

# Notes on Formal Compiler Construction with the $\pi$ Framework

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<http://github.com/ChristianoBraga/BPLC>



## 1. Introduction

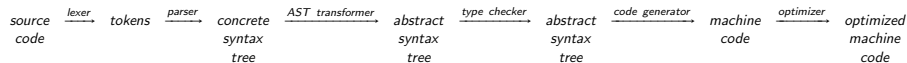
Example

## 2. $\pi$ expressions

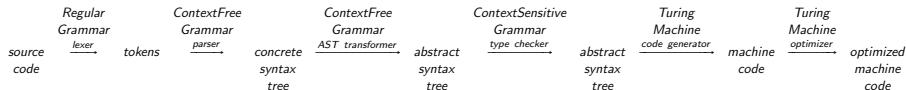
## 3. $\pi$ commands

## 4. $\pi^2$ : $\pi$ Framework in Python

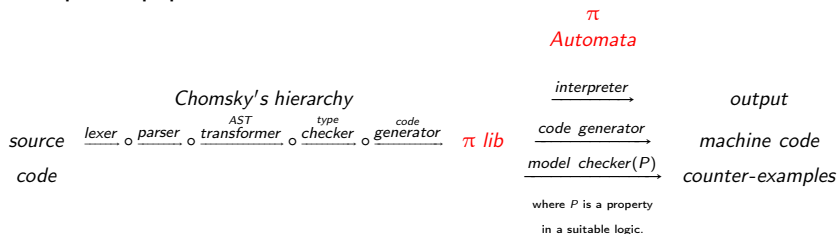
# Compiler pipeline



# Compiler pipeline and formal languages



# Compiler pipeline with the $\pi$ Framework



- $\pi$  lib defines a set of constructions common to many programming languages.
- $\pi$  lib constructions have a formal automata-based semantics in  $\pi$  automata.
- One may execute (or validate) a program in a given language by running its associated  $\pi$  lib program.
- $\pi$  Framework: <http://github.com/ChristianBraga/BPLC>
- Notes on Formal Compiler Construction with the  $\pi$  Framework: <https://github.com/ChristianBraga/BPLC/blob/master/notes/notes.pdf>.

# A calculator

We wish to compute simple arithmetic expressions such as  $5 * (3 + 2)$ .

# A calculator: Lexer

$\langle \textit{digit} \rangle \quad ::= [0..9]$

$\langle \textit{digits} \rangle \quad ::= \langle \textit{digit} \rangle^+$

$\langle \textit{boolean} \rangle \quad ::= \text{'true'} \mid \text{'false'}$

# A calculator: concrete syntax

$\langle \text{exp} \rangle ::= \langle \text{aexp} \rangle \mid \langle \text{bexp} \rangle$

$\langle \text{aexp} \rangle ::= \langle \text{aexp} \rangle '+' \langle \text{term} \rangle \mid \langle \text{aexp} \rangle '-' \langle \text{term} \rangle \mid \langle \text{term} \rangle$

$\langle \text{term} \rangle ::= \langle \text{term} \rangle '*' \langle \text{factor} \rangle \mid \langle \text{term} \rangle '/' \langle \text{factor} \rangle \mid \langle \text{factor} \rangle$

$\langle \text{factor} \rangle ::= '(' \langle \text{aexp} \rangle ')' \mid \langle \text{digits} \rangle$

$\langle \text{bexp} \rangle ::= \langle \text{boolean} \rangle \mid '\sim' \langle \text{bexp} \rangle \mid \langle \text{bexp} \rangle \langle \text{boolop} \rangle \langle \text{bexp} \rangle$   
 $\mid \langle \text{aexp} \rangle \langle \text{iop} \rangle \langle \text{aexp} \rangle$

