

Soft Concurrent Constraint Programming with Local Variables ^{*}

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Abstract. ???

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1 Introduction

This work originates from [6], where a first implementation of polyadic constraints was ideated (together with a polynomial representation of soft constraints). However, this paper extends that first attempt with a concurrent constraint language on top of it, and process-equivalence relations. The work is organised as follows: in Sect. 2 we present the necessary background on the algebraic structure needed to model polyadic constraints. Then, Sect ??,

2 An Introduction to Residuated Monoids

This section reports some results on residuated monoids, which are the algebraic structure adopted for modelling soft constraints in the following of the paper. Results are mostly drawn from [8], where also proofs can be found.

2.1 Preliminaries on Ordered Monoids

The first step is to define an algebraic structure for modelling preferences, where it is possible to compare values and combine them. Our choice falls into the range of *bipolar* approaches, in order to represent both positive and negative preferences: we refer to [7] for a detailed introduction and a comparison with other proposals.

Definition 1 (partial order). A *partial order (PO)* is a pair $\langle A, \leq \rangle$ such that A is a set and $\leq \subseteq A \times A$ is a reflexive, transitive, and anti-symmetric relation. A (join) *semi-lattice (SL)* is a PO such that any non-empty finite subset of A has a least upper bound (LUB).

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The LUB of a (possibly infinite or empty) subset $X \subseteq A$ is denoted $\bigvee X$, and it is clearly unique. Should they exist, $\bigvee A$ and $\bigvee \emptyset$ correspond respectively to the top, denoted as \top , and to the bottom, denoted as \perp , of the PO.

Definition 2 (monoid). A (commutative) monoid is a triple $\langle A, \otimes, \mathbf{1} \rangle$ such that A is a set, $\otimes : A \times A \rightarrow A$ is a commutative and associative function, and $\mathbf{1} \in A$ is the identity element, namely, $\forall a \in A. a \otimes \mathbf{1} = a$.

A partially ordered (semi-lattice) monoid is a 4-tuple $\langle A, \leq, \otimes, \mathbf{1} \rangle$ such that $\langle A, \leq \rangle$ is a PO (SL) and $\langle A, \otimes, \mathbf{1} \rangle$ a monoid.

As usual, we use the infix notation: $a \otimes b$ stands for $\otimes(a, b)$.

Definition 3 (distributivity). Let $\langle A, \leq, \otimes, \mathbf{1} \rangle$ be a semi-lattice monoid. It is distributive if for any non-empty finite $X \subseteq A$

$$- \forall a \in A. a \otimes \bigvee X = \bigvee \{a \otimes x \mid x \in X\}.$$

Note that distributivity implies that \otimes is monotone with respect to \leq .

Remark 1. It is almost straightforward to show that our proposal encompasses many other formalisms in the literature. Indeed, distributive semi-lattice monoids are *tropical* semirings (also known as dioids), namely, semirings with an idempotent sum operator $a \oplus b$, which in our formalism is obtained as $\bigvee \{a, b\}$. If $\mathbf{1}$ is the top of the SL we end up in *absorptive* semirings [9], which are known as *c-semirings* in the soft constraint jargon [2] (see e.g. [3] for a brief survey on residuation for such semirings). Note that requiring the monotonicity of \otimes and imposing $\mathbf{1}$ to be the top of the partial order means that preferences are negative, i.e., that it holds $\forall a, b \in A. a \otimes b \leq a$.

Example 1. Given a (possibly infinite) set V of variables, two semi-lattice monoids are going to play a key role in the following sections. The first one is the semi-lattice monoid $\mathbb{M}(V) = \langle 2_{fin}^V, \subseteq, \cup, \emptyset \rangle$ of finite sub-sets of V , with the usual order given by sub-set inclusion. For the second one, we start by defining the support of an endofunction $f : V \rightarrow V$ as the set $sv(f) = \{x \in V \mid f(x) \neq x\}$ and $F(V)$ as the set of functions $f : V \rightarrow V$ with finite support. The semi-lattice monoid of interest is $\mathbb{F}(V) = \langle F(V), id, \circ, \iota \rangle$ where ι is the identity function, \circ is function composition and id is the discrete ordering on $F(V)$.

2.2 Remarks on Residuation

It is often needed to be able to “remove” part of a preference, due e.g. to the non-monotone nature of the language at hand for manipulating constraints. The structure of our choice is given by residuated monoids [9]. They introduce a new operator \oplus , which represents a “weak” (due to the presence of partial orders) inverse of \otimes .

Definition 4 (residuation). A residuated monoid (RePO) is a 5-tuple $\langle A, \leq, \otimes, \oplus, \mathbf{1} \rangle$ such that $\langle A, \leq, \otimes, \mathbf{1} \rangle$ is a partially ordered monoid and $\oplus : A \times A \rightarrow A$ is a function satisfying $\forall a, b, c \in A. b \otimes c \leq a \iff c \leq a \oplus b$. An ReSL is an RePO such that the underlying PO is a SL.

In order to confirm the intuition about weak inverses, Lemma 1 below precisely states that residuation conveys the meaning of an approximated form of subtraction.

Lemma 1. *Let $\langle A, \leq, \otimes, \oplus, \mathbf{1} \rangle$ be an RePO. Then*

$$- \forall a, b \in A. a \oplus b = \bigvee \{c \mid b \otimes c \leq a\},$$

In order to ease the verification of the algebraic structure, it is often needed a characterisation of residuation via simpler properties, as the ones given below.

