

Semantics of Functional Programming

PCF and its Operational Semantics

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Why semantics?

The hitch is that defining a language a posteriori, i.e. after its design has been frozen by the existence of implementations and uses, can hardly improve it. To create a good programming language, semantics must be used a priori, as a design tool that embodies and extends the intuitive notion of uniformity.

— John C. Reynolds

- Implementation-led design.
- *C++ The International Standard*, 1338 pp., 2012.
Note that the committee consists of 200+ people.
- 1900+ language issues!

Revision 89, 2014-05-27: Issues [1351](#), [1356](#), [1465](#), [1590](#), [1639](#), [1708](#), and [1810](#) were returned to "review" status for further discussion. Restored [issue 1397](#) to "ready"; it had incorrectly been moved back to "drafting" because of a misunderstood comment. Added new issues [1866](#), [1867](#), [1868](#), [1869](#), [1870](#), [1871](#), [1872](#), [1873](#), [1874](#), [1875](#), [1876](#), [1877](#), [1878](#), [1879](#), [1880](#), [1881](#), [1882](#), [1883](#), [1884](#), [1885](#), [1886](#), [1887](#), [1888](#), [1889](#), [1890](#), [1891](#), [1892](#), [1893](#), [1894](#), [1895](#), [1896](#), [1897](#), [1898](#), [1899](#), [1900](#), [1901](#), [1902](#), [1903](#), [1904](#), [1905](#), [1906](#), [1907](#), [1908](#), [1909](#), [1910](#), [1911](#), [1912](#), [1913](#), [1914](#), [1915](#), [1916](#), [1917](#), [1918](#), [1919](#), [1920](#), [1921](#), [1922](#), [1923](#), [1924](#), [1925](#), [1926](#), [1927](#), [1928](#), [1929](#), [1930](#), and [1931](#).

Standard ML

- Semantics-led design.
- R. Milner, M. Tofte, R. Harper, and D. MacQueen *The Definition of **Standard ML** (Revised)*, 128 pp., 1997.
- Standard ML is a safe, modular, strict, functional, polymorphic programming language . . . and a formal definition with a proof of soundness.

Overview

In this lecture, we will present simply typed lambda calculus in a different manner, where terms and typing rules are introduced separately. In this approach, terms might not be well-typed at all.

Then, we discuss its computational meaning by **one-step reduction** and define many-step reduction. Later we introduce the concept of **type safety**.

Finally, we extend simply typed lambda calculus with natural numbers and general recursion. This extension is called **PCF**, *Programming Computable Functional*. We formalise new features by what we have learnt later.

The approach *à la* Curry

We introduce a different approach to simply typed lambda calculus where terms and typing rules are introduced separately.

$$\frac{x \text{ var}}{x \text{ term}}$$

$$\frac{x \text{ var} \quad M \text{ term}}{\lambda x. M \text{ term}}$$

$$\frac{M \text{ term} \quad N \text{ term}}{M N \text{ term}}$$

$$\frac{}{\Gamma, x : \sigma, \Delta \vdash x : \sigma} \text{ (var)}$$

$$\frac{\Gamma, x : \sigma \vdash M : \tau}{\Gamma \vdash \lambda x. M : \sigma \rightarrow \tau} \text{ (abs)}$$

$$\frac{\Gamma \vdash M : \sigma \rightarrow \tau \quad \Gamma \vdash N : \sigma}{\Gamma \vdash M N : \tau} \text{ (app)}$$

The existence of ill-typed terms

In contrast the approach *à la* Church where every term is introduced with a type, there are ill-typed terms in the approach *à la* Curry:

Example 1

$(\lambda x. x x)$ is a term if x is a variable, because

$$\frac{x \text{ var} \quad \frac{\frac{x \text{ var}}{x \text{ term}} \quad \frac{x \text{ var}}{x \text{ term}}}{x x \text{ term}}}{\lambda x. x x \text{ term}}$$

However, $(\lambda x. x x)$ cannot be assigned a type unless $\sigma \rightarrow \sigma = \sigma$.

