Concurrency Theory

Winter Semester 2019/20

Lecture 10: Variations of π-Calculus

Joost-Pieter Katoen and Thomas Noll
Software Modeling and Verification Group
RWTH Aachen University

https://moves.rwth-aachen.de/teaching/ws-19-20/ct/

Software Modeling and Verification Chair | RWTH AACHEN UNIVERSITY

Outline of Lecture 10

Syntax of the Monadic π-Calculus

Definition (Syntax of monadic π-Calculus)

- Let $A = \{a, b, c \ldots, x, y, z, \ldots\}$ be a set of names.
- The set of action prefixes is given by

$$\begin{aligned} \pi ::= {} & x(y) && \text{(receive } y \text{ along } x\text{)} \\ \mid {} & \overline{x}\langle y \rangle && \text{(send } y \text{ along } x\text{)} \\ \mid {} & \tau && \text{(unobservable action)} \end{aligned}$$

- The set Prc^π of π-Calculus process expressions is defined by the following syntax:

$$\begin{aligned} P ::= {} & \textstyle\sum_{i \in I} \pi_i.P_i && \text{(guarded sum)} \\ \mid {} & P_1 \parallel P_2 && \text{(parallel composition)} \\ \mid {} & \mathsf{new}\, x\, P && \text{(restriction)} \\ \mid {} & !P && \text{(replication)} \end{aligned}$$

(where I finite index set, $x \in A$)

Conventions: $\mathsf{nil} := \sum_{i \in \emptyset} \pi_i.P_i$, $\mathsf{new}\, x_1, \ldots, x_n\, P := \mathsf{new}\, x_1\, (\ldots \mathsf{new}\, x_n\, P)$

Structural Congruence

Goal: simplify definition of operational semantics by ignoring "purely syntactic" differences between processes

Definition (Structural congruence)

$P, Q \in Prc^\pi$ are structurally congruent, written $P \equiv Q$, if one can be transformed into the other by applying the following operations and equations:

1. renaming of bound names (α-conversion)
2. reordering of terms in a summation (commutativity of $+$)
3. $P \parallel Q \equiv Q \parallel P$, $P \parallel (Q \parallel R) \equiv (P \parallel Q) \parallel R$, $P \parallel \mathrm{nil} \equiv P$ (Abelian monoid laws for $\parallel$)
4. $\mathrm{new}\, x\, \mathrm{nil} \equiv \mathrm{nil}$, $\mathrm{new}\, x, y\, P \equiv \mathrm{new}\, y, x\, P$,
   $P \parallel \mathrm{new}\, x\, Q \equiv \mathrm{new}\, x\, (P \parallel Q)$ if $x \notin fn(P)$ (scope extension)
5. $!P \equiv P \parallel !P$ (unfolding)

A Standard Form

Theorem (Standard form)

Every process expression is structurally congruent to a process of the standard form

$$\text{new } x_1, \ldots, x_k \, (P_1 \parallel \ldots \parallel P_m \parallel !Q_1 \parallel \ldots \parallel !Q_n)$$

where each P_i is a non-empty sum, and each Q_j is in standard form.

(If $m = n = 0$: nil; if $k = 0$: restriction absent)

Proof.

by induction on the structure of $R \in Prc^\pi$ (on the board) □

The Reaction Relation

Thanks to Theorem 8.7, only processes in standard form need to be considered for defining the operational semantics:

Definition

The reaction relation $\longrightarrow \subseteq Prc^\pi \times Prc^\pi$ is generated by the rules:

$$\text{(Tau)}\frac{}{\tau.P + Q \longrightarrow P}$$

$$\text{(React)}\frac{}{(x(y).P + R) \parallel (\overline{x}\langle z\rangle.Q + S) \longrightarrow P[z/y] \parallel Q}$$

$$\text{(Par)}\frac{P \longrightarrow P'}{P \parallel Q \longrightarrow P' \parallel Q} \qquad \text{(Res)}\frac{P \to P'}{\text{new } x\, P \longrightarrow \text{new } x\, P'}$$

$$\text{(Struct)}\frac{P \longrightarrow P'}{Q \longrightarrow Q'} \quad \text{if } P \equiv Q \text{ and } P' \equiv Q'$$

- $P[z/y]$ replaces every free occurrence of y in P by z.
- In (React), the pair $(x(y), \overline{x}\langle z\rangle)$ is called a redex.

Outline of Lecture 10

Recap: The Monadic π-Calculus

The Polyadic π-Calculus

Adding Recursive Process Calls

The Asynchronous π-Calculus

Polyadic Communication I

- **So far:** messages with exactly one name
- **Now:** arbitrary number

Polyadic Communication I

- **So far:** messages with exactly one name
- **Now:** arbitrary number
- New types of action prefixes:

$$x(y_1, \ldots, y_n) \qquad \text{and} \qquad \overline{x}\langle z_1, \ldots, z_n\rangle$$

where $n \in \mathbb{N}$ and all y_i distinct

Polyadic Communication I

- **So far:** messages with exactly one name
- **Now:** arbitrary number
- New types of action prefixes:

$$x(y_1, \ldots, y_n) \qquad \text{and} \qquad \overline{x}\langle z_1, \ldots, z_n\rangle$$

  where $n \in \mathbb{N}$ and all y_i distinct
- Expected behaviour (cf. Example 9.2):

$$\text{(React')}\frac{}{(x(\vec{y}).P + R) \parallel (\overline{x}\langle\vec{z}\rangle.Q + S) \longrightarrow P[\vec{z}/\vec{y}] \parallel Q}$$

Polyadic Communication I

- **So far:** messages with exactly one name
- **Now:** arbitrary number
- New types of action prefixes:

$$x(y_1, \ldots, y_n) \qquad \text{and} \qquad \overline{x}\langle z_1, \ldots, z_n\rangle$$

  where $n \in \mathbb{N}$ and all y_i distinct
- Expected behaviour (cf. Example 9.2):

$$\text{(React')}\frac{}{(x(\vec{y}).P + R) \parallel (\overline{x}\langle\vec{z}\rangle.Q + S) \longrightarrow P[\vec{z}/\vec{y}] \parallel Q}$$

- Obvious attempt for encoding:

$$x(y_1, \ldots, y_n).P \mapsto x(y_1) \ldots x(y_n).P$$
$$\overline{x}\langle z_1, \ldots, z_n\rangle.Q \mapsto \overline{x}\langle z_1\rangle \ldots \overline{x}\langle z_n\rangle.Q$$

Polyadic Communication II

- But consider the following counterexample.