Lemma 2. *Let $\langle A, \leq, \otimes, \mathbf{1} \rangle$ be a partially ordered monoid and $\oplus : A \times A \rightarrow A$ a function. Then $\langle A, \leq, \otimes, \oplus, \mathbf{1} \rangle$ is an RePO if and only if*

$$\begin{aligned} - & \forall a, b \in A. b \otimes (a \oplus b) \leq a \leq (b \otimes a) \oplus b, \\ - & \forall a, b, c \in A. a \leq b \implies a \otimes c \leq b \otimes c \text{ and } a \oplus c \leq b \oplus c. \end{aligned}$$

It is easy to show that in any RePO the \oplus operator is also anti-monotone on the second argument, i.e., $\forall a, b, c \in A. a \leq b \implies c \oplus b \leq c \oplus a$. Other properties are also straightforward, such as $\forall a \in A. \mathbf{1} \leq a \oplus a$, which in turn implies that $\forall a \in A. a \otimes (a \oplus a) = a$ and $\forall a, b \in A. a < b \implies \mathbf{1} \not\leq a \oplus b$, where $a < b$ means $a \leq b$ and $a \neq b$. The latter fact suggests the definition below, which identifies sub-classes of residuated monoids that are suitable for an easier manipulation of constraints (see e.g. [3]).

Definition 5 (localisation / invertibility). *An RePO $\langle A, \leq, \otimes, \oplus, \mathbf{1} \rangle$ is*

- localised if $\forall a, b \in A. a \leq b \implies a \oplus b \leq \mathbf{1}$;
- invertible if $\forall a, b \in A. a \leq b \implies b \otimes (a \oplus b) = a$.

Note that if a RePO is localised then $\forall a \in A. a \oplus a = \mathbf{1}$.

Remark 2. Some well-known structures used for soft constraints are the *Fuzzy* ($([0, 1], \leq, \min, 1)$), *Probabilistic* ($([0, 1], \leq, \times, 1)$), and *Tropical* ($(\mathbb{R}^+, \geq, +, 0)$) semirings, for \geq the inverse of the standard order (thus 0 the top of the SL). In all these cases the underlying monoids are both invertible and localised, thus the \oplus operator can be also used to (partially) relax constraints (see again [3]).

Moving to ReSLs, next lemma ensures that residuation implies distributivity.

Lemma 3. *Let $\langle A, \leq, \otimes, \oplus, \mathbf{1} \rangle$ be an ReSL. Then the underlying SL is distributive.*

Distributivity holds also for the empty set and for infinite sets, if the necessary LUBs exist. Instead, it holds only partially for \oplus : this follows directly from the monotonicity of \oplus on the first argument, since it implies that $x \oplus a \leq \bigvee X \oplus a$ for all $x \in X$.

Lemma 4. *Let $\langle A, \leq, \otimes, \oplus, \mathbf{1} \rangle$ be an ReSL and $X \subseteq A$ a finite non-empty set. Then*

$$- \forall a \in A. \bigvee \{x \oplus a \mid x \in X\} \leq \bigvee X \oplus a$$

Also this inequation holds for the empty set and for infinite sets, if the necessary LUBs exist. Moreover, it also holds that $\bigvee \{a \oplus x \mid x \in X\} \geq a \oplus \bigvee X$, since \oplus is anti-monotone on the second argument.

Proposition 1. *Let $\langle A, \leq, \otimes, \oplus, \mathbf{1} \rangle$ be an ReSL. The following are equivalent*

1. $\forall a \in A. a \leq \mathbf{1}$
2. $\forall a \in A. \mathbf{1} \oplus a = \mathbf{1}$
3. $\forall a, b \in A. a \leq b \implies b \oplus a = \mathbf{1}$

There are some important classes of ReSLs such that \oplus is easily proved to be distributive in the first argument, while it is not so with respect to the second argument, not even in the absorptive case.

Lemma 5. *Let $\langle A, \leq, \otimes, \oplus, \mathbf{1} \rangle$ be an ReSL such that $\langle A, \leq \rangle$ is a total order and $X \subseteq A$ a finite non-empty set. Then*

$$- \forall a \in A. \bigvee \{x \oplus a \mid x \in X\} = \bigvee X \oplus a$$

Example 2. Let n be a positive integer and $[n] = \{0, \dots, n\}$ the segment of integers from 0 to n . We can now define the (bounded) monoid \mathbb{M}_n as the tuple $\langle [n], \geq, \oplus, \ominus, 0 \rangle$, where \oplus and \ominus are the bounded sum and subtraction, which are given as $m \oplus p = \min\{n, m + p\}$ and $m \ominus p = \max\{0, m - p\}$.

Now, it can be shown that \mathbb{M}_n is an absorptive ReSL, and since it is a total order, \ominus is distributive on the first argument. However, in general it is not distributive on the second one. Consider an integer m such that $m \neq n$ and the set $\{m, m + 1\}$: we then have that $(m + 1) \ominus \bigvee \{m, m + 1\} = 1$, while instead $\bigvee \{(m + 1) \ominus m, (m + 1) \ominus (m + 1)\} = 0$.

3 An Alternative Proposal for Constraint Manipulation

This section presents our personal take on polyadic algebras for ordered monoids: the standard axiomatisation of e.g. [11] has been completely reworked, in order to be adapted to the constraints formalism. We close the section by offering some preliminary insights on the laws for polyadic operators in residuated monoids.

3.1 Cylindric and Polyadic Operators for Ordered Monoids

We now introduce two families of operators that will be used for modelling variables hiding and substitution, which represent key features in languages for manipulating constraints. One is a well-known abstraction for existential quantifiers, the other an axiomatisation of the notion of substitution, and it is proposed as a weaker alternative to diagonals [12], the standard tool for modelling equivalence in constraint programming.³

Cylindric operators. We fix a partially ordered monoid $\mathbb{S} = \langle A, \leq, \otimes, \mathbf{1} \rangle$ and a set V of variables, and we then define a family of cylindric operators axiomatising existential quantifiers.

Definition 6 (cylindrification). *A cylindric operator \exists over \mathbb{S} and V is a family of monotone operators $\exists_x : A \rightarrow A$ indexed by elements in V such that for all $a, b \in A$ and $x, y \in V$*

³ “Weaker alternative” here means that diagonals allow for axiomatising substitutions at the expenses of working with complete partial orders: see e.g. [8, Definition 11].