$\langle \text{boolop} \rangle ::= '=' \mid '/\backslash' \mid '\backslash/'$

$\langle \text{iop} \rangle ::= '<' \mid '>' \mid '<=' \mid '>='$



# A calculator: abstract syntax

$$\langle exp \rangle ::= \langle digits \rangle \mid \langle boolean \rangle \mid \langle exp \rangle \langle bop \rangle \langle exp \rangle$$
$$\langle bop \rangle ::= '+' \mid '-' \mid '*' \mid '/' \mid '=' \mid '\backslash' \mid '/' \mid '<' \mid '>' \mid '<=' \mid '>='$$

# A calculator: $\pi$ denotations I

Let  $D$  in  $\langle \text{digits} \rangle$ ,  $B$  in  $\langle \text{boolean} \rangle$  and  $E_1, E_2$  in  $\langle \text{exp} \rangle$ ,

$$\llbracket D \rrbracket_{\pi} = \text{Num}(D) \quad (1)$$

$$\llbracket B \rrbracket_{\pi} = \text{Boo}(B) \quad (2)$$

$$\llbracket E_1 + E_2 \rrbracket_{\pi} = \text{Sum}(\llbracket E_1 \rrbracket_{\pi}, \llbracket E_2 \rrbracket_{\pi}) \quad (3)$$

$$\llbracket E_1 - E_2 \rrbracket_{\pi} = \text{Sub}(\llbracket E_1 \rrbracket_{\pi}, \llbracket E_2 \rrbracket_{\pi}) \quad (4)$$

$$\llbracket E_1 * E_2 \rrbracket_{\pi} = \text{Mul}(\llbracket E_1 \rrbracket_{\pi}, \llbracket E_2 \rrbracket_{\pi}) \quad (5)$$

$$\llbracket E_1 / E_2 \rrbracket_{\pi} = \text{Div}(\llbracket E_1 \rrbracket_{\pi}, \llbracket E_2 \rrbracket_{\pi}) \quad (6)$$

$$\llbracket E_1 < E_2 \rrbracket_{\pi} = \text{Lt}(\llbracket E_1 \rrbracket_{\pi}, \llbracket E_2 \rrbracket_{\pi}) \quad (7)$$

$$\llbracket E_1 \leq E_2 \rrbracket_{\pi} = \text{Le}(\llbracket E_1 \rrbracket_{\pi}, \llbracket E_2 \rrbracket_{\pi}) \quad (8)$$

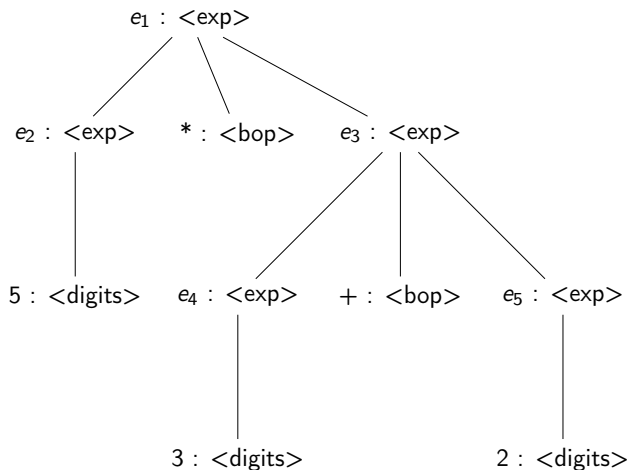
$$\llbracket E_1 > E_2 \rrbracket_{\pi} = \text{Gt}(\llbracket E_1 \rrbracket_{\pi}, \llbracket E_2 \rrbracket_{\pi}) \quad (9)$$

$$\llbracket E_1 \geq E_2 \rrbracket_{\pi} = \text{Ge}(\llbracket E_1 \rrbracket_{\pi}, \llbracket E_2 \rrbracket_{\pi}) \quad (10)$$

