each slot of the class becomes a data member in the class structure. This class will be used to access CLAIRE objects within a C++ program as if it was a standard C++ object. For instance, a definition like

```
C <: object(x:string,y:int,z:float)
```

will produce

```
class C : public object
        {       char *x;
                int y;
                double *z;}
```

The name used for the structure is exactly the same as the CLAIRE name, with the exception of special characters in {'.', '&', '-', '"','+', '%', '*', '?', '!', '<', '>', '=', '^', '@'} that are translated into a short sequence of characters that are acceptable for C++. Using the CLAIRE name for the structure has the advantage of simplicity but the user must keep this in mind to avoid name conflicts (such as using a C++ keyword for a class name).

A new feature in CLAIRE 3.1 is the ability to introduce member methods in the C++ interface. Suppose that you have defined the following method:

```
foo(x:C, s:string) : integer -> …
```

Then the declaration:

```
interface(C, foo)
```

Will tell CLAIRE that *foo* should be provided as a C++ method for the class C. The header file (.h) will contain

```
class C : public object
        {       …
                int foo(char *s);
                … }
```

Note that the fact that we use the exact same name for C in C++ and CLAIRE is an option, depending on the value of *compiler.naming* (cf. Section 3.5). It is also possible to generate prefixes to forbid name conflicts.

The second output of the CLAIRE compiler is a set of C++ classes that represent each namespace. A namespace is a C++ subclass from NameSpace, simply defined by its slots, which correspond to the set of CLAIRE named objects within the module. There is one C++ identifier created for each namespace, that uses the same name as the module. For instance, the C++ variable Kernel contains the unique C++ instance of the KernelClass namespace.

For each named object x in the module m (i.e. that belongs to thing), CLAIRE generates a C++ reference m.x. As previously, special characters are translated, to avoid conflict with C++ reserved keywords. Moreover, a "_" is added to the identifier generated for each class, thus, for example, class is represented as Kernel._class. To find out which identifier is generated, one may use the c_test method. This method is an on-line compiler that is intended to show what to expect. `c_test(x:any)` takes an instruction x and shows what type will be inferred and what code will be produced. For instance, c_test(x:thing) will show which identifier will be generated. To use *c_test* with a complex instruction, one may use the ` (backquote) special character that prevents evaluation. For instance, one may try

```
c_test(`(for x in class show(x)))
```

Let us consider a small example that will show how to create a claire object from C++ or how to invoke a method. Suppose that we define :

```
point <: class(x:integer, y:integer, tag:string)
f(p:point,s:string) -> (p.tag := s)
```

The code shown by

```
c_test(`f(point(x = 1), "test"))
```

will be (modulo the GC statements that depend on the settings and that will be discussed later) :

```
{  point * v_arg1;
        char * v_arg2;
```

```
{ point * _CL_obj = (point *) make_object_class(L_point);
        _CL_obj->x = 1;
        add_I_property(L_instances, L_point, 11, _object_(CL_obj));
        v_arg1 = _CL_obj;}
v_arg2 = "test";
f_point_claire(v_arg1,v_arg2);}
```

The third output of the CLAIRE compiler is a set of functions. CLAIRE generates a C++ function for each method in the CLAIRE file. The function uses a name that is unique to the method as explained in Section 6.5. The function name associated to a method can be printed with the `c_interface(m:method)` method. The input variables (as for any local variables) are a straightforward translation from CLAIRE (same name, equivalent C++ type). The body of the function is the C code that is equivalent to the original CLAIRE body of the method. The C++ code generated by CLAIRE is an almost straightforward translation of the source code. The only exceptions are the additional GC protection instructions that are added by the compiler. These macros (GC...) can be ignored when reading the code (they are semantically transparent) but they should not be removed ! In addition, CLAIRE also produces one load function for each file f (with name "load_f") that contains code that builds all the objects, including the classes and methods, contained in the file.

Although the garbage collecting of CLAIRE should be ignored by most, it may be interesting to understand the principles used by the compiler to write your own C++ definitions for new methods. Garbage collection in CLAIRE is performed through a classical mark-and-sweep algorithm that is carefully optimized to provide minimal overhead when GC is not necessary. To avoid undue garbage collection, CLAIRE must perform some bookkeeping on values that are stored in compiled variables. This is achieved with the following strategy: each newly generated C++ function starts with the macro GC_BIND, which puts a marker in a GC stack. Each newly created value that needs to be protected is pushed on this stack with the GC_PUSH macro (In CLAIRE 3.0, GC_PUSH has many equivalent forms such as GC_ANY, GC_OBJECT, GC_OID, GC_ARRAY, GC_STRING …). At the end of the function call the space on the stack is freed with the GC_UNBIND macro. The compiler tries to use these protecting macros as scarcely as possible based on type inference information. It also uses special forms (GC_RESERVE, PROTECT, LOOP and UNLOOP) for protecting the objects that are created inside a loop, which is out of scope for this document. On the other hand, if a user defines an external function (using C++) that creates new CLAIRE entities that needs to be protected, it is a good idea to include the use of GC_BIND, GC_UNBIND and GC_PUSH. Entities that need to be protected are bags (lists and sets), ephemeral objects (but not the «□egular□ objects) and imported objects (strings, floats, etc.).

