

Guard and Continuation Optimization for Occurrence Representations of Constraint Handling Rules

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Overview

1. Constraint Handling Rules
2. Occurrence Representation
3. Guard Optimization
4. Continuation Optimization
5. Type and mode information
6. Experiments
7. Future work

1. Constraint Handling Rules

(Thom Frühwirth)

- Write your own constraint solver as CHRs:
 - ◆ application tailored solvers
 - ◆ embedded in Prolog (or other host language)
 - ⇒ no interfacing problems
 - ◆ high-level specification
 - focus on what, not how
 - fixpoint computation is taken care of
 - very compact programs
 - easy to understand, modify and experiment with
- Also useful as general-purpose language: everything can be implemented in CHR with optimal complexity (cfr our CHR workshop paper on computability and complexity of CHR)

1. Constraint Handling Rules

Three kinds of CHR rules:

- Simplification rules:

$\text{RemovedHeads} \Leftarrow \text{Guard} \mid \text{Body}.$

- Propagation rules:

$\text{KeptHeads} \Rightarrow \text{Guard} \mid \text{Body}.$

- Simplification rules:

$\text{KeptHeads} \setminus \text{RemovedHeads} \Leftarrow \text{Guard} \mid \text{Body}.$

A rule can be applied if:

- head constraints are in the constraint store
- the guard is satisfied

1. CHR example: interval solver

$\text{: - constraints in/2.}$

$X \text{ in } A:B \iff A>B \mid \text{fail.}$

$X \text{ in } A:B \iff A ::= B \mid X \text{ is } A.$

$X \text{ in } A:B, X \text{ in } C:D \iff A<B, C<D \mid X \text{ in } \max(A,C):\min(B,D).$

- First rule: X is in an empty interval $\iff \text{fail}$
- Second rule: X is in $[a, a]$ $\iff X$ is a
- Third rule: interval intersection

1. CHR: Operational semantics

- abstract (theoretical) operational semantics ω_t
 - ◆ rules can be applied in any order
- refined oper. sem. ω_r [Duck, Stuckey, de la Banda, Holzbaaur]
 - ◆ an instance of ω_t
 - ◆ rules applied in textual order \rightarrow more deterministic
 - ◆ better termination/complexity possible
 - ◆ used in all major CHR implementations

1. CHR: Operational semantics

Implementations use refined operational semantics:

$a \setminus b \langle == \rangle \text{true}.$

$a, a \langle == \rangle b.$

$b == \rangle a.$

$a, c \langle == \rangle d.$

Query:

?- $b, c.$

Constraint store:

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$b \implies a.$

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$b \Rightarrow a.$

$a, c \Leftrightarrow d.$

Query:

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Constraint store:

d

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Implementations use refined operational semantics:

$a \setminus b \Leftrightarrow \text{true}.$

$a, a \Leftrightarrow b.$

$b \Rightarrow a.$

$a, c \Leftrightarrow d.$

Query:

?- b, c.

d

Yes

Constraint store:

1. CHR: Operational semantics

Implementations use refined operational semantics:

$a \setminus b \langle == \rangle \text{true}.$

$a, a \#X \langle == \rangle b \text{ pragma passive}(X) .$

$b == \rangle a.$

$a, c \langle == \rangle d.$

Query:

?- b, c.

d

Yes

Constraint store:

1. CHR: Operational semantics

- In refined operational semantics ω_r , rule order is implicit guard:
 $X \text{ leq } X \iff \text{true}.$
 $X \text{ leq } Y, Y \text{ leq } X \iff X \setminus == Y \mid X=Y.$
 $X \text{ leq } Y, Y \text{ leq } Z \implies X \setminus == Y, Y \setminus == Z, X \setminus == Z \mid X \text{ leq } Z.$
- Programmers remove implied guards to improve performance
- Problem for logical reading of a rule: meaning of a rule depends on all previous rules!
- Solution: keep all necessary guards in program, let compiler remove redundant guards

2. Occurrence Representation

Occurrence representation:

- Defined in terms of *occurrences*, not *rules*
- Every occurrence has...
 - ◆ partner constraints
 - ◆ guard (default: rule guard)
 - ◆ body (default: rule body)
 - ◆ success continuation (if occ is not removed) (default: next occ)
 - ◆ fail continuation (default: next occ)