  Polyadic representation: $x(y_1, y_2).P \parallel \overline{x}\langle z_1, z_2\rangle.Q \parallel \overline{x}\langle z'_1, z'_2\rangle.Q'$

$$\swarrow \quad \searrow$$

$$P[z_1/y_1, z_2/y_2] \parallel Q \parallel \overline{x}\langle z'_1, z'_2\rangle.Q' \qquad P[z'_1/y_1, z'_2/y_2] \parallel \overline{x}\langle z_1, z_2\rangle.Q \parallel Q'$$

Polyadic Communication II

- But consider the following counterexample.

Polyadic representation: $x(y_1, y_2).P \parallel \overline{x}\langle z_1, z_2\rangle.Q \parallel \overline{x}\langle z'_1, z'_2\rangle.Q'$

$$\swarrow \quad \searrow$$

$$P[z_1/y_1, z_2/y_2] \parallel Q \parallel \overline{x}\langle z'_1, z'_2\rangle.Q' \qquad P[z'_1/y_1, z'_2/y_2] \parallel \overline{x}\langle z_1, z_2\rangle.Q \parallel Q'$$

Monadic encoding: $P[z_1/y_1, z_2/y_2] \parallel \ldots$ ✓ $\qquad P[z'_1/y_1, z'_2/y_2] \parallel \ldots$ ✓

$$\nwarrow^{2} \qquad \nearrow^{2}$$

$$x(y_1).x(y_2).P \parallel \overline{x}\langle z_1\rangle.\overline{x}\langle z_2\rangle.Q \parallel \overline{x}\langle z'_1\rangle.\overline{x}\langle z'_2\rangle.Q'$$

$$\swarrow^{2} \qquad \searrow^{2}$$

$$P[z_1/y_1, z'_1/y_2] \parallel \ldots \ \lightning \qquad P[z'_1/y_1, z_1/y_2] \parallel \ldots \ \lightning$$

Polyadic Communication II

- But consider the following counterexample.

  Polyadic representation: $x(y_1, y_2).P \parallel \overline{x}\langle z_1, z_2\rangle.Q \parallel \overline{x}\langle z'_1, z'_2\rangle.Q'$

  $$\swarrow \quad \searrow$$

  $$P[z_1/y_1, z_2/y_2] \parallel Q \parallel \overline{x}\langle z'_1, z'_2\rangle.Q' \qquad P[z'_1/y_1, z'_2/y_2] \parallel \overline{x}\langle z_1, z_2\rangle.Q \parallel Q'$$

  Monadic encoding: $P[z_1/y_1, z_2/y_2] \parallel \ldots \ \checkmark \qquad P[z'_1/y_1, z'_2/y_2] \parallel \ldots \ \checkmark$

  $$\nwarrow 2 \qquad \nearrow 2$$

  $$x(y_1).x(y_2).P \parallel \overline{x}\langle z_1\rangle.\overline{x}\langle z_2\rangle.Q \parallel \overline{x}\langle z'_1\rangle.\overline{x}\langle z'_2\rangle.Q'$$

  $$\swarrow 2 \qquad \searrow 2$$

  $$P[z_1/y_1, z'_1/y_2] \parallel \ldots \ \lightning \qquad P[z'_1/y_1, z_1/y_2] \parallel \ldots \ \lightning$$

- **Solution:** avoid interferences by first introducing a fresh communication channel:

  $$x(y_1, \ldots, y_n).P \mapsto x(w).w(y_1)\ldots w(y_n).P$$
  $$\overline{x}\langle z_1, \ldots, z_n\rangle.Q \mapsto \text{new } w\,(\overline{x}\langle w\rangle.\overline{w}\langle z_1\rangle \ldots \overline{w}\langle z_n\rangle.Q)$$

  where $w \notin fn(Q) \cup \{y_1, \ldots, y_n, z_1, \ldots, z_n\}$

Polyadic Communication II

- But consider the following counterexample.

  Polyadic representation: $x(y_1, y_2).P \parallel \overline{x}\langle z_1, z_2\rangle.Q \parallel \overline{x}\langle z'_1, z'_2\rangle.Q'$

  $$\swarrow \quad \searrow$$

  $$P[z_1/y_1, z_2/y_2] \parallel Q \parallel \overline{x}\langle z'_1, z'_2\rangle.Q' \qquad P[z'_1/y_1, z'_2/y_2] \parallel \overline{x}\langle z_1, z_2\rangle.Q \parallel Q'$$

  Monadic encoding: $P[z_1/y_1, z_2/y_2] \parallel \ldots$ ✓ $\qquad P[z'_1/y_1, z'_2/y_2] \parallel \ldots$ ✓

  $$\nwarrow 2 \qquad \nearrow 2$$

  $$x(y_1).x(y_2).P \parallel \overline{x}\langle z_1\rangle.\overline{x}\langle z_2\rangle.Q \parallel \overline{x}\langle z'_1\rangle.\overline{x}\langle z'_2\rangle.Q'$$

  $$\swarrow 2 \qquad \searrow 2$$

  $$P[z_1/y_1, z'_1/y_2] \parallel \ldots \;\lightning \qquad P[z'_1/y_1, z_1/y_2] \parallel \ldots \;\lightning$$

