ASP_{fun}: a Deadlock-free Calculus for Distributed Active Objects

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Synchrony and Asynchrony in Distributed Systems

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Motivation and goals

- New language ASP_{fun}
  - functional
  - active objects
  - distributed
  - plus typing
- Formal, mechanically supported language development
  - "Killer-Application" of theorem proving in Higher Order Logic (HOL)
  - Java (with JVM) completely formalized in Isabelle/HOL (Tobias Nipkow, TU München)
  - Complete re-engineering of a C-Compiler in Coq (Xavier Leroy, INRIA Roquencourt)

$\Longrightarrow$ ASP_{fun} in Isabelle/HOL

Overview

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3. Example for ASP_{fun}
4. Results, Discussion, Outlook

ASP$_{fun}$– Asynchronous Sequential Processes – functional

- ProActive (Inria/ActiveEON): Java API for active objects

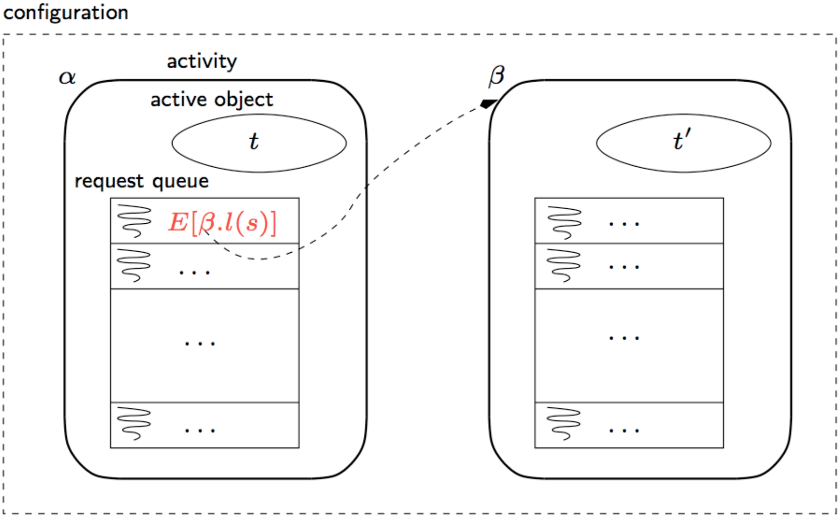
ProActive
Programming, Composing, Deploying on the Grid

- New calculus ASP$_{fun}$ for ProActive
- Functional better properties: many applications can be seen as *functions*, for example web-services
- Asynchronous communication with *futures*
  - Futures : asynchronous method calls
  - Objects: ς-calculus of Abadi/Cardelli
  - Future access may cause deadlock: *wait-by-necessity*
  - Functional: *reply* with partially evaluated *requests*

