CLooG

A Loop Generator For Scanning Polyhedra
Edition 2.1, for CLooG
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`Cédric Bastoul`
: SCHEDULES GENERATE !!! I just need to apply them now, where can I find a good code generator ?!

`Paul Feautrier`
: Hmmm. I fear that if you want something powerful enough, you'll have to write it yourself !

This manual is for CLooG version , a software which generates loops for scanning Z-polyhedra. That is, CLooG produces a code visiting each integral point of a union of parametrized polyhedra. CLooG is designed to avoid control overhead and to produce a very efficient code.

It would be quite kind to refer the following paper in any publication that results from the use of the CLooG software or its library:

```
@InProceedings{Bas04,
  author =    {C. Bastoul},
  title =     {Code Generation in the Polyhedral Model
               Is Easier Than You Think},
  booktitle = {PACT'13 IEEE International Conference on
               Parallel Architecture and Compilation Techniques},
  year =      2004,
  pages =     {7--16},
  month =     {september},
  address =   {Juan-les-Pins}
}
```

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1 Introduction

CLooG is a free software and library generating loops for scanning Z-polyhedra. That is, it finds a code (e.g. in C, FORTRAN...) that reaches each integral point of one or more parameterized polyhedra. CLooG has been originally written to solve the code generation problem for optimizing compilers based on the polytope model. Nevertheless it is used now in various area, e.g., to build control automata for high-level synthesis or to find the best polynomial approximation of a function. CLooG may help in any situation where scanning polyhedra matters. It uses the best state-of-the-art code generation algorithm known as the Quilleré et al. algorithm (see [Qui00], page 41) with our own improvements and extensions (see [Bas04], page 41). The user has full control on generated code quality. On one hand, generated code size has to be tuned for sake of readability or instruction cache use. On the other hand, we must ensure that a bad control management does not hamper performance of the generated code, for instance by producing redundant guards or complex loop bounds. CLooG is specially designed to avoid control overhead and to produce a very efficient code.

CLooG stands for *Chunky Loop Generator*: it is a part of the Chunky project, a research tool for data locality improvement (see [Bas03a], page 41). It is designed also to be the back-end of automatic parallelizers like LooPo (see [Gri04], page 41). Thus it is very compilable code oriented and provides powerful program transformation facilities. Mainly, it allows the user to specify very general schedules where, e.g., unimodularity or invertibility of the transformation doesn't matter.

The current version is still under evaluation, and there is no guarantee that the upward compatibility will be respected (but the previous API has been stable for two years, we hope this one will be as successful -and we believe it-). A lot of reports are necessary to freeze the library API and the input file shape. Most API changes from 0.12.x to 0.14.x have been requested by the users themselves. Thus you are very welcome and encouraged to post reports on bugs, wishes, critics, comments, suggestions or successful experiences in the forum of `http://www.CLooG.org` or to send them to cedric.bastoul@inria.fr directly.

1.1 Basically, what's the point ?

If you want to use CLooG, this is because you want to scan or to find something inside the integral points of a set of polyhedra. There are many reasons for that. Maybe you need the generated code itself because it actually implements a very smart program transformation you found. Maybe you want to use the generated code because you know that the solution of your problem belongs to the integral points of those damned polyhedra and you don't know which one. Maybe you just want to know if a polyhedron has integral points depending on some parameters, which is the lexicographic minimum, maximum, the third on the basis of the left etc. Probably you have your own reasons to use CLooG.

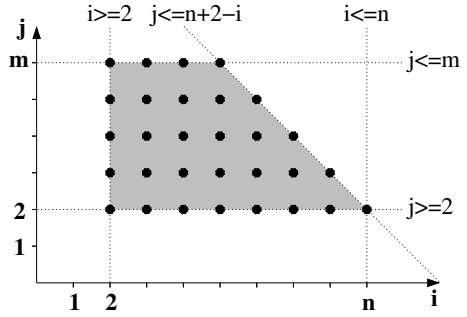
Let us illustrate a basic use of CLooG. Suppose we have a set of affine constraints that describes a part of a whatever-dimensional space, called a **domain**, and we want to scan it. Let us consider for instance the following set of constraints where '`i`' and '`j`' are the unknown (the two dimensions of the space) and '`m`' and '`n`' are the parameters (some symbolic constants):

```
2<=i<=n
2<=j<=m
j<=n+2-i
```

Let us also consider that we have a partial knowledge of the parameter values, called the **context**, expressed as affine constraints as well, for instance:

```
m>=2
n>=2
```

Note that using parameters is optional, if you are not comfortable with parameter manipulation, just replace them with any scalar value that fits `m>=2` and `n>=2`. A graphical representation of this part of the 2-dimensional space, where the integral points are represented using heavy dots would be for instance:



The affine constraints of both the domain and the context are what we will provide to CLooG as input (in a particular shape that will be described later). The output of CLooG is a pseudo-code to scan the integral points of the input domain according to the context:

```
for (i=2;i<=n;i++) {
  for (j=2;j<=min(m,-i+n+2);j++) {
    S1(i,j) ;
  }
}
```

If you felt such a basic example is yet interesting, there is a good chance that CLooG is appropriate for you. CLooG can do much more: scanning several polyhedra or unions of polyhedra at the same time, applying general affine transformations to the polyhedra, generate compilable code etc. Welcome to the CLooG's user's guide !

1.2 Defining a Scanning Order: Scattering Functions

In CLooG, domains only define the set of integral points to scan and their coordinates. In particular, CLooG is free to choose the scanning order for generating the most efficient code. This means, for optimizing/parallelizing compiler people, that CLooG doesn't make any speculation on dependences on and between statements (by the way, it's not its job !). For instance, if an user give to CLooG only two domains `S1:1<=i<=n`, `S2:1<=i<=n` and the context `n>=1`, the following pseudo-codes are considered to be equivalent:

```
/* A convenient target pseudo-code. */
for (i=1;i<=N;i++) {
 S1(i) ;
}
for (i=1;i<=N;i++) {
 S2(i) ;
}
```

```
/* Another convenient target pseudo-code. */
for (i=1;i<=N;i++) {
 S1(i) ;
 S2(i) ;
}
```

The default behaviour of CLooG is to generate the second one, since it is optimized in control. It is right if there are no data dependences between `S1` and `S2`, but wrong otherwise.

Thus it is often useful to force scanning to respect a given order. This can be done in CLooG by using **scattering functions**. Scattering is a shortcut for scheduling, allocation, chunking functions and the like we can find in the restructuring compilation literature. There are a lot of reasons to scatter the integral points of the domains (i.e. the statement instances of a program, for compilation people), parallelization or optimization are good examples. For instance, if the user wants for any reason to set some precedence constraints between the statements of our example above in order to force the generation of the first code, he can do it easily by setting (for example) the following scheduling functions:

$$\theta_{S1}(i) = (1)$$

$$\theta_{S2}(j) = (2)$$

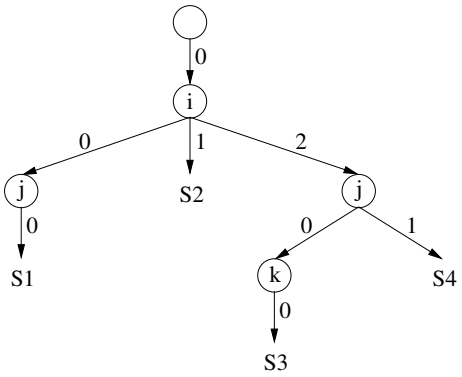
This scattering means that each integral point of the domain `S1` is scanned at logical date `1` while each integral point of the domain `S2` is scanned at logical date `2`. As a result, the whole domain `S1` is scanned before domain `S2` and the first code in our example is generated.

The user can set every kind of affine scanning order thanks to the scattering functions. Each domain has its own scattering function and each scattering function may be multi-dimensional. A multi-dimensional logical date may be seen as classical date (year,month,day,hour,minute,etc.) where the first dimensions are the most significant. Each scattering dimension may depend linearly on the original dimensions (e.g., `i`), the parameters (e.g., `n`) ans scalars (e.g., `2`).

A very useful example of multi-dimensional scattering functions is, for compilation people, the scheduling of the original program. The basic data to use for code generation are statement iteration domains. As we saw, these data are not sufficient to rebuild the original program (what is the ordering between instances of different statements ?). The missing data can be put in the scattering functions as the original scheduling. The method to compute it is quite simple (see [Fea92], page 41). The idea is to build an abstract syntax tree of the program and to read the scheduling for each statement. For instance, let us consider the following implementation of a Cholesky factorization:

```
/* A Cholesky factorization kernel. */
for (i=1;i<=N;i++) {
  for (j=1;j<=i-1;j++) {
    a[i][i] -= a[i][j] ;           /* S1 */
  }
  a[i][i] = sqrt(a[i][i]) ;        /* S2 */
  for (j=i+1;j<=N;j++) {
    for (k=1;k<=i-1;k++) {
      a[j][i] -= a[j][k]*a[i][k] ; /* S3 */
    }
    a[j][i] /= a[i][i] ;           /* S4 */
    }
  }
}
```

The corresponding abstract syntax tree is given in the following figure. It directly gives the scattering functions (schedules) for all the statements of the program.



$$\begin{cases} \theta_{S1}(i,j)^T & = (0,i,0,j,0)^T \\ \theta_{S2}(i) & = (0,i,1)^T \\ \theta_{S3}(i,j,k)^T & = (0,i,2,j,0,k,0)^T \\ \theta_{S4}(i,j)^T & = (0,i,2,j,1)^T \end{cases}$$

These schedules depend on the iterators and give for each instance of each statement a unique execution date. Using such scattering functions allow CLooG to re-generate the input code.