3.4 System Integration

Methods are usually defined within CLAIRE. However, it is also possible to define a method through a C++ function, since most entities in CLAIRE can be shared with C++. The C++ function must accept the method's parameters with the C++ types that correspond to the CLAIRE types of the parameters and return accordingly a result of the type associated with the range. The ability to exchange entities with the "outside world" was a requirement for CLAIRE and is a key feature.

To understand how C++ and CLAIRE can share entities, we must introduce the notion of "sort", which is a class of entities that share the same physical representation. There are five sorts in CLAIRE: **object**, **integer**, char, imported and **any**, which cover all other entities. Objects are represented as pointers to C++ classes: to each class we associate a C++ class with the same name where each slot of the object becomes a field (instance variable) in the structure. Integers share the same representation with C++ and characters are also represented with integers. Imported objects are "tagged pointers" and are represented physically by this associated pointer. For instance, a CLAIRE string is the association of the tag *string* and the "char*" pointer which is the C++ representation of the string. Imported objects include strings, floats (where the pointer is of type "double*"), ports (pointer of type "FILE *"), arrays and external functions. Last, the sort **any** contains all other entities (such as symbols or bags) that have no equivalent in C and are, therefore, represented in the same way, with an object identifier with C++ type "OID" (OID is a system-dependent macro).

The method *c_interface*(c) (cf. Appendix C) can be used to obtain the C++ type used for the external representation of entities from the class c.

```
claire> c_interface(float)
  eval[1]> "double *"
```

Now that we understand the external representation of entities in CLAIRE, we can define, for instance, the *cos* method for floats. The first part goes in the CLAIRE file and stands as follows.

```
cos(x:float) : float -> function!(cos_for_claire)
```

We then need to define in the proper C++ file the C function *cos_for_claire* as follows.

```
double *cos_for_claire(double *y)
        {double *x;
            x = malloc(size_of(double));
            *x = cos(*y);
            return x;}
```

When the two files are compiled and linked together, the method cos is defined on floats and can be used freely.

When the two files are compiled and linked together, the method cos is defined on floats and can be used freely. The linking is either left to the user when a complex integration task is required, or it can be done automatically by CLAIRE when a module *m* is compiled. The slot *external*(m) may contain a string such as "XX", which tells CLAIRE that the external functions can be found in a library file XX.lib and that the header file with the proper interface definitions is XX.h.

There is one special case when importing an external function if this external function makes use of CLAIRE memory allocation either directly or through a call back to CLAIRE. In this case, the compiler must be warned to insure proper protection from garbage collection. This is done with the additional argument NEW_ALLOC in the *function!*(...) constructor. Note that this cannot be the case unless the external function makes explicit use of CLAIRE's API. Here is a simple example.

```
mycopy(x:bag) : bag -> function!(mycopy,NEW_ALLOC)

OID mycopy(OID x)
        {count++; return (copy_bag(x)); }
```

The *function!*(...) constructor can take up to four arguments, the first of which is mandatory because it is the name of the C++ function. The other three optional arguments are NEW_ALLOC, which tells CLAIRE that the function uses a CLAIRE allocation, SLOT_UPDATE, which tells CLAIRE that the slot value of an object passed as an argument is modified (side-effect) and BAG_UPDATE, which says that a list or a set passed as an argument is modified. Note that this information is computed automatically by the compiler for methods that are defined with a CLAIRE body.

When a method is defined within CLAIRE and compiled later, the compiler produces an equivalent C++ function that operates on the external representation of the parameters. This has two advantages: on one hand, the C++ code generated by the compiler is perfectly readable (thus we can use the compiler as a code generator or modify its output by hand); on the other hand, the compiled methods can be invoked very easily from another C++ file, making the integration between compiled CLAIRE module and C++ programs reasonably simple (especially when compared with the LAURE language).

The only catch is the naming convention due to polymorphism and extensibility. The default strategy is to generate the function *m_c* for the method *m* defined on the class *c* (i.e. a method which is a restriction of the property *m* and whose first type in the signature is the class *c*). When this first type *t* is not a class, the class *class!(t)* is used instead. However, this is ambiguous in two cases: either there are already multiple definitions of *m* on *c*, or the property *m* is open and further definitions are allowed. In the first case a number is added to the function name; in the second case, the name of the module is added to the function name. Therefore, the preferred strategy is to avoid overloading for methods that are used as interfaces for other programs, or to look at the generated C++ code otherwise to check the exact name (this topic is further continued in the next section, when we discuss the compiler.naming slot).