# A calculator: $\pi$ denotations II

- $\pi$  denotations are *functions*  $\llbracket \cdot \rrbracket_{\pi} : AST \rightarrow \pi \text{ lib}$ , where *AST* denotes the *datatype* for the abstract syntax tree and  $\pi \text{ lib}$  denotes the datatype for  $\pi \text{ lib}$  programs.
- Note that  $\llbracket \cdot \rrbracket_{\pi}$  has *trees* as parameters, instances of *AST*. The example expression  $5 * (3 + 2)$  becomes

# A calculator: $\pi$ denotations III



# A calculator: $\pi$ denotations IV

$$\llbracket 5 * (3 + 2) \rrbracket_{\pi} = \text{Mul}(\llbracket 5 \rrbracket_{\pi}, \llbracket (3 + 2) \rrbracket_{\pi}) \quad \text{by Equation 5}$$

$$\text{Mul}(\llbracket 5 \rrbracket_{\pi}, \llbracket (3 + 2) \rrbracket_{\pi}) = \text{Mul}(\text{Num}(5), \llbracket (3 + 2) \rrbracket_{\pi}) \quad \text{by Equations 1}$$

$$\text{Mul}(\text{num}(5), \llbracket (3 + 2) \rrbracket_{\pi}) = \text{Mul}(\text{Num}(5), \text{Sum}(\llbracket 3 \rrbracket_{\pi}, \llbracket 2 \rrbracket_{\pi})) \quad \text{by Equation 3}$$

$$\text{Mul}(\text{Num}(5), \text{Sum}(\llbracket 3 \rrbracket_{\pi}, \llbracket 2 \rrbracket_{\pi})) = \text{Mul}(\text{Num}(5), \text{Sum}(\text{Num}(3), \llbracket 2 \rrbracket_{\pi})) \quad \text{by Equation 1}$$

$$\text{Mul}(\text{Num}(5), \text{Sum}(\text{Num}(3), \llbracket 2 \rrbracket_{\pi})) = \text{Mul}(\text{Num}(5), \text{Sum}(\text{Num}(3), \text{Num}(2))) \quad \text{by Equation 1}$$

# A calculator: executing $\pi$ lib with $\pi$ automata

A  $\pi$  automaton is a 5-tuple  $\mathcal{A} = (G, Q, \delta, q_0, F)$ , where  $G$  is a context-free grammar,  $Q$  is the set of states,  $q_0$  is the initial state,  $F \subseteq Q$  is the set of final states and

$$\delta : L(G)^* \times L(G)^* \times Store \rightarrow Q,$$

where  $L(G)$  is the language generated by  $G$  and  $Store$  represents the memory. (Elements in a set  $S^*$  are represented by terms  $[s_1, s_2, \dots, s_n].$ )

$$\begin{aligned} \delta([Mul(Num(5), Sum(Num(3), Num(2))), \emptyset, \emptyset) &= \delta([Num(5), Sum(Num(3), Num(2)), \#MUL], \emptyset, \emptyset) \\ \delta([Num(5), Sum(Num(3), Num(2)), \#MUL], \emptyset, \emptyset) &= \delta([Sum(Num(3), Num(2)), \#MUL], [Num(5)], \emptyset) \\ \delta([Sum(Num(3), Num(2)), \#MUL], [Num(5)], \emptyset) &= \delta([Num(3), Num(2), \#SUM, \#MUL], [Num(5)], \emptyset) \\ \delta([Num(3), Num(2), \#SUM, \#MUL], [Num(5)], \emptyset) &= \delta([Num(2), \#SUM, \#MUL], [Num(3), Num(5)], \emptyset) \\ \delta([Num(2), \#SUM, \#MUL], [Num(3), Num(5)], \emptyset) &= \delta([\#SUM, \#MUL], [Num(2), Num(3), Num(5)], \emptyset) \\ \delta([\#SUM, \#MUL], [Num(2), Num(3), Num(5)], \emptyset) &= \delta([\#MUL], [Num(5), Num(5)], \emptyset) \\ \delta([\#MUL], [Num(5), Num(5)], \emptyset) &= \delta(\emptyset, [Num(25)], \emptyset) \\ \delta(\emptyset, [Num(25)], \emptyset) &= Num(25) \end{aligned}$$