- **Solution:** avoid interferences by first introducing a fresh communication channel:

  $$x(y_1, \ldots, y_n).P \mapsto x(w).w(y_1)\ldots w(y_n).P$$
  $$\overline{x}\langle z_1, \ldots, z_n\rangle.Q \mapsto \text{new } w\,(\overline{x}\langle w\rangle.\overline{w}\langle z_1\rangle \ldots \overline{w}\langle z_n\rangle.Q)$$

  where $w \notin fn(Q) \cup \{y_1, \ldots, y_n, z_1, \ldots, z_n\}$
- **Correctness:** see exercises

Outline of Lecture 10

Recursive Process Calls I

- **So far:** process replication $!P$
- **Now:** parametric process definitions of the form

$$A(x_1, \dots, x_n) = P_A$$

  where $A \in Pid$ is a process identifier and $P_A \in Prc^\pi$ a process expression containing calls of A (and possibly other parametric processes)

Recursive Process Calls I

- **So far:** process replication $!P$
- **Now:** parametric process definitions of the form

$$A(x_1, \ldots, x_n) = P_A$$

  where $A \in Pid$ is a process identifier and $P_A \in Prc^\pi$ a process expression containing calls of A (and possibly other parametric processes)
- Semantic interpretation by new congruence rule (cf. Example 9.2):

$$A(y_1, \ldots, y_n) \equiv P_A[y_1/x_1, \ldots, y_n/x_n]$$

Recursive Process Calls I

- **So far:** process replication $!P$
- **Now:** parametric process definitions of the form

$$A(x_1, \dots, x_n) = P_A$$

  where $A \in Pid$ is a process identifier and $P_A \in Prc^\pi$ a process expression containing calls of A (and possibly other parametric processes)
- Semantic interpretation by new congruence rule (cf. Example 9.2):

$$A(y_1, \dots, y_n) \equiv P_A[y_1/x_1, \dots, y_n/x_n]$$

- Again: possible to simulate in basic calculus by using
  - message passing to model parameter passing to A
  - replication to model the multiple activations of A
  - restriction to model the scope of the definition of A

Recursive Process Calls II

The encoding

- of a process definition $A(\vec{x}) = P_A$
- with right-hand side $P_A = \ldots A(\vec{u}) \ldots A(\vec{v}) \ldots \in Prc^\pi$
- for main process $Q = \ldots A(\vec{y}) \ldots A(\vec{z}) \ldots \in Prc^\pi$

is defined as follows:

Recursive Process Calls II

The encoding

- of a process definition $A(\vec{x}) = P_A$
- with right-hand side $P_A = \ldots A(\vec{u}) \ldots A(\vec{v}) \ldots \in Prc^\pi$
- for main process $Q = \ldots A(\vec{y}) \ldots A(\vec{z}) \ldots \in Prc^\pi$

is defined as follows:

1. Let $a \in A$ be a new name (standing for A).
2. For any process R, let $\hat{R}$ be the result of replacing every call $A(\vec{w})$ by $\overline{a}\langle\vec{w}\rangle.\mathrm{nil}$.
3. Replace Q by $Q' := \mathrm{new}\, a\, (\hat{Q} \parallel !a(\vec{x}).\hat{P}_A)$.

(In the presence of more than one process identifier, Q' will contain a replicated component for each definition.)

Recursive Process Calls II

The encoding

- of a process definition $A(\vec{x}) = P_A$
- with right-hand side $P_A = \ldots A(\vec{u}) \ldots A(\vec{v}) \ldots \in Prc^\pi$
- for main process $Q = \ldots A(\vec{y}) \ldots A(\vec{z}) \ldots \in Prc^\pi$

is defined as follows:

1. Let $a \in A$ be a new name (standing for A).
2. For any process R, let $\hat{R}$ be the result of replacing every call $A(\vec{w})$ by $\overline{a}\langle\vec{w}\rangle$.nil.
3. Replace Q by $Q' := \text{new}\, a\,(\hat{Q} \parallel !a(\vec{x}).\hat{P}_A)$.

(In the presence of more than one process identifier, Q' will contain a replicated component for each definition.)

Example 10.1

- One-place buffer: $B(in, out) = in(x).\overline{out}\langle x\rangle.B(in, out)$
- Main process: $Q := \overline{in}\langle y\rangle.\text{nil} \parallel B(in, out) \parallel out(z).\text{nil}$

(encoding on the board)

Outline of Lecture 10

Asynchronous Communication

- So far: CCS and π-Calculus feature synchronous communication: interaction involves joint participation of processes ("handshaking")
- Prefix operator expresses temporal precedence:
  - $\overline{x}\langle y\rangle.P$ requires y to be sent before executing P
  - $x(z).Q$ requires (of course) z to be received before executing Q

Asynchronous Communication

- So far: CCS and π-Calculus feature synchronous communication: interaction involves joint participation of processes ("handshaking")
- Prefix operator expresses temporal precedence:
  - $\overline{x}\langle y \rangle.P$ requires y to be sent before executing P
  - $x(z).Q$ requires (of course) z to be received before executing Q
- But: many concurrent (especially distributed) systems use asynchronous communication where sending and receiving are separated: sender can continue before actual reception
- Often involves explicit medium of certain characteristic
  - bounded or unbounded capacity
  - preserving sending order or not

Asynchronous Communication

- So far: CCS and π-Calculus feature synchronous communication: interaction involves joint participation of processes ("handshaking")
- Prefix operator expresses temporal precedence:
  - $\overline{x}\langle y\rangle.P$ requires y to be sent before executing P
  - $x(z).Q$ requires (of course) z to be received before executing Q
- But: many concurrent (especially distributed) systems use asynchronous communication where sending and receiving are separated: sender can continue before actual reception
- Often involves explicit medium of certain characteristic
  - bounded or unbounded capacity
  - preserving sending order or not
- Now: introduce subcalculus of π-Calculus with asynchronous communication
- "Trick": output prefix can only be followed by nil
  - (unguarded) subprocess $\overline{x}\langle y\rangle.\mathrm{nil}$ ("output particle") can be understood as message y in (implicit) communication medium
  - available for reception to any (unguarded) subprocess of the form $x(z).Q$
  - y is sent when $\overline{x}\langle y\rangle.\mathrm{nil}$ becomes unguarded
  - y is received when $\overline{x}\langle y\rangle.\mathrm{nil}$ disappears via reaction $\overline{x}\langle y\rangle.\mathrm{nil} \parallel (x(z).Q + R) \longrightarrow Q[y/z]$

$\Rightarrow$ syntactic modification sufficient, no change of semantics

The Asynchronous π-Calculus I

Definition 10.2 (Syntax of asynchronous π-Calculus)

- Let $A = \{a, b, c \ldots, x, y, z, \ldots\}$ be a set of names.

