Concurrency: Theory, Languages and Programming

– Equivalences for CCS –

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Uwe Nestmann

EPFL-LAMP

Bisimulation on CCS

- check out Session 4, again
- add 1+1 . . .

"Algebraic" Properties (I)

- $\beta.P + \beta.P + M \sim \beta.P + M$
- $(\boldsymbol{\nu} a)\, a.P \sim \mathbf{0}$
- $(\boldsymbol{\nu} a)\, \overline{a}.P \sim \mathbf{0}$
- $(\boldsymbol{\nu} c)\,(\ a.c.P \mid b.\overline{c}.Q\ ) \sim (\boldsymbol{\nu} c)\,(\ a.c.Q \mid b.\overline{c}.P\ )$
- $\ldots$
- Why *algebraic* ?

"Algebraic" Properties (II)

- $a \mid b \sim a.b + b.a$

- For all $P \in \mathcal{P}$, $P \sim \sum\{\ \beta.Q \mid P \xrightarrow{\beta} Q\ \}$.

- For all $n \geq 0$ and $P_1, \ldots, P_n \in \mathcal{P}$:

$$P_1 | \cdots | P_n \sim \left\{ \begin{array}{l} + \\ \\ \\ \\ \\ \\ \\ \end{array} \right. \begin{array}{l} \sum\{\ \beta.(\ P_1 | \cdots | P_i' | \cdots | P_n\ ) \\ \qquad \mid 1 \leq i \leq n, P_i \xrightarrow{\beta} P_i'\ \} \\ \\ \sum\{\ \tau.(\ P_1 | \cdots | P_i' | \cdots | P_j' | \cdots | P_n\ ) \\ \qquad \mid 1 \leq i < j \leq n, P_i \xrightarrow{\lambda} P_i', P_j \xrightarrow{\overline{\lambda}} P_j'\ \} \end{array}$$

"Algebraic" Properties (III)

For all $n \geq 0$, $P_1, \ldots, P_n \in \mathcal{P}$, and $\vec{a}$:

$$(\boldsymbol{\nu}\vec{a})\,(\ P_1|\cdots|P_n\ ) \sim \left\{ + \right.$$

$$\sum\{\ \beta.(\boldsymbol{\nu}\vec{a})\,(\ P_1|\cdots|P_i'|\cdots|P_n\ )$$
$$\quad |\ 1{\leq}i{\leq}n, P_i \xrightarrow{\beta} P_i',\ \text{and}\ \beta, \overline{\beta} \notin \vec{a}\ \}$$

$$\sum\{\ \tau.(\boldsymbol{\nu}\vec{a})\,(\ P_1|\cdots|P_i'|\cdots|P_j'|\cdots|P_n\ )$$
$$\quad |\ 1{\leq}i{<}j{\leq}n, P_i \xrightarrow{\lambda} P_i', P_j \xrightarrow{\overline{\lambda}} P_j'\ \}$$

Expansion Law ! (also called: *Interleaving*)
Compare to the notions of *standard forms* in Milner's book:
every process term can be transformed into a form
that matches the left-hand side of the above equation.

Process Contexts

Definition:A **process context** $C[\cdot]$ is (precisely) defined by the following syntax:

$$\begin{array}{rcccccc} C[\cdot] & ::= & [\cdot] & \mid & \alpha.C[\cdot] + M & \mid & M + \alpha.C[\cdot] \\ & \mid & (\boldsymbol{\nu} a)\, C[\cdot] & \mid & C[\cdot]|P & \mid & P|C[\cdot] \end{array}$$

The **elementary contexts** are

$\alpha.[\cdot] + M$, $M + \alpha.[\cdot]$, $(\boldsymbol{\nu} a)\,[\cdot]$, $[\cdot]|P$, $P|[\cdot]$.

$C[Q]$ denotes the result of filling the hole $[\cdot]$ of $C[\cdot]$ with process Q.

Process congruence

Definition:(Process congruence)
Let $\cong$ be an *equivalence relation* over $\mathcal{P}$.

Then $\cong$ is said to be a ***process congruence***, if
for *all* contexts $C[\cdot]$,
$P \cong Q$ implies $C[P] \cong C[Q]$.

