Resource-Passing Concurrent Programming

Kazunori Ueda
Waseda University
Tokyo, Japan

Talk Outline

- Constraint-based concurrency (CBC)
  - Essence of constraint-based communication
  - Relation to name-based concurrency
- Type systems and analyses for CBC
  - modes (directional types) and linear types
- Strict linearity and its implications
- Capabilities: types for strict linearity with sharing

Constraint-Based Concurrency

- Concurrency formalism & language based on
  - *single-assignment* (write-once) channels and
  - constructors

  cf. name-based concurrency
- Also known as
  - concurrent logic programming
  - concurrent constraint programming (CCP)
- Born and used as languages (early 1980's); then recognized and studied as formalisms

Single-Assignment Channels

- Also known as logical variables
- Can be written at most once
  - by *tell*ing a constraint (= partial information) on the value of the channel (*unification*)
    - e.g., tell S=[read(X)|S']
- Reading is non-destructive
  - by *ask*ing if a constraint is entailed (*term matching*)
    - e.g., ask ∃A∃S'(S=[A|S'])
  - covers both *input* and *match* in the π-calculus

Constraint-Based Communication

- Asynchronous
  - *tell* is an independent process (as in the asynchronous π-calculus)
- Polyadic
  - constructors provide built-in structuring and encoding mechanisms
  - essential in the single-assignment setting
- Mobile
- Non-strict

Constraint-Based Communication

- Asynchronous
- Polyadic
- Mobile – channel mobility in the sense of the π-calculus
  - Channels
    - can be passed using another channel
    - can be fused with another channel
    - are first-class (processes aren't)
  - available since 1983 (Concurrent Prolog)
- Non-strict

Constraint-Based Communication

- Asynchronous
- Polyadic
- Mobile
- Non-strict
  - "Constraint-based" means computing with partial information
  - Yielded many programming idioms, including
    - (streams of)* streams
    - difference lists
    - messages with reply boxes

The Language (traditional LP syntax)

(program)	P ::= set of R's
(program clause)	R ::= A :- | B
(body)	B ::= multiset of G's
(goal)	G ::= $T_1 = T_2$ | A
(non-unif. atom)	A ::= $p(T_1, \ldots, T_n)$, $p \neq$ '='
(term)	T ::= (as in first-order logic)
(goal clause)	Q ::= :- B

The Language (alternative syntax)

(program)	P ::= set of R's
(program clause)	R ::= $!\forall(A\ .\ B)$
(body)	B ::= multiset of G's
(goal)	G ::= $T_1 = T_2 \ \mid\ A$
(non-unif. atom)	A ::= $p(T_1, \ldots, T_n),\ \ p \neq$ '='
(term)	T ::= (as in first-order logic)
(goal clause)	Q ::= $B,\ P$

The Language

(program)	P ::= set of R's
(program clause)	R ::= $!\forall(A\ .\ B)$
(body)	B ::= multiset of G's
(goal)	G ::= $T_1 = T_2 \ \mid\ A$
(non-unif. atom)	A ::= $p(T_1, \ldots, T_n),\ \ p \neq$ '='
(term)	T ::= (as in first-order logic)
(goal clause)	Q ::= $B,\ P$

tell

rewrite rule with *ask*, choice, reduction & hiding

parallel composition

Reduction Semantics

- Concurrency

$$\frac{\langle B_1, C, P\rangle \rightarrow \langle B_1', C', P\rangle}{\langle B_1 \cup B_2, C, P\rangle \rightarrow \langle B_1' \cup B_2, C', P\rangle}$$

- Tell

$$\frac{}{\langle \{t_1 = t_2\}, C, P\rangle \rightarrow \langle \phi, C \cup \{t_1 = t_2\}, P\rangle}$$

Reduction Semantics

- Concurrency

$$\frac{\langle B_1, C, P\rangle \rightarrow \langle B_1', C', P\rangle}{\langle B_1 \cup B_2, C, P\rangle \rightarrow \langle B_1' \cup B_2, C', P\rangle}$$

- Tell

send t_2 through t_1 / fuse t_1 with t_2

defines an mgu unless collapsed

$$\frac{}{\langle \{t_1 = t_2\}, C, P\rangle \rightarrow \langle \phi, C \cup \{t_1 = t_2\}, P\rangle}$$

unguarded constraint is made observable

Reduction Semantics (cont'd)

