Deadlock and lock freedom in the linear π-calculus

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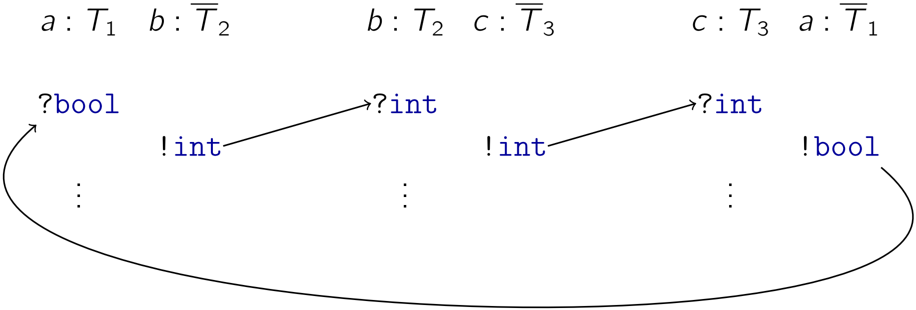
Outline

1. Introduction
2. The linear π-calculus
3. Examples
4. Concluding remarks

Progress in binary systems

$a : T$		$a : \overline{T}$
`!int`	$\rightarrow$	`?int`
`!int`	$\rightarrow$	`?int`
`?bool`	$\leftarrow$	`!bool`
$\vdots$	$\vdots$	$\vdots$

From binary to *n*-ary systems



$a : T_1 \quad b : \overline{T}_2$

$?\texttt{bool}$

$!\texttt{int}$

$\vdots$

$b : T_2 \quad c : \overline{T}_3$

$?\texttt{int}$

$!\texttt{int}$

$\vdots$

$c : T_3 \quad a : \overline{T}_1$

$?\texttt{int}$

$!\texttt{bool}$

$\vdots$

From binary to multiparty session types

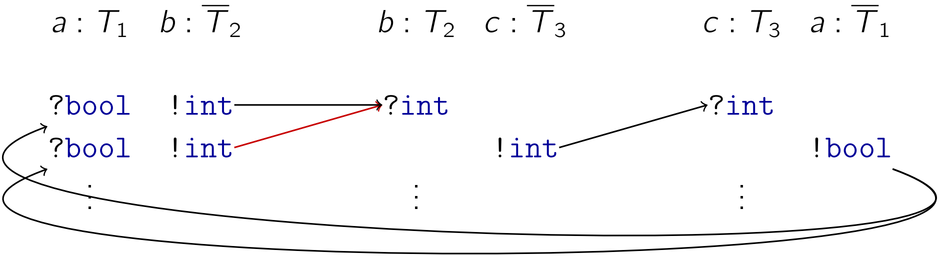
- Bravetti, Zavattaro, **A Foundational Theory of Contracts for Multi-party Service Composition**, Fundamenta Informaticae 2008
- Honda, Yoshida, Carbone, **Multiparty asynchronous session types**, POPL 2008
- ...

$$G = \mathtt{A} \xrightarrow{\mathtt{int}} \mathtt{B}.\mathtt{B} \xrightarrow{\mathtt{int}} \mathtt{C}.\mathtt{C} \xrightarrow{\mathtt{bool}} \mathtt{A}.G$$

$$\xcancel{\mathtt{A} \xrightarrow{\mathtt{int}} \mathtt{B} + \mathtt{C} \xrightarrow{\mathtt{bool}} \mathtt{D}}$$

Well-formed global type ⇒ progress

$$G = \mathtt{A} \xrightarrow{\mathtt{int}} \mathtt{B}.\mathtt{B} \xrightarrow{\mathtt{int}} \mathtt{C}.\mathtt{C} \xrightarrow{\mathtt{bool}} \mathtt{A}.G$$



$a : T_1$ $b : \overline{T}_2$ $b : T_2$ $c : \overline{T}_3$ $c : T_3$ $a : \overline{T}_1$