1. $a \leq \exists_x a$,
2. $\exists_x \exists_y a = \exists_y \exists_x a$,
3. $\exists_x (a \otimes \exists_x b) = \exists_x a \otimes \exists_x b$.

Let $a \in A$. The support of a is the set of variables $sv(a) = \{x \mid \exists_x a \neq a\}$.

Polyadic operators. We now move to define a family of operators axiomatising substitutions. They interact with quantifiers, thus, beside a partially ordered monoid \mathbb{S} and a set V of variables, we fix a cylindric operator \exists over \mathbb{S} and V .

As for notation, for a function $\sigma : V \rightarrow V$ and a set $X \subseteq V$, we denote by $\sigma|_X : X \rightarrow V$ the obvious restriction, and by $\sigma^c(X) \subseteq V$ the counter-image of X along σ .

Definition 7 (polyadification). A polyadic operator s for \exists is a family of monotone operators $s_\sigma : A \rightarrow A$ indexed by elements in $F(V)$ such that for all $x \in V$ and $\sigma, \tau \in F(V)$

1. $sv(\sigma) \cap sv(a) = \emptyset \implies s_\sigma a = a$
2. $\forall a, b \in A. s_\sigma(a \otimes b) = s_\sigma a \otimes s_\sigma b$,
3. $\forall a \in A. \sigma|_{sv(a)} = \tau|_{sv(a)} \implies s_\sigma a = s_\tau a$,
4. $\forall a \in A. \exists_x s_\sigma a = \begin{cases} s_\sigma \exists_y a & \text{if } \sigma^c(x) = \{y\} \\ s_\sigma a & \text{if } \sigma^c(x) = \emptyset \end{cases}$.

A polyadic operator offers enough structure for modelling variable substitution. In the following, we fix a polyadic operator s for \exists .

3.2 Cylindric and Polyadic Operators for Residuated Monoids

Both algebraic structures introduced in the previous section are quite standard, even if polyadic operators are less-known in the soft-constraints literature: we tailored their presentation to our needs, and indeed the properties presented in Section ?? appear to be original. It is now time to consider the interaction of such structures with residuation. To this end, in the following we assume that \mathbb{S} is a RePO (see Definition 4).

Lemma 6. Let $x \in V$. Then it holds

$$- \forall a, b \in A. \exists_x(a \oplus \exists_x b) \leq \exists_x a \oplus \exists_x b \leq \exists_x(\exists_x a \oplus b).$$

Proof. As for the inequality on the left, we have

$$\begin{aligned} \exists_x b \otimes (a \oplus \exists_x b) \leq a &\implies \exists_x(\exists_x b \otimes (a \oplus \exists_x b)) \leq \exists_x a \implies \\ \exists_x b \otimes \exists_x(a \oplus \exists_x b) &\leq \exists_x a \implies \exists_x(a \oplus \exists_x b) \leq \exists_x a \oplus \exists_x b \end{aligned}$$

For the inequality on the right, note that \oplus is anti-monotone on the second argument and \exists is increasing, so that $\exists_x a \oplus \exists_x b \leq \exists_x a \oplus b \leq \exists_x(\exists_x a \oplus b)$. \square

Remark 3. Looking at the proof above, it is clear that $\exists_x(a \oplus \exists_x b) \leq \exists_x a \oplus \exists_x b$ is actually equivalent to state that $\exists_x(a \otimes \exists_x b) \geq \exists_x a \otimes \exists_x b$.

We can now show that \oplus does not substantially alter the free variables of its arguments, namely, that $sv(a \oplus b) \subseteq sv(a) \cup sv(b)$ holds. Indeed, if $x \notin sv(a) \cup sv(b)$

$$\exists_x(a \oplus b) = \exists_x(a \oplus \exists_x b) \leq \exists_x a \oplus \exists_x b \leq \exists_x(\exists_x a \oplus b) = \exists_x(a \oplus b)$$

and since $\exists_x(a \oplus b) = \exists_x a \oplus \exists_x b = a \oplus b$, the result follows.

A result similar to Lemma 6 relates residuation and polyadic operators.

Lemma 7. *Let $\sigma \in F(V)$. Then it holds*

$$- \forall a, b \in A. s_\sigma(a \oplus b) \leq s_\sigma a \oplus s_\sigma b.$$

Furthermore, if σ is invertible, then the equality holds.

Proof. As for the inequality, we have

$$a \otimes (b \oplus a) \leq b \implies s_\sigma[a \otimes (b \oplus a)] \leq s_\sigma b \implies$$

$$s_\sigma a \otimes s_\sigma(b \oplus a) \leq s_\sigma b \implies s_\sigma(b \oplus a) \leq s_\sigma b \oplus s_\sigma a$$

As for the equality, σ invertible implies $s_{\sigma^{-1}} s_\sigma a = a = s_\sigma s_{\sigma^{-1}} a$. Then we have

$$s_\sigma b \otimes (s_\sigma a \oplus s_\sigma b) \leq s_\sigma a \implies s_{\sigma^{-1}}(s_\sigma b \otimes (s_\sigma a \oplus s_\sigma b)) \leq s_{\sigma^{-1}} s_\sigma a \implies$$

$$s_{\sigma^{-1}} s_\sigma b \otimes s_{\sigma^{-1}}(s_\sigma a \oplus s_\sigma b) \leq a \implies b \otimes s_{\sigma^{-1}}(s_\sigma a \oplus s_\sigma b) \leq a \implies$$

$$s_{\sigma^{-1}}(s_\sigma a \oplus s_\sigma b) \leq a \oplus b \implies s_\sigma(s_{\sigma^{-1}}(s_\sigma a \oplus s_\sigma b)) \leq s_\sigma(a \oplus b) \implies$$

$$s_\sigma a \oplus s_\sigma b \leq s_\sigma(a \oplus b)$$

3.3 Polyadic Soft Constraints

We are now ready to advance our proposal of soft constraints; follows yet generalises [4], whose underlying algebraic structure is the one of absorptive semirings.

