

Signatures and models for syntax and operational semantics in the presence of variable binding

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Outline

1 Reduction monads

- Graphs
- Substitution

2 Syntax

- Operations
- Equations

3 Semantics

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Ingredients

- Programming languages (PLs) as graphs
 - (**Syntax**) vertices = terms
 - (**Semantics**) arrows = reductions between terms
- Parallel substitution: variables \mapsto terms
 - monads and modules over them
- (untyped PLs)

Example

λ -calculus with β -reduction:

• **Syntax:** $S, T ::= x \mid S \ T \mid \lambda x. S$

• **Reductions:** $(\lambda x. t) \ u \xrightarrow{\beta} t[x \mapsto u] \quad + \quad \text{congruences}$

modulo α -equivalence, e.g.

$$\lambda x. x = \lambda y. y$$

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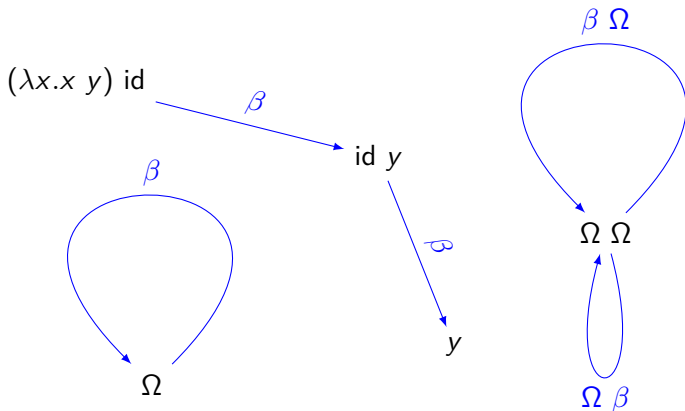
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PLs as graphs

Example: λ -calculus with β -reduction



- **(Syntax)** vertices = terms
- **(Semantics)** arrows = reductions (dedicated syntax: Cf labels)

Graphs

Definition

Graph = a quadruple (A, V, σ, τ) where

$$A \begin{matrix} \xrightarrow{\sigma} \\ \xrightarrow{\tau} \end{matrix} V$$

$$A = \{\text{arrows}\}$$

$$V = \{\text{vertices}\}$$

$$\sigma : \begin{array}{ccc} A & \rightarrow & V \\ t \xrightarrow{r} u & \mapsto & t \end{array}$$

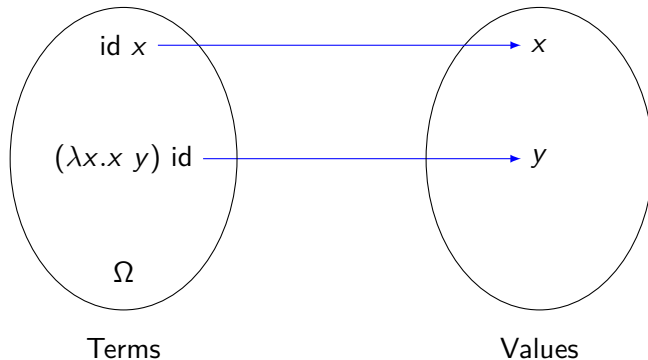
$$\tau : \begin{array}{ccc} A & \rightarrow & V \\ t \xrightarrow{r} u & \mapsto & u \end{array}$$

$$\sigma(r) \xrightarrow{r} \tau(r)$$

PLs as bipartite graphs

Example: λ -calculus cbv with big-step operational semantics

- term \rightarrow value
- variables = placeholders for values



Bipartite graphs

Definition

Bipartite graph = a quadruple (A, V_1, V_2, ∂) where

$$V_1 \xleftarrow{\sigma} A \xrightarrow{\tau} V_2$$

$$A = \{\text{arrows}\}$$

$$V_1 = \{\text{vertices in first group}\}$$

$$V_2 = \{\text{vertices in second group}\}$$

For simplicity, we focus on the particular case of **graphs**: $V_1 = V_2$.