The Asynchronous π-Calculus I

Definition 10.2 (Syntax of asynchronous π-Calculus)

- Let $A = \{a, b, c \ldots, x, y, z, \ldots\}$ be a set of names.
- The set of action prefixes is given by

$$\begin{aligned} \pi ::= &\ x(y) && \text{(receive } y \text{ along } x\text{)} \\ \mid &\ \tau && \text{(unobservable action)} \end{aligned}$$

The Asynchronous π-Calculus I

Definition 10.2 (Syntax of asynchronous π-Calculus)

- Let $A = \{a, b, c \ldots, x, y, z, \ldots\}$ be a set of names.
- The set of action prefixes is given by

$$
\begin{aligned}
\pi ::= \; & x(y) && \text{(receive } y \text{ along } x\text{)} \\
\mid \; & \tau && \text{(unobservable action)}
\end{aligned}
$$

- The set $Prc^{a\pi}$ of asynchronous π-Calculus process expressions is defined by the following syntax:

$$
\begin{aligned}
P ::= \; & \textstyle\sum_{i \in I} \pi_i . P_i && \text{(guarded sum)} \\
\mid \; & \overline{x}\langle y \rangle.\text{nil} && \text{(asynchronous output)} \\
\mid \; & P_1 \parallel P_2 && \text{(parallel composition)} \\
\mid \; & \text{new}\, x\, P && \text{(restriction)} \\
\mid \; & !P && \text{(replication)}
\end{aligned}
$$

(where I finite index set, $x, y \in A$)

The Asynchronous π-Calculus II

- As $Prc^{a\pi} \subseteq Prc^{\pi}$, the semantics of the asynchronous π-Calculus does not have to be defined explicitly

The Asynchronous π-Calculus II

- As $Prc^{a\pi} \subseteq Prc^{\pi}$, the semantics of the asynchronous π-Calculus does not have to be defined explicitly
- $Prc^{a\pi}$ actually imposes two restrictions:
  - output particles can only be followed by nil (as discussed before)
  - output particles cannot be summands in an expression $\sum_{i \in I} \pi_i.P_i$ where $|I| > 1$

The Asynchronous π-Calculus II

- As $Prc^{a\pi} \subseteq Prc^{\pi}$, the semantics of the asynchronous π-Calculus does not have to be defined explicitly
- $Prc^{a\pi}$ actually imposes two restrictions:
  - output particles can only be followed by nil (as discussed before)
  - output particles cannot be summands in an expression $\sum_{i \in I} \pi_i.P_i$ where $|I| > 1$
- Second restriction also in line with asynchronous communication:
  - (unguarded) particle $\overline{x}\langle y \rangle.\mathrm{nil}$ represents message that *has been* sent
  - process $\overline{x}\langle y \rangle.\mathrm{nil} + v(w).Q$ is *capable* of sending via x, but also capable of receiving via v (which disables sending)
  - thus: correspondence between sent (but unreceived) message and presence of (unguarded) output particle would get lost

Encoding Synchronous Communication

- Synchronous communication: sender only allowed to continue if message has been received

Encoding Synchronous Communication

- Synchronous communication: sender only allowed to continue if message has been received
- Usual asynchronous implementation: enforce synchronous behaviour by two asynchronous communication operations
  - sending of actual data
  - waiting for acknowledgement

Encoding Synchronous Communication

- Synchronous communication: sender only allowed to continue if message has been received
- Usual asynchronous implementation: enforce synchronous behaviour by two asynchronous communication operations
  - sending of actual data
  - waiting for acknowledgement
- Here: encoding carried out in two steps
  1. encoding (monadic) synchronous by polyadic asynchronous communication
  2. encoding polyadic asynchronous by monadic asynchronous communication

Encoding Synchronous by Polyadic Asynchronous Communication

- **Encoding:**
  - sending: $\overline{x}\langle y\rangle.P \mapsto \text{new}\ v\ (\overline{x}\langle y, v\rangle.\text{nil} \parallel v().P)$
  - receiving: $x(z).Q \mapsto x(z, v).(\overline{v}\langle\rangle.\text{nil} \parallel Q)$

  where $v \notin fn(P) \cup fn(Q) \cup \{x, y\}$ (“acknowledgement channel”)

Software Modeling and Verification Chair

RWTH AACHEN UNIVERSITY

Encoding Synchronous by Polyadic Asynchronous Communication

- **Encoding:**
  - sending: $\overline{x}\langle y\rangle.P \mapsto \text{new } v\,(\overline{x}\langle y, v\rangle.\text{nil} \parallel v().P)$
  - receiving: $x(z).Q \mapsto x(z, v).(\overline{v}\langle\rangle.\text{nil} \parallel Q)$

  where $v \notin fn(P) \cup fn(Q) \cup \{x, y\}$ ("acknowledgement channel")
- **Correctness:** synchronous transition

$$\overline{x}\langle y\rangle.P \parallel x(z).Q \longrightarrow P \parallel Q[y/z]$$

Encoding Synchronous by Polyadic Asynchronous Communication

- **Encoding:**
  - sending: $\overline{x}\langle y\rangle.P \mapsto \text{new}\, v\, (\overline{x}\langle y, v\rangle.\text{nil} \parallel v().P)$
  - receiving: $x(z).Q \mapsto x(z, v).(\overline{v}\langle\rangle.\text{nil} \parallel Q)$

  where $v \notin fn(P) \cup fn(Q) \cup \{x, y\}$ (“acknowledgement channel”)
- **Correctness:** synchronous transition

$$\overline{x}\langle y\rangle.P \parallel x(z).Q \longrightarrow P \parallel Q[y/z]$$

  is mimicked by polyadic asynchronous transition sequence

$$\text{new}\, v\, (\overline{x}\langle y, v\rangle.\text{nil} \parallel v().P) \parallel x(z, v).(\overline{v}\langle\rangle.\text{nil} \parallel Q) \quad \text{(encoding)}$$