Excerpt of  $\pi$  lib expressions

$\langle \text{Statement} \rangle ::= \langle \text{Exp} \rangle$

$\langle \text{Exp} \rangle ::= \langle \text{ArithExp} \rangle \mid \langle \text{BoolExp} \rangle$

$\langle \text{ArithExp} \rangle ::= \text{'Num'}(\langle \text{digits} \rangle) \mid \text{'Sum'}(\langle \text{Exp} \rangle, \langle \text{Exp} \rangle) \mid$   
 $\text{'Sub'}(\langle \text{Exp} \rangle, \langle \text{Exp} \rangle) \mid \text{'Mul'}(\langle \text{Exp} \rangle, \langle \text{Exp} \rangle)$

$\langle \text{BoolExp} \rangle ::= \text{'Eq'}(\langle \text{Exp} \rangle, \langle \text{Exp} \rangle) \mid \text{'Not'}(\langle \text{Exp} \rangle)$

$\pi$  automata semantics for  $\pi$  lib expressions

- Recall that  $\delta : L(G)^* \times L(G)^* \times Store \rightarrow Q$ , and let  $N, N_i \in \mathbb{N}$ ,  $C, V \in L(G)^*$ ,  $S \in Store$ ,

$$\delta(Num(N) :: C, V, S) = \delta(C, Num(N) :: V, S) \quad (11)$$

$$\delta(Sum(E_1, E_2) :: C, V, S) = \delta(E_1 :: E_2 :: \#SUM :: C, V, S) \quad (12)$$

$$\delta(\#SUM :: C, Num(N_1) :: Num(N_2) :: V, S) = \delta(C, Num(N_1 + N_2) :: V, S) \quad (13)$$

...

$$\delta(Not(E) :: C, V, S) = \delta(E :: \#NOT :: C, V, S) \quad (14)$$

$$\delta(\#NOT :: C, Boo(true) :: V, S) = \delta(C, Boo(false) :: V, S) \quad (15)$$

$$\delta(\#NOT :: C, Boo(false) :: V, S) = \delta(C, Boo(true) :: V, S) \quad (16)$$

- Notation  $h :: ls$  denotes the concatenation of element  $h$  with the list  $ls$ .
- $C$  represents the *control* stack.  $V$  represents the *value* stack.  $S$  denotes the memory store.
- $\delta(\emptyset, V, S)$  denotes an *accepting state*.



# $\pi$ lib commands

- Commands are language constructions that require both an *environment* and a *memory* store to be evaluated.

$\langle \text{Statement} \rangle ::= \langle \text{Cmd} \rangle$

$\langle \text{Exp} \rangle ::= \text{'Id'}(\langle \text{String} \rangle)$

$\langle \text{Cmd} \rangle ::= \text{'Assign'}(\langle \text{Id} \rangle, \langle \text{Exp} \rangle)$   
          |  $\text{'Loop'}(\langle \text{BoolExp} \rangle, \langle \text{Cmd} \rangle)$   
          |  $\text{'CSeq'}(\langle \text{Cmd} \rangle, \langle \text{Cmd} \rangle)$

- From a syntactic standpoint, they extend both statements and expressions, as an identifier is an expression.

# $\pi$ automata semantics for $\pi$ lib commands I

- A location  $l \in Loc$  denotes a memory cell.
- Storable and Bindable sets denote the data that may be mapped to by identifiers and locations on the memory and environment respectively.
- $Store = Id \mapsto Storable$ ,  $Env = Loc \mapsto Bindable$ ,  $Loc \subseteq Store$ ,  $\mathbb{N} \subseteq Loc, Bindable$ .
- Now the transition function is  $\delta : L(G)^* \times L(G)^* \times Env \times Store \rightarrow Q$ , and let  $W \in String$ ,  $C, V \in L(G)^*$ ,  $S \in Store$ ,  $E \in Env$ ,  $B \in Bindable$ ,  $l \in Loc$ ,  $T \in Storable$ ,  $X \in \langle Exp \rangle$ ,  $M, M_1, M_2 \in \langle Cmd \rangle$ , and