- Ask + Reduction

$$\frac{}{\langle \{b\}, C, P \cup \{h :- \mid B\} \rangle \;\longrightarrow\; \langle B, C \cup \{b = h\}, P \cup \{h :- \mid B\} \rangle} \left(\begin{array}{l} \text{if } E \models \forall \left(C \Rightarrow \exists vars(h)(b = h) \right) \\ \text{and } \; vars(h, B) \cap vars(b, C) = \phi \end{array} \right)$$

Reduction Semantics (cont'd)

- Ask + Reduction

$$\frac{}{\langle \{b\}, C, P \cup \{h :- \mid B\} \rangle \;\longrightarrow\; \langle B, C \cup \{b = h\}, P \cup \{h :- \mid B\} \rangle} \left(\begin{array}{l} \text{if } E \models \forall \left(C \Rightarrow \exists vars(h)(b = h) \right) \\ \text{and } \; vars(h, B) \cap vars(b, C) = \phi \end{array} \right)$$

ask done and constraints were received by *h*'s args

syntactic equality theory over finite terms

h matches *b* under *C*

Relation to Name-Based Concurrency

- Predicates (names of recursive procedures) can be regarded as global names of conventional (destructive) channels.
  - the only source of arbitration in CBC
- Variables are local names of write-once channels.
- Constructors are global, non-channel names for composing messages with reply boxes, streams, and other data structures.

Channels in CBC and NBC

- Write-once channels allow buffering by using stream constructors
  - e.g., `S=[read(X)|S']` (S': continuation)
- Channels in the asynchronous π-calculus are *multisets* of messages from which *input* operations take messages away
  - e.g., $a(y).Q \mid \bar{a}b \rightarrow Q\{b/y\}$
  - Being a multiset is another source of arbitration

Channels in CBC and NBC

- CBC and NBC get closer with *type systems*:
  - *mode* (= directional type) system for CBC
  - *linear* types for the π-calculus
- Both guarantees that only one process holds a write capability and use it once
  - hence they leave no sharp difference in non-destructive and destructive read,
  - except that CBC still allows multicasting and channel fusion

Communication in CBC and NBC

- In CBC,
  - *tell* subsumes two operations
    - output e.g., `X=3`, `X=[push(5)|X']`
    - fusion (of two channel names) e.g., `X=Y`
  - *ask* subsumes two operations
    - input (synchronization and value passing)
    - match (checking of values)
- However, match in *moded* CBC doesn't allow the checking of channel equality (cf. Lπ)

Channels in CBC Are Local Names

- Fallacy: constraint store is global, shared, single-assignment memory
- Channels are all created as fresh local names that cannot be forged by the third party
- A new channel can be exported and imported only by using an existing channel
  - e.g., `p([create(S)|X']) :- | server(S), p(X').`

Talk Outline

- Constraint-based concurrency
  - Essence of constraint-based communication
  - Relation to name-based concurrency
- Type systems and analyses for CBC
  - modes (directional types) and linear types
- Strict linearity and its implications
- Capabilities: types for strict linearity with sharing

I/O Modes: Motivations

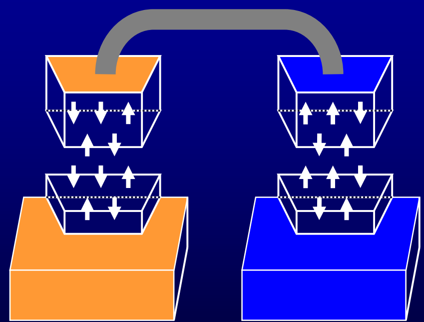
- Our experience with concurrent logic languages (Flat GHC) shows that logical variables are used mostly as *cooperative* communication channels with statically established protocol (point-to-point, multicasting)
- Non-cooperative use may cause collapse of the constraint store
  - e.g., $X=1 \wedge X=2 \wedge 1 \neq 2$ entails anything!