Reduction

One-step reduction relation \rightsquigarrow between terms is introduced to describe the flow of computation from a term to another term in a single step, regardless of types. We introduce two rules for applications:

$$\frac{M \rightsquigarrow M'}{M N \rightsquigarrow M' N} (\rightsquigarrow\text{-lapp})$$
$$\frac{}{(\lambda x. M) N \rightsquigarrow M[N/x]} (\rightsquigarrow\text{-app})$$

Example 2

$(\lambda x. \lambda y. x) M N$ can reduce to M by the following derivation

$$\frac{\frac{}{(\lambda x. \lambda y. x) M \rightsquigarrow (\lambda y. M)} (\rightsquigarrow\text{-app})}{((\lambda x. \lambda y. x) M) N \rightsquigarrow (\lambda y. M) N} (\rightsquigarrow\text{-lapp})$$

Many-step reduction

As we will mostly discuss a sequence of reductions, it is convenient to define another relation \rightsquigarrow^* so that $M \rightsquigarrow^* N$ means M reduces to N in finitely many steps.

Definition 3

The many-step reduction relation \rightsquigarrow^* is defined inductively by

$$\frac{}{M \rightsquigarrow^* M} \quad \frac{M_1 \rightsquigarrow M_2 \quad M_2 \rightsquigarrow^* M_3}{M_1 \rightsquigarrow^* M_3}$$

Proposition 4 (Reflexivity of \rightsquigarrow^*)

For every term M , $M \rightsquigarrow^ M$.*

For example, one has

$$(\lambda x. \lambda y. x) M N \rightsquigarrow^* (\lambda y. M) N$$

by the derivation

$$\frac{\frac{(\lambda x. \lambda y. x) M \rightsquigarrow (\lambda y. M)}{((\lambda x. \lambda y. x) M) N \rightsquigarrow (\lambda y. M) N} \quad (\lambda y. M) N \rightsquigarrow^* (\lambda y. M) N}{(\lambda x. y. x) M N \rightsquigarrow^* (\lambda y. M) N}$$

Exercise. Evaluate the following terms (formally or informally).

1 $(\lambda x. x) y$

2 $(\lambda x. x x) (\lambda x. x x)$

3 $(\lambda x. \lambda y. \lambda z. y) M_0 M_1 M_2$

Induction on derivation

Every instance of $M \rightsquigarrow^* N$ must be constructed by one of the cases, so we can analyse its structure case by case.

Proposition 5 (Transitivity of \rightsquigarrow^*)

For every three terms M_1 , M_2 , and M_3 , if $M_1 \rightsquigarrow^ M_2$ and $M_2 \rightsquigarrow^* M_3$, then $M_1 \rightsquigarrow^* M_3$.*

Given derivations of $M_1 \rightsquigarrow^* M_2$ and $M_2 \rightsquigarrow^* M_3$, we do case analysis on the derivation of $M_1 \rightsquigarrow^* M_2$. Also, we can assume that the premise satisfy this property, that is, the induction hypothesis.

Proof.

- 1 For $\overline{M_1 \rightsquigarrow^* M_1}$, it unifies M_2 to M_1 , so the given derivation $M_2 \rightsquigarrow^* M_3$ is just the goal derivation as $M_1 = M_2$.
- 2 For $\frac{M_1 \rightsquigarrow M \quad M \rightsquigarrow^* M_2}{M_1 \rightsquigarrow^* M_2}$, we infer that $M \rightsquigarrow^* M_3$ by induction hypothesis, so we derive the goal

$$\frac{M_1 \rightsquigarrow M \quad M \rightsquigarrow^* M_3}{M_1 \rightsquigarrow^* M_3}$$



Similarly, we can do induction on the formation of terms, typing rules, and any other inductive definitions.

Exercise. Show that if $M \rightsquigarrow^* M'$ then $M N \rightsquigarrow^* M' N$ for any term N by induction on the derivation of $M \rightsquigarrow^* M'$.

Type safety: well-typed programs don't go wrong

Well-typed closed terms have some nice properties. First, every well-typed closed term can reduce further or it is a **value**.

Theorem 6 (Progress Theorem)

If $\vdash M : \tau$, then either $M \rightsquigarrow M'$ for some M' or $M = \lambda x. M'$.

To show this property, we do structural induction on the derivation of $\vdash M : \tau$ and either produce a derivation of $M \rightsquigarrow M'$ or show that $M = \lambda x. M'$.

Proof.

- 1 The context of $\overline{\Gamma, x : \sigma, \Delta \vdash x : \sigma}$, is non-empty, so it does not satisfy the assumption.
- 2 For that case $\frac{x : \sigma \vdash M : \tau}{\vdash \lambda x. M : \sigma \rightarrow \tau}$ (abs), we have already given a term in this form $\lambda x. M$.
- 3 For $\frac{\vdash M : \sigma \rightarrow \tau \quad \vdash N : \sigma}{\vdash M N : \tau}$ (app), by introduction hypothesis either $M \rightsquigarrow M'$ for some M' or $M = \lambda x. M'$. For the former case, we apply (\rightsquigarrow -lapp):

$$\frac{M \rightsquigarrow M'}{M N \rightsquigarrow M' N}$$

For the latter case, we apply (\rightsquigarrow -app)

$$\frac{}{(\lambda x. M') N \rightsquigarrow M'[N/x]}$$



Moreover, the type of a well-typed closed term is always preserved by reductions:

Theorem 7 (Preservation Theorem)

If $\vdash M : \tau$ and $M \rightsquigarrow M'$, then $\vdash M' : \tau$.