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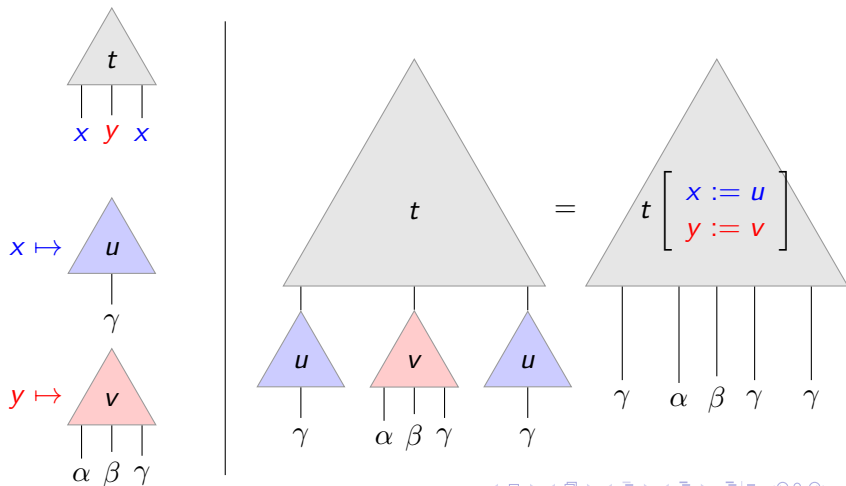
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Parallel substitution

Syntax comes with substitution

terms (e.g. λ -terms) = trees with free variables as (distinguished) leaves.



Parallel substitution made formal

Free variables indexing

$$X \mapsto \{\text{terms taking free variables in } X\}$$

Example: λ -calculus

$$L(\{x, y\}) = \left\{ \begin{array}{c} \triangle \\ \lambda z. z \end{array} , \begin{array}{c} \triangle \\ x \\ | \\ x \end{array} , \begin{array}{c} \triangle \\ y \\ | \\ y \end{array} , \begin{array}{c} \triangle \\ x \ y \\ | \quad | \\ x \quad y \end{array} , \dots \right\}$$

Parallel substitution

For any $f : X \rightarrow L(Y)$,

$$\begin{aligned} \text{bind}_f : L(X) &\rightarrow L(Y) \\ t &\mapsto t[x \mapsto f(x)] \quad (\text{or } t[f]) \end{aligned}$$

Monads

λ -calculus as a monad (L, bind, η)

① Parallel substitution (L, bind)

② Variables are terms

$$\eta_X : X \rightarrow L(X)$$

$$x \mapsto \begin{array}{c} \triangle \\ \underline{x} \\ | \\ x \end{array}$$

③ Monadics laws:

$$\underline{x}[f] = f(x)$$

$$t[x \mapsto \underline{x}] = t$$

+ associativity:

$$t[f][g] = t[x \mapsto f(x)[g]]$$

Substitution for semantics

Our notion of PL:

- **Syntax:** a monad (L, bind, η)
- **Semantics:**

- graphs $R(X) \xRightarrow[\tau]{\sigma} L(X)$ for each X

$R(X) =$ total set of reductions between terms taking free variables in X

- substitution of reduction: variables \mapsto **L -terms**.

$$\frac{t \xrightarrow{r} u}{t[f] \xrightarrow{r[f]} u[f]}$$

Substitution for semantics made formal

R as a **module** over L

For any $f : X \rightarrow L(Y)$,

$$\begin{aligned} \text{bind}_f : R(X) &\rightarrow R(Y) \\ r &\mapsto r[x \mapsto f(x)] \quad (\text{or } r[f]) \end{aligned}$$

s.t.

$$r[x \mapsto \underline{x}] = r \qquad r[f][g] = r[x \mapsto f(x)][g]$$

σ and τ as L -**module morphisms**

$$\begin{array}{ccc} \sigma(r[f]) & \xrightarrow{r[f]} & \tau(r[f]) \\ \text{Then, } \frac{\sigma(r) \xrightarrow{r} \tau(r)}{\sigma(r)[f] \xrightarrow{r[f]} \tau(r)[f]} & \text{enforces} & \begin{array}{l} \sigma(r[f]) = \sigma(r)[f] \\ \tau(r[f]) = \sigma(r)[f] \end{array} \end{array}$$

Commutation with substitution \Leftrightarrow Module morphisms $\sigma, \tau : R \rightarrow L$.

Reduction monads

Definition

A **reduction monad** is a quadruple $R \xRightarrow[\tau]{\sigma} T$ s.t.

- $T = \text{monad}$
- $R = \text{module over } T$
- $\sigma, \tau : R \rightarrow T$ are T -module morphisms.

Example

λ -calculus with β -reduction.

How can we specify a reduction monad?

- 1 signature for the (syntactic) operations for the monad;
- 2 reduction rules, **involving some specified syntactic operations**.

Use of a general notion of **signature** managing this **dependency**.