2 Using the CLooG Software

2.1 A First Example

CLooG takes as input a file that must be written accordingly to a grammar described in depth in a further section (see Section 2.2 [Writing The Input File], page 6). Moreover it supports many options to tune the target code presentation or quality as discussed in a dedicated section (see Section 2.3 [Calling CLooG], page 10). However, a basic use of CLooG is not very complex and we present in this section how to generate the code corresponding to a basic example discussed earlier (see Section 1.1 [Basics], page 1).

The problem is to find the code that scans a 2-dimensional polyhedron where '`i`' and '`j`' are the unknown (the two dimensions of the space) and '`m`' and '`n`' are the parameters (the symbolic constants), defined by the following set of constraints:

```
2<=i<=n
2<=j<=m
j<=n+2-i
```

We also consider a partial knowledge of the parameter values, expressed thanks to the following affine constraints:

```
m>=2
n>=2
```

An input file that corresponds to this problem, and asks for a generated code in C, may be the following. Note that we do not describe here precisely the structure and the components of this file (see Section 2.2 [Writing The Input File], page 6 for such information, if you feel it necessary):

```
# ---------------------- CONTEXT ----------------------
c # language is C

# Context (constraints on two parameters)
2 4                   # 2 lines and 4 columns
# eq/in m  n  1         eq/in: 1 for inequality >=0, 0 for equality =0
    1   1  0 -2       # 1*m + 0*n -2*1 >= 0, i.e. m>=2
    1   0  1 -2       # 0*m + 1*n -2*1 >= 0, i.e. n>=2

1 # We want to set manually the parameter names
m n                   # parameter names

# --------------------- STATEMENTS --------------------
1 # Number of statements

1 # First statement: one domain
# First domain
5 6                   # 5 lines and 6 columns
# eq/in i  j  m  n  1
    1   1  0  0  0 -2 # i >= 2
    1  -1  0  0  1  0 # i <= n
```

```
    1   0  1  0  0 -2 # j >= 2
    1   0 -1  1  0  0 # j <= m
    1  -1 -1  0  1  2 # n+2-i>=j
0  0  0               # for future options

1 # We want to set manually the iterator names
i j                   # iterator names

# ---------------------- SCATTERING --------------------
0 # No scattering functions
```

This file may be called '`basic.cloog`' (this example is provided in the CLooG distribution as `test/manual_basic.cloog`) and we can ask CLooG to process it and to generate the code by a simple calling to CLooG with this file as input: '`cloog basic.cloog`'. By default, CLooG will print the generated code in the standard output:

```
/* Generated by CLooG v in 0.00s. */
for (i=2;i<=n;i++) {
  for (j=2;j<=min(m,-i+n+2);j++) {
    S1(i,j) ;
  }
}
```

2.2 Writing The Input File

The input text file contains a problem description, i.e. the context, the domains and the scattering functions. Because CLooG is very 'compilable code generation oriented', we can associate some additional informations to each domain. We call this association a *statement*. The set of all informations is called a *program*. The input file respects the grammar below (terminals are preceded by "_"):

```
File             ::= Program
Program          ::= Context Statements Scattering
Context          ::= Language      Domain_union   Naming
Statements       ::= Nb_statements Statement_list Naming
Scatterings      ::= Nb_functions  Scattering_list Naming
Naming           ::= Option Name_list
Name_list        ::= _String   Name_list      | (void)
Statement_list   ::= Statement Statement_list | (void)
Domain_list      ::= _Domain   Domain_list    | (void)
Scattering_list  ::= Domain_union Scattering_list | (void)
Statement        ::= Iteration_domain 0 0 0
Iteration_domain ::= Domain_union
Domain_union     ::= Nb_domains Domain_list
Option           ::= 0 | 1
Language         ::= c | f
Nb_statements    ::= _Integer
Nb_domains       ::= _Integer
Nb_functions     ::= _Integer
```

Note: if there is only one domain in a '`Domain_union`', i.e., if '`Nb_domains`' is 1, then this 1 may be omitted.

- '`Context`' represents the informations that are shared by all the statements. It consists on the language used (which can be '`c`' for C or '`f`' for FORTRAN 90) and the global constraints on parameters. These constraints are essential since they give to CLooG the number of parameters. If there is no parameter or no constraints on parameters, just give a constraint always satisfied like $1 \geq 0$. '`Naming`' sets the parameter names. If the naming option '`Option`' is 1, parameter names will be read on the next line. There must be exactly as many names as parameters. If the naming option '`Option`' is 0, parameter names are automatically generated. The name of the first parameter will be '`M`', and the name of the $(n+1)^{th}$ parameter directly follows the name of the n^{th} parameter in ASCII code. It is the user responsibility to ensure that parameter names, iterators and scattering dimension names are different.
- '`Statements`' represents the informations on the statements. '`Nb_statements`' is the number of statements in the program, i.e. the number of '`Statement`' items in the '`Statement_list`'. '`Statement`' represents the informations on a given statement. To each statement is associated a domain (the statement iteration domain: '`Iteration_domain`') and three zeroes that represents future options. '`Naming`' sets the iterator names. If the naming option '`Option`' is 1, the iterator names will be read on the next line. There must be exactly as many names as nesting level in the deepest iteration domain. If the naming option '`Option`' is 0, iterator names are automatically generated. The iterator name of the outermost loop will be '`i`', and the iterator name of the loop at level $n+1$ directly follows the iterator name of the loop at level n in ASCII code.
- '`Scatterings`' represents the informations on scattering functions. '`Nb_functions`' is the number of functions (it must be equal to the number of statements or 0 if there is no scattering function). The functions themselves are represented through '`Scattering_list`'. '`Naming`' sets the scattering dimension names. If the naming option '`Option`' is 1, the scattering dimension names will be read on the next line. There must be exactly as many names as scattering dimensions. If the naming option '`Option`' is 0, scattering dimension names are automatically generated. The name of the n^{th} scattering dimension will be '`cn`'.

2.2.1 Domain Representation

As shown by the grammar, the input file describes the various informations thanks to characters, integers and domains. Each domain is defined by a set of constraints in the PolyLib format (see [Wil93], page 41). They have the following syntax:

1. some optional comment lines beginning with '`#`',
2. the row and column numbers, possibly followed by comments,
3. the constraint rows, each row corresponds to a constraint the domain have to satisfy. Each row must be on a single line and is possibly followed by comments. The constraint is an equality $p(x) = 0$ if the first element is 0, an inequality $p(x) \geq 0$ if the first element is 1. The next elements are the unknown coefficients, followed by the parameter coefficients. The last element is the constant factor.

For instance, assuming that '`i`', '`j`' and '`k`' are iterators and '`m`' and '`n`' are parameters, the domain defined by the following constraints :

$$\begin{cases} -i+m & \geq 0 \\ -j+n & \geq 0 \\ i+j-k & \geq 0 \end{cases}$$

can be written in the input file as follows :

```
# This is the domain
3 7                      # 3 lines and 7 columns
# eq/in i  j  k  m  n  1
    1  -1  0  0  1  0  0 #    -i + m >= 0
    1   0 -1  0  0  1  0 #    -j + n >= 0
    1   1  1 -1  0  0  0 # i + j - k >= 0
```

Each iteration domain '`Iteration_domain`' of a given statement is a union of polyhedra '`Domain_union`'. A union is defined by its number of elements '`Nb_domains`' and the elements themselves '`Domain_list`'. For instance, let us consider the following pseudo-code:

```
for (i=1;i<=n;i++) {
  if ((i >= m) || (i <= 2*m))
    S1 ;
  for (j=i+1;j<=m;j++)
    S2 ;
}
```

The iteration domain of '`S1`' can be divided into two polyhedra and written in the input file as follows:

```
2 # Number of polyhedra in the union
# First domain
3 5                # 3 lines and 5 columns
# eq/in i  m  n  1
    1   1  0  0 -1 #  i >= 1
    1  -1  0  1  0 #  i <= n
    1   1 -1  0  0 #  i >= m
# Second domain
3 5                # 3 lines and 5 columns
# eq/in i  m  n  1
    1   1  0  0 -1 #  i >= 1
    1  -1  0  1  0 #  i <= n
    1  -1  2  0  0 #  i <= 2*m
```

2.2.2 Scattering Function Representation

Scattering functions are depicted in the input file thanks a representation very close to the domain one. An integer gives the number of functions '`Nb_functions`' and each function is represented by a domain. Each line of the domain corresponds to an equality defining a dimension of the function. Note that at present (CLooG) **all functions must have the same scattering dimension number**. If a user wants to set scattering functions with different dimensionality, he has to complete the smaller one with zeroes to reach the maximum dimensionality. For instance, let us consider the following code and scheduling functions:

```
for (i=1;i<=n;i++) {
  if ((i >= m) || (i <= 2*m))
    S1 ;
  for (j=i+1;j<=m;j++)
    S2 ;
}
```

$$\begin{cases} \theta_{S1}(i) & = (i,0)^T \\ \theta_{S2}(i,j)^T & = (n,i+j)^T \end{cases}$$

