School of informatics

A theorem proving framework for the formal verification of Web Services Composition

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Web Services Composition

- Mechanically combine Web Services for complex tasks

- In this work:
  - Offline
  - Non-functional properties (Quality driven)
  - Exceptions
  - Formal

WS Composition Methodologies

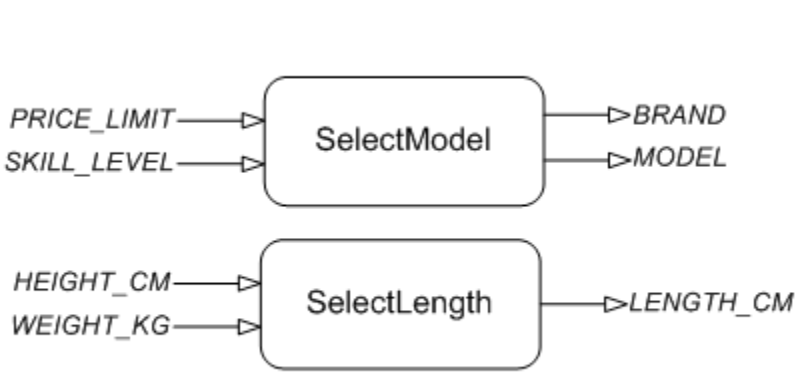
- Workflow techniques (eg. EFlow)
- AI Planning (eg. SWORD)
- Theorem Proving

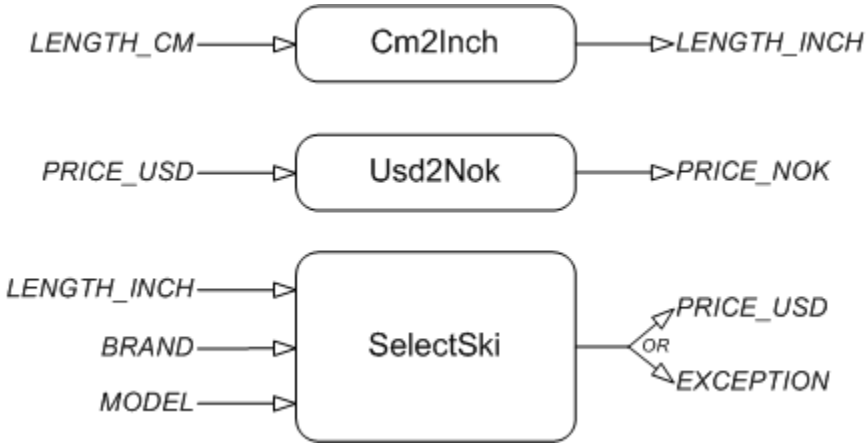
WS Composition using Theorem Proving

- Waldinger (2001):
  - program synthesis in SNARK - FOL
- Lammermann (2002):
  - structural synthesis in Java – Intuitionistic Propositional Logic
- Rao et al. (2006):
  - proofs-as-processes in RAPS – ILL
- Current work:
  - proofs-as-processes in HOL Light – CLL

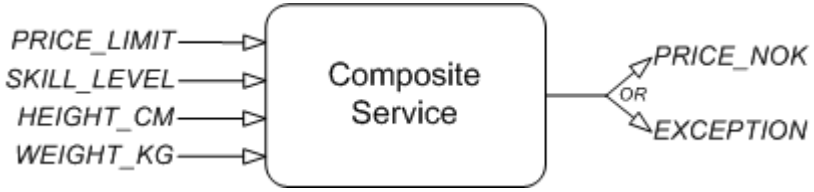
Ski Example

- Ski purchasing (Rao 2004)
- Available services:





- Requested service:



Proofs-as-processes

- Similar to "formulae-as-types" (Curry-Howard 1980)
- Introduced by Abramsky (1994)
- Bellin and Scott (1994)
- Classical Linear Logic and π-calculus

Classical Linear Logic

- Girard (1987)

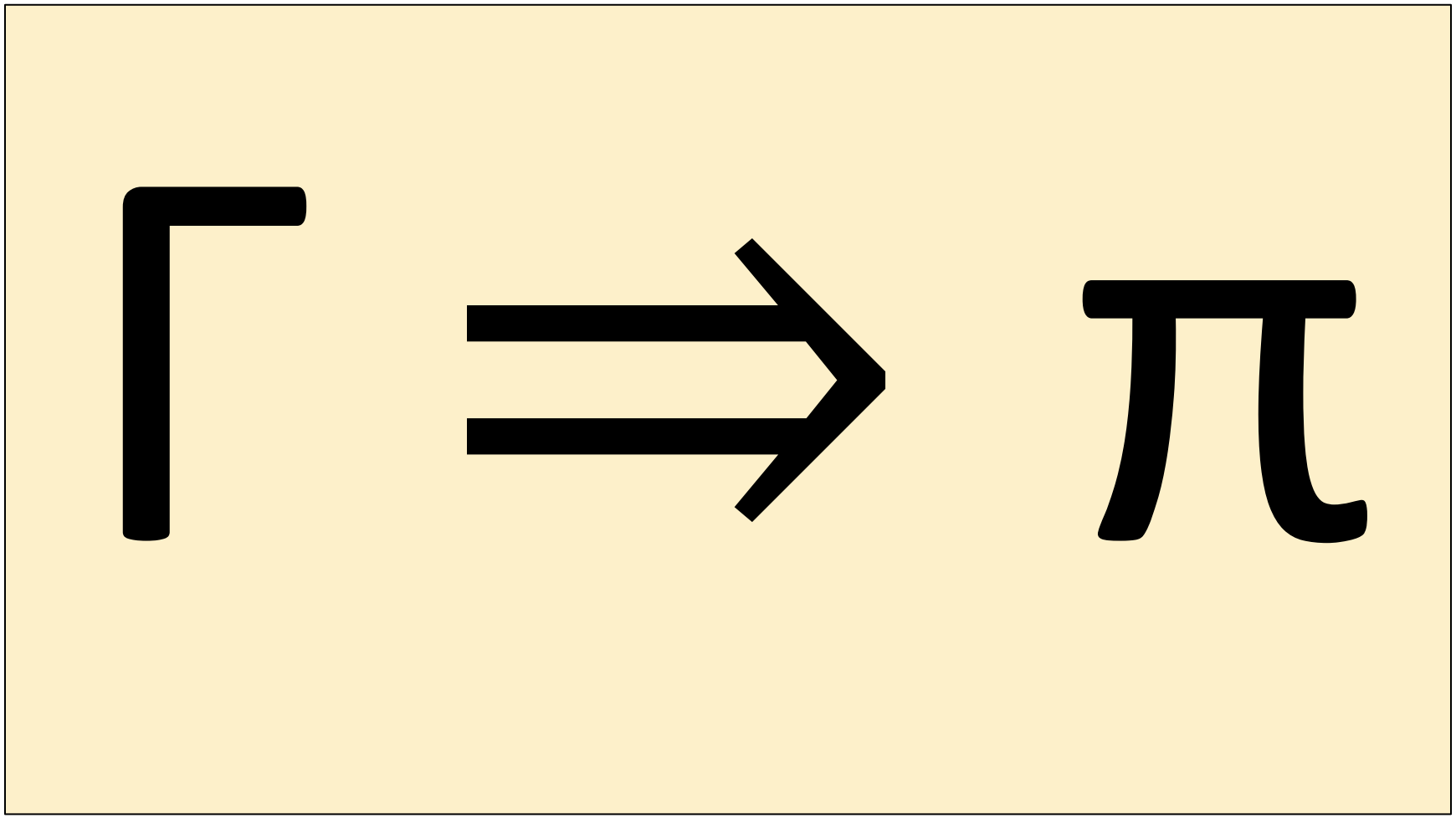
	Disjunction	Conjunction
Multiplicative	$\parr$	$\otimes$
Additive	$\oplus$	$\&$
Negation	$(\cdot)^{\perp}$	