Call-based refined **operational semantics**
for occurrence representations (ω_0)

2. Occurrence Representation

- Very close to how CHR rules are compiled
- Mapping CHR program \rightarrow Occ. Repr. such that $\omega_r = \omega_o$
- Can be used to formulate (and show correctness of) optimizations
- Skipping occurrences (pragma passive) can be done by changing continuations

3. Guard Optimization: Idea

$X \text{ in } A:B \iff A > B \mid \text{fail.}$

$X \text{ in } A:B \iff A ::= B \mid X \text{ is } A.$

$X \text{ in } A:B, X \text{ in } C:D \iff A < B, C < D \mid X \text{ in } \max(A,C):\min(B,D).$

- When last rule is tried, first two rules did not fire (otherwise active constraint was removed)
 \Rightarrow guards of first two rules failed for both constraints

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- When last rule is tried, first two rules did not fire (otherwise active constraint was removed)
 \Rightarrow guards of first two rules failed for both constraints
- negations of first guard: $A \leq B$ and $C \leq D$
negations of second guard: $A \neq B$ and $C \neq D$
 \Rightarrow this entails $A < B$ and $C < D$
 \Rightarrow guard of 3rd and 4th occurrence can be simplified

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- When last rule is tried, first two rules did not fire (otherwise active constraint was removed)
 \Rightarrow guards of first two rules failed for both constraints
- negations of first guard: $A = < B$ and $C = < D$
negations of second guard: $A = \backslash = B$ and $C = \backslash = D$
 \Rightarrow this entails $A < B$ and $C < D$
 \Rightarrow guard of 3rd and 4th occurrence can be simplified

3. Guard Optimization

$X \text{ in}_1 A:B \iff A>B \mid \dots$

$X \text{ in}_2 A:B \iff A ::= B \mid \dots$

$X \text{ in}_3 A:B, X \text{ in}_4 C:D \iff A<B, C<D \mid \dots$

- New guard for the 3rd occurrence: true
- New guard for the 4th occurrence: fail

$X \text{ in}_3 A:B, X \text{ in}_4 \# \text{Id } C:D \iff \text{true} \mid \dots \text{pragma passive}(\text{Id})$

$X \text{ in}_3 \# \text{Id } A:B, X \text{ in}_4 C:D \iff \text{fail} \mid \dots \text{pragma passive}(\text{Id})$

3. Guard Optimization

- Never-stored constraints are removed before they actually *need* to be inserted
 \rightsquigarrow avoid constraint store insert/remove overhead
- Currently detects only single-head no-guard simplification rules, e.g. $X \text{ geq } Y \iff Y \text{ leq } X$.
- Do guard optimization first:
 - ◆ $X \text{ geq } X \iff \text{true}$.
 - ◆ $X \text{ geq } Y \iff X \setminus == Y \mid Y \text{ leq } X$.
 - ◆ $\text{sign}(X, S) \iff X > 0 \mid S = \text{pos}$.
 - ◆ $\text{sign}(X, S) \iff X ::= 0 \mid S = \text{zero}$.
 - ◆ $\text{sign}(X, S) \iff X < 0 \mid S = \text{neg}$.

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- Do guard optimization first:
 - ◆ $X \text{ geq } X \iff \text{true}$.
 - ◆ $X \text{ geq } Y \iff Y \text{ leq } X$. \rightsquigarrow **geq/2 is never-stored!**
 - ◆ $\text{sign}(X, S) \iff X > 0 \mid S = \text{pos}$.
 - ◆ $\text{sign}(X, S) \iff X ::= 0 \mid S = \text{zero}$.
 - ◆ $\text{sign}(X, S) \iff S = \text{neg}$. \rightsquigarrow **sign/2 is never-stored!**

4. Continuation Optimization

- Idea: skip occurrences that cannot result in rule application
- Guard optimization can simplify an occ guard to fail
 \rightsquigarrow modify continuation of previous occurrence
- Always failing occ guard = `pragma passive(occ) =`
 continuations of `occ-1` are `occ+1`