Definition 8 ((soft) constraints). *Let V be a set of variables, D a finite domain of interpretation and $\mathbb{S} = \langle A, \leq, \otimes, \oplus, \mathbf{1} \rangle$ a ReSL. A (soft) constraint $c : (V \rightarrow D) \rightarrow A$ is a function associating a value in A with each assignment $\eta : V \rightarrow D$ of the variables.*

In this section and in the following one, we denote by \mathcal{C} the set of constraints that can be built starting from chosen \mathbb{S} , V , and D . The application of a constraint function $c : (V \rightarrow D) \rightarrow A$ to a variable assignment $\eta : V \rightarrow D$ is denoted $c\eta$.

Even if a constraint involves all the variables in V , it may depend on the assignment of a finite subset of them, called its support. For instance, a binary constraint c with $supp(c) = \{x, y\}$ is a function $c : (V \rightarrow D) \rightarrow A$ that depends only on the assignment of variables $\{x, y\} \subseteq V$, meaning that two assignments $\eta_1, \eta_2 : V \rightarrow D$ differing only for the image of variables $z \notin \{x, y\}$ coincide (i.e., $c\eta_1 = c\eta_2$). The support corresponds to the classical notion of scope of a constraint. We often refer to a constraint with support X as c_X . Moreover, an assignment over a support X of cardinality k is concisely represented by a tuple t in D^k , and we often write $c_X(t)$ instead of $c_X\eta$.

The set of constraints forms a ReSL, with the structure lifted from \mathbb{S} .

Lemma 8 (the ReSL of constraints). *The ReSL of constraints \mathbb{C} is defined as the tuple $\langle \mathcal{C}, \leq, \otimes, \oplus, \mathbf{1} \rangle$ such that*

- $c_1 \leq c_2$ if $c_1 \eta \leq c_2 \eta$ for all $\eta : V \rightarrow D$,
- $(c_1 \otimes c_2) \eta = c_1 \eta \otimes c_2 \eta$,
- $(c_1 \oplus c_2) \eta = c_1 \eta \oplus c_2 \eta$,
- $\mathbf{1} \eta = \mathbf{1}$.

Combining constraints by the \otimes operator means building a new constraint whose support involves at most the variables of the original ones. The resulting constraint associates with each tuple of domain values for such variables the element that is obtained by multiplying those associated by the original constraints to the appropriate sub-tuples.

Lemma 9 (Cylindric and polyadic operators for (soft) constraints). *The ReSL of constraints \mathbb{C} admits cylindric and polyadic operators, defined as*

- $(\exists_x c) \eta = \bigvee \{ c \rho \mid \eta|_{V \setminus \{x\}} = \rho|_{V \setminus \{x\}} \}$ for all $c \in \mathcal{C}, x \in V$
- $(s_\sigma c) \eta = c(\eta \circ \sigma)$ for all $c \in \mathcal{C}, \sigma \in F(V)$

Hiding means eliminating variables from the support: $\text{supp}(\exists_x c) \subseteq \text{supp}(c) \setminus x$.⁴

Proof. The properties of the pomonoid action (see Definition ??) are easily shown to hold for both operators. As for the cylindric laws (see Definition 6), first note that the set of functions ρ such that $\eta|_{V \setminus \{x\}} = \rho|_{V \setminus \{x\}}$ is actually finite. Thus, we have that

$$\begin{aligned}
 (\exists_x (c \otimes \exists_x d)) \eta &= \bigvee_{\rho} \{ (c \otimes \exists_x d) \rho \mid \eta|_{V \setminus \{x\}} = \rho|_{V \setminus \{x\}} \} \\
 &= \bigvee_{\rho} \{ c \rho \otimes (\exists_x d) \rho \mid \eta|_{V \setminus \{x\}} = \rho|_{V \setminus \{x\}} \} \\
 &= \bigvee_{\rho} \{ c \rho \otimes (\bigvee_{\xi} \{ d \xi \mid \rho|_{V \setminus \{x\}} = \xi|_{V \setminus \{x\}} \}) \mid \eta|_{V \setminus \{x\}} = \rho|_{V \setminus \{x\}} \} \\
 &= \bigvee_{\rho} \{ c \rho \mid \eta|_{V \setminus \{x\}} = \rho|_{V \setminus \{x\}} \} \otimes \bigvee_{\xi} \{ d \xi \mid \eta|_{V \setminus \{x\}} = \xi|_{V \setminus \{x\}} \} \\
 &= (\exists_x c) \eta \otimes (\exists_x d) \eta
 \end{aligned}$$

[da rivedere] Let us now move to the polyadic laws (see Definition 7). We just consider the third item, and we assume that $\sigma|_{\sigma^c(X)}$ is injective, thus

$$\begin{aligned}
 (\exists_x s_\sigma c) \eta &= \bigvee_{\rho} \{ (s_\sigma c) \rho \mid \eta|_{V \setminus X} = \rho|_{V \setminus X} \} = \bigvee_{\rho} \{ c(\rho \circ \sigma) \mid \eta|_{V \setminus X} = \rho|_{V \setminus X} \} \\
 &= \bigvee_{\xi} \{ c \xi \mid (\eta \circ \sigma)|_{V \setminus \sigma^c(X)} = \xi|_{V \setminus \sigma^c(X)} \} \\
 &= (\exists_{\sigma^c(X)} c)(\eta \circ \sigma) = (s_\sigma \exists_{\sigma^c(X)} c) \eta
 \end{aligned}$$

where it always holds that $\eta|_{V \setminus X} = \rho|_{V \setminus X}$ implies $(\eta \circ \sigma)|_{V \setminus \sigma^c(X)} = (\rho \circ \sigma)|_{V \setminus \sigma^c(X)}$, while since $\sigma|_{\sigma^c(X)}$ is injective we have that a ξ satisfying $(\eta \circ \sigma)|_{V \setminus \sigma^c(X)} = \xi|_{V \setminus \sigma^c(X)}$ can be decomposed as $\rho \circ \sigma$ for a ρ such that $\eta|_{V \setminus X} = \rho|_{V \setminus X}$ (otherwise, it could happen that for some $\{x, y\} \subseteq \sigma^c(X)$ we have that $\sigma(x) = \sigma(y)$ and $\xi(x) \neq \xi(y)$). \square

⁴ The operator is called *projection* in the soft framework, and $\exists_x c$ is denoted $c \Downarrow_{V \setminus \{x\}}$.

