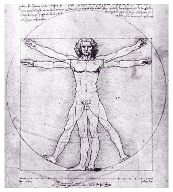
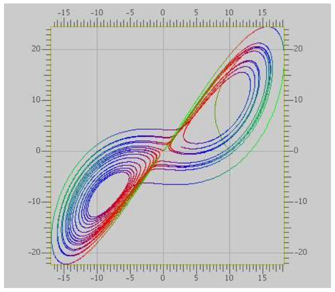
Anatomy of a Small Compiler

COMS W4115



Prof. Stephen A. Edwards
Fall 2003
Columbia University
Department of Computer Science

Mx



Mx

A Programming Langauge for Scientific Computation

Resembles Matlab, Octave, Mathematica, etc.

Project from Spring 2003

Authors:

Tiantian Zhou

Hanhua Feng

Yong Man Ra

Chang Woo Lee

Example

Plotting the Lorenz equations

$$\begin{aligned}\frac{dy_0}{dt} &= \alpha(y_1 - y_0)\\ \frac{dy_1}{dt} &= y_0(r - y_2) - y_1\\ \frac{dy_2}{dt} &= y_0 y_1 - b y_2\end{aligned}$$

Mx source part 1

```
/* Lorenz equation parameters */

a = 10;
b = 8/3.0;
r = 28;

/* Two-argument function returning a vector */
 func Lorenz ( y, t ) = [ a*(y[1]-y[0]);
                        -y[0]*y[2] + r*y[0] - y[1];
                        y[0]*y[1] - b*y[2] ];

/* Runge-Kutta numerical integration procedure */
func RungeKutta( f, y, t, h ) {
    k1 = h * f( y, t );
    k2 = h * f( y+0.5*k1, t+0.5*h );
    k3 = h * f( y+0.5*k2, t+0.5*h );
    k4 = h * f( y+k3, t+h );
    return y + (k1+k4)/6.0 + (k2+k3)/3.0;
}
```

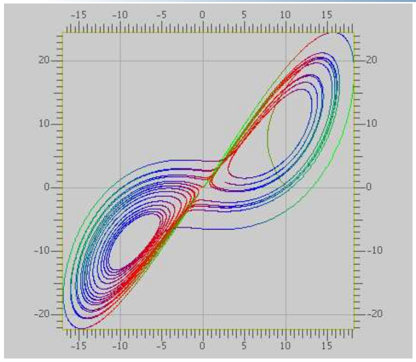
Mx source part 2

```
/* Parameters for the procedure */
N = 20000;
p = zeros(N+1,3);
t = 0.0;
h = 0.001;
x = [ 10; 0; 10 ];
p[0,:] = x’; /* matrix transpose */

for ( i = 1:N ) {
    x = RungeKutta( Lorenz, x, t, h );
    p[i,:] = x’;
    t += h;
}

colormap(3);
plot(p);
return 0;
```

Result



file	lines	role
Scanner and Parser: Builds the tree		
grammar.g	314	Lexer/Parser (ANTLR source)
Interpreter: Walks the tree, invokes objects’ methods		
walker.g	170	Tree Walker (ANTLR source)
MxInterpreter.java	359	Function invocation, etc.
MxSymbolTable.java	109	Name-to-object mapping
Top-level: Invokes the interpreter		
MxMain.java	153	Command-line interface
MxException.java	13	Error reporting
Runtime system: Represents data, performs operations		
MxDataType.java	169	Base class
MxBool.java	63	Booleans
MxInt.java	152	Integers
MxDouble.java	142	Floating-point
MxString.java	47	String
MxVariable.java	26	Undefined variable
MxFunction.java	81	User-defined functions
MxInternalFunction.m4	410	sin, cos, etc. (macro processed)
jamaica/Matrix.java	1387	Matrices
MxMatrix.java	354	Wrapper
jamaica/Range.java	163	e.g., 1:10
MxRange.java	67	Wrapper
jamaica/BitArray.java	226	Matrix masks
MxBitArray.java	47	Wrapper
jamaica/Painter.java	339	Bitmaps
jamaica/Plotter.java	580	2-D plotting
total	5371	