π-calculus

- Milner (1989)

P ::=	
| 0	null process
| x(y).P	input
| $\bar{x}$<y>.P	output
| (ν x) P	local variable
| P || P	parallel processes
| P + P	choice

Proofs-as-processes



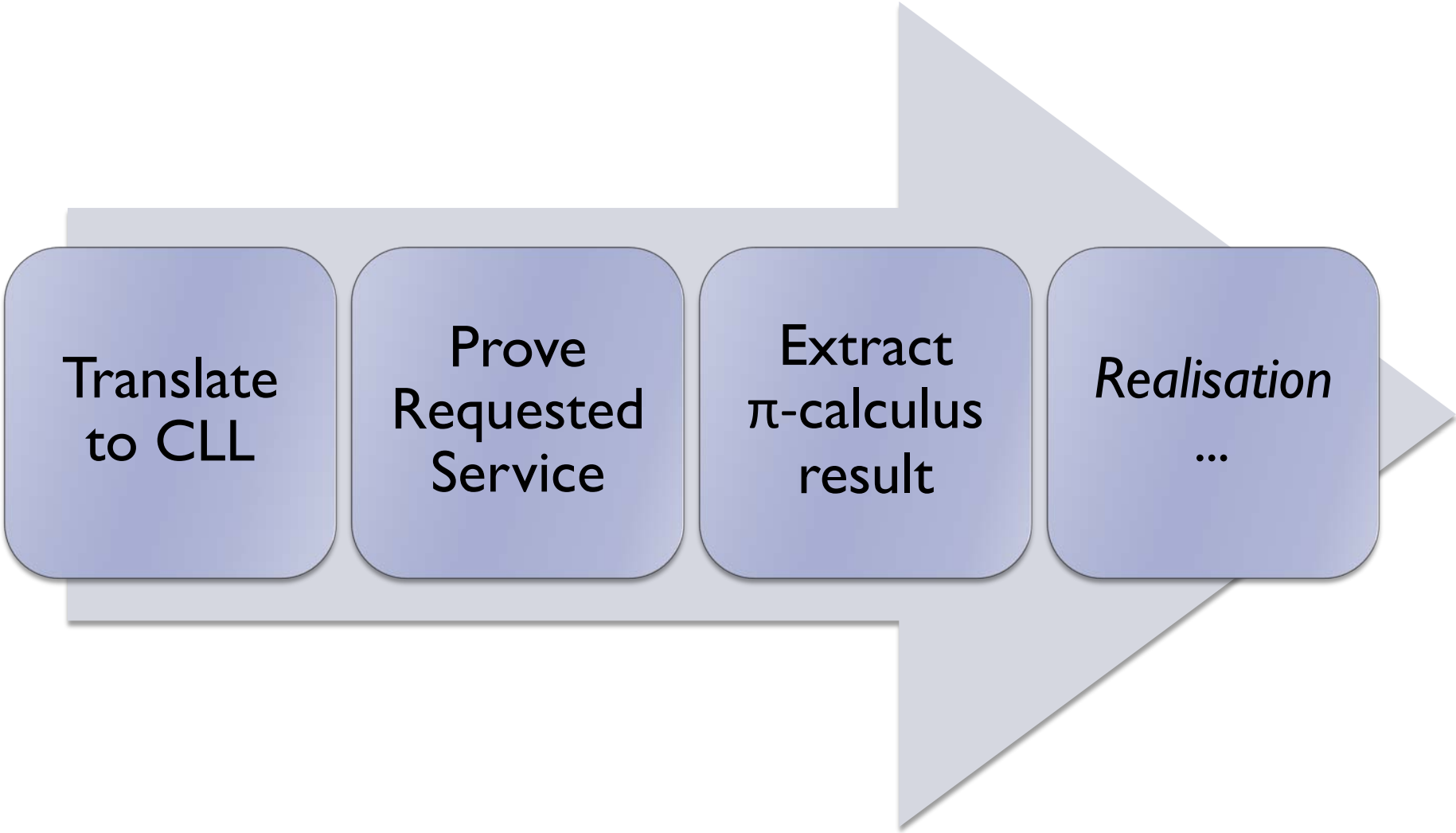
Example: Tensor ($\otimes$) rule

$$\frac{\begin{array}{cc} \vdots\ F & \vdots\ G \\ \vdash \vec{w}:\Gamma,\ x:A & \vdash \vec{u}:\Delta,\ y:B \end{array}}{\vdash \vec{w}:\Gamma,\ \vec{u}:\Delta,\ z:A \otimes B}\ \otimes$$