$\Rightarrow$ ASP$_{fun}$ avoids deadlocks when accessing futures

ASP$_{fun}$

ASP$_{fun}$: at a glance



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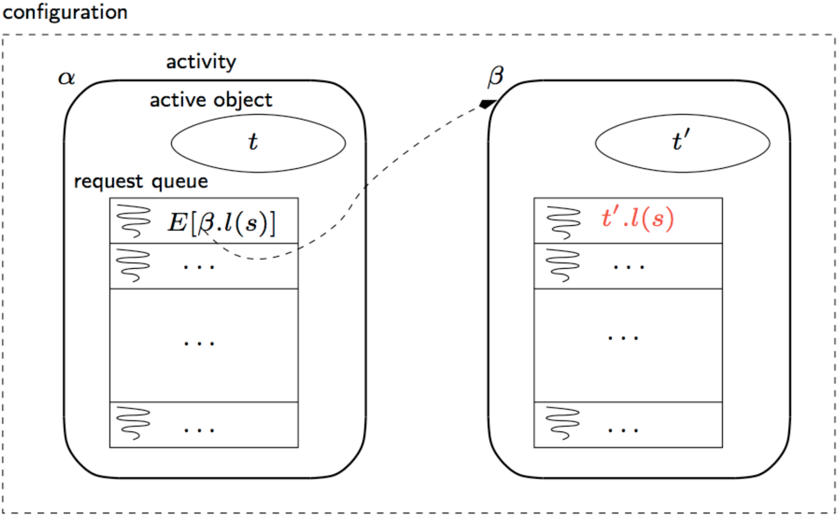
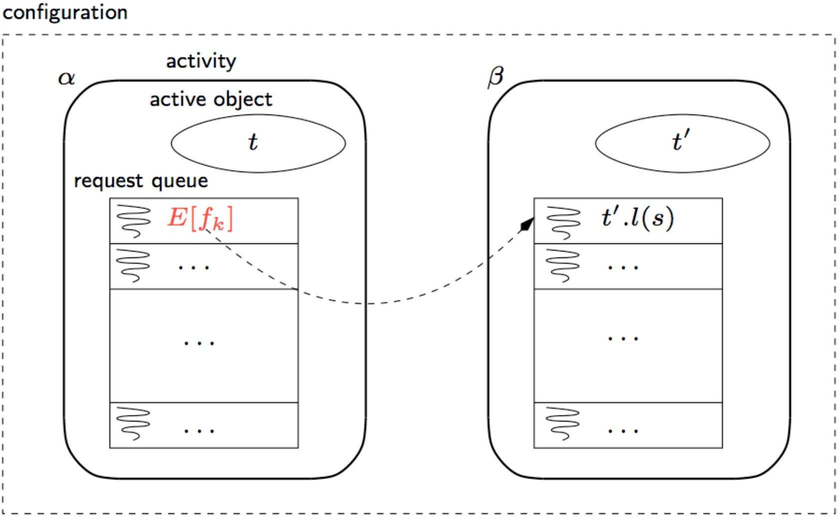


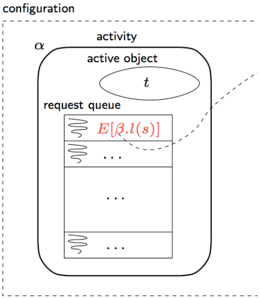
ASP$_{fun}$: at a glance



From ς-calculus to ASP$_{\text{fun}}$

Syntactic extension of ς-calculus by:

- *Active*: creation of a new active object
- *FutRef* and *ActRef*: references for activities and futures (transparent)



- Semantics: *local* $\to_\varsigma$ and *parallel* evaluation
- Parallel semantics $\to_\parallel$: inductive relation on configurations

$$\textit{configuration} = \textit{ActRef} \rightharpoonup (\textit{FutRef} \rightharpoonup \textit{term}) \times \textit{term}$$

Parallel semantics $\rightarrow_{\parallel}$ informally

idea: evaluate terms (only) in future-lists

- LOCAL: reduction $\rightarrow_{\varsigma}$ of ς-calculus
- REQUEST: *method call* $\beta.l$ creates new future f_k in future-list of activity β
- REPLY: *return result*, i.e. replace future f_k by referenced result term

$$\text{REPLY}\ \frac{\beta[f_k \mapsto s :: R, t'] \in \alpha[f_i \mapsto E[f_k] :: Q, t] :: C}{\alpha[f_i \mapsto E[f_k] :: Q, t] :: C \rightarrow_{\parallel} \alpha[f_i \mapsto E[s] :: Q, t] :: C}$$

- UPDATE-AO: *update activity*, creates a copy on which update (change) - original remains the same (*immutable*)

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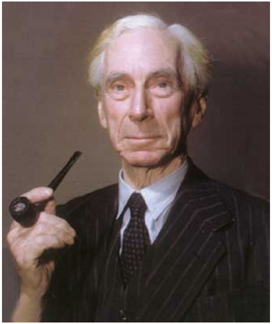
Language development in Isabelle/HOL

- Isabelle/HOL: interactive theorem prover for HOL
- Enables formalization of syntax, semantics, and type systems of languages
- Proofs of language properties



- Example property: typing is unique
  $\vdash x : T \wedge \vdash x : T' \Rightarrow T = T'$

$\Longrightarrow$ interactive proof tool enables control (and code generation)

ASP_{fun} is type safe and deadlock free

- Proof of properties in Isabelle/HOL, for example
  - Wellformedness: no dangling activity references or futures
  - Typing implies wellformedness
- Type safety: preservation and progress