The Scanner

```
class MxAntlrLexer extends Lexer;

options {
    k = 2;
    charVocabulary = ’\3’..’\377’;
    testLiterals = false;
    exportVocab = MxAntlr;
}

protected ALPHA : ’a’..’z’ | ’A’..’Z’ | ’_’;

protected DIGIT : ’0’..’9’;

WS : (’ ’ | ’\t’)+ { $setType(Token.SKIP); } ;

NL : (’\n’ | (’\r’ ’\n’) => ’\r’ ’\n’ | ’\r’)
     { $setType(Token.SKIP); newline(); } ;
```

The Scanner

```
COMMENT : ( "/*" ( options {greedy=false;} :
                   NL
                   | ~( ’\n’ | ’\r’ )
                 )* "*/"
            | "//" (~( ’\n’ | ’\r’ ))* NL
          ) { $setType(Token.SKIP); } ;

LDV_LDVEQ : "/’" (
                   (’=’) => ’=’ { $setType(LDVEQ); }
                   | { $setType(LDV); }
                 );
```

The Scanner

```
LPAREN  : ’(’;
RPAREN  : ’)’;
/* ... */
TRSP    : ’\’’;
COLON   : ’:’;
DCOLON  : "::";

ID options { testLiterals = true; }
  : ALPHA (ALPHA|DIGIT)* ;

NUMBER : (DIGIT)+ (’.’ (DIGIT)*)?
         ((’E’|’e’) (’+’|’-’)? (DIGIT)+)? ;

STRING : ’"’!
         ( ~(’"’ | ’\n’) | (’"’! ’"’) )*
         ’"’! ;
```

The Parser: Top-level

```
class MxAntlrParser extends Parser;

options {
    k = 2;
    buildAST = true;
    exportVocab = MxAntlr;
}

tokens {
   STATEMENT;
   FOR_CON;
   /* ... */
}

program : ( statement | func_def )* EOF!
          { #program = #([STATEMENT,"PROG"], program); }
        ;
```

The Parser: Statements

```
statement
  : for_stmt
  | if_stmt
  | loop_stmt
  | break_stmt
  | continue_stmt
  | return_stmt
  | load_stmt
  | assignment
  | func_call_stmt
  | LBRACE! (statement)* RBRACE!
      {#statement = #([STATEMENT,"STATEMENT"], statement); }
  ;
```

The Parser: Statements 1

```
for_stmt : "for"^ LPAREN! for_con RPAREN! statement ;

for_con : ID ASGN! range (COMMA! ID ASGN! range)*
          { #for_con = #([FOR_CON,"FOR_CON"], for_con); }
        ;

if_stmt : "if"^ LPAREN! expression RPAREN! statement
          (options {greedy = true;}: "else"! statement )?
        ;

loop_stmt! : "loop" ( LPAREN! id:ID RPAREN! )? stmt:statement
      { if ( null == #id )
           #loop_stmt = #([LOOP,"loop"], #stmt);
        else
           #loop_stmt = #([LOOP,"loop"], #stmt, #id);
      } ;
```

The Parser: Statements 2

```
break_stmt : "break"^ (ID)? SEMI! ;
continue_stmt : "continue"^ (ID)? SEMI! ;
return_stmt : "return"^ (expression)? SEMI! ;
load_stmt : "include"^ STRING SEMI! ;

assignment
  : l_value ( ASGN^ | PLUSEQ^ | MINUSEQ^ | MULTEQ^
            | LDVEQ^ | MODEQ^ | RDVEQ^
            ) expression SEMI!
  ;

func_call_stmt : func_call SEMI! ;

func_call
  : ID LPAREN! expr_list RPAREN!
    { #func_call = #([FUNC_CALL,"FUNC_CALL"], func_call); }
  ;
```

The Parser: Function Definitions

```
func_def
  : "func"^ ID LPAREN! var_list RPAREN! func_body
  ;

var_list
  : ID ( COMMA! ID )*
    { #var_list = #([VAR_LIST,"VAR_LIST"], var_list); }
  | { #var_list = #([VAR_LIST,"VAR_LIST"], var_list); }
  ;

func_body
   : ASGN! a:expression SEMI!
     { #func_body = #a; }
   | LBRACE! (statement)* RBRACE!
     { #func_body = #([STATEMENT,"FUNC_BODY"], func_body); }
   ;
```

