

The IMP Programming Language

Christiano Braga
cbraga@ic.uff.br

Instituto de Computação
Universidade Federal Fluminense



Abstract. IMP is a simple imperative programming language created to illustrate the use of the Basic Programming Languages Constructs library (BPLC). It is implemented in the Maude language.

1 IMP syntax

$\langle \text{program} \rangle ::= \text{'module' } \langle \text{ident} \rangle \langle \text{clauses} \rangle \text{'end'}$

$\langle \text{clauses} \rangle ::= \langle \text{var} \rangle^? \langle \text{const} \rangle^? \langle \text{init} \rangle^? \langle \text{proc} \rangle^+$

$\langle \text{var} \rangle ::= \text{'var' } \langle \text{ident} \rangle^+$

$\langle \text{const} \rangle ::= \text{'const' } \langle \text{ident} \rangle^+$

$\langle \text{init} \rangle ::= \text{'init' } \langle \text{ini} \rangle^+$

$\langle \text{ini} \rangle ::= \langle \text{ident} \rangle \text{'=' } \langle \text{exp} \rangle$

$\langle \text{proc} \rangle ::= \text{'proc' } \langle \text{ident} \rangle \text{'(' } \langle \text{ident} \rangle^* \text{' ')} \langle \text{block} \rangle$

$\langle \text{block} \rangle ::= \text{'{' } \langle \text{cmd} \rangle^+ \text{'}'}$

$\langle \text{cmd} \rangle ::= \langle \text{ident} \rangle \text{' := ' } \langle \text{exp} \rangle$
| $\langle \text{if} \rangle$ | $\langle \text{while} \rangle$ | $\langle \text{print} \rangle$ | $\langle \text{exit} \rangle$
| $\langle \text{call} \rangle$ | $\langle \text{seq} \rangle$ | $\langle \text{choice} \rangle$

$\langle \text{if} \rangle ::= \text{'if' } \langle \text{boolexp} \rangle \langle \text{cmd} \rangle \text{'else' } \langle \text{cmd} \rangle$
| $\text{'if' } \langle \text{boolexp} \rangle \langle \text{cmd} \rangle \text{'else' } \langle \text{block} \rangle$
| $\text{'if' } \langle \text{boolexp} \rangle \langle \text{block} \rangle \text{'else' } \langle \text{cmd} \rangle$
| $\text{'if' } \langle \text{boolexp} \rangle \langle \text{block} \rangle \text{'else' } \langle \text{block} \rangle$

$\langle \text{while} \rangle ::= \text{'while' } \langle \text{boolexp} \rangle \langle \text{block} \rangle$

$\langle \text{print} \rangle ::= \text{'print' '(' } \langle \text{exp} \rangle \text{'}'}$

$\langle \text{exit} \rangle ::= \text{'exit' '(' } \langle \text{exp} \rangle \text{'}'}$

$\langle call \rangle := \langle ident \rangle ' (' \langle exp \rangle * ') '$
 $\langle seq \rangle := \langle cmd \rangle ' ; ' \langle cmd \rangle$
 $\langle choice \rangle := \langle cmd \rangle ' | ' \langle cmd \rangle$
 $\langle exp \rangle := \langle ident \rangle$
 $\quad | \langle ident \rangle \langle arithop \rangle \langle ident \rangle$
 $\quad | \langle boolexp \rangle$
 $\langle arithop \rangle := ' + ' | ' - ' | ' * ' | ' / '$
 $\langle boolexp \rangle := \langle ident \rangle \langle boolop \rangle \langle ident \rangle$
 $\langle boolop \rangle := ' \sim ' | ' = ' | ' < ' | ' < = ' | ' > ' | ' > = '$

2 IMP semantics

2.1 Genralized SMC Machines & BPLC

2.2 GSMC Rules for IMP

3 Maude implementation

3.1 A Maude primer

Syntax

- Modules
- Signatures
- Equations
- Rules

Semantics. Modules, transition systems and Kripke structures.

Metalevel

3.2 Parser

Module `TOKEN` specifies what `Tokens`, `TokenLists` and `NeTokenList` are. They are constructed with operators `token`, `bubble` and `neTokenList`, where attribute `Exclude` specify which terms are not to be constructed by the given constructor.

```

<token-module>≡
  fmod TOKEN is
    pr QID-LIST .
    sorts Token Bubble TokenList NeTokenList .
    subsort Token < TokenList .

    op _,_ : TokenList TokenList -> TokenList [assoc prec 5] .

```

```

op token : Qid -> Token
[special
  (id-hook Bubble      (1 1)
   op-hook qidSymbol   (<Qids> : ~> Qid)
   id-hook Exclude     ( true false nop print ))) .

op bubble : QidList -> Bubble
[special
  (id-hook Bubble      (1 -1)
   op-hook qidListSymbol (__ : QidList QidList ~> QidList)
   op-hook qidSymbol   (<Qids> : ~> Qid)
   id-hook Exclude     ( | if then else end { }
                        while ; := = nop )) ] .

op neTokenList : QidList -> NeTokenList
[special
  (id-hook Bubble      (1 -1)
   op-hook qidListSymbol (__ : QidList QidList ~> QidList)
   op-hook qidSymbol   (<Qids> : ~> Qid)
   id-hook Exclude     ( . ))] .
endfm

```

Module IMP-GRAMMAR implements the grammar of Section 1 in Maude. Each sort implements a non-terminal of the grammar in Section 1 whereas constants, tokens, as described in module TOKEN, or operators implement terminals. For instance, the following rule in the grammar of Section 1

