Documentation of APTE v0.3.2beta : Algorithm for Proving Trace Equivalence

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Contents

Chapter 1

Standard Library

1.1 Module `Term` : Operations on terms

This module regroups all the functions that manipulate terms. In [Che12], the terms are splitted into first (resp. second) order terms called messages (resp. recipe). In this module, we focus on the messages. The recipe are handled in a different module.

1.1.1 Symbol

A symbol can be a destructor or a constructor.

`type symbol`

The type `symbol` represents the type of function symbol.

Built-in signature

The algorithm described in [Che12] considers a fix set of cryptographic primitives whose behaviour is defined by rewrite rules plus any number of constructors. Thus, we directly defined here this set of cryptographics primitives.

Built-in constructors

`val senc : symbol`

`senc` is the symbol for symmetric encryption (arity 2).

`val aenc : symbol`

`aenc` is the symbol for asymmetric encryption (arity 2).

`val pk : symbol`

`pk` is the symbol for asymmetric public key (arity 1).

`val vk : symbol`

`vk` is the symbol for public verification key used in signature (arity 1).

`val sign : symbol`

`sign` is the symbol for asymmetric public key (arity 1).

`val hash : symbol`

`hash` is the symbol for hash function (arity 1).

Built-in destructors

`val sdec : symbol`

`sdec` is the symbol for symmetric decryption (arity 2).

`val adec : symbol`

`adec` is the symbol for asymmetric decryption (arity 2).

`val checksign : symbol`

`checksign` is the symbol for signature verification (arity 2).

Although the algorithm described in [Che12] only have a pair function of arity 2 with its associated projection, it can be extended to tuple of any arity. Thus, a user we be allowed to use such tuple.

`val nth_projection : symbol -> int -> symbol`

`nth_projection f i` returns the projection function symbol of the $\mathtt{i}^{th}$ element of tuple function symbol `f`. Note that for a tuple of arity `n`, the range of `i` is `1...n`.

Raises

- `Internal_error` if `f` is not a tuple.
- `Not_found` if `f` was not previously introduced by `get_tuple`.

`val get_projections : symbol -> symbol list`

`get_projections f` returns the list `[f_1;...;f_n]` with `f_i` is the projection function symbol of the $\mathtt{i}^{th}$ element of the tuple function symbol `f`. It returns the same result as `[nth_projection f 1; ...; nth_projection f n]`.

Raises

- `Internal_error` if `f` is not a tuple.
- `Not_found` if `f` was not previously introduced by `get_tuple`.

`val all_tuple : symbol list Pervasives.ref`

The list contains all tuples introduced by the algorithm.

`val all_constructors : symbol list Pervasives.ref`

The list of all constructors (included the tupple function symbol) used in the algorithm.

`val number_of_constructors : int Pervasives.ref`

The number of constructors used in the algorithm.

Addition

`val new_constructor : int -> string -> symbol`

`new_symbol ar s` creates a constructor function symbol with the name `s` and the arity `ar`. The resulting symbol is automatically added into `all_constructors`. Moreover, `number_of_constructors` is increased by 1. Note that if the constructor is in fact a tuple, it is better to use `get_tuple`.

`val get_tuple : int -> symbol`

`get_tuple ar` get the function symbol for tuple of arity `ar`. If such function symbol was not created yet, it creates it and the resulting symbol is automatically added into `all_constructors`. Moreover, `number_of_constructors` is increased by 1. At last, the associated projection function symbol are automatically added into `all_projection`.

Symbol testing

```
val is_equal_symbol : symbol -> symbol -> bool
```

`is_equal_symbol f1 f2` returns `true` iff `f1` and `f2` are the same function symbol.

```
val is_tuple : symbol -> bool
```

`is_tuple f` returns `true` iff `f` is a tuple.

```
val is_constructor : symbol -> bool
```

`is_constructor f` returns true iff `f` is a constructor or a tuple. Note that all tuples are constructors.

```
val is_destructor : symbol -> bool
```

`is_destructor f` returns true iff `f` is a destructor.

Symbol Access

```
val get_arity : symbol -> int
```

`get_arity f` returns the arity of the function symbol `f`.

Symbol Display

```
val display_symbol_without_arity : symbol -> string
val display_symbol_with_arity : symbol -> string
```

1.1.2 Messages

```
type quantifier =
  | Free
  | Existential
  | Universal
```

The type `quantifier` is associated to a variable to quantify it.

```
type variable
```

A `variable` is always quantified. It corresponds to the set $\mathcal{X}^1$ in [Che12].

```
type name_status =
  | Public
  | Private
```

A `name` is can be either public or private.

```
type name
```

The type `name` corresponds to the set $\mathcal{N}$ in [Che12].

```
type term
```

The type `term` corresponds to the set $\mathcal{T}(\mathcal{F}, \mathcal{N} \cup \mathcal{X}^1)$ in [Che12].

Variable generation

The variables created by the functions below are structuraly and physically different

`val fresh_variable : quantifier -> variable`

`fresh_variable q` creates a fresh variable quantified by `q`.

`val fresh_variable_from_id : quantifier -> string -> variable`

`fresh_variable_from_id q s` creates a fresh variable quantified as `q` with display identifier `s`.

`val fresh_variable_from_var : variable -> variable`

`fresh_variable_from_var v` creates a fresh variable with the same display identifier and quantifier as the variable `v`.

`val fresh_variable_list : quantifier -> int -> variable list`

`fresh_variable_list q n` creates a list of `n` fresh variables all quantified as `q`.

`val fresh_variable_list2 : quantifier -> int -> term list`

`fresh_variable_list2 q n` creates a list of `n` fresh variables all quantified as `q` and considered as terms.

Name generation

`val fresh_name : name_status -> name`

`fresh_name ns` creates a fresh name with the status `ns`.

`val fresh_name_from_id : name_status -> string -> name`

`fresh_name_from_id ns s` creates a fresh name with status `ns` and with display identifier `s`.

`val fresh_name_from_name : name -> name`

`fresh_name_from_name n` creates a fresh name with the same display identifier and same status as `n`.

Generation of terms

`val term_of_variable : variable -> term`

`term_of_variable v` returns the variable `v` considered as a term.

`val term_of_name : name -> term`

`term_of_name n` returns the name `n` considered as a term.

`val variable_of_term : term -> variable`

`variable_from_term t` returns the term `t` as a variable.

Raises `Internal_error` if `t` is not a variable.

`val name_of_term : term -> name`

`name_from_term t` returns the term `t` as a name.

Raises `Internal_error` if `t` is not a name.

`val apply_function : symbol -> term list -> term`

`apply_function f args` applies the the function symbol `f` to the arguments `args`. If `args` is the list `[t1;...;tn]` then the term obtained is `f(t1,...,tn)`.

[Low debugging]Raise an internal error if the number of arguments in `args` does not coincide with the arity of `f`.

```
val rename :
  (variable * variable) list ->
  (name * name) list -> term -> term
```

`rename v_list n_list t` creates a new term from `t` where each `v_i` is replaced by `v'_i` and each `n_i` is replaced by `n'_i` where `v_list` is the list `(v_1,v'_1),...,(v_p,v'_p)` and `n_list` is the list `(n_1,n'_1),...,(n_q,n'_q)`.

Access functions

`val top : term -> symbol`

`top t` returns the symbol at the root position of `t`.

Raises `Internal_error` if `t` is not a function symbol application.

`val nth_args : term -> int -> term`

`nth_args t i` returns the $\mathtt{i}^{th}$ argument of the constructed term `t`. Note that the index `i` start with 1 and not 0. For example, if `t` is the term $f(t_1, \ldots t_n)$ then `nth_args t i` returns the term t_i .

Raises `Internal_error` if `t` is not a function symbol application.

`val get_args : term -> term list`

`get_args t` returns the list of argument of the constructed term `t`. For example, if `t` is the term $f(t_1, \ldots t_n)$ then `get_args t` returns the list $[t_1; \ldots; t_n]$.

Raises `Internal_error` if `t` is not a function symbol application.

`val get_quantifier : variable -> quantifier`

`get_quantifier v` returns the quantifier of `v`.

Scanning

`val var_occurs : variable -> term -> bool`

`occurs v t` returns `true` iff the variable `v` occurs in the term `t`.

`val var_occurs_list : variable list -> term -> bool`

`occurs_list v_list t` returns `true` iff one of the variable in `v_list` occurs in the term `t`.

`val exists_var : quantifier -> term -> bool`

`exists_var q t` returns `true` iff there exists a variable quantified as `q` in the term `t`.

`val for_all_var : quantifier -> term -> bool`

`for_all_var q t` returns `true` iff all variables in the term `t` are quantified as `q`.

`val exists_name_with_status : name_status -> term -> bool`

`exists_name s t` returns `true` iff there exists a name in `t` with status `s`.

`val exists_name : term -> bool`

`exists_name t` returns `true` iff there exists a name in `t`.

`val is_equal_term : term -> term -> bool`

`is_equal_term t1 t2` returns `true` iff the terms `t1` and `t2` are equal.

`val is_equal_and_closed_term : term -> term -> bool`

`is_equal_term t1 t2` returns `true` iff the terms `t1` and `t2` are equal.

`val is_equal_name : name -> name -> bool`

`is_equal_name n1 n2` returns `true` iff the name `n1` and `n2` are equal.

`val is_variable : term -> bool`

`is_variable t` returns `true` iff the term `t` is a variable.

`val is_name : term -> bool`

`is_name t` returns `true` iff the term `t` is a name.

`val is_name_status : name_status -> term -> bool`

`is_name_status s t` returns `true` iff the term `t` is a name with status `s`.

`val is_function : term -> bool`

`is_function t` returns `true` iff the term `t` is a function symbol application.

`val is_constructor_term : term -> bool`

`is_constructor_term t` returns `true` iff $t \in \mathcal{T}(\mathcal{F}_c, \mathcal{X}^1 \cup \mathcal{N})$.

Iterators

`val fold_left_args : ('a -> term -> 'a) -> 'a -> term -> 'a`

`fold_left_args f acc t` is `f (...(f (f acc t1) t2) ...) tn` if `t` is the term $g(t_1, ..., t_n)$ for some function symbol g .

Raises `Internal_error` if `t` is not a function application.

`val fold_right_args : (term -> 'a -> 'a) -> term -> 'a -> 'a`

`fold_right_args f t acc` is `f t1 (f t2 (...(f tn acc)...))` if `t` is the term $g(t_1, ..., t_n)$ for some function symbol g .

Raises `Internal_error` if `t` is not a function application.

`val map_args : (term -> 'a) -> term -> 'a list`

`map_args f t` is the list `[f t1; ...; f tn]` if `t` is the term $g(t_1, ..., t_n)$ for some function symbol g .

Raises `Internal_error` if `t` is not a function application.

`val fold_left_args2 : ('a -> term -> 'b -> 'a) -> 'a -> term -> 'b list -> 'a`

`fold_left_args2 f acc t l` is `f (...(f (f acc t1 e1) t2 e2) ...) tn en` if `t` is the term $g(t_1, ..., t_n)$ for some function symbol g and `l` is the list `[e1;...;en]`.

Raises `Internal_error` if `t` is not a function application.