Process congruence (II)

Proposition:

An arbitrary equivalence relation $\cong$ is a process congruence if, and only if, it is preserved by all *elementary contexts*; i.e., if $P \cong Q$, then

$$\begin{array}{lcllcl} \alpha.P + M & \cong & \alpha.Q + M & \qquad P|R & \cong & Q|R \\ M + \alpha.P & \cong & M + \alpha.Q & \qquad R|P & \cong & R|Q \end{array}$$

$$(\boldsymbol{\nu} a)\, P \;\cong\; (\boldsymbol{\nu} a)\, Q \;\; .$$

Note:

For proving that an equivalence relation is a congruence, the elementary contexts suffice.

Congruence Properties

Proposition:

Bisimilarity is a process congruence, i.e., . . .

Towards Observation Equivalence

Let us assume that our LTSs may dispose of a single distinguished *internal action* symbol, say: τ, as is the case for our language of concurrent process expressions. Then:

"Different internal behavior" should "not count" !

Definition:(observations / weak actions)

1. $\Rightarrow \stackrel{\text{def}}{=} \stackrel{\tau}{\longrightarrow}^*$
2. $\stackrel{\lambda}{\Longrightarrow} \stackrel{\text{def}}{=} \Rightarrow \stackrel{\lambda}{\longrightarrow} \Rightarrow$

Weak Simulation

Definition:

$\mathcal{S}$ is a weak simulation **iff**, whenever $P \; \mathcal{S} \; Q$,

- if $P \xrightarrow{\tau} P'$ then there is $Q' \in \mathcal{P}$ such that $Q \Rightarrow Q'$ and $P' \; \mathcal{S} \; Q'$.
- if $P \xrightarrow{\lambda} P'$ then there is $Q' \in \mathcal{P}$ such that $Q \stackrel{\lambda}{\Rightarrow} Q'$ and $P' \; \mathcal{S} \; Q'$.

q **weakly simulates** p,
if there is a weak simulation $\mathcal{S}$ such that $p \; \mathcal{S} \; q$.

Example:

Prove that $Q = \tau.a.\tau.b.Q$ weakly simulates $P = a.b.P$.
Prove that $P = a.b.P$ weakly simulates $Q = \tau.a.\tau.b.Q$.

Weak Bisimulation

Definition:(* straightforward / should be no surprise *)
A binary relation $\mathcal{B}$ is *a* **weak bisimulation**
if both $\mathcal{B}$ and its converse $\mathcal{B}^{-1}$ are weak simulations.

P and Q are **weakly bisimilar**, **weakly equivalent**, or **observation equivalent**, written $P \approx Q$,
if there exists a weak bisimulation $\mathcal{B}$ with $P \; \mathcal{B} \; Q$.

Alternatively:

$$\approx \stackrel{\text{def}}{=} \bigcup \{ \; \mathcal{B} \mid \mathcal{B} \text{ is weak bisimulation} \; \}$$

Proposition:

1. $\approx$ is itself a weak bisimulation.
2. $\approx$ is an equivalence relation.

Strong vs Weak

1. every strong simulation is also a weak one
2. $P \sim Q$ implies $P \approx Q$

Examples ?

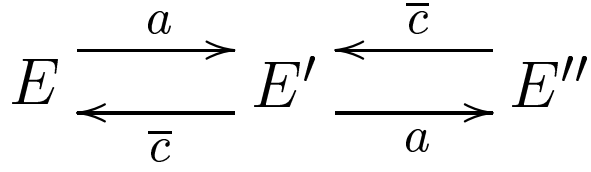
Proof ?