$\langle proc \rangle := 'proc' \langle ident \rangle '(' \langle ident \rangle^* ')'$ $\langle block \rangle$

is implemented in Module IMP-GRAMMAR by the operation declarations

```
1 op proc_ : Token BlockCommandDecl -> ProcDecl [prec 50] .
2 op proc_ '(' _ : Token TokenList BlockCommandDecl -> ProcDecl [prec 50] .
```

together with the declarations for sorts ProcDecl and BlockCommandDecl.

```
 $\langle imp\text{-}grammar\text{-}module \rangle \equiv$ 
fmod IMP-GRAMMAR is
  pr TOKEN .
  pr RAT .
  inc PREDICATE-DECL .
  inc COMMAND-DECL .
  sorts VariablesDecl ConstantsDecl OperationsDecl ProcDeclList
         ProcDecl FormalsDecl BlockCommandDecl ExpressionDecl
         InitDecl InitDeclList InitDecls ClausesDecl
         ModuleDecl Expression .

  subsort InitDecl < InitDeclList .
  subsort VariablesDecl ConstantsDecl ProcDeclList
         InitDecls < ClausesDecl .
  subsort BlockCommandDecl < CommandDecl .
  subsort ProcDecl < ProcDeclList .
  subsort PredicateDecl < ExpressionDecl .

  *** Boolean expressions
  op _==_ : Token Token -> PredicateDecl [prec 30] .
  op _==_ : Token ExpressionDecl -> PredicateDecl [prec 30] .
  op _==_ : ExpressionDecl Token -> PredicateDecl [prec 30] .
  op _==_ : ExpressionDecl ExpressionDecl -> PredicateDecl
         [prec 30] .
  op _/\_ : PredicateDecl PredicateDecl -> PredicateDecl
         [assoc comm prec 35] .
  op ~ : PredicateDecl -> PredicateDecl .

  *** Arithmetic expressions
  op _+_ : Token Token -> ExpressionDecl [gather(e E) prec 15] .
  op _+_ : Token ExpressionDecl -> ExpressionDecl [gather(e E) prec 15] .
  op _+_ : ExpressionDecl Token -> ExpressionDecl [gather(e E) prec 15] .
  op _+_ : ExpressionDecl ExpressionDecl -> ExpressionDecl
         [gather(e E) prec 15] .
```

```

op _- : Token Token -> ExpressionDecl [gather(e E) prec 15] .
op _- : Token ExpressionDecl -> ExpressionDecl [gather(e E) prec 15] .
op _- : ExpressionDecl Token -> ExpressionDecl [gather(e E) prec 15] .
op _- : ExpressionDecl ExpressionDecl -> ExpressionDecl
    [gather(e E) prec 15] .

op *_ : Token Token -> ExpressionDecl [gather(e E) prec 10] .
op *_ : Token ExpressionDecl -> ExpressionDecl [gather(e E) prec 10] .
op *_ : ExpressionDecl Token -> ExpressionDecl [gather(e E) prec 10] .
op *_ : ExpressionDecl ExpressionDecl -> ExpressionDecl
    [gather(e E) prec 10] .

op _/ : Token Token -> ExpressionDecl [prec 20] .
op _/ : Token ExpressionDecl -> ExpressionDecl [prec 20] .
op _/ : ExpressionDecl Token -> ExpressionDecl [prec 20] .
op _/ : ExpressionDecl ExpressionDecl -> ExpressionDecl [prec 20] .

*** Commands
op _:= : Token Token -> CommandDecl [prec 40] .
op _:= : Token ExpressionDecl -> CommandDecl [prec 40] .

op _() : Token -> CommandDecl .
op _(_) : Token Bubble -> CommandDecl .
op print : Token -> CommandDecl .
op print : ExpressionDecl -> CommandDecl .
op _;_ : CommandDecl CommandDecl -> CommandDecl [assoc prec 50] .
op _|_ : CommandDecl CommandDecl -> CommandDecl [assoc prec 50] .
op while_do_ : PredicateDecl BlockCommandDecl -> CommandDecl [prec 40] .
op {_} : CommandDecl -> BlockCommandDecl [prec 35] .
op if__else_ : PredicateDecl CommandDecl CommandDecl -> CommandDecl
    [prec 40] .

*** Declarations
op module__end : Token ClausesDecl -> ModuleDecl [prec 80] .
op __ : ClausesDecl ClausesDecl -> ClausesDecl [assoc comm prec 70] .
op var_ : TokenList -> VariablesDecl [prec 60] .
op const_ : TokenList -> ConstantsDecl [prec 60] .
op init_ : InitDecl -> InitDecls [prec 60] .
op init_ : InitDeclList -> InitDecls [prec 60] .
op _=_ : Token Token -> InitDecl [prec 40] .
op _=_ : Token ExpressionDecl -> InitDecl [prec 40] .
op _,_ : InitDeclList InitDeclList -> InitDeclList [assoc prec 50] .
op proc__ : Token BlockCommandDecl -> ProcDecl [prec 50] .
op proc_'(_)' : Token TokenList BlockCommandDecl -> ProcDecl
    [prec 50] .

```

```

    op __ : ProcDeclList ProcDeclList -> ProcDeclList
      [assoc comm prec 60] .
endfm

```

3.3 Compiling to BPLC

Compilation from IMP to BPLC is quite trivial as there exists a one-to-one correspondence between IMP constructions and BPLC. Essentially, an IMP module gives rise to a BPLC dec. IMP var and const are declarations and so is a proc declaration that gives rise to a prc declaration in BPLC.

<compile-imp-to-bplc>≡

```

mod COMPILE-IMP-TO-BPLC is
  inc PREDICATE-DECL .
  inc COMMAND-DECL .
  pr BPLC .
  pr META-LEVEL .