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Theorem (Preservation)

$$\vdash C : \langle \Gamma_{act}, \Gamma_{fut} \rangle \wedge C \to_{\parallel} C' \Longrightarrow \exists\, \Gamma'_{act}, \Gamma'_{fut} \,.\; \vdash C' : \langle \Gamma'_{act}, \Gamma'_{fut} \rangle$$

where $\Gamma_{act} \subseteq \Gamma'_{act} \wedge \Gamma_{fut} \subseteq \Gamma'_{fut}$

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Theorem (Progress)

$$\vdash C : \langle \Gamma_{act}, \Gamma_{fut} \rangle \;\wedge\; \alpha[f_i \mapsto a :: Q, t] \in C$$
$$\Longrightarrow isvalue(a) \vee \exists\, C' \,.\; C \rightarrow_{\parallel} C'$$

ASP_{fun} is type safe and deadlock free

- Proof of properties in Isabelle/HOL, for example
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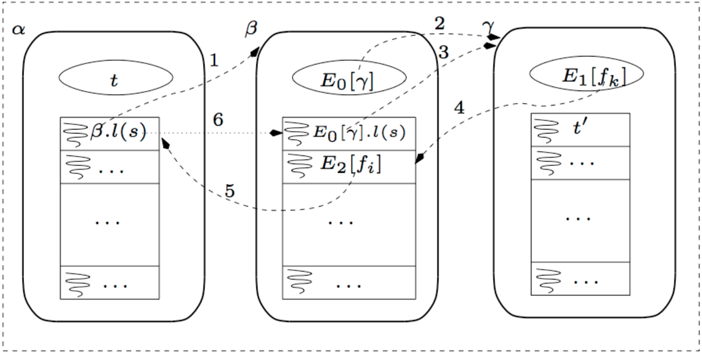
$\Rightarrow$ Always progress, hence no deadlock!

Further results

- *Cycles of futures*: reduction introduces no cycles



- General results for Isabelle/HOL
  - `FMaps`: axiomatic type classes for *finite maps*
  - *Theory of Objects* ς
  - Contexts: “contextual semantics”, à la $E(\bullet)$
  - *Locally nameless* for ς

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Example: service broker

Client reserves a hotel using a *broker*

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$$\text{customer}[f_0 \mapsto \text{broker.find(date,limit)}, \varnothing]$$
$$\parallel \text{broker}[\varnothing, [\text{find} = \varsigma(x, (\mathit{date}, \mathit{limit})).\text{hotel.room}(\mathit{date}), \ldots]]$$
$$\parallel \text{hotel}[\varnothing, [\text{room} = \varsigma(x, \mathit{date})\text{bookingref}, \ldots]$$

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$$
\begin{aligned}
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\rightarrow_{\parallel}^{*} \quad & (\text{REQUEST, LOCAL}) \\
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& \parallel \text{broker}[f_1 \mapsto f_2, \ldots] \\
& \parallel \text{hotel}[f_2 \mapsto \text{bookingref}, [\text{room} = \varsigma(x, \mathit{date})\text{bookingref}, \ldots]
\end{array}
$$

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\rightarrow^{*}_{\parallel} & (\text{REPLY}) \\
 & \text{customer}[f_0 \mapsto \text{bookingref}, \varnothing] \\
 & \parallel \text{broker}[f_1 \mapsto f_2, \ldots] \\
 & \parallel \text{hotel}[f_2 \mapsto \text{bookingref}, [\text{room} = \varsigma(x, \mathit{date})\text{bookingref}, \ldots]
\end{array}
$$

Observations

- Service broker has a private domain of hotel addresses.
- He searches, negotiates with hotel, and gives only the future f_2 to client.
- Client receives bookingref using f_2 without viewing details of the hotel nor others from broker's domain.

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Next goal: security, noninterference

- Noninterference: formal definition of security (confidentality)
- Security types for static security analysis, [3]
    - *Type safety* ⇒ *security*

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- Challenge: *Literature [2] shows that for parallel programs noninterference more difficult because a process can observe termination of others.*

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⇒ ASP_{fun} separate date spaces in active objects; stronger noninterference property expected

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Discussion and outlook

- $\text{ASPEN}_{\text{DFG}}$: Security analysis of distributed active objects
- Development of a new language ASP_{fun}
  - Modelling language concepts
  - Proof of meta-theorems: well-formedness, no cycles
  - Type system and proof of type safety
    - ⇒ deadlock freedom
    - ⇒ security
- Development in Isabelle/HOL
  - 100 % consistency (correctness)
  - Generation of prototypical tools (interpreter and type checker)
- Outlook: components with futures in Isabelle/HOL
- Synergies with formalisation of aspect-oriented programming ($\text{ASCOT}_{\text{DFG}}$)

Current papers (selection)

[1] L. Henrio, F. Kammüller. A Mechanized Model of the Theory of Objects. 9th IFIP Int. Conference on Formal Methods for Open Object-Based Distributed Systems, FMOODS'07. LNCS **4468**, Springer 2007.