`?bool` `!int` `?int` `?int`

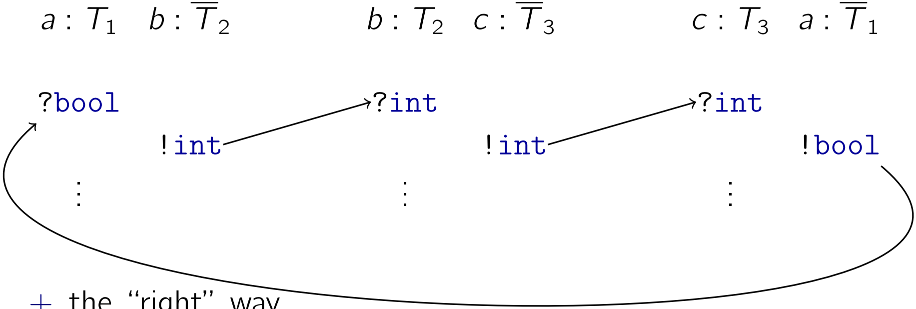
`?bool` `!int` `!int` `!bool`

$\vdots$ $\vdots$ $\vdots$

Tracking dependencies between sessions

- Dezani, de'Liguoro, Yoshida, **On Progress for Structured Communications**, TGC 2007
- Bettini, Coppo, D'Antoni, De Luca, Dezani, Yoshida, **Global Progress in Dynamically Interleaved Multiparty Sessions**, CONCUR 2008
- Coppo, Dezani, Padovani, Yoshida, **Inference of Global Progress Properties for Dynamically Interleaved Multiparty Sessions**, COORDINATION 2013
- Coppo, Dezani, Yoshida, Padovani, **Global Progress in Dynamically Interleaved Multiparty Sessions**, MSCS, to appear

Tracking dependencies between **sessions**



$a : T_1 \quad b : \overline{T}_2$ $\qquad$ $b : T_2 \quad c : \overline{T}_3$ $\qquad$ $c : T_3 \quad a : \overline{T}_1$

`?bool` $\qquad$ `?int` $\qquad$ `?int`

`!int` $\qquad$ `!int` $\qquad$ `!bool`

$\vdots$ $\qquad$ $\vdots$ $\qquad$ $\vdots$

\+ the “right” way

− coarse-grained

− recursion+session interleaving

Tracking dependencies between **sessions**

$$\Gamma, u : S \vdash u : S \ (\textsc{Name}) \qquad \Gamma \vdash \ \mathsf{true}, \mathsf{false} : \mathsf{bool} \qquad \frac{\Gamma \vdash e_i : \mathsf{bool} \qquad (i = 1, 2)}{\Gamma \vdash e_1 \ \mathsf{and} \ e_2 : \mathsf{bool}} \ (\textsc{Bool}),(\textsc{And})$$

$$\frac{\Gamma \vdash u : \mathsf{G} \quad \Gamma \vdash P \triangleright \Delta, y : \mathsf{G} \upharpoonright \mathsf{p} \quad \mathsf{p} = \mathrm{mp}(\mathsf{G})}{\Gamma \vdash \overline{u}[\mathsf{p}](y).P \triangleright \Delta} \ (\textsc{MCast}) \qquad \frac{\Gamma \vdash u : \mathsf{G} \quad \Gamma \vdash P \triangleright \Delta, y : \mathsf{G} \upharpoonright \mathsf{p} \quad \mathsf{p} < \mathrm{mp}(\mathsf{G})}{\Gamma \vdash u[\mathsf{p}](y).P \triangleright \Delta} \ (\textsc{MAcc})$$

$$\frac{\Gamma \vdash e : S \quad \Gamma \vdash P \triangleright \Delta, c : T}{\Gamma \vdash c!\langle \Pi, e \rangle.P \triangleright \Delta, c : !\langle \Pi, S \rangle.T} \ (\textsc{Send}) \qquad \frac{\Gamma, x : S \vdash P \triangleright \Delta, c : T}{\Gamma \vdash c?(\mathsf{q}, x).P \triangleright \Delta, c : ?(\mathsf{q}, S).T} \ (\textsc{Rcv})$$

