Manifest Sharing with Session Types

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Work in Progress!

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Background

- Session types rooted in logic [CP’10, CPT’16, W’12]
- Curry-Howard correspondence
  - Linear propositions as session types
  - Sequent proofs as message-passing concurrent programs
  - Proof reduction as communication
- Many threads and contributors
  - Luís Caires, Bernardo Toninho, Jorge Pérez, Dennis Griffith, Henry DeYoung, Limin Jia, Hanna Gommerstadt, Stephanie Balzer, Max Willsey, Coşku Acay, Miguel Silva, Mário Florido
- Implementations
  - Concurrent C0 (Demo Thursday!)
  - SILL (Sessions in Intuitionistic Linear Logic)
Interpreting the linear logical judgment and proofs

\[ A_1, \ldots, A_n \vdash C \quad x_1:A_1, \ldots, x_n:A_n \vdash P :: (z : C) \]

Cut as parallel composition (spawn \( P \) which provides along fresh channel \( x \))

\[
\Delta \vdash P_x :: (x : A) \quad \Delta', x:A \vdash Q_x :: (z : C)
\]

\[
\Delta, \Delta' \vdash x \leftarrow P_x ; Q_x :: (z : C) \quad \text{cut}
\]

Identity as forward (\( x \) is implemented by \( y \))

\[
y:A \vdash x \leftarrow y :: (x : A) \quad \text{id}
\]
SILL: the Operational Reading

- Every channel has a **provider** and a **client**
- Session is tied to provider’s thread of control
- Provider and client perform complementary actions
- From the provider perspective:

  
  \[
  A \rightarrow B \quad \text{receive channel of type } A, \text{ continue as } B
  \]
  
  \[
  A \otimes B \quad \text{send channel of type } A, \text{ continue as } B
  \]
  
  \[
  1 \quad \text{send ‘end’ and terminate}
  \]
  
  \[
  \&\{\ell_i : A_i\}_{i \in I} \quad \text{receive label } \ell_k, \text{ continue as } A_k
  \]
  
  \[
  \oplus\{\ell_i : A_i\}_{i \in I} \quad \text{send label } \ell_k, \text{ continue as } A_k
  \]
  
  \[
  \forall x : \tau. B(x) \quad \text{receive value } v \text{ of type } \tau, \text{ continue as } B(v)
  \]
  
  \[
  \exists x : \tau. B(x) \quad \text{send value } v \text{ of type } \tau, \text{ continue as } B(v)
  \]
Equirecursive types (must be contractive)
list \( A = \oplus\{\text{nil} : 1, \text{cons} : A \otimes \text{list } A\} \)
queue \( A = \&\{\text{enq} : A \rightarrow \text{queue } A, \text{deq} : \oplus\{\text{none} : 1, \text{some} : A \otimes \text{queue } A\}\} \)

Recursive processes implement these interfaces
Programming experience in Concurrent C0 and SILL
- Many fun and interesting concurrent programs
- Limitations on shared resources
  - Database, input/output, event loop

Wadler’s challenge
- Functional programming: recursive types recover the full expressive power of the untyped \( \lambda \)-calculus
- Concurrent programming: how can we recover the full expressive power of the untyped \( \pi \)-calculus?
- Note: SILL satisfies session-fidelity (preservation) and deadlock-freedom (global progress)
Of Course!

- !A represents persistence/replication in linear logic
- Operationally [CP’10]

  \[ c : !A \quad \text{send fresh persistent channel } u \text{ along } c \]
  \[ \quad \text{then provide } A \text{ along } u \text{ persistently} \]

  \[ u : A \quad \text{receive fresh linear channel } y \]
  \[ \quad \text{then provide fresh instance of } A \text{ along } y \]

- This **copying semantics** is appropriate for pure functional programming, but just supports “read only” sharing
Decomposing $\triangleright A$

- $\triangleright A$ actually represents two interactions
- Decompose $\triangleright A = \downarrow^S L \uparrow^S L A$
- Two layers of propositions/types (as in LNL [Benton’94], Adjoint Logic [Reed’09])

$$\begin{align*}
\text{Shared} & \quad A_S ::= \uparrow^S L A_L \mid A_S \to B_S \mid A_S \times B_S \mid \cdots \\
\text{Linear} & \quad A_L ::= \downarrow^S L A_S \mid A_L \to B_L \mid A_L \otimes B_L \mid 1 \mid \cdots
\end{align*}$$