For instance, in the previous example with the fib method, the generated C++ function will simply be (as it will appear in the generated header file) :

```
int fib_integer(int x);
```

Another interesting consequence is that all the library functions on strings can be used within any C++ program that is linked with the compiled CLAIRE code. Since these functions use the same "char *" type as other string functions in C++, we can freely use the following (as they appear in the header files):

```
char * copy_string(char *s);
char * substring_string(char *s, int n1, int n2);
```

The API with CLAIRE is not limited to the use of functions associated with methods. It also includes access to all the objects, which are seen as C++ objects. When a CLAIRE file is compiled, the class definitions associated with the classes are placed in a header file. The name of the header file is the name of the module, and the file contains a class that represent the name space. This header file allows the C++ user to manipulate the C++ pointers obtained from CLAIRE in a very natural way (see Appendix C). The pointers that represent objects can be obtained in two ways: either as a parameter of a function that is invoked from CLAIRE, or through a C++ identifier when the object is a named object. More precisely, the compiler generated a global variable m with the name of the module, which

contains a unique instance of the class that is associated to the namespace. The compiler generates an instance variable for this object m for each named object x[7]. For instance, if John is an object from the class person, the following declaration will be placed into the header file:

```
class mClass: public NameSpace {
public:
…
extern person *John;
…};
extern mClass m;
```

Thus the CLAIRE object john will be accessible as m.john in the C++ files.

The set of primitive classes (symbol, boolean, char, bag) is fixed once for all and trying to add a new one will provoke an error. On the other hand, the set of imported object can be enriched with new classes. More details about the integration between CLAIRE and C++ code will be given in the Appendix C, where we examine the CLAIRE compiler and its output.

WARNING: the use of C++ keywords as names for CLAIRE named objects is not supported and will cause errors when the C++ compiler is called (e.g., short).

3.5 Customizing The Compiler

There are a few parameters that the user can control the CLAIRE compiler. They are all represented by slots of the compiler object. The string *source*(compiler) is the directory where all generated C++ code will be placed. You must replace the default value of this slot by the directory that will contain the generated code.

The second slot *safety*(compiler) contains an integer that tells which level of safety and optimization is required, according to the following table:

- 0 □ super-safe: the type of each value returned by a method is checked against its range, and the size of the GC protection stack is minimized. All assertions are checked
- 1 □ safe (default)
- 2 □ we trust explicit types & super. The type information contained in local variable definition (inside a let) and in a super (f@c(...)) has priority over type inference and run-time checks are removed. We also suppose that destructive operations on lists or sets are type-safe.
- 3 □ no overflow checking (integer & arrays), in addition to level 2
- 4 □ we assume that there will be no selector errors or range errors at run-time. This allows the compiler to perform further static binding.
- 5 □ we assume that there will be no type errors of any kind at run-time.
- 6 □ unsafe (level 5 + no GC protection). Assumes that garbage collection will never be used at run-time

The slot *overflow?*(compiler) is used to control separately the overflow checking for integer arithmetic. When it is turned to true, the compiler will produce safe code with respect to overflows. This is useful since un-detected overflow errors can yield run-time crashes that are hard to debug (cf. troubleshooting).

The slot *inline?*(compiler) tells the compiler that inline methods should include their original CLAIRE body in the compiled code so that further programs that use these inline methods can be compiled with macroexpansion. The default is false, since this option (turning to true) requires the reader module to be linked with the generated module. This is only necessary is you are developing a module that will be used as a library for some other programs.

---

[7] As for external functions, special characters (e.g., +, /) are dealt with through a transformation described in the last Appendix.

The two slots *active?*(compiler) and *loading?*(compiler) are used to represent the status of the compiler. The first one simply tells if the compiler is in use or not. The second one distinguishes between the first step of the compiler (loading the program to be compiled) and the second step (actually compiling code).

The slot *external*(compiler) contains the name of the C++ compiler that should be used by the -cm and -cf options. For instance, its default UNIX value is "gcc". It could be changed to "gcc -p" to use the profiler (for instance).

The slot *headers*(compiler) contains a list of strings, each of which is a header file that needs to be used the generated C file. This is useful when you define methods by external functions, whose prototypes are in a given header (such as a GUI library header). Similarly, the slot *libraries*(compiler) contains a list of strings, each of which is the name of a library that needs to be linked with the generated C file.