$$\frac{\Gamma \vdash P \triangleright \Delta, c : T}{\Gamma \vdash c!\langle\langle \mathsf{p}, c' \rangle\rangle.P \triangleright \Delta, c : !\langle \{\mathsf{p}\}, \mathsf{T} \rangle.T, c' : \mathsf{T}} \ (\textsc{Deleg}) \qquad \frac{\Gamma \vdash P \triangleright \Delta, c : T, y : \mathsf{T}}{\Gamma \vdash c?((\mathsf{q}, y)).P \triangleright \Delta, c : ?(\mathsf{q}, \mathsf{T}).T} \ (\textsc{Srcv})$$

$$\frac{\Gamma \vdash P \triangleright \Delta, c : T_j \qquad j \in I}{\Gamma \vdash c \oplus \langle \Pi, l_j \rangle.P \triangleright \Delta, c : \oplus \langle \Pi, \{l_i : T_i\}_{i \in I} \rangle} \ (\textsc{Sel}) \qquad \frac{\Gamma \vdash P_i \triangleright \Delta, c : T_i \quad \forall i \in I}{\Gamma \vdash c \& (\mathsf{p}, \{l_i : P_i\}_{i \in I}) \triangleright \Delta, c : \& (\mathsf{p}, \{l_i : T_i\}_{i \in I})} \ (\textsc{Branch})$$

$$\frac{\Gamma \vdash P \triangleright \Delta \quad \Gamma \vdash Q \triangleright \Delta'}{\Gamma \vdash P \mid Q \triangleright \Delta, \Delta'} \ (\textsc{Par}) \qquad \frac{\Gamma \vdash e : \mathsf{bool} \quad \Gamma \vdash P \triangleright \Delta \quad \Gamma \vdash Q \triangleright \Delta}{\Gamma \vdash \mathsf{if} \ e \ \mathsf{then} \ P \ \mathsf{else} \ Q \triangleright \Delta} \ (\textsc{If})$$

$$\frac{\Delta \ \mathsf{end\ only}}{\Gamma \vdash \mathbf{0} \triangleright \Delta} \ (\textsc{Inact}) \qquad \frac{\Gamma, a : G \vdash P \triangleright \Delta}{\Gamma \vdash (\nu a : G) P \triangleright \Delta} \ (\textsc{NRes})$$

$$\frac{\Gamma \vdash e : S \qquad \Delta \ \mathsf{end\ only}}{\Gamma, X : S\, T \vdash X\langle e, c \rangle \triangleright \Delta, c : T} \ (\textsc{Var}) \qquad \frac{\Gamma, X : S\, \mathbf{t}, x : S \vdash P \triangleright y : T \qquad \Gamma, X : S\, \mu\mathbf{t}.T \vdash Q \triangleright \Delta}{\Gamma \vdash \mathsf{def} \ X(x, y) = P \ \mathsf{in} \ Q \triangleright \Delta} \ (\textsc{Def})$$

$$\frac{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash P \blacktriangleright \mathscr{D} \quad a \in \mathscr{R}}{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash \tilde{a}[\mathsf{p}](y).P \blacktriangleright \mathscr{D}\{a/y\}^{+}} \ \{\textsc{InitR}\} \qquad \frac{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash P \blacktriangleright \mathscr{D} \quad a \in \mathscr{N}}{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash \tilde{a}[\mathsf{p}](y).P \blacktriangleright \mathscr{D} \setminus\!\setminus y} \ \{\textsc{InitN}\}$$

$$\frac{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash P \blacktriangleright \mathscr{D} \quad a \in \mathscr{B} \quad \mathsf{fc}(P) \subseteq \{y\}}{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash \tilde{a}[\mathsf{p}](y).P \blacktriangleright \mathscr{D} \setminus\!\setminus y} \ \{\textsc{InitB}\ \} \qquad \frac{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash P \blacktriangleright \mathscr{D} \quad \mathsf{fc}(P) \subseteq \{y\}}{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash \tilde{x}[\mathsf{p}](y).P \blacktriangleright \mathscr{D} \setminus\!\setminus y} \ \{\textsc{InitV}\}$$