- Each modality now is one interaction
- Shifts form an adjunction
- $\downarrow\uparrow$ forms a comonad, $\uparrow\downarrow$ a strong monad
Shared channels may not depend on linear channels

Providing shared channel \( \Gamma_S \vdash P :: (x_S : A_S) \)
Providing linear channel \( \Gamma_S ; \Delta_L \vdash P :: (x_L : A_L) \)

Shared channels are typed as if persistent
  - Can be used arbitrarily often

Proof reduction semantics is still copying
Sharing: Logical Rules

- Omitting shared identity and cut
- Logically, exactly the same as for persistence
- Modal rules, based on independence principle

\[
\begin{align*}
\Gamma ; \cdot & \vdash A_L \\
\Gamma & \vdash ^S A_L \\
\Gamma ; \cdot & \vdash _L A_S \\
\Gamma & \vdash _L ^S A_S \\
\Gamma, \Gamma & \vdash _L ^S A_L ; \Delta, A_L \vdash C_L \\
\Gamma, \Delta & \vdash _L ^S A_L ; \Delta \vdash C_L \\
\Gamma ; \Delta & \vdash _L ^S A_S \vdash C_L \\
\Gamma & \vdash _L ^S A_S \vdash C_L
\end{align*}
\]
Sharing: Process Expressions

- From provider perspective

\[ x_S : \uparrow^S_L A_L \]  
accept connection request along \( x_S \)  
continue along linear \( x_0 \)

\[ x_i : \downarrow^S_L A_S \]  
detach from linear client \( x_i \)  
continue along shared \( x_S \)

- Matching constructs

\[ x \leftarrow \text{accept } s ; P_x \]  
provider \( s : \uparrow^S_L A_L \)

\[ x \leftarrow \text{acquire } s ; Q_x \]  
client \( s : \uparrow^S_L A_L \)

\[ s \leftarrow \text{detach } x ; P_s \]  
provider \( x : \downarrow^S_L A_L \)

\[ s \leftarrow \text{release } x ; Q_s \]  
client \( x : \downarrow^S_L A_L \)
Example: Producer/Consumer Type

- Earlier purely linear type
  \[
  \text{queue } A = \&\{ \text{enq} : A \rightarrow \text{queue } A, \text{deq} : \oplus\{ \text{none} : 1, \text{some} : A \otimes \text{queue } A \} \} \\
  \]

- Modify type to make sharing manifest
  \[
  \text{squeue } A = \uparrow^S_L \&\{ \text{enq} : A \rightarrow \downarrow^S_L \text{squeue } A, \text{deq} : \oplus\{ \text{none} : \downarrow^S_L \text{squeue } A, \text{some} : A \otimes \downarrow^S_L \text{squeue } A \} \} \}
  \]

- Require types to be equi-synchronizing
  - Release (if there is one) is at the same type as acquire
  - On any continuation path from \( \uparrow^S_L A \) to \( \downarrow^S_L B \) we have \( B = \uparrow^S_L A \).
  - Otherwise, dynamic type checking would be required
Example: Producer/Consume Code

\[
squeue A = \uparrow^S_L \&\& \{ \text{enq : } A \rightarrow \downarrow^S_L \text{squeue } A, \\
\quad \text{deq : } \bigoplus\{ \text{none : } \downarrow^S_L \text{squeue } A, \\
\quad \quad \text{some : } A \otimes \downarrow^S_L \text{squeue } A \} \}
\]

elem : squeue A <- A, squeue A

\[
#s <- \text{elem } #x #t = \\
\quad c <- \text{accept } #s \\
\quad \text{case } c \text{ of} \\
\quad | \text{enq } => \ #y <- \text{recv } c \\
\quad \quad d <- \text{acquire } #t \quad % \text{begin critical region} \\
\quad \quad d.\text{enq ; send } d \ #y \\
\quad \quad #t <- \text{release } d \quad % \text{end critical region} \\
\quad \quad #s <- \text{detach } c \\
\quad \quad #s <- \text{elem } #x #t \quad % \text{recurse} \\
\quad | \text{deq } => \ c.\text{some ; send } c \ #x \\
\quad \quad #s <- \text{detach } c \\
\quad \quad #s <- \ #t \quad % \text{implement } #s \text{ by } #t
\]
Example: Producer/Consume Code

\[
\text{squeue } A = \uparrow^S_L \&\{ \text{ enq : } A \rightarrow \downarrow^S_L \text{squeue } A, \\
\text{ deq : } \oplus\{ \text{ none : } \downarrow^S_L \text{squeue } A, \\
\text{ some : } A \otimes \downarrow^S_L \text{squeue } A\} \} \\
\]