The Mode System of Moded Flat GHC

- Assigns *polarity* (+/–) *structures* to the arguments of processes so that the write capability of each part of data structures is held by exactly one process
- Unlike standard types in that modes are resource-sensitive
- Moding rules are given in terms of mode constraints (cf. inference rules)
- Can be solved (mostly) as unification over mode graphs (feature graphs with cycles)

An Electric Device Metaphor

- Signal cables may have various structures (arrays of wires and pins), but
  - the two ends of a cable, viewed from outside, should have opposite polarity structures, and
  - a plug and a socket should have opposite polarity structures when viewed from outside.



goal = device
variable = cable

Modes as Functions

- Given a "position" (of any procedure, of arbitrary depth), a mode function will answer the I/O mode of that position.

  $m : P_{Atom} \rightarrow \{in, out\}$

  - P_{Atom} : set of *paths* of the form
    $\langle p, i\rangle\langle f_1, i_1\rangle \ldots \langle f_n, i_n\rangle \ (n \geq 0)$
    e.g.: <append, 2><., 2><., 1>
  - P_{Term} : set of *paths* of the form
    $\langle f_1, i_1\rangle \ldots \langle f_n, i_n\rangle \ (n \geq 0)$
  - $m(p)$: mode at p
  - m/p : modes at and below p ($P_{Term} \rightarrow \{in, out\}$)

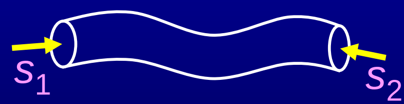
Mode Constraints on A Well-Moding *m*

- Constructors occur at *input* positions
- Non-linear head variables occurs at *fully input* positions (to check if they hold identical values)
- The two arguments of a unification goal (tell) have complementary modes
- Variable occuring at $p_1, \ldots, p_k$ (head) and $p_{k+1}, \ldots, p_n$ (body) satisfies
  - $\mathbf{R}(\{m/p_1, \ldots, m/p_n\})$ (k=0)
  - $\mathbf{R}(\{\overline{m/p_1}, m/p_{k+1}, \ldots, m/p_n\})$ (k>0)

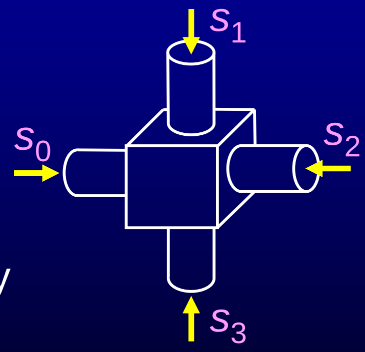
  where $\mathbf{R}(S) = \forall q \in P_{Term}\, \exists s \in S\, (s(q) = out \wedge \forall s' \in S \setminus \{s\} (s'(q) = in))$

Principles Behind the Constraints

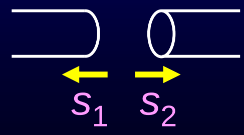
- A variable is a cable . . . . . or a hub.



$\mathbf{R}(\{s_1, s_2\}) \Leftrightarrow s_1 = \overline{s_2}$



- Constraint for connectivity

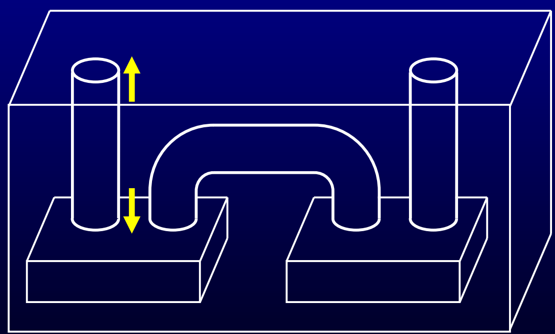


$s_1 = \overline{s_2}$

$\mathbf{R}(\{s_0, s_1, s_2, s_3\})$

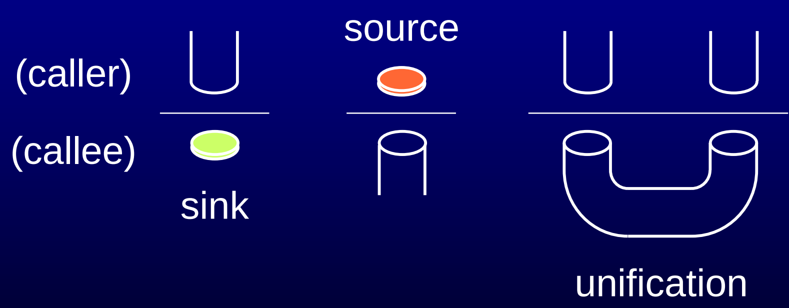
Principles Behind the Constraints

- Clause heads and body goals have opposite polarities, so do their arguments.