Display

`val display_term : term -> string`

`val display_name : name -> string`

`val display_variable : variable -> string`

1.1.3 Mapping table

```
module VariableMap :
  sig
```

```
type 'a map
```

'a map is the type that represents the mapping of variable to element of type 'a.

```
val empty : 'a map
```

empty is the empty mapping function.

```
val is_empty : 'a map -> bool
```

is_empty map returns true iff map is empty.

```
val add : Term.variable -> 'a -> 'a map -> 'a map
```

add v elt map returns a map containing the same bindings as map, plus a binding of v to elt. If v was already bound in map, its previous binding disappears.

```
val find : Term.variable -> 'a map -> 'a
```

find v map returns the current binding of v in map.
Raises Not_found if no binding exists.

```
val mem : Term.variable -> 'a map -> bool
```

mem v map returns true iff map contains a binding for v.

```
val display : ('a -> string) -> 'a map -> unit
```

```
end
```

1.1.4 Substitution

```
type substitution
```

```
val identity : substitution
```

identity corresponds to the identity substitution.

```
val is_identity : substitution -> bool
```

is_identity s returns true iff s is the identity substitution.

```
val create_substitution : variable -> term -> substitution
```

create_substitution v t creates the substitution $v \to t$.

```
val compose : substitution -> substitution -> substitution
```

compose σ_1 σ_2 returns the substitution $\sigma_1\sigma_2$.

[Low debugging]Raise an internal error if the domain of two substitutions are not disjoint.

```
val filter_domain : (variable -> bool) -> substitution -> substitution
```

filter_domain f s returns the substitution s restricted to variables that satisfy f.

```
val apply_substitution :
  substitution -> 'a -> ('a -> (term -> term) -> 'a) -> 'a
```

`apply_substitution subst elt map_elt` applies the substitution `subst` on the element `elt`. The function `map_elt` should map the terms contained in the element `elt` on which `subst` should be applied.

For example, applying a substitution `subst` on a list of terms `term_list` could be done by applying `apply_substitution subst term_list (fun l f -> List.map f l)`.

Another example: applying a substitution `subst` on the second element of a couple of terms could be done by applying `apply_substitution subst term_c (fun (t1,t2) f -> (t1, f t2))`.

```
val apply_substitution_change_detected :
  substitution ->
  'a -> ('a -> (term -> bool * term) -> 'a) -> 'a
```

`apply_substitution_change_detected subst elt map_elt` is similar to `apply_substitution` except that the function `map_elt`, which should map the term to be substituted, will consider a function that returns if a term was modify or not.

`apply_substitution_change_detected subst elt map_elt` is faster but has the same result as

```
apply_substitution subst elt (fun a f ->
  map_elt a (fun t ->
    let t' = f t in not (is_equal_term t t'),t'))
```

```
val equations_of_substitution : substitution -> (term * term) list
```

`equations_of_substitution s` returns the list `[(x1,t1);...;(xn,tn)]` where `s` is the substitution $x_1 \to t_1, \ldots, x_n \to t_n$.

1.1.5 Rewrite rules

```
val fresh_rewrite_rule : symbol -> term list * term
```

`fresh_rewrite_rule f` returns the couple `([t1,...,tn],t)` where $f(t_1, \ldots, t_n) \to t$ is a fresh rewrite rule of `f`.

```
val link_destruc_construc : symbol -> symbol -> bool
```

`link_destruc_construc s_d s_c` returns `true` iff `s_d` is the destructor symbol of the constructor symbol `s_c`.

Raises `Internal_error` if `s_c` is not a constructor or if it is a tuple symbol.

Example : `link_destruc_construc sdec senc` returns `true`.

```
val constructor_to_destructor : symbol -> symbol
```

`constructor_to_destructor s_c` returns the destructor symbol of the constructor symbol `s_c`.

Raises `Internal_error` if `s_c` is not a constructor or if it is a tuple symbol.

1.1.6 Unification

```
exception Not_unifiable
val unify : (term * term) list -> substitution
```

`unify l` unifies the pairs of term in `l` and returns the substitution that unifies them

Raises `Not_unifiable` if no unification is possible.

```
val is_unifiable : (term * term) list -> bool
```

`is_unifiable l` returns `true` iff the pairs of term in `l` are unifiable.

```
val unify_and_apply :
  (term * term) list ->
  'a -> ('a -> (term -> term) -> 'a) -> 'a
```

`unify_and_apply l elt map_elt` unifies the pairs of term in `l` and apply the substitution that unifies them on the terms in `elt` according to the function `map_elt`.

Raises `Not_unifiable` if no unification is possible.

It is faster but returns the same as `apply_substitution (unify l) elt map_elt`.

```
val unify_and_apply_change_detected :
  (term * term) list ->
  'a -> ('a -> (term -> bool * term) -> 'a) -> 'a
```

`unify_and_apply_change_detected l elt map_elt` unifies the pairs of term in `l` and apply the substitution that unifies them on the terms in `elt` according to the function `map_elt`.

Raises `Not_unifiable` if no unification is possible.

It is faster but returns the same as `apply_substitution_change_detected (unify l) elt map_elt`.

```
val unify_modulo_rewrite_rules : (term * term) list -> substitution
```

`unify_modulo_rewrite_rules l` unifies the pairs of term in `l` modulo the rewriting systems. All variables introduced by the unification are quantified existentially.

Raises `Not_unifiable` if no unification is possible or if a destructor cannot be reduced

```
val unify_modulo_rewrite_rules_and_apply :
  (term * term) list ->
  'a -> ('a -> (term -> term) -> 'a) -> 'a
```

`unify_modulo_rewrite_rules_and_apply l elt map_elt` unifies the pairs of term in `l` modulo the rewriting systems and apply the substitution that unifies them on the terms in `elt` according to the function `map_elt`. All variables introduced by the unification are quantified existentially.

Raises `Not_unifiable` if no unification is possible.

It is faster but returns the same as `apply_substitution (unify l) elt map_elt`.

1.1.7 Formula

```
type formula
```

The type `formula` represents a disjunction of inequation of the form $\forall \tilde{x}. \bigvee_{i=1}^{n} u_i \overset{?}{\neq} v_i$ for some terms u_i,v_i that may contain destructor symbol. Note that the semantics of $u \overset{?}{\neq} v$ is given in [Che12].

```
val top_formula : formula
```

`top_formula` is the always true formula.

```
val bottom_formula : formula
```

`bottom_formula` is the always false formula.

```
val create_inequation : term -> term -> formula
```

`create_inequation t_1 t_2` creates the formula $t_1 \overset{?}{\neq} t_n$. Note that the quantifier of the variables are not modified. For instance, the existential vairiables in `t_1` and `t_2` do not become universal variables. Note that `create_inequation` is not commutative, i.e. `create_inequationt t_1 t_2` is different from `create_inequation t_2 t_1`.

```
val create_disjunction_inequation : (term * term) list -> formula
```

`create_disjunction_inequation [(u_1,v_1);...;(u_n,v_n)]` creates the formula $\bigvee_{i=1}^{n} u_i \overset{?}{\neq} v_i$. Note that the quantifier of the variables are not modified.

Iterators

`val iter_inequation_formula : (term -> term -> unit) -> formula -> unit`

`iter_inequation_formula f phi` is `f u1 v1; f u2 v2; ...; f un vn` where `phi` is the formula $\forall \tilde{x}. \bigvee_{i=1}^{n} u_i \overset{?}{\neq} v_i$.

`val map_term_formula : formula -> (term -> term) -> formula`

`map_term_formula phi f` is the formula `create_disjunction_inequation [(f u1,f v1);...;(f un,f vn)]` where `phi` is the formula $\forall \tilde{x}. \bigvee_{i=1}^{n} u_i \overset{?}{\neq} v_i$.

```
val map_term_formula_change_detected :
  formula -> (term -> bool * term) -> bool * formula
```

Similar to `map_term_formula` except that it returns the couple `(b,phi')` where `phi'` is the formula `phi` on which we applied `f` and `b` is `true` iff one of the application of `f` returned true.

Formula scanning

```
val find_and_apply_formula :
  (term -> term -> bool) ->
  (term -> term -> 'a) -> (unit -> 'a) -> formula -> 'a
```

`find_and_apply_formula f_test f_apply f_no formula` searches in `formula` an inequation satisfying `f_test`. If such inequation exists then it applies `f_apply` on it else it apply the function `f_no`.

Note that since an inequation $u \overset{?}{\neq} v$ is semantically the same as $v \overset{?}{\neq} u$, it is recommanded that `f_test u v` and `f_test v u` are equal. Same for `f_apply`.

`val is_bottom : formula -> bool`

`is_bottom formula` returns `true` iff `formula` is the always false formula.

`val is_top : formula -> bool`

`is_true formula` returns `true` iff `formula` is the always true formula.

`val is_in_formula : term -> term -> formula -> bool`

`is_in_formula t_1 t_2 formula` returns `true` iff `formula` is of the form $\forall \tilde{x}. t_1 \overset{?}{\neq} t_2 \vee F$ where F is a disjunction of inequation. Note that this function is commutative, i.e. `is_in_formula t_1 t_2 phi` is the same as `is_in_formula t_2 t_1 phi`.

Simplification

Following [Che12], a substitution σ of constructor terms models a formula $u \overset{?}{\neq} v$, denoted $\sigma \vDash_c u \overset{?}{\neq} v$, if $u\sigma\!\downarrow\, \neq v\sigma\!\downarrow$ or $\mathsf{Message}(u)$ or $\mathsf{Message}(v)$. $\vDash_c$ is naturally extended to formula $\forall \tilde{x}. \bigvee_i u_i \overset{?}{\neq} v_i$. The simplification functions in this section preserve the models of the formulas.

`val simplify_formula : formula -> formula`

This function transforms a formula of the form $\forall \tilde{x} \bigvee_i u_i \neq v_i$ into a formula of the form $\forall \tilde{y} \bigvee_j x_j \overset{?}{\neq} t_j$ where u_i, v_i, t_i are all constructors terms and all x_j are distinct.

`val simplify_formula_phase_2 : formula -> formula`

This function simplifies a formula containing only constructor term by the simplification rules defined in [Che12, Figure 7.3].

`val simplify_formula_modulo_rewrite_rules : formula -> formula`

This function simplifies a formula that may contain destructor symbols into a formula that contains only constructor terms.

Display

`val display_formula : formula -> string`

1.2 Module `Recipe` : Operations on recipes

This module regroups all the functions that manipulate recipes. In [Che12], the terms are splitted into first (resp. second) order terms called messages (resp. recipe). In this module, we focus on the recipes. The message are handled in a different module. In theory a recipe and a message are both terms hence one could consider this module almost as a copy of the module `Term`. However, in the algorithm presented in [Che12], the usage of message and recipe are really different.

1.2.1 Recipe

`type variable`

The type `variable` corresponds to the set $\mathcal{X}^2$ in [Che12]. Since the recipe variable are always introduced in the algorithm with a deducibility constraint, a recipe variable is always associated to an integer called the support in [Che12]. For example, if $X, i \overset{?}{\vdash} u$ is a deducibility constraint, the support of X is i. Hence a variable is always associated to a support in our module

`type axiom`

The type `axiom` corresponds to the set $\mathcal{AX}$ in [Che12]. Similarly to the variable, a axiom is always associated to a support. In [Che12], for an axiom ax_i, i is the support.

`type recipe`

The type `recipe` corresponds to the set $\mathcal{T}(\mathcal{F}, \mathcal{AX} \cup \mathcal{X}^2)$ in [Che12]. Note that the recipes does not have names. It corresponds to the recipes used in Chapter 7 and 8 of [Che12].