$$\frac{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash P \blacktriangleright \mathscr{D} \quad e \in \mathscr{S} \Rightarrow e \in \mathscr{N} \cup \mathscr{B}}{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash c!\langle \Pi, e \rangle.P \blacktriangleright \mathscr{D}} \ \{\textsc{Send}\} \qquad \frac{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash P \blacktriangleright \mathscr{D}}{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash c?(\mathsf{q}, x).P \blacktriangleright (\mathsf{pre}(c, \mathsf{fc}(P)) \cup \mathscr{D})^{+}} \ \{\textsc{Rcv}\}$$

$$\frac{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash P \blacktriangleright \mathscr{D}}{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash c!\langle\langle \mathsf{p}, c' \rangle\rangle.P \blacktriangleright (\{\curlywedge(c) \prec \curlywedge(c')\} \cup \mathscr{D})^{+}} \ \{\textsc{Deleg}\} \qquad \frac{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash P \blacktriangleright \mathscr{D} \quad \mathscr{D} \setminus \mathscr{S} \subseteq \{\curlywedge(c) \prec y\}}{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash c?((\mathsf{q}, y)).P \blacktriangleright \mathscr{D} \setminus \{y\}} \ \{\textsc{SRcv}\}$$

$$\frac{}{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash \mathbf{0} \blacktriangleright \emptyset} \ \{\textsc{Inact}\} \qquad \frac{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash P \blacktriangleright \mathscr{D} \quad a \in \mathscr{B}}{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \setminus \{a\} \vdash (\nu a : \mathsf{G}) P \blacktriangleright \mathscr{D} \setminus \{a\}} \ \{\textsc{NRes}\}$$

$$\frac{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash P_1 \blacktriangleright \mathscr{D}_1 \quad \Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash P_2 \blacktriangleright \mathscr{D}_2}{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash P_1 \mid P_2 \blacktriangleright (\mathscr{D}_1 \cup \mathscr{D}_2)^{+}} \ \{\textsc{Par}\} \qquad \frac{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash P_1 \blacktriangleright \mathscr{D}_1 \quad \Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash P_2 \blacktriangleright \mathscr{D}_2}{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash \mathsf{if} \ e \ \mathsf{then} \ P_1 \ \mathsf{else} \ P_2 \blacktriangleright (\mathscr{D}_1 \cup \mathscr{D}_2)^{+}} \ \{\textsc{If}\}$$

$$\frac{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash P \blacktriangleright \mathscr{D}}{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash c \oplus \langle \Pi, l \rangle.P \blacktriangleright \mathscr{D}} \ \{\textsc{Sel}\} \qquad \frac{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash P_i \blacktriangleright \mathscr{D}_i \quad \forall i \in I}{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash c \& (\mathsf{p}, \{l_i : P_i\}_{i \in I}) \blacktriangleright (\mathsf{pre}(c, \bigcup_{i \in I} \mathsf{fc}(P_i)) \cup \bigcup_{i \in I} \mathscr{D}_i)^{+}} \ \{\textsc{Branch}\}$$

$$\frac{e \in \mathscr{S} \Rightarrow e \in \mathscr{N} \cup \mathscr{B}}{\Theta, X[y] \blacktriangleright \mathscr{D}; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash X\langle e, c \rangle \blacktriangleright \mathscr{D}\{\curlywedge(c)/y\}} \ \{\textsc{Var}\}$$

$$\frac{\Theta, X[y] \blacktriangleright \mathscr{D}; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash P \blacktriangleright \mathscr{D} \qquad \Theta, X[y] \blacktriangleright \mathscr{D}; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash Q \blacktriangleright \mathscr{D}'}{\Theta; \mathscr{R}; \mathscr{N}; \mathscr{B} \vdash \mathsf{def} \ X(x, y) = P \ \mathsf{in} \ Q \blacktriangleright \mathscr{D}'} \ \{\textsc{Def}\}$$

