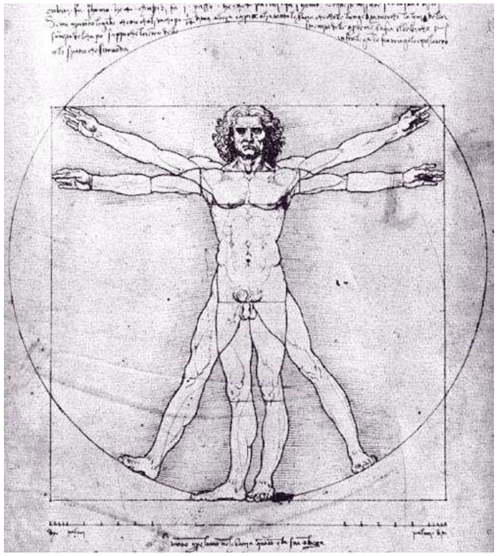
Anatomy of a Small Compiler

COMS W4115



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Spring 2007

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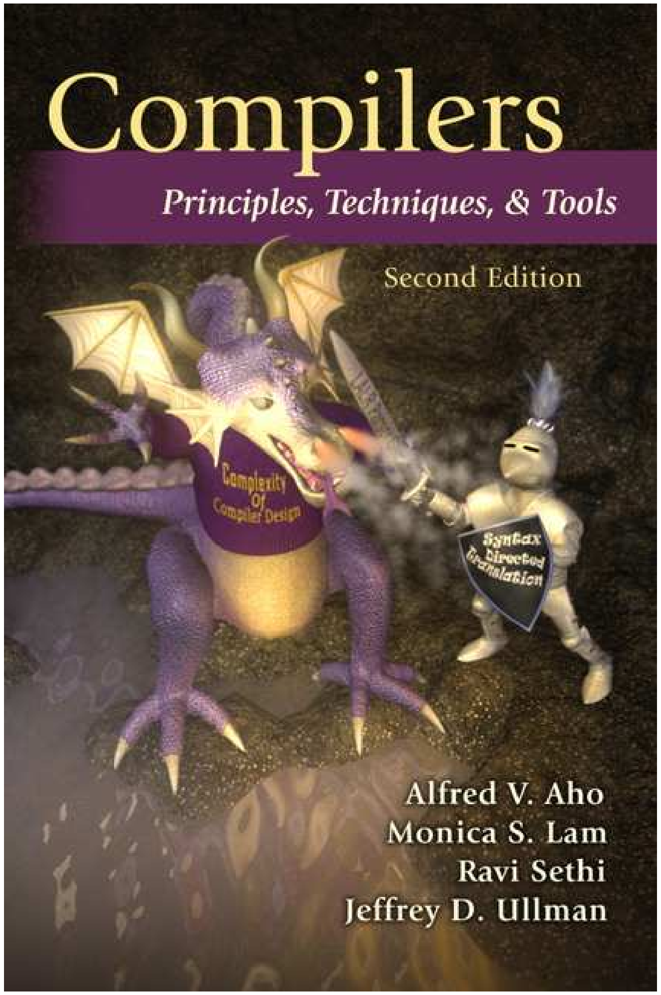
Appendix A of the Dragon Book


Compilers
Principles, Techniques, & Tools
Second Edition
Complexity Of Compiler Design
Syntax Directed Translation
Alfred V. Aho
Monica S. Lam
Ravi Sethi
Jeffrey D. Ullman

A simple C-like language

```
{
  int i; int j;
  float[10][10] a;
  i = 0;
  while ( i < 10 ) {
    j = 0;
    while ( j < 10 ) {
      a[i][j] = 0;
      j = j+1;
    }
    i = i+1;
  }
  i = 0;
  while ( i < 10 ) {
    a[i][i] = 1;
    i = i+1;
  }
}
```

```
L1:  i = 0
L3:  iffalse i < 10 goto L4
L5:  j = 0
L6:  iffalse j < 10 goto L7
L8:  t1 = i * 80
     t2 = j * 8
     t3 = t1 + t2
     a [ t3 ] = 0
L9:  j = j + 1
     goto L6
L7:  i = i + 1
     goto L3
L4:  i = 0
L10: iffalse i < 10 goto L2
L11: t4 = i * 80
     t5 = i * 8
     t6 = t4 + t5
     a [ t6 ] = 1
L12: i = i + 1
     goto L10
L2:
```

The compiler only generates this three-address code.