The Parser: Expressions

```
expression : logic_term ( "or"^ logic_term )* ;
logic_term : logic_factor ( "and"^ logic_factor )* ;
logic_factor : ("not"^)? relat_expr ;
relat_expr : arith_expr ( (GE^ | LE^ | GT^
                          | LT^ | EQ^ | NEQ^) arith_expr )? ;
arith_expr : arith_term ( (PLUS^ | MINUS^) arith_term )* ;
arith_term : arith_factor
    ( (MULT^ | LDV^ | MOD^ | RDV^) arith_factor )* ;
arith_factor
 : PLUS! r_value
   { #arith_factor = #([UPLUS,"UPLUS"], arith_factor); }
 | MINUS! r_value
   { #arith_factor = #([UMINUS,"UMINUS"], arith_factor); }
 | r_value (TRSP^)*;
r_value
  : l_value | func_call | NUMBER | STRING | "true" | "false"
  | array | LPAREN! expression RPAREN! ;
l_value : ID^ ( LBRK! index RBRK! )* ;
```

The Walker: Top-level

```
{
  import java.io.*;
  import java.util.*;
}

class MxAntlrWalker extends TreeParser;
options{
    importVocab = MxAntlr;
}

{
    static MxDataType null_data = new MxDataType( "<NULL>" );
    MxInterpreter ipt = new MxInterpreter();
}
```

The Walker: Expressions

```
expr returns [ MxDataType r ]
{
    MxDataType a, b;
    Vector v;
    MxDataType[] x;
    String s = null;
    String[] sx;
    r = null_data;
}
  : #("or" a=expr right_or:.)
      { if ( a instanceof MxBool )
          r = ( ((MxBool)a).var ? a : expr(#right_or) );
        else
          r = a.or( expr(#right_or) );
      }
  | #("and" a=expr right_and:.)
      { if ( a instanceof MxBool )
           r = ( ((MxBool)a).var ? expr(#right_and) : a );
        else
           r = a.and( expr(#right_and) );
      }
```

The Walker: Simple operators

```
| #("not" a=expr)             { r = a.not(); }
| #(GE a=expr b=expr)         { r = a.ge( b ); }
| #(LE a=expr b=expr)         { r = a.le( b ); }
| #(GT a=expr b=expr)         { r = a.gt( b ); }
| #(LT a=expr b=expr)         { r = a.lt( b ); }
| #(EQ a=expr b=expr)         { r = a.eq( b ); }
| #(NEQ a=expr b=expr)        { r = a.ne( b ); }
| #(PLUS a=expr b=expr)       { r = a.plus( b ); }
| #(MINUS a=expr b=expr)      { r = a.minus( b ); }
| #(MULT a=expr b=expr)       { r = a.times( b ); }
| #(LDV a=expr b=expr)        { r = a.lfracts( b ); }
| #(RDV a=expr b=expr)        { r = a.rfracts( b ); }
| #(MOD a=expr b=expr)        { r = a.modulus( b ); }
| #(COLON (c1:. (c2:.)?)?)
   {
     r = MxRange.create( (null==#c1) ? null : expr(#c1),
                         (null==#c2) ? null : expr(#c2) );
   }
| #(ASGN a=expr b=expr)       { r = ipt.assign( a, b ); }
| #(FUNC_CALL a=expr x=mexpr){ r = ipt.funcInvoke(this,a,x); }
```

The Walker: Literals, Variables, and Functions

```
| #(ARRAY                      { v = new Vector(); }
     (a=expr                   { v.add( a ); }
     )*
   ) { r = MxMatrix.joinVert( ipt.convertExprList( v ) ); }
| #(ARRAY_ROW                  { v = new Vector(); }
     (a=expr                   { v.add( a ); }
     )+
   ) { r = MxMatrix.joinHori( ipt.convertExprList( v ) ); }
| num:NUMBER                   { r = ipt.getNumber( num.getText() );
| str:STRING                   { r = new MxString( str.getText() );
| "true"                       { r = new MxBool( true ); }
| "false"                      { r = new MxBool( false ); }
| #(id:ID                      { r = ipt.getVariable( id.getText() )
    ( x=mexpr { r = ipt.subMatrix( r, x ); } )*
   )
| #("func" fname:ID sx=vlist fbody:.)
  { ipt.funcRegister( fname.getText(), sx, #fbody ); }
```

The Walker: For and If statements

```
| #("for" x=mexpr forbody:.)
    {
        MxInt[] values = ipt.forInit( x );
        while ( ipt.forCanProceed( x, values ) ) {
          r = expr( #forbody );
          ipt.forNext( x, values );
        }
        ipt.forEnd( x );
    }
| #("if" a=expr thenp:. (elsep:.)?)
    {
        if ( !( a instanceof MxBool ) )
            return a.error( "if: expression should be bool" );
        if ( ((MxBool)a).var )
            r = expr( #thenp );
        else if ( null != elsep )
            r = expr( #elsep );
    }
```