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Overview

- Syntax = monad L
- Operations = module morphisms $\Sigma(L) \rightarrow L$
- 1-signatures specify operations
- 2-signatures specify operations + equations.

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Operations as module morphisms

Application commutes with substitution

$$(t \ u)[x \mapsto v_x] = t[x \mapsto v_x] \ u[x \mapsto v_x]$$

Categorical formulation

$L \times L$ supports
 L -substitution



$L \times L$ is a **module over** L

application commutes
with substitution



$\text{app} : L \times L \rightarrow L$ is a
module morphism

[Hirschowitz-Maggesi 2007 : Modules over Monads and Linearity]

Examples of modules

module over a monad T : supports the T -monadic substitution

Examples

- T itself
- $M \times N$ for any modules M and N :

$$\forall (t, u) \in M(X) \times N(X), \quad X \xrightarrow{f} T(Y),$$

$$\boxed{(t, u)[f] = (t[f], u[f])} \in M(Y) \times N(Y)$$

- $M' =$ **derivative** of a module M :

X extended with a fresh variable \diamond

$$M'(X) = M(\overbrace{X \amalg \{\diamond\}})$$

used to model an operation binding a variable (Cf next slide).

Operations as module morphisms

Case of λ -calculus

Operations = module morphisms = maps commuting with substitution:

Example: λ -calculus

$$\text{app} : L \times L \rightarrow L$$

$$\text{abs} : L' \rightarrow L \quad \left\{ \begin{array}{l} \text{abs}_X : L(X \amalg \{\diamond\}) \rightarrow L(X) \\ t \mapsto \lambda \diamond . t \end{array} \right.$$

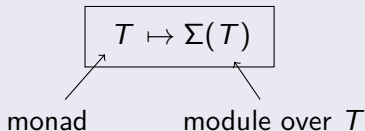
Combine operations into a single one:

$$[\text{app}, \text{abs}] : (L \times L) \amalg L' \rightarrow L$$

1-signatures and their models

Definition

A **1-signature** Σ is a (functorial) assignment



e.g. $\Sigma_{LC}(T) = (T \times T) \amalg T'$

Definition

A **model** of a 1-signature Σ is a pair $M = (T, m)$ where

- T is a monad
- $\Sigma(T) \xrightarrow{m} T$ is a module morphism

Example: λ -calculus

$$[\text{app}, \text{abs}] : \Sigma_{LC}(L) \rightarrow L$$

Syntax

(suitable notion of model morphism [Hirschowitz-Maggesi 2012])

Definition


The **syntax** specified by a 1-signature Σ is the initial object in its category of models.

Question: Does the syntax exist for every 1-signature?

Answer: No.

Counter-example: $\Sigma(R) = \mathcal{P} \circ R$

Powerset endofunctor on *Set*.



Examples of 1-signatures generating syntax

λ -calculus

Signature	$T \mapsto (T \times T) \times T'$
Model	$(T \times T) \amalg T' \rightarrow T$, or $\left(\begin{array}{c} T \times T \rightarrow T \\ T' \rightarrow T \end{array} \right)$
Syntax	initial model: $(L \times L) \amalg L' \xrightarrow{[\text{app}, \text{abs}]} L$

Language with a constant and a binary operation

Signature	$T \mapsto 1 \amalg (T \times T)$
Model	$1 \amalg (T \times T) \rightarrow T$, or $\left(\begin{array}{c} 1 \rightarrow T \\ T \times T \rightarrow T \end{array} \right)$
Syntax	initial model

Can we generalize this pattern?

Initial semantics for algebraic 1-signatures

Definition

Algebraic 1-signatures = 1-signatures built out of derivatives, finite products, disjoint unions, and the 1-signature $\Theta : T \mapsto T$.

Algebraic 1-signatures \simeq binding signatures [Fiore-Plotkin-Turi 1999]
 \Rightarrow specification of n -ary operations, possibly binding variables.

Theorem (Hirschowitz-Maggesi 2007)

Syntax exists for any algebraic 1-signature.

Question: Can we enforce some equations in the syntax?

e.g. *commutativity* or *associativity* of a binary operation.

Quotient of algebraic signatures

Theorem (Ahrens-Lafont-Hirschowitz-Maggesi 2018)

Syntax exists for any “quotient” of algebraic 1-signatures.

Example

a *commutative* binary operation $+$:

$$\forall a, b, \quad a + b = b + a$$

What about an
associative
operation?