Encoding Synchronous by Polyadic Asynchronous Communication

- **Encoding:**
  - sending: $\overline{x}\langle y\rangle.P \mapsto \text{new}\, v\, (\overline{x}\langle y, v\rangle.\text{nil} \parallel v().P)$
  - receiving: $x(z).Q \mapsto x(z, v).(\overline{v}\langle\rangle.\text{nil} \parallel Q)$

  where $v \notin fn(P) \cup fn(Q) \cup \{x, y\}$ ("acknowledgement channel")
- **Correctness:** synchronous transition

$$\overline{x}\langle y\rangle.P \parallel x(z).Q \longrightarrow P \parallel Q[y/z]$$

is mimicked by polyadic asynchronous transition sequence

$$\begin{aligned} & \text{new}\, v\, (\overline{x}\langle y, v\rangle.\text{nil} \parallel v().P) \parallel x(z, v).(\overline{v}\langle\rangle.\text{nil} \parallel Q) && \text{(encoding)} \\ \equiv\ & \text{new}\, v\, (\overline{x}\langle y, v\rangle.\text{nil} \parallel v().P \parallel x(z, v).(\overline{v}\langle\rangle.\text{nil} \parallel Q)) && \text{(scope extension)} \end{aligned}$$

Encoding Synchronous by Polyadic Asynchronous Communication

- **Encoding:**
  - sending: $\overline{x}\langle y\rangle.P \mapsto \mathsf{new}\ v\ (\overline{x}\langle y, v\rangle.\mathsf{nil} \parallel v().P)$
  - receiving: $x(z).Q \mapsto x(z, v).(\overline{v}\langle\rangle.\mathsf{nil} \parallel Q)$

  where $v \notin fn(P) \cup fn(Q) \cup \{x, y\}$ ("acknowledgement channel")
- **Correctness:** synchronous transition

$$\overline{x}\langle y\rangle.P \parallel x(z).Q \longrightarrow P \parallel Q[y/z]$$

  is mimicked by polyadic asynchronous transition sequence

$$\begin{array}{rll} & \mathsf{new}\ v\ (\overline{x}\langle y, v\rangle.\mathsf{nil} \parallel v().P) \parallel x(z, v).(\overline{v}\langle\rangle.\mathsf{nil} \parallel Q) & \text{(encoding)} \\ \equiv & \mathsf{new}\ v\ (\overline{x}\langle y, v\rangle.\mathsf{nil} \parallel v().P \parallel x(z, v).(\overline{v}\langle\rangle.\mathsf{nil} \parallel Q)) & \text{(scope extension)} \\ \longrightarrow & \mathsf{new}\ v\ (v().P \parallel \overline{v}\langle\rangle.\mathsf{nil} \parallel Q[y/z]) & \text{(reaction)} \end{array}$$

Encoding Synchronous by Polyadic Asynchronous Communication

- **Encoding:**
  - sending: $\overline{x}\langle y\rangle.P \mapsto \text{new}\, v\, (\overline{x}\langle y, v\rangle.\text{nil} \parallel v().P)$
  - receiving: $x(z).Q \mapsto x(z, v).(\overline{v}\langle\rangle.\text{nil} \parallel Q)$

  where $v \notin fn(P) \cup fn(Q) \cup \{x, y\}$ ("acknowledgement channel")
- **Correctness:** synchronous transition

$$\overline{x}\langle y\rangle.P \parallel x(z).Q \longrightarrow P \parallel Q[y/z]$$

  is mimicked by polyadic asynchronous transition sequence

$$\begin{array}{rll} & \text{new}\, v\, (\overline{x}\langle y, v\rangle.\text{nil} \parallel v().P) \parallel x(z, v).(\overline{v}\langle\rangle.\text{nil} \parallel Q) & \text{(encoding)} \\ \equiv & \text{new}\, v\, (\overline{x}\langle y, v\rangle.\text{nil} \parallel v().P \parallel x(z, v).(\overline{v}\langle\rangle.\text{nil} \parallel Q)) & \text{(scope extension)} \\ \longrightarrow & \text{new}\, v\, (v().P \parallel \overline{v}\langle\rangle.\text{nil} \parallel Q[y/z]) & \text{(reaction)} \\ \longrightarrow & \text{new}\, v\, (P \parallel Q[y/z]) & \text{(reaction)} \end{array}$$

Encoding Synchronous by Polyadic Asynchronous Communication

- **Encoding:**
  - sending: $\overline{x}\langle y\rangle.P \mapsto \text{new}\, v\, (\overline{x}\langle y, v\rangle.\text{nil} \parallel v().P)$
  - receiving: $x(z).Q \mapsto x(z, v).(\overline{v}\langle\rangle.\text{nil} \parallel Q)$

  where $v \notin fn(P) \cup fn(Q) \cup \{x, y\}$ ("acknowledgement channel")
- **Correctness:** synchronous transition

$$\overline{x}\langle y\rangle.P \parallel x(z).Q \longrightarrow P \parallel Q[y/z]$$

  is mimicked by polyadic asynchronous transition sequence

$$\begin{array}{lll}
& \text{new}\, v\, (\overline{x}\langle y, v\rangle.\text{nil} \parallel v().P) \parallel x(z, v).(\overline{v}\langle\rangle.\text{nil} \parallel Q) & \text{(encoding)} \\
\equiv & \text{new}\, v\, (\overline{x}\langle y, v\rangle.\text{nil} \parallel v().P \parallel x(z, v).(\overline{v}\langle\rangle.\text{nil} \parallel Q)) & \text{(scope extension)} \\
\longrightarrow & \text{new}\, v\, (v().P \parallel \overline{v}\langle\rangle.\text{nil} \parallel Q[y/z]) & \text{(reaction)} \\
\longrightarrow & \text{new}\, v\, (P \parallel Q[y/z]) & \text{(reaction)} \\
\equiv & P \parallel Q[y/z] & \text{(congruence)}
\end{array}$$