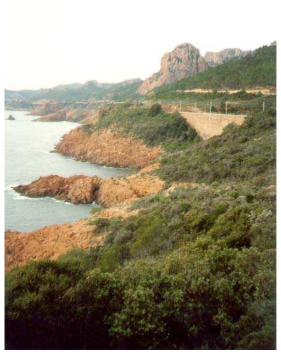
The Walker: Multiple expressions

```
mexpr returns [ MxDataType[] rv ]
{
    MxDataType a;
    rv = null;
    Vector v;
}
  : #(EXPR_LIST         { v = new Vector(); }
          ( a=expr      { v.add( a ); }
          )*
     )                  { rv = ipt.convertExprList( v ); }
  | a=expr              { rv = new MxDataType[1]; rv[0] = a; }
  |  #(FOR_CON          { v = new Vector(); }
          ( s:ID a=expr { a.setName( s.getText() ); v.add(a); }
          )+
      )                 { rv = ipt.convertExprList( v ); }
  ;
```

The Walker: Variable list

```
vlist returns [ String[] sv ]
{
    Vector v;
    sv = null;
}
  : #(VAR_LIST     { v = new Vector(); }
        (s:ID      { v.add( s.getText() ); }
        )*
    )              { sv = ipt.convertVarList( v ); }
  ;
```

CEC



CEC

CEC is the Columbia Esterel Compiler that my group is currently developing.

You can find the source code (well-documented C++) off the “software” link on my homepage.

Compiles the Esterel language into hardware and software.

A concurrent language: uses a concurrent control-flow graph as an intermediate representation.

Esterel Syntax

Standard free-form style:

```
module test_present2:
input A;
output B, C;

present A then
  emit B
else
  emit C
end present

end module
```

The Scanner

Options

```
class EsterelLexer extends Lexer;

options {
  // Lookahead to distinguish, e.g., : and :=
  k = 2;
  // Handle all 8-bit characters
  charVocabulary = ’\3’..’\377’;
  // Export these token types for tree walkers
  exportVocab = Esterel;
  // Disable checking every rule against keywords
  testLiterals = false;
}
```

Punctuation and Identifiers

```
PERIOD :   ’.’ ;
POUND :    ’#’ ;
PLUS :     ’+’ ;
DASH :     ’-’ ;
SLASH :    ’/’ ;
STAR :     ’*’ ;
PARALLEL : "||" ;
/* etc. */

ID options { testLiterals = true; }
  : (’a’..’z’ | ’A’..’Z’)
    (’a’..’z’ | ’A’..’Z’ | ’_’ | ’0’..’9’)*
  ;
```

C-style numeric constants

```
Number
  : (’0’..’9’)+
      ( ’.’ (’0’..’9’)* (Exponent)?
        ( (’f’|’F’) { $setType(FloatConst); }
        | /* empty */
          { $setType(DoubleConst); }
        )
      | /* empty */ { $setType(Integer); }
      )
  ;
```

C-style numeric constants contd.

```
FractionalNumber
  : ’.’ (’0’..’9’)+ (Exponent)?
        ( (’f’|’F’) { $setType(FloatConst); }
        | /* empty */
          { $setType(DoubleConst); }
        )
  ;

protected
Exponent
  : (’e’|’E’) (’+’|’-’)? (’0’..’9’)+
  ;
```

Strings, whitespace, newlines

```
StringConstant
  : ’"’! ( ˜(’"’ | ’\n’) | (’"’! ’"’))* ’"’!
  ;

Whitespace
  : (’ ’ | ’\t’ | ’\f’)+
    { $setType(antlr::Token::SKIP); }
  ;

Newline
  : ( ’\n’ | "\r\n" | ’\r’ )
    { $setType(antlr::Token::SKIP);
      newline(); }
  ;
```

The Parser

Options

```
class EsterelParser extends Parser;
options {
  // Lookahead
  k = 2;
  // Construct an AST during parsing
  buildAST = true;
  // Export these token types for the tree walker
  exportVocab = Esterel;
  // Create AST nodes with line numbers
  ASTLabelType = "RefLineAST";
  // Don’t automatically catch every exception
  defaultErrorHandler = false;
}
```