Tracking dependencies between **actions**

- Kobayashi, **A Type System for Lock-Free Processes**, Inf. & Comp. 2002
- Kobayashi, **A New Type System for Deadlock-Free Processes**, CONCUR 2006
- ...
- Padovani, **From Lock Freedom to Progress Using Session Types**, PLACES 2013
- Vieira, Vasconcelos, **Typing Progress in Communication-Centred Systems**, COORDINATION 2013

+ fine-grained

− recursion+channel interleaving

From sessions to the linear π-calculus

- Dardha, Giachino, Sangiorgi, **Session types revisited**, PPDP 2012

Session	**Linear π-calculus**
$a!\langle 45\rangle.a?(x)$	$(\nu b)a!\langle 45, b\rangle.b?(x)$
$a : \mathtt{!}\mathtt{int}.\mathtt{?}\mathtt{bool}$	$a : \mathtt{!}[\mathtt{int} \times \mathtt{!}[\mathtt{bool}]]$

The linear π-calculus

- Kobayashi, Pierce, Turner, **Linearity and the pi-calculus**, TOPLAS 1999

$$p^{\iota}[t]$$

Theorem (soundness)

Each linear channel of a well-typed process is used at most once

Deadlock and lock freedom

Definition (deadlock freedom)

no pending communications on linear channels in irreducible states

$$a?(x).b!\langle x\rangle \mid b?(y).a!\langle y\rangle$$

Definition (lock freedom)

each pending communication on a linear channel can be completed

$$c!\langle a\rangle \mid {*c?(x)}.c!\langle x\rangle \mid a!\langle 1984\rangle$$

$$
\begin{array}{rcl}
t & ::= & \texttt{int} \\
 & | & \alpha \\
 & | & \mu\alpha.t \\
 & | & t \times s \\
 & | & p^{\iota}[t]^{\overset{m}{\downarrow},\overset{n}{\downarrow}}
\end{array}
$$

+ priority (⇔ deadlock freedom)

+ rank (⇒ lock freedom)

Conditions for deadlock freedom

Inputs

$$\frac{u \text{ has higher priority than all the channels in } P}{u?(x).P \text{ is well typed}}$$

Outputs

$$\frac{u \text{ has higher priority than } v}{u!\langle v\rangle \text{ is well typed}}$$

Examples

$$a : \#[\mathtt{int}]^{m}, b : \#[\mathtt{bool}]^{h} \vdash \overbrace{a^{m}?(x).b^{h}}^{<}!\langle x\rangle \mid \overbrace{b^{h}?(y).a^{m}}^{\not<}!\langle y\rangle$$

$$a : \#[\mathtt{int}]^{m} \vdash \overbrace{a^{m}?(x).a^{m}}^{\not<}!\langle x\rangle$$

$$a : \#[\mu\alpha.?[\alpha]^{m}]^{m} \vdash \overbrace{a^{m}!\langle a^{m}}^{\not<}\rangle$$

Recursive processes

$$\begin{aligned} &*\mathit{fact}?(x, y^{\textcircled{0}}).\texttt{if}\ x = 0\ \texttt{then}\ y^{0}!\langle 1\rangle \\ &\qquad\qquad\qquad \texttt{else}\ (\nu a^{-1})(\mathit{fact}!\langle x - 1, a^{\textcircled{-1}}\rangle \mid a^{\textcircled{-1}}?(z).y^{\textcircled{0}}!\langle x \times z\rangle) \end{aligned}$$

- Kobayashi, **A New Type System for Deadlock-Free Processes**, CONCUR 2006

$$*\mathit{stream}?(x, y^{\textcircled{0}}).(\nu a^{1})(y^{\textcircled{0}}!\langle x, a^{\textcircled{1}}\rangle \mid \mathit{stream}!\langle x + 1, a^{\textcircled{1}}\rangle)$$

Spot the differences

$c?(x^{8}).y^{7}!\langle x^{8}\rangle$

$c?(x^{8}, y^{7}).y^{7}!\langle x^{8}\rangle$

- y free
- x's priority $\prec 7$
- c monomorphic

- y bound
- x's priority $\prec$ y's priority
- c **polymorphic**

When is a channel polymorphic?