However, to show this property, we need the following lemma saying that types are preserved by substitution.

Lemma 8 (Substitution Lemma)

If $\Gamma, x : \sigma \vdash M : \tau$ and $\Gamma \vdash N : \sigma$, then $\Gamma \vdash M[N/x] : \tau$.

By the introduction on the derivation of $\vdash M : \tau$ and $M \rightsquigarrow M'$ at the same time.

Proof of Preservation Theorem.

- 1 $\vdash M : \tau$ cannot be constructed by (*var*), since the context is empty.
- 2 For $\frac{x : \sigma \vdash M : \tau}{\vdash \lambda x. M : \sigma \rightarrow \tau}$, there is no reduction rule for $\lambda x. M$, so a derivation $(\lambda x. M) \rightsquigarrow M'$ cannot exist.
- 3 For $\frac{\vdash M : \sigma \rightarrow \tau \quad \vdash N : \sigma}{\vdash M N : \tau}$, we do induction on the derivation of $M N \rightsquigarrow M'$.



Reductions on ill-typed terms

Reductions can be applied to ill-typed terms and it reduces to a well-typed closed term!

$$(\lambda x. \lambda y. x) (\lambda x. x) (\lambda x. x x) \rightsquigarrow^* (\lambda x. x)$$

On the other hand, the reduction of ill-typed terms may not reduce to a value at all

$$x x \not\rightarrow$$

Summary

To define a language, we specify following sets of rules

Syntax type, term, and typing rules.

Semantics reduction rules.

In particular, well-typed closed terms share type safety:

Progress Theorem for every well-typed closed term, it either can reduce further or is a value;

Preservation Theorem for every well-typed closed term, its type is preserved by reduction.

Next, we add some features to simply typed lambda calculus and type safety remains.

Introduction to PCF

PCF, which stands for **P**rogramming **C**omputable **F**unctionals, is a functional programming language and it consists of

- 1 simply typed lambda calculus,
- 2 natural numbers, and
- 3 general recursion (to be explained).

We will introduce the latter two features step by step.

It has two rules of type formation:

$$\frac{}{\text{nat } \mathbf{set}} \qquad \frac{\tau_1 \mathbf{set} \quad \tau_2 \mathbf{set}}{\tau_1 \rightarrow \tau_2 \mathbf{set}}$$

Still, 'set' is a synonyms of 'type'.

Term formation, typing, and reduction for natural numbers

Every natural number is either zero or a successor of some natural number.

$$\frac{}{\text{zero \textbf{term}}}$$

$$\frac{}{\Gamma \vdash \text{zero} : \text{nat}} \text{ (z)}$$

$$\frac{M \textbf{ term}}{\text{suc } M \textbf{ term}}$$

$$\frac{\Gamma \vdash M : \text{nat}}{\Gamma \vdash \text{suc } M : \text{nat}} \text{ (s)}$$

The reduction of (suc M) is given by its subterm M:

$$\frac{M \rightsquigarrow M'}{\text{suc } M \rightsquigarrow \text{suc } M'} \text{ (}\rightsquigarrow\text{-suc)}$$

Values: canonical elements

Values are basic forms of terms of each kind of types and they are defined independent of their types in the approach *à la* Curry.

Definition 9

A **value** is a term of the following form:

$$\frac{}{\text{zero } \mathbf{val}} \quad \frac{M \mathbf{val}}{\text{suc } M \mathbf{val}} \quad \frac{}{\lambda x. M \mathbf{val}}$$

Define **numerals** $\underline{0}$ for zero and $\underline{n+1}$ for $\text{suc } \underline{n}$ inductively.

Example 10

By this formation, we have well-typed values $\text{suc } (\text{suc } \text{zero})$, $\lambda x. \text{suc } x$, and $\lambda x. x$, and also ill-typed values $\text{suc } \lambda x. x$, $\lambda y. y \ y$.