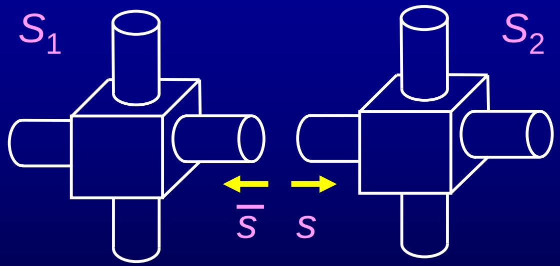


Principles Behind the Constraints

- Goal-head connection

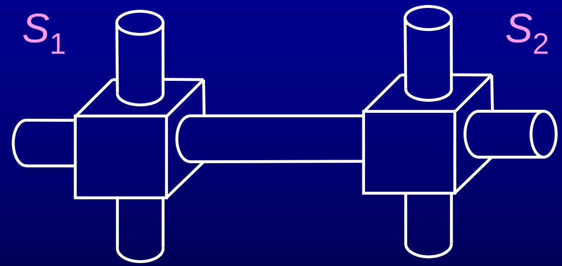


Resolution Principle



$$\boldsymbol{R}(\{\bar{s}\}\cup S_1) \;\wedge\; \boldsymbol{R}(\{s\}\cup S_2)$$

Resolution Principle



$$\boldsymbol{R}(\{\bar{s}\}\cup S_1) \;\wedge\; \boldsymbol{R}(\{s\}\cup S_2)$$
$$\Rightarrow \boldsymbol{R}(S_1 \cup S_2)$$

Moding: Implications and Experiences

- A process can pass a (variable containing) write capability to somebody else, but cannot duplicate or discard it.
- Two write capabilities cannot be compared
- Read capabilities can be copied, discarded and compared
  - cf. Linearity system
- Extremely useful for debugging – pinpointng errors and automated correction (!)
- Encourages resource-conscious programming

Theorems

- Unification degenerates to assignment to a variable.
- (Subject Reduction) A well-moding *m* is preserved by reduction
- (Groundness) When a program terminates successfully, every variable is bound to a constructor.

Linearity: An Observation (cf. LNCS 1068)

- In (concurrent) logic programs, many of the program variables have *exactly two* occurrences.
  - Example:

```
append([],     Y,Z  ) :- true | Z=Y.
append([A|X],Y,Z0) :- true |
                Z0=[A|Z], append(X,Y,Z).
```

  - Counter-example:

```
p(...X...) :- true | r(...X...), p(...X...).
```

An Observation

- Another example: quicksort

```
qsort(Xs,Ys) :- true | qsort(Xs,Ys,[]).
qsort([],Ys0,Ys) :- true | Ys=Ys0.
qsort([X|Xs],Ys0,Ys3) :- true |
      part(X,Xs,S,L), qsort(S,Ys0,Ys1),
      Ys1=[X|Ys2], qsort(L,Ys2,Ys3).
part(_,[],S,L) :- true | S=[], L=[].
part(A,[X|Xs],S0,L) :- A≥X |
      S0=[X|S], part(A,Xs,S,L).
part(A,[X|Xs],S,L0) :- A<X |
      L0=[X|L], part(A,Xs,S,L).
```

An Observation

- Another example: quicksort

```
qsort(Xs,Ys) :- true | qsort(Xs,Ys,[]).
qsort([],Ys0,Ys) :- true | Ys=Ys0.
qsort([X|Xs],Ys0,Ys3) :- true |
      part(X,Xs,S,L), qsort(S,Ys0,Ys1),
      Ys1=[X|Ys2], qsort(L,Ys2,Ys3).
part(_,[],S,L) :- true | S=[], L=[].
part(A,[X|Xs],S0,L) :- A≥X |
      S0=[X|S], part(A,Xs,S,L).
part(A,[X|Xs],S,L0) :- A<X |
      L0=[X|L], part(A,Xs,S,L).
```