```

<Compiling IMP expressions to BPLC Exp>

<Compiling IMP commands to BPLC Cmd>

<Compiling IMP declarations to BPLC Dec>

The compilation from IMP to BPLC exp relates IMP tokens to BPLC Id, IMP arithmetic and boolean expressions to BPLC Exp. In particular, the compilation of a token has to check if the token is a primitive type, either Rat (for Rational numbers) or Bool (for Boolean values), or an identifier. Since Rat and Bool are tokenized and we need Maude metalevel descent function `downTerm` to help us parse them into proper constants

<Compiling tokens>≡

```

op compileId : Qid -> Id .
eq compileId(I:Qid) = idn(downTerm(I:Qid, 'Qid)) .

op compileId : Term -> Id .
eq compileId('token[I:Qid]) =
  if (metaParse(upModule('RAT, false),
    downTerm(I:Qid, 'Qid), 'Rat) :: ResultPair)
  then rat(downTerm(getTerm(metaParse(upModule('RAT, false),
    downTerm(I:Qid, 'Qid), 'Rat)), 1/2))
  else
    if (metaParse(upModule('BOOL, false),
      downTerm(I:Qid, 'Qid), 'Bool) :: ResultPair)
    then boo(downTerm(getTerm(metaParse(upModule('BOOL, false),
      downTerm(I:Qid, 'Qid), 'Bool)), true))
    else idn(downTerm(I:Qid, 'Qid))
  fi
fi .

```

Arithmetic expressions are mapped to their prefixed counterpart in BPLC, e.g. an IMP expression $a + b$ is compiled to `add(compileExp(a), compileExp(b))`.

⟨Compiling arithmetic expressions⟩≡

```

op compileExp : Term -> Exp .
ceq compileExp(I:Qid) = compileId(I:Qid)
  if not(I:Qid :: Constant) .
eq compileExp('token[I:Qid]) = compileId('token[I:Qid]) .
eq compileExp('+_ [T1:Term, T2:Term]) =
  add(compileExp(T1:Term), compileExp(T2:Term)) .
eq compileExp('-_ [T1:Term, T2:Term]) =
  sub(compileExp(T1:Term), compileExp(T2:Term)) .
eq compileExp('*_ [T1:Term, T2:Term]) =
  mul(compileExp(T1:Term), compileExp(T2:Term)) .
eq compileExp('/_ [T1:Term, T2:Term]) =
  div(compileExp(T1:Term), compileExp(T2:Term)) .

```

A treatment similar to arithmetic expressions is given to Boolean expressions, with a particular care with constants, as we did in «Compiling tokens». Here, however, we do not require a call to `downTerm` as the constants for `PredicateDecl` are already typed.

⟨Compiling boolean expressions⟩≡

```

eq compileExp('true.PredicateDecl) = boo(true) .
eq compileExp('false.PredicateDecl) = boo(false) .
eq compileExp('~[T:Term]) = neg(compileExp(T:Term)) .
eq compileExp('&/_ [T1:Term, T2:Term]) =
  and(compileExp(T1:Term), compileExp(T2:Term)) .
eq compileExp('|/_ [T1:Term, T2:Term]) =
  or(compileExp(T1:Term), compileExp(T2:Term)) .
eq compileExp('==_ [T1:Term, T2:Term]) =
  eq(compileExp(T1:Term), compileExp(T2:Term)) .
eq compileExp('>_ [T1:Term, T2:Term]) =
  gt(compileExp(T1:Term), compileExp(T2:Term)) .
eq compileExp('>=_ [T1:Term, T2:Term]) =
  ge(compileExp(T1:Term), compileExp(T2:Term)) .
eq compileExp('<_ [T1:Term, T2:Term]) =
  lt(compileExp(T1:Term), compileExp(T2:Term)) .
eq compileExp('<=_ [T1:Term, T2:Term]) =
  le(compileExp(T1:Term), compileExp(T2:Term)) .

```

<Compiling IMP commands to BPLC Cmd>=

```

op compileCmd : Term -> Cmd .
eq compileCmd('nop.CommandDecl) = nop .
eq compileCmd('_:=[ 'token[I:Qid], T:Term]) =
    assign(compileId('token[I:Qid]), compileExp(T:Term)) .
eq compileCmd('_{_}[T:Term]) = blk(compileCmd(T:Term)) .
eq compileCmd('_;_[T1:Term, T2:Term]) =
    seq(compileCmd(T1:Term), compileCmd(T2:Term)) .
eq compileCmd('|_[T1:Term, T2:Term]) =
    choice(compileCmd(T1:Term), compileCmd(T2:Term)) .
eq compileCmd('if__else_[T1:Term, T2:Term, T3:Term]) =
    if(compileExp(T1:Term), compileCmd(T2:Term),
        compileCmd(T3:Term)) .
eq compileCmd('while_do_[T1:Term, T2:Term]) =
    loop(compileExp(T1:Term), compileCmd(T2:Term)) .
eq compileCmd('print[T:Term]) = print(compileId(T:Term)) .

*** Compiling IMP commands to BPLC Cmd:
*** Procedure calls deserve more attention...

eq compileCmd('_( '([ 'token[I:Qid])) =
    cal(compileId('token[I:Qid])) .
eq compileCmd('_( '([ 'token[I:Qid], 'bubble[Q:Qid])) =
    cal(compileId('token[I:Qid]), compileActuals(Q:Qid)) .
eq compileCmd('_( '([ 'token[I:Qid],
    'bubble['__[TL:TermList]])) =
    cal(compileId('token[I:Qid]), compileActuals(TL:TermList)) .

op compileActuals : TermList -> Actuals .
eq compileActuals(Q:Qid) = compileId('token[Q:Qid]) .
eq compileActuals((TL1:TermList, __, .Qid , TL2:TermList)) =
    act(makeExp(TL1:TermList) , compileActuals(TL2:TermList)) .
eq compileActuals(TL:TermList) = makeExp(TL:TermList) [owise] .

op makeExp : TermList -> Exp .
eq makeExp(Q:Qid) = compileId(Q:Qid) .
ceq makeExp(TL:TermList) =
    compileExp(
        getTerm(
            metaParse(upModule('IMP-GRAMMAR, false),
                makeExprDeclQidList(TL:TermList), 'ExpressionDecl)))
    if (metaParse(upModule('IMP-GRAMMAR, false),
        makeExprDeclQidList(TL:TermList), 'ExpressionDecl) ::
        ResultPair) .

```



```

op makeExprDeclQidList : TermList -> QidList .
eq makeExprDeclQidList((empty).TermList) = (nil).QidList .
ceq makeExprDeclQidList(Q:Qid) = downTerm(Q:Qid, 'error)
  if downTerm(Q:Qid, 'error) /= 'error .
eq makeExprDeclQidList((Q:Qid , TL:TermList)) =
  makeExprDeclQidList(Q:Qid) makeExprDeclQidList(TL:TermList) .