Fresh function

`val fresh_variable : int -> variable`

`fresh_variable n` creates a fresh variable with support `n`.

`val fresh_variable_from_id : string -> int -> variable`

`fresh_variable_from_id s n` creates a fresh variable with support `n` and display identifier `s`.

`val fresh_variable_list : int -> int -> variable list`

`fresh_variable_list nb n` creates a list of `nb` fresh variables all with support `n`.

`val fresh_variable_list2 : int -> int -> recipe list`

`fresh_variable_list2 nb n` creates a list of `nb` fresh variables considered as recipes and all with support `n`.

`val fresh_free_variable : int -> variable`

`fresh_free_variable n` creates a fresh free variable with support `n`.

`val fresh_free_variable_from_id : string -> int -> variable`

`fresh_free_variable_from_id s n` creates a fresh free variable with support `n` and display identifier `s`.

`val fresh_free_variable_list : int -> int -> variable list`

`fresh_free_variable_list nb n` creates a list of `nb` fresh free variables all with support `n`.

`val axiom : int -> axiom`

`axiom n` creates an axiom with support `n`.

Generation of recipe

`val recipe_of_variable : variable -> recipe`

`recipe_of_variable v` returns the variable `v` considered as a recipe.

`val recipe_of_axiom : axiom -> recipe`

`recipe_of_axiom ax` returns the axiom `ax` considered as a recipe.

`val variable_of_recipe : recipe -> variable`

`variable_of_recipe r` returns the recipe `r` as a variable.

Raises `Internal_error` if `r` is not a variable.

`val axiom_of_recipe : recipe -> axiom`

`axiom_of_recipe r` returns the recipe `r` as an axiom.

Raises `Internal_error` if `r` is not an axiom.

`val apply_function : Term.symbol -> recipe list -> recipe`

`apply_function f args` applies the the function symbol `f` to the arguments `args`. If `args` is the list `[r1;...;rn]` then the recipe obtained is `f(r1,...,rn)`.

[Low debugging]Raise an internal error if the number of arguments in `args` does not coincide with the arity of `f`.

Access

`val top : recipe -> Term.symbol`

`top r` returns the symbol at the root position of `r`.

Raises `Internal_error` if `r` is not a function symbol application.

`val get_support : variable -> int`

`get_support v` returns the support of the variable `v`.

Testing

`val is_equal_variable : variable -> variable -> bool`

`is_equal_variable v1 v2` returns `true` iff `v1` and `v2` are the same variable.

`val is_equal_axiom : axiom -> axiom -> bool`

`is_equal_axiom ax1 ax2` returns `true` iff `ax1` and `ax2` are the same axioms.

`val is_equal_recipe : recipe -> recipe -> bool`

`is_equal_recipe r1 r2` returns `true` iff `r1` and `r2` are the same recipes.

`val occurs : variable -> recipe -> bool`

`occurs v r` return true iff the variable `v` is in the recipe `r`

`val is_free_variable : variable -> bool`

`is_free_variable v` returns `true` iff `v` is free.

`val is_free_variable2 : recipe -> bool`

`is_free_variable2 r` returns `true` iff `r` is a free variable.

`val is_variable : recipe -> bool`

`is_variable r` returns `true` iff `r` is a variable.

`val is_axiom : recipe -> bool`

`is_axiom r` returns `true` iff `r` is an axiom.

`val is_function : recipe -> bool`

`is_function r` returns `true` iff `r` is a function symbol application.

Iterators

`val iter_args : (recipe -> unit) -> recipe -> unit`

`iter_args f r` is `f r1; ...; f rn` if `r` is the recipe $g(r_1, ..., r_n)$ for some function symbol g.

Raises `Internal_error` if `r` is not a function application.

`val map_args : (recipe -> 'a) -> recipe -> 'a list`

`map_args f r` is the list `[f r1; ...; f rn]` if `r` is the recipe $g(r_1, ..., r_n)$ for some function symbol g.

Raises `Internal_error` if `r` is not a function application.

Display

```
val display_variable : variable -> string
val display_axiom : axiom -> string
val display_recipe : recipe -> string
val display_recipe2 :
  (recipe * 'a) list -> ('a -> string) -> recipe -> string
```

`display_recipe assoc f_display r` display the recipe `r` but each variable and axiom `r'` in `r` is displayed as `f_display b` if `(r',b)` is in `assoc` else is normally displayed.

1.2.2 Variable Mapping

```
module VariableMap :
  sig
```

`type 'a map`

`'a map` is the type that represents the mapping of variable to element of type `'a`.

`val empty : 'a map`

`empty` is the empty mapping function.

`val is_empty : 'a map -> bool`

`is_empty map` returns `true` iff `map` is empty.

```
val add : Recipe.variable ->
  'a -> 'a map -> 'a map
```

`add v elt map` returns a map containing the same bindings as `map`, plus a binding of `v` to `elt`. If `v` was already bound in `map`, its previous binding disappears.

`val find : Recipe.variable -> 'a map -> 'a`

`find v map` returns the current binding of `v` in `map`.

Raises `Not_found` if no binding exists.

`val mem : Recipe.variable -> 'a map -> bool`

`mem v map` returns `true` iff `map` contains a binding for `v`.

```
  end
```

1.2.3 Substitution and unify

`type substitution`

`substitution` corresponds to a mapping from $\mathcal{X}^2$ to $\mathcal{T}(\mathcal{F}, \mathcal{AX} \cup \mathcal{X}^2)$.

`val is_identity : substitution -> bool`

`is_identity s` returns `true` iff `s` is the identity substitution.

`val unify : (recipe * recipe) list -> substitution`

`unify l` returns the most general unifier of the pairs of recipes in `l`.

`val create_substitution : variable -> recipe -> substitution`

`create_substitution v r` returns the substitution $\{v \mapsto r\}$.

`val create_substitution2 : recipe -> recipe -> substitution`

`create_substitution2 v r` returns the substitution $\{v \mapsto r\}$.

Raises `Internal_error` if `v` is not a variable.

```
val apply_substitution :
  substitution ->
  'a -> ('a -> (recipe -> recipe) -> 'a) -> 'a
```

`apply_substitution subst elt map_elt` applies the substitution `subst` on the element `elt`. The function `map_elt` should map the recipes contained in the element `elt` on which `subst` should be applied. See `Term.apply_substitution` for more explanation.

`val equations_from_substitution : substitution -> (recipe * recipe) list`

`equations_from_substitution subst` returns `[(v1,r1);...;(vn,rn)]` if `subst` is the substitution $\{v_1 \mapsto r_1, \ldots, v_n \mapsto r_n\}$.

`val filter_domain : (variable -> bool) -> substitution -> substitution`

`filter_domain f s` returns the substitution `s` restricted to variables that satisfy `f`.

1.2.4 Path

`type path`

The `path` corresponds to the path of a recipe defined in [Che12, Definition 7.4]. It corresponds to the set $\mathcal{F}_d^* \cdot \mathcal{AX}$ in [Che12].

`val path_of_recipe : recipe -> path`

`path_of_recipe xi` returns the path of a recipe. It corresponds to $\mathsf{path}(\xi)$ in [Che12] where ξ is a recipe.

Raises `Internal_error` if the path of `xi` is not closed or if the path if not defined.

`val apply_function_to_path : Term.symbol -> path -> path`

`apply_function_to_path f p` returns the path $f \cdot p$.

`val axiom_path : axiom -> path`

`axiom_path ax` returns the path `ax`.

Testing path

`val is_equal_path : path -> path -> bool`

`is_equal_path p1 p2` returns `true` iff `p1` and `p2` are the same path.

`val is_recipe_same_path : recipe -> recipe -> bool`

`is_recipe_same_path r1 r2` returns `true` iff the paths of `r1` and of `r2` are the same. Note that two recipes having the same path does not imply that the recipes are equal.

`val is_path_of_recipe : recipe -> path -> bool`

`is_path_of_recipe r p` returns `true` iff the path of `r` is `p`.

Display

`val display_path : path -> string`

1.2.5 Recipe context

`type context`

The type `context` corresponds to the set $\mathcal{T}(\mathcal{F}_c, \mathcal{F}_d^* \cdot \mathcal{AX} \cup \mathcal{X}^2)$ in [Che12]. The context of a recipe, defined in [Che12, Definition 7.6], is used in the algorithm for dealing with the inequations.

`val context_of_recipe : recipe -> context`

`context_of_recipe r` returns the context of the recipe `r` following [Che12, Definition 7.6]. Note that in this definition, a frame is needed as parameter. But since we consider context with only constructor function symbol as application function, such frame is not necessary.

`val recipe_of_context : context -> recipe`

`recipe_of_context c` transforms the context `c` as a recipe if `c` is included in $\mathcal{T}(\mathcal{F}, \mathcal{X}^2)$. `c` cannot contain a path since one cannot reconstruct a recipe from a path.

Raises `Internal_error` if `c` is not included in $\mathcal{T}(\mathcal{F}, \mathcal{X}^2)$.

```
val path_of_context : context -> path
val top_context : context -> Term.symbol
val apply_substitution_on_context :
  substitution ->
  'a -> ('a -> (context -> context) -> 'a) -> 'a
```

`apply_substitution_on_context theta elt map_elt` first transforms the substitution $\theta = \{X_i \mapsto \xi_i\}_i$ into a substitution $\theta' = \{X_i \mapsto \gamma_i\}_i$ where `gamma_i` is the result of `context_of_recipe xi_i`. Then it applies the substitution `theta'` on the `elt`. The function `map_elt` should map the contexts contained in the element `elt` on which `theta'` should be applied.

Testing

`val is_variable_context : context -> bool`

`is_variable_context c` returns `true` iff `c` is a variable, i.e. is in $\mathcal{X}^2$.

`val is_path_context : context -> bool`

`is_path_context c` returns `true` iff `c` is a path, i.e. is in $\mathcal{F}^* \cdot \mathcal{AX}$.

`val is_closed_context : context -> bool`

`is_closed_context c` returns `true` iff `c` is closed, i.e. is in $\mathcal{T}(\mathcal{F}, \mathcal{F}^* \cdot \mathcal{AX})$.

`val exists_path_in_context : context -> bool`

`is_closed_context c` returns `true` iff there exists a path subterm of `c`.

Access

```
val get_max_param_context : context -> int
```

`get_max_param_context c` returns the maximal parameter of the recipe context `c`, defined in [Che12, Section 7.4.2.2] and denoted $\mathsf{paramC}^{\mathcal{C}}_{\mathsf{max}}(c)$ where $\mathcal{C}$ is a constraint system. Note that our function does not have a constraint system as argument. Indeed, the purpose of the constraint system is to allow the association support/variable in [Che12] which is coded directly in the variables in this module.

Display

```
val display_context : context -> string
```

1.2.6 Formula on contexts of recipes

```
type formula
```

The type `formula` correspond to a disjunction of inequation between context of recipe. It corresponds to the formulas contains in the association table in [Che12, Section 7.4.2.2].

```
exception Removal_transformation
```

This exception will be trigerred when a formula will satisfy the removal transformation described in [Che12, Section 7.4.2.5].

```
val create_formula : variable -> recipe -> formula
```

`create_formula x xi` creates the formula $X \overset{?}{\neq} \mathsf{C}\lfloor\xi\rfloor$.