This scheduling can be written in the input file as follows:

```
2 # Number of scattering functions
# First function
2 7                          # 2 lines and 7 columns
# eq/in c1 c2  i  m  n  1
    0    1  0 -1  0  0  0    #  c1 = i
    0    0  1  0  0  0  0    #  c2 = 0
# Second function
2 8                          # 2 lines and 8 columns
# eq/in c1 c2  i  j  m  n  1
    0    1  0  0  0  0 -1  0 #  c1 = n
    0    0  1 -1 -1  0  0  0 #  c2 = i+j
```

The complete input file for the user who wants to generate the code for this example with the preceding scheduling would be (this file is provided in the CLooG distribution as `test/manual_scattering.cloog`:

```
# ---------------------- CONTEXT ----------------------
c # language is C

# Context (no constraints on two parameters)
1 4                   # 1 lines and 4 columns
# eq/in m  n  1
    1   0  0  0       # 0 >= 0, always true

1 # We want to set manually the parameter names
m n                   # parameter names

# --------------------- STATEMENTS --------------------
2 # Number of statements

2 # First statement: two domains
# First domain
3 5                   # 3 lines and 5 columns
# eq/in i  m  n  1
    1   1  0  0 -1    # i >= 1
    1  -1  0  1  0    # i <= n
    1   1 -1  0  0    # i >= m
# Second domain
```

```
3 5                   # 3 lines and 5 columns
# eq/in i  m  n  1
    1   1  0  0 -1    # i >= 1
    1  -1  0  1  0    # i <= n
    1  -1  2  0  0    # i <= 2*m
0  0  0               # for future options

1 # Second statement: one domain
4 6                   # 4 lines and 6 columns
# eq/in i  j  m  n  1
    1   1  0  0  0 -1 # i >= 1
    1  -1  0  0  1  0 # i <= n
    1  -1  1  0  0 -1 # j >= i+1
    1   0 -1  1  0  0 # j <= m
0  0  0               # for future options

1 # We want to set manually the iterator names
i j                   # iterator names

# ---------------------- SCATTERING --------------------
2 # Scattering functions
# First function
2 7                   # 2 lines and 7 columns
# eq/in p1 p2  i  m  n  1
    0    1  0 -1  0  0  0    # p1 = i
    0    0  1  0  0  0  0    # p2 = 0
# Second function
2 8                   # 2 lines and 8 columns
# eq/in p1 p2  i  j  m  n  1
    0    1  0  0  0  0 -1  0 # p1 = n
    0    0  1 -1 -1  0  0  0 # p2 = i+j

1 # We want to set manually the scattering dimension names
p1 p2                 # scattering dimension names
```

2.3 Calling CLooG

CLooG is called by the following command:

```
cloog [ options | file ]
```

The default behavior of CLooG is to read the input informations from a file and to print the generated code or pseudo-code on the standard output. CLooG's behavior and the output code shape is under the user control thanks to many options which are detailed a further section (see Section 2.4 [CLooG Options], page 11). `file` is the input file. `stdin` is a special value: when used, input is standard input. For instance, we can call CLooG to treat the input file `basic.cloog` with default options by typing: `cloog basic.cloog` or `more basic.cloog | cloog stdin`.

2.4 CLooG Options

2.4.1 Last Depth to Optimize Control `-l <depth>`

`-l <depth>`: this option sets the last loop depth to be optimized in control. The higher this depth, the less control overhead. For instance, with some input file, a user can generate different pseudo-codes with different `depth` values as shown below.

```
/* Generated using a given input file and option -l 1 */
for (i=0;i<=M;i++) {
  S1 ;
  for (j=0;j<=N;j++) {
    S2 ;
  }
  for (j=0;j<=N;j++) {
    S3 ;
  }
  S4 ;
}

/* Generated using the same input file but option -l 2 */
for (i=0;i<=M;i++) {
  S1 ;
  for (j=0;j<=N;j++) {
    S2 ;
    S3 ;
  }
  S4 ;
}
```

In this example we can see that this option can change the operation execution order between statements. Let us remind that CLooG does not make any speculation on dependences between statements (see Section 1.2 [Scattering], page 2). Thus if nothing (i.e. scattering functions) forbids this, CLooG considers the above codes to be equivalent. If there is no scattering functions, the minimum value for `depth` is 1 (in the case of 0, the user doesn't really need a loop generator !), and the number of scattering dimensions otherwise (CLooG will warn the user if he doesn't respect such constraint). The maximum value for depth is -1 (infinity). Default value is infinity.

2.4.2 First Depth to Optimize Control `-f <depth>`

`-f <depth>`: this option sets the first loop depth to be optimized in control. The lower this depth, the less control overhead (and the longer the generated code). For instance, with some input file, a user can generate different pseudo-codes with different `depth` values as shown below. The minimum value for `depth` is 1, and the maximum value is -1 (infinity). Default value is 1.

```
/* Generated using a given input file and option -f 3 */
for (i=1;i<=N;i++) {
  for (j=1;j<=M;j++) {
    S1 ;
    if (j >= 10) {
      S2 ;
    }
  }
}

/* Generated using the same input file but option -f 2 */
for (i=1;i<=N;i++) {
  for (j=1;j<=9;j++) {
    S1 ;
  }
  for (j=10;j<=M;j++) {
    S1 ;
    S2 ;
  }
}
```

2.4.3 Statement-wise First and Last Depths to Optimize Control `options->fs, options->ls`

option->f/l (command-line arguments: -f and -l) provide first and last levels to optimize control overhead at a global level (across the entire program / all statements) by separating / splitting loops. option->fs/ls allow the equivalent of setting -f/-l options on a statement-wise basis. Integer arrays options->fs, options->ls should be allocated by the user with options->fs_ls_size set to the number of elements (always equal to the number of statements). For any given loop, the first and last depths of all statements under it are looked at to determine if the loop should be separated (max across all fs' and ls' is taken). A user has to set fs meaningfully, i.e., for eg., if two statements i & j have a fused loop and fs[i], fs[j] specify separation for that level for stmt i but not for stmt j, the input is ambiguous and we will in this case not separate (since a max is taken). options->fs/ls override f/l; if fs/ls are not set or are set inconsistently (max across ls[i] < max across fs[i]), f/l take over.

fs/ls can only be set via the library interface for now.

2.4.4 Simple Convex Hull `-sh <boolean>`

`-sh <boolean>`: this option enables (`boolean=1`) or forbids (`boolean=0`) the use of an overapproximation of the convex hull that may be easier to compute (especially in the isl backend) and that may result in simpler bounds. This option works only for generated code without code duplication (it means, you have to tune `-f` and `-l` options first to generate only a loop nest with internal guards). For instance, with the input file `test/union.cloog`, a user can generate different pseudo-codes as shown below. Default value is 0.

```
/* Generated using test/union.cloog and option -f -1 -l 2 -override */
for (i=0;i<=11;i++) {
  for (j=max(0,5*i-50);j<=min(15,5*i+10);j++) {
    if ((i <= 10) && (j <= 10)) {
      S1 ;
    }
    if ((i >= 1) && (j >= 5)) {
      S2 ;
    }
  }
}

/* Generated using the same input file but option -sh 1 -f -1 -l 2 -override */
for (i=0;i<=11;i++) {
  for (j=0;j<=15;j++) {
    if ((i <= 10) && (j <= 10)) {
      S1 ;
    }
    if ((i >= 1) && (j >= 5)) {
      S2 ;
    }
  }
}
```

2.4.5 Once Time Loop Elimination `-otl <boolean>`

`-otl <boolean>`: this option allows (`boolean=1`) or forbids (`boolean=0`) the simplification of loops running once. Default value is 1.

```
/* Generated using a given input file and option -otl 0 */
for (j=i+1;j<=i+1;j++) {
  S1 ;
}

/* Generated using the same input file but option -otl 1 */
j = i+1 ;
S1 ;
```

2.4.6 Equality Spreading `-esp <boolean>`

`-esp <boolean>`: this option allows (`boolean=1`) or forbids (`boolean=0`) values spreading when there are equalities. Default value is 1.

```
/* Generated using a given input file and option -esp 0 */
i = M+2 ;
j = N ;
for (k=i;k<=j+M;k++) {
  S1 ;
}
```

```
/* Generated using the same input file but option -esp 1 */
for (k=M+2;k<=N+M;k++) {
  S1(i = M+2, j = N) ;
}
```

2.4.7 First Level for Spreading -fsp <level>

`-fsp <level>`: it can be useful to set a first level to begin equality spreading. Particularly when using scattering functions, the user may want to see the scattering dimension values instead of spreading or hiding them. If user has set a spreading, `level` is the first level to start it. Default value is 1.

```
/* Generated using a given input file and option -fsp 1 */
for (j=0;j<=N+M;j++) {
  S1(i = N) ;
}
for (j=0;j<=N+M;j++) {
  S1(i = M) ;
}

/* Generated using the same input file but option -fsp 2 */
c1 = N ;
for (j=0;j<=c1+M;j++) {
  S1(i = c1) ;
}
c1 = M ;
for (j=0;j<=N+c1;j++) {
  S1(i = c1) ;
}
```