The slot *naming*(compiler) contains an integer which tells which naming policy is desired. The three values that are currently supported are:

0 □ default: use long and explicit names

1 □ simple: use shorter names for generated functions (without using the module name as a prefix). This may be more convenient but may cause name conflicts

2 □ protected: generate simple alphanumeric names that have no explicit meaning. This is useful is the generated code is to be distributed without revealing too much of the design.

The last slot, *debug?*(compiler), contains a list of the modules for which debuggable code must be generated. This slot is usually set up directly using the -D option. By default, generated code is not instrumented which means that the tracer, the debugger or the stepper cannot be used for compiled methods. On the other hand, when debuggable code is generated, they can be used just as for interpreted code. One just needs to activate the compiled module with a trace(m) statement. The overhead of the instrumentation is marginal when the module is not active. Once it is active, the overhead can vary in the 10-100% range.

The last way to customize the compiler is to introduce new imported sorts, as defined in Section 6.5. This is done by defining a new class *c t*hat inherits from the root `imported` and telling the compiler what the equivalent C type is with the *c_interface* method. c_interface(c:class,s:string) instructs the compiler to use s as the C type for the external representation of entities of type c. For instance, here is a short CLAIRE program that defines a new type: long integer (32bits integers).

```
long <: imported()
(#if loaded(Compile) c_interface(long,"long"))

+(x:long,y:long) : long -> function!(plus_long)
self_print(x:long) : void -> function!(print_long)
```

Notice that we guard the c_interface declaration with an #if to make sure that the compiler is loaded. We may now define the C implementation of the previous method as follows.

```
long plus_long(long x, long y) { return x + y;}
void print_long(long x) {fprintf(LO.port,"%dL",x);}
```

Last, we must make sure that the header file corresponding to the previous functions is included by the CLAIRE compiler using the headers(compiler) slot. The global variable *fe* is a string that contains the extension for the generated files.

The CLAIRE compiler also generates code to check that object slots do not contain the special “unknown” value. This can be avoided by declaring one or many properties as “known”, through the following declaration :

```
known!(<relation>*)
```

The compiler will not generate any safety check for the relations (properties or tables) that are given as parameters in a *known!* statement.

3.6 Iteration and Patterns

We have seen how CLAIRE supports the optimization of iteration and membership for sets that are represented with new data structure. This is done through the addition of inline restrictions to respectively the *iterate* and the % property. However, there are cases where sets are better represented with expressions than with data structures. Let us consider two examples, *but* and *xor*, with the following samples

```
for c in ({c in class | length(c.slots) > 5} but class) ....

(for x in (s1 & s2) ...          ;; iterate the intersection
   for x in (s1 xor s2) ...              ;; iterate the rest of (s1 U s2)
```

The definition of the sets are as follows; (s but x) is the set of members of s that are different from x; (s1 xor s2) is the set of members of s1 or s2 but not both. It would be perfectly possible to implement these sets with either simple methods (set computation) or new data structures, with the appropriate optimization code. However, there are two strong drawbacks to such an approach

- it implies an additional object instantiation, which is not necessary,
- it implies evaluating the component sets to create the instance, which could have been prevented as shown by our first example (the selection set can be iterated without being built explicitly).

A better approach is to manipulate expressions that represent sets directly and to express the optimization rules directly. Although this is supported by CLAIRE through the use of reflexion and thus out of scope for this manual, we have identified a subset of expressions for which a better (simpler) support for such operations is provided.

The key concept is the *pattern* concept, which is a set of function calls with a given selector and a list of types of the arguments (that is a list of types to which the results of the expressions that are the arguments to the call must belong). A pattern in CLAIRE is written p[tuple(A,B,...)] and contains calls p(a,b,...) such that a is an expression of type A ... and so on. Patterns have two uses: the iteration of sets represented by expressions and the optimization of function composition (including membership on the same expressions). To better understand what will follow, it is useful to know that each function call is represented in CLAIRE by an object with two slots: *selector* (a property) and *args* (the list of arguments).

First, the CLAIRE compiler can be customized by telling explicitly how to iterate a certain set represented by a function call. This is done by defining a new inline restriction of the property *Iterate*, with signature `(x:p[tuple(A,B,...)],v:Variable,e:any)`. The principle is that the compiler will replace any occurrence of (for v in p(a,b,...) e) by the body of the inline method as soon as the type of the expressions a,b,... matches with A,B,.... This is very similar to the use of *iterate*, but we leave as an exercise for the reader to find out why two different properties are needed.