Another Observation

```
qsort(Xs,Ys) :- true | qsort(Xs,Ys,[]).
qsort([],Ys0,Ys) :- true | Ys=Ys0.
qsort([X|Xs],Ys0,Ys3) :- true |
      part(X,Xs,S,L), qsort(S,Ys0,Ys1),
      Ys1=[X|Ys2], qsort(L,Ys2,Ys3).
```

- Virtually all variables with ≥3 occurrences (nonlinear variables) are used for simple, one-way communication
- Many variables with 2 occurrences (linear variables) have quite complex communication protocols

Linearity System

- Deals with the sharing aspects of programs
- Assigns linearity structures to the arguments of processes so that as many parts of data structures as possible are guaranteed to be "non-shared"
- Unlike standard types in that linearities are resource-sensitive
- Can be solved (mostly) as unification over linearity graphs (feature graphs with cycles)

Talk Outline

- Constraint-based concurrency
  - Essence of constraint-based communication
  - Relation to name-based concurrency
- Type systems and analyses
  - modes (directional types) and linear types
- Strict linearity and its implications
- Capabilities: types for strict linearity with sharing

Linear Variables Are Dipoles (1st step)

- Insertion sort

```
sort([],      S) :- | S=[].
sort([X|L0],S) :- | sort(L0,S0), insert(X,S0,S).
insert(X,[],     R) :-        | R=[X].
insert(X,[Y|L],  R) :- X ≤ Y | R=[X,Y|L].
insert(X,[Y|L0],R) :- X > Y | R=[Y|L],
                              insert(X,L0,L).
```

- From now on we disallow monopole (singleton) variables

Polarizing Constructors (2nd step)

- Insertion sort

```
sort([],      S) :- | S=[].
sort([X|L0],S) :- | sort(L0,S0), insert([X|S0],S).
insert([X],       R) :-        | R=[X].
insert([X,Y|L],  R) :- X ≤ Y | R=[X,Y|L].
insert([X,Y|L0],R) :- X > Y | R=[Y|L],
                              insert([X],L0,L).
```

- Linear constructors are also dipoles; the two occurrences of a linear constructor are two polarized instances of the same constructor.

Strict Linearity

- A program clause is called *strictly linear* if all variables and constructors are dipoles.
  - Constructors can now be regarded as channels that convey fixed values (and more importantly, *resources*) from head to body.
- A further step towards resource-conscious programming

Polarizing Constructors (cont'd)

- Are initial constructors and variables monopoles?

```
:- sort([3,1,4,1,5,9],X).
```

- A strictly linear (and symmetric) version is:

```
main([3,1,4,1,5,9],X) :- | sort([3,1,4,1,5,9],X).
```

which will be reduced finally to

```
main([3,1,4,1,5,9],X) :- | X = [1,1,3,4,5,9].
```

Programming Under Strict Linearity

- Append

```
append([],Y,Z) :- | Z=Y.
append([A|X],Y,Z0) :- |
          Z0=[A|Z], append(X,Y,Z).
```

- Strictly linear version

```
append([],Y,Z,U) :- | Z=Y, U=[].
append([A|X],Y,Z0,U) :- |
          Z0=[A|Z], append(X,Y,Z,U).
```

- The former is a *slice* of the latter.

Linearizing Server Processes (Hard)

- Stack server

```
stack([],           D     ) :- | true.
stack([push(X)|S],D      ) :- | stack(S,[X|D]).
stack([pop(X)|S],  [Y|D]) :- | X=Y, stack(S,D).
```

- Strictly linear version

```
stack([](Z),              D     ) :- | Z=[](D).
stack([push([X|*],Y)|S],D      ) :- |
       Y=[push(*,*)|*], stack(S,[X|D]).
stack([pop(X)|S],         [Y|D]) :- |
       X=[pop([Y|*])|*], stack(S,D).
```

Linearizing Server Processes (Hard)

- Strictly linear version

```
stack([](Z),               D      ) :- | Z=[](D).
stack([push([X|*],Y)|S],D      ) :- |
        Y=[push(*,*)|*], stack(S,[X|D]).
stack([pop(X)|S],          [Y|D]) :- |
        X=[pop([Y|*])|*], stack(S,D).
```