Encoding Synchronous by Polyadic Asynchronous Communication

- **Encoding:**
  - sending: $\overline{x}\langle y\rangle.P \mapsto \text{new}\, v\, (\overline{x}\langle y, v\rangle.\text{nil} \parallel v().P)$
  - receiving: $x(z).Q \mapsto x(z, v).(\overline{v}\langle\rangle.\text{nil} \parallel Q)$

  where $v \notin fn(P) \cup fn(Q) \cup \{x, y\}$ ("acknowledgement channel")
- **Correctness:** synchronous transition

$$\overline{x}\langle y\rangle.P \parallel x(z).Q \longrightarrow P \parallel Q[y/z]$$

  is mimicked by polyadic asynchronous transition sequence

$$\begin{array}{rll} & \text{new}\, v\, (\overline{x}\langle y, v\rangle.\text{nil} \parallel v().P) \parallel x(z, v).(\overline{v}\langle\rangle.\text{nil} \parallel Q) & \text{(encoding)} \\ \equiv & \text{new}\, v\, (\overline{x}\langle y, v\rangle.\text{nil} \parallel v().P \parallel x(z, v).(\overline{v}\langle\rangle.\text{nil} \parallel Q)) & \text{(scope extension)} \\ \longrightarrow & \text{new}\, v\, (v().P \parallel \overline{v}\langle\rangle.\text{nil} \parallel Q[y/z]) & \text{(reaction)} \\ \longrightarrow & \text{new}\, v\, (P \parallel Q[y/z]) & \text{(reaction)} \\ \equiv & P \parallel Q[y/z] & \text{(congruence)} \end{array}$$

- **Note:** P only executable after completion of Q's input

Encoding Polyadic by Monadic Asynchronous Communication

- **Encoding:** (for two parameters, using v/w for sender from/to receiver)
  - sending: $\overline{x}\langle y_1, y_2\rangle.\mathrm{nil} \mapsto \mathrm{new}\, v\, (\overline{x}\langle v\rangle.\mathrm{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\mathrm{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\mathrm{nil}))$
  - receiving: $x(z_1, z_2).R \mapsto x(v).\mathrm{new}\, w\, (\overline{v}\langle w\rangle.\mathrm{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\mathrm{nil} \parallel w(z_2).R))$

  where $v, w \notin fn(R) \cup \{x, y_1, y_2\}$

Software Modeling and Verification Chair
RWTH AACHEN UNIVERSITY

Encoding Polyadic by Monadic Asynchronous Communication

- **Encoding:** (for two parameters, using v/w for sender from/to receiver)
  - sending: $\overline{x}\langle y_1, y_2\rangle.\text{nil} \mapsto \text{new}\, v\, (\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}))$
  - receiving: $x(z_1, z_2).R \mapsto x(v).\text{new}\, w\, (\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))$

  where $v, w \notin fn(R) \cup \{x, y_1, y_2\}$
- **Correctness:** polyadic transition

$$\overline{x}\langle y_1, y_2\rangle.\text{nil} \parallel x(z_1, z_2).R \longrightarrow R[y_1/z_1, y_2/z_2]$$

Encoding Polyadic by Monadic Asynchronous Communication

- **Encoding:** (for two parameters, using v/w for sender from/to receiver)
  - sending: $\overline{x}\langle y_1, y_2\rangle.\text{nil} \mapsto \text{new } v\,(\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}))$
  - receiving: $x(z_1, z_2).R \mapsto x(v).\text{new } w\,(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))$

  where $v, w \notin fn(R) \cup \{x, y_1, y_2\}$
- **Correctness:** polyadic transition

$$\overline{x}\langle y_1, y_2\rangle.\text{nil} \parallel x(z_1, z_2).R \longrightarrow R[y_1/z_1, y_2/z_2]$$

  is mimicked by monadic transition sequence

$$\begin{aligned}&\text{new } v\,(\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil})) \parallel && \text{(encoding)}\\ &x(v).\text{new } w\,(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))\end{aligned}$$

Encoding Polyadic by Monadic Asynchronous Communication

- **Encoding:** (for two parameters, using v/w for sender from/to receiver)
  - sending: $\overline{x}\langle y_1, y_2\rangle.\text{nil} \mapsto \text{new}\, v\, (\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}))$
  - receiving: $x(z_1, z_2).R \mapsto x(v).\text{new}\, w\, (\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))$

  where $v, w \notin fn(R) \cup \{x, y_1, y_2\}$
- **Correctness:** polyadic transition

$$\overline{x}\langle y_1, y_2\rangle.\text{nil} \parallel x(z_1, z_2).R \longrightarrow R[y_1/z_1, y_2/z_2]$$

  is mimicked by monadic transition sequence

$$\begin{aligned}
& \text{new}\, v\, (\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil})) \parallel && \text{(encoding)}\\
& x(v).\text{new}\, w\, (\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))\\
\equiv\ & \text{new}\, v\, (\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}) \parallel && \text{(scope extension)}\\
& x(v).\text{new}\, w\, (\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R)))
\end{aligned}$$

Encoding Polyadic by Monadic Asynchronous Communication

- **Encoding:** (for two parameters, using v/w for sender from/to receiver)
  - sending: $\overline{x}\langle y_1, y_2\rangle.\text{nil} \mapsto \text{new } v\,(\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}))$
  - receiving: $x(z_1, z_2).R \mapsto x(v).\text{new } w\,(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))$

  where $v, w \notin fn(R) \cup \{x, y_1, y_2\}$
- **Correctness:** polyadic transition

$$\overline{x}\langle y_1, y_2\rangle.\text{nil} \parallel x(z_1, z_2).R \longrightarrow R[y_1/z_1, y_2/z_2]$$

  is mimicked by monadic transition sequence

$$\begin{aligned}
& \text{new } v\,(\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil})) \parallel && \text{(encoding)}\\
& x(v).\text{new } w\,(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R)) &&\\
\equiv\ & \text{new } v\,(\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}) \parallel && \text{(scope extension)}\\
& x(v).\text{new } w\,(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))) &&\\
\longrightarrow\ & \text{new } v\,(v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}) \parallel \text{new } w\,(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))) && \text{(reaction)}
\end{aligned}$$