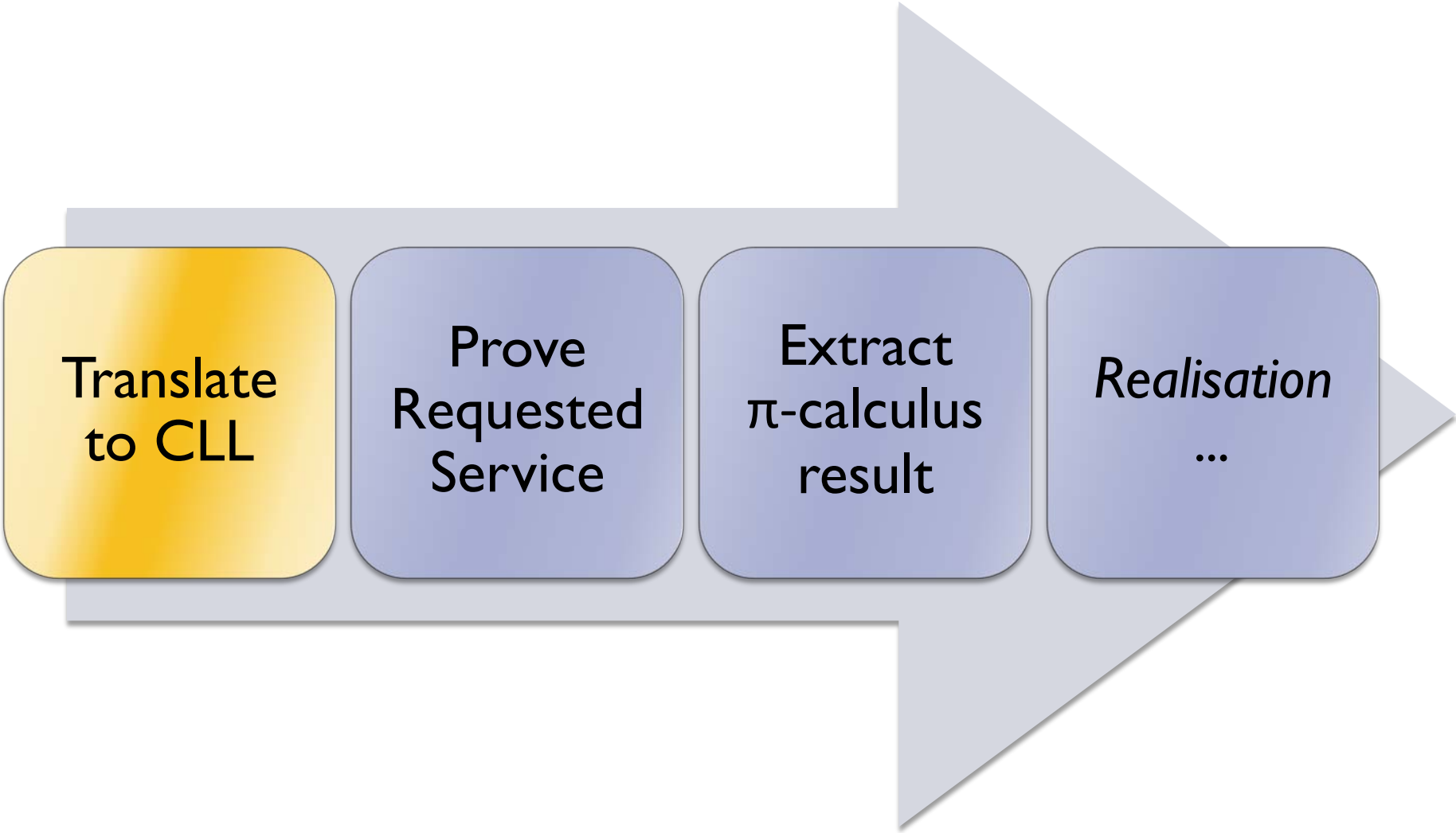
$$\bigotimes_{z}^{x,y}(F,G)\vec{w}\vec{u}z \equiv \nu xy(\overline{z}\langle xy\rangle(F_{\vec{w}x}||G_{\vec{u}y}))$$

CLL inference rule	π-calculus translation
$\vdash x:A,\ y:A^{\perp}$	$Ixy = y(a)\overline{x}\langle a\rangle$
$\dfrac{\vdots\ F \qquad \vdots\ G}{\vdash \vec{w}:\Gamma,\ x:A \quad \vdash \vec{u}:\Delta,\ y:B}\ \otimes$	$\overset{x,y}{\underset{z}{\bigotimes}}(F,G)\vec{w}\vec{u}z = \nu xy(\overline{z}\langle xy\rangle(F_{\vec{w}x}\|\|G_{\vec{u}y}))$
$\dfrac{\vdots\ F}{\vdash \vec{w}:\Gamma,\ x:A,\ y:B}\ \parr$	$\overset{x,y}{\underset{z}{\parr}}(F)\vec{w}z = z(xy)F_{\vec{w}xy}$
$\dfrac{\vdots\ P}{\vdash \vec{w}:\Gamma,\ x:A}\ \oplus$	$\overset{x}{\underset{z}{\mathrm{L}}}(P)\vec{w}z = \nu x(z(uv)\overline{u}\langle x\rangle P_{\vec{w}x})$
$\dfrac{\vdots\ Q}{\vdash \vec{w}:\Gamma,\ y:B}\ \oplus$	$\overset{y}{\underset{z}{\mathrm{R}}}(Q)\vec{w}y = \nu y(z(uv)\overline{v}\langle y\rangle Q_{\vec{w}y})$
$\dfrac{\vdots\ P \qquad \vdots\ Q}{\vdash \vec{w}:\Gamma,\ x:A \quad \vdash \vec{w}:\Gamma,\ y:B}\ \&$	$\overset{x,y}{\underset{z}{\&}}(P,Q)\vec{w}z = \nu uv(\overline{z}\langle uv\rangle[u(x)P_{\vec{w}x} + v(y)Q_{\vec{w}y}])$
$\dfrac{\vdots\ F \qquad \vdots\ G}{\vdash \vec{u}:\Gamma,\ x:C \quad \vdash \vec{v}:\Delta,\ y:C^{\perp}}\ Cut$	$Cut^{z}(F,G)\vec{u}\vec{v} = \nu z(F_{\vec{u}}[z/x]\|\|G_{\vec{v}}[z/y])$