For instance, we can define two new restrictions of *Iterate* as follows.

```
Iterate(x:but[tuple(any,any)],v:Variable,e:any)
        => (for v in eval(args(x)[1]) (if (v != eval(args(x)[2])) e))

Iterate(x:xor[tuple(any,any)],v:Variable,e:any)
        => (for v in eval(args(x)[1]) (if not(v % eval(args(x)[2])) e),
                for v in eval(args(x)[2]) (if not(v % eval(args(x)[1])) e)
```

If we need to have access to a component of the call that matches the pattern, we use a special *eval* call: instead of performing the substitution, the compiler will evaluate what is inside the *eval* call. Here is what will be obtained for our two initial examples :

```
for c in get_instances(class)
        (if (length(c.slots) > 5)
                (if (c != class) ....

(for x in (s1 & s2) ...          ;; iterate the intersection
   (for x in s1 (if not(x % s2) ...
    for x in s2 (if not(x % s1) ...
```

A word of warning about the iteration of complex expression□ this type of optimization is based on code substitution and will not work if the construction of the set is encapsulated in a method. Consider the following example□

```
f1() => list{f(x) | x in {i in (1 .. n) | Q(i) > 0}}
for x in f1() print(x)
f2() -> list{f(x) | x in {i in (1 .. n) | Q(i) > 0}}
for x in f2() print(x)
```

The first iteration will be thoroughly optimized and will not yield any set allocation, whereas the second example will yield the construction and the allocation of the set that is being iterated.

Patterns are also useful to add new code substitution rules. This is achieved with a restriction (an inline method) whose signature contains one or more patterns and the class *any*. The compiler tries to use it based on the matching of

the expressions (pattern-matching as opposed to type-matching). For instance, here is how we optimize the membership to sets represented by a "but" expression.

```
%(x:any,y:but[tuple(any,any)])
    => (x % eval(args(y)[1]) & (x != eval(args(y)[2])))
```

The use of patterns is an advanced feature of CLAIRE, which is not usually available in programming languages. It corresponds to what could be called composition polymorphism, where the implementation of a call *f(...,y, ...)* may change if *y* is itself the result of applying another function *g*. It allows to implement simplification rules such as

(A + B)[i,j] = A[i,j] + B[i,j]

by declaring

```
nth(x:+[tuple(matrix,matrix)],i:any,j:any)
    => (eval(args(x)[1])[i,j] + eval(args(x)[2])[i,j])
```

The use of *patterns* and *Iterate* is geared towards expressions of the language (meta-programming), whereas iterate is intended to describe data structures. Notice that if you define *iterate* on a new data structure, say a FloatInterval, it will only be used by the compiler to macroexpand the iteration for x in s e when the compiler can determine precisely that s is of type FloatInterval. There is a way to tell the compiler that all existing iteration strategies that apply to s should be applied. We use Id as a syntactical marker (as for explicit evaluation during compiling) and write for x in Id(s) e. For instance, if there are two possible types for s that have a restrictions of iterate (FloatInterval et otherType), the following code should be produced:

```
if (s % type1)   <iteration with iterate@s1>
else if (s % type2) <iteration with iterate@s1>
else <usual iteration>
```

One can see that this technique should be used carefully, especially when the type inferred for s is too general. This is why we rely on an explicit syntactical marking from the programmer. This is, on the other hand, very convenient to write fast and generic code when sub-classing is used to provide with different implementations (with different iteration strategies) of one single generic data structure.

3.7 Diet Claire _ and Light Code Producers

Diet CLAIRE is a fragment of CLAIRE that can be easily compiled into mostly any target language. To date, only two diet code producers are available (C++ and Java), but others can be developed easily. A "diet" program is a program that is mostly statically typed, with some well-behaved and well-understood exceptions, and that does not use explicitly the reflective nature of CLAIRE, that is, that does not handle classes, types or properties as objects.

Diet CLAIRE can be defined as follows:

- **User-defined objects**: The only two references to classes that are supported are membership to a class and the iteration of a class without subclasses (a leaf in the class hierarchy). Let us remind ourselves that final(x) is used to declare x as such a leaf.
- The following **kernel classes** are supported: char, float, integer, list, set, string and symbol. Only contradictions and general_errors (created through the error(…) construct) are supported in Diet CLAIRE.
- Methods are fully supported, but method calls should either be statically defined or the dynamic selection of the method should only depend on the class of the first argument. That is to say, as in Java, that all the restrictions of a property that is used in a dynamically-bound call **must have the same types for their arguments and their range**. This is a strong constraint, that can be checked with the uniform?(p) method, which returns true if all restrictions of a property p satisfy such a condition. This also applies to the **super** construct (cf. Section 4.4), which is only "diet" when it can be resolved statically.
- Tables are supported in "Diet CLAIRE", as well as hypothetical reasoning using worlds. Complex types such as unions, parameterized types or intervals can be used as ranges of variables, slots or method parameters but should not be used as set expressions. **Global variables** are also "diet", as long as their range is simply a class or an integer interval.

It can also be defined negatively, by telling what is not supported in Diet CLAIRE:

- Explicit use of meta-objects such as types, modules, classes or properties.