2.4.8 Statement Block -block <boolean>

`-block <boolean>`: this option allows (`boolean=1`) to create a statement block for each new iterator, even if there is only an equality. This can be useful in order to parse the generated pseudo-code. When `boolean` is set to 0 or when the generation language is FORTRAN, this feature is disabled. Default value is 0.

```
/* Generated using a given input file and option -block 0 */
i = M+2 ;
j = N ;
S1 ;

/* Generated using the same input file but option -block 1 */
{ i = M+2 ;
  { j = N ;
    S1 ;
  }
}
```

2.4.9 Loop Strides `-strides <boolean>`

`-strides <boolean>`: this options allows (`boolean=1`) to handle non-unit strides for loop increments. This can remove a lot of guards and make the generated code more efficient. Default value is 0.

```
/* Generated using a given input file and option -strides 0 */
for (i=1;i<=n;i++) {
  if (i%2 == 0) {
    S1(j = i/2) ;
  }
  if (i%4 == 0) {
    S2(j = i/4) ;
  }
}
```

```
/* Generated using the same input file but option -strides 1 */
for (i=2;i<=n;i+=2) {
  S1(j = i/2) ;
  if (i%4 == 0) {
    S2(j = i/4) ;
  }
}
```

2.4.10 First Depth to Unroll `-first-unroll <depth>`

`-first-unroll <depth>`: this option sets the first loop depth to unroll. Note that a loop is only unrolled when it is supported by the backend. In case of the isl backend, a loop is unrolled if it has a lower bound that can only be incremented a fixed (non-parametric) amount of times.

2.4.11 Compilable Code `-compilable <value>`

`-compilable <value>`: this options allows (`value` is not 0) to generate a compilable code where all parameters have the integral value `value`. This option creates a macro for each statement. Since CLooG do not know anything about the statement sources, it fills the macros with a basic increment that computes the total number of scanned integral points. The user may change easily the macros according to his own needs. This option is possible only if the generated code is in C. Default value is 0.

```
/* Generated using a given input file and option -compilable 0 */
for (i=0;i<=n;i++) {
  for (j=0;j<=n;j++) {
    S1 ;
    S2 ;
  }
  S3 ;
}
```

```
/* Generated using the same input file but option -compilable 10 */
/* DON'T FORGET TO USE -lm OPTION TO COMPILE. */
```

```
/* Useful headers. */
#include <stdio.h>
#include <stdlib.h>
#include <math.h>

/* Parameter value. */
#define PARVAL 10

/* Statement macros (please set). */
#define S1(i,j) {total++;}
#define S2(i,j) {total++;}
#define S3(i)   {total++;}

int main() {
  /* Original iterators. */
  int i, j ;
  /* Parameters. */
  int n=PARVAL, total=0 ;

  for (i=0;i<=n;i++) {
    for (j=0;j<=n;j++) {
      S1(i,j) ;
      S2(i,j) ;
    }
    S3(i) ;
  }

  printf("Number of integral points: %d.\n",total) ;
  return 0 ;
}
```

2.4.12 Callable Code `-callable <boolean>`

`-callable <boolean>`: if `boolean=1`, then a `test` function will be generated that has the parameters as arguments. Similarly to the `-compilable` option, a macro for each statement is generated. The generated definitions of these macros are as used during the correctness testing, but they can easily be changed by the user to suit her own needs. This option is only available if the target language is C. The default value is 0.

```
/* Generated from double.cloog with option -callable 0 */
for (i=0;i<=M;i++) {
  S1 ;
  for (j=0;j<=N;j++) {
    S2 ;
    S3 ;
  }
  S4 ;
}
```

```
/* Generated from double.cloog with option -callable 1 */
extern void hash(int);

/* Useful macros. */
#define floord(n,d) (((n)<0) ? ((n)-(d)+1)/(d) : (n)/(d))
#define ceild(n,d)  (((n)<0) ? (n)/(d) : ((n)+(d)+1)/(d))
#define max(x,y)    ((x) > (y) ? (x) : (y))
#define min(x,y)    ((x) < (y) ? (x) : (y))

#define S1(i) { hash(1); hash(i); }
#define S2(i,j) { hash(2); hash(i); hash(j); }
#define S3(i,j) { hash(3); hash(i); hash(j); }
#define S4(i) { hash(4); hash(i); }

void test(int M, int N)
{
  /* Original iterators. */
  int i, j;
  for (i=0;i<=M;i++) {
    S1(i) ;
    for (j=0;j<=N;j++) {
      S2(i,j) ;
      S3(i,j) ;
    }
    S4(i) ;
  }
}
```

2.4.13 Output `-o <output>`

`-o <output>`: this option sets the output file. `stdout` is a special value: when used, output is standard output. Default value is `stdout`.

2.4.14 OpenScop `-openscop`

`-openscop`: this option states that the input file complies to the OpenScop specification instead of the native file format (see [Bas11], page 41). This option is available only if the OpenScop support has been enabled at compile time (see Section 4.4 [Optional Features], page 37). The following OpenScop extensions are supported by CLooG (for the details about those extensions, see [Bas11], page 41):

- *scatnames* to set the scattering dimension names.
- *coordinates* to inject the generated code at the place of a given SCoP in a given file. The use of this extension is disabled when the options *-compilable* or *-callable* are set.

2.4.15 Help `--help` or `-h`

`--help` or `-h`: this option ask CLooG to print a short help.

2.4.16 Version `--version` or `-v`

`--version` or `-v`: this option ask CLooG to print some version informations.

2.4.17 Quiet `--quiet` or `-q`

`--quiet` or `-q`: this option tells CLooG not to print any informational messages.

2.5 A Full Example

Let us consider the allocation problem of a Gaussian elimination, i.e. we want to distribute the various statement instances of the compute kernel onto different processors. The original code is the following:

```
for (i=1;j<=N-1;i++) {
  for (j=i+1;j<=N;j++) {
    c[i][j] = a[j][i]/a[i][i] ;    /* S1 */
    for (k=i+1;k<=N;k++) {
      a[j][k] -= c[i][j]*a[i][k] ; /* S2 */
    }
  }
}
```

The best affine allocation functions can be found by any good automatic parallelizer like LooPo (see [Gri04], page 41):

$$\begin{cases} \theta_{S1}(i,j)^T & = (i) \\ \theta_{S2}(i,j,k)^T & = (k) \end{cases}$$

To ensure that on each processor, the set of statement instances is executed according to the original ordering, we add as minor scattering dimensions the original scheduling (see Section 1.2 [Scattering], page 2):

$$\begin{cases} \theta_{S1}(i,j)^T & = (i,0,i,0,j,0)^T \\ \theta_{S2}(i,j,k)^T & = (k,0,i,0,j,1,k,0)^T \end{cases}$$

To ensure that the scattering functions have the same dimensionality, we complete the first function with zeroes (this is a CLooG and previous versions requirement, it should be removed in a future version, don't worry it's absolutely legal !):

$$\begin{cases} \theta_{S1}(i,j)^T & = (i,0,i,0,j,0,0,0)^T \\ \theta_{S2}(i,j,k)^T & = (k,0,i,0,j,1,k,0)^T \end{cases}$$

The input file corresponding to this code generation problem could be (this file is provided in the CLooG distribution as `test/manual_gauss.cloog`:

```
# ---------------------- CONTEXT ----------------------
c # language is C

# Context (no constraints on one parameter)
1 3                     # 1 line and 3 columns
# eq/in n  1
```

```
    1   0  0            # 0 >= 0, always true

1 # We want to set manually the parameter name
n                        # parameter name

# ---------------------- STATEMENTS --------------------
2 # Number of statements

1 # First statement: one domain
4 5                      # 4 lines and 3 columns
# eq/in i  j  n  1
    1   1  0  0 -1       # i >= 1
    1  -1  0  1 -1       # i <= n-1
    1  -1  1  0 -1       # j >= i+1
    1   0 -1  1  0       # j <= n
0  0  0                  # for future options

1
# Second statement: one domain
6 6                      # 6 lines and 3 columns
# eq/in i  j  k  n  1
    1   1  0  0  0 -1    # i >= 1
    1  -1  0  0  1 -1    # i <= n-1
    1  -1  1  0  0 -1    # j >= i+1
    1   0 -1  0  1  0    # j <= n
    1  -1  0  1  0 -1    # k >= i+1
    1   0  0 -1  1  0    # k <= n
0  0  0                  # for future options

0 # We let CLooG set the iterator names

# ---------------------- SCATTERING --------------------
2 # Scattering functions
# First function
8 13                     # 3 lines and 3 columns
# eq/in p1 p2 p3 p4 p5 p6 p7 p8  i  j  n  1
    0    1  0  0  0  0  0  0  0 -1  0  0  0     # p1 = i
    0    0  1  0  0  0  0  0  0  0  0  0  0     # p2 = 0
    0    0  0  1  0  0  0  0  0 -1  0  0  0     # p3 = i
    0    0  0  0  1  0  0  0  0  0  0  0  0     # p4 = 0
    0    0  0  0  0  1  0  0  0  0 -1  0  0     # p5 = j
    0    0  0  0  0  0  1  0  0  0  0  0  0     # p6 = 0
    0    0  0  0  0  0  0  1  0  0  0  0  0     # p7 = 0
    0    0  0  0  0  0  0  0  1  0  0  0  0     # p8 = 0
# Second function
8 14                     # 3 lines and 3 columns
# eq/in p1 p2 p3 p4 p5 p6 p7 p8  i  j  k  n  1
```

```
  0    1  0  0  0  0  0  0  0  0  0 -1  0  0  # p1 = k
  0    0  1  0  0  0  0  0  0  0  0  0  0  0  # p2 = 0
  0    0  0  1  0  0  0  0  0 -1  0  0  0  0  # p3 = i
  0    0  0  0  1  0  0  0  0  0  0  0  0  0  # p4 = 0
  0    0  0  0  0  1  0  0  0  0 -1  0  0  0  # p5 = j
  0    0  0  0  0  0  1  0  0  0  0  0  0 -1  # p6 = 1
  0    0  0  0  0  0  0  1  0  0  0 -1  0  0  # p7 = k
  0    0  0  0  0  0  0  0  1  0  0  0  0  0  # p8 = 0

1 # We want to set manually the scattering dimension names
p1 p2 p3 p4 p5 p6 p7 p8 # scattering dimension names
```