Tokens

Extra token types; don’t correspond to keywords. Used to build additional structure into the AST.

```
tokens {
 SIGS;
 VARS;
 TYPES;
 DECLS;
 TRAPS;
 SEQUENCE;
 ARGS;
 /* etc. */
}
```

File and module

```
file
  : (module)+ EOF!
  ;

module
  : "module"^ moduleIdentifier COLON!
      declarations
      statement
    (
      "end"! "module"!
    | PERIOD!  // Deprecated syntax
    )
  ;
```

Declarations

```
declarations
  : (interfaceDecls)*
    { #declarations = #([DECLS, "decls"],
                        #declarations); }
  ;
interfaceDecls :
    typeDecls
  | constantDecls
  | functionDecls
  | procedureDecls
  | taskDecls
  | interfacesignalDecls
  | sensorDecls
  | relationDecls
  ;
```

Various Declarations

```
typeDecls
  : "type"^ typeIdentifier
    (COMMA! typeIdentifier)* SEMICOLON!
  ;

constantDecls
  : "constant"^ constantDecl
    (COMMA! constantDecl )* SEMICOLON!
  ;
```

Expressions

```
expression
  : orexpr
  ;
orexpr
  : andexpr ("or"^ andexpr)*
  ;
andexpr
  : notexpr ("and"^ notexpr)*
  ;
notexpr
  : "not"^ cmpexpr
  | cmpexpr
  ;
```

Expressions

```
mulexpr
  : unaryexpr
    ( (STAR^ | SLASH^ | "mod"^) unaryexpr )*
  ;

unaryexpr
  : DASH^ unaryexpr
  | LPAREN! expression RPAREN!
  | QUESTION^ signalIdentifier
  | "pre"^
    LPAREN! QUESTION^ signalIdentifier RPAREN!
  | DQUESTION^ trapIdentifier
  | functionCall
  | constant
  ;
```

Statements in Parallel

```
statement
  : sequence (PARALLEL! sequence)*
    { if (#statement &&
            #statement->getNextSibling()) {
          #statement = #([PARALLEL, "||"],
                         #statement);
      }
    }
  ;
```

Statements in Sequence

```
sequence
  : atomicStatement
    (options {greedy=true;} :
      SEMICOLON! atomicStatement)*
    (SEMICOLON!)?
    { if (#sequence &&
            #sequence->getNextSibling()) {
        #sequence = #([SEQUENCE, ";"],
                      #sequence);
      }
    }
  ;
```

The Present (if) Statement

Two forms:

```
present S then          present
   nothing                case C do nothing
else                      case D
   nothing                else pause
end                     end present
```

```
present
  : "present"^
    (presentThenPart | (presentCase)+)
     (elsePart)? "end"! ("present"!)?
  ;
```

The Present (if) Statement

```
presentThenPart
  : presentEvent ("then"! statement)?
    { #presentThenPart = #([CASE,"case"],
                           presentThenPart); }
  ;
elsePart
  :  "else"^ statement
  ;
presentCase
  : "case"! presentEvent ("do"! statement)?
    { #presentCase = #([CASE,"case"],
                       presentCase); }
  ;
```

The AST Classes

My AST Classes

ANTLR, by default, builds its AST out of one type of object, an AST node with numeric type, a string, a first child, and a next sibling.

It has a facility for building heterogeneous ASTs (one class per token type), but I chose not to use it.

Instead, I created a new set of AST classes and translated the homogeneous AST into these classes during static semantics.

AST Classes

- Symbols (modules, signals, variables, functions)
  Name and usually a type
- Symbol table
  Holds symbols, points to a parent symbol table
- Expressions (literals, variables, operators)
  Each has a type
- Modules (like a function declaration)
  Has many symbol tables and a body
- Statement sequences and parallel groups
- Statements, one class per statement type

Example AST class

```
class Assignment : Statement {
  VariableSymbol *variable;
  Expression *value;
};
```

Example AST Classes

```
class CaseStatement : Statement {
  vector<PredicatedStatement *> cases;
  Statement *default;
};

class BodyStatement : Statement {
  Statement *body;
};

class PredicatedStatement : BodyStatement {
  Expression *predicate;
};
```

The Symbol Table Class

```
class SymbolTable : public ASTNode {
public:
  SymbolTable *parent;
  typedef map<string, Symbol*> stmap;
  stmap symbols;

  SymbolTable() : parent(NULL) {}

  bool local_contains(const string) const;
  bool contains(const string) const;
  void enter(Symbol *);
  Symbol* get(const string);
};
```

