

# IMP — A WHILE-language and two semantics

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## Abstract

The formalization of the denotational and operational semantics of a simple while-language together with an equivalence proof between the two semantics. The whole development essentially formalizes/transcribes chapters 2 and 5 of [1]. A much extended version of this development is found in HOL/IMP of the Isabelle distribution.

## Contents

<b>1</b>	<b>Arithmetic expressions, boolean expressions, commands</b>	<b>1</b>
1.1	Arithmetic expressions . . . . .	1
1.2	Boolean expressions . . . . .	2
1.3	Commands . . . . .	3
1.4	Misc lemmas . . . . .	3
<b>2</b>	<b>Denotational semantics of expressions and commands</b>	<b>4</b>
2.1	Definitions . . . . .	4
2.2	Misc lemmas . . . . .	5
<b>3</b>	<b>Equivalence</b>	<b>5</b>
3.1	Main theorem . . . . .	7

## 1 Arithmetic expressions, boolean expressions, commands

theory Com imports Main begin

### 1.1 Arithmetic expressions

consts

loc :: i

aexp :: i

datatype  $\subseteq$  "univ(loc  $\cup$  (nat  $\rightarrow$  nat)  $\cup$  ((nat  $\times$  nat)  $\rightarrow$  nat))"

aexp = N ("n  $\in$  nat")

```

| X ("x ∈ loc")
| Op1 ("f ∈ nat -> nat", "a ∈ aexp")
| Op2 ("f ∈ (nat × nat) -> nat", "a0 ∈ aexp", "a1 ∈ aexp")

consts evala :: i
syntax "_evala" :: "[i, i] => o"      (infixl "-a->" 50)
translations "p -a-> n" == "<p,n> ∈ evala"

inductive
  domains "evala" ⊆ "(aexp × (loc -> nat)) × nat"
  intros
    N: "[| n ∈ nat; sigma ∈ loc->nat |] ==> <N(n),sigma> -a-> n"
    X: "[| x ∈ loc; sigma ∈ loc->nat |] ==> <X(x),sigma> -a-> sigma`x"
    Op1: "[| <e,sigma> -a-> n; f ∈ nat -> nat |] ==> <Op1(f,e),sigma> -a-> f`n"
    Op2: "[| <e0,sigma> -a-> n0; <e1,sigma> -a-> n1; f ∈ (nat×nat) -> nat |]
          ==> <Op2(f,e0,e1),sigma> -a-> f`<n0,n1>"
  type_intros aexp.intros apply_funtype

```

## 1.2 Boolean expressions

```

consts bexp :: i

datatype ⊆ "univ(aexp ∪ ((nat × nat)->bool))"
  bexp = true
        | false
        | ROp ("f ∈ (nat × nat)->bool", "a0 ∈ aexp", "a1 ∈ aexp")
        | noti ("b ∈ bexp")
        | andi ("b0 ∈ bexp", "b1 ∈ bexp")      (infixl "andi" 60)
        | ori  ("b0 ∈ bexp", "b1 ∈ bexp")      (infixl "ori" 60)

consts evalb :: i
syntax "_evalb" :: "[i,i] => o"      (infixl "-b->" 50)
translations "p -b-> b" == "<p,b> ∈ evalb"

inductive
  domains "evalb" ⊆ "(bexp × (loc -> nat)) × bool"
  intros
    true: "[| sigma ∈ loc -> nat |] ==> <true,sigma> -b-> 1"
    false: "[| sigma ∈ loc -> nat |] ==> <false,sigma> -b-> 0"
    ROp: "[| <a0,sigma> -a-> n0; <a1,sigma> -a-> n1; f ∈ (nat*nat)->bool |]
          ==> <ROp(f,a0,a1),sigma> -b-> f`<n0,n1> "
    noti: "[| <b,sigma> -b-> w |] ==> <noti(b),sigma> -b-> not(w)"
    andi: "[| <b0,sigma> -b-> w0; <b1,sigma> -b-> w1 |]
          ==> <b0 andi b1,sigma> -b-> (w0 and w1)"
    ori: "[| <b0,sigma> -b-> w0; <b1,sigma> -b-> w1 |]
          ==> <b0 ori b1,sigma> -b-> (w0 or w1)"
  type_intros bexp.intros
    apply_funtype and_type or_type bool_1I bool_0I not_type

```

```
type_elims evala.dom_subset [THEN subsetD, elim_format]
```

### 1.3 Commands

```
consts com :: i
datatype com =
  skip                                ("skip" [])
| assignment ("x ∈ loc", "a ∈ aexp") (infixl "⊢=" 60)
| semicolon ("c0 ∈ com", "c1 ∈ com") ("_;_" [60, 60] 10)
| while ("b ∈ bexp", "c ∈ com") ("while _ do _" 60)
| "if" ("b ∈ bexp", "c0 ∈ com", "c1 ∈ com") ("if _ then _ else _" 60)
```

```
consts evalc :: i
syntax "_evalc" :: "[i, i] => o"      (infixl "-c->" 50)
translations "p -c-> s" == "<p,s> ∈ evalc"
```