Calling CLooG, with for instance the command line `cloog -fsp 2 gauss.cloog` for a better view of the allocation (the processor number is given by `p1`), will result on the following target code that actually implements the transformation. A minor processing on the dimension `p1` to implement, e.g., MPI calls, which is not shown here may result in dramatic speedups !

```
if (n >= 2) {
  p1 = 1 ;
  for (p5=2;p5<=n;p5++) {
    S1(i = 1,j = p5) ;
  }
}
for (p1=2;p1<=n-1;p1++) {
  for (p3=1;p3<=p1-1;p3++) {
    for (p5=p3+1;p5<=n;p5++) {
      S2(i = p3,j = p5,k = p1) ;
    }
  }
  for (p5=p1+1;p5<=n;p5++) {
    S1(i = p1,j = p5) ;
  }
}
if (n >= 2) {
  p1 = n ;
  for (p3=1;p3<=n-1;p3++) {
    for (p5=p3+1;p5<=n;p5++) {
      S2(i = p3,j = p5,k = n) ;
    }
  }
}
```

3 Using the CLooG Library

The CLooG Library was implemented to allow the user to call CLooG directly from his programs, without file accesses or system calls. The user only needs to link his programs with C libraries. The CLooG library mainly provides one function (`cloog_clast_create_from_input`) which takes as input the problem description with some options, and returns the data structure corresponding to the generated code (a `struct clast_stmt` structure) which is more or less an abstract syntax tree. The user can work with this data structure and/or use our pretty printing function to write the final code in either C or FORTRAN. Some other functions are provided for convenience reasons. These functions as well as the data structures are described in this section.

3.1 CLooG Data Structures Description

In this section, we describe the data structures used by the loop generator to represent and to process a code generation problem.

3.1.1 CloogState

```
CloogState *cloog_state_malloc(void);
void cloog_state_free(CloogState *state);
```

The `CloogState` structure is (implicitly) needed to perform any CLooG operation. It should be created using `cloog_state_malloc` before any other CLooG objects are created and destroyed using `cloog_state_free` after all objects have been freed. It is allowed to use more than one `CloogState` structure at the same time, but an object created within the state of a one `CloogState` structure is not allowed to interact with an object created within the state of an other `CloogState` structure.

3.1.1.1 isl

```
#include <cloog/isl/cloog.h>
CloogState *cloog_isl_state_malloc(isl_ctx *ctx);
```

When using the isl backend, CLooG will internally create many isl objects. If the user creates any CLooG objects from isl objects (e.g., through `cloog_domain_from_isl_set` below), then the user needs to make sure that these isl objects live in the same `isl_ctx` as those created by CLooG internally. The best way to ensure this property is to pass the `isl_ctx` created by the user to CLooG by calling `cloog_isl_state_malloc` to create a `CloogState`. Note that this makes the created `CloogState` a user of the given `isl_ctx`, meaning that the `CloogState` needs to be freed before the `isl_ctx` is freed.

3.1.2 CloogMatrix

The `CloogMatrix` structure is equivalent to the PolyLib `Matrix` data structure (see [Wil93], page 41). This structure is devoted to represent a set of constraints.

```
struct cloogmatrix
{ unsigned NbRows ;    /* Number of rows. */
  unsigned NbColumns ; /* Number of columns. */
  cloog_int_t **p;     /* Array of pointers to the matrix rows. */
  cloog_int_t *p_Init; /* Matrix rows contiguously in memory. */
};
typedef struct cloogmatrix CloogMatrix;

CloogMatrix *cloog_matrix_alloc(unsigned NbRows, unsigned NbColumns);
void cloog_matrix_print(FILE *foo, CloogMatrix *m);
void cloog_matrix_free(CloogMatrix *matrix);
```

The whole matrix is stored in memory row after row at the `p_Init` address. `p` is an array of pointers where `p[i]` points to the first element of the i^{th} row. `NbRows` and `NbColumns` are respectively the number of rows and columns of the matrix. Each row corresponds to a constraint. The first element of each row is an equality/inequality tag. The constraint is an equality $p(x) = 0$ if the first element is 0, but it is an inequality $p(x) \geq 0$ if the first element is 1. The next elements are the coefficients of the unknowns, followed by the coefficients of the parameters, and finally the constant term. For instance, the following three constraints:

$$\begin{cases} -i + m & = 0 \\ -j + n & \geq 0 \\ j + i - k & \geq 0 \end{cases}$$

would be represented by the following rows:

```
# eq/in  i   j   k   m   n   cst
    0    0  -1   0   1   0    0
    1   -1   0   0   0   1    0
    1    1   1  -1   0   0    0
```

To be able to provide different precision version (CLooG supports 32 bits, 64 bits and arbitrary precision through the GMP library), the `cloog_int_t` type depends on the configuration options (it may be `long int` for 32 bits version, `long long int` for 64 bits version, and `mpz_t` for multiple precision version).

3.1.3 CloogDomain

```
CloogDomain *cloog_domain_union_read(CloogState *state,
                                     FILE *input, int nb_parameters);
CloogDomain *cloog_domain_from_cloog_matrix(CloogState *state,
                                    CloogMatrix *matrix, int nb_par);
void cloog_domain_free(CloogDomain *domain);
```

`CloogDomain` is an opaque type representing a polyhedral domain (a union of polyhedra). A `CloogDomain` can be read from a file using `cloog_domain_union_read` or converted from a `CloogMatrix`. The input format for `cloog_domain_union_read` is that of Section 2.2.1 [Domain Representation], page 7. The function `cloog_domain_from_cloog_matrix` takes a `CloogState`, a `CloogMatrix` and `int` as input and returns a pointer to a `CloogDomain`. `matrix` describes the domain and `nb_par` is the number of parameters in this domain. The input data structures are neither modified nor freed. The `CloogDomain` can be freed

using `cloog_domain_free`. There are also some backend dependent functions for creating `CloogDomain`s.

3.1.3.1 PolyLib

```
#include <cloog/polylib/cloog.h>
CloogDomain *cloog_domain_from_polylib_polyhedron(CloogState *state,
                                                  Polyhedron *, int nb_par);
```

The function `cloog_domain_from_polylib_polyhedron` takes a PolyLib `Polyhedron` as input and returns a pointer to a `CloogDomain`. The `nb_par` parameter indicates the number of parameters in the domain. The input data structure if neither modified nor freed.

3.1.3.2 isl

```
#include <cloog/isl/cloog.h>
CloogDomain *cloog_domain_from_isl_set(__isl_take isl_set *set);
__isl_give isl_set *isl_set_from_cloog_domain(CloogDomain *domain);
```

The function `cloog_domain_from_isl_set` takes an `isl_set` as input and returns a pointer to a `CloogDomain`. The function consumes a reference to the given `isl_set`. Similarly, `isl_set_from_cloog_domain` consumes a reference to a `CloogDomain` and returns an `isl_set`.

3.1.4 CloogScattering

```
CloogScattering *cloog_domain_read_scattering(CloogDomain *domain,
                                              FILE *foo);
CloogScattering *cloog_scattering_from_cloog_matrix(CloogState *state,
                          CloogMatrix *matrix, int nb_scat, int nb_par);
void cloog_scattering_free(CloogScattering *);
```

The `CloogScattering` type represents a scattering function. A `CloogScattering` for a given `CloogDomain` can be read from a file using `cloog_scattering_read` or converted from a `CloogMatrix` using `cloog_scattering_from_cloog_matrix`. The function `cloog_scattering_from_cloog_matrix` takes a `CloogState`, a `CloogMatrix` and two `int`s as input and returns a pointer to a `CloogScattering`. `matrix` describes the scattering, while `nb_scat` and `nb_par` are the number of scattering dimensions and the number of parameters, respectively. The input data structures are neither modified nor freed. A `CloogScattering` can be freed using `cloog_scattering_free`. There are also some backend dependent functions for creating `CloogScattering`s.

3.1.4.1 PolyLib

```
#include <cloog/polylib/cloog.h>
CloogScattering *cloog_scattering_from_polylib_polyhedron(
        CloogState *state, Polyhedron *polyhedron, int nb_par);
```

The function `cloog_scattering_from_polylib_polyhedron` takes a PolyLib `Polyhedron` as input and returns a pointer to a `CloogScattering`. The `nb_par` parameter indicates the number of parameters in the domain. The input data structure if neither modified nor freed.