WS Composition using proofs-as-processes



WS Composition using proofs-as-processes



Web Services in Classical Linear Logic

$$\vdash \vec{P}^{\perp}, \vec{I}^{\perp}, ((\otimes_{i} \vec{F}) \otimes (\otimes_{i} \vec{O})) \oplus E$$

$$\text{Where}: \otimes_{i}(\alpha_1, \alpha_2, ..., \alpha_n) = \alpha_1 \otimes \alpha_2 \otimes ... \otimes \alpha_n \ , \ i \geq 0$$

$\vec{P}$: Preconditions

$\vec{I}$: Input

$\vec{F}$: Postconditions (effects)

$\vec{O}$: Output

$\vec{E}$: Exception

Ski example specified in CLL

- `SelectModel`:

  $\vdash \text{PRICE\_LIMIT}^{\perp}, \text{SKILL\_LEVEL}^{\perp}, \text{BRAND} \otimes \text{MODEL}$

- `SelectLength`:

  $\vdash \text{HEIGHT\_CM}^{\perp}, \text{WEIGHT\_KG}^{\perp}, \text{LENGTH\_CM}$

- `Cm2Inch`:

  $\vdash \text{LENGTH\_CM}^{\perp}, \text{LENGTH\_IN}$

- `Usd2Nok`:

  $\vdash \text{PRICE\_USD}^{\perp}, \text{PRICE\_NOK}$

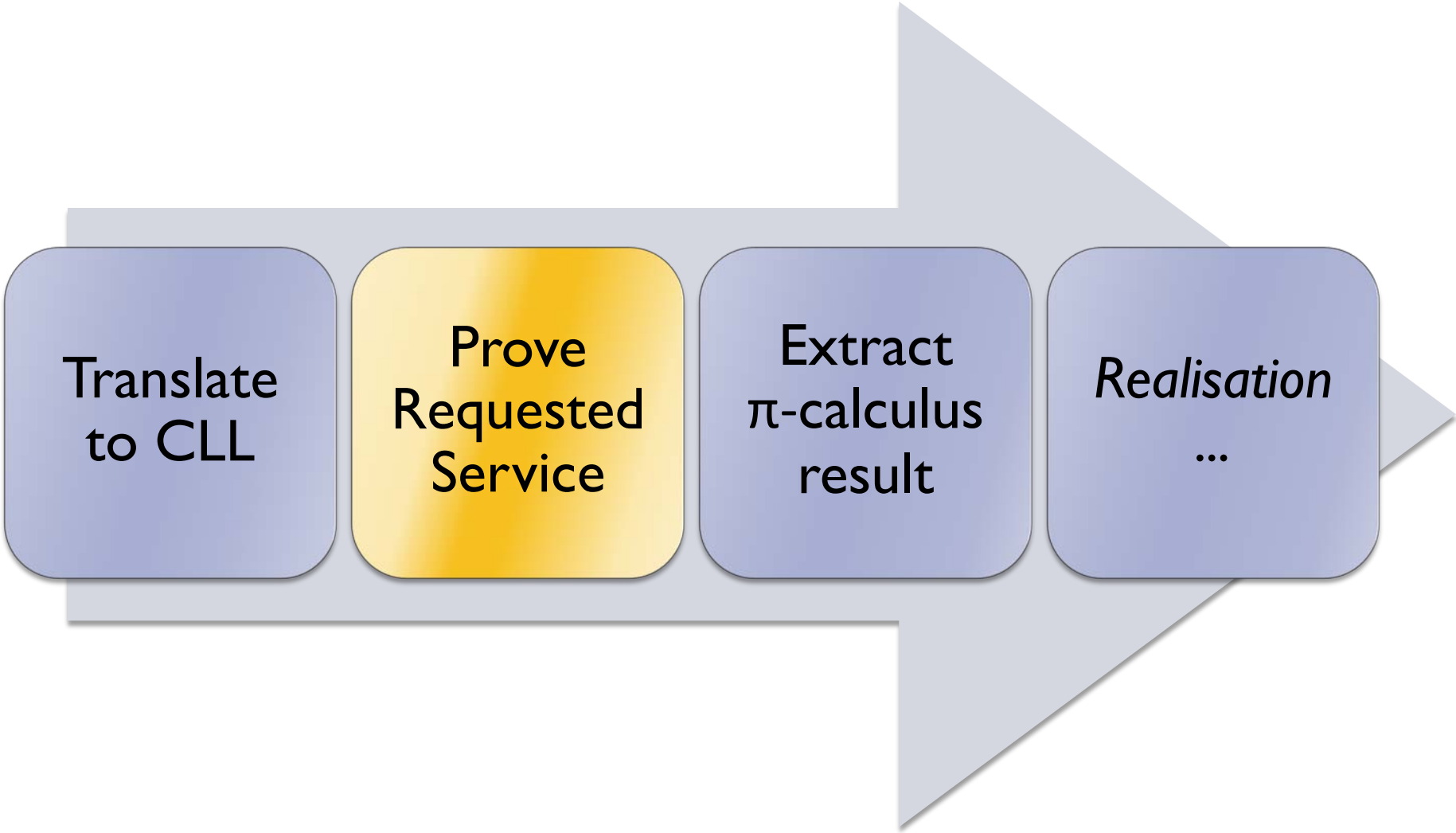
- `SelectSki`:

  $\vdash \text{LENGTH\_IN}^{\perp}, \text{BRAND}^{\perp}, \text{MODEL}^{\perp}, \text{PRICE\_USD} \oplus \text{EXCEPTION}$

Ski Request in CLL

$$\vdash \text{PRICE\_LIMIT}^{\perp},\ \text{SKILL\_LEVEL}^{\perp},\ \text{HEIGHT\_CM}^{\perp},\ \text{WEIGHT\_KG}^{\perp},\ \text{PRICE\_NOK} \oplus \text{EXCEPTION}$$