Note also that the diagonal elements are not guaranteed to be \otimes -compact, even if they have finite support, since \top is not necessarily so. To this end, we close the section by adding the simple result below to the soft constraint lore.

Proposition 2. *Let $c \in \mathbb{C}$ be a constraint. It is \otimes -compact if and only if it has finite support and $c\eta$ is \otimes -compact for all η .*

4 Polyadic Soft CCP: syntax and reduction semantics

This section introduces our (meta-)language. We fix a set of variables V , ranged over by x, y, \dots , and an invertible CLIM $\mathbb{S} = \langle \mathcal{C}, \leq, \otimes \rangle$, which is polyadic over V and whose elements are ranged over by c, d, \dots .

Definition 9 (Agents). *The set \mathcal{A} of all agents, parametric with respect to a set \mathcal{P} of (unary) procedure declarations $p(x) = A$, is given by the following grammar*

$$A ::= \text{stop} \mid \text{tell}(c) \mid \text{ask}(c) \rightarrow A \mid A \parallel A \mid p(x) \mid \exists_x^\rho A.$$

We consider here the extended agent $\exists_x^\rho A$, where ρ is meant to represent a local store. More precisely, the extended agent carries some information about the hidden variable x in an incremental way. In the following, we often write $\exists_x A$ for $\exists_x^1 A$.

We denote by $fv(A)$ the set of free variables of an agent, defined in the expected way by structural induction, assuming that $fv(\text{tell}(c)) = sv(c)$, $fv(\text{ask}(c) \rightarrow A) = sv(c) \cup fv(A)$, and $fv(\exists_x^\rho A) = (fv(A) \cup sv(\rho)) \setminus \{x\}$. In the following, we restrict our attention to procedure declarations $p(x) = A$ such that $fv(A) = \{x\}$.

Definition 10 (Substitutions). *Let $[^y/x] : V \rightarrow V$ be the substitution defined as*

$$[^y/x](w) = \begin{cases} y & \text{if } w = x \\ w & \text{otherwise} \end{cases}$$

It induces a substitution operator $[^y/x] : \mathcal{A} \rightarrow \mathcal{A}$ on agents as follows

- $\text{stop}[^y/x] = \text{stop}$
- $\text{tell}(c)[^y/x] = \text{tell}(s[^y/x]c)$
- $(\text{ask}(c) \rightarrow A)[^y/x] = \text{ask}(s[^y/x]c) \rightarrow A[^y/x]$
- $p(w)[^y/x] = p([^y/x](w))$
- $(A_1 \parallel A_2)[^y/x] = (A_1[^y/x] \parallel A_2[^y/x])$
- $(\exists_w^\rho A)[^y/x] = \begin{cases} \exists_w^{(s[^y/x]\rho)} A[^y/x] & \text{if } w \notin \{x, y\} \\ (\exists_z^{(s[^z/w]\rho)} A[^z/w])[^y/x] & \text{for } z \notin fv(\exists_w^\rho A) \text{ otherwise} \end{cases}$

Note that the choice of z in the rule above is immaterial, since for the polyadic operator it holds $\exists_x c = \exists_y s[^y/x](c)$ if $y \notin sv(c)$. In the following we consider terms to be equivalent up-to α -conversion, meaning that terms differing only for hidden variables are considered equivalent, i.e., $\exists_w^\rho A = \exists_z^{(s[^z/w]\rho)} A[^z/w]$ for $z \notin fv(\exists_w^\rho A)$.

Lemma 10. *Let $A \in \mathcal{A}$ and $x \notin \text{fv}(A)$. Then $A[y/x] = A$.*

We now move to consider the reduction semantics of our calculus.

Definition 11 (Reductions). *Let $\Gamma = \mathcal{A} \times \mathcal{C}$ be the set of configurations. The direct reduction semantics for SCCP is the pair $\langle \Gamma, \mapsto \rangle$ such that $\mapsto \subseteq \Gamma \times \Gamma$ is the binary relations obtained by the rules in Table 1.*

The reduction semantics for SCCP is the pair $\langle \Gamma, \rightarrow \rangle$ such that $\rightarrow \subseteq \Gamma \times \Gamma$ is the binary relation obtained by the rules in Table 1 and Table 2.

A1	$\langle \text{tell}(c), \sigma \rangle \mapsto \langle \text{stop}, \sigma \otimes c \rangle$	Tell
A2	$\frac{\sigma \leq c}{\langle \text{ask}(c) \rightarrow A, \sigma \rangle \mapsto \langle A, \sigma \rangle}$	Ask
A3	$\frac{p(x) = A \in \mathcal{P}}{\langle p(y), \sigma \rangle \mapsto \langle A[y/x], \sigma \rangle}$	Rec
A4	$\frac{\langle A, \rho \otimes \sigma_0 \rangle \mapsto \langle B, \sigma_1 \rangle \text{ with } \sigma_0 = \sigma \oplus \exists_x \rho}{\langle \exists_x^\rho A, \sigma \rangle \mapsto \langle \exists_x^{\rho \otimes \rho_0} B, \sigma \otimes \exists_x \rho_0 \rangle \text{ with } \rho_0 = \sigma_1 \oplus (\rho \otimes \sigma_0)} \text{ for } x \notin \text{sv}(\sigma)$	Hide

Table 1. Axioms of the reduction semantics for SCCP.