```

DRAFT

⟨Compiling IMP declarations to BPLC Dec⟩=

```

*** Compiling variables. The initialization clause is
*** necessary to properly declare variables according to BPLC
*** ref construct.

op compileVar : Term Term -> Dec .
op $compileVar : Term Term -> Dec .
eq compileVar('var_[TL1:TermList], 'init_[TL2:TermList]) =
  $compileVar(TL1:TermList, TL2:TermList) .
eq $compileVar('token[I:Qid], '_=[ 'token[I:Qid], T:Term]) =
  ref(compileId('token[I:Qid]), compileExp(T:Term)) .
eq $compileVar('token[I:Qid],
  ('_',[ '_=[ 'token[I:Qid], T:Term], TL:TermList])) =
  ref(compileId('token[I:Qid]), compileExp(T:Term)) .
ceq $compileVar('token[I1:Qid],
  ('_',[ '_=[ 'token[I2:Qid], T:Term], TL:TermList])) =
  $compileVar('token[I1:Qid], TL:TermList)
if I1:Qid /= I2:Qid .
eq $compileVar('_',[ 'token[I:Qid], IS:TermList],
  '_=[ 'token[I:Qid], T:Term]) =
  ref(compileId('token[I:Qid]), compileExp(T:Term)) .
eq $compileVar('_',[ 'token[I:Qid], IS:TermList],
  '_',[ TL:TermList]) =
  dec($compileVar('token[I:Qid], '_',[ TL:TermList]),
    $compileVar(IS:TermList, '_',[ TL:TermList])) .

*** Compiling constants.
op compileConst : Term Term -> Dec .
op $compileConst : Term Term -> Dec .
eq compileConst('const_[T1:Term], 'init_[T2:Term]) =
  $compileConst(T1:Term, T2:Term) .
eq $compileConst('token[I:Qid],
  '_=[ 'token[I:Qid], T:Term]) =
  cns(compileId('token[I:Qid]), compileExp(T:Term)) .
eq $compileConst('token[I:Qid],
  ('_',[ '_=[ 'token[I:Qid], T:Term], TL:TermList])) =
  cns(compileId('token[I:Qid]), compileExp(T:Term)) .
ceq $compileConst('token[I1:Qid],
  ('_',[ '_=[ 'token[I2:Qid], T:Term], TL:TermList])) =
  $compileConst('token[I1:Qid], TL:TermList)
if I1:Qid /= I2:Qid .
eq $compileConst('_',[ 'token[I:Qid], IS:TermList],
  '_=[ 'token[I:Qid], T:Term]) =
  cns(compileId('token[I:Qid]), compileExp(T:Term)) .
eq $compileConst('_',[ 'token[I:Qid], IS:TermList], '_',[ TL:TermList]) =

```

```

dec($compileConst('token[I:Qid], '_',[TL:TermList]),
  $compileConst(IS:TermList, '_',[TL:TermList])) .

*** Compiling procedure declarations.
op compileProc : TermList -> Dec .
op compileToFormals : TermList -> Formals .
eq compileProc('__[TL1:TermList, TL2:TermList]) =
  dec(compileProc(TL1:TermList), compileProc(TL2:TermList)) .
eq compileProc('proc__[token[0:Qid], TL:TermList, T:Term]) =
  prc(compileId('token[0:Qid]), compileCmd(T:Term)) .
eq compileProc('proc_'('')[token[0:Qid], TL:TermList, T:Term]) =
  prc(compileId('token[0:Qid]),
    compileToFormals(TL:TermList), compileCmd(T:Term)) .
eq compileToFormals('token[0:Qid]) = par(compileId('token[0:Qid])) .
eq compileToFormals('_',__[TL1:TermList, TL2:TermList]) =
  for(compileToFormals(TL1:TermList), compileToFormals(TL2:TermList)) .

*** Compiling modules.
op compileMod : Term -> Dec .
eq compileMod('module__end[token[I:Qid],
  '__[var_[T1:Term],
  '__[const_[T2:Term],
  '__[init_[T3:Term],
  T:Term]]]) =
  dec(compileVar('var_[T1:Term], 'init_[T3:Term]),
    dec(compileConst('const_[T2:Term], 'init_[T3:Term]),
      compileProc(T:Term))) .
eq compileMod('module__end[token[I:Qid],
  '__[var_[T1:Term],
  '__[init_[T3:Term],
  T:Term]]) =
  dec(compileVar('var_[T1:Term], 'init_[T3:Term]),
    compileProc(T:Term)) .
eq compileMod('module__end[token[I:Qid],
  '__[var_[T1:Term],
  '__[const_[T2:Term],
  '__[init_[T3:Term],
  '__[TL:TermList]]]) =
  dec(compileVar('var_[T1:Term], 'init_[T3:Term]),
    dec(compileConst('const_[T2:Term], 'init_[T3:Term]),
      compileProc('__[TL:TermList]))) .
eq compileMod('module__end[token[I:Qid],
  '__[var_[T1:Term],
  '__[init_[T3:Term],
  '__[TL:TermList]]]) =

```

```
      dec(compileVar('var_[T1:Term]', 'init_[T3:Term]'),  
          compileProc('__[TL:TermList]')) .  
    endm
```