$\pi$  automata semantics for  $\pi$  lib commands II

expression  $S' = S/[I \mapsto N]$  means that  $S'$  equals to  $S$  in all indices but  $I$  that is bound to  $N$ ,

$$\delta(Id(W) :: C, V, E, S) = \delta(C, B :: V, E, S), \quad (17)$$

where  $E[W] = I$  and  $S[I] = B$ ,

$$\delta(Assign(W, X) :: C, V, E, S) = \delta(X :: \#ASSIGN :: C, W :: V, E, S'), \quad (18)$$

$$\delta(\#ASSIGN :: C, T :: W :: V, E, S) = \delta(C, V, E, S'), \quad (19)$$

where  $E[W] = I$  and  $S' = S/[I \mapsto T]$ ,

$$\delta(Loop(X, M) :: C, V, E, S) = \delta(X :: \#LOOP :: C, Loop(X, M) :: V, E, S), \quad (20)$$

$$\delta(\#LOOP :: C, Bool(true) :: Loop(X, M) :: V, E, S) = \delta(M :: Loop(X, M) :: C, V, E, S), \quad (21)$$

$$\delta(\#LOOP :: C, Bool(false) :: Loop(X, M) :: V, E, S) = \delta(C, V, E, S), \quad (22)$$

$$\delta(CSeq(M_1, M_2) :: C, V, E, S) = \delta(M_1 :: M_2 :: C, V, E, S). \quad (23)$$

# $\pi$ lib expressions in Python I

<https://github.com/ChristianoBraga/BPLC/blob/master/python/pi.ipynb>

```
1 class Statement:
2     def __init__(self, *args):
3         self.opr =args
4     def __str__(self):
5         ret =str(self.__class__.__name__)+ "("
6         for o in self.opr:
7             ret +=str(o)
8         ret +=")"
9         return ret
10 class Exp(Statement): pass
11 class ArithExp(Exp): pass
```

## $\pi$ lib expressions in Python II

```
1 class Num(ArithExp):
2     def __init__(self, f):
3         assert(isinstance(f, int))
4         ArithExp.__init__(self, f)
5 class Sum(ArithExp):
6     def __init__(self, e1, e2):
7         assert(isinstance(e1, Exp) and isinstance(e2, Exp))
8         ArithExp.__init__(self, e1, e2)
9 ...
```

## $\pi$ lib expressions in Python III

```
1 class BoolExp(Exp): pass
2 class Eq(BoolExp):
3     def __init__(self, e1, e2):
4         assert(isinstance(e1, Exp) and isinstance(e2, Exp))
5         BoolExp.__init__(self, e1, e2)
6 ...
```

# $\pi$ lib expressions in Python IV

```
1 exp = Sum(Num(1), Mul(Num(2), Num(4)))  
2 print(exp)  
3  
4 Sum(Num(1)Mul(Num(2)Num(4)))
```

# $\pi$ lib expressions in Python V

```

1 exp2 =Mul(2, 1)
2 -----
3
4
5
6
7
8
9
10
11
12
13
14

```

AssertionError Traceback (most recent call last)

<ipython-input-7-00fd40a79a54> in <module>()

---->1 exp2 =Mul(2, 1)

<ipython-input-5-42a82e58862f> in \_\_init\_\_(self, e1, e2)

```

28 class Mul(ArithExp):
29 def __init__(self, e1, e2):
30 assert(isinstance(e1, Exp) and isinstance(e2, Exp))
31 ArithExp.__init__(self, e1, e2)
32 class BoolExp(Exp): pass

```

AssertionError:



# $\pi$ automaton for $\pi$ lib expressions I

```
1  ## Expressions
2  class ValueStack(list): pass
3  class ControlStack(list): pass
4  class ExpKW:
5      SUM = "#SUM"
6      SUB = "#SUB"
7      MUL = "#MUL"
8      EQ = "#EQ"
9      NOT = "#NOT"
```

## $\pi$ automaton for $\pi$ lib expressions II

```
1 class ExpPiAut(dict):
2     def __init__(self):
3         self["val"] = ValueStack()
4         self["cnt"] = ControlStack()
5     def __evalSum(self, e):
6         e1 = e.opr[0]
7         e2 = e.opr[1]
8         self.pushCnt(ExpKW.SUM)
9         self.pushCnt(e1)
10        self.pushCnt(e2)
11    def pushCnt(self, e):
12        cnt = self.cnt()
13        cnt.append(e)
14    ...
```

# $\pi$ automaton for $\pi$ lib expressions III

```
1 ea =ExpPiAut()  
2 print(exp)  
3 ea.pushCnt(exp)  
4 while not ea.emptyCnt():  
5     ea.eval()  
6     print(ea)
```

$\pi$  automaton for  $\pi$  lib expressions IV

```

1 Sum(Num(1)Mul(Num(2)Num(4)))
2 {'val': [], 'cnt': ['#SUM', <__main__.Num object at 0x111851470>, <
    __main__.Mul object at 0x1118516d8>]}
3 {'val': [], 'cnt': ['#SUM', <__main__.Num object at 0x111851470>, '#MUL',
    , <__main__.Num object at
    0x111851630>, <__main__.Num object
    at 0x1118516a0>]}
4 {'val': [4], 'cnt': ['#SUM', <__main__.Num object at 0x111851470>, '#MUL',
    , <__main__.Num object at
    0x111851630>]}
5 {'val': [4, 2], 'cnt': ['#SUM', <__main__.Num object at 0x111851470>, '#MUL']}
6 {'val': [8], 'cnt': ['#SUM', <__main__.Num object at 0x111851470>]}
7 {'val': [8, 1], 'cnt': ['#SUM']}
8 {'val': [9], 'cnt': []}

```

## $\pi$ lib commands I

```
1 class Cmd(Statement): pass
2 class Id(Exp):
3     def __init__(self, s):
4         assert(isinstance(s, str))
5         Exp.__init__(self, s)
6 class Assign(Cmd):
7     def __init__(self, i, e):
8         assert(isinstance(i, Id) and isinstance(e, Exp))
9         Cmd.__init__(self, i, e)
10 class Loop(Cmd):
11     def __init__(self, be, c):
12         assert(isinstance(be, BoolExp) and isinstance(c, Cmd))
13         Cmd.__init__(self, be, c)
14 class CSeq(Cmd):
15     def __init__(self, c1, c2):
16         assert(isinstance(c1, Cmd) and isinstance(c2, Cmd))
17         Cmd.__init__(self, c1, c2)
```

## $\pi$ lib commands II

```
1 cmd =Assign(Id("x"), Num(1))
2 print(type(cmd))
3 print(cmd)
4 <class '__main__.Assign'>
5 Assign(Id(x)Num(1))
```

# $\pi$ automaton for $\pi$ lib commands I

Environment, Location, Store and commands opcodes.

```
1 ## Commands
2 class Env(dict): pass
3 class Loc(int): pass
4 class Sto(dict): pass
5 class CmdKW:
6     ASSIGN = "#ASSIGN"
7     LOOP = "#LOOP"
```

## $\pi$ automaton for $\pi$ lib commands II

$\pi$  automaton for commands extends the  $\pi$  automaton for expressions.

```
1 class CmdPiAut(ExpPiAut):
2     def __init__(self):
3         self["env"] = Env()
4         self["sto"] = Sto()
5         ExpPiAut.__init__(self)
6     def env(self):
7         return self["env"]
8     def getLoc(self, i):
9         en = self.env()
10        return en[i]
11    def sto(self):
12        return self["sto"]
13    def updateStore(self, l, v):
14        st = self.sto()
15        st[l] = v
```