- input on c has free linear channels in continuation
  $\Rightarrow$ c monomorphic
- input on c has no free linear channels in continuation
  $\Rightarrow$ c polymorphic

$$\frac{\Gamma, x : t \vdash P \qquad \mathsf{un}(\Gamma)}{\Gamma \vdash *u?(x).P}$$

Fact

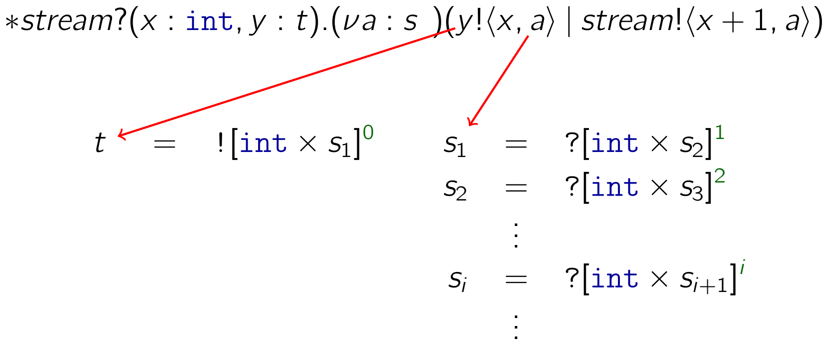
Every replicated channel is polymorphic in the linear π-calculus

Back to *fact* and *stream*

$$
\begin{aligned}
&{*}\mathit{fact}?(x, y^{\textcircled{0}}).\texttt{if } x = 0 \texttt{ then } y^{0}!\langle 1\rangle \\
&\qquad\qquad \texttt{else } (\nu a^{-1})(\mathit{fact}!\langle x-1, a^{\textcircled{-1}}\rangle \mid a^{-1}?(z).y^{0}!\langle x \times z\rangle)
\end{aligned}
$$

$$
{*}\mathit{stream}?(x, y^{\textcircled{0}}).(\nu a^{1})(y^{0}!\langle x, a^{1}\rangle \mid \mathit{stream}!\langle x+1, a^{\textcircled{1}}\rangle)
$$

A technical issue



$$*stream?(x : \texttt{int}, y : t).(\nu a : s\ )(y!\langle x, a\rangle \mid stream!\langle x + 1, a\rangle)$$

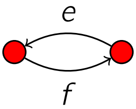
$$\begin{aligned} t &= \,![\texttt{int} \times s_1]^0 \end{aligned} \qquad \begin{aligned} s_1 &= ?[\texttt{int} \times s_2]^1 \\ s_2 &= ?[\texttt{int} \times s_3]^2 \\ &\vdots \\ s_i &= ?[\texttt{int} \times s_{i+1}]^i \\ &\vdots \end{aligned}$$

$$t = \,![\texttt{int} \times s]^0 \qquad s = ?[\texttt{int} \times s]^1$$

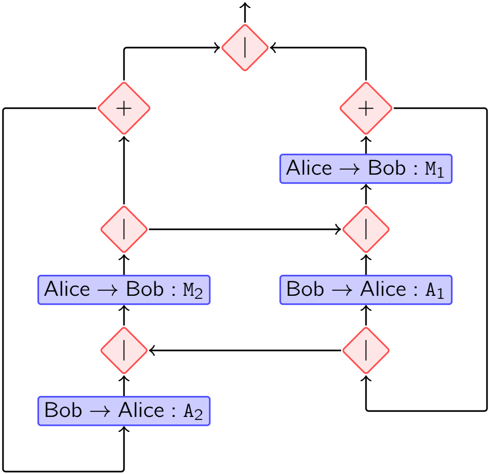
Lock-free full-duplex communication

$$*c?(x^{0}, y^{0}).(\nu a^{1})(x^{0}!\langle a^{1}\rangle \mid y^{0}?(z^{1}).c!\langle a^{1}, z^{1}\rangle)$$

$$c!\langle e, f\rangle \mid c!\langle f, e\rangle$$



Lock-free alternating bit protocol



- Deniélou, Yoshida, **Multiparty Session Types Meet Communicating Automata**, ESOP 2012