R1	$\frac{\langle A, \sigma \rangle \mapsto \langle A', \sigma' \rangle}{\langle A \parallel B, \sigma \rangle \mapsto \langle A' \parallel B, \sigma' \rangle}$	Par1
R2	$\frac{\langle A, \sigma \rangle \mapsto \langle A', \sigma' \rangle}{\langle B \parallel A, \sigma \rangle \mapsto \langle B \parallel A', \sigma' \rangle}$	Par2

Table 2. Contextual rules of the reduction semantics for SCCP.

The split distinguishes between axioms and rules guaranteeing the closure with respect to the parallel operator. Indeed, rules **R1** and **R2** model the interleaving of two agents in parallel. In **A1** a constraint c is added to the store σ . **A2** checks if c is entailed by σ : if not, the computation is blocked. Axiom **A3** replaces a procedure identifier with the associated body, renaming the formal parameter with the actual one.

Let us discuss instead in some details the more complex axiom **A4**. The intuition is that if we reach an agent $\langle \exists_x^\rho A, \sigma \rangle$, then during the computation at least $\exists_x \rho$ has been added to the global store by the local agent. In order to evaluate A , the chosen store is $\rho \otimes \sigma_0$ for $\sigma_0 = \sigma \oplus \exists_x \rho$, thus removing $\exists_x \rho$ and adding ρ , which may carry information about x . Now, $\rho_0 = \sigma_1 \oplus (\rho \otimes \sigma_0)$ is precisely the information added by

the step originating from A , which is then restricted and added to σ . The same effect on the local store is instead cumulative, and it is obtained by $\rho \otimes \rho_0$.

Let $\gamma = \langle A, \sigma \rangle$ be a configuration. We denote by $fv(\gamma)$ the set $fv(A) \cup sv(\sigma)$ and by $\gamma^{[z/w]}$ the component-wise application of the substitution $[z/w]$.

Lemma 11 (On monotonicity). *Let $\langle A, \sigma \rangle \rightarrow \langle B, \sigma' \rangle$ be a reduction. Then*

- $\exists \sigma''. \sigma' = \sigma \otimes \sigma''$
- $fv(\langle B, \sigma' \rangle) \subseteq fv(\langle A, \sigma \rangle)$

Note that item 1 implies that $\sigma' = (\sigma' \oplus \sigma) \otimes \sigma$.

Remark 4. The choice for the resulting local and global store could have been $\sigma_1 \oplus \sigma_0$ and $\sigma_0 \otimes \exists_x(\sigma_1 \oplus \sigma_0)$, respectively. Indeed, these expressions have a nicer appearance, and $\sigma_1 \oplus \sigma_0$ seems to better represent the cumulative effect of the changes of the local store. However, this is a misleading impression, since the composition of the single updates has to take into account the existential quantifications.

Let us consider constraints c and d such that $\exists_x c = \exists_x d = \mathbf{1}$ and $c \otimes d = \perp$. As far as our running example is concerned, it might be that $c = x \leq 1$ and $d = x \geq 5$. Now, let A be the agent $\mathbf{tell}(c) \parallel \mathbf{tell}(d)$ and γ the configuration $\langle \exists_x^1 A, \mathbf{1} \rangle$. Assuming that c is added to the store, with both choices we end up with the reduction $\gamma \rightarrow \langle \exists_x^c \mathbf{tell}(d), \mathbf{1} \rangle$. Now note that $(d \otimes c) \oplus \mathbf{1} = c \otimes ((d \otimes c) \oplus (c \otimes \mathbf{1})) = d \otimes c = \perp$, hence the choice of the definition for the local store is immaterial. With the alternative definition for the global store, we would then reach $\langle \exists_x^c \mathbf{tell}(d), \mathbf{1} \rangle \rightarrow \langle \exists_x^\perp \mathbf{stop}, \perp \rangle$, thus lifting to the global store the unsatisfiability of the local one. Instead, with our choice we obtain $\langle \exists_x^c \mathbf{tell}(d), \mathbf{1} \rangle \rightarrow \langle \exists_x^\perp \mathbf{stop}, \exists_x(\perp \oplus c) \rangle$. Now, obviously $\perp \leq \perp \oplus c$: the equality may hold if e.g. the semiring does not have zero divisors, but going back to our running example, with $c = x \leq 1$ we have $\perp \oplus c = \emptyset \oplus x \leq 1 = x > 1$ and thus $\exists_x(\perp \oplus c) = \mathbf{1}$.

Let us now consider the alternative choice for the local store. First of all, note that under Lemma 11 we have that $\rho \otimes (\sigma_1 \oplus (\rho \otimes \sigma_0)) \leq \sigma_1 \oplus \sigma_0$: the smaller term represents a better approximation of the intuitive local store. Indeed, let us consider again the agent $A = \mathbf{tell}(c) \parallel \mathbf{tell}(d)$ with no hypothesis and the configuration $\langle \exists^1 A, \sigma \rangle$. After both commands are fired, the local store should intuitively be (the best approximation of) $c \otimes d$. Assuming that c is added to the store, with both choices of the definition for the local store we end up with the reduction $\langle \exists^1 A, \sigma \rangle \mapsto \langle \exists^{\rho'} \mathbf{tell}(d), \sigma' \rangle$ such that $\rho' = (c \otimes \sigma) \oplus \sigma$, since the initial local store is $\mathbf{1}$, and $\sigma' = \sigma \otimes \exists_x((c \otimes \sigma) \oplus \sigma) = \sigma \otimes \exists_x c$, since $x \notin sv(\sigma)$. Now, we need to evaluate the configuration $\langle \exists_x^{\rho'} \mathbf{tell}(d), \sigma' \rangle$, which we already argued must evolve to a global store $\sigma \otimes \exists_x c \otimes \exists_x((d \otimes \rho' \otimes \sigma'') \oplus (\rho' \otimes \sigma''))$ for $\sigma'' = \sigma' \oplus \exists_x \rho'$. Now we have that $c \otimes d \leq \rho' \otimes ((d \otimes \rho' \otimes \sigma'') \oplus (\rho' \otimes \sigma'')) \leq (d \otimes \rho' \otimes \sigma'') \oplus \sigma''$, hence confirming our choice of the definition for the local store.