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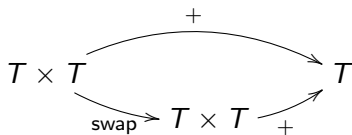
Example: a commutative binary operation

Specification of a binary operation

1-signature	$T \mapsto T \times T$
model	$T \times T \xrightarrow{+} T$

Question What is an appropriate notion of model for a **commutative** binary operation?

Answer A monad T equipped with a binary operation $T \times T \xrightarrow{+} T$ which is commutative, i.e.:



where $\text{swap}(t, u) = \text{swap}(u, t)$

Equations

$\Sigma = 1$ -signature (e.g. binary operation $\Sigma(T) = T \times T$)

Definition

A Σ -**equation** $A \xRightarrow[u]{v} B$ is a (functorial) assignment

$$M \mapsto \left(A(M) \xRightarrow[u_M]{v_M} B(M) \right)$$

model of Σ parallel pair of ' M '-module morphisms

Example (Binary commutative operation)

$$\Sigma(T) = T \times T$$

$$\begin{array}{ccc} T \times T & & \\ \downarrow + & \mapsto & T \times T \\ T & & \end{array} \quad \begin{array}{ccc} & + & \\ & \curvearrowright & \\ T \times T & \xrightarrow{\text{swap}} & T \times T \end{array} \quad \begin{array}{ccc} & & \\ & & + \\ & \nearrow & \end{array}$$

2-signatures and their models

Definition

A **2-signature** is a pair (Σ, E) where

- Σ is a 1-signature for monads
- E is a set of Σ -equations

Definition

A **model** of a 2-signature (Σ, E) consists of:

- a model $M = \Sigma(T) \xrightarrow{m} T$ of Σ s.t.

$$\forall A \xRightarrow[u]{v} B \in E, \quad \boxed{u_M = v_M} : A(M) \rightarrow B(M)$$

morphism of models = morphisms between underlying models of Σ .

Initial semantics for algebraic 2-signatures

Theorem (Ahrens-Lafont-Hirschowitz-Maggesi 2019)

Any **algebraic** 2-signature has an initial model.

Definition

A 2-signature (Σ, E) is **algebraic** if:

- Σ is algebraic
- E consists of **elementary** Σ -equations

Main examples of elementary Σ -equations

$A \rightrightarrows B$ s.t.

$$A \left(\begin{array}{c} \Sigma(T) \\ \downarrow \\ T \end{array} \right) = \Phi(T) \quad B \left(\begin{array}{c} \Sigma(T) \\ \downarrow \\ T \end{array} \right) = T$$

for some *algebraic* 1-signature Φ .

Example: fixpoint operator

Definition [AHLM CSL 2018]

A **fixpoint operator** in a monad R is a module morphism $\text{fix}: R' \rightarrow R$ s.t. for any term $t \in R(X \amalg \{\diamond\})$, $\text{fix}(t) = t[\diamond \mapsto \text{fix}(t)]$

Intuition:

$\text{fix}(t) := \text{let rec } \diamond = t \text{ in } t$

Algebraic 2-signature $(\Sigma_{\text{fix}}, E_{\text{fix}})$ of a fixpoint operator:

$$\Sigma_{\text{fix}}(R) := R' \qquad E_{\text{fix}} = \left\{ \begin{array}{ccc} & \xrightarrow{\text{fix}(t)} & \\ R' & & R \\ & \xleftarrow{t[\diamond \mapsto \text{fix}(t)]} & \\ & t & \end{array} \right\}$$

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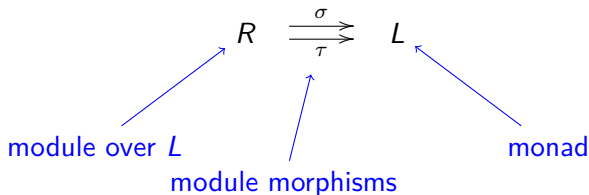
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Specifying reduction monads

λ -calculus with β -reduction as a reduction monad:



- vertices = L = initial model of the signature of λ -calculus.
- arrows = $R, \sigma, \tau = ?$
 - **Idea:** defined inductively through reduction rules.

$$(\lambda x.t) u \rightarrow t[x := u] \qquad \frac{t \rightarrow t'}{t u \rightarrow t' u} \qquad \dots$$

Analysis of a reduction rule

Example: binary congruence for application.