WS Composition using proofs-as-processes



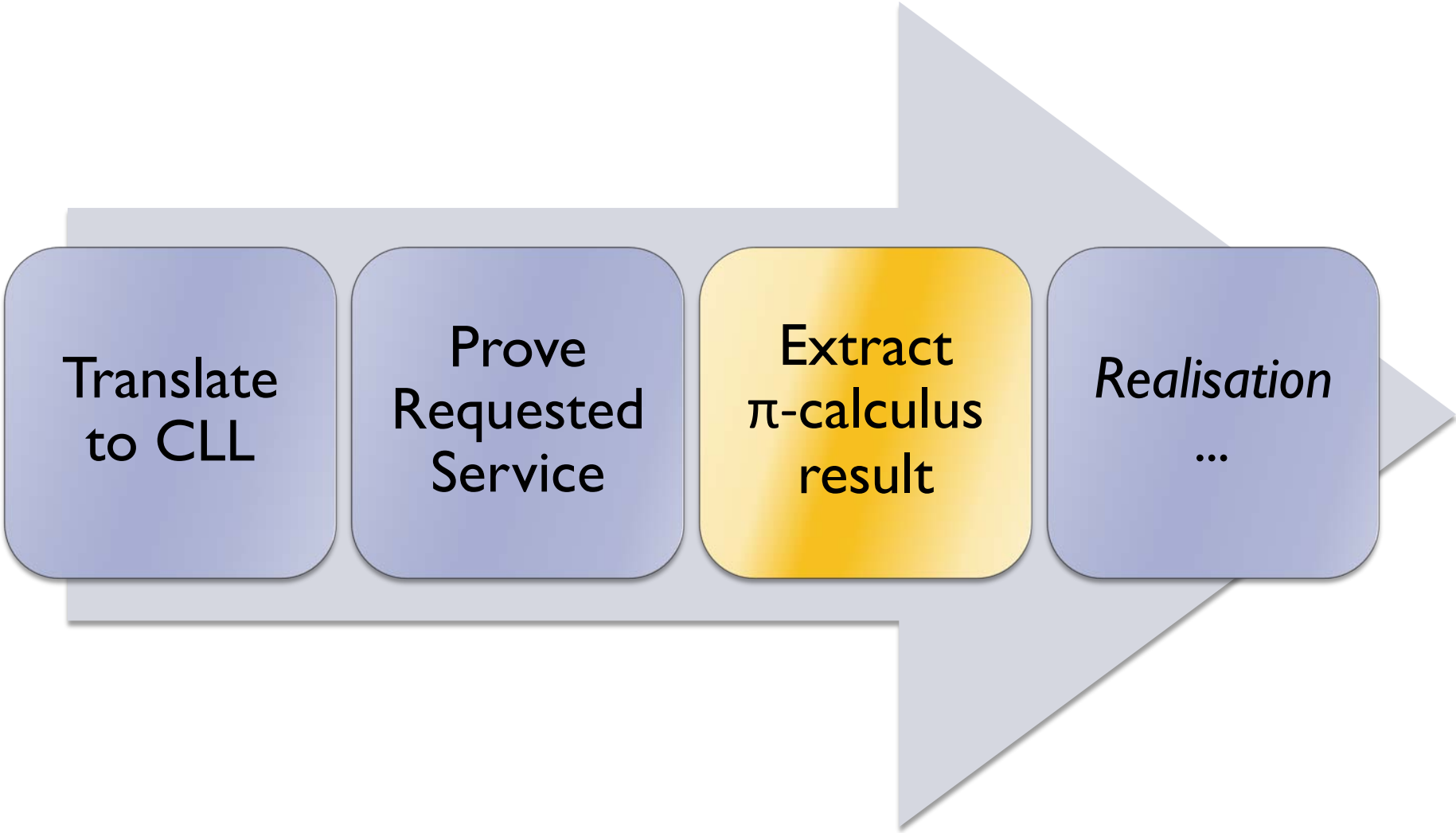
Proof for the Ski example

$$\dfrac{\dfrac{}{\vdash PL^{\perp},\ SL^{\perp},\ BR \otimes MO}\ SelMod \qquad \dfrac{\dfrac{}{\vdash HC^{\perp},\ WK^{\perp},\ LC}\ SelLen \qquad \dfrac{}{\vdash LC^{\perp},\ LI}\ Cm2Inch}{\vdash HC^{\perp},\ WK^{\perp},\ LI}\ Cut}{\vdash PL^{\perp},\ SL^{\perp},\ HC^{\perp},\ WK^{\perp},\ (BR \otimes MO) \otimes LI}\ \otimes \qquad (1)$$

$$\dfrac{\dfrac{\dfrac{\dfrac{}{\vdash BR^{\perp},\ MO^{\perp},\ LI^{\perp},\ PU \oplus EXE}\ SelSki}{\vdash BR^{\perp} \parr MO^{\perp},\ LI^{\perp},\ PU \oplus EXE}\ \parr}{\vdash (BR^{\perp} \parr MO^{\perp}) \parr LI^{\perp},\ PU \oplus EXE}\ \parr \qquad \dfrac{\dfrac{\dfrac{\dfrac{}{\vdash PU^{\perp},\ PN}\ Usd2Nok}{\vdash PU^{\perp},\ PN \oplus EXE}\ \oplus \qquad \dfrac{\dfrac{}{\vdash EXE^{\perp},\ EXE}\ Id}{\vdash EXE^{\perp},\ PN \oplus EXE}\ \oplus}{\vdash PU^{\perp} \,\&\, EXE^{\perp},\ PN \oplus EXE}\ \&}{\vdash (PU \oplus EXE)^{\perp},\ PN \oplus EXE}\ neg\_eq}{\vdash (BR^{\perp} \parr MO^{\perp}) \parr LI^{\perp},\ PN \oplus EXE}\ Cut \qquad \text{(2)}$$

$$\dfrac{\dfrac{\vdash (BR^{\perp} \parr MO^{\perp}) \parr LI^{\perp},\ PN \oplus EXE}{\vdash ((BR \otimes MO) \otimes LI)^{\perp},\ PN \oplus EXE}\ neg\_eq}{\vdash PL^{\perp},\ SL^{\perp},\ HC^{\perp},\ WK^{\perp},\ PN \oplus EXE}\ Cut\ with\ (1)$$