5 Saturated Bisimulation

As proposed in [1] for crisp languages, we define a barbed equivalence between two agents [10]. Intuitively, barbs are basic observations (predicates) on the states of a system, and in our case they correspond to the constraints in \mathcal{C} .

Definition 12 (Barbs). Let $\langle A, \sigma \rangle$ be a configuration and $c \in \mathcal{C}$ and we say that $\langle A, \sigma \rangle$ verifies c , or that $\langle A, \sigma \rangle \downarrow_c$ holds, if $\sigma \leq c$.

In other terms, $\mathbf{ask}(c)$ must be enabled in $\langle A, \sigma \rangle$. Since *barbed bisimilarity* is an equivalence already for CCP, along [1] we propose the use of *saturated bisimilarity* in order to obtain a congruence: Definition 13 and Definition 15 respectively provide the strong and weak definition of saturated bisimilarity.

Definition 13 (Saturated bisimilarity). A saturated bisimulation is a symmetric relation R on configurations such that whenever $(\langle A, \sigma \rangle, \langle B, \rho \rangle) \in R$

1. if $\langle A, \sigma \rangle \downarrow_c$ then $\langle B, \rho \rangle \downarrow_c$;
2. if $\langle A, \sigma \rangle \mapsto \gamma'_1$ then there is γ'_2 such that $\langle B, \rho \rangle \mapsto \gamma'_2$ and $(\gamma'_1, \gamma'_2) \in R$;
3. $(\langle A, \sigma \otimes d \rangle, \langle B, \rho \otimes d \rangle) \in R$ for all $d \in \mathcal{C}$.

We say that γ_1 and γ_2 are saturated bisimilar ($\gamma_1 \sim_s \gamma_2$) if there exists a saturated bisimulation R such that $(\gamma_1, \gamma_2) \in R$. We write $A \sim_s B$ if $\langle A, \mathbf{1} \rangle \sim_s \langle B, \mathbf{1} \rangle$.

We now let \mapsto^* denote the reflexive and transitive closure of \mapsto , restricted to increasing computations.

Definition 14 (Weak barbs). Let $\langle A, \sigma \rangle$ be a configuration and $c \in \mathcal{C}$. We say that $\langle A, \sigma \rangle$ weakly verifies c , or that $\langle A, \sigma \rangle \Downarrow_c$ holds, if there exists $\gamma' = \langle B, \rho \rangle$ such that $\gamma \mapsto^* \gamma'$ and $\rho \leq c$.

Definition 15 (Weak saturated bisimilarity). A weak saturated bisimulation is a symmetric relation R on configurations such that whenever $(\langle A, \sigma \rangle, \langle B, \rho \rangle) \in R$

1. if $\langle A, \sigma \rangle \downarrow_c$ then $\langle B, \rho \rangle \Downarrow_c$;
2. if $\langle A, \sigma \rangle \mapsto \gamma'_1$ then there is γ'_2 such that $\langle B, \rho \rangle \mapsto^* \gamma'_2$ and $(\gamma'_1, \gamma'_2) \in R$;
3. $(\langle A, \sigma \otimes d \rangle, \langle B, \rho \otimes d \rangle) \in R$ for all $d \in \mathcal{C}$.

We say that γ_1 and γ_2 are weakly saturated bisimilar ($\gamma_1 \approx_s \gamma_2$) if there exists a weak saturated bisimulation R such that $(\gamma_1, \gamma_2) \in R$. We write $A \approx_s B$ if $\langle A, \mathbf{1} \rangle \approx_s \langle B, \mathbf{1} \rangle$.

The asymmetry is functional to later sections. However, it is clearly equivalent to the standard symmetric version.

Definition 16 (Weak saturated bisimilarity, 2). Weak saturated bisimilarity coincides with the relation obtained from Definition 13 by replacing \mapsto with \mapsto^* and \downarrow_c with \Downarrow_c .

Since \sim_s and \approx_s are saturated bisimulations, they are clearly upward closed and they are also congruences. Indeed, a context can modify the behaviour of a configuration only by adding constraints to its store. CHECK!!!

6 Labelled transition system

Although \approx_s is fully abstract, it is somewhat unsatisfactory because of the upward-closure, i.e., the quantification in condition 3 of Definition 15.

Definition 17 (Labelled reductions). Let $\Gamma = \mathcal{A} \times \mathcal{C}$ be the set of configurations and V the set of variables. The labelled direct reduction semantics for SCCP is the pair $\langle \Gamma, \mapsto \rangle$ such that $\mapsto \subseteq \Gamma \times \Gamma$ is indexed over the couple $\langle \mathcal{C}, 2^V \rangle$, i.e., $\mapsto = \bigcup_{\alpha \in \mathcal{C}, \Delta \subseteq V} \xrightarrow{\alpha, \Delta}$ and $\xrightarrow{\alpha, \Delta} \subseteq \Gamma \times \Gamma$, obtained by the rules in Table 3.

The labelled reduction semantics for SCCP is the pair $\langle \Gamma, \rightarrow \rangle$ such that $\rightarrow \subseteq \Gamma \times \Gamma$ is the family of binary relations indexed over the couple $\langle \mathcal{C}, 2^V \rangle$; $\rightarrow \subseteq \Gamma \times \Gamma$ can be obtained by the rules in Table 3 and Table 4.