[2] L. Henrio and F. Kammüller. Functional Active Objects: Typing and Formalisation. Foundations of Coordination Languages and System Architectures, FOCLASA'09. Satellite to ICALP'09. To appear in ENTCS, 2009.

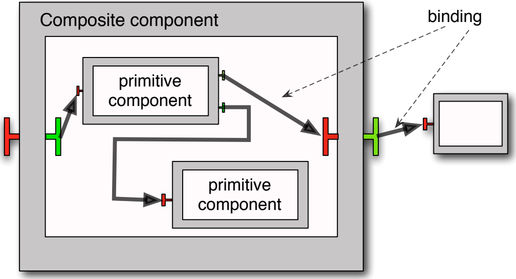
[3] F. Kammüller. Formalizing Non-Interference for A Small Bytecode-Language in Coq. Formal Aspects of Computing: **20**(3):259–275. Springer, 2008.

[4] F. Kammüller, H. Sudhof. Composing safely – A Type System for Aspects. Software Composition, Satellite to ETAPS'08. LNCS **4954**:231–247, Springer 2008.

[5] F. Kammüller, H. Sudhof. Compositionality of Aspect Weaving. Autonomous Systems – Self-Organisation, Management, and Control. B. Mahr, Z. Sheng (Eds.), Springer, 2008.

[6] F. Kammüller, R. Kammüller. Enhancing Privacy Implementations of Database Enquiries. The Fourth International Conference on Internet Monitoring and Protection. IEEE Computer Press, to appear 2009.

Further goals: components



- Too much detail at object level
- Formalising components
  - Abstraction of data and algorithms
  - Model only structure of communication, i.e futures
  - Primitive und composite components
  - Specification of behaviour for primitive components
  - Composition of behaviour for composites

ASP_{fun} : Premier Exemple

- Création d'une Activité paràllele, qui incrément 5 par 1

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- Request restant $\beta.\mathtt{m}$ crée Future, en résumé :
  $\alpha([f_0 \mapsto f_1], \emptyset) \| \beta([f_1 \mapsto [m = \varsigma(x)x.z + 1, z = 5].m], \ldots)$

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- Evaluation suivant règle LOCAL donne
  $\alpha([f_0 \mapsto f_1], \emptyset) \| \beta([f_1 \mapsto 6, [m = \varsigma(x)x.z + 1, z = 5])$

ASP_{fun} : Premier Exemple

- Création d'une Activité parallele, qui incrément 5 par 1
- Supposition : Nombres naturels en ς-calcul
- Configuration initial contient objet vide $\emptyset$ et le program comme suivant
  $\alpha([f_0 \mapsto Active([m = \varsigma(x)x.z + 1, z = 5]).m], \emptyset)$
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- Evaluation suivant règle LOCAL donne
  $\alpha([f_0 \mapsto f_1], \emptyset) \| \beta([f_1 \mapsto 6, [m = \varsigma(x)x.z + 1, z = 5])$
- Par REPLY le résultat est rendu.
  $\alpha([f_0 \mapsto 6], \emptyset) \| \beta([f_1 \mapsto 6, [m = \varsigma(x)x.z + 1, z = 5])$

ASP$_{\text{fun}}$-Semantik

LOCAL

$$\frac{s \to_\varsigma s'}{\alpha[f_i \mapsto s :: Q, t] :: C \to_\parallel \alpha[f_i \mapsto s' :: Q, t] :: C}$$

ACTIVE

$$\frac{\gamma \notin (\mathrm{dom}(C) \cup \{\alpha\}) \qquad noFV(s)}{\alpha[f_i \mapsto E[Active(s)] :: Q, t] :: C \to_\parallel \alpha[f_i \mapsto E[\gamma] :: Q, t] :: \gamma[\varnothing, s] :: C}$$