Encoding Polyadic by Monadic Asynchronous Communication

- **Encoding:** (for two parameters, using v/w for sender from/to receiver)
  - sending: $\overline{x}\langle y_1, y_2\rangle.\text{nil} \mapsto \text{new}\, v\, (\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}))$
  - receiving: $x(z_1, z_2).R \mapsto x(v).\text{new}\, w\, (\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))$

  where $v, w \notin fn(R) \cup \{x, y_1, y_2\}$
- **Correctness:** polyadic transition

$$\overline{x}\langle y_1, y_2\rangle.\text{nil} \parallel x(z_1, z_2).R \longrightarrow R[y_1/z_1, y_2/z_2]$$

is mimicked by monadic transition sequence

$$\begin{aligned}
& \text{new}\, v\, (\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil})) \parallel & \text{(encoding)}\\
& x(v).\text{new}\, w\, (\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R)) & \\
\equiv\; & \text{new}\, v\, (\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}) \parallel & \text{(scope extension)}\\
& x(v).\text{new}\, w\, (\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))) & \\
\longrightarrow\; & \text{new}\, v\, (v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}) \parallel \text{new}\, w\, (\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))) & \text{(reaction)}\\
\equiv\; & \text{new}\, v, w\, (v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}) \parallel \overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R)) & \text{(scope extension)}
\end{aligned}$$

Encoding Polyadic by Monadic Asynchronous Communication

- **Encoding:** (for two parameters, using v/w for sender from/to receiver)
  - sending: $\overline{x}\langle y_1, y_2\rangle.\mathrm{nil} \mapsto \mathrm{new}\, v\, (\overline{x}\langle v\rangle.\mathrm{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\mathrm{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\mathrm{nil}))$
  - receiving: $x(z_1, z_2).R \mapsto x(v).\mathrm{new}\, w\, (\overline{v}\langle w\rangle.\mathrm{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\mathrm{nil} \parallel w(z_2).R))$

  where $v, w \notin fn(R) \cup \{x, y_1, y_2\}$
- **Correctness:** polyadic transition

$$\overline{x}\langle y_1, y_2\rangle.\mathrm{nil} \parallel x(z_1, z_2).R \longrightarrow R[y_1/z_1, y_2/z_2]$$

is mimicked by monadic transition sequence

$$\begin{array}{lll}
& \mathrm{new}\, v\, (\overline{x}\langle v\rangle.\mathrm{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\mathrm{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\mathrm{nil})) \parallel & \text{(encoding)} \\
& x(v).\mathrm{new}\, w\, (\overline{v}\langle w\rangle.\mathrm{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\mathrm{nil} \parallel w(z_2).R)) & \\
\equiv & \mathrm{new}\, v\, (\overline{x}\langle v\rangle.\mathrm{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\mathrm{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\mathrm{nil}) \parallel & \text{(scope extension)} \\
& x(v).\mathrm{new}\, w\, (\overline{v}\langle w\rangle.\mathrm{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\mathrm{nil} \parallel w(z_2).R))) & \\
\longrightarrow & \mathrm{new}\, v\, (v(w).(\overline{w}\langle y_1\rangle.\mathrm{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\mathrm{nil}) \parallel \mathrm{new}\, w\, (\overline{v}\langle w\rangle.\mathrm{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\mathrm{nil} \parallel w(z_2).R))) & \text{(reaction)} \\
\equiv & \mathrm{new}\, v, w\, (v(w).(\overline{w}\langle y_1\rangle.\mathrm{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\mathrm{nil}) \parallel \overline{v}\langle w\rangle.\mathrm{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\mathrm{nil} \parallel w(z_2).R)) & \text{(scope extension)} \\
\longrightarrow & \mathrm{new}\, v, w\, (\overline{w}\langle y_1\rangle.\mathrm{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\mathrm{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\mathrm{nil} \parallel w(z_2).R)) & \text{(reaction)}
\end{array}$$

Encoding Polyadic by Monadic Asynchronous Communication

- **Encoding:** (for two parameters, using v/w for sender from/to receiver)
  - sending: $\overline{x}\langle y_1, y_2\rangle.\text{nil} \mapsto \text{new}\, v\, (\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}))$
  - receiving: $x(z_1, z_2).R \mapsto x(v).\text{new}\, w\, (\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))$

  where $v, w \notin fn(R) \cup \{x, y_1, y_2\}$
- **Correctness:** polyadic transition

$$\overline{x}\langle y_1, y_2\rangle.\text{nil} \parallel x(z_1, z_2).R \longrightarrow R[y_1/z_1, y_2/z_2]$$

  is mimicked by monadic transition sequence

$$\begin{array}{lll}
 & \text{new}\, v\, (\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil})) \parallel & \text{(encoding)} \\
 & x(v).\text{new}\, w\, (\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R)) & \\
\equiv & \text{new}\, v\, (\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}) \parallel & \text{(scope extension)} \\
 & x(v).\text{new}\, w\, (\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))) & \\
\longrightarrow & \text{new}\, v\, (v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}) \parallel \text{new}\, w\, (\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))) & \text{(reaction)} \\
\equiv & \text{new}\, v, w\, (v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}) \parallel \overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R)) & \text{(scope extension)} \\
\longrightarrow & \text{new}\, v, w\, (\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R)) & \text{(reaction)} \\
\longrightarrow & \text{new}\, v, w\, (v(w).\overline{w}\langle y_2\rangle.\text{nil} \parallel \overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R[y_1/z_1]) & \text{(reaction)}
\end{array}$$