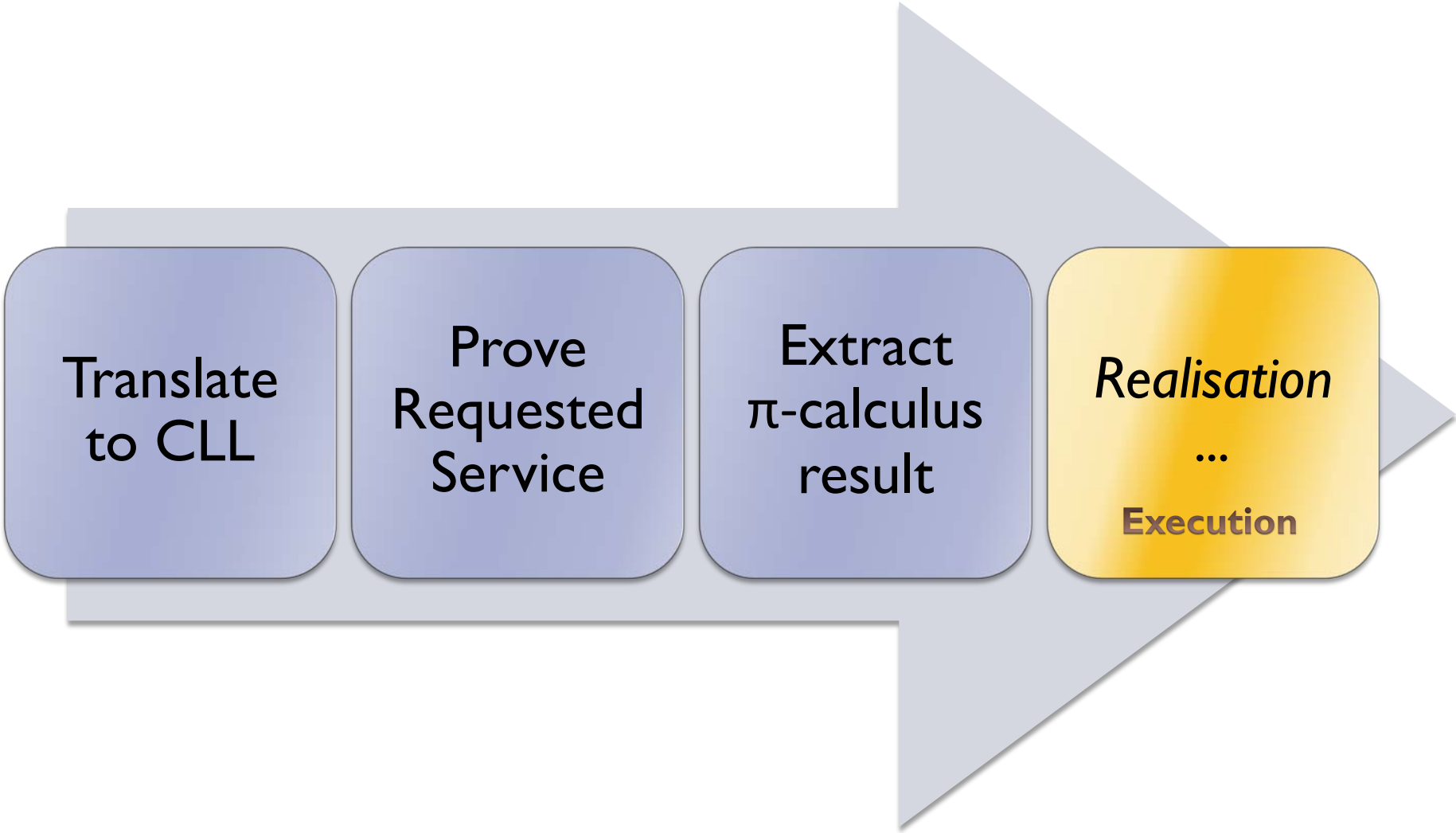
WS Composition using proofs-as-processes



Ski Result in π-calculus

$$
\begin{aligned}
&Composition(smp, sms, slh, slw, t, puc, exc) \equiv \\
&\quad (\nu\ z_1) \\
&\qquad ((\nu\ smo, cii) \\
&\qquad\quad (\overline{z_1}\langle smo, cii\rangle. \\
&\qquad\quad (SelMod \mid\mid (\nu\ z_3)(SelLen[z_3/sll] \mid\mid Cm2Inch[z_3/cic])) \\
&\qquad) \mid\mid (\nu\ z_4) \\
&\qquad\quad (((z_1(x_5, ssl).x_5(ssb, ssm).SelSki[z_4/sso]) \mid\mid \\
&\qquad\quad (\nu\ u_7, v_7) \\
&\qquad\qquad ((\overline{z_4}\langle (u_7, v_7)\rangle. \\
&\qquad\qquad\quad ((u_7(unu).(\nu\ unn)(t(u_8, v_8).\overline{u_8}\langle unn\rangle.Usd2Nok)) + \\
&\qquad\qquad\qquad (v_7(y_7).(\nu\ y_9)(t(u_9, v_9).\overline{v_9}\langle y_9\rangle.y_7(a_{10}).\overline{y_9}\langle a_{10}\rangle.0))) \\
&\qquad\quad)) \\
&\qquad) \\
&\quad)
\end{aligned}
$$

WS Composition using proofs-as-processes



Execution

- Available services are "black-boxes"

- Empirical translations:

$$
\begin{array}{rl}
A & \overline{a}\langle\ldots\rangle.0 \\
A^{\perp} & a(\ldots).0 \\
A \otimes B & (\nu a,b)(\overline{z}\langle a,b\rangle.(\overline{a}\langle\ldots\rangle.0 \mid\mid \overline{b}\langle\ldots\rangle.0)) \\
A^{\perp} \parr B^{\perp} & z(a,b).(a(\ldots).0 \mid\mid b(\ldots).0) \\
A \oplus B & (\nu a,b)(z(u,v).(\overline{u}\langle x\rangle.\overline{x}\langle\ldots\rangle.0 + \overline{v}\langle y\rangle.\overline{y}\langle\ldots\rangle.0)) \\
A^{\perp} \,\&\, B^{\perp} & (\nu a,b)(\overline{z}\langle u,v\rangle.(u(x).x(\ldots).0 + v(y).y(\ldots).0))
\end{array}
$$

Ski example specified in π-calculus

$$SelLen(slh, slw, sll, lc) \equiv slh(hc).slw(wk).\overline{sll}\langle lc\rangle.0$$

$$Cm2In(cic, cli, li) \equiv cic(lc).\overline{cli}\langle li\rangle.0$$

$$Usd2Nok(unu, unn, pn) \equiv unu(pu).\overline{unn}\langle pn\rangle.0$$

$$SelMod(smp, sms, smm, br, mo) \equiv smp(pl).sms(sl).(\nu\ smb, smo)(\overline{smm}\langle smb, smo\rangle.\overline{smb}\langle br\rangle.\overline{smo}\langle mo\rangle.0)$$