#### inductive

```
domains "evalc" ⊆ "(com × (loc -> nat)) × (loc -> nat)"
```

#### intros

```
skip: "[| sigma ∈ loc -> nat |] ==> <skip,sigma> -c-> sigma"
```

```
assign: "[| m ∈ nat; x ∈ loc; <a,sigma> -a-> m |]
==> <x := a,sigma> -c-> sigma(x:=m)"
```

```
semi: "[| <c0,sigma> -c-> sigma2; <c1,sigma2> -c-> sigma1 |]
==> <c0; c1, sigma> -c-> sigma1"
```

```
if1: "[| b ∈ bexp; c1 ∈ com; sigma ∈ loc->nat;
<b,sigma> -b-> 1; <c0,sigma> -c-> sigma1 |]
==> <if b then c0 else c1, sigma> -c-> sigma1"
```

```
if0: "[| b ∈ bexp; c0 ∈ com; sigma ∈ loc->nat;
<b,sigma> -b-> 0; <c1,sigma> -c-> sigma1 |]
==> <if b then c0 else c1, sigma> -c-> sigma1"
```

```
while0: "[| c ∈ com; <b, sigma> -b-> 0 |]
==> <while b do c,sigma> -c-> sigma"
```

```
while1: "[| c ∈ com; <b,sigma> -b-> 1; <c,sigma> -c-> sigma2;
<while b do c, sigma2> -c-> sigma1 |]
==> <while b do c, sigma> -c-> sigma1"
```

```
type_intros com.intros update_type
```

```
type_elims evala.dom_subset [THEN subsetD, elim_format]
```

```
evalb.dom_subset [THEN subsetD, elim_format]
```

### 1.4 Misc lemmas

```
lemmas evala_1 [simp] = evala.dom_subset [THEN subsetD, THEN SigmaD1, THEN SigmaD1]
```

```

and evala_2 [simp] = evala.dom_subset [THEN subsetD, THEN SigmaD1, THEN SigmaD2]
and evala_3 [simp] = evala.dom_subset [THEN subsetD, THEN SigmaD2]

lemmas evalb_1 [simp] = evalb.dom_subset [THEN subsetD, THEN SigmaD1, THEN SigmaD1]
and evalb_2 [simp] = evalb.dom_subset [THEN subsetD, THEN SigmaD1, THEN SigmaD2]
and evalb_3 [simp] = evalb.dom_subset [THEN subsetD, THEN SigmaD2]

lemmas evalc_1 [simp] = evalc.dom_subset [THEN subsetD, THEN SigmaD1, THEN SigmaD1]
and evalc_2 [simp] = evalc.dom_subset [THEN subsetD, THEN SigmaD1, THEN SigmaD2]
and evalc_3 [simp] = evalc.dom_subset [THEN subsetD, THEN SigmaD2]

inductive_cases
  evala_N_E [elim!]: "<N(n),sigma> -a-> i"
  evala_X_E [elim!]: "<X(x),sigma> -a-> i"
  and evala_Op1_E [elim!]: "<Op1(f,e),sigma> -a-> i"
  and evala_Op2_E [elim!]: "<Op2(f,a1,a2),sigma> -a-> i"

end

```

## 2 Denotational semantics of expressions and commands

theory Denotation imports Com begin

### 2.1 Definitions

consts

```

A      :: "i => i => i"
B      :: "i => i => i"
C      :: "i => i"

```

definition

```

Gamma :: "[i,i,i] => i"  ("Γ") where
  "Γ(b,cden) ==
    (λphi. {io ∈ (phi 0 cden). B(b,fst(io))=1} ∪
      {io ∈ id(loc->nat). B(b,fst(io))=0})"

```

primrec

```

"A(N(n), sigma) = n"
"A(X(x), sigma) = sigma`x"
"A(Op1(f,a), sigma) = f`A(a,sigma)"
"A(Op2(f,a0,a1), sigma) = f`<A(a0,sigma),A(a1,sigma)>"

```

primrec

```

"B(true, sigma) = 1"
"B(false, sigma) = 0"
"B(ROp(f,a0,a1), sigma) = f`<A(a0,sigma),A(a1,sigma)>"
"B(noti(b), sigma) = not(B(b,sigma))"
"B(b0 andi b1, sigma) = B(b0,sigma) and B(b1,sigma)"