  - A server doesn’t want to keep envelopes ([|]) or cover sheets (push/pop)
  - “ * ” (void) is a non-constructor-non-variable symbol with *zero capability* (no write, no read)

Polarizing Predicates (3rd step)

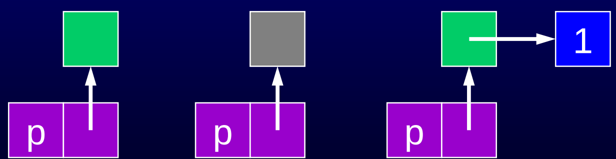
- Insertion sort

```
sort([],      S) :- | S=[], sort(*,*).
sort([X|L0],S), insert(*,*) :- |
      sort(L0,S0), insert([X|S0],S).
```

  - cf. Constraint Handling Rules (CHR)
- Goals with void arguments are free goals waiting for habitants
  - can be considered as implicitly given

Resource Aspect of Values

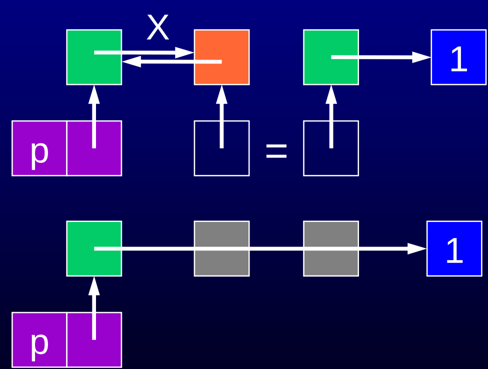
- Standard counting under the untyped setting
  - Void: 1 unit
  - Variable: 1 unit per occurrence
  - N-ary constructor and predicate: N+1 units
    - Arguments should point to variables or voids
  - e.g., p(X): 3 units, p(*): 3 units, p(1): 4 units



  - Typing can reduce dereferencing and space

Constant-Time Property

- All entities are accessed by dereferencing exactly twice (yes, two is the magic number).



Talk Outline

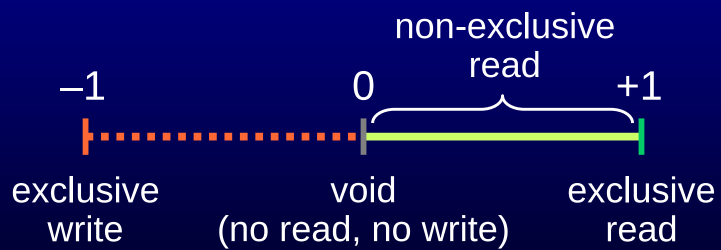
- Constraint-based concurrency
  - Essence of constraint-based communication
  - Relation to name-based concurrency
- Type systems and analyses
  - modes (directional types) and linear types
- Strict linearity and its implications
- Capabilities: types for strict linearity with sharing

Sharing under Strict Linearity

- Goals:
  1. To allow concurrent access to shared resource
     - e.g., large arrays used for table lookup
  2. To recover linearity after concurrent access
     - Can ω get back to 1?
- Two modes of concurrent access
  - *multiplicative* = full access to disjoint parts
    - already supported by mode+linearity
  - *additive* = read access to the whole structure

Let's Take a Reciprocal

- Mode {*in*,*out*} and linearity {*nonshared*, *shared*} can be unified and generalized in a simple setting, the [–1,+1] capability system.



- cf. Weighted reference counting

In Pursuit of Symmetry

- What's the meaning of (–1,0) capabilities?
- Example: concurrent read

```
read(X0,X) :- |
      read1(X0,X1), read2(X0,X2), join(X1,X2,X).
```

  - Suppose read receives X0 with exclusive read capability **1** (**1**(p)=+1) and split it into two non-exclusive capabilities, α and $\mathbf{1}-\alpha$.
  - Then these capabilities will be returned through X1 ($-\alpha$) and X2 ($\alpha-\mathbf{1}$)
    - because they cannot be disposed

In Pursuit of Symmetry

- Example: concurrent read (cont'd)

```
read(X0,X) :- |
        read1(X0,X1), read2(X0,X2), join(X1,X2,X).
```

  - X1 ($-\alpha$) and X2 ($\alpha-1$) become logically the same as X0 (they must alias unless read*n* diverges or deadlocks)
  - Then the two aliases are joined by a clause with a nonlinear head:

```
join(A,A,B) :- | B = A.
```

    - The capabilities of the three args sum up to **0**.