metavariables: as a L -module L^4

$$\overbrace{t, t', u, u'} \mapsto$$

\mapsto

$$\frac{t \rightarrow t' \quad u \rightarrow u'}{t u \rightarrow t' u'}$$

hypotheses

conclusion

Hypothesis/conclusion = pair of λ -terms using metavariables

- as parallel module morphisms $L^4 \rightrightarrows L$

$$\text{e.g. } t u \rightarrow t' u' : \quad \begin{array}{l} (t, t', u, u') \mapsto t u \\ (t, t', u, u') \mapsto t' u' \end{array}$$

- Generalization:** $L \rightsquigarrow$ any model T of Σ_{LC} , with application denoted by $\text{app} : T \times T \rightarrow T$,

$$\text{e.g. } t u \rightarrow t' u' : \quad \begin{array}{l} (t, t', u, u') \mapsto \text{app}(t, u) \\ (t, t', u, u') \mapsto \text{app}(t', u') \end{array}$$

Reduction rules

Definition

Let Σ = signature for monads (e.g. $\Theta \times \Theta$ for congruence for application).

Definition of Σ -reduction rules

A Σ -**reduction rule** $(\vec{\sigma}, \vec{\tau})$

$$\frac{\sigma_1 \rightarrow \tau_1 \quad \dots \quad \sigma_n \rightarrow \tau_n}{\sigma_0 \rightarrow \tau_0}$$

assigns (functorially) to each Σ -model T :

- $V(T) = T$ -module of metavariables (e.g. $V(T) = T^4$)
- parallel T -module morphisms $V(T) \begin{matrix} \xrightarrow{\sigma_{i,T}} \\ \xrightarrow{\tau_{i,T}} \end{matrix} T'^{\dots'}$

We write

$$\sigma_i, \tau_i : V \rightarrow \Theta^{(n_i)} \quad n_i = \text{number of derivatives}$$

Reduction signatures

Definition

A **reduction signature** is a pair (Σ, \mathfrak{R}) where

- Σ is a signature for monads
- \mathfrak{R} is a family of Σ -reduction rules

Example: λ -calculus with β -reduction

- $\Sigma = \Theta \times \Theta + \Theta'$ for app and abs.
- Σ -reduction rules:
 - congruence for application
 - congruence for abstraction:

$$\frac{u \rightarrow u'}{\lambda x. u \rightarrow \lambda x. u'} \rightsquigarrow \frac{\pi_1 \rightarrow \pi_2}{\text{abs} \circ \pi_1 \rightarrow \text{abs} \circ \pi_2} \quad T' \times T' \xRightarrow[\pi_2, T]{\pi_1, T} T'$$

- β -reduction

Models

Definition

A **model** of a signature (Σ, \mathfrak{R}) consists of:

- a reduction monad $R \xRightarrow[\tau]{\sigma} T$ with a Σ -model structure on T
- for each reduction rule

$$\boxed{\frac{\sigma_1 \rightarrow \tau_1 \quad \dots \quad \sigma_n \rightarrow \tau_n}{\sigma_0 \rightarrow \tau_0}} \quad V \xRightarrow[\tau_i]{\sigma_i} \Theta(n_i) \quad \text{in } \mathfrak{R},$$

- a mapping, for each $v \in V(T)(X)$,

$$\begin{pmatrix} \sigma_1(v) \xrightarrow{r_1} \tau_1(v) \\ \dots \\ \sigma_n(v) \xrightarrow{r_n} \tau_n(v) \end{pmatrix} \mapsto \sigma_0(v) \xrightarrow{op(r_1, \dots, r_n)} \tau_0(v)$$

- compatible with substitution:

$$op(r_1, \dots, r_n)[f] = op(r_1[f], \dots, r_n[f])$$

Initiality

(appropriate notion of model morphisms)

Theorem

Σ has an initial model (e.g. Σ is algebraic) $\Rightarrow (\Sigma, \mathfrak{R})$ has an initial model.

Examples

- The reduction signature of the previous slide for λ -calculus with β -reduction has an initial model.
- λ -calculus with explicit substitution [Kesner 2009].
A Theory of Explicit Substitutions with Safe and Full Composition

Generalizing from graphs to bipartite graphs yields more examples:

Examples

- (big step) cbv λ -calculus.
- π -calculus

Summary

- The **first main message** of your talk in one or two lines.
- The **second main message** of your talk in one or two lines.
- Perhaps a **third message**, but not more than that.
- Outlook
 - What we have not done yet.
 - Even more stuff.

For Further Reading I



A. Author.

Handbook of Everything.

Some Press, 1990.



S. Someone.

On this and that.

Journal on This and That. 2(1):50–100, 2000.