In Table 3 and Table 4 we refine the notion of transition (respectively given in Table 1 and Table 2) by adding a label that carries additional information about the constraints that cause the reduction. Hence, we define a new labelled transition system (LTS) obtained by the family of relations $\xrightarrow{\alpha, \Delta} a \subseteq \Gamma \times \Gamma$ indexed over $\langle \mathcal{C}, 2^V \rangle$; Rules in Table 3 and Table 4 are identical to those in Table 1 and Table 2, except for a constraint α that represents the minimal information that must be added to σ in order to fire an action from $\langle A, \sigma \rangle$ to $\langle A', \sigma' \rangle$, i.e., $\langle A, \sigma \otimes \alpha \rangle \rightarrow \langle A', \sigma' \rangle$.

LA1	$\langle \text{tell}(c), \sigma \rangle \xrightarrow{\perp} \langle \text{stop}, \sigma \otimes c \rangle$	Tell
LA2	$\langle \text{ask}(c) \rightarrow A, \sigma \rangle \xrightarrow{c \oplus \sigma} \langle A, \sigma \otimes (c \oplus \sigma) \rangle$	Ask
LA3	$\frac{p(x) = A \in \mathcal{P}}{\langle p(y), \sigma \rangle \xrightarrow{\perp} \langle A[y/x], \sigma \rangle}$	Rec
LA4	$\frac{\langle A, c \otimes d_0 \rangle \xrightarrow{\alpha} \langle B, d_1 \rangle \wedge d_0 = (d \otimes \alpha) \oplus \exists_x c \wedge x \notin \text{sv}(d) \cup \text{sv}(c) \wedge c_1 = d_1 \oplus d_0}{\langle \exists_x^c A, d \rangle \xrightarrow{\alpha} \langle \exists_x^{c_1} B, d_0 \otimes \exists_x c_1 \rangle}$	Hide

Table 3. Axioms of the labelled semantics for SCCP.

LR1	$\frac{\langle A, \sigma \rangle \xrightarrow{\alpha} \langle A', \sigma' \rangle \wedge \text{fv}(B) \subseteq \Delta}{\langle A \parallel B, \sigma \rangle \xrightarrow{\alpha} \langle A' \parallel B, \sigma' \rangle} \text{Par1}$
LR2	$\frac{\langle A, \sigma \rangle \xrightarrow{\alpha} \langle A', \sigma' \rangle \wedge \text{fv}(B) \subseteq \Delta}{\langle B \parallel A, \sigma \rangle \xrightarrow{\alpha} \langle B \parallel A', \sigma' \rangle} \text{Par2}$

Table 4. Contextual rules of the labelled semantics for SCCP.

7 Semantics equivalence

Theorem 1 (Soundness). $\langle A, a \rangle \xrightarrow{c} \langle B, b \rangle \implies \langle A, a \otimes c \rangle \mapsto \langle B, b \rangle$

Proof. Tell and Rec

$$\sigma \otimes \perp = \sigma$$

$$\langle \text{tell}(c), \sigma \rangle \xrightarrow{\perp} \langle \text{stop}, \sigma \rangle \implies$$

$$\langle \text{tell}(c), \sigma \otimes \perp \rangle = \langle \text{tell}(c), \sigma \rangle \mapsto \langle \text{stop}, \sigma \rangle$$

$$\langle p(y), \sigma \rangle \xrightarrow{\perp} \langle A[y/x], \sigma \rangle \implies$$

$$\langle p(y), \sigma \otimes \perp \rangle = \langle p(y), \sigma \rangle \mapsto \langle A[y/x], \sigma \rangle$$

Ask

$$\langle \text{ask}(c) \rightarrow A, \sigma \rangle \xrightarrow{c \oplus \sigma} \langle A, \sigma \otimes (c \oplus \sigma) \rangle \implies$$

NB $\sigma \otimes (c \oplus \sigma) \leq c$

$$\langle \text{ask}(c) \rightarrow A, \sigma \otimes (c \oplus \sigma) \rangle \mapsto \langle A, \sigma \otimes (c \oplus \sigma) \rangle$$

Hide

$$\text{hyp: } \langle A, c \otimes d_0 \rangle \xrightarrow{\alpha} \langle B, d_1 \rangle \implies \langle A, c \otimes d_0 \otimes \alpha \rangle \mapsto \langle B, d_1 \rangle$$

$$d_0 = (d \otimes \alpha) \oplus \exists_x c$$

$$c_1 = d_1 \oplus d_0$$

$$\langle \exists_x^c A, d \rangle \xrightarrow{\alpha} \langle \exists^{d_1} \oplus ((d \otimes \alpha) \oplus \exists_x c) B, ((d \otimes \alpha) \oplus \exists_x c) \otimes \exists_x (d_1 \otimes ((d \otimes \alpha) \oplus \exists_x c)) \rangle \implies$$

$$\langle \exists_x^c A, d \otimes \alpha \rangle \mapsto \langle \exists^{d_1} \oplus ((d \otimes \alpha) \oplus \exists_x c) B, ((d \otimes \alpha) \oplus \exists_x c) \otimes \exists_x (d_1 \otimes ((d \otimes \alpha) \oplus \exists_x c)) \rangle$$

Theorem 2 (Completeness). $c \leq a?$, $\langle A, a \rangle \mapsto \langle B, b \rangle \implies \langle A, c \rangle \xrightarrow{\alpha} \langle B, d \rangle$ with $c \otimes \alpha \otimes \beta = a \wedge d \otimes \beta = b$ for some β .

Proof. Tell and Rec

$$\langle \text{tell}(c), \sigma \rangle \mapsto \langle \text{stop}, \sigma \rangle \wedge (c \leq a)$$

$$\langle \text{tell}(c), \sigma' \rangle \xrightarrow{\perp} \langle \text{stop}, \sigma' \rangle$$

$$\implies \beta = \sigma \oplus \sigma' = \bigvee \{c \mid \sigma' \otimes c \leq \sigma\}$$

8 Concluding Remarks

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