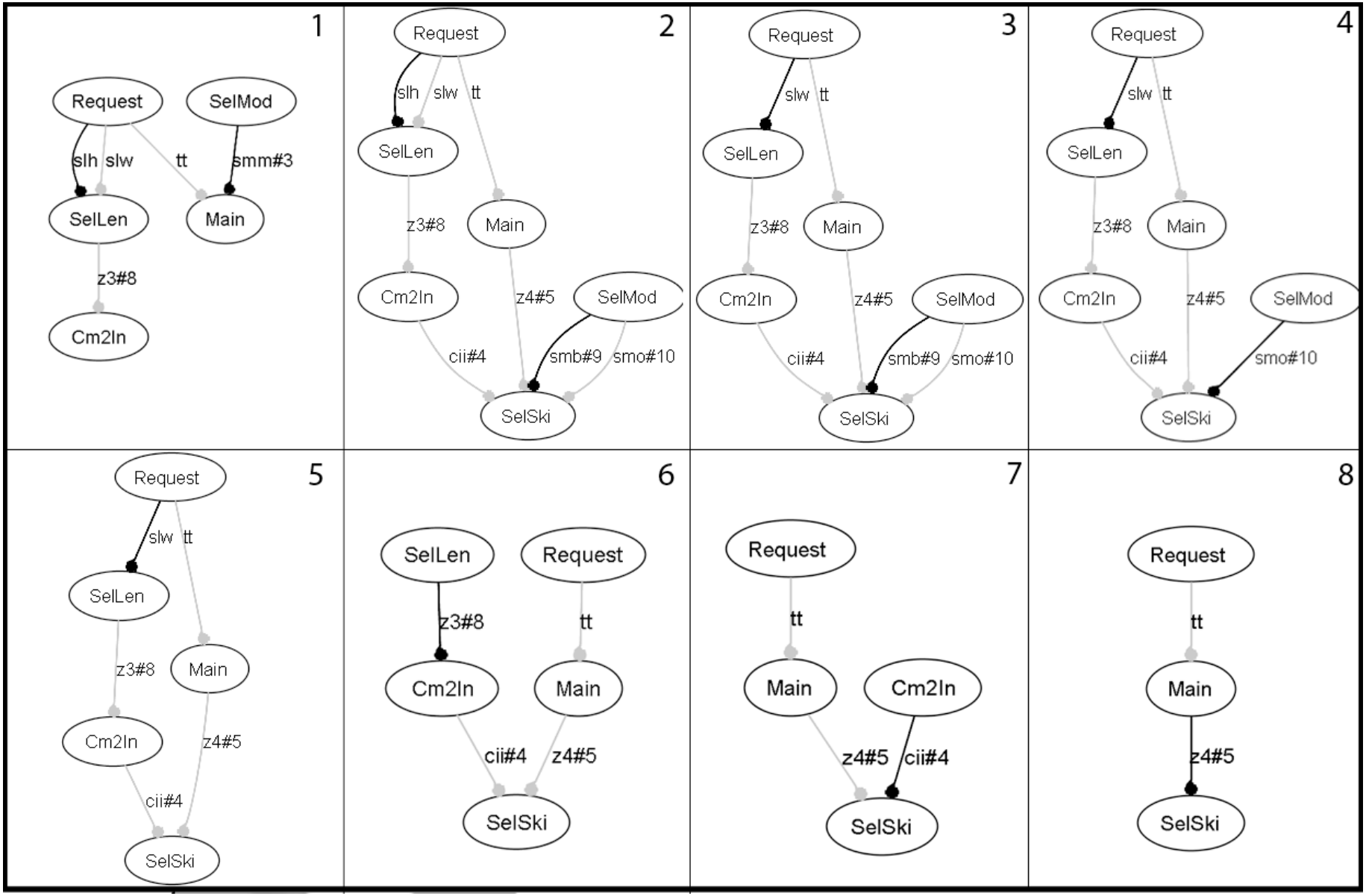
$$SelSki(ssb, ssm, ssl, sso, pu, ex) \equiv (\nu\ ssp, sse)(ssb(br).ssm(mo).ssl(li).sso(u, v).(\overline{u}\langle ssp\rangle.\overline{ssp}\langle pu\rangle.0 + \overline{v}\langle sse\rangle.\overline{sse}\langle ex\rangle.0))$$

$$Request(smp, pl, sms, sl, slh, hc, slw, wk, t, puc, exc) \equiv \overline{smp}\langle pl\rangle.\overline{sms}\langle sl\rangle.\overline{slh}\langle hc\rangle.\overline{slw}\langle wk\rangle.\overline{t}\langle puc, exc\rangle.(puc(x).x(pu).0 + exc(y).y(ex).0)$$