Scanning

```
val for_all_formula : (context * context -> bool) -> formula -> bool
```

`for_all_formula f phi` returns `true` iff `f xi_i beta_i` returns `true` for all `i` where `phi` is the formula $\bigvee_i \xi_i \overset{?}{\neq} \beta_i$.

```
val exists_formula : (context * context -> bool) -> formula -> bool
```

`exists_formula f phi` returns `true` iff there exists `i` s.t. `f xi_i beta_i` returns `true` where `phi` is the formula $\bigvee_i \xi_i \overset{?}{\neq} \beta_i$.

```
val find_and_apply_formula :
  (context -> context -> bool) ->
  (context -> context -> 'a) ->
  (unit -> 'a) -> formula -> 'a
```

`find_and_apply_formula f_test f_apply f_no formula` searches in `formula` an inequation satisfying `f_test`. If such inequation exists then it applies `f_apply` on it else it apply the function `f_no`.

Note that since an inequation $\xi \overset{?}{\neq} \beta$ is semantically the same as $\beta \overset{?}{\neq} \xi$, it is recommanded that `f_test xi beta` and `f_test beta xi` are equal. Same for `f_apply`.

Modification

```
val apply_substitution_on_formulas :
  substitution ->
  'a -> ('a -> (formula -> formula) -> 'a) -> 'a
```

`apply_substitution_on_formulas theta elt map_elt` first transforms a substitution $\theta = \{X \mapsto \xi\}$ into a substitution $\theta' = \{X \mapsto \gamma\}$ where `gamma` is the result of `context_of_recipe xi`. Then it applies the substitution `theta'` on the formulas of `elt`. The function `map_elt` should map the formulas contained in the element `elt` on which `theta'` should be applied.

Raises `Internal_error` if the domain of `theta` is different from a singleton.

```
val simplify_formula : formula -> formula
```

`simplify_formula phi` returns the formula `phi` simplified as detailed in [Che12, Section 7.4.2.2].

Raises

- `Internal_error` if `phi` can be simplified into a formula $f(\beta_1, \ldots, \beta_n) \stackrel{?}{\neq} g(\beta'_1, \ldots, \beta'_m) \vee \Phi'$ for some $f \neq g$.
- `Removal_transformation` if `phi` can be simplified into a formula of the form $\bigvee_i \xi_i \stackrel{?}{\neq} \beta_i$ where for all i, $\xi_i \in \mathcal{F}_d^* \cdot \mathcal{AX}$ or $\beta_i \in \mathcal{F}_d^* \cdot \mathcal{AX}$.

```
val apply_simplify_substitution_on_formulas :
  substitution ->
  'a -> ('a -> (formula -> formula) -> 'a) -> 'a
```

`apply_simplify_substitution_on_formulas theta elt map_elt` returns the same as `simplify_formula (apply_substitution_on_formulas theta elt map_elt)` but computes it more quickly.

```
val display_formula : formula -> string
```

1.3 Module `Constraint` : Frame and deducibility constraints

This module regrous all the functions that manipulate the deduciblity constraints and the frame. Hence it corresponds to the elements of the form $X, i \stackrel{?}{\vdash} u$ and $\xi, j \rhd v$ in [Che12, Chapter 7,8].

1.3.1 Support set

```
type 'a support_set
```

Both frame and deducibility constraints are theorically a sets of elements of the form $X, i \stackrel{?}{\vdash} u$ and $\xi, j \rhd v$ in [Che12]. However, both of these element depend of a support, i.e. an integer. Hence to improve the efficiency of our algorithm, the type `support_set` is an optimised set of element parametrised by an integer.

```
type position
```

The type `position` corresponds to the specific position of an element in a `support_set`. It is used to speed-up the access to element of a `support_set`.

```
val empty_set : 'a support_set
```

`empty_set` is an empty support set.

Modification

```
val add : ('a -> int) -> 'a -> 'a support_set -> 'a support_set
```

`add f elt set` add the element `elt` with support `f elt` in the set `set`. `f` should correspond to the function that return the support of `elt`.

```
val add_new_support : (int -> 'a) -> 'a support_set -> 'a support_set
```

`add_new_support f set` add the element `f s` in `set` where `s-1` is the support maximal of the element in `set`.

```
val add_list : ('a -> int) ->
  'a list -> 'a support_set -> 'a support_set
```

`add_list f elt_list set` add the elements in `elt_list` in the set `set`. `f` should correspond to the function that return the support of the elements of `elt_list`.

Raises `Internal_error` if the application of `f` on the elements of `elt_list` does not return the same value. **[Low debugging]**

```
val replace :
  position ->
  ('a -> 'a list) ->
  'a support_set -> 'a * 'a support_set
```

`replace p f set` replace the element in `set` at the position `p` by the elements `f elt` if `elt` is the element in `set` at the position `p`.

Raises `Internal_error` if the position `p` does not correspond to any element in `set`.

```
val replace2 :
  position ->
  ('a -> 'a list * 'a list) ->
  'a support_set ->
  'a * 'a support_set * 'a support_set
```

`replace2 p f set` returns two sets `set1,set2` where `set1` (resp. `set2`) is the set `set` where the element `elt` at the position `p` in `set` is replaced by `elt_l1` (resp. `elt_l2`) with `elt_l1,elt_l2` being the result of `f elt`.

Raises `Internal_error` if the position `p` does not correspond to any element in `set`.

Scanning

```
type support_range =
  | SUnique of int
```

`SUnique s` Consider only the elements of support `s`.

```
  | SAll
```

Consider all the elements in the set.

```
  | SUntil of int
```

`SUntil s` considers only the elements of support inferior or equal to `s`.

```
  | SFrom of int
```

`SFrom s` considers only the elements of support superior or equal to `s`.

```
  | SBetween of int * int
```

`SBetween s1 s2` considers only the elements of support superior or equal to `s1`, and inferior or equal to `s2`.

`support_range` is a parameter for scanning function. It allows more efficient and precise search on the sets.

```
val search :
  support_range ->
  ('a -> bool) -> 'a support_set -> 'a * position
```

`search s_range test set` returns `elt,pos` where `elt` is an element in `set` whose support satisfies `s_range` and such that `test elt` returns true. `pos` is the position of `elt` in `set`.

Raises `Not_found` if no element of `set` satisfies the function `test`.

```
val search_and_replace :
  support_range ->
  ('a -> bool) ->
  ('a -> 'a list) ->
  'a support_set ->
  'a * position * 'a support_set
```

`search_and_replace s_range test f set` is an optimisation of `{ let (elt,pos) = search s_range test set in elt,pos, replace pos f set}`

```
val search_and_replace2 :
  support_range ->
  ('a -> bool) ->
  ('a -> 'a list * 'a list) ->
  'a support_set ->
  'a * position * 'a support_set *
  'a support_set
```

`search_and_replace2 s_range test f set` is an optimisation of `{ let (elt,pos) = search s_range test set in let set1,set2 = replace2 pos f set in elt,pos,set1,set2}`

```
val for_all : support_range -> ('a -> bool) -> 'a support_set -> bool
```

`for_all s_range test set` returns `true` iff for all elements `elt` in `set` whose support satisfies `s_range`, `test elt` returns `true`.

```
val exists : support_range -> ('a -> bool) -> 'a support_set -> bool
```

`exists s_range test set` returns `true` iff there exists an element `elt` in `set` whose support satisfies `s_range` and such that `test elt` returns `true`.

Access

```
val get : position -> 'a support_set -> 'a
```

`get pos set` returns the element of `set` at the position `pos`.

Raises `Internal_error` if `pos` is not a position in `set`.

Iterators

```
val iter : support_range -> ('a -> unit) -> 'a support_set -> unit
```

`iter s_range f set` is `f e1; ...; f en` where apply the function `f` to all elements of `set` whose support satisfies `s_range`. The order on the element on which `f` is applied is by increasing support first and then in the order in which they were added in the set.

Note that the function `replace` modifies the order in which elements are added: For example, consider a set `set` of elements with same support such that `elt1`, `elt2`, `elt3` was added in this particular order by call the function `add`. Consider `pos2` the position of `elt2` in `set` and the function `g = fun e -> [e;e]`. We have that `iter SAll f (replace pos2 g set)` is `f elt1; f elt2; f elt2; f elt3`.

```
val map : support_range ->
  ('a -> 'a) -> 'a support_set -> 'a support_set
```

`map s_range f set` returns the set `set` where the function `f` was applied on all the elements of `set` satisfying `s_range`.

```
val fold_left :
  support_range ->
  ('a -> 'b -> 'a) -> 'a -> 'b support_set -> 'a
```

```
val iter2 :
  support_range ->
  ('a -> 'a -> unit) ->
  'a support_set -> 'a support_set -> unit
```

`iter2 s_range f set1 set2` is `f e1 d1; f e2 d2; ...; fen dn` where `set1` (resp. `set2`) is a set whose elements satisfying `s_range` have the application order `e1;...; en` (resp. `d1;...;dn`). See `Constraint.iter` for more details on the application order.

Raises `Internal_error` if `set1` and `set2` do not have the same number of elements of equal support.

Display

```
val display_horizontally : ('a -> string) -> 'a support_set -> string
```

```
val display_vertically : ('a -> string) -> string -> 'a support_set -> string
```

1.3.2 Frame

In [Che12], a frame is a set $\{\xi_1, i_1 \rhd u_1; \ldots; \xi_n, i_n \rhd u_n\}$ where $\xi_j \in \mathcal{T}(\mathcal{F}, \mathcal{AX} \cup \mathcal{X}^2)$, $\mathsf{path}(\xi_j)$ exists and $u_j \in T(\mathcal{F}_c, \mathcal{N} \cup \mathcal{X}^1)$ for all $j \in \{1, \ldots, n\}$. Note that compare to [Che12], a frame in this implementation is extented by the addition of some flags which will represents different notions used later on in the constraint systems.

```
module Frame :
  sig
```

```
type elt
```

A frame constraint represents in [Che12] an element of the form $\xi, i \rhd_F u$ with ξ a recipe, i a integer, u a constructor term and F a set of flags.

```
val create : Recipe.recipe -> int -> Term.term -> elt
```

`create frame_constraint xi s m` returns the frame constraint $\xi, s \rhd_\emptyset m$.
Raises `Internal_error` if `m` is not a constructor term. **[High debugging]**

Access

```
val get_recipe : elt -> Recipe.recipe
```

`get_recipe fc` returns the recipe of `fc`.

```
val get_support : elt -> int
```

`get_suport fc` returns the support of `fc`.

```
val get_message : elt -> Term.term
```

`get_message fc` returns the message of `fc`.

Modification

```
val replace_recipe : elt ->
  (Recipe.recipe -> Recipe.recipe) -> elt
```

> `replace_recipe fc rep` returns the frame constraint `fc` with the recipe `rep r` where `r` was the recipe of `fc`.

```
val replace_message : elt -> (Term.term -> Term.term) -> elt
```

> `replace_message fc rep` returns the frame constraint `fc` with the message `rep m` where `m` was the message of `fc`.

