Citation for published version:

DOI:
10.1016/j.entcs.2015.12.017

Publication date:
2015

Document Version
Peer reviewed version

Link to publication

Publisher Rights
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The published version is available via: http://dx.doi.org/10.1016/j.entcs.2015.12.017

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Download date: 07. Jan. 2019
Polymorphic Games and Program Equivalence

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Parametric Polymorphism, or genericity, is a key feature of high-level languages, often combined with state (e.g. dynamic dispatch).

By hiding information, it creates interesting problems for reasoning about program equivalence.

Games give concrete models of higher-order objects and functions with state (and other effects), which lend themselves to verification.
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Object of this work: To develop games models for programming languages with effects and higher-rank polymorphism, and use it to reason about program behaviour and equivalence.

Most material from “Game Semantics for a Polymorphic Programming Language”, JACM, 2013
System F Typing

Types:

\[ S, T ::= X \mid 1 \mid S \to T \mid S \times T \mid \forall X.T \]

\[ \Theta; \Gamma, x: T \vdash x: T \quad FV(T) \subseteq \Theta \]

\[ \Theta; \Gamma, x: S \vdash t: T \quad \Theta; \Gamma \vdash s: S \to T \]

\[ \Theta, X; \Gamma \vdash t: T \quad X \notin FV(\Gamma) \]

\[ \Theta; \Gamma \vdash \Lambda(X). t: \forall X. T \]

\[ \Theta; \Gamma \vdash \{ S \}: T[S/X] \quad FV(S) \subseteq \Theta \]

We write \( I \) for \( \forall X.X \to X \)
What are the inhabitants of $S \rightarrow T$?

- **Extensionally** — functions from the set of inhabitants of $S$ to the set of inhabitants of $T$.
- **Intensionally** — a blueprint for computing an inhabitant of $T$ by interaction with an inhabitant of $S$.

What are the inhabitants of $\forall X. T$:

- **Extensionally** — a product or intersection of the sets of inhabitants of $T[S]$ over all possible $S$. (Predicativity?)
- **Intensionally** — a blueprint for computing an inhabitant of $T[S/X]$ for any $S$.

“Type variables in generic programs act as placeholders for types which may be instantiated later”. 
Key Properties for our Model

- **Genericity** — capturing “uniformity” in a more intensional way than e.g. relational parametricity or dinaturality (although these play a role).

- **Full abstraction** — capturing *information hiding* in polymorphism, e.g. in equivalences such as
\[
\lambda x. (x \{l\}) \lambda y. y \simeq \lambda x. x : \forall X. (X \to X) \to \forall X. (X \to X).
\]

- **Effective presentability** — holding the prospect of verification applications. (Note that inhabitation in System F is not decidable).
A type $T$ is generic (w.r.t. a given theory) if for all terms $s, t : \forall X.S$, $s\{T\} = t\{T\}$ implies $s = t$.  

**Theorem** [Longo et. al.] Extending System F with genericity at all types* yields a consistent theory.

- The syntactic (Böhm tree) model is not generic.
- Any generic *extensional* model will contain “junk” — e.g. infinitely many elements at each type.
A type $T$ is \textit{generic} (w.r.t. a given theory) if for all terms $s, t : \forall X.S$, $s\{T\} = t\{T\}$ implies $s = t$.

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- The syntactic (Böhm tree) model is not generic.
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*Note that including e.g. the unit type breaks genericity.
Types with free variables are interpreted as “context arenas” with holes into which arenas may be plugged.

Second-order type structure is captured by a generalization of question/answer labelling and the bracketing condition.

To instantiate a generic strategy, the question/answer relation is used to infer a *copycat* relation between occurrences of the instantiated arena.
A context arena $A$ is a labelled bipartite forest $(M_A, \triangleright_A, \lambda_A, \triangleright_A)$, where

- $M_A$ is a set of *moves*.
- $\triangleright \subseteq M_A \times M_A$ is an *enabling relation*, making
- $\lambda_A : M_A \to \{Q, A\} \cup \mathbb{N}$ labels moves as *questions*, *answers* or “$i$-holes” for $i \in \mathbb{N}$.
- $\triangleright \subseteq Q_A \times M_A \times \text{Ans}_A$ is a *scoped question/answer relation* determining which (Player/Opponent) answers may be given in response to each (Opponent/Player) question.
We can interpret the syntax trees of second order types $X_1, \ldots, X_n \vdash A$ directly as context games:

- Moves are (paths to the) leaves of the tree (type variables).
- Each path enables the moves (paths) immediately to its left.
- A path which ends with a free variable $X_i$ is labelled with $i$ (an $i$-hole).

Leaves which are positively bound variables are questions.
Leaves which are negatively bound variables are answers.
Example: $\forall X. X \to X \to X$
\[ \forall X. (S \rightarrow X) \rightarrow (T \rightarrow X) \rightarrow X \] is the lifted sum arena \([S] \oplus [T]\).

\[ \forall X. (S \rightarrow X) \rightarrow (T \rightarrow X) \rightarrow X \]
Given an alternating path through the forest, we match up answers and questions as closing and opening parentheses:

\[
\left( \left[ \left( \left[ \right] \right) \right] \right)
\]

and require that:

If answer move \( a \) closes question \( q \), there is a move \( m \) such that
\[
m \vdash^* q, \ m \vdash^* a \text{ and } q \triangleright_m a.
\]
Play in $[\land X. \lambda f. \lambda x.(f \lambda y.x\{X\})]$: 

$$\forall X. \ ((((X \to X) \to \forall Y.Y) \to \forall Y.Y)$$
Play in $[[\lambda f. f \land X. \lambda x. (f \lambda y.y)\{X\}]].$