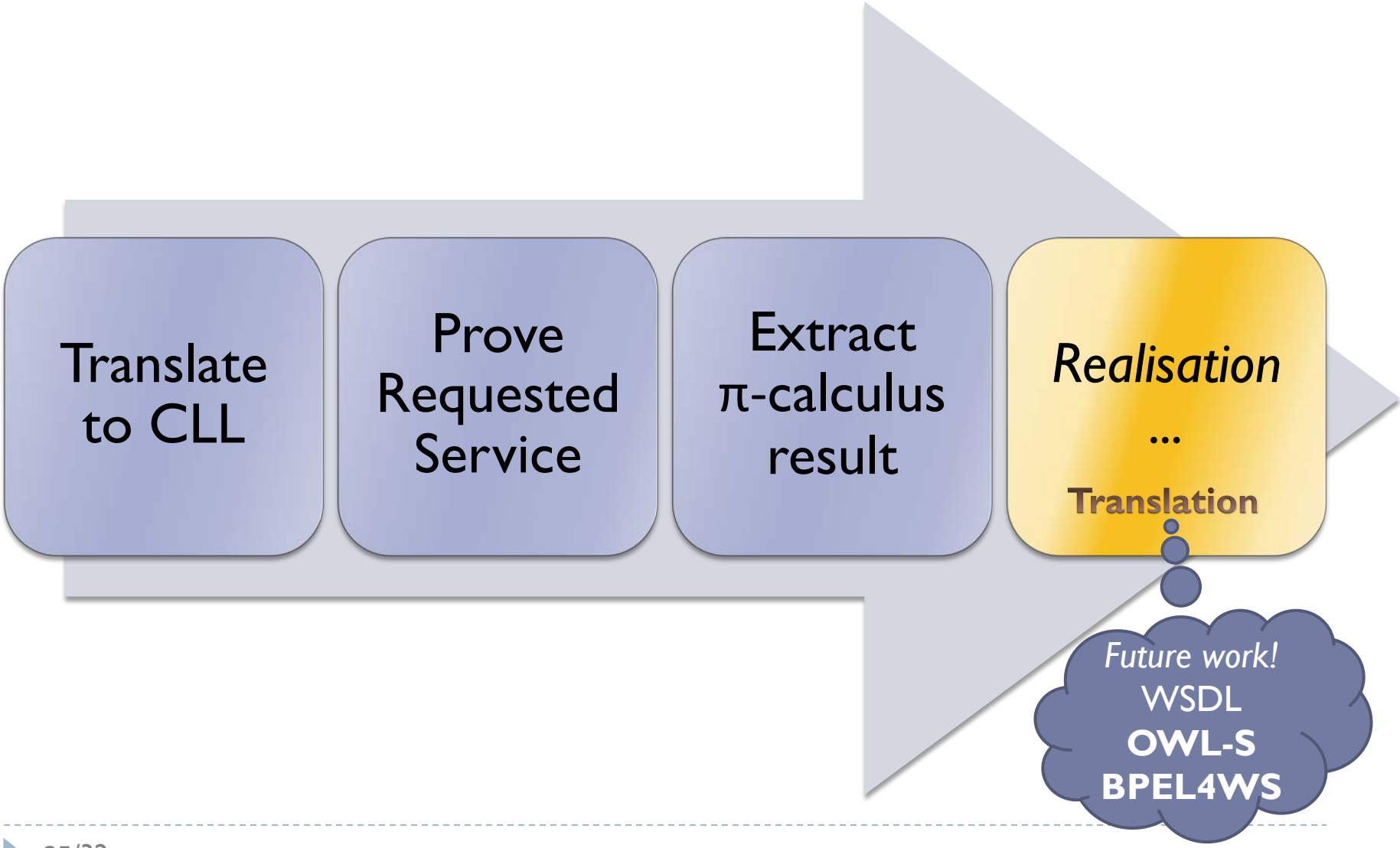
$$Main() \equiv Request(smp, pl, sms, sl, slh, hc, slw, wk, t, puc, exc) \mid\mid Composition(smp, sms, slh, slw, t, puc, exc)$$

PiVizTool

- Bog (2006)
- Visualisation of connections
- Animation of execution
- Empirical verification


1
Request
SelMod
slh
slw
tt
smm#3
SelLen
Main
z3#8
Cm2In
2
Request
slh
slw
tt
SelLen
Main
z3#8
Cm2In
z4#5
SelMod
cii#4
smb#9
smo#10
SelSki
3
Request
slw
tt
SelLen
Main
z3#8
Cm2In
z4#5
SelMod
cii#4
smb#9
smo#10
SelSki
4
Request
slw
tt
SelLen
Main
z3#8
Cm2In
z4#5
SelMod
cii#4
smo#10
SelSki
5
Request
slw
tt
SelLen
Main
z3#8
Cm2In
z4#5
cii#4
SelSki
6
SelLen
Request
z3#8
tt
Cm2In
Main
cii#4
z4#5
SelSki
7
Request
tt
Main
Cm2In
z4#5
cii#4
SelSki
8
Request
tt
Main
z4#5
SelSki

WS Composition using proofs-as-processes



Implementation: Requirements

- Deep embedding
  - CLL rules + proofs-as-processes translations
- Theory + automation of reasoning for multisets
  - No need for Exchange rule:

$$\frac{\vdash \mathrm{A}, B, \Gamma, \Delta}{\vdash \mathrm{A}, \Gamma, B, \Delta}\, Exchange$$

- Metavariables
  - Construction of π-calculus translations
  - Synthesis of exceptions

Implementation: Details

- HOL Light – flexible, programmable
- Isabelle Light – procedural proofs, metavariables

CLL

- Inspired by Power et al. (1999) and Sadrzadeh (2003)
- Conservative
- Combined inference rules – proofs-as-processes

π-calculus

- Based on Melham (1992)
- Syntax (polymorphic type)
- Substitution
- A few functions

Implementation: π-calculus

P ::=	**define_type (A) Agent =**
| 0	Zero
| x(y).P	| In A (A list) Agent
| x<y>.P	| Out A (A list) Agent
| (ν x) P	| Res (A list) Agent
| P || P	| Comp Agent Agent
| P + P	| Plus Agent Agent

Implementation: CLL

CLL connective	HOL Light definition	HOL Light syntax
!	`OfCourse`	`!!`
?	`WhyNot`	`??`
$\otimes$	`LinTimes`	`**`
$\parr$	`LinPar`	`%`
$\oplus$	`LinPlus`	`++`
&	`LinWith`	`&`

Implementation: Proofs-as-processes

$$\frac{\vdash P :: \vec{w}:\Gamma,\ x:A \qquad \vdash Q :: \vec{u}:\Delta,\ y:B}{\vdash \nu xy(\overline{z}\langle xy\rangle(P_{\vec{w}x} \,||\, Q_{\vec{u}y})) :: \vec{w}:\Gamma,\ \vec{u}:\Delta,\ z:A \otimes B}\ \otimes$$

```
!x y z P Q A B Gamma Delta.
 |-- (Gamma ^ ' (A <> x)) P /\ |-- (Delta ^ ' (B <> y)) Q ==>
  |-- (Gamma ^ Delta ^ ' ((A ** B) <> z)) (Res [x;y] (Out z [x;y] (Comp P Q)))
```

Future Work

- Translation:
  - From OWL-S/BPEL4WS to CLL.
  - From π-calculus to OWL-S/BPEL4WS.
- Automation
  - External + internal tools
- Further Evaluation
  - Already a case-study involving 10 WS - real-estate domain
  - More examples
- Embedding
  - Modalities

Conclusion

- Formally verified Web Services composition.
  - Based on the proofs-as-processes paradigm.
  - Using CLL + π-calculus.
  - Implemented in HOL Light
- Rao's Ski example

- Contribution:
  - Web Services community: Rigorous WS composition
  - Theorem Proving community: Framework for theoretical investigation
- Much room for further development.