The Scanner

```
class MyLexer extends Lexer;
options { k = 2; }

WHITESPACE : (' ' | '\t' | '\n' { newline(); } )+
             { $setType(Token.SKIP); } ;

protected DIGITS : ('0'..'9')+ ;

NUM : DIGITS ('.' DIGITS { $setType(REAL); } )? ;

AND :    "&&" ;   LE :     "<=" ;   SEMI :   ';'  ;
OR  :    "||" ;   GT :     '>'  ;   LPAREN : '('  ;
ASSIGN : '='  ;   GE :     ">=" ;   RPAREN : ')'  ;
EQ :     "==" ;   LBRACE : '{'  ;   PLUS :   '+'  ;
NOT :    '!'  ;   RBRACE : '}'  ;   MINUS :  '-'  ;
NE :     "!=" ;   LBRACK : '['  ;   MUL :    '*'  ;
LT :     '<'  ;   RBRACK : ']'  ;   DIV :    '/'  ;

ID : ('_' | 'a'..'z' | 'A'..'Z')
     ('_' | 'a'..'z' | 'A'..'Z' | '0'..'9')* ;
```

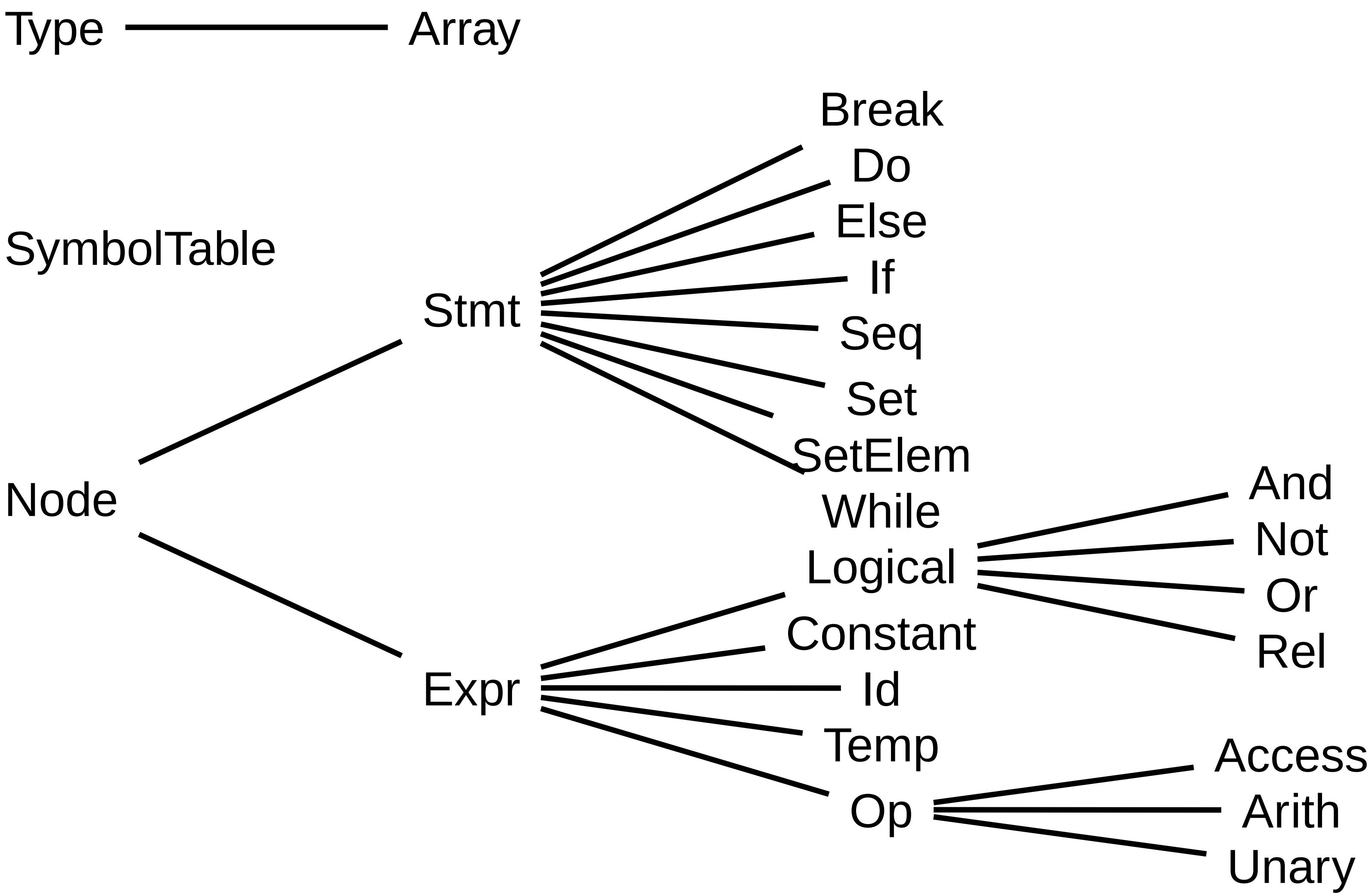
The Parser: Statements

```
class MyParser extends Parser;
options { buildAST = true; }
tokens  { NEGATE; DECLS; }

program : LBRACE^ decls (stmt)* RBRACE! ;

decls : (decl)* { #decls = #([DECLS, "DECLS"], #decls); } ;

decl : ("int" | "char" | "bool" | "float")
       (LBRACK! NUM RBRACK!)* ID SEMI! ;

stmt : loc ASSIGN^ bool SEMI!
     | "if"^ LPAREN! bool RPAREN! stmt
       (options {greedy=true;}: "else"! stmt)?
     | "while"^ LPAREN! bool RPAREN! stmt
     | "do"^ stmt "while"! LPAREN! bool RPAREN! SEMI!
     | "break" SEMI!
     | program
     | SEMI
     ;
```