DRAFT

3.4 Pretty-printing IMP programs, their execution and model checking results

```
<imp-pretty-printing>≡
mod IMP-PRETTY-PRINTING is
  pr BPLC-MODEL-CHECKER .
  pr INT .

  *** Some auxiliary constants and functions.
  ops level incr : -> Nat .
  eq level = 3 .
  eq incr = 3 .

  op printSpaces : Nat -> QidList .
  eq printSpaces(0) = (nil).QidList .
  eq printSpaces(N:Nat) = '\s printSpaces(sd(N:Nat, 1)) .

  op printTermList : TermList -> QidList .
  eq printTermList(empty) = (nil).QidList .
  eq printTermList((Q:Qid, TL:TermList)) =
    downTerm(Q:Qid, 'Qid) printTermList(TL:TermList) .

  op printTokens : Term -> QidList .
  eq printTokens(Q:Qid) = Q:Qid .
  eq printTokens('token[Q:Qid]) = downTerm(Q:Qid, 'Qid) .
  eq printTokens('_',[T1:Term, T2:Term]) =
    printTokens(T1:Term) printToken('_,) '\s printTokens(T2:Term) .

  *** Pretty-printing IMP Expressions
  op printExp : Term -> QidList .
  eq printExp('true.PredicateDecl) = 'true .
  eq printExp('false.PredicateDecl) = 'false .
  eq printExp('bubble['_[TL:TermList]]) = printTermList(TL:TermList) .
  eq printExp('token[Q:Qid]) = downTerm(Q:Qid, 'Qid) .
  eq printExp('==_[T1:Term, T2:Term]) =
    printExp(T1:Term) printToken('==) printExp(T2:Term) .
  eq printExp('\/_[T1:Term, T2:Term]) =
    printExp(T1:Term) printToken('\/) printExp(T2:Term) .
  eq printExp('_/\_[T1:Term, T2:Term]) =
    printExp(T1:Term) printToken('_\/) printExp(T2:Term) .
  eq printExp('~[T:Term]) =
    printToken('~) printExp(T:Term) .
  eq printExp('<_[T1:Term, T2:Term]) =
    printExp(T1:Term) printToken('<) printExp(T2:Term) .
  eq printExp('<=_[T1:Term, T2:Term]) =
    printExp(T1:Term) printToken('<=) printExp(T2:Term) .
  eq printExp('>_[T1:Term, T2:Term]) =
```

```

    printExp(T1:Term) printToken('>') printExp(T2:Term) .
eq printExp('_>=[T1:Term, T2:Term]) =
    printExp(T1:Term) printToken('>=') printExp(T2:Term) .
eq printExp('_+_[T1:Term, T2:Term]) =
    printExp(T1:Term) printToken('+') printExp(T2:Term) .
eq printExp('_*_[T1:Term, T2:Term]) =
    printExp(T1:Term) printToken('*') printExp(T2:Term) .
eq printExp('_-_[T1:Term, T2:Term]) =
    printExp(T1:Term) printToken('-') printExp(T2:Term) .
eq printExp('_/_[T1:Term, T2:Term]) =
    printExp(T1:Term) printToken('/') printExp(T2:Term) .
eq printExp(T:Term) =
    metaPrettyPrint(upModule('IMP-GRAMMAR, false), T:Term) [owise] .

*** Pretty-printing IMP Commands
op printCmd : Term Nat -> QidList .
eq printCmd('nop.CommandDecl, N:Nat) = 'nop .
eq printCmd('print[T:Term], N:Nat) =
    printToken('print') printToken('(') printExp(T:Term) printToken('') .
eq printCmd('_( '[T1:Term, T2:Term], N:Nat) =
    printExp(T1:Term) printToken('(') printExp(T2:Term) printToken('') .
eq printCmd('_|_[T1:Term, '[_;_[T2:TermList]], N:Nat) =
    printSpaces(N:Nat)
    printCmd(T1:Term, N:Nat) printToken('|') '\n
    printSpaces(N:Nat) printToken('(')
    printCmd('[_;_[T2:TermList], N:Nat) printToken('') .
ceq printCmd('_|_[T:TermList, F:Qid[TL:TermList]], N:Nat) =
    printSpaces(N:Nat) printCmd(T:TermList, N:Nat) printToken('|')
    printCmd(F:Qid[TL:TermList], N:Nat)
if F:Qid /= '[_;_ .
ceq printCmd('[_;_[F1:Qid[TL1:TermList], F2:Qid[TL2:TermList]], N:Nat) =
    printCmd(F1:Qid[TL1:TermList], N:Nat) '\s printToken(';')
    printCmd(F2:Qid[TL2:TermList], N:Nat)
if F1:Qid /= '[_;_ and F2:Qid /= '[_;_ .
ceq printCmd('[_;_[F1:Qid[TL1:TermList], F2:Qid[TL2:TermList]], N:Nat) =
    printSpaces(N:Nat)
    printCmd(F1:Qid[TL1:TermList], N:Nat) '\s printToken(';') '\n
    printSpaces(N:Nat)
    printCmd(F1:Qid[TL1:TermList], N:Nat)
if F1:Qid == '[_;_ or F2:Qid == '[_;_ .
eq printCmd('_:=[T1:Term, T2:Term], N:Nat) =
    printExp(T1:Term) printToken(':=') printExp(T2:Term) .
eq printCmd('while_do_[T1:Term, T2:Term], N:Nat) =
    printToken('while') ' printToken('(') printExp(T1:Term) printToken('') '
    printToken('do')