REQUEST

$$\frac{f_k \text{ fresh} \qquad noFV(s)}{\alpha\,[f_i \mapsto E[\beta.l(s)] :: Q, t] :: \beta[R, t'] :: C \to_\parallel \alpha\,[f_i \mapsto E[f_k] :: Q, t] :: \beta\,[f_k \mapsto t'.l(s) :: R, t'] :: C}$$

SELF-REQUEST

$$\frac{f_k \text{ fresh} \qquad noFV(s)}{\alpha\,[f_i \mapsto E[\alpha.l(s)] :: Q, t] :: C \to_\parallel \alpha\,[f_k \mapsto t.l(s) :: f_i \mapsto E[f_k] :: Q, t] :: C}$$

REPLY

$$\frac{\beta[f_k \mapsto s :: R, t'] \in \alpha[f_i \mapsto E[f_k] :: Q, t] :: C}{\alpha[f_i \mapsto E[f_k] :: Q, t] :: C \to_\parallel \alpha[f_i \mapsto E[s] :: Q, t] :: C}$$

UPDATE-AO

$$\frac{\begin{array}{c}\gamma \notin (\mathrm{dom}(C) \cup \{\alpha\}) \\ noFV(\varsigma(x,y)s) \qquad \beta[Q, t'] \in (\alpha[f_i \mapsto E[\beta.l := \varsigma(x,y)s] :: Q, t] :: C)\end{array}}{\alpha[f_i \mapsto E[\beta.l := \varsigma(x,y)s] :: Q, t] :: C \to_\parallel \alpha[f_i \mapsto E[\gamma] :: Q, t] :: \gamma[\varnothing, t'.l := \varsigma(x,y)s] :: C}$$

Table 1. ASP$_{\text{fun}}$ semantics

ASP_{fun}-Typsystem Lokal

Val x

$$x{:}A :: T \vdash x : A$$

Val not x

$$\frac{y \neq x \qquad T \vdash x : B}{y{:}A :: T \vdash x : B}$$

Object Formation

$$\frac{\forall i \in 1..n, \vdash B_i \;\wedge\; \vdash D_i \qquad \forall i,j \in 1..n, i \neq j \Rightarrow l_i \neq l_j}{\vdash [l_i : B_i {\rightarrow} D_i]^{i \in 1..n}}$$

Type Object

$$\frac{A = [l_i : B_i {\rightarrow} D_i]^{i \in 1..n} \qquad \forall i \in 1..n,\ x_i{:}A :: y_i{:}B_i :: T \vdash b_i : D_i}{T \vdash [l_i = \varsigma(x_i : A, y_i : B_i)b_i]^{i \in 1..n} : A}$$

Type Call

$$\frac{T \vdash a : [l_i : B_i {\rightarrow} D_i]^{i \in 1..n} \qquad j \in 1..n \qquad T \vdash b : B_j}{T \vdash a.l_j(b) : D_j}$$

Type Update

$$\frac{A = [l_i : B_i {\rightarrow} D_i]^{i \in 1..n} \qquad T \vdash a : A \qquad j \in 1..n \qquad x{:}A :: y{:}B :: T \vdash b : D_j}{T \vdash a.l_j := \varsigma(x : A, y : B)b : A}$$

Table 2. Typing the local calculus

ASP$_{fun}$-Typsystem Global

Type Active

$$\frac{\langle \Gamma_{act}, \Gamma_{fut}\rangle, T \vdash a : A}{\langle \Gamma_{act}, \Gamma_{fut}\rangle, T \vdash Active(a) : A}$$

Type Activity Reference

$$\frac{\beta \in \mathrm{dom}(\Gamma_{act})}{\langle \Gamma_{act}, \Gamma_{fut}\rangle, T \vdash \beta : \Gamma_{act}(\beta)}$$

Type Future Reference

$$\frac{f_k \in \mathrm{dom}(\Gamma_{fut})}{\langle \Gamma_{act}, \Gamma_{fut}\rangle, T \vdash f_k : \Gamma_{fut}(f_k)}$$