Encoding Polyadic by Monadic Asynchronous Communication

- **Encoding:** (for two parameters, using v/w for sender from/to receiver)
  - sending: $\overline{x}\langle y_1, y_2\rangle.\text{nil} \mapsto \text{new } v\,(\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}))$
  - receiving: $x(z_1, z_2).R \mapsto x(v).\text{new } w\,(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))$

  where $v, w \notin fn(R) \cup \{x, y_1, y_2\}$
- **Correctness:** polyadic transition

  $$\overline{x}\langle y_1, y_2\rangle.\text{nil} \parallel x(z_1, z_2).R \longrightarrow R[y_1/z_1, y_2/z_2]$$

  is mimicked by monadic transition sequence

$$\begin{array}{lll}
 & \text{new } v\,(\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil})) \parallel & \text{(encoding)}\\
 & x(v).\text{new } w\,(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R)) & \\
\equiv & \text{new } v\,(\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}) \parallel & \text{(scope extension)}\\
 & x(v).\text{new } w\,(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))) & \\
\longrightarrow & \text{new } v\,(v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}) \parallel \text{new } w\,(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))) & \text{(reaction)}\\
\equiv & \text{new } v, w\,(v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}) \parallel \overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R)) & \text{(scope extension)}\\
\longrightarrow & \text{new } v, w\,(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R)) & \text{(reaction)}\\
\longrightarrow & \text{new } v, w\,(v(w).\overline{w}\langle y_2\rangle.\text{nil} \parallel \overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R[y_1/z_1]) & \text{(reaction)}\\
\longrightarrow & \text{new } v, w\,(\overline{w}\langle y_2\rangle.\text{nil} \parallel w(z_2).R[y_1/z_1]) & \text{(reaction)}
\end{array}$$

Encoding Polyadic by Monadic Asynchronous Communication

- **Encoding:** (for two parameters, using v/w for sender from/to receiver)
  - sending: $\overline{x}\langle y_1, y_2\rangle.\text{nil} \mapsto \text{new}\, v\, (\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}))$
  - receiving: $x(z_1, z_2).R \mapsto x(v).\text{new}\, w\, (\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))$

  where $v, w \notin fn(R) \cup \{x, y_1, y_2\}$
- **Correctness:** polyadic transition

$$\overline{x}\langle y_1, y_2\rangle.\text{nil} \parallel x(z_1, z_2).R \longrightarrow R[y_1/z_1, y_2/z_2]$$

  is mimicked by monadic transition sequence

$$\begin{array}{lll}
& \text{new}\, v\, (\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil})) \parallel & \text{(encoding)} \\
& x(v).\text{new}\, w\, (\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R)) & \\
\equiv & \text{new}\, v\, (\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}) \parallel & \text{(scope extension)} \\
& x(v).\text{new}\, w\, (\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))) & \\
\longrightarrow & \text{new}\, v\, (v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}) \parallel \text{new}\, w\, (\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))) & \text{(reaction)} \\
\equiv & \text{new}\, v, w\, (v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}) \parallel \overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R)) & \text{(scope extension)} \\
\longrightarrow & \text{new}\, v, w\, (\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R)) & \text{(reaction)} \\
\longrightarrow & \text{new}\, v, w\, (v(w).\overline{w}\langle y_2\rangle.\text{nil} \parallel \overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R[y_1/z_1]) & \text{(reaction)} \\
\longrightarrow & \text{new}\, v, w\, (\overline{w}\langle y_2\rangle.\text{nil} \parallel w(z_2).R[y_1/z_1]) & \text{(reaction)} \\
\longrightarrow & \text{new}\, v, w\, R[y_1/z_1, y_2/z_2] & \text{(reaction)}
\end{array}$$

Encoding Polyadic by Monadic Asynchronous Communication

- **Encoding:** (for two parameters, using v/w for sender from/to receiver)
  - sending: $\overline{x}\langle y_1, y_2\rangle.\text{nil} \mapsto \text{new } v\,(\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}))$
  - receiving: $x(z_1, z_2).R \mapsto x(v).\text{new } w\,(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))$

  where $v, w \notin fn(R) \cup \{x, y_1, y_2\}$
- **Correctness:** polyadic transition
$$\overline{x}\langle y_1, y_2\rangle.\text{nil} \parallel x(z_1, z_2).R \longrightarrow R[y_1/z_1, y_2/z_2]$$
  is mimicked by monadic transition sequence

$$
\begin{array}{lll}
& \text{new } v\,(\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil})) \parallel & \text{(encoding)} \\
& x(v).\text{new } w\,(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R)) & \\
\equiv & \text{new } v\,(\overline{x}\langle v\rangle.\text{nil} \parallel v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}) \parallel & \text{(scope extension)} \\
& x(v).\text{new } w\,(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))) & \\
\longrightarrow & \text{new } v\,(v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}) \parallel \text{new } w\,(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R))) & \text{(reaction)} \\
\equiv & \text{new } v, w\,(v(w).(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil}) \parallel \overline{v}\langle w\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R)) & \text{(scope extension)} \\
\longrightarrow & \text{new } v, w\,(\overline{w}\langle y_1\rangle.\text{nil} \parallel v(w).\overline{w}\langle y_2\rangle.\text{nil} \parallel w(z_1).(\overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R)) & \text{(reaction)} \\
\longrightarrow & \text{new } v, w\,(v(w).\overline{w}\langle y_2\rangle.\text{nil} \parallel \overline{v}\langle w\rangle.\text{nil} \parallel w(z_2).R[y_1/z_1]) & \text{(reaction)} \\
\longrightarrow & \text{new } v, w\,(\overline{w}\langle y_2\rangle.\text{nil} \parallel w(z_2).R[y_1/z_1]) & \text{(reaction)} \\
\longrightarrow & \text{new } v, w\; R[y_1/z_1, y_2/z_2] & \text{(reaction)} \\
\equiv & R[y_1/z_1, y_2/z_2] & \text{(congruence)}
\end{array}
$$

Software Modeling and Verification Chair

RWTH AACHEN UNIVERSITY