Moreover, we can do branching according to the argument is zero or not.

$$\frac{\text{M term} \quad \text{M}_0 \text{ term} \quad x \text{ var} \quad \text{M}_1 \text{ term}}{\text{ifz}(\text{M}; \text{M}_0; x. \text{M}_1) \text{ term}}$$

$$\frac{\Gamma \vdash \text{M} : \text{nat} \quad \Gamma \vdash \text{M}_0 : \tau \quad \Gamma, x : \text{nat} \vdash \text{M}_1 : \tau}{\Gamma \vdash \text{ifz}(\text{M}; \text{M}_0; x. \text{M}_1) : \tau} \text{ (ifz)}$$

accompanying with three reductions rules

$$\frac{\text{M} \rightsquigarrow \text{M}'}{\text{ifz}(\text{M}; \text{M}_0; x. \text{M}_1) \rightsquigarrow \text{ifz}(\text{M}'; \text{M}_0; x. \text{M}_1)} (\rightsquigarrow\text{-ifz})$$

$$\frac{}{\text{ifz}(\text{zero}; \text{M}_0; x. \text{M}_1) \rightsquigarrow \text{M}_0} (\rightsquigarrow\text{-ifz}_0)$$

$$\frac{\text{suc M val}}{\text{ifz}(\text{suc M}; \text{M}_0; x. \text{M}_1) \rightsquigarrow \text{M}_1[\text{M}/x]} (\rightsquigarrow\text{-ifz}_1)$$

Example: predecessor

The predecessor of natural numbers can be defined as

$$\text{pred} := \lambda x. \text{ifz}(x; \underline{0}; y. y) : \text{nat} \rightarrow \text{nat}$$

with the following typing derivation:

$$\frac{\frac{\frac{\Gamma \vdash x : \text{nat} \quad \Gamma \vdash \underline{0} : \text{nat} \quad \Gamma, y : \text{nat} \vdash y : \text{nat}}{\Gamma \vdash \text{ifz}(x; \underline{0}; y. y) : \text{nat}}}{\vdash \lambda x. \text{ifz}(x; \underline{0}; y. y) : \text{nat} \rightarrow \text{nat}}}$$

where $\Gamma := x : \text{nat}$.

Exercise.

- 1 Show that $\text{pred } \underline{0} \rightsquigarrow^* \underline{0}$ and $\text{pred } \underline{n+1} \rightsquigarrow^* \underline{n}$.
- 2 Define $\text{flip} : \text{nat} \rightarrow \text{nat}$ such that $\text{flip } \underline{0} \rightsquigarrow^* \underline{1}$ and $\text{flip } \underline{n+1} \rightsquigarrow^* \underline{0}$.

Term formation, typing rule, and reduction for general recursion

The Y operator, used to do general recursion, has the same term formation as λ -abstraction and a similar typing rules.

$$\frac{x \text{ var} \quad M \text{ term}}{Yx. M \text{ term}}$$

$$\frac{\Gamma, x : \sigma \vdash M : \sigma}{\Gamma \vdash Yx. M : \sigma} (Y)$$

Each occurrence of $Yx. M$ reduces to an substitution of x in M by itself:

$$\frac{}{Yx. M \rightsquigarrow M[Yx. M/x]} (\rightsquigarrow\text{-fix})$$

Example 11 (Divergent term)

Consider the term $Yx. x$ which never reduces to any value

$$Yx. x \rightsquigarrow x[Yx. x] = Yx. x \rightsquigarrow Yx. x \rightsquigarrow \dots$$

Example: calculating the factorials

The factorial of n is usually defined recursively

$$\text{fact}: n \mapsto \begin{cases} 1 & \text{if } n = 0 \\ n \times \text{fact}(n') & \text{if } n = n' + 1 \end{cases}$$

This is a *fixpoint* of the higher-order function

$F: (\mathbb{N} \rightarrow \mathbb{N}) \rightarrow (\mathbb{N} \rightarrow \mathbb{N})$ defined by

$$F(f): n \mapsto \begin{cases} 1 & \text{if } n = 0 \\ n \times f(n') & \text{if } n = n' + 1 \end{cases}$$

for any $f: \mathbb{N} \rightarrow \mathbb{N}$, satisfying $F(\text{fact}) = \text{fact}$.