4. Continuation Optimization

$X \text{ in}_1 A:B \Leftrightarrow A>B \mid \dots$

$X \text{ in}_2 A:B \Leftrightarrow A ::= B \mid \dots$

$X \text{ in}_3 A:B, X_4 \text{ in } C:D \Leftrightarrow A<B, C<D \mid \dots$

- Removed occurrences (e.g. simplification rules):
only fail continuation is relevant
- Recall: after guard optimization: $g'(X \text{ in}_4 C : D) = \text{fail}$
- Optimizing $n_f(\text{in}_3) = \text{in}_4$ results in $n'_f(\text{in}_3) = \text{in}_5$
(skipping 4th occurrence)

4. Continuation Optimization

$\text{fib}_1(0, M) \implies M = 1.$

$\text{fib}_2(1, M) \implies M = 1.$

$\text{fib}_3(N, M) \implies N > 1 \mid \text{fib}(N-1, M1), \text{fib}(N-2, M2), M \text{ is } M1+M2.$

- Occurrences in Occ^k (e.g. propagation rules):
fail *and* success continuations are relevant
current subderivation has to continue whether or not the rule was applied
- Optimizing $n_s(\text{fib}_1) = \text{fib}_2$ results in $n'_s(\text{fib}_1) = \text{fib}_4$
(skipping 2nd and 3rd occurrence)
- Optimizing $n_s(\text{fib}_2) = \text{fib}_3$ results in $n'_s(\text{fib}_2) = \text{fib}_4$
- Fail continuations cannot be optimized in this example

5. Type and mode information

- Type and mode information can be used to improve optimizations
- Optional type/mode declarations:
:- chr_type list(T) —> [] ; [T | list(T)].
:- constraints sum(+list(int), ?int).
- Mode: + for ground arguments, ? for unknown mode.
- Type: built-in types like any, int, natural, ...
new types can be defined using (generic) type definitions
- Backwards-compatibility:
:- constraints sum/2 is now syntactic sugar for
:- constraints sum(?any,?any).

5. Type and mode information

- Can use hash-table store for ground constraints!
- Mode/type also useful in guard/continuation optimization
- E.g. if first argument is ground list:
sum([],S) \Leftrightarrow S=0.
sum([X|Xs] ,S) \Leftrightarrow sum(Xs,T), S is X+T.

5. Type and mode information

- Can use hash-table store for ground constraints!
- Mode/type also useful in guard/continuation optimization
- E.g. if first argument is ground list:
 $\text{sum}([],S) \iff S=0.$
 $\text{sum}(L,S) \iff L=[X|Xs], \text{sum}(Xs,T), S \text{ is } X+T.$
- \rightsquigarrow $\text{sum}/2$ is never-stored!
- Generated code: ...