\text{empty : squeue } A \\
#s <- empty = \\
c <- accept #s \\
\text{ case } c \text{ of} \\
| \text{ enq } => \#y <- \text{ recv } c \\
\#s <- \text{ detach } c \\
\#e <- \text{ empty} \\
\#s <- \text{ elem } \#y \#e \% \text{ continue as elem } \#y \\
| \text{ deq } => c.\text{none} \\
\#s <- \text{ detach } c \\
\#s <- \text{ empty} \% \text{ continue as empty}
\]
Typing Rules

\[ \uparrow^S A_L : \text{accept (provider) and acquire (client)} \]

\[
\frac{
\Gamma ; \cdot \vdash P_x :: (x : A_L)
}{
\Gamma \vdash x \leftarrow \text{accept } s ; P_x :: (s : \uparrow^L A_L)
} \quad \uparrow^S R
\]

\[
\frac{
\Gamma, s:\uparrow^S A_L ; \Delta, x:A_L \vdash Q_x :: (z : C_L)
}{
\Gamma, s:\uparrow^S A_L ; \Delta \vdash x \leftarrow \text{acquire } s ; Q_x :: (z : C_L)
} \quad \uparrow^S L
\]
Typing Rules

\[ \downarrow^S_A \text{S}: \text{detach (provider) and release (client)} \]

\[
\Gamma \vdash P_s :: (s : A_S) \\
\Gamma ; \cdot \vdash s \leftarrow \text{detach } x ; P_s :: (x : \downarrow^L_S A_S) \quad \downarrow^S_L R
\]

\[
\Gamma, s:A_S ; \Delta \vdash Q_s :: (z : C_L) \\
\Gamma ; \Delta, x:\downarrow^L_S A_S \vdash s \leftarrow \text{release } x ; Q_s :: (z : C_L) \quad \downarrow^L_L
\]
Operational Semantics

- Asynchronous message passing
- Specify with multiset rewriting over predicates

\[
\begin{align*}
\text{proc}(x_i, P) & \quad P \text{ provides along linear channel } x, \text{ generation } i \\
\text{proc}(x_S, P) & \quad P \text{ provides along shared channel } x_S \\
\text{unavail}(x_S) & \quad \text{no process currently providing } x_S \\
\text{msg}(x_i, M) & \quad \text{message } P \text{ is sent along } x_i
\end{align*}
\]

- Processes cycle through linear (\(x_i\)) and shared (\(x_S\)) phases
- Think of \(i\) as index into message buffer for \(x\)
- Think of \(S\) as lock on shared process
Properties

- Session fidelity (type preservation)
  - Need either equi-synchronous types or runtime checking
  - Proof is somewhat complex due to forwarding
- “Progress”
  - Failure of progress only due to deadlock in acquiring shared channels
- Proofs are in progress as we speak . . .
A $\pi$-calculus channel may have multiple endpoints

Represent a $\pi$ channel by a buffer process

Version 1: single-element buffer of shared type $U$

$$U = \up^S \oplus \{ \text{none} : \& \{ U \rightarrow \down^S U, \text{loop} : \down^S U \},$$

$$\text{some} : \& \{ U \otimes \down^S U, \text{loop} : \down^S U \} \}$$

Version 2: multi-element buffer (like shared queue)

- Use coin flip to model nondeterminism in buffer
- Coin flip implementable with a simple shared channel

Process is represented by a worker process of type $1$

Replication is modeled by recursion

Conjecture: constitute asynchronous bisimulation (of some form . . .)
Use continuations channels as part of every interaction

- Represent a SILL channel by a pair of $\pi$-channels $(a_i, a_S)$
  - $a_i$ is $i$th continuation of linear channel $a$
  - $a_S$ is associated shared channel

- Conjecture: constitute bisimulation (of some form . . .)
Summary and Questions

- Model sharing by decomposing $!A$ into $\downarrow^S_L \uparrow^S_L A$
- Typing rules just as in LNL [Benton’94]
- Depart from the Curry-Howard isomorphism in operational semantics
  - Computation interleaves proof construction and proof reduction
  - Deadlock if proof cannot be constructed
  - Is this a general approach to multi-party session types?
- Expressive enough to interpret the asynchronous $\pi$-calculus
- Examples include dining philosophers, producer/consumer, database
- Elegant criteria for freedom from deadlock?