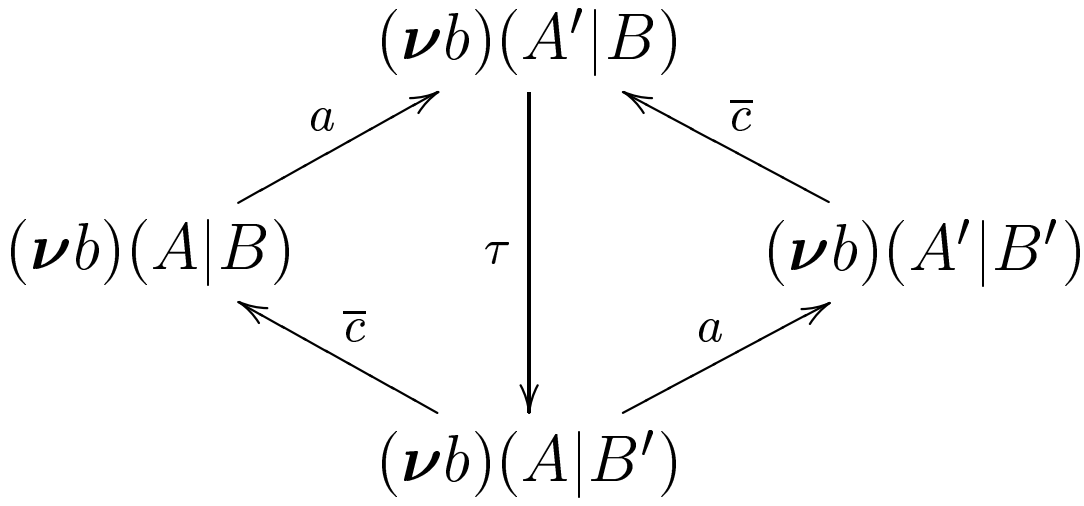
Example

$$
\begin{array}{lcll}
A & \stackrel{\text{def}}{=} & a.A' & (= a.\overline{b}.A) \\
A' & \stackrel{\text{def}}{=} & \overline{b}.A & \\
B & \stackrel{\text{def}}{=} & b.B' & (= b.\overline{c}.B) \\
B' & \stackrel{\text{def}}{=} & \overline{c}.B &
\end{array}
$$

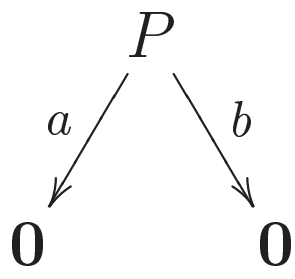
$$
\begin{array}{lcl}
E & \stackrel{\text{def}}{=} & a.E' \\
E' & \stackrel{\text{def}}{=} & a.E'' + \overline{c}.E \\
E'' & \stackrel{\text{def}}{=} & \overline{c}.E'
\end{array}
$$

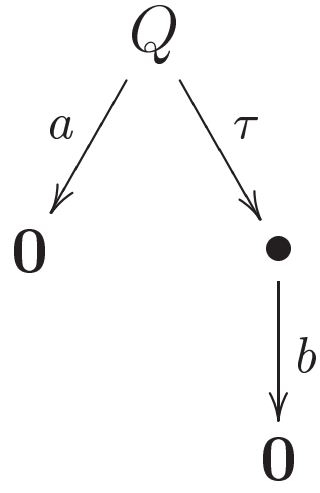
Prove that $(\boldsymbol{\nu} b)(A|B) \approx E$.

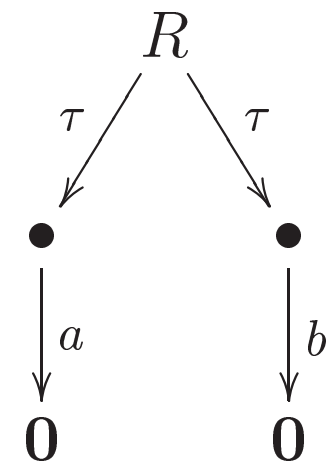




Some Inequivalences

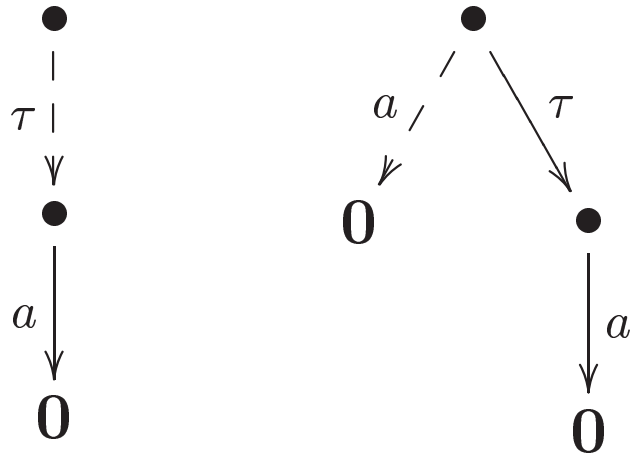






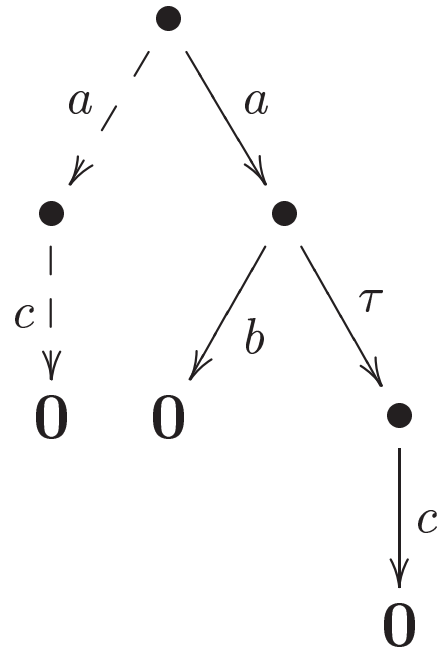
$P = a + b$ $Q = a + \tau.b$ $R = \tau.a + \tau.b$

Some Equivalences



$\tau.a \approx a$

$a + \tau.a \approx \tau.a$



$$a.c + a.(b + \tau.c) \approx a.(b + \tau.c)$$

Some Equations

Theorem:

Let P be any process.