5. Effect of Optimizations

```
:-use_module(library(chr_runtime)). :-use_module(library(chr_hashtable_store)). 'attach_sum/2'([],_). 'attach_sum/2'([E|D],C):- (get_attr(E,user,B)->A=[C|B],put_attr(E,user,A);put_attr(E,user,[C])), 'attach_sum/2'(D,C). 'detach_sum/2'([],_). 'detach_sum/2'([E|D],C):- (get_attr(E,user,B)->chr_runtime:sbag_del_element(B,C,A), (A==[]->del_attr(E,user);put_attr(E,user,A));true), 'detach_sum/2'(D,C). '$indexed_variables'(C,B):-C=sum(A,_), term_variables(A,B). attach_increment([],_). attach_increment([F|E],D):-chr_runtime:not_locked(F), (get_attr(F,user,C)->sort(C,B), chr_runtime:merge_attributes(D,B,A), put_attr(F,user,A);put_attr(F,user,D)), attach_increment(E,D). attr_unify_hook(G,F):-sort(G,E), (var(F)->(get_attr(F,user,D)->true;D=[]), sort(D,C), chr_runtime:merge_attributes(E,C,B), put_attr(F,user,B), chr_runtime:run_suspensions(B);(compound(F)->term_variables(F,A), attach_increment(A,E);true), chr_runtime:run_suspensions(G)). activate_constraint(H,G,F,E):-arg(2,F,D), D=mutable(C), chr_runtime:update_mutable(active,D), (nonvar(E)->true;arg(4,F,B), B=mutable(A), E is A+1, chr_runtime:update_mutable(E,B)), (compound(C)->term_variables(C,G), chr_runtime:none_locked(G), H=yes;C==removed->chr_indexed_variables(F,G), H=yes;G=[], H=no). remove_constraint_internal(E,D,C):-arg(2,E,B), B=mutable(A), chr_runtime:update_mutable(removed,B), (compound(A)->D=[], C=no;A==removed->D=[], C=no;C=yes, chr_indexed_variables(E,D)). insert_constraint_internal(yes,J,I,H,G,F):-I=..[suspension,E,D,H,C,B,G|F], chr_indexed_variables(I,J), chr_runtime:none_locked(J), chr_runtime:create_mutable(active,D), chr_runtime:create_mutable(0,C), chr_runtime:create_mutable(A,B), chr_runtime:empty_history(A), chr_runtime:gen_id(E). chr_indexed_variables(C,B):-C=..[_,_,_,_,_,_,_|_], '$indexed_variables'(A,B). '$insert_in_store_sum/2'(D):-chr_runtime:global_term_ref_1(C), (get_attr(C,user,B)->A=[D|B], put_attr(C,user,A);put_attr(C,user,[D])). '$delete_from_store_sum/2'(D):-chr_runtime:global_term_ref_1(C), (get_attr(C,user,B)->chr_runtime:sbag_del_element(B,D,A), (A==[]->del_attr(C,user);put_attr(C,user,A));true). '$enumerate_suspensions'(C):-chr_runtime:global_term_ref_1(B), get_attr(B,user,A), chr_runtime:sbag_member(C,A). sum(B,A):-'sum/2__0'(B,A,_). 'sum/2__0'(E,D,C):-E==[],!, (var(C)->true;remove_constraint_internal(C,B,A), (A==yes->'$delete_from_store_sum/2'(C), 'detach_sum/2'(B,C);true)), D=0. 'sum/2__0'(H,G,F):-nonvar(H), H=[E|D],!, (var(F)->true;remove_constraint_internal(F,C,B), (B==yes->'$delete_from_store_sum/2'(F), 'detach_sum/2'(C,F);true)), sum(D,A), G is E+A. 'sum/2__0'(E,D,C):- (var(C)->insert_constraint_internal(B,A,C,user:'sum/2__0'(E,D,C), sum(E,D), [E,D])); activate_constraint(B,A,C,_), (B==yes->'$insert_in_store_sum/2'(C), 'attach_sum/2'(A,C);true).
```



```
:- use_module(library(chr_runtime)).
:- use_module(library(chr_hashtable_store)).
'$enumerate_suspensions'(_) :- fail.
sum([],A) :- !, A=0.
sum([D|C],B) :- sum(C,A), B is D+A.
```

6. Experiments

Never-stored constraints: (guard optimization)

<i>Benchmark</i>	<i>Optimize</i>	<i># clauses</i>	<i># lines</i>	<i>Runtime (%)</i>	
sum (10000,500)	no	3	10	5.03	(100)
	type	2	6	4.49	(89)
nrev (30,50000)	no	6	20	13.97	(100)
	type	4	11	8.44	(60)
dfsearch (16,500)	no	4	16	37.58	(100)
	yes	4	15	31.63	(84)
	type	3	11	29.97	(80)

6. Experiments

“Real” constraint solvers: (continuation optimization)

<i>Benchmark</i>	<i>Optimize</i>	<i># clauses</i>	<i># lines</i>	<i>Runtime (%)</i>	
bool_chain (200)	no	180	2861	12.8	(100)
	yes	147	2463	7.0	(55)
fib (22)	no	10	154	11.2	(100)
	yes	9	125	8.5	(76)
leq (60)	no	18	218	14.1	(100)
	yes	13	162	11.7	(83)

7. Future work

- Stronger simplification:
now: conditions are only simplified to true or fail
better: also simplify expensive conditions to cheap conditions
- Specialize generated code to call patterns in rule bodies
- Type-checking
- New types for more efficient constraint stores
e.g. `dense_int` for array stores
- Automatic type/mode inference?
- Based on query pattern declarations?