- The definition of methods with external functions is not “diet” by definition, since it depends on the target language.
- The use of an error handler with an error class different from any (any error) or contradiction.
- Using non-uniform methods in a non-statically typed manner. This has the following side effect: any method that actually required to be used dynamically, such as self_print, must be defined in a uniform manner. Thus defining a restriction of self_print with a different range than void will create a non-diet situation.

Diet CLAIRE is actually an interesting language, since most of the stand-alone algorithms are usually described using Diet CLAIRE. The benefit of a Diet CLAIRE encoding is that a Java Light compiler is already available as a public domain library for CLAIRE. Another benefit of a Diet Claire program is the ability to generate a small executable, since the diet kernel is much smaller that the regular set of modules that is linked with a compiled Claire program. It is a good idea to stick to diet CLAIRE when possible; however, be advised that writing statically type-checked programs is a strict discipline …

From a module perspective, the kernel that is supported in Diet Claire is a subset of the Kernel and Core modules. The complete specification is included in the Appendix B, since we indicate for each method whether the method is diet or not.

4. Troubleshooting

4.1 Debugging CLAIRE Errors

The easiest way to debug a CLAIRE error (i.e., an error that is reported by CLAIRE) is to use the debugger. If the error occurs in a compiled program, you must use the –D option when you compile your code. There are three tools that run under the debugger and that are most useful: trace, spy and stop (cf. Section 2). The inspector (?) is also very convenient to observe your own data structure and find out what went wrong. Also, notice that stat() will produce a detailed report about memory usage if the verbosity level is more than 5.

The error “class hierarchy too large: remove the CLSMALL installation option” is a special case, since it indicates that you are using large class hierarchies and that your CLAIRE system was installed using the CLSMALL installation option (a C++ flag) that assumes that class hierarchies will be small. You need to contact your system administrator to re-install CLAIRE with the proper options.

Here is a list of the CLAIRE-generated errors. They are all represented by an integer code (0-100 for “system” error and 100-200 for high-level error; the codes over 200 are used by the compiler as we shall later see). Most error message are self-explanatory but some may tolerate a few additional explanations …

[1] dynamic allocation, item is too big (~S)
There is not enough memory to allocate an objet – the parameter is the size (in cells) that is required for this object.

[2] dynamic allocation, too large for available memory (~S)

[3] object allocation, too large for available memory (~S)

[5] nth[~S] outside of scope for ~S

[7] Skip applied on ~S with a negative argument ~S

[8] List operation: cdr(()) is undefined

[9] String buffer is full: ~S

[10] Cannot create an imported entity from NULL reference

[11] nth_string[~S]: string too short~S

[12] Symbol Table table full"

[13] Cannot create a subclass for ~S [~A]

[16] Temporary output string buffer too small"

[17] Bag Type Error: ~S not in ~S"

[18] definition of ~S is in conflict with an object from ~S

[19] Integer overflow

[20] Integer arithmetic: division/modulo of ~A by 0

[21] Integer to character: ~S is a wrong value

[22] Cannot create a string with negative length ~S

[23] Not enough memory to instal claire

[24] execution stack is full [~A]

[26] Wrong usage of time counter [~A]"

[27] internal garbage protection stack overflow

[29] There is no module ~S

[30] Attempt to read a private symbol ~S

[31] External function not compiled yet

[32] Too many arguments (~S) for function ~S

[33] Exception handling: stack overflow

[34] User interrupt: EXECUTION ABORTED

[35] reading char '~S': wrong char: ~S

[36] cannot open file ~A

[37] world stack is full

[38] Undefined access to ~S

[39] cannot convert ~S to an integer"

[40] integer multiplication overflow with ~S and ~S

[41] wrong NTH access on ~S and ~S
A list/set access l[i] failed because the index i was not in (1 .. length(l))

[42] Wrong array[~S] init value: ~S

[101] ~S is not a variable:
An assignment (x := …) is executed where x is not a variable

[102] the first argument in ~S must be a string

[103] not enough arguments in ~S

[104] Syntax error with ~S (one arg. expected)

[105] cannot instantiate ~S
The class cannot be instantiated because it was declared as asbtract.

[106] the object ~S does not understand ~S

[107] class re-definition is not valid: ~S

[108] default(~S) = ~S does not belong to ~S

[109] the parent class ~S of ~S is closed
Cannot create a subclass of X, which was declared final.

[110] wrong signature definition ~S"

[111] wrong typed argument ~S"
While reading the signature of a method (list of typed arguments)

[112] wrong type expression ~S"

[113] Wrong lambda definition lambda[~S]

[114] Wrong parametrization ~S

[115] the (resulting) range ~S is not a type

[116] ~S not allowed in function!