Let N, M any summations. Then:

1. $P \approx \tau.P$
2. $M + N + \tau.N \approx M + \tau.N$
3. $M + \alpha.P + \alpha(\tau.P + N) \approx M + \alpha(\tau.P + N)$

Congruence Properties

Proposition:

Weak bisimilarity is a process congruence, i.e., . . .

Example:

- Observe $b \approx \tau.b$!
- Let $C[\cdot] = a + [\cdot]$.

  Compare $C[b] = \boxed{a + b \stackrel{?}{\approx} a + \tau.b} = C[\tau.b]$!

Two-Place Buffers

$\mathsf{Buff}_s^{(1)}(\,\vec{a}\,)$	:	1-place buffer containing s, where $\vec{a} = \{\mathsf{in}, \mathsf{out}\}$
$\mathsf{Buff}_\epsilon^{(1)}(\,\vec{a}\,)$	$\stackrel{\text{def}}{=}$	$\mathsf{in}(x).\mathsf{Buff}_x^{(1)}\langle\,\vec{a}\,\rangle$
$\mathsf{Buff}_v^{(1)}(\,\vec{a}\,)$	$\stackrel{\text{def}}{=}$	$\overline{\mathsf{out}}\langle v\rangle.\mathsf{Buff}_\epsilon^{(1)}\langle\,\vec{a}\,\rangle$
$\mathsf{Buff}_s^{(2)}(\,\vec{a}\,)$	:	2-place buffer containing s — SPECIFICATION
$\mathsf{Buff}_\epsilon^{(2)}(\,\vec{a}\,)$	$\stackrel{\text{def}}{=}$	$\mathsf{in}(x).\mathsf{Buff}_x^{(2)}\langle\,\vec{a}\,\rangle$
$\mathsf{Buff}_v^{(2)}(\,\vec{a}\,)$	$\stackrel{\text{def}}{=}$	$\overline{\mathsf{out}}\langle v\rangle.\mathsf{Buff}_\epsilon^{(2)}\langle\,\vec{a}\,\rangle + \mathsf{in}(w).\mathsf{Buff}_{wv}^{(2)}\langle\,\vec{a}\,\rangle$
$\mathsf{Buff}_{wv}^{(2)}(\,\vec{a}\,)$	$\stackrel{\text{def}}{=}$	$\overline{\mathsf{out}}\langle w\rangle.\mathsf{Buff}_v^{(2)}\langle\,\vec{a}\,\rangle$
$\mathsf{Bluff}_s^{(2)}(\,\vec{a}\,)$	:	2-place buffer containing s — IMPLEMENTATION
$\mathsf{Bluff}_\epsilon^{(2)}(\,\vec{a}\,)$	$\stackrel{\text{def}}{=}$	$(\boldsymbol{\nu}\mathsf{x})\left(\,\mathsf{Buff}^{(1)}\langle\,\mathsf{in},\mathsf{x}\,\rangle \mid \mathsf{Buff}^{(1)}\langle\,\mathsf{x},\mathsf{out}\,\rangle\,\right)$

□ prove that $\mathsf{Buff}_\epsilon^{(2)}\langle\,\vec{a}\,\rangle \approx \mathsf{Bluff}_\epsilon^{(2)}\langle\,\vec{a}\,\rangle$

Unique Solution of Equations

Theorem:

Let $\vec{X} = X_1, X_2, \ldots$ be a (possibly infinite) sequence of process variables. In the equations

$$\begin{array}{lcl} X_1 & \approx & \alpha_{11}.X_{k(11)} + \cdots + \alpha_{1n_1}.X_{k(1n_1)} \\ X_2 & \approx & \alpha_{21}.X_{k(11)} + \cdots + \alpha_{2n_1}.X_{k(2n_1)} \\ \ldots & \approx & \ldots \end{array}$$

assume that $\alpha_{ij} \neq \tau$. Then, up to $\approx$, there is a unique sequence $P_1, P_2, \ldots$ of processes which satisfies the equations.