Flags

In [Che12], the notion of flag does not exist. However they correspond to other elements or properties of constraint systems. Hence, we will give the semantics of each flag when introducting their adding function. For this, we will consider a constraint system $\mathcal{C}$, its associated frame Φ and let `fc` be a frame element $(\xi, i \rhd_F u) \in \Phi$.

```
val add_noDedSubterm : elt -> Term.symbol -> int -> elt
```

> `add_noDedSubterm fc f s` adds a flag $\textsc{noDedSubterm}(\mathsf{f}, s) \in \mathcal{F}$ with $\mathsf{f} \in \mathcal{F}_c$. It corresponds to the non-deducibility constraint $\mathsf{f}(x_1, \ldots, x_n) \overset{?}{\neq} u \vee s \overset{?}{\not\vdash} x_1 \vee \ldots \vee s \overset{?}{\not\vdash} x_n$ where $x_1, \ldots, x_n$ are fresh variables.
>
> **Raises**
>
> - `Internal_error` if a flag $\textsc{noUse}$ is alreafy in $\mathcal{F}$. **[Low debugging]**
> - `Internal_error` if a flag $\textsc{yesDedSubterm}(\mathsf{g}, s')$ was already in F for any g, s' except when $\mathsf{g} = \mathsf{f}$ and $s < s'$.
> - `Internal_error` if `f` is not a constructor function symbol or if it is a tuple. **[Low debugging]**
> - `Internal_error` if $u \in \mathcal{X}^1$ **[Low debugging]**.

```
val add_yesDedSubterm : elt -> Term.symbol -> int -> elt
```

> `add_YesDedSubterm fc f s` adds a flag $\textsc{YesDedSubterm}(\mathsf{f}, s) \in \mathcal{F}$. It corresponds to there exists $X_1, \ldots, X_n \in vars^2(\mathcal{C})$ such that for all $i \in \{1, \ldots, n\}$, $\mathsf{param}^{\mathcal{C}}_{\mathsf{max}}(X_i\theta) \leq s$ and
>
> $$\mathsf{C}\lfloor \mathsf{f}(X_1, \ldots, X_n)\theta \rfloor_\Phi \mathsf{acc}^1(\mathcal{C}) = v$$
>
> Intuitively, it indicates that u can be constructed in $\mathcal{C}$ by applying f with support inferior or equal to s.
>
> **Raises**
>
> - `Internal_error` if a flag $\textsc{noDedSubterm}(\mathsf{f}, s')$ or $\textsc{noUse}$ was already in F with $s \leq s'$. **[Low debugging]**
> - `Internal_error` if `f` is not a constructor function symbol or if it is a tuple. **[Low debugging]**
> - `Internal_error` if $u \in \mathcal{X}^1$ **[Low debugging]**.

```
val add_noDest : elt -> Term.symbol -> int -> elt
```

> `add_noDest fc f s` adds a flag $\textsc{NoDest}(\mathsf{f}, s) \in \mathcal{F}$ with $f \in \mathcal{F}_d$. It corresponds to the non-deducibility constraint $\forall \tilde{x}. u \overset{?}{\neq} v_1 \vee s \overset{?}{\not\vdash} v_2 \vee \ldots vees \overset{?}{\not\vdash} v_n$ where $\mathsf{f}(v_1, \ldots, v_n) \to w$ is a fresh rewrite rule with $\tilde{x} = vars(v_1)$.
>
> **Raises**
>
> - `Internal_error` if a flag $\textsc{yesDest}$ or $\textsc{noUse}$ was already in F

- `Internal_error` if `f` is not a destructor function symbol. **[Low debugging]**
- `Internal_error` if `f` is a projection function symbol. **[High debugging]**
- `Internal_error` if $u \in \mathcal{X}^1$ **[Low debugging]**.

```
val add_yesDest : elt -> elt
```

`add_yesDest fc` adds a flag $\textsc{YesDest} \in F$. It corresponds to the fact that there exists $(\zeta, k \rhd v) \in \Phi$ such that $\mathsf{path}(\zeta) = \mathsf{g} \cdot \mathsf{path}(\xi)$ and `Term.link_destruc_construc g f` returns `true` where $\mathsf{g} = \mathsf{root}(u)$.

Raises

- `Internal_error` if a flag $\textsc{noUse}$ is already in $\mathcal{F}$.
- `Internal_error` if $u \in \mathcal{X}^1$ **[Low debugging]**.

```
val add_noUse : elt -> elt
```

`add_noUse fc` adds a flag $\textsc{NoUse} \in F$. It corresponds to the fact that $(\xi, i \rhd u) \in \mathsf{NoUse}(\mathcal{C})$.

```
val is_noDedSubterm : elt -> int -> bool
```

`is_noDedSubterm fc s` returns `true` iff there is a flag $\textsc{NoDedSubterm}(\mathsf{f}, s') \in F$ with $s \leq s'$ where $\mathsf{f} = \mathsf{root}(u)$.

```
val is_yesDedSubterm : elt -> int -> bool
```

`is_yesDedSubterm fc s` returns `true` iff there is a flag $\textsc{YesDedSubterm}(\mathsf{f}, s') \in F$ with $s \geq s'$ where $\mathsf{f} = \mathsf{root}(u)$.

```
val is_noDest : elt -> int -> bool
```

`is_noDest fc s` returns `true` iff there is a flag $\textsc{NoDest}(\mathsf{f}, s') \in F$ with $s \leq s'$ where f is the corresponding destructor of $\mathsf{root}(u)$.

```
val is_yesDest : elt -> bool
```

`is_yesDest fc` returns `true` iff there is a flag $\textsc{YesDest} \in F$ where $\mathsf{f} = \mathsf{root}(u)$.

```
val is_noUse : elt -> bool
```

`is_noUse fc` returns `true` iff there is a flag $\textsc{NoUse}$.

Testing on frame

```
val is_same_structure :
  elt Constraint.support_set ->
  elt Constraint.support_set -> bool
```

`is_same_structure frame1 frame2` checks that every couple of frame constraints in `frame1` and `frame2` of same application order have:

- the same recipe
- the same support
- the same set of flags

Display

```
val display : elt -> string
```

`display fc` display the frame constraint without considering the flags.

```
end
```

1.3.3 Deducibility constraint

In [Che12], the deducibility constraints are element of the form $X, i \overset{?}{\vdash} u$ where $X \in \mathcal{X}^2$, $i \in \mathbb{N}$ and $u \in \mathcal{T}(\mathcal{F}_c, \mathcal{N} \cup \mathcal{X}^1)$. Note that compare to [Che12], a deducibility constraints in this implementation is extented by the addition of some flags which will represents different notions used later on in the constraint systems.

```
module Deducibility :
  sig
```

```
type elt
```

```
val create : Recipe.variable -> int -> Term.term -> elt
```

`create v s t` creates a deducibility constraint with the variable `v`, the support `s` and the term `t`.

Raises

- `Internal_error` if `t` is not a constructor term. **[High debugging]**
- `Internal_error` if `s` is different from the support of `v`.

Access

```
val get_recipe_variable : elt -> Recipe.variable
```

`get_recipe_variable dc` returns the recipe variable of `dc`.

```
val get_support : elt -> int
```

`get_support dc` returns the support of `dc`.

```
val get_message : elt -> Term.term
```

`get_message dc` returns the message of `dc`.

Modification

```
val replace_message : elt ->
  (Term.term -> Term.term) -> elt
```

`replace_message cc rep` returns the deducibility constraint `dc` with the message `rep m` where `m` was the message of `dc`.

Flags

Similarly to the module [Frame], the flags in deducibility constraint correspond to other elements or properties of constraint systems. Hence, we will give the semantics of each flag when introducting their adding function. For this, we will consider a constraint system $\mathcal{C}$, its associated deducibility constraint set D and let `dc` be a deducibility constraint $(X, i \overset{?}{\vdash}_F u) \in D$.

```
val add_noCons : elt -> Term.symbol -> elt
```

`add_noCons dc f` adds the flag $\textsc{NoCons}(\mathsf{f}) \in F$. It corresponds to the inequation $\mathsf{root}(()X) \overset{?}{\neq} \mathsf{f}$.

Raises `Internal_error` if the flag was already added. **[Low debugging]**

```
val add_noAxiom : elt ->
  Constraint.position -> elt
```

add_noAxiom dc p add the flag $\text{NoAxiom}(p) \in \mathcal{F}$. It corresponds to the inequation $X \stackrel{?}{\neq} \xi$ where $(\xi, j \rhd v)$ is the frame constraint in $\Phi(\mathcal{C})$ at the position p. Note: the flags $\text{NoAxiom} must be added by the rule \text{Axiom} for all cases except when a \text{NoUse}$ is detected.
Raises Internal_error if the flag was already added. **[Low debugging]**

```
val compare_noCons : elt ->
  elt -> Term.symbol list * Term.symbol list
```

compare_noCons dc1 dc2 compare the flags NoCons in dc1 and dc2. It returns a pair of set of function symbols (S_1, S_2) where:

- for all $\mathsf{f} \in S_1$, $\text{NoCons}(\mathsf{f}) \in \mathcal{F}_2$ but $\text{NoCons}(\mathsf{f}) \notin \mathcal{F}_1$.
- for all $\mathsf{f} \in S_2$, $\text{NoCons}(\mathsf{f}) \in \mathcal{F}_1$ but $\text{NoCons}(\mathsf{f}) \notin \mathcal{F}_2$.

```
val compare_noAxiom :
  elt ->
  elt ->
  int -> Constraint.position list * Constraint.position list
```

compare_noAxiom c1 c2 s compare the flags NoAxiom in dc1 and dc2. It returns a pair of set of position (P_1, P_2) where:

- for all $p \in P_1$ of support s, $\text{NoAxiom}(p) \in F_2$ but $\text{NoAxiom}(p) \notin F_1$.
- for all $p \in P_2$ of support s, $\text{NoAxiom}(p) \in F_1$ but $\text{NoAxiom}(p) \notin F_2$.

```
val fold_left_frame_free_of_noAxiom :
  elt ->
  ('a -> Constraint.Frame.elt -> 'a) ->
  'a -> Constraint.Frame.elt Constraint.support_set -> 'a
```

fold_left_frame_free_of_noAxiom dc f acc frame is similar to fold_left (SUntil s) f acc frame but f is only applied to the element of position pos of frame such that the flag NoAxiom pos is not in dc. Moreover, s is the support of dc

Scanning

```
val is_all_noCons : elt -> bool
```

is_all_noCons dc returns true iff the flags NoCons f is in dc for all constructors f.

```
val is_same_structure :
  elt Constraint.support_set ->
  elt Constraint.support_set -> bool
```

is_same_structure dc_set1 dc_set2 checks that every couple of deducibility constraints in dc_set1 and dc_set2 of same application order have:

- the same variable
- the same support
- the same set of flags

```
val is_noCons : elt -> Term.symbol -> bool
val is_unsatisfiable :
  Constraint.Frame.elt Constraint.support_set ->
  elt -> bool
```

Display

```
val display : elt -> string
end
```

1.4 Module Constraint_system : Operations on (matrices of) constraint systems

This module regrous all the functions that manipulate the constraint systems and the matrices of constraint system. In [Che12], there are several definitions of constraint systems but we are only interested in the constraint system of [Che12, Chapter 7].

1.4.1 Constraint system

```
type constraint_system
```

constraint_system corresponds to [Che12, Definition 7.6] . Moreover, it will contain additional information used in the algorithm such as association table (see [Che12, Section 7.4.2.2]).

```
val empty : constraint_system
```

empty is the constraint system that accept any solution. It does not contain any deducibility constraint, nor frame constraint, nor equation, nor inequation.

```
val bottom : constraint_system
```

bottom is the constraint system with no solution. It corresponds to $\perp$ in [Che12].