```

```
"B(b0 ori b1, sigma) = B(b0,sigma) or B(b1,sigma)"
```

```
primrec
```

```
"C(skip) = id(loc->nat)"
"C(x := a) =
  {io ∈ (loc->nat) × (loc->nat). snd(io) = fst(io)(x := A(a,fst(io)))}"
"C(c0; c1) = C(c1) ∪ C(c0)"
"C(if b then c0 else c1) =
  {io ∈ C(c0). B(b,fst(io)) = 1} ∪ {io ∈ C(c1). B(b,fst(io)) = 0}"
"C(while b do c) = lfp((loc->nat) × (loc->nat), Γ(b,C(c)))"
```

## 2.2 Misc lemmas

```
lemma A_type [TC]: "[|a ∈ aexp; sigma ∈ loc->nat|] ==> A(a,sigma) ∈ nat"
  by (erule aexp.induct) simp_all
```

```
lemma B_type [TC]: "[|b ∈ bexp; sigma ∈ loc->nat|] ==> B(b,sigma) ∈ bool"
  by (erule bexp.induct, simp_all)
```

```
lemma C_subset: "c ∈ com ==> C(c) ⊆ (loc->nat) × (loc->nat)"
  apply (erule com.induct)
  apply simp_all
  apply (blast dest: lfp_subset [THEN subsetD])
done
```

```
lemma C_type_D [dest]:
  "[| <x,y> ∈ C(c); c ∈ com |] ==> x ∈ loc->nat & y ∈ loc->nat"
  by (blast dest: C_subset [THEN subsetD])
```

```
lemma C_type_fst [dest]: "[| x ∈ C(c); c ∈ com |] ==> fst(x) ∈ loc->nat"
  by (auto dest!: C_subset [THEN subsetD])
```

```
lemma Gamma_bnd_mono:
  "cden ⊆ (loc->nat) × (loc->nat)
  ==> bnd_mono ((loc->nat) × (loc->nat), Γ(b,cden))"
  by (unfold bnd_mono_def Gamma_def) blast
```

```
end
```

## 3 Equivalence

```
theory Equiv imports Denotation Com begin
```

```
lemma aexp_iff [rule_format]:
  "[| a ∈ aexp; sigma: loc -> nat |]
  ==> ALL n. <a,sigma> -a-> n <-> A(a,sigma) = n"
  apply (erule aexp.induct)
  apply (force intro!: evala.intros)+
```

```

done

declare aexp_iff [THEN iffD1, simp]
        aexp_iff [THEN iffD2, intro!]

inductive_cases [elim!]:
  "<true,sigma> -b-> x"
  "<false,sigma> -b-> x"
  "<ROp(f,a0,a1),sigma> -b-> x"
  "<noti(b),sigma> -b-> x"
  "<b0 andi b1,sigma> -b-> x"
  "<b0 ori b1,sigma> -b-> x"

lemma bexp_iff [rule_format]:
  "[| b ∈ bexp; sigma: loc -> nat |]
   ==> ALL w. <b,sigma> -b-> w <-> B(b,sigma) = w"
  apply (erule bexp.induct)
  apply (auto intro!: evalb.intros)
done

declare bexp_iff [THEN iffD1, simp]
        bexp_iff [THEN iffD2, intro!]

lemma com1: "<c,sigma> -c-> sigma' ==> <sigma,sigma'> ∈ C(c)"
  apply (erule evalc.induct)
  apply (simp_all (no_asm_simp))

assign
  apply (simp add: update_type)

comp
  apply fast

while
  apply (erule Gamma_bnd_mono [THEN lfp_unfold, THEN ssubst, OF C_subset])
  apply (simp add: Gamma_def)

recursive case of while
  apply (erule Gamma_bnd_mono [THEN lfp_unfold, THEN ssubst, OF C_subset])
  apply (auto simp add: Gamma_def)
done

declare B_type [intro!] A_type [intro!]
declare evalc.intros [intro]

lemma com2 [rule_format]: "c ∈ com ==> ∀ x ∈ C(c). <c,fst(x)> -c-> snd(x)"
  apply (erule com.induct)

```

```

skip
  apply force
assign
  apply force
comp
  apply force
while
  apply safe
  apply simp_all
  apply (frule Gamma_bnd_mono [OF C_subset], erule Fixedpt.induct, assumption)
  apply (unfold Gamma_def)
  apply force
if
  apply auto
done

```

### 3.1 Main theorem

```

theorem com_equivalence:
  "c ∈ com ==> C(c) = {io ∈ (loc->nat) × (loc->nat). <c,fst(io)> -c-> snd(io)}"
  by (force intro: C_subset [THEN subsetD] elim: com2 dest: com1)
end

```

## References

- [1] Glynn Winskel. *The Formal Semantics of Programming Languages*. 1993.