3.1.4.2 isl

```
#include <cloog/isl/cloog.h>
```

```
CloogScattering *cloog_scattering_from_isl_map(__isl_take isl_map *map);
```

The function `cloog_scattering_from_isl_map` takes an `isl_map` as input and returns a pointer to a `CloogScattering`. The output dimensions of the `isl_map` correspond to the scattering dimensions, while the input dimensions correspond to the domain dimensions. The function consumes a reference to the given `isl_map`.

3.1.5 CloogUnionDomain

```
enum cloog_dim_type { CLOOG_PARAM, CLOOG_ITER, CLOOG_SCAT };

CloogUnionDomain *cloog_union_domain_alloc(int nb_par);
CloogUnionDomain *cloog_union_domain_add_domain(CloogUnionDomain *ud,
        const char *name, CloogDomain *domain,
        CloogScattering *scattering, void *usr);
CloogUnionDomain *cloog_union_domain_set_name(CloogUnionDomain *ud,
        enum cloog_dim_type type, int index, const char *name);
void cloog_union_domain_free(CloogUnionDomain *ud);
```

A `CloogUnionDomain` structure represents a union of scattered named domains. A `CloogUnionDomain` is initialized by a call to `cloog_union_domain_alloc`, after which domains can be added using `cloog_union_domain_add_domain`.

`cloog_union_domain_alloc` takes the number of parameters as input. `cloog_union_domain_add_domain` takes a previously created `CloogUnionDomain` as input along with an optional name, a domain, an optional scattering function and a user pointer. The name may be `NULL` and is duplicated if it is not. If no name is specified, then the statements will be named according to the order in which they were added. `domain` and `scattering` are taken over by the `CloogUnionDomain`. `scattering` may be `NULL`, but it must be consistently `NULL` or not over all calls to `cloog_union_domain_add_domain`. `cloog_union_domain_set_name` can be used to set the names of parameters, iterators and scattering dimensions. The names of iterators and scattering dimensions can only be set after all domains have been added.

There is also a backend dependent function for creating `CloogUnionDomain`s.

3.1.5.1 isl

```
#include <cloog/isl/cloog.h>
CloogUnionDomain *cloog_union_domain_from_isl_union_map(
        __isl_take isl_union_map *umap);
CloogUnionDomain *cloog_union_domain_from_isl_set(
__isl_take isl_set *set);
```

The function `cloog_union_domain_from_isl_union_map` takes a `isl_union_map` as input and returns a pointer to a `CloogUnionDomain`. The input is a mapping from different spaces (different tuple names and possibly different dimensions) to a common space. The iteration domains are set to the domains in each space. The statement names are set to the names of the spaces. The parameter names of the result are set to those of the input, but the iterator and scattering dimension names are left unspecified. The function consumes a reference to the given `isl_union_map`. The function `cloog_union_domain_from_isl_set` is similar, but takes an unscattered domain as input. It is not defined for an union_set, because the order of iterations from two different isl_sets is undefined, if no scattering is provided.

3.1.6 CloogStatement

```
struct cloogstatement
{ int number ;                  /* The statement unique number. */
  char *name;                   /* Name of the statement. */
  void * usr ;                  /* Pointer for user's convenience. */
  struct cloogstatement * next ;/* Next element of the linked list. */
} ;
typedef struct cloogstatement CloogStatement ;

CloogStatement *cloog_statement_malloc(CloogState *state);
void cloog_statement_print(FILE *, CloogStatement *);
void cloog_statement_free(CloogStatement *);
```

The `CloogStatement` structure represents a `NULL` terminated linked list of statements. In CLooG, a statement is only defined by its unique number (`number`). The user can use the pointer `usr` for his own convenience to link his own statement representation to the corresponding `CloogStatement` structure. The whole management of the `usr` pointer is under the responsibility of the user, in particular, CLooG never tries to print, to allocate or to free a memory block pointed by `usr`.

3.1.7 CloogOptions

```
struct cloogoptions
{ int l;                    /* -l option.                                */
  int f;                    /* -f option.                                */
  int *ls;                  /* Statement-wise l option                   */
  int *fs;                  /* Statement-wise f option                   */
  int fs_ls_size;           /* Size of the fs and ls arrays (same size)  */
  int strides;              /* -strides option.                          */
  int sh;                   /* -sh option.                               */
  int first_unroll;         /* -first-unroll option.                     */
  int esp;                  /* -esp option.                              */
  int fsp;                  /* -fsp option.                              */
  int otl;                  /* -otl option.                              */
  int block;                /* -block option.                            */
  int compilable;           /* -compilable option.                       */
  int language;             /* CLOOG_LANGUAGE_C or CLOOG_LANGUAGE_FORTRAN */
  int save_domains;         /* Save unsimplified copy of domain.         */
} ;
typedef struct cloogoptions CloogOptions ;

CloogOptions *cloog_options_malloc(CloogState *state);
void cloog_options_print(FILE *foo, CloogOptions *options);
void cloog_options_free(CloogOptions *options);
```

The `CloogOptions` structure contains all the possible options to rule CLooG's behaviour (see Section 2.3 [Calling CLooG], page 10). As a reminder, the default values are:

- $l = -1$ (optimize control until the innermost loops),
- $f = 1$ (optimize control from the outermost loops),

- $ls/fs = NULL$ and $fs_ls_size = 0$ (statement-wise l/f are not set),
- $strides = 0$ (use only unit strides),
- $sh = 0$ (do not compute simple convex hulls),
- $first_unroll = -1$ (do not perform unrolling),
- $esp = 1$ (spread complex equalities),
- $fsp = 1$ (start to spread from the first iterators),
- $otl = 1$ (simplify loops running only once).
- $block = 0$ (do not make statement blocks when not necessary).
- $compilable = 0$ (do not generate a compilable code).

The `save_domains` option is only useful for users of the CLooG library. This option defaults to 0, but when it is set, the `domain` field of each `clast_user_stmt` will be set to the set of values for the scattering dimensions for which this instance of the user statement is executed. The `domain` field of each `clast_for` contains the set of values for the scattering dimensions for which an instance of a user statement is executed inside the `clast_for`. It is only available if the `clast_for` enumerates a scattering dimension.

3.1.8 CloogInput

```
CloogInput *cloog_input_read(FILE *file, CloogOptions *options);
CloogInput *cloog_input_alloc(CloogDomain *context,
                              CloogUnionDomain *ud);
void cloog_input_free(CloogInput *input);

void cloog_input_dump_cloog(FILE *, CloogInput *, CloogOptions *);
```

A `CloogInput` structure represents the input to CLooG. It is essentially a `CloogUnionDomain` along with a context `CloogDomain`. A `CloogInput` can be created from a `CloogDomain` and a `CloogUnionDomains` using `cloog_input_alloc`, or it can be read from a CLooG input file using `cloog_input_read`. The latter also modifies the `language` field of the `CloogOptions` structure. The constructed `CloogInput` can be used as input to a `cloog_clast_create_from_input` call.

A `CloogInput` data structure and a `CloogOptions` contain the same information as a .cloog file. This function dumps the .cloog description of the given data structures into a file.

3.1.9 Dump CLooG Input File Function

3.2 CLooG Output

Given a description of the input, an AST corresponding to the `CloogInput` can be constructed using `cloog_clast_create_from_input` and destroyed using `free_clast_stmt`.

```
struct clast_stmt *cloog_clast_create_from_input(CloogInput *input,
                                                 CloogOptions *options);
void free_clast_stmt(struct clast_stmt *s);
```

`clast_stmt` represents a linked list of “statements”.

```
struct clast_stmt {
    const struct clast_stmt_op    *op;
    struct clast_stmt *next;
};
```

The entries in the list are not of type `clast_stmt` itself, but of some larger type. The following statement types are defined by CLooG.

```
struct clast_root {
    struct clast_stmt   stmt;
    CloogNames *        names;
};
struct clast_root *new_clast_root(CloogNames *names);

struct clast_assignment {
    struct clast_stmt   stmt;
    const char *        LHS;
    struct clast_expr * RHS;
};
struct clast_assignment *new_clast_assignment(const char *lhs,
                                              struct clast_expr *rhs);

struct clast_block {
    struct clast_stmt   stmt;
    struct clast_stmt * body;
};
struct clast_block *new_clast_block(void);

struct clast_user_stmt {
    struct clast_stmt   stmt;
    CloogDomain * domain;
    CloogStatement *    statement;
    struct clast_stmt * substitutions;
};
struct clast_user_stmt *new_clast_user_stmt(CloogDomain *domain,
    CloogStatement *stmt, struct clast_stmt *subs);

struct clast_for {
    struct clast_stmt   stmt;
    CloogDomain *       domain;
    const char *        iterator;
    struct clast_expr * LB;
    struct clast_expr * UB;
    cloog_int_t         stride;
    struct clast_stmt * body;
};
struct clast_for *new_clast_for(CloogDomain *domain, const char *it,
                                struct clast_expr *LB, struct clast_expr *UB,
```

```
                                cloog_int_t stride);

struct clast_guard {
    struct clast_stmt   stmt;
    struct clast_stmt * then;
    int                 n;
    struct clast_equation       eq[1];
};
struct clast_guard *new_clast_guard(int n);
```

The `clast_stmt` returned by `cloog_clast_create` is a `clast_root`. It contains a placeholder for all the variable names that appear in the AST and a (list of) nested statement(s).