The higher-order function $F: (\mathbb{N} \rightarrow \mathbb{N}) \rightarrow (\mathbb{N} \rightarrow \mathbb{N})$ can be presented in **PCF** as

$$F := \lambda f. F'$$

with

$$F' := \lambda n. \text{ifz}(n; \underline{1}; m. n \times (f \ m)).$$

$\Upsilon f. F''$ is a a fixpoint of F

$$\begin{aligned} (\lambda f. F') (\Upsilon f. F') &\rightsquigarrow F'[(\Upsilon f. F')/f] \\ &= \lambda n. \text{ifz}(n; \underline{1}; m. n \times (\Upsilon f. F') \ m) \end{aligned}$$

Exercise. Show that fact $\underline{n} \rightsquigarrow^* \underline{n!}$ by induction on \underline{n} .

Type safety for **PCF**

Theorem 12 (Progress Theorem)

If $\vdash M : \tau$ then either M is a value or there exists M' such that $M \rightsquigarrow M'$.

Theorem 13 (Preservation Theorem)

If $\vdash M : \tau$ and $M \rightsquigarrow N$ then $\vdash N : \tau$.

All follow the same pattern in the situation for simply typed lambda calculus.¹

¹To be proved in **Agda** formally.

Another reduction relation

Instead of the one-step reduction relation \rightsquigarrow , we turn to the **big-step** reduction relation \Downarrow between terms, formulating the notion that a term M reduce to a value V eventually.

- simply typed lambda calculus

$$\frac{}{\lambda x. M \Downarrow \lambda x. M} (\Downarrow\text{-lam})$$

$$\frac{M \Downarrow \lambda x. E \quad E[N/x] \Downarrow V}{M N \Downarrow V} (\Downarrow\text{-app})$$

- natural numbers

$$\frac{}{\text{zero} \Downarrow \text{zero}} (\Downarrow\text{-zero})$$

$$\frac{M \Downarrow V}{\text{suc } M \Downarrow \text{suc } V} (\Downarrow\text{-suc})$$

■ if-zero test

$$\frac{M \Downarrow \text{zero} \quad M_0 \Downarrow V}{\text{ifz}(M; M_0; x. M_1) \Downarrow V} (\Downarrow\text{-ifz}_0)$$

$$\frac{M \Downarrow \text{suc } N \quad M_1[N/x] \Downarrow V}{\text{ifz}(M; M_0; x. M_1) \Downarrow V} (\Downarrow\text{-ifz}_1)$$

■ general recursion

$$\frac{M[Yx. M/x] \Downarrow V}{Yx. M \Downarrow V} (\Downarrow\text{-fix})$$

$$\frac{\frac{\lambda x. \text{ifz}(x; \underline{0}; y. y) \Downarrow \lambda x. \text{ifz}(x; \underline{0}; y. y)}{\lambda x. \text{ifz}(x; \underline{0}; y. y) \underline{3} \Downarrow \underline{2}} \quad \frac{\frac{\vdots}{\underline{3} \Downarrow \text{suc } \underline{2}} \quad \frac{\vdots}{y[\underline{2}/y] \Downarrow \underline{2}}}{\text{ifz}(x; \underline{0}; y. y)[\underline{3}/x] \Downarrow \underline{2}}$$

Figure: Derivation of $\text{pred } \underline{3} \Downarrow \underline{2}$

Exercise.

- 1 Show that $\text{fact } \underline{0} \Downarrow \underline{1}$.
- 2 Show that $\text{flip } \underline{0} \Downarrow \underline{1}$ and $\text{flip } \underline{n+1} \Downarrow \underline{0}$.

Reduction on values

We shall justify the intended meaning. Whenever $M \Downarrow V$, the term V is always a value; every value is in its simplest form.

Lemma 14

For every terms M and V , the term V is a value if $M \Downarrow V$.

Proof.

By induction on the derivation of $M \Downarrow V$. □

Lemma 15

If V is a value, then $V \Downarrow V$.

Proof.

By induction on the derivation of V **val**. □

Agreement of big-step and one-step semantics

Theorem 16

For every term M and V , $M \Downarrow V$ if and only if $M \rightsquigarrow^ V$ with V **val**.*

Proof sketch.

- 1 Show that if $M \Downarrow V$ then $M \rightsquigarrow^* V$ by induction on \Downarrow and \rightsquigarrow^* .
- 2 Show that if $M \rightsquigarrow N$ and $N \Downarrow V$ then $M \Downarrow V$.
- 3 Show that if $M \rightsquigarrow^* N$ and $N \Downarrow V$ then $M \Downarrow V$.

In particular, every $M \rightsquigarrow^* V$ with V **val**, has $V \Downarrow V$, so it follows that $M \Downarrow V$. □

Corollary 17 (Preservation Theorem for \Downarrow)

If $\vdash M : \tau$ and $M \Downarrow V$ then $\vdash V : \tau$.