Type Configuration

$$\frac{\begin{array}{l} \mathrm{dom}(\Gamma_{act}) = \mathrm{dom}(C) \qquad \mathrm{dom}(\Gamma_{fut}) = \bigcup\{\mathrm{dom}(Q) \mid \exists\, \alpha, a.\ \alpha[Q,a] \in C\} \\ \forall\, \alpha, Q, a, C'.\ C = \alpha[Q,a] :: C' \Rightarrow \begin{cases} \langle \Gamma_{act}, \Gamma_{fut}\rangle, \varnothing \vdash a : \Gamma_{act}(\alpha)\ \wedge \\ \forall\, f_i \in \mathrm{dom}(Q).\ \langle \Gamma_{act}, \Gamma_{fut}\rangle, \varnothing \vdash Q(f_i) : \Gamma_{fut}(f_i) \end{cases} \end{array}}{\vdash C : \langle \Gamma_{act}, \Gamma_{fut}\rangle}$$

Typsysteme und Typkorrektheit

- Typsystem gestattet statische Überprüfung gewisser semantischer Eigenschaften
- Typsicherheit informell: Ein wohlgetyptes Programm `t` verhält sich *vernünftig*
  1. Auswertung von `t` respektiert die Typen (*Preservation/Subject Reduction*)

     $\llbracket \mathtt{E} \vdash \mathtt{t} : \mathtt{T};\ \mathtt{t} \longrightarrow_{\varsigma}^{*} \mathtt{t'} \rrbracket \Longrightarrow \mathtt{E} \vdash \mathtt{t'} : \mathtt{T}$
  2. Programm `t` bleibt nicht stecken (*Progress*)

     $\llbracket \mathtt{E} \vdash \mathtt{t} : \mathtt{T};\ \neg\ \mathtt{value}\ (\mathtt{t}) \rrbracket \Longrightarrow \exists\ \mathtt{t'},\ \mathtt{t} \longrightarrow_{\varsigma} \mathtt{t'}$
  - $\mathtt{E} \vdash \mathtt{t} : \mathtt{T}$ heisst *term* `t` *hat Typ* `T` *in Typumgebung* `E`

Bindungs-Techniken in Isabelle

- Wir benutzen DeBruijn-Indizes
- Sehr gewöhnungsbedürftig aber praktisch und einfach
- Nominal Techniques leider nicht einsatzbar
- Locally Nameless:
  - noch experimentell
  - Vorteile noch unklar
  - Vermutung: insbesondere bei Konfigurationen weniger Problem mit “fresh”

Vom ς-Kalkül zu ASP$_{\text{fun}}$

- Isabelle datatype für ς-Terme

```
datatype term = Var nat
    | Obj label ⇀f term
    | Call term label
    | Upd term label term
```

Vom ς-Kalkül zu ASP$_{\text{fun}}$

- Isabelle datatype für ς-Terme
- Erweiterung um `Active-`, `ActRef-` und `FutRef-`Terme für Activation, Activity- und Futurereferenzen

```
datatype term = Var nat
    | Obj label ⇀f term
    | Call term label
    | Upd term label term
    | Active term
    | ActRef ActivityRef
    | FutRef FutureRef
```

O: Theory of Objects, ς-calculus

- Terms in the ς-calculus

$$
\begin{array}{rll}
a, b ::= & [l_j = \varsigma(x_j)a_j]^{j\in 1..n} & \text{object definition} \\
& \mid a.l_j & (j \in 1..n) \text{ method call} \\
& \mid a.l_j := \varsigma(x)b & (j \in 1..n) \text{ update}
\end{array}
$$

- Semantics/Reduction for $o \equiv [l_j = \varsigma(x_j)a_j]^{j\in 1..n}$ (l_i distinct).

$$
\begin{array}{ll}
o & \text{object with method names } l_i \\
& \text{methods } \varsigma(x_i)b_i \\
o.l_j(b) \rightarrow_\varsigma b_j\{x_j \leftarrow o\} & (j \in 1..n) \text{ selection / method call} \\
o.l_j := \varsigma(x)b \rightarrow_\varsigma [l_j = \varsigma(y)b, & l_i = \varsigma(x_i)b_i^{i\in(1..n)-\{j\}}] \\
& (j \in 1..n) \text{ update/override}
\end{array}
$$

Die Theorie der Objekte: ς-Kalkül

Definition (Sigma-Term)

Ein Sigma-Term ist ein Wort der folgenden Grammatik:

$a, b ::=$		Terme
	x	Variable
	$[l_i = \varsigma(x_i)b_i]^{i \in 1..n}$	Objekt
	$a.l$	Feld-Auswahl / Methodenaufruf
	$a.l \Leftarrow \varsigma(x)b$	Feld-Update / Methoden-Update

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- Semantik: Reduktionsrelation $\rightarrow_\varsigma$
- Substitution des formalen Parameters mit a it”self”

$$a \equiv [l_j = \varsigma(x_j)b_j]^{j \in 1..n}$$

$$a.l_j \rightarrow_\varsigma b_j[a/x_j] \qquad j \in 1..n$$

Beispiel ς-Kalkül

```
zero = [ iszero = true;
         pred   = ς(x)x,
         succ   = ς(x)(x.iszero := false).pred := x]
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Beispiel ς-Kalkül

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   →ς[iszero = false,
       pred   = zero,
       succ   = ς(x)(x.iszero := false).pred := x]
```
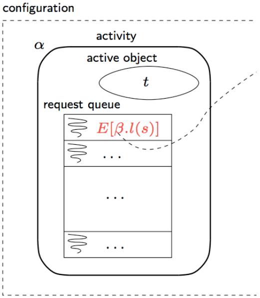

T: Typing rules for Sigma only

```
inductive typing
intros
  Var: ⟦x < length E; (E!x) = T ⟧⟹ E ⊢ Var x : T
  Obj: ⟦length b = len B;
        ∀ i < len B. E ⟨0:B ⟩⊢ (b!i): (B!i)⟧
        ⟹ E ⊢ (Obj b) : B
  Call: ⟦E ⊢ a: A; l < len A ⟧⟹ E ⊢ (Call a l): (A!l)
  Upd: ⟦E ⊢ a: A; l < len A; E ⟨0:A ⟩⊢ n: (A!l) ⟧
        ⟹ E ⊢ (Upd a l n) : A
```

From ς-calculus to ASP_{fun}

- ASP_{fun} builds on ς-Kalkül of Abadi and Cardelli
- Activities $\alpha[R, t]$:
  - Lists of futures R (request queue)
  - ς-Objekt t (immutable)



- Syntactic extension of ς-calculus by:
  - *Active*: creation of a new active object
  - *FutRef* and *ActRef*: references for activities and futures (transparent)
- Semantics: *local* and *parallel* evaluation

Illustration: rule in semantic notation and in Isabelle/HOL

REPLY

$$\frac{\beta[f_k \mapsto s :: R, t'] \in \alpha[f_i \mapsto E[f_k] :: Q, t] :: C}{\alpha[f_i \mapsto E[f_k] :: Q, t] :: C \rightarrow_{\parallel} \alpha[f_i \mapsto E[s] :: Q, t] :: C}$$

Illustration: rule in semantic notation and in Isabelle/HOL

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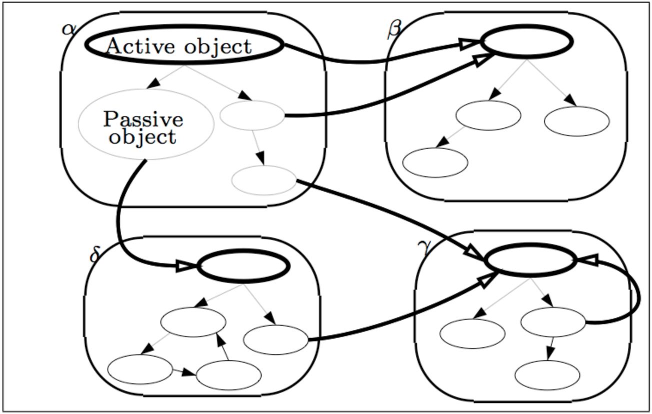
```
reply:
⟦ C α = Some (Ra, t); Ra(fi) = Some(E ↑(FutRef(fk)));
  C β = Some(Rb, t'); Rb(fk) = Some(s) ⟧
 ⟹ C →‖ C (α↦(Ra (fi ↦(E↑s)), t)
```

ASP: Topology of Activities



Characteristics of ASP

- Object-oriented language
- Asynchronous communication
- Parallel processes (active objects)
- Futures
  - Asynchronous method calls to active objects
  - Results of such calls are represented by futures until corresponding response is returned
- Synchronization through wait-by-necessity: wait occurs when a strict operation on a future is performed