A `clast_assignment` assigns the value given by the `clast_expr RHS` to a variable named `LHS`.

A `clast_block` groups a list of statements into one statement. These statements are only generated if the `block` option is set, see Section 2.4.8 [Statement Block], page 14 and Section 3.1.7 [CloogOptions], page 25.

A `clast_user_stmt` represents a call to a statement specified by the user, see Section 3.1.6 [CloogStatement], page 25. `substitutions` is a list of `clast_assignment` statements assigning an expression in terms of the scattering dimensions to each of the original iterators in the original order. The `LHS`s of these assignments are left blank (`NULL`). The `domain` is set to `NULL` if the `save_domains` option is not set. Otherwise, it is set to the set of values for the scattering dimensions for which this instance of the user statement is executed. Note that unless the `noscalars` option has been set, the constant scattering dimensions may have been removed from this set.

A `clast_for` represents a for loop, iterating `body` for each value of `iterator` between `LB` and `UB` in steps of size `stride`. The `domain` is set to `NULL` if the `save_domains` option is not set. Otherwise, it is set to the set of values for the scattering dimensions for which a user statement is executed inside this `clast_for`. Note that unless the `noscalars` option has been set, the constant scattering dimensions may have been removed from this set.

A `clast_guard` represents the guarded execution of the `then` (list of) statement(s) by a conjunction of `n` (in)equalities. Each (in)equality is represented by a `clast_equation`.

```
struct clast_equation {
    struct clast_expr * LHS;
    struct clast_expr * RHS;
    int sign;
};
```

The condition expressed by a `clast_equation` is `LHS <= RHS`, `LHS == RHS` or `LHS >= RHS` depending on whether `sign` is less than zero, equal to zero, or greater than zero.

The dynamic type of a `clast_stmt` can be determined using the macro `CLAST_STMT_IS_A(stmt,type)`, where `stmt` is a pointer to a `clast_stmt` and `type` is one of `stmt_root`, `stmt_ass`, `stmt_user`, `stmt_block`, `stmt_for` or `stmt_guard`. Users are allowed to define their own statement types by assigning the `op` field of the statements a pointer to a `clast_stmt_op` structure.

```
struct clast_stmt_op {
    void (*free)(struct clast_stmt *);
```

```
};
```

The `free` field of this structure should point to a function that frees the user defined statement.

A `clast_expr` can be an identifier, a term, a binary expression or a reduction.

```
enum clast_expr_type {
    clast_expr_name,
    clast_expr_term,
    clast_expr_bin,
    clast_expr_red
};
struct clast_expr {
    enum clast_expr_type type;
};
void free_clast_expr(struct clast_expr *e);
```

Identifiers are of subtype `clast_name`.

```
struct clast_name {
    struct clast_expr expr;
    const char * name;
};
struct clast_name *new_clast_name(const char *name);
void free_clast_name(struct clast_name *t);
```

The character string pointed to by `name` is assumed to be part of the `CloogNames` structure in the root of the clast as is therefore not copied.

Terms are of type `clast_term`.

```
struct clast_term {
    struct clast_expr   expr;
    cloog_int_t         val;
    struct clast_expr  *var;
};
struct clast_term *new_clast_term(cloog_int_t c, struct clast_expr *v);
void free_clast_term(struct clast_term *t);
```

If `var` is set to `NULL`, then the term represents the integer value `val`. Otherwise, it represents the term `val * var`. `new_clast_term` simply copies the `v` pointer without copying the underlying `clast_expr`. `free_clast_term`, on the other hand, recursively frees `var`.

Binary expressions are of type `clast_bin_type` and represent either the floor of a division (fdiv), the ceil of a division (cdiv), an exact division or the remainder of an fdiv.

```
enum clast_bin_type { clast_bin_fdiv, clast_bin_cdiv,
                      clast_bin_div, clast_bin_mod };
struct clast_binary {
    struct clast_expr   expr;
    enum clast_bin_type type;
    struct clast_expr*  LHS;
    cloog_int_t         RHS;
};
```

```
struct clast_binary *new_clast_binary(enum clast_bin_type t,
                            struct clast_expr *lhs, cloog_int_t rhs);
void free_clast_binary(struct clast_binary *b);
```

Reductions are of type `clast_reduction` and can represent either the sum, the minimum or the maximum of its elements.

```
enum clast_red_type { clast_red_sum, clast_red_min, clast_red_max };
struct clast_reduction {
    struct clast_expr   expr;
    enum clast_red_type type;
    int                 n;
    struct clast_expr*  elts[1];
};
struct clast_reduction *new_clast_reduction(enum clast_red_type t,
                                            int n);
void free_clast_reduction(struct clast_reduction *r);
```

3.3 Retrieving version information

CLooG provides static and dynamic version checks to assist on including a compatible version of the library. A static version check at compile time can be achieved by querying the version constants defined in `version.h`:

- `CLOOG_VERSION_MAJOR`
- `CLOOG_VERSION_MINOR`
- `CLOOG_VERSION_REVISION`

This way it is possible to ensure the included headers are of the correct version. It is still possible that the installed CLooG library version differs from the installed headers. In order to avoid this, a dynamic version check is provided with the functions:

```
int cloog_version_major(void);
int cloog_version_minor(void);
int cloog_version_revision(void);
```

By using both the static and the dynamic version check, it is possible to match CLooG's header version with the library's version.

3.4 Example of Library Utilization

3.4.1 Basic Library Utilization

Here is a basic example showing how it is possible to use the CLooG library, assuming that a standard installation has been done. The following C program reads a CLooG input file on the standard input, then prints the solution on the standard output. Options are preselected to the default values of the CLooG software. This example is provided in the `example` directory of the CLooG distribution.

```
/* example.c */
# include <stdio.h>
# include <cloog/cloog.h>
```

```
int main() {
  CloogState *state;
  CloogInput *input;
  CloogOptions *options ;
  struct clast_stmt *root;

  /* Setting options and reading program informations. */
  state = cloog_state_malloc();
  options = cloog_options_malloc(state);
  input = cloog_input_read(stdin, options);

  /* Generating and printing the code. */
  root = cloog_clast_create_from_input(input, options);
  clast_pprint(stdout, root, 0, options);

  cloog_clast_free(root);
  cloog_options_free(options) ;
  cloog_state_free(state);
  return 0;
}
```

The compilation (with default isl/GMP version installed) command could be:

```
gcc -DCLOOG_INT_GMP example.c -lcloog-isl -o example
```

A calling command with the input file test.cloog could be:

```
more test.cloog | ./example
```

3.4.2 Scanning isl Sets

Here is an isl-level example to prepare a convenient input, to generate the Clast of the scanning code for this input, to pretty-print the code and to de-allocate memory in a clean way. This example is provided in the `example` directory of the CLooG distribution.

```
/* example-isl.c */
#include <cloog/cloog.h>
#include <cloog/isl/cloog.h>

/* Input problem */
int nb_parameters = 1;
char *parameter_name[]  = {"N"};
char *iterator_name[]   = {"i", "j"};
char *scattering_name[] = {"t0", "t1", "t2"};
char *str_context       = "[N] -> { : N > 0}";
char *str_domain1       = "[N] -> {[i, j] : 0 <= i < N and 0 <= j < N}";
char *str_domain2       = "[N] -> {[i, j] : 0 <= i < N and 0 <= j < N}";
char *str_scattering1   = "[N] -> {[i, j] -> [0, i + j, j]}";
char *str_scattering2   = "[N] -> {[i, j] -> [1, i,    -j]}";

int main() {
  isl_ctx *ctx;
```

```
isl_set *set_context, *set1, *set2;
isl_map *map1, *map2;
CloogDomain *context, *domain1, *domain2;
CloogScattering *scattering1, *scattering2;
CloogUnionDomain *domains;
CloogInput *input;
CloogState *state;
CloogOptions *options;
struct clast_stmt *root;

/* Build isl structures for context, sets and mapping */
ctx = isl_ctx_alloc();
set_context = isl_set_read_from_str(ctx, str_context);
set1 = isl_set_read_from_str(ctx, str_domain1);
set2 = isl_set_read_from_str(ctx, str_domain2);
map1 = isl_map_read_from_str(ctx, str_scattering1);
map2 = isl_map_read_from_str(ctx, str_scattering2);

/* Translate them to CLooG context, domains and scattering */
context = cloog_domain_from_isl_set(set_context);
domain1 = cloog_domain_from_isl_set(set1);
domain2 = cloog_domain_from_isl_set(set2);
scattering1 = cloog_scattering_from_isl_map(map1);
scattering2 = cloog_scattering_from_isl_map(map2);

/* Prepare the list of domains to scan */
domains = cloog_union_domain_alloc(nb_parameters);
cloog_union_domain_add_domain(domains,"S1",domain1,scattering1,NULL);
cloog_union_domain_add_domain(domains,"S2",domain2,scattering2,NULL);
cloog_union_domain_set_name(domains,CLOOG_PARAM,0,parameter_name[0]);
cloog_union_domain_set_name(domains,CLOOG_ITER, 0,iterator_name[0]);
cloog_union_domain_set_name(domains,CLOOG_ITER, 1,iterator_name[1]);
cloog_union_domain_set_name(domains,CLOOG_SCAT, 0,scattering_name[0]);
cloog_union_domain_set_name(domains,CLOOG_SCAT, 1,scattering_name[1]);
cloog_union_domain_set_name(domains,CLOOG_SCAT, 2,scattering_name[2]);

/* Build the input, generate a scanning code AST and print the code */
input = cloog_input_alloc(context, domains);
state = cloog_isl_state_malloc(ctx);
options = cloog_options_malloc(state);
root = cloog_clast_create_from_input(input, options);
clast_pprint(stdout, root, 0, options);

/* Recycle allocated memory */
cloog_clast_free(root);
cloog_options_free(options);
cloog_state_free(state);
```

```
  isl_ctx_free(ctx);
}
```

The compilation (with default isl/GMP version installed) command could be:

```
gcc -DCLOOG_INT_GMP example-isl.c -lcloog-isl -o example-isl
```

A calling command could be:

```
./example-isl
```

4 Installing CLooG

4.1 License

First of all, it would be very kind to refer the following paper in any publication that result from the use of the CLooG software or its library, see [Bas04], page 41 (a bibtex entry is provided behind the title page of this manual, along with copyright notice, and in the CLooG home `http://www.CLooG.org`.