SymbolTable contains tests

```
bool SymbolTable::
local_contains(const string s) const {
  return symbols.find(s) != symbols.end();
}

bool SymbolTable::
contains(const string s) const {
  for ( const SymbolTable *st = this ; st ;
        st = st->parent )
    if (st->symbols.find(s) !=
        st->symbols.end()) return true;
  return false;
}
```

SymbolTable::enter

```
void SymbolTable::enter(Symbol *sym) {
  assert(sym);
  assert(symbols.find(sym->name) ==
         symbols.end());
  symbols.insert(
    std::make_pair(sym->name, sym)
  );
}
```

SymbolTable::get

```
Symbol* SymbolTable::get(const string s) {
  map<string, Symbol*>::const_iterator i;
  for ( SymbolTable *st = this; st ;
        st = st->parent ) {
    i = st->symbols.find(s);
    if (i != st->symbols.end()) {
      assert((*i).second);
      assert((*i).second->name == s);
      return (*i).second;
    }
  }
  assert(0);
}
```

Static Semantics

Static Semantics

Checks that every symbol is defined

Checks types (simple in Esterel)

Translates the ANTLR-generated AST into my own specialized version.

Written as a tree walker

The Tree Walker

```
class EsterelTreeParser extends TreeParser;

options {
  // Get the Esterel token types
  importVocab = Esterel;
  // Expect AST nodes with line numbers
  ASTLabelType = "RefLineAST";
}

file [Modules *ms, string filename]
    : { assert(ms); }
      ( module[ms] )+
    ;
```

The Module Rule

```
module [Modules* modules]
  : #( "module" moduleName:ID
{
  assert(modules);
  string name = moduleName->getText();
  if (modules->
      module_symbols.local_contains(name))
    throw LineError(moduleName,
                    "Duplicate module " + name);
  ModuleSymbol *ms = new ModuleSymbol(name);
  Module *m = new Module(ms);
  ms->module = m;
  modules->add(m);
```

The notion of a Context

When you're translating, say, an expression, you need to know in which symbol table to look for symbols and other useful things.

I implemented a class called "Context" to hold this information.

Encountering a scope-generating statement creates a new context.

Translation routines pass the context to whatever they call.

Contexts are not part of the AST and are discarded after a scope closes.

Context

```
struct Context {
  Module *module;
  SymbolTable *variables;
  SymbolTable *traps;
  SymbolTable *signals;
  BuiltinTypeSymbol *boolean_type;
  BuiltinTypeSymbol *integer_type;
  BuiltinTypeSymbol *float_type;
  BuiltinTypeSymbol *double_type;
  BuiltinConstantSymbol *true_constant;
  BuiltinConstantSymbol *false_constant;
  Context(Module *m) :
    module(m), variables(m->constants),
    traps(0), signals(m->signals) {}
 };
```

The Module Rule

```
  Context c(m);

  m->types->enter(c.boolean_type =
      new BuiltinTypeSymbol("boolean"));
  m->constants->enter(c.false_constant =
    new BuiltinConstantSymbol("false", c.boolean_type, 0)
  m->functions->enter(new BuiltinFunctionSymbol("and"));
  /* ... */

  VariableSymbol *vs =
     new VariableSymbol("tick", c.boolean_type, 0);
  m->variables->enter(vs);
  m->signals->enter(
    new BuiltinSignalSymbol("tick", 0,
                        "input", 0, vs, 0));
```

The Module Rule

```
   Statement *s; /* Local variable in module rule */
  }

  declarations[&c]
  s=statement[&c] { m->body = s; }
  ) /* matches #("module" ... */
  ;
```

Signal Declarations

```
input s1,
      s2 : boolean,
      s3 : combine integer with +,
      s8 := 3 : integer,
      s9 := 5 : combine integer with +;
```

Signal Declarations

```
signalDecl [Context *c, string direction,
            bool isGlobal]
  : #( SDECL signalName:ID
       {
         string name = signalName->getText();
         if (c->signals->local_contains(name))
           throw LineError(signalName,
                    "Redeclaration of " + name);
         Expression *e = 0;
       }
       ( #(COLEQUALS e=expr:expression[c]) )?
       { TypeSymbol *t = 0; FunctionSymbol *fs = 0; }
```