[117] loose delimiter ~S in program [line ~A ?]

[118] read wrong char ~S after ~S

[119] read X instead of a Y in a Z
This is produced when the parser finds a grammar error. Please check the syntax for instructions of type Z

[120] the file ~A cannot be opened Produced by a load_file

[121] unprintable error has occurred.
This happens if the printing of an error produced another error. The most common reason is because the self_print method of one of the arguments it itself bugged.

[122] ~A is not a float

[123] YOU ARE USING PRINT_in_string_void RECURSIVELY.
In CLAIRE 3.0, print_in_string() cannot be used recursively

[124] the value ~S does not belong to the range ~S.
This error is produced by type safety checks produced by the compiler. You may look at the generated code to understand which range is violated if it is not self-evident.

[125] ephemeral classes cannot be abstract

[126] ephemeral classes cannot be set as final

[127] ~S can no longer become abstract.
The property was 'closed' by the compiler and cannot be set as an 'open' property

[128] ~S should be an integer.
within the inspector loop, the proper syntax to store a value in a variable is
put(<**integer**>, <name of variable>).

[129] trace not implemented on ~S

[130] untrace not implemented on ~S

[131] Cannot profile a reified property ~S

[132] Cannot change ~S(~S)
The property was declared as a read-only

[133] Inversion of ~S(~S,~S) impossible

[134] Cannot apply add to ~S.
The property is not multi-valued

[135] ~S does not belong to the domain of ~S

[136] ~S is not a collection
In CLAIRE 3.0, only members of the **collection** class may be iterated.

[137] ~S and ~S cannot be inverses for one another

[138] The value of ~S(~S) is unknown
The value of a slot or an array is unknown

[139] ~S: range error, ~S does not belong? to ~S.

[140] The property ~S is not defined (was applied to ~S).
There are no restrictions for the property, probably a typo …

[141] ~S is a wrong arg list for ~S.
No method was found corresponding to the types of the parameters

[142] return called outside of a loop (for or while).

[143] ~I not allowed in format
Format is a method, not a control structure like printf. Thus, it does not support the ~I option.

[144] evaluate(~S) is not defined

[145] the symbol ~A is unbound

[146] The variable ~S is not defined

[147] a name cannot be made from ~S

[148] Wrong selector: ~S, cannot make a property

[149] wrong keyword (~S) after ~S.
expecting a -> or => in a method definition

[150] Illegal use of :~S after ~S.

[151] ~S not allowed after ~S

[152] Separation missing between ~S and ~S [~S?

[153] eof inside an expression

[154] ~S<~S not allowed .
The form C<X> is reserved for parameterized classes

[155] missing | in exists / forall

[156] wrong use of exists(~S ~S ...

[157] ~S cannot follow list{

[158] wrong type in call ~S@~S

[159] missing (after ~S@~S

[160] wrong use of special char #

[161] Missing keyword ~S after ~S

[162] Missing separator ~S after ~S

[163] wrong separator ~S after ~S

[164] ~S cannot be assigned with :=

[165] ~S is illegal after a let/when

[166] Missing (after case ~S

[167] missing) or , after ~S

[168] missing | in selection

[169] missing separation between ~S and ~S

[170] cannot use ~S in a set constant"

[171] Read the character ~S inside a sequence

[172] the sequence ...~S must end with ~A

[173] Expression starting with else

[174] Wrong instantiation list ~S(~S...

[175] Wrong form ~S in ~S(~S)

[176] Missing] after ~S

[177] subtyping of ~S not allowed

[178] cannot enumerate ~S
Iteration is only supported for sets expressions (i.e., members of the collection root class, arrays and integers)

[179] (~S % ~S): not a set!
Membership is only supported for sets expressions (i.e., members of the collection root class, arrays and integers)

[180] nth[~S] out of scope for ~S
There is not enough memory to allocate an objet – the parameter is the size (in cells) that is required for this object.

[181] cannot override a slot for a closed property ~S
You are redefining an existing (inherited) slot for a new class while the property is closed.

[182] the interval (~A -- ~A) is empty
You cannot define an empty interval with -- . This is precisely what - - is there for: guarantee that the returned value is a true, non-empty, interval.

[183] min/max of an empty set is not defined
The min or max method was applied to the empty set.

[184] the close method … has the wrong range
The close method is called automatically after a new instantiation and must return the new object onto which it is applied.

[185] cannot define … as a uniform property
The declaration interface(p) was applied onto a property that is not uniform. Uniformity is the fact that all restrictions have the same signature with the exception of the first member (the domain).

[186] Definition conflict between … and … on a closed property … is not allowed
Once a property is closed, a new restriction may be added only if it does not cause an inheritance conflict with another restriction of this property.