```

```

    printCmd(T2:Term, N:Nat) .
eq printCmd('if__else_[T1:Term, T2:Term, T3:Term], N:Nat) =
    printToken('if) ' printToken('(') printExp(T1:Term) printToken(')') '
    printCmd(T2:Term, N:Nat)
    '\s printToken('else) printCmd(T3:Term, N:Nat) .
eq printCmd('{_}[C:Constant], N:Nat) =
    '\s printToken('{)
    printCmd(C:Constant, 0)
    printToken('}') .
eq printCmd('{_}[_;_][TL:TermList]], N:Nat) =
    '\s printToken('{) '\n
    printSpaces(N:Nat + incr)
    printCmd('[_;_][TL:TermList], N:Nat + incr) '\n
    printSpaces(N:Nat) printToken('}') .
eq printCmd('{_}[_|_][TL:TermList]], N:Nat) =
    '\s printToken('{) '\n
    printCmd('_|_][TL:TermList], N:Nat + incr) '\n
    printSpaces(N:Nat) printToken('}') .
ceq printCmd('{_}[F:Qid[TL:TermList]], N:Nat) =
    '\s printToken('{) '\n
    printSpaces(N:Nat + incr)
    printCmd(F:Qid[TL:TermList], N:Nat + incr) '\n
    printSpaces(N:Nat) printToken('}')
if F:Qid /= '[_;_ / \ F:Qid /= '_|_ .

eq printCmd(T:Term, N:Nat) =
    printSpaces(N:Nat)
    metaPrettyPrint(upModule('IMP-GRAMMAR, false), T:Term) [owise] .

*** Pretty-printing IMP Declarations
op printModule : Term -> QidList .
eq printModule('module__end[T1:Term, T2:Term]) =
    printToken('module) printTokens(T1:Term)
    printClauses(T2:Term)
    '\n printToken('end) .

op printClauses : Term -> QidList .
eq printClauses('proc__[T1:Term, T2:Term]) =
    '\n printSpaces(level)
    printToken('proc) printTokens(T1:Term)
    printCmd(T2:Term, level) .
eq printClauses('__[proc__[T1:Term, T2:Term], T3:Term]) =
    '\n printSpaces(level) printToken('proc) printTokens(T1:Term)
    printCmd(T2:Term, level)
    printClauses(T3:Term) .

```

```

eq printClauses('proc_'[_']_ [T1:Term, T2:Term, T3:Term]) =
  '\n printSpaces(level)
  printToken('proc') printTokens(T1:Term)
  printToken(''() printTokens(T2:Term) printToken('')
  printCmd(T3:Term, level) .
eq printClauses('__[']_proc_'[_']_ [T1:Term, T2:Term, T3:Term], T4:Term]) =
  '\n printSpaces(level) printToken('proc')
  printTokens(T1:Term) printToken(''() printTokens(T2:Term) printToken('')
  printCmd(T3:Term, level)
  printClauses(T4:Term) .
eq printClauses('__[']_init_ [T1:Term], T2:Term]) =
  '\n printSpaces(level) printToken('init')
  printInit(T1:Term) printClauses(T2:Term) .
eq printClauses('__[']_const_ [T1:Term], T2:Term]) =
  '\n printSpaces(level) printToken('const')
  printTokens(T1:Term) printClauses(T2:Term) .
eq printClauses('__[']_var_ [T1:Term], T2:Term]) =
  '\n printSpaces(level) printToken('var')
  printTokens(T1:Term) printClauses(T2:Term) .

op printInit : Term -> QidList .
eq printInit('=_ [T1:Term, T2:Term]) =
  printTokens(T1:Term) printToken('=') printExp(T2:Term) .
eq printInit('=_', _ [T1:Term, T2:Term]) =
  printInit(T1:Term) printToken(',') '\s printInit(T2:Term) .

*** Pretty-printing parse error
op printQidList : QidList -> QidList .
eq printQidList(nil) = (nil).QidList .
eq printQidList(Q:Qid QL:QidList) = printToken(Q:Qid) printQidList(QL:QidList) .

op printToken : Qid -> Qid .
eq printToken(Q:Qid) = '\b '\! Q:Qid '\o .

op printInputWithError : QidList Nat -> QidList .
op $printInputWithError : QidList Int QidList -> QidList .
eq printInputWithError(QL:QidList, N:Nat) =
  $printInputWithError(QL:QidList, N:Nat, (nil).QidList) .
eq $printInputWithError(nil, I:Int, QL:QidList) = QL:QidList .
eq $printInputWithError(QL:QidList, 0, (nil).QidList) = (nil).QidList .
ceq $printInputWithError(QL1:QidList, 0, (QL2:QidList Q:Qid)) =
  QL2:QidList '\r '\u '>> Q:Qid '<< 'HERE '\o
  printQidList(QL1:QidList)
if QL2:QidList /= nil .
eq $printInputWithError(Q:Qid QL1:QidList, I:Int, QL2:QidList) =

```



```

$printInputWithError(QL1:QidList, (I:Int + (- 1)), QL2:QidList
  printToken(Q:Qid)) .

op printParseError : QidList ResultPair? -> Qid .
eq printParseError('module Q:Qid QL:QidList , noParse(N:Nat)) =
  'IMP: 'Error 'at 'position
  metaPrettyPrint(upModule('NAT, false), upTerm(N:Nat))
  'while 'parsing 'Module Q:Qid ': '\n
  printInputWithError(('module Q:Qid QL:QidList), N:Nat) .
eq printParseError(QL:QidList, ambiguity(T1:ResultPair, T2:ResultPair)) =
  'IMP: '\r 'Ambiguous 'parse '\o '\n
  metaPrettyPrint(upModule('IMP-GRAMMAR, false), getTerm(T1:ResultPair)) '\n
  '\r 'vs. '\o '\n
  metaPrettyPrint(upModule('IMP-GRAMMAR, false), getTerm(T2:ResultPair)) .

*** Pretty-print exec and mc output
op printState : Env Store -> QidList .
eq printState(noEnv, S:Store) = (nil).QidList .
eq printState((I:Id |-> bind(L:Loc)) , ((L:Loc |-> store(R:Rat)), S:Store)) =
  printId(I:Id) '= metaPrettyPrint(upModule('RAT, false), upTerm(R:Rat)) .
ceq printState(((I:Id |-> bind(L:Loc)), E:Env) ,
  ((L:Loc |-> store(R:Rat)), S:Store)) =
  printId(I:Id) '=
  metaPrettyPrint(upModule('RAT, false), upTerm(R:Rat))
  printState(E:Env , (L:Loc |-> store(R:Rat), S:Store))
if E:Env /= noEnv .
eq printState((I:Id |-> bind(L:Loc)), (L:Loc |-> store(B:Bool), S:Store)) =
  printId(I:Id) '= metaPrettyPrint(upModule('BOOL, false), upTerm(B:Bool)) .
ceq printState(((I:Id |-> bind(L:Loc)), E:Env) ,
  ((L:Loc |-> store(B:Bool)), S:Store)) =
  printId(I:Id) '= metaPrettyPrint(upModule('RAT, false), upTerm(B:Bool)) ' ',
  printState(E:Env , (L:Loc |-> store(B:Bool), S:Store))
if E:Env /= noEnv .
eq printState(((I:Id |-> B:Bindable), E:Env) , S:Store) =
  printState(E:Env , S:Store) [owise] .

op printId : Id -> Qid .
eq printId(idn(Q:Qid)) = (Q:Qid).Qid .

op printCnt : ControlStack ValueStack -> QidList .
eq printCnt((LOOP C:ControlStack),
  (V:Value val(loop(E:Exp, K:Cmd)) VS:ValueStack)) =
  printToken('while) printToken('('() printExp(E:Exp) printToken('')) '... .
eq printCnt((choice(K1:Cmd, K2:Cmd) C:ControlStack), VS:ValueStack) =
  printCmd(K1:Cmd) printToken('|) printCmd(K2:Cmd) .