Iterators

```
val map_message_inequation :
  (Term.formula -> Term.formula) ->
  constraint_system -> constraint_system
```

Modification functions

```
val add_message_equation :
  constraint_system ->
  Term.term -> Term.term -> constraint_system
```

add_message_equation csys t1 t2 returns the constraint system csys with the added equation $t_1 \stackrel{?}{=} t_2$.

```
val add_message_formula :
  constraint_system ->
  Term.formula -> constraint_system
```

add_message_formula csys phi returns the constraint system csys with the added message formula phi

```
val add_new_deducibility_constraint :
  constraint_system ->
  Recipe.variable -> Term.term -> constraint_system
```

add_new_deducibility_constraint csys X t returns the constraint system csys with the added deducibility constraint $X, i \stackrel{?}{\vdash} t$ where i is the maximal support of csys.

Raises

- Internal_error if csys is the bottom constraint system.
- Internal_error if t is not a constructor term. **[High debugging]**
- Internal_error if the support associated to X is not equal to the maximal support of csys.

```
val add_deducibility_constraint :
  constraint_system ->
  Constraint.Deducibility.elt list -> constraint_system
```

```
val add_new_axiom : constraint_system ->
  Term.term -> constraint_system
```

add_new_axiom csys t returns the constraint system csys with the frame $\Phi \cup \{ax_i, i \rhd t\}$ where Φ is the frame of csys and $i-1$ is the maximal support of Φ .

Raises Internal_error if csys is the bottom constraint system.

```
val add_frame_constraint :
  constraint_system ->
  Constraint.Frame.elt list -> constraint_system
```

```
val frame_replace :
  constraint_system ->
  Constraint.position ->
  (Constraint.Frame.elt -> Constraint.Frame.elt list) ->
  Constraint.Frame.elt * constraint_system
```

frame_replace c p f replace the element in the frame of c at the position p by the elements f elt if elt is the element in the frame of c at the position p.

Raises Internal_error if the position p does not correspond to any element in the frame of c.

```
val frame_replace2 :
  constraint_system ->
  Constraint.position ->
  (Constraint.Frame.elt ->
   Constraint.Frame.elt list * Constraint.Frame.elt list) ->
  Constraint.Frame.elt * constraint_system *
  constraint_system
```

frame_replace2 c p f returns two constraint systems c1,c2 where c1 (resp. c2) is the constraint system c where the element elt at the position p in the frame of c is replaced by elt_l1 (resp. elt_l2) with elt_l1,elt_l2 being the result of f elt.

Raises Internal_error if the position p does not correspond to any element in the frame of c.

```
val frame_search_and_replace :
  constraint_system ->
  Constraint.support_range ->
  (Constraint.Frame.elt -> bool) ->
  (Constraint.Frame.elt -> Constraint.Frame.elt list) ->
  Constraint.Frame.elt * Constraint.position *
  constraint_system
```

frame_search_and_replace c s_range test f is an optimisation of { let (elt,pos) = Constraint.search s_range test (get_frame c) in elt,pos, frame_replace c pos f}

```
val frame_search_and_replace2 :
  constraint_system ->
  Constraint.support_range ->
  (Constraint.Frame.elt -> bool) ->
  (Constraint.Frame.elt ->
   Constraint.Frame.elt list * Constraint.Frame.elt list) ->
  Constraint.Frame.elt * Constraint.position *
  constraint_system * constraint_system
```

frame_search_and_replace2 c s_range test f is an optimisation of { let (elt,pos) = Constraint.search s_range test (get_frame c) in let set1,set2 = frame_replace2 c pos f in elt,pos,set1,set2}

Access functions

```
val get_deducibility_constraint_set :
  constraint_system ->
  Constraint.Deducibility.elt Constraint.support_set
```

`get_deducibility_constraint_set csys` returns the set of deducibility constraints of `csys`.

Raises `Internal_error` if `csys` is the bottom constraint system.

```
val get_frame :
  constraint_system ->
  Constraint.Frame.elt Constraint.support_set
```

`get_frame csys` returns the frame of `csys`.

Raises `Internal_error` if `csys` is the bottom constraint system.

```
val get_message_equations : constraint_system -> (Term.term * Term.term) list
```

`get_message_equations csys` returns the list `[(u_1,v_1);...;(u_n,v_n)]` where $\bigwedge_{i=1}^{n} u_i \stackrel{?}{=} v_i$ is the conjunction of equations between constructor terms in `csys`.

Raises `Internal_error` if `csys` is the bottom constraint system.

```
val get_recipe_equations :
  constraint_system -> (Recipe.recipe * Recipe.recipe) list
```

`get_recipe_equations csys` returns the list `[(xi_1,zeta_1);...;(xi_n,zeta_n)]` where $\bigwedge_{i=1}^{n} \xi_i \stackrel{?}{=} \zeta_i$ is the conjunction of equations between recipes in `csys`.

Raises `Internal_error` if `csys` is the bottom constraint system.

```
val get_maximal_support : constraint_system -> int
```

`get_maximal_support csys` returns maximal support of the frame of `csys`.

Raises `Internal_error` if `csys` is the bottom constraint system.

Testing functions

```
val is_semi_solved_form : constraint_system -> bool
val set_semi_solved_form : constraint_system -> constraint_system
val unset_semi_solved_form : constraint_system -> constraint_system
val is_no_universal_variable : constraint_system -> bool
val set_no_universal_variable : constraint_system -> constraint_system
val unset_no_universal_variable : constraint_system -> constraint_system
val is_bottom : constraint_system -> bool
```

`is_bottom c` returns `true` iff `c` is the constraint system $\perp$.

```
val check_same_structure : constraint_system ->
  constraint_system -> unit
```

`check_same_structure c1 c2` does nothing if `c1` and `c2` have same structure else it raises the exception `Internal_error`. The definition of structure is given in [Che12, Section 7.1.2].

```
val check_same_shape : constraint_system ->
  constraint_system -> unit
```

`check_same_shape c1 c2` does nothing if `c1` and `c2` have same shape else it raises the exception `Internal_error`. The definition of shape is given in [Che12, Definition 7.11].

```
val display : constraint_system -> string
val is_unsatisfiable : constraint_system -> bool
```

1.4.2 Functionnalities of Phase 1

In the strategy on the rules described in [Che12, Section 7.4], there are two different phases of rule application. Hence this section describes the optimised functions used in Phase 1 of the strategy. Due to the lack of invariant during this phase, these functions are quite general.

```
module Phase_1 :
  sig

     val activate_phase :
       Constraint_system.constraint_system -> Constraint_system.constraint_system
```

`activate_phase csys` returns the constraint system `csys` optimised for Phase 1 of the strategy.

Modifications

```
     val deducibility_replace :
       Constraint_system.constraint_system ->
       Constraint.position ->
       (Constraint.Deducibility.elt -> Constraint.Deducibility.elt list) ->
       Constraint.Deducibility.elt * Constraint_system.constraint_system
```

`deducibility_replace c p f` replace the deducibility constraint of `c` at the position `p` by the deducibility constraints `f dc` if `dc` is the deducibility constraint of `c` at the position `p`.

Raises `Internal_error` if the position `p` does not correspond to any deducibility constraint in `c`.

```
     val deducibility_replace2 :
       Constraint_system.constraint_system ->
       Constraint.position ->
       (Constraint.Deducibility.elt ->
        Constraint.Deducibility.elt list * Constraint.Deducibility.elt list) ->
       Constraint.Deducibility.elt * Constraint_system.constraint_system *
       Constraint_system.constraint_system
```

`deducibility_replace2 c p f` returns two constraint systems `c1,c2` where `c1` (resp. `c2`) is the constraint system `c` where the deducibility constraint `dc` at the position `p` in `c` is replaced by `dc_l1` (resp. `dc_l2`) with `dc_l1,dc_l2` being the result of `f dc`.

Raises `Internal_error` if the position `p` does not correspond to any deducibility constraint in `c`.

```
     val deducibility_search_and_replace :
       Constraint_system.constraint_system ->
       Constraint.support_range ->
       (Constraint.Deducibility.elt -> bool) ->
       (Constraint.Deducibility.elt -> Constraint.Deducibility.elt list) ->
       Constraint.Deducibility.elt * Constraint.position *
       Constraint_system.constraint_system
```

`deducibility_search_and_replace c s_range test f` is an optimisation of `{ let (elt,pos) = Constraint.search s_range test (get_deducibility_constraint_set c) in elt,pos, deducibility_replace c pos f}`

```
     val deducibility_search_and_replace2 :
       Constraint_system.constraint_system ->
       Constraint.support_range ->
       (Constraint.Deducibility.elt -> bool) ->
       (Constraint.Deducibility.elt ->
```

```
 Constraint.Deducibility.elt list * Constraint.Deducibility.elt list) ->
Constraint.Deducibility.elt * Constraint.position *
Constraint_system.constraint_system * Constraint_system.constraint_system
```

`deducibility_search_and_replace2 c s_range test f` is an optimisation of `{ let (elt,pos) = Constraint.search s_range test (get_deducibility_constraint_set c) in let set1,set2 = deducibility_replace2 c pos f in elt,pos,set1,set2}`

Substitution

```
val unify_and_apply_message_equations :
  Constraint_system.constraint_system ->
  (Term.term * Term.term) list -> Constraint_system.constraint_system
```

`unify_and_apply_message_equations csys eq_l` returns the normalised constraint system `csys` on which the most general unifier of `eq_l` was applied.

Raises `Term.Not_unifiable` if `eq_l` is no unifiable.

```
val apply_message_substitution :
  Constraint_system.constraint_system ->
  Term.substitution -> Constraint_system.constraint_system
```

`apply_message_equations csys subst` returns the normalised constraint system `csys` on which `subst` was applied.

```
val apply_recipe_substitution :
  Constraint_system.constraint_system ->
  Recipe.substitution -> Constraint_system.constraint_system
```

`apply_recipe_substitution csys subst` returns the normalised constraint system `csys` on which `subst` was applied.

Raises `Internal_error` if the domain of `subst` intersects with the left hand side variables of `csys`. **[High debugging]**

```
val normalise :
  Constraint_system.constraint_system -> Constraint_system.constraint_system
```

`normalise csys` returns the constraint system `csys` normalised. It may contain destructors function symbol in inequations and equations. This normalisation corresponds to the transformation induced by [Che12, Lemma 6.10].

```
end
```

1.4.3 Functionnalities of Phase 2

As mention in the previous section, there are two different phases of rule application described in the strategy (see [Che12, Section 7.4]). This section describes the optimised functions used in Phase 2 of the strategy. These functions will benefit from the fact that the right hand term of constraint system are variables. On the other hand, they consider the association tables in the constraint system.

```
module Phase_2 :
  sig

    val activate_phase :
      Constraint_system.constraint_system -> Constraint_system.constraint_system
```

`activate_phase csys` returns the constraint system `csys` optimised for Phase 2 of the strategy.

```
val add_message_inequation :
  Constraint_system.constraint_system ->
  Term.variable ->
  Term.term ->
  Recipe.variable -> Recipe.recipe -> Constraint_system.constraint_system
```

Modifications

```
val deducibility_replace :
  Constraint_system.constraint_system ->
  Constraint.position ->
  (Constraint.Deducibility.elt -> Constraint.Deducibility.elt list) ->
  Constraint.Deducibility.elt * Constraint_system.constraint_system
```

See Phase_1.deducibility_replace.

```
val deducibility_replace2 :
  Constraint_system.constraint_system ->
  Constraint.position ->
  (Constraint.Deducibility.elt ->
   Constraint.Deducibility.elt list * Constraint.Deducibility.elt list) ->
  Constraint.Deducibility.elt * Constraint_system.constraint_system *
  Constraint_system.constraint_system
```

See Phase_1.deducibility_replace2.

```
val deducibility_search_and_replace :
  Constraint_system.constraint_system ->
  Constraint.support_range ->
  (Constraint.Deducibility.elt -> bool) ->
  (Constraint.Deducibility.elt -> Constraint.Deducibility.elt list) ->
  Constraint.Deducibility.elt * Constraint.position *
  Constraint_system.constraint_system
```

See Phase_1.deducibility_search_and_replace.

```
val deducibility_search_and_replace2 :
  Constraint_system.constraint_system ->
  Constraint.support_range ->
  (Constraint.Deducibility.elt -> bool) ->
  (Constraint.Deducibility.elt ->
   Constraint.Deducibility.elt list * Constraint.Deducibility.elt list) ->
  Constraint.Deducibility.elt * Constraint.position *
  Constraint_system.constraint_system * Constraint_system.constraint_system
```

See Phase_1.deducibility_search_and_replace2.