Capability Annotations

- We annotate all constructors in (initial or reduced) goal clauses.
  - The annotations are to be comiled away

$f^{1}(\ \ ,\ \ ,\ \ )$	or	$f^{\kappa}(\ \ ,\ \ ,\ \ )$
exclusive		$(0<\kappa<1)$ non-exclusive

- Closure condition:
  - $f^{\kappa}(\ldots\ g^{1}(\ldots)\ \ldots)$ — NO
  - $f^{1}(\ldots\ g^{\kappa}(\ldots)\ \ldots)$ — OK

Extending Operational Semantics

```
  :- … p(… X …) … X = t … q(… X …)
→ :- … p(… t …) …         … q(… t …)
```

```
  :- … p(… t …) …
       p(… X …) :- | q(… X …), r(… X …).
→ :- … q(… t …), r(… t …) …
```

- X nonlinear → split the capabilities in the term *t* using random numbers
- X linear → retain the original capabilities

Capability System

- A capability is a function

$$c : P_{Atom} \to [-1,+1]$$

- Polymorphic w.r.t. non-exclusive capabilites because they decrease by repeated splitting
  - So all goals created at runtime are distinguished using suffixes

Capability Constraints (= Typing Rules)

- For a unification goal (of the form $t_1 =_s t_2$),
  $c/\langle =_s,1\rangle + c/\langle =_s,2\rangle = \mathbf{0}$
- For a variable occurring at $p_1, \ldots, p_k$ (head) and $p_{k+1}, \ldots, p_n$ (body),
  $-c/p_1 - \ldots - c/p_k + c/p_{k+1} + \ldots + c/p_n = \mathbf{0}$
  (Kirchhoff's Current Law)
  and exactly one of $\{-c/p_1, +c/p_{k+1}, \ldots, +c/p_n\}$ is negative
- For a nonlinear head variable at p, $c/p > \mathbf{0}$

Capability Constraints (= Typing Rules)

- A constructor f in head / body must find its partner with matching capability ($> \mathbf{0}$) in body / head
  - If f is exclusive, only top-level capability match is required; the constructor name and the arguments can be changed
  - Otherwise, full match is required
- A void path has a zero capability
- A non-void path has a non-zero capability

Example

```
p(X,Y,...) :- | r(X,Y1), p(X,Y2,...), join(Y1,Y2,Y).
p(X,Y,...) :- | X=Y.
join(A,A,B) :- | B=A.
```

- Suppose $c/\langle r_{s.1},1\rangle + c/\langle r_{s.1},2\rangle = \mathbf{0}$ **and** $c/\langle p_{s_0},1\rangle = \mathbf{1}$. Then $c/\langle p_{s_0},2\rangle = \bar{\mathbf{1}}$ holds, while all subgoals carry non-exclusive capabilities.
  - All capabilities distributed to the r's will be fully collected as long as all the r's return what they are given.

Properties

- Degeneration of unification to assignment
- Subject reduction
- Conservation of constructors
  - A reduction wll not gain or lose any constructor in the goal
- Groundness
- Non-sharing of constructors at "exclusive" positions

Related Work

- Relating CCP and π
  - new calculus (γ, ρ, Fusion, Solo, ...)
  - encoding one in the other
- Variants of π with nicer properties
- (Linear) types in other computational models
  - π, λ, typed MM, session types, ...
- Linear languages
  - Linear Lisp, Lirac, Linear LP, ...
- Compile-time GC
  - Mercury, Janus, ...
  - compiling streams into message passing

Conclusions

- A strictly linear, polarized subset of Guarded Horn Clauses
  - retains most of the power of CBC
  - allows resource sharing within the linear framework
- Capability type system supporting strict linearity
- A step towards a unified framework for non-sequential computing

Future Work

- Type reconstructor
- Occur-check problem
- Time (+ space) bounds
- Programming support
  - help writing strictly linear programs or reconstructing them from their slices
- Constructs for mobile/real-time/embedded computing + implementation