```

```

eq printCnt(C:ControlStack, VS:ValueStack) =
  '\n 'Constrol 'stack:
  metaPrettyPrint(upModule('BPLC+META-LEVEL, false),
    upTerm(C:ControlStack))
  '\n 'Value 'stack:
  metaPrettyPrint(upModule('BPLC+META-LEVEL, false),
    upTerm(VS:ValueStack)) .

op printExp : Exp -> QidList .
eq printExp(rat(R:Rat)) = '\g metaPrettyPrint(upModule('RAT, false),
  upTerm(R:Rat)) '\o .
eq printExp(boo(B:Bool)) = '\g metaPrettyPrint(upModule('B00L, false),
  upTerm(B:Bool)) '\o .
eq printExp(neg(E:Exp)) = printToken('~') printExp(E:Exp) .
eq printExp(and(E1:Exp, E2:Exp)) =
  printExp(E1:Exp) printToken('/') printExp(E2:Exp) .
eq printExp(eq(E1:Exp, E2:Exp)) =
  printExp(E1:Exp) printToken('==') printExp(E2:Exp) .
eq printExp(idn(Q:Qid)) = printTokens(Q:Qid) .
eq printExp(E:Exp) = metaPrettyPrint(upModule('BPLC, false), upTerm(E:Exp)) .

op printCmd : Cmd -> QidList .
eq printCmd(seq(C1:Cmd, C2:Cmd)) =
  printCmd(C1:Cmd) printToken(';') printCmd(C2:Cmd) .
eq printCmd(assign(I:Id, E:Exp)) =
  printExp(I:Id) printToken(':=') printExp(E:Exp) .
eq printCmd(if(E:Exp, C1:Cmd, C2:Cmd)) =
  printToken('if') printExp(E:Exp) '... .
eq printCmd(choice(C1:Cmd, C2:Cmd)) = printCmd(C1:Cmd)
  printToken('|') printCmd(C2:Cmd) .
eq printCmd(C:Cmd) = metaPrettyPrint(upModule('BPLC, false), upTerm(C:Cmd)) .

op printConf : Conf -> QidList .
eq printConf(< env : E:Env , sto : S:Store , exc : X:Exc ,
  cnt : C:ControlStack, val : V:ValueStack, ...:Set{SemComp} > ) =
  if X:Exc == CNT
  then printCnt(C:ControlStack, V:ValueStack) '[' printState(E:Env, S:Store) '['
  else 'IMP: 'Internal 'error 'while 'printing 'configuration.
  fi .

op printValueStack : ValueStack -> QidList .
eq printValueStack(evs) = '\b 'No 'output. '\o .
eq printValueStack(val(R:Rat) evs) =
  metaPrettyPrint(upModule('RAT, false), upTerm(R:Rat)) .
eq printValueStack(val(B:Bool) evs) =

```

```

    metaPrettyPrint(upModule('BOOL, false), upTerm(B:Bool)) .
eq printValueStack(V:Value VS:ValueStack) =
    printValueStack(V:Value) printValueStack(VS:ValueStack) .

op printOut : Conf -> QidList .
eq printOut(< out : O:ValueStack , ...:Set{SemComp} > ) =
    printValueStack(O:ValueStack) .

op printExec : Term ~> QidList .
ceq printExec(T:Term) = printOut(downTerm(T:Term, < noSemComp >))
if downTerm(T:Term, < noSemComp >) /= < noSemComp > .

op printTraceStep : TraceStep -> QidList .
eq printTraceStep({T:Term, Y:Type, R:Rule}) =
    printConf(downTerm(T:Term, < noSemComp >)) .

op printTrace : Trace Nat -> QidList .
eq printTrace(nil, N:Nat) = (nil).QidList .
eq printTrace(TS:TraceStep, N:Nat) =
    '\b 'State
    metaPrettyPrint(upModule('NAT, false),
        upTerm(N:Nat)) ': '\o '\n
    printTraceStep(TS:TraceStep) .
ceq printTrace(TS:TraceStep T:Trace, N:Nat) =
    '\b 'State
    metaPrettyPrint(upModule('NAT, false),
        upTerm(N:Nat)) ': '\o '\n
    printTraceStep(TS:TraceStep) '\n printTrace(T:Trace, (N:Nat + 1))
if T:Trace /= nil .

op printTransitionList : TransitionList -> QidList .
eq printTransitionList(nil) = (nil).QidList .
eq printTransitionList({C:Conf, R:RuleName}) = printConf(C:Conf) .
ceq printTransitionList({C:Conf, R:RuleName} TL:TransitionList) =
    printConf(C:Conf) '\b '-> '\o printTransitionList(TL:TransitionList)
if TL:TransitionList /= nil .

op printModelCheckResult : ModelCheckResult QidList -> QidList .
eq printModelCheckResult(B:Bool, QL:QidList) =
    'IMP: '\b 'Model 'check 'result 'to 'command
    '\c QL:QidList '\o '\b ': '\o '\n
    metaPrettyPrint(upModule('BOOL, false), upTerm(B:Bool)) .

eq printModelCheckResult(
    counterexample(TL1:TransitionList, TL2:TransitionList), QL:QidList) =