$[[((\forall X. (X \rightarrow X) \rightarrow \forall Y.Y) \rightarrow \forall Y.Y)]]$
Given a strategy (non-empty, even-branching, even-prefix-closed set of legal sequences) $\sigma : \forall X_{n+1}.A$, define $\sigma[B] : A[B/X_{n+1}]$ — the *instantiation* of a context arena $B$ into $\sigma$ at $X_{n+1}$ by replacing each question-answer pair in $\sigma$ with a *copycat link*. 
Plugging the arena ∀Y.Y → Y → Y:

∀Y.Y → Y → Y:

into the identity strategy on ∀X.X → X:

q

a

gives the identity on (∀Y.Y → Y → Y) → ∀Y.Y → Y → Y:
An Indexed Category of Context Arenas

We define an indexed category $\mathcal{G} : \mathcal{I}^{op} \to \text{CCC}$, where:

- $\mathcal{I}$ is the category in which objects are natural numbers and morphisms from $m$ to $n$ are $n$-tuples of second order types over $m$ free variables (composed by substitution).

- For each $n$, $\mathcal{G}(n)$ is the (cartesian closed) category in which object are second-order types over $n$ free variables and morphisms from $A$ to $B$ are strategies on $\forall X_1 \ldots \forall X_n.(A \Rightarrow B)$ (composed by parallel composition plus hiding).

- For each tuple $\langle B_1, \ldots, B_n \rangle : m \to n$, $\mathcal{G}\langle B_1, \ldots, B_n \rangle : \mathcal{G}(m) \to \mathcal{G}(n)$ is the corresponding substitution functor.

The inclusion $\{ J_{n+1} : \mathcal{G}(n) \to \mathcal{G}(n + 1) \mid n \in \mathbb{N} \}$ has an indexed left adjoint $\forall X_{n+1} : \mathcal{G}(n + 1) \to \mathcal{G}(n)$. 
**Proposition** For any type \( A \), instantiation is a *retraction*
\[
\]
Proposition For any type $A$, instantiation is a retraction
\[ \forall X. A[X] \sqsubseteq A[I/X]. \]

(\textbf{Corollary} $I$ is a \textit{generic} type for our model. (If
\([M : \forall X. T] \neq [N : \forall X. T]\) then \([M\{I\} : T[I/X] \neq [N\{I\} : T[I/X]])\).
Our model is not fully complete for System F — strategies do not satisfy the visibility condition (and so they are not innocent or total, either).

In particular: the instantiation strategy $\sigma : \forall X. A \rightarrow A[B]$ does not satisfy visibility.
Example of a violation of visibility

At type $\forall X.((\forall Y.((X \rightarrow Y \rightarrow X) \rightarrow Y \rightarrow X)) \rightarrow X)$:

$\land X.\lambda f^{\forall Y.((X\rightarrow Y\rightarrow X)\rightarrow Y\rightarrow X)}.(f\{X \rightarrow X\} (\lambda x^X.\lambda g^{X\rightarrow X}.g \; x)) \; \lambda y^X.y$

$[\forall X.((\forall Y.(( X \rightarrow Y \rightarrow X) \rightarrow Y \rightarrow X)) \rightarrow X)]$
We add a constant $\text{new} : \forall X. \forall Y. (Y \rightarrow (Y \rightarrow I) \rightarrow X) \rightarrow X$
declaring a reference cell, and denoting a strategy with the same underlying play as the preceding example.
We add a constant \( \text{new} : \forall X.\forall Y. (Y \rightarrow (Y \rightarrow I) \rightarrow X) \rightarrow X \) declaring a reference cell, and denoting a strategy with the same underlying play as the preceding example.

Using \( \text{new} \), the section \( p : A[I/X] \rightarrow \forall X.A \) is definable as a term which stores pointers to preceding \( X \)-moves as references. We use this fact to prove finite definability/full abstraction for our model, reducing it to (essentially) the simply-typed model of Abramsky, Honda and McCusker.
Intensional semantics of polymorphic value types (“data driven”) is fundamentally different to computational types (“demand driven”).

Based on (re-engineering of) Honda and Yoshida’s semantics of call-by-value \( \lambda \)-calculus.
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Specifically, we need to break down moves into tuples of smaller “atoms”, including holes into which arenas may be plugged.
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Full abstraction is established by showing that \texttt{nat} is a generic type.
$\forall (X \times X \rightarrow X)$ has two initial Opponent $\bullet$ questions — which must be played together, and a single, contingent $\bullet$ answer which may point to either of them —

\[
X \times X \rightarrow X
\]

$\langle \bullet Q, \bullet Q \rangle$
∀(X × X → X) has two initial Opponent • questions — which must be played together, and a single, contingent • answer which may point to either of them —

\[
X \times X \rightarrow X
\]

\[
\langle •Q, •Q \rangle
\]

\[
•A
\]
Subtype polymorphism (System $F_{\leq}$) using dinaturality properties of instantiation to represent *bounded quantification*.

Type-operators — extending the syntactic representation of games with $\lambda$-abstraction and application of type variables in arenas.

Constraining the model — can we describe models with fewer/different effects, linear types, etc.

Verification — when the references can be tamed, the model appears to be suitable for an algorithmic approach.