Lock-free alternating bit protocol

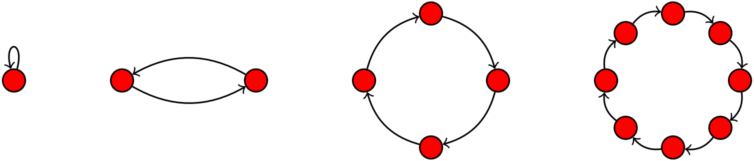
$$
\begin{aligned}
\text{Bob} \;&\stackrel{\text{def}}{=}\; *\mathit{bob}?(x^{0}, y^{2}).\\
&\qquad (\nu a^{3} b^{5})\big(x^{0}?(\bar{x}^{1}).(\bar{x}^{1}!\langle a^{3}\rangle \mid\\
&\qquad\qquad y^{2}?(\bar{y}^{3}).(\bar{y}^{3}!\langle b^{5}\rangle \mid \mathit{bob}!\langle a^{3}, b^{5}\rangle)))\big)
\end{aligned}
$$

$$
\begin{aligned}
\text{Alice}_1 \;&\stackrel{\text{def}}{=}\; *\mathit{alice}_1?(x^{0}, z^{1}).\\
&\qquad (\nu a^{1} c^{2})\big(x^{0}!\langle a^{1}\rangle \mid z^{1}!\langle c^{2}\rangle \mid\\
&\qquad\qquad a^{1}?(\bar{x}^{3}).c^{2}?(\bar{z}^{4}).\mathit{alice}_1!\langle \bar{x}^{3}, \bar{z}^{4}\rangle\big)
\end{aligned}
$$

$$
\begin{aligned}
\text{Alice}_2 \;&\stackrel{\text{def}}{=}\; *\mathit{alice}_2?(y^{2}, z^{1}).\\
&\qquad (\nu b^{3} c^{4})\big(z^{1}?(\bar{z}^{2}).(y^{2}!\langle b^{3}\rangle \mid \bar{z}^{2}!\langle c^{4}\rangle \mid\\
&\qquad\qquad b^{3}?(\bar{y}^{5}).\mathit{alice}_2!\langle \bar{y}^{5}, c^{4}\rangle)\big)
\end{aligned}
$$

Lock-free fairy ring

$$*c?(x^0, y^0).(\nu a^1 b^1)\big(x^0?(z^1).c!\langle z^1, b^1\rangle \mid c!\langle b^1, a^1\rangle \mid y^0!\langle a^1\rangle\big)$$



Back to sessions

Strategy #1

$$\underline{a?(x)}.\underline{b?(x')}.\underline{a?(y)}.\underline{b?(y')}.(\underline{a!\langle x+x'\rangle} \mid \underline{b!\langle y+y'\rangle})$$

$$\Downarrow$$

$$\underline{a?(x,a')}.\underline{b?(x',b')}.\underline{a'?(y,a'')}.\underline{b'?(y',b'')}.(\underline{a''!\langle x+x'\rangle} \mid \underline{b''!\langle y+y'\rangle})$$

Strategy #2

$$?[\mathtt{int}]^{m}.![\mathtt{bool}]^{n}$$

$$\Uparrow$$

$$?[\mathtt{int} \times ![\mathtt{bool}]^{n}]^{m}$$

$$\mathtt{A} \xrightarrow{\mathtt{int}} \mathtt{B}^{m}.\mathtt{B} \xrightarrow{\mathtt{bool}} \mathtt{C}^{n}$$

Final considerations

- + simple
- + accurate
- − unlimited channels (concurrent objects, dining philosophers)

`<troll-mode>`

- (dead)lock freedom $\not\Longrightarrow$ sessions

`<troll-mode/>`

What's next

Type reconstruction (with Tzu-Chun Chen)

1. collect constraints
2. integer programming problem
3. solve constraints between types

Unlimited channels?