```

```
'IMP: '\b 'Model 'check 'counter 'example 'to 'command
'\c QL:QidList '\o '\b ': '\o '\n
'\b 'Path 'from 'the 'initial 'state: '\o
'\n printTransitionList(TL1:TransitionList)
'\n '\b 'Loop: '\o
'\n printTransitionList(TL2:TransitionList) .
endm
```

3.5 IMP command line interface

<imp-interface>≡

```
mod IMP-INTERFACE is
  pr LOOP-MODE * (sort State to LoopState).
  pr COMPILE-IMP-TO-BPLC .
  pr IMP-PRETTY-PRINTING .

  sorts Dec? MetaIMPModule Command IMPState .
  subsort Term < MetaIMPModule .
  subsort Dec < Dec? .
  subsort IMPState < LoopState .

  op noDec : -> Dec? .
  op noModule : -> MetaIMPModule .
  op idle : -> Command .
  op <_<_> : MetaIMPModule Dec? QidList -> IMPState .
  op init : -> System .
  op init'IMP'no'banner : -> System .
  op banner : -> QidList .

  eq banner = '\g 'IMP 'Prototype '\o '
              '( '\y '\! 'March '2018 '\o '' ) .
  eq init = [nil, < noModule ; noDec ; nil >, banner] .
  eq init'IMP'no'banner = [nil, < noModule ; noDec ; nil >, nil] .

  vars QIL QIL' QIL'' QIL1 QIL2 : QidList .

  rl [version] : ['version, L:LoopState, QIL] =>
    [nil, L:LoopState, banner] .

  *** Loading a module.
  crl [in] : ['module Q:Qid QIL,
              < M:MetaIMPModule ; D:Dec? ; QIL' >, QIL''] =>
    if (T:ResultPair? :: ResultPair)
    then [nil, < getTerm(T:ResultPair?) ;
              compileMod(getTerm(T:ResultPair?)) ;
              'IMP: '\b 'Module Q:Qid 'loaded. '\o >, QIL'']
    else [nil, < noModule ; noDec ; nil >,
          printParseError('module Q:Qid QIL, T:ResultPair?)]
    fi
  if T:ResultPair? :=
    metaParse(upModule('IMP-GRAMMAR, false),
              'module Q:Qid QIL, 'ModuleDecl) .

  *** Viewing a module.
```

```

crl [view] : ['view , < M:MetaIMPModule ; D:Dec ; QIL' >, QIL'] =>
    [nil, < M:MetaIMPModule ; D:Dec ; QIL' >,
      printModule(M:MetaIMPModule)]
if M:MetaIMPModule /= noModule .

*** Executing a command.
crl [exec-unbounded] : [('exec QIL),
    < M:MetaIMPModule ; D:Dec ; QIL' >, QIL'] =>
if P:ResultPair? :: ResultPair
then [nil, < M:MetaIMPModule ; D:Dec ; QIL' > ,
    if compileCmd(getTerm(P:ResultPair?)) :: Cmd
    then
        'IMP: '\b 'Execution 'result 'for '\c QIL '\o '\b ': '\o
        printExec(getTerm(metaRewrite(upModule('BPLC+META-LEVEL, false),
            'run[upTerm(compileCmd(getTerm(P:ResultPair?))),
                upTerm(D:Dec)], unbounded)))
        else 'IMP: '\r 'Internal 'Error 'while 'compiling '\s QIL
    fi ]
else [nil, < M:MetaIMPModule ; D:Dec ; QIL' >,
    'IMP: '\r 'Error 'while 'processing 'command '\o 'exec '\s QIL ]
fi
if P:ResultPair? :=
    metaParse(upModule('IMP-GRAMMAR, false), QIL, 'CommandDecl) .

*** Model check command
crl [mc] : [('mc QIL1 '|= QIL2),
    < 'module__end[T1:Term, T2:Term] ; D:Dec ; QIL' >, QIL'] =>
if ((P1:ResultPair? :: ResultPair) and (P2:ResultPair? :: ResultPair))
then [nil, < 'module__end[T1:Term, T2:Term] ; D:Dec ; QIL' >,
    if compileCmd(getTerm(P1:ResultPair?)) :: Cmd
    then
        printModelCheckResult(downTerm(
            getTerm(metaReduce(
                makeMCMModule(printTokens(T1:Term), D:Dec),
                '_','_|=?'[upTerm(D:Dec),
                upTerm(compileCmd(getTerm(P1:ResultPair?))),
                getTerm(P2:ResultPair?)])),true), QIL1 '\s '|= '\s QIL2)
        else 'IMP: '\r 'Internal 'Error 'while
            'processing 'command '\o 'mc QIL1 '|= QIL2
    fi ]
else [nil, < 'module__end[T1:Term, T2:Term] ; D:Dec ; QIL' >,
    'IMP: '\r 'Error 'while 'processing 'command '\o
    'mc QIL1 '|= QIL2]
fi
if P1:ResultPair? :=

```

```

        metaParse(upModule('IMP-GRAMMAR, false), QIL1, 'CommandDecl) /\
P2:ResultPair? :=
        metaParse(makeMCMModule(printTokens(T1:Term), D:Dec), QIL2, 'Formula) .

*** Output
crl [out] : [nil, < M:MetaIMPModule ; D:Dec? ; QIL' > , QIL''] =>
            [nil, < M:MetaIMPModule ; D:Dec? ; nil > , QIL']
if QIL' /= nil .

*** Command error
crl [com-error] : [Q:Qid QIL, < M:MetaIMPModule ; D:Dec ; QIL' > , QIL''] =>
            [nil, < M:MetaIMPModule ; D:Dec ; QIL' > ,
            'IMP: '\r 'Error 'no 'such 'command '\o Q:Qid QIL]
if (Q:Qid /= 'module) /\ (Q:Qid /= 'view) /\
    (Q:Qid /= 'exec) /\ (Q:Qid /= 'mc) .
endm

loop init .

```