Substitution

```
val unify_and_apply_message_equations :
  Constraint_system.constraint_system ->
  (Term.term * Term.term) list -> Constraint_system.constraint_system
```

See Phase_1.unify_and_apply_message_equations.

```
val apply_message_substitution :
  Constraint_system.constraint_system ->
  Term.substitution -> Constraint_system.constraint_system
```

See `Phase_1.apply_message_substitution`.

```
val apply_recipe_substitution :
  Constraint_system.constraint_system ->
  Recipe.substitution -> Constraint_system.constraint_system
```

See `Phase_1.apply_recipe_substitution`.

Access functions

```
val term_of_recipe :
  Constraint_system.constraint_system -> Recipe.recipe -> Term.term
```

`term_of_recipe c xi` returns the term $\xi\mathsf{acc}^1(\mathcal{C})$.

Raises

- `Internal_error` if $\xi \notin \mathcal{T}(\mathcal{F}_c, \mathcal{X}^2)$
- `Not_found` if $vars^2(\xi) \smallsetminus vars^2(D(\mathcal{C})) \neq \emptyset$.

```
val recipe_of_term :
  Constraint_system.constraint_system -> Term.term -> Recipe.recipe
```

`recipe_of_term c t` returns the recipe ξ such that $\xi\mathsf{acc}^1(\mathcal{C}) = t$.

Raises

- `Internal_error` if $t \notin \mathcal{T}(\mathcal{F}_c, \mathcal{X}^1)$
- `Not_found` if $vars^1(\xi) \smallsetminus vars^1(D(\mathcal{C})) \neq \emptyset$.

```
val get_max_param_context :
  Constraint_system.constraint_system -> Recipe.recipe -> int
```

`get_max_param_context c xi` returns the interger $\mathsf{paramC}^{\mathcal{C}}_{\mathsf{max}}(\mathsf{C}\lfloor\xi\rfloor_{\mathcal{C}})$.

```
val get_max_param_context_from_term :
  Constraint_system.constraint_system -> Term.term -> int
```

`get_max_param_context_from_term c t` returns the same result as `get_max_param_context c (recipe_of_term c t)` but is more efficient.

Formula inequation functions

```
val map_message_inequations :
  (Term.formula ->
   Recipe.formula option -> Term.formula * Recipe.formula option) ->
  Constraint_system.constraint_system -> Constraint_system.constraint_system
val fold_left_message_inequation :
  ('a -> Term.formula -> Recipe.formula option -> 'a) ->
  'a -> Constraint_system.constraint_system -> 'a
end
```

1.4.4 Row matrix of constraint system

The types `vector` and `matrix` corresponds to the vectors and matrices of constraint systems used in [Che12, Chapter 7-8].

```
type row_matrix
module Row :
  sig
```

```
exception All_bottom
val create :
  int ->
  Constraint_system.constraint_system list -> Constraint_system.row_matrix
```

Row.create_row_matrix s csys_l creates a row matrix of constraint system of size s where the element are the constraint systems in csys_l.

Raises

- Internal_error if the constraint systems in csys_l do not have the same structure. **[High debugging]**
- Internal_error if s is different from the number of element in csys_l
- Internal_error if the elements of csys_l do not have the same maximal support.

```
val get :
  Constraint_system.row_matrix -> int -> Constraint_system.constraint_system
val get_number_column : Constraint_system.row_matrix -> int
```

Row.get_number_column rm returns the number of column of rm.

```
val get_maximal_support : Constraint_system.row_matrix -> int
```

get_maximal_support rm returns the maximal support of the constraint systems in rm.

```
val iter :
  (Constraint_system.constraint_system -> unit) ->
  Constraint_system.row_matrix -> unit
val map :
  (Constraint_system.constraint_system -> Constraint_system.constraint_system) ->
  Constraint_system.row_matrix -> Constraint_system.row_matrix
val map2 :
  ('a ->
   Constraint_system.constraint_system -> Constraint_system.constraint_system) ->
  'a list -> Constraint_system.row_matrix -> Constraint_system.row_matrix
val fold_right :
  (Constraint_system.constraint_system -> 'a -> 'a) ->
  Constraint_system.row_matrix -> 'a -> 'a
val fold_left :
  ('a -> Constraint_system.constraint_system -> 'a) ->
  'a -> Constraint_system.row_matrix -> 'a
val check_structure : Constraint_system.row_matrix -> unit
```

check_structure rm does nothing if rm have is well structured else it raises the exception Internal_error. The definition of well structured row matrix is given in [Che12, Section 7.3.2.1].

```
end
```

1.4.5 Matrix of constraint systems

```
type matrix
module Matrix :
  sig
    val empty : Constraint_system.matrix
    val matrix_of_row_matrix :
      Constraint_system.row_matrix -> Constraint_system.matrix
```

`matrix_of_row_matrix rm` returns the row matrix `rm` considered as a matrix with one line.

```
val add_row :
  Constraint_system.matrix ->
  Constraint_system.row_matrix -> Constraint_system.matrix
```

Access

```
val get_number_column : Constraint_system.matrix -> int
```

`get_number_column m` returns the number of column of `m`.

```
val get_number_line : Constraint_system.matrix -> int
```

`get_number_line m` returns the number of line of `m`.

```
val get_maximal_support : Constraint_system.matrix -> int
```

`get_maximal_support m` returns the maximal support of the constraint systems in `m`.

Iterators

```
val replace_row :
  (Constraint_system.row_matrix -> Constraint_system.row_matrix list) ->
  Constraint_system.matrix -> Constraint_system.matrix
```

If `m` is the matrix $[V_1; \ldots; V_n]$ where the V_i are row matrices, then `replace_row m f` returns the matrix $[V_1^1; \ldots; V_1^{k_1}; V_2^1; \ldots; V_n^{k_n}]$ where for all $i \in 1, \ldots, n$, the application of `f` on V_i is the list of row matrices $V_i^1, \ldots, V_i^{k_i}$.

Raises `Internal_error` if the maximal support of the number of column of the row matrices produced by `f` do not match.

```
val fold_left_on_column :
  int ->
  ('a -> Constraint_system.constraint_system -> 'a) ->
  'a -> Constraint_system.matrix -> 'a
```

`fold_left_column j f acc m` is `f (.. f (f acc c1) c2 ..) cn` where `[c1;...;cn]` is the vector of constraint systems corresponding to the `j`th column of `m`.

```
val fold_left_on_row :
  int ->
  ('a -> Constraint_system.constraint_system -> 'a) ->
  'a -> Constraint_system.matrix -> 'a
```

`fold_left_row j f acc m` is `f (.. f (f acc c1) c2 ..) cn` where `[c1;...;cn]` is the vector of constraint systems corresponding to the `j`th line of `m`.

```
val fold_left_row :
  ('a -> Constraint_system.row_matrix -> 'a) ->
  'a -> Constraint_system.matrix -> 'a
val fold_right_row :
  (Constraint_system.row_matrix -> 'a -> 'a) ->
  Constraint_system.matrix -> 'a -> 'a
val iter :
  (Constraint_system.constraint_system -> unit) ->
  Constraint_system.matrix -> unit
```

`iter f matrix` is `f c_1_1; f c_1_2; ...; f c_1_m; f c_2_1; ...; f c_n_m` where `matrix` is the matrix

$$\begin{bmatrix} c_{1,1} & \cdots & c_{1,m} \\ \vdots & \ddots & \vdots \\ c_{n,1} & \cdots & c_{n,m} \end{bmatrix}$$

```
val iter_row :
  (Constraint_system.row_matrix -> unit) -> Constraint_system.matrix -> unit
```

```
val map :
  (Constraint_system.constraint_system -> Constraint_system.constraint_system) ->
  Constraint_system.matrix -> Constraint_system.matrix
```

```
val map_on_column :
  int ->
  (Constraint_system.constraint_system -> Constraint_system.constraint_system) ->
  Constraint_system.matrix -> Constraint_system.matrix
```

Matrix searching

```
val find_in_row :
  int ->
  (Constraint_system.constraint_system -> bool) ->
  Constraint_system.matrix -> Constraint_system.constraint_system * int
```

`find_in_row i f_test matrix` searches the first constraint system in the line `i` of `matrix` that satisfies `f_test`.
Raises `Not_found` if no such constraint system exists.

```
val find_in_col :
  int ->
  (Constraint_system.constraint_system -> bool) ->
  Constraint_system.matrix -> Constraint_system.constraint_system * int
```

`find_in_col j f_test matrix` searches the first constraint system in the column `j` of `matrix` that satisfies `f_test`.
Raises `Not_found` if no such constraint system exists.

```
val find_in_row_between_col_index :
  int ->
  int ->
  int ->
  (Constraint_system.constraint_system -> bool) ->
  Constraint_system.matrix -> Constraint_system.constraint_system * int
```

`find_in_row_between_col_index i j j' f_test matrix` searches the first constraint system in line `i` of `matrix` that satisfies `f_test` and whose column index is between `j` and `j'`.
Raises

- `Not_found` if no such constraint system exists.
- `Internal_error` if the column indexes are not correct. **[Low debugging]**

```
val find_in_col_between_row_index :
  int ->
  int ->
  int ->
  (Constraint_system.constraint_system -> bool) ->
  Constraint_system.matrix -> Constraint_system.constraint_system * int
```

`find_in_col_between_row_index j i i' f_test matrix` searches the first constraint system in column `j` of `matrix` that satisfies `f_test` and whose line index is between `i` and `i'`.
Raises `Not_found` if no such constraint system exists.