Signal Declarations

```
(t=typeToken:type[c]
  ( func:ID
    {
      string name = func->getText();
      if (!c->module->functions
            ->local_contains(name))
        throw LineError(func,
           "Undeclared function " + name);
      Symbol *sym = c->module->functions->get(name);
      fs = dynamic_cast<FunctionSymbol*>(sym);
      assert(fs);
    }
```

Signal Declarations

```
  | pcf:predefinedCombineFunction
    {
      string name = pcf->getText();
      assert(c->module->functions->contains(name));
      Symbol *sym = c->module->functions->get(name);
      fs = dynamic_cast<BuiltinFunctionSymbol*>(sym);
      assert(fs);
    }
  )?
)?
```

Signal Declarations

```
       {
          new_signal(c, name, t, direction, fs, e);
          if (e && (e->type != t))
            throw LineError(signalName,
              "initializer does not "
              "match type of signal");
       }
     )
  ;
```

Signal Expressions

```
sigExpression [Context *c] returns [Expression *e]
 : { Expression *e1, *e2; }
 ( #( "and" e1=sigExpression[c] e2=sigExpression[c] )
   { e = new BinaryOp(c->boolean_type,"and",e1,e2); }
 | sig:ID
   {
     string name = sig->getText();
     if (!c->signals->contains(name))
       throw LineError(sig,
                  "unrecognized signal " + name);
     SignalSymbol *ss = dynamic_cast<SignalSymbol*>(
                          c->signals->get(name));
     e = new LoadSignalExpression(ss);
   }
 );
```

Local Signal Statements

```
signal ls2,
       ls3 : boolean,
       ls4 := 3 + v1 : integer,
       ls5 := v3 or true :
          combine boolean with or in
   emit ls2;
   emit ls4(10);
   emit ls5(false)
end
```

Local Signal Statement

```
| #( "signal"
     {
       Signal *sig = new Signal();
       Context nc = *c;
       nc.signals = sig->symbols = new SymbolTable();
       sig->symbols->parent = c->signals;
     }
     #( SIGS ( signalDecl[&nc, "local", false] )+ )
     { Statement *s; }
     s=statement[&nc]
     {
       sig->body = s;
       st = sig;
     }
   )
```

Type checking expressions

```
expression [Context *c] returns [Expression *e]
  :
  {
    Expression *e1 = 0, *e2 = 0; // for safety
    e = 0; // for safety
  }
  (#( PLUS e1=expression[c] e2=expression[c] )
    { e = numeric_binop(#expression,
                        c, "+", e1, e2); }
  | #( STAR e1=expression[c] e2=expression[c] )
    { e = numeric_binop(#expression,
                        c, "*", e1, e2); }
```

Type checking expressions

```
static Expression*
numeric_binop(RefLineAST l, Context *c, string op,
              Expression *e1, Expression *e2)
{
  assert(c); assert(e1); assert(e2);

  if (e1->type != e2->type ||
      !(e1->type == c->integer_type ||
        e1->type == c->float_type ||
        e1->type == c->double_type ))
    throw LineError(l,
      "arguments of " + op + " must be numeric");
  return new BinaryOp(e1->type, op, e1, e2);
}
```

Dismantling

Dismantling

Many more complicated Esterel statement are equivalent to multiple simple statements, e.g.,

```
present                 if (p1) s1
  case p1 do s1         else if (p2) s2
  case p2 do s2         else s3
  else s3
end
```

Dismantling Case Statements

```
IfThenElse *dismantle_case(CaseStatement &c) {
  IfThenElse *result = 0; IfThenElse *lastif = 0;
  for (vector<PredicatedStatement*>::iterator i =
       c.cases.begin() ; i != c.cases.end() ; i++ ) {
    IfThenElse *thisif =
       new IfThenElse((*i)->predicate);
    thisif->then_part = transform((*i)->body);
    if (result) lastif->else_part = thisif;
    else result = thisif;
    lastif = thisif;
  }
  lastif->else_part = c.default_stmt;
  return transform(result); // Recurse
}
```

Some Statistics

File	Role	# lines
esterel.g	Parser/Scanner	850
staticsemantics.g	AST builder	1030
AST.nw	AST class source	1301
IR.nw	XML Serialization	827
Dismantle.nw	Dismantling	744
ExpandModules.nw	Macro Expansion	1606
AST.hpp*	AST classes	1746
AST.cpp*	AST classes	1421

* auto-generated