4.2 Debugging System Errors

A system error here is an error reported by your operating system (a core dump, a crash, etc.). A system error that occurs during the execution of an interpreted program is due to a bug in CLAIRE. You should:

- use the tracing methods to detect where the problem occurs and try to find an alternate programming paradigm
- see if an endless loop occurs by using the –s * 0 option that will make a small execution stack. An endless loop often produces a system error that is not properly handled by the operating system.
- send a bug report to clairebugs@yahoo.fr

If a system error occurs with a compiled program, it may be due to a bug in the compiler or to the use of an optimization level that is not appropriate (cf. the discussion about compiler safety). You must first make sure that you reduce the optimization level to 2 or lower. This can be done easily by using the –safe option of the compiler. If the bug persists, it should be treated as previously with the additional option of using a C++ debugger to find out where the bug is occurring. A bug that occurs only with low levels of safety (i.e., high numerical values of compiler.optimizing) is probably due to a compiler warning that got ignored.

A most annoying source of system errors is the garbage collection of unused items. Although the GC is CLAIRE is now quite robust, here are a few tips if you suspect that you have such a bug (system stops in the middle of a GC, the location of the bug changes with the size allocated for CLAIRE using the –s option, etc.).

- use –s a b to see if the problem goes away with enough memory
- try to check the compiler options of your C++ compiler and make sure that the execution stack is large enough
- make explicit calls to gc() in your CLAIRE code in a preventive manner
- use CLAIRE mem() to gather statistics about your memory use

- The slot system.exception! is a back door access to the GC: when it is set to x (an object), the GC will print a message if the object is seen (marked) or freed.
- send a bug report !

However, it must be noticed that the garbage collector is usually the place where other errors get detected. An array overflow or an integer overflow, that happens because the safety level is too low, will corrupt the memory and this will be picked by the garbage collector later on. In the past two years, no real garbage collector problem has been found, while it was unjustly suspected many times.

4.3 Debugging Compiler Errors

During the compilation, the compiler may detect three kinds of anomalies, and will issue respectively a note, a warning or an error. A note is meant to inform the user and does not necessarily reflect a problem. Notes can be ignored safely, although it is better to look into them. A warning is usually associated to a real problem and they must be looked into. A warning may simply point to a non-usual but nevertheless correct situation, yielding a correct executable program. However, most often it produces a non-correct executable and yields a system error at run-time. Therefore, it is necessary to observe all warnings and treat them accordingly. Last, the compiler may detect a situation which makes code generation impossible and stop with an error message.

The next release of the documentation will include a list of the compiler warnings. Here is the current list of compiler errors:

[201] Loose delimiter in program,
most often an unmatched) or] that was not caught by the CLAIRE reader.

[202] A do should have been used for …,
a list or a set construction is not necessary if the result is not used.

[203] You should have used a FOR here: …,
an image or selection is built and not used (a for was enough)

[204] break not inside a For or While: …,
a break statement must be embedded into a for or a while loop, and must not be embedded into an inner try/catch statement

[205] message … sent to void object
the receiver (first argument) of the function call is of type void.

[206] use of void … in … :
use of a void argument, that is a an expression that has received a void type (for instance the “return value” of a method with range void).

[207] inline …: range … is incompatible with … (inferred) : the type inferred for an inline method (=>) is not compatible with the one that was declared

[208] wrong type declaration for case … in … : A case must use type expressions as tags for branches

[209] the first argument in … must be a string: the first argument of a printf is the format string

[210] not enough arguments in … :
a printf must have exactly as many arguments as there are ~X in the format string

[212] the value … of type … cannot be placed in the variable …: the type inferred for the argument of an assignment is not compatible with the type of the variable. This is often the case if the type of the variable is itself inferred (wrongly) from the initial value. It is, therefore, necessary to give an explicit type to this variable.

[213] … is not a variable : assignment require variables

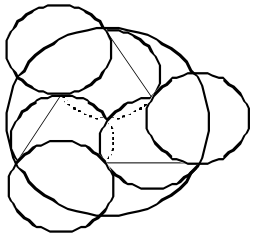
[214] cannot assign …: a global constant was assigned

[215] the symbol … is unbound :
an identifier that was never defined is used (most often a typo).

[216] … has more than 10 parameters :
The compiler only supports dynamic calls with fewer than 12 parameters.

[217] … and … cannot be defined in the same module :
There is a conflict name between two properties.

[218] sort error: cannot compile … :
the given range for a method and the one inferred by CLAIRE are very different and correspond to different sorts, making code generation impossible.



The CLAIRE logo represents:

- three foundation paradigms: Objects, Relations, Functions
- three high-level features: Types, Rules, Versions
- the triangle stands for the tight integration
- the circle is a symbol of unity and ease of use

INDEX

NOTES