Matrix scanning

```
val exists_in_row :
  int ->
  (Constraint_system.constraint_system -> bool) ->
  Constraint_system.matrix -> bool
```

`exists_in_row i f_test matrix` retrurns true iff there exists a constraint system in the line `i` of `matrix` that satisfies `f_test`.

```
val exists_in_row_between_col_index :
  int ->
  int ->
  int ->
  (Constraint_system.constraint_system -> bool) ->
  Constraint_system.matrix -> bool
```

`exists_in_row i j j' f_test matrix` retrurns true iff there exists a constraint system in the line `i` of `matrix` that satisfies `f_test` and whose column index is between `j` and `j'`.

```
val exists_in_col :
  int ->
  (Constraint_system.constraint_system -> bool) ->
  Constraint_system.matrix -> bool
```

`exists_in_col j f_test matrix` retrurns true iff there exists a constraint system in the column `j` of `matrix` that satisfies `f_test`.

```
val exists_in_col_between_row_index :
  int ->
  int ->
  int ->
  (Constraint_system.constraint_system -> bool) ->
  Constraint_system.matrix -> bool
```

`exists_in_col j i i' f_test matrix` retrurns true iff there exists a constraint system in the column `j` of `matrix` that satisfies `f_test` and whose line index is between `i` and `i'`.

```
val is_empty : Constraint_system.matrix -> bool
```

`is_empty m` returns `true` iff and only `m` is the empty matrix.

```
val check_structure : Constraint_system.matrix -> unit
```

`check_structure m` does nothing if `m` have is well structured else it raises the exception `Internal_error`. The definition of well structured matrix is given in [Che12, Section 7.3.2.1].

```
val display : Constraint_system.matrix -> string
val normalise : Constraint_system.matrix -> Constraint_system.matrix
end
```

1.4.6 Rule applications

`exception Not_applicable`

The exception `Not_applicable` is launched when a rule cannot be applied on a row matrix usually due to a condition of the structure of the constraint systems in the row.

The following functions describe the mechanism for applying a rule on matrices of constraint system. Each of these functions have as arguments at least the two following functions:

- `search : constraint_system -> 'a * constraint_system * constraint_system`
- `apply : 'a -> constraint_system -> constraint_system * constraint_system`

Typically, applying a rule on a constraint system depend on parameter that can depend themselves on elements of the frame, deducibility constraints, equations, ... The function `search` searches for the correspondances between the paramaters of the rule and the constraint system, then it applies the rule on the constraint system hence producing two new constraint systems. However, since a rule will always be applied on row matrices that contains constraint systems of same structure, `search` also returns enough informations for the function `apply` to apply the rules on a constraint system without having to search again the correspondance between parameter and the constrain system.

```
val apply_rule_on_row_matrix :
  (constraint_system ->
   'a * constraint_system *
   constraint_system) ->
  ('a ->
   constraint_system ->
   constraint_system * constraint_system) ->
  row_matrix ->
  row_matrix option * row_matrix option
```

`apply_rule_on_row_matrix search apply r` apply the rule on the row matrix `r`. It returns a pair of row matrix option `(r_left,r_right)` where `r_left` (resp. `r_right`) is `None` if the application of the rule produces an unsatisfiable left (resp. right) row matrix, i.e. a row matrice with only $\perp$ as constraint systems. See [Che12, Definition 7.10] for more detail on the application of a rule on a row matrix.

Raises `Internal_error` if the constraint systems produced by `search` or `apply` do not have the same maximal supports as those in `r`.

```
val apply_external_rule :
  (constraint_system ->
   'a * constraint_system *
   constraint_system) ->
  ('a ->
   constraint_system ->
   constraint_system * constraint_system) ->
  matrix ->
  matrix * matrix
```

`apply_external_rule search apply m` apply an external rule on the matrix `m`. See [Che12, Section 7.3.2.2] for more detail on the application of an external rule on a matrix.

Raises `Internal_error` if the constraint systems produced by `search` or `apply` do not have the same maximal supports as those in `m`.

```
val apply_internal_rule :
  (constraint_system ->
   'a * constraint_system *
   constraint_system) ->
  ('a ->
   constraint_system ->
   constraint_system * constraint_system) ->
  int -> matrix -> matrix
```

`apply_internal_rule search apply i m` apply an internal rule on the `i`th line of matrix `m`. See [Che12, Section 7.3.2.2] for more detail on the application of an internal rule on a matrix.

Raises

- `Internal_error` if the constraint systems produced by `search` or `apply` do not have the same maximal supports as those in `m`.

- `Internal_error` if `i` is not the index of a line of `m`.

```
val apply_internal_rule_full_column :
  (constraint_system ->
   'a * constraint_system *
   constraint_system) ->
  ('a ->
   constraint_system ->
   constraint_system * constraint_system) ->
  matrix -> matrix
```

`apply_internal_rule_full_column search apply m` apply an internal rule on each line line of matrix `m` hence returning a matrix with twice the number of line as `m` (when counting the line with only bottom constraint system). It will be used to apply rule Dest and Eq-left-right. See [Che12, Section 7.4.1.1] for more detail on the application of these rules.

Raises `Internal_error` if the constraint systems produced by `search` or `apply` do not have the same maximal supports as those in `m`.

1.5 Module `Process` : Process

```
type label
val fresh_label : unit -> label
type formula =
  | Eq of Term.term * Term.term
  | Neq of Term.term * Term.term
  | And of formula * formula
  | Or of formula * formula
type pattern =
  | Var of Term.variable
  | Tuple of Term.symbol * pattern list
type process =
  | Nil
  | Choice of process * process
  | Par of process * process
  | New of Term.name * process * label
  | In of Term.term * Term.variable * process * label
  | Out of Term.term * Term.term * process * label
  | Let of pattern * Term.term * process * label
  | IfThenElse of formula * process * process * label
val refresh_label : process -> process
val rename : process -> process
val iter_term_process : process -> (Term.term -> Term.term) -> process
val get_free_names : process -> Term.name list
val display_process : process -> string
```

1.5.1 Symbolic process

```
type symbolic_process
val create_symbolic :
  (Recipe.recipe * Term.term) list ->
  process ->
```

```
  Constraint_system.constraint_system -> symbolic_process
val display_trace : symbolic_process -> string
val display_trace_no_unif : symbolic_process -> string
```

Testing

```
val is_bottom : symbolic_process -> bool
```

Access and modification

```
val get_constraint_system :
  symbolic_process -> Constraint_system.constraint_system
val replace_constraint_system :
  Constraint_system.constraint_system ->
  symbolic_process -> symbolic_process
val simplify : symbolic_process -> symbolic_process
val size_trace : symbolic_process -> int
val instanciate_trace : symbolic_process -> symbolic_process
```

Transition application

```
val apply_internal_transition :
  bool ->
  (symbolic_process -> unit) -> symbolic_process -> unit
val apply_input :
  (symbolic_process -> unit) ->
  Recipe.variable -> Recipe.variable -> symbolic_process -> unit
val apply_output :
  (symbolic_process -> unit) ->
  Recipe.variable -> symbolic_process -> unit
```

Optimisation

```
val is_same_input_output : symbolic_process -> symbolic_process -> bool
```

Chapter 2

Trace equivalence

2.1 Module Rules : Definitions of the rules

This module regroups all the functions that describes the application of rules on constraint systems.

2.1.1 Rule Cons

```
val apply_cons_row_matrix :
  Standard_library.Recipe.variable ->
  Standard_library.Term.symbol ->
  Standard_library.Constraint_system.row_matrix ->
  Standard_library.Constraint_system.row_matrix option *
  Standard_library.Constraint_system.row_matrix option
```

```
val apply_external_cons_phase_1 :
  Standard_library.Recipe.variable ->
  Standard_library.Term.symbol ->
  Standard_library.Constraint_system.matrix ->
  Standard_library.Constraint_system.matrix *
  Standard_library.Constraint_system.matrix
```

```
val apply_external_cons_phase_2 :
  Standard_library.Recipe.variable ->
  Standard_library.Term.symbol ->
  Standard_library.Constraint_system.matrix ->
  Standard_library.Constraint_system.matrix *
  Standard_library.Constraint_system.matrix
```

2.1.2 Rule Axiom

```
val apply_axiom_row_matrix :
  int ->
  Standard_library.Recipe.variable ->
  Standard_library.Recipe.path ->
  Standard_library.Constraint_system.row_matrix ->
  Standard_library.Constraint_system.row_matrix option *
  Standard_library.Constraint_system.row_matrix option
```

```
val apply_external_axiom_phase_1 :
  int ->
  Standard_library.Recipe.variable ->
  Standard_library.Recipe.path ->
  Standard_library.Constraint_system.matrix ->
```

```
  Standard_library.Constraint_system.matrix *
  Standard_library.Constraint_system.matrix
val apply_external_axiom_phase_2 :
  int ->
  Standard_library.Recipe.variable ->
  Standard_library.Recipe.path ->
  Standard_library.Constraint_system.matrix ->
  Standard_library.Constraint_system.matrix *
  Standard_library.Constraint_system.matrix
```

2.1.3 Rule Dest

```
val apply_full_column_dest :
  int ->
  Standard_library.Recipe.path ->
  int ->
  Standard_library.Term.symbol ->
  Standard_library.Constraint_system.matrix ->
  Standard_library.Constraint_system.matrix *
  (Standard_library.Recipe.path * Standard_library.Recipe.variable) list
val apply_full_column_dest_tuple :
  int ->
  Standard_library.Recipe.path ->
  Standard_library.Term.symbol ->
  Standard_library.Constraint_system.matrix ->
  Standard_library.Constraint_system.matrix *
  (Standard_library.Recipe.path * Standard_library.Recipe.variable) list
```

2.1.4 Rule Eq-left-left

```
val apply_eqll :
  int ->
  Standard_library.Constraint_system.matrix ->
  Standard_library.Constraint_system.matrix
```

2.1.5 Rule Eq-left-right

```
val apply_full_column_eqlr :
  int ->
  Standard_library.Recipe.path ->
  Standard_library.Recipe.variable ->
  Standard_library.Constraint_system.matrix ->
  Standard_library.Constraint_system.matrix
val apply_full_column_eqlr_frame :
  int ->
  Standard_library.Recipe.path ->
  int ->
  Standard_library.Recipe.path ->
  Standard_library.Constraint_system.matrix ->
  Standard_library.Constraint_system.matrix
```

2.1.6 Rule Eq-right-right

```
val apply_eqrr_row_matrix :
  Standard_library.Recipe.variable ->
```

```
  Standard_library.Recipe.variable ->
  Standard_library.Constraint_system.row_matrix ->
  Standard_library.Constraint_system.row_matrix option *
  Standard_library.Constraint_system.row_matrix option
val apply_external_eqrr_phase_1 :
  Standard_library.Recipe.variable ->
  Standard_library.Recipe.variable ->
  Standard_library.Constraint_system.matrix ->
  Standard_library.Constraint_system.matrix *
  Standard_library.Constraint_system.matrix
val apply_external_eqrr_phase_2 :
  Standard_library.Recipe.variable ->
  Standard_library.Recipe.recipe ->
  Standard_library.Constraint_system.matrix ->
  Standard_library.Constraint_system.matrix *
  Standard_library.Constraint_system.matrix
```

2.1.7 Rule Ded-st

```
val apply_dedsubterm_row_matrix :
  Standard_library.Recipe.path ->
  int ->
  Standard_library.Term.symbol ->
  int ->
  Standard_library.Constraint_system.row_matrix ->
  Standard_library.Constraint_system.row_matrix option *
  Standard_library.Constraint_system.row_matrix option
```

2.2 Module Strategy

```
val apply_strategy_input :
  (Standard_library.Constraint_system.matrix -> unit) ->
  Standard_library.Constraint_system.matrix -> unit
val apply_strategy_output :
  (Standard_library.Constraint_system.matrix -> unit) ->
  Standard_library.Constraint_system.matrix -> unit
```

2.3 Module Algorithm

```
val decide_trace_equivalence :
  Standard_library.Process.process -> Standard_library.Process.process -> bool
val internal_communication : bool Pervasives.ref
```

Bibliography

[Che12] Vincent Cheval. *Automatic verification of cryptographic protocols: privacy-type properties.* Thèse de doctorat, Laboratoire Spécification et Vérification, ENS Cachan, France, December 2012.