## $\pi$ automaton for $\pi$ lib commands III

$\pi$  semantics for assignment.

$$\begin{aligned}\delta(\text{Assign}(W, X) :: C, V, E, S) &= \delta(X :: \# \text{ASSIGN} :: C, W :: V, E, S'), \\ \delta(\# \text{ASSIGN} :: C, T :: W :: V, E, S) &= \delta(C, V, E, S'), \\ \text{where } E[W] &= I \text{ and } S' = S / [I \mapsto T].\end{aligned}$$

```

1  def __evalAssign(self, c):
2      i = c.opr[0]
3      e = c.opr[1]
4      self.pushVal(i.opr[0])
5      self.pushCnt(CmdKW.ASSIGN)
6      self.pushCnt(e)
7  def __evalAssignKW(self):
8      v = self.popVal()
9      i = self.popVal()
10     l = self.getLoc(i)
11     self.updateStore(l, v)

```

## $\pi$ automaton for $\pi$ lib commands IV

$\pi$  semantics for identifiers.

$$\delta(Id(W) :: C, V, E, S) = \delta(C, B :: V, E, S),$$

where  $E[W] = I$  and  $S[I] = B$ .

```
1  def __evalId(self, i):  
2      s =self.sto()  
3      l =self.getLoc(i)  
4      self.pushVal(s[l])
```

## $\pi$ automaton for $\pi$ lib commands V

$\pi$  semantics for loop: recursive step.

$$\delta(\text{Loop}(X, M) :: C, V, E, S) = \delta(X :: \#LOOP :: C, \text{Loop}(X, M) :: V, E, S).$$

```
1  def __evalLoop(self, c):  
2      be = c.opr[0]  
3      bl = c.opr[1]  
4      self.pushVal(Loop(be, bl))  
5      self.pushVal(bl)  
6      self.pushCnt(CmdKW.LOOP)  
7      self.pushCnt(be)
```

## $\pi$ automaton for $\pi$ lib commands VI

$\pi$  semantics for loop: basic steps.

$$\delta(\#LOOP :: C, \text{Boo}(\text{true}) :: \text{Loop}(X, M) :: V, E, S) = \delta(M :: \text{Loop}(X, M) :: C, V, E, S),$$
$$\delta(\#LOOP :: C, \text{Boo}(\text{false}) :: \text{Loop}(X, M) :: V, E, S) = \delta(C, V, E, S).$$

```
1 def __evalLoopKW(self):  
2     t =self.popVal()  
3     if t:  
4         c =self.popVal()  
5         lo =self.popVal()  
6         self.pushCnt(lo)  
7         self.pushCnt(c)  
8     else:  
9         self.popVal()  
10        self.popVal()
```

## $\pi$ automaton for $\pi$ lib commands VII

$\pi$  semantics for command composition.

$$\delta(CSeq(M_1, M_2) :: C, V, E, S) = \delta(M_1 :: M_2 :: C, V, E, S).$$

```
1  def __evalCSeq(self, c):  
2      c1 = c.opr[0]  
3      c2 = c.opr[1]  
4      self.pushCnt(c2)  
5      self.pushCnt(c1)
```

## $\pi$ automaton for $\pi$ lib commands VIII

Commands are now on the top of the food chain.

```
1  def eval(self):
2      c =self.popCnt()
3      if isinstance(c, Assign):
4          self.__evalAssign(c)
5      elif c ==CmdKW.ASSIGN:
6          self.__evalAssignKW()
7      elif isinstance(c, Id):
8          self.__evalId(c.opr[0])
9      elif isinstance(c, Loop):
10         self.__evalLoop(c)
11      elif c ==CmdKW.LOOP:
12         self.__evalLoopKW()
13      elif isinstance(c, CSeq):
14         self.__evalCSeq(c)
15      else:
16         self.pushCnt(c)
17         ExpPiAut.eval(self)
```