The Parser: Expressions

```
bool     : join (OR^ join)* ;

join     : equality (AND^ equality)* ;

equality : rel ((EQ^ | NE^) rel)* ;

rel      : expr ((LT^ | LE^ | GT^ | GE^) expr)* ;

expr     : term ((PLUS^ | MINUS^) term)* ;

term     : unary ((MUL^ | DIV^) unary)* ;

unary    : MINUS^ unary { #unary.setType(NEGATE); }
         | NOT^ unary | factor ;

factor   : LPAREN! bool RPAREN! | loc
         | NUM | REAL | "true" | "false" ;

loc      : ID^ (LBRACK! bool RBRACK!)* ;
```

The IR Classes



Type

Array

SymbolTable

Node

Stmt

Break

Do

Else

If

Seq

Set

SetElem

While

Expr

Logical

And

Not

Or

Rel

Constant

Id

Temp

Op

Access

Arith

Unary

Type.java (Basic types)

```
public class Type {
    public int width = 0;     // Number of bytes
    public String name = "";

    public Type(String s, int w) { name = s; width = w; }

    // Fundamental built-in types
    public static final Type
      Int = new Type("int", 4), Float = new Type("float", 8),
      Char = new Type("char", 1), Bool = new Type("bool", 1);

    // True if the type is numeric
    public static boolean numeric(Type p) {
        return p == Type.Char || p == Type.Int || p == Type.Float; }

    // Used to implement "Standard conversion rules"
    public static Type max(Type p1, Type p2) {
        if (!numeric(p1) || !numeric(p2)) return null;
        else if (p1 == Type.Float || p2 == Type.Float)
            return Type.Float;
        else if (p1 == Type.Int || p2 == Type.Int)
            return Type.Int;
        else return Type.Char;
    }
}
```

Node.java (Stmts and Exprs)

```
public class Node {
    // General-purpose error handler
    void error(String s) { throw new Error(s); }

    // Number of next "fresh label"
    static int labels = 0;

    public static int newlabel() { return ++labels; }

    // Print a label
    public static void emitlabel(int i) {
       System.out.print("L" + i + ":");
    }

    // Print a three-address code statement (indented)
    public static void emit(String s) {
       System.out.println("\t" + s);
    }
}
```

Expr.java (has a type)

```
public class Expr extends Node {
  public String s;
  public Type type;

  Expr(String tok, Type p) { s = tok; type = p; }

  // Return a simple Expr holding the result
  public Expr gen() { return this; }

  // Return a Temp holding the result
  public Expr reduce() { return this; }

  // Generate code that tests this expression then jumps to t or f
  public void jumping(int t, int f) { emitjumps(toString(), t, f); }

  // Generate code that tests the predicate and jumps to t or f
  public void emitjumps(String test, int t, int f) {
    if (t != 0 && f != 0) {
      emit("if " + test + " goto L" + t);
      emit("goto L" + f);
    } else if (t != 0) emit("if " + test + " goto L" + t);
    else if (f != 0) emit("iffalse " + test + " goto L" + f);
  }

  public String toString() { return s; }
}
```

Id.java

```
public class Id extends Expr {
    public int offset;  // Offset from Frame pointer

    public Id(String id, Type p, int b) {
      super(id,p); offset = b;
    }
}
```

Op.java (operator)

```
public class Op extends Expr {
    public Op(String tok, Type p) { super(tok,p); }

    // Generate code that puts the result of this
    // operator in a new temporary and return it.
    public Expr reduce() {
        Expr x = gen();
        Temp t = new Temp(type);
        emit(t.toString() + " = " + x.toString());
        return t;
    }
}
```

Arith.java (binary arithmetic ops.)

```
public class Arith extends Op {
    public Expr expr1, expr2;

    public Arith(String op, Expr x1, Expr x2) {
        super(op, null); expr1 = x1;  expr2 = x2;
        type = Type.max(expr1.type, expr2.type);
        if (type == null) error("type error");
    }

    // Generate code that puts the result of the two
    // sub-expressions and return an expression that
    // performs the operation on them.