This library is free software; you can redistribute it and/or modify it under the terms of the GNU Lesser General Public License as published by the Free Software Foundation; either version 2.1 of the License, or (at your option) any later version. This library is distributed in the hope that it will be useful, but WITHOUT ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the GNU Lesser General Public License for more details. `http://www.gnu.org/licenses/lgpl-2.1.html`

Note, though, that if you link CLooG against a GPL library such as the PolyLib backend, then the combination becomes GPL too. In particular, a CLooG library based on the PolyLib backend is GPL version 2 only. Since the isl backend is LGPL, linking against it does not affect the license of CLooG.

4.2 Requirements

CLooG can be used with one of two possible backends, one using isl and one using PolyLib. The isl library is included in the CLooG distribution, while the PolyLib library needs to be obtained separately. On the other hand, isl requires GMP, while PolyLib can be compiled with or without the use of GMP. The user therefore needs to install at least one of PolyLib or GMP.

4.2.1 PolyLib (optional)

To successfully install CLooG with the PolyLib backend, the user first needs to install PolyLib version 5.22.1 or above (default 64 bits version is satisfying as well as 32 bits or GMP multiple precision version). Polylib can be downloaded freely at `http://icps.u-strasbg.fr/PolyLib/` or `http://www.irisa.fr/polylib/`. Once downloaded and unpacked (e.g. using the '`tar -zxvf polylib-5.22.3.tar.gz`' command), the user can compile it by typing the following commands on the PolyLib's root directory:

- `./configure`
- `make`
- And as root: `make install`

Alternatively, the latest development version can be obtained from the git repository:

- `git clone git://repo.or.cz/polylib.git`
- `cd polylib`
- `./autogen.sh`
- `./configure`

- `make`
- And as root: `make install`

The PolyLib default installation is `/usr/local`. This directory may not be inside your library path. To fix the problem, the user should set

```
export LD_LIBRARY_PATH=$LD_LIBRARY_PATH:/usr/local/lib
```

if your shell is, e.g., bash or

```
setenv LD_LIBRARY_PATH $LD_LIBRARY_PATH:/usr/local/lib
```

if your shell is, e.g., tcsh. Add the line to your .bashrc or .tcshrc (or whatever convenient file) to make this change permanent. Another solution is to ask PolyLib to install in the standard path by using the prefix option of the configure script: '`./configure --prefix=/usr`'.

CLooG makes intensive calls to polyhedral operations, and PolyLib functions do the job. Polylib is a free library written in C for the manipulation of polyhedra. The library is operating on objects like vectors, matrices, lattices, polyhedra, Z-polyhedra, unions of polyhedra and a lot of other intermediary structures. It provides functions for all the important operations on these structures.

4.2.2 GMP Library (optional)

To be able to deal with insanely large coefficient, the user will need to install the GNU Multiple Precision Library (GMP for short) version 4.1.4 or above. It can be freely downloaded from `http://www.swox.com/gmp`. Note that the isl backend currently requires GMP. The user can compile GMP by typing the following commands on the GMP root directory:

- `./configure`
- `make`
- And as root: `make install`

The GMP default installation is `/usr/local`, the same method to fix a library path problem applies as with PolyLib (see Section 4.2.1 [PolyLib], page 35).

If you want to use the PolyLib backend, then PolyLib has to be built using the GMP library by specifying the option '`--with-libgmp=PATH_TO_GMP`' to the PolyLib configure script (where `PATH_TO_GMP` is `/usr/local` if you did not change the GMP installation directory). Then you have to set the convenient CLooG configure script options to build the GMP version (see Section 4.4 [Optional Features], page 37).

4.3 CLooG Basic Installation

Once downloaded and unpacked (e.g. using the '`tar -zxvf cloog-.tar.gz`' command), you can compile CLooG by typing the following commands on the CLooG's root directory:

- `./configure`
- `make`
- And as root: `make install`

Alternatively, the latest development version can be obtained from the git repository:

- `git clone git://repo.or.cz/cloog.git`
- `cd cloog`

- `./get_submodules.sh`
- `./autogen.sh`
- `./configure`
- `make`
- And as root: `make install`

Depending on which backend you want to use and where they are located, you may need to pass some options to the configure script, see Section 4.4 [Optional Features], page 37.

The program binaries and object files can be removed from the source code directory by typing `make clean`. To also remove the files that the `configure` script created (so you can compile the package for a different kind of computer) type `make distclean`.

Both the CLooG software and library have been successfully compiled on the following systems:

- PC's under Linux, with the `gcc` compiler,
- PC's under Windows (Cygwin), with the `gcc` compiler,
- Sparc and UltraSparc Stations, with the `gcc` compiler.

4.4 Optional Features

The `configure` shell script attempts to guess correct values for various system-dependent variables and user options used during compilation. It uses those values to create the `Makefile`. Various user options are provided by the CLooG's configure script. They are summarized in the following list and may be printed by typing `./configure --help` in the CLooG top-level directory.

- By default, the installation directory is `/usr/local`: `make install` will install the package's files in `/usr/local/bin`, `/usr/local/lib` and `/usr/local/include`. The user can specify an installation prefix other than `/usr/local` by giving `configure` the option `--prefix=PATH`.
- By default, the isl backend will use the version of isl that is `bundled` together with CLooG. Using the `--with-isl` option of `configure` the user can specify that `no` isl, a previously installed (`system`) isl or a `build` isl should be used. In the latter case, the user should also specify the build location using `--with-isl-builddir=PATH`. In case of an installed isl, the installation location can be specified using the `--with-isl-prefix=PATH` and `--with-isl-exec-prefix=PATH` options of `configure`.
- By default, the PolyLib backend will use an installed (`system`) PolyLib, if any. The installation location can be specified using the `--with-polylib-prefix=PATH` and `--with-polylib-exec-prefix=PATH` options of `configure`. Using the `--with-polylib` option of `configure` the user can specify that `no` PolyLib or a `build` PolyLib should be used. In the latter case, the user should also specify the build location using `--with-polylib-builddir=PATH`.
- By default, the PolyLib backend of CLooG is built in 64bits version if such version of the PolyLib is found by `configure`. If the only existing version of the PolyLib is the 32bits or if the user give to `configure` the option `--with-bits=32`, the 32bits version of CLooG will be compiled. In the same way, the option `--with-bits=gmp` have to be used to build the multiple precision version.

- By default, `configure` will look for the GMP library (necessary to build the multiple precision version) in standard locations. If necessary, the user can specify the GMP path by giving `configure` the option `--with-gmp-prefix=PATH` and/or `--with-gmp-exec-prefix=PATH`.
- By default, the OpenScop Library (osl) support is not enabled. Using the `--with-osl` option of `configure` the user can specify that `no` osl, a previously installed (`system`) osl, a `bundled` osl, or a `build` osl should be used. In the latter case, the user should also specify the build location using `--with-osl-builddir=PATH`. In case of an installed osl, the installation location can be specified using the `--with-osl-prefix=PATH` and `--with-osl-exec-prefix=PATH` options of `configure`.

4.5 Uninstallation

The user can easily remove the CLooG software and library from his system by typing (as root if necessary) from the CLooG top-level directory `make uninstall`.

5 Documentation

The CLooG distribution provides several documentation sources. First, the source code itself is as documented as possible. The code comments use a Doxygen-compatible presentation (something similar to what JavaDoc does for JAVA). The user may install Doxygen (see `http://www.stack.nl/~dimitri/doxygen`) to automatically generate a technical documentation by typing `make doc` or `doxygen ./autoconf/Doxyfile` at the CLooG top-level directory after running the configure script (see Chapter 4 [Installing], page 35). Doxygen will generate documentation sources (in HTML, LaTeX and man) in the `doc/source` directory of the CLooG distribution.

The Texinfo sources of the present document are also provided in the `doc` directory. You can build it in either DVI format (by typing `texi2dvi cloog.texi`) or PDF format (by typing `texi2pdf cloog.texi`) or HTML format (by typing `makeinfo --html cloog.texi`, using `--no-split` option to generate a single HTML file) or info format (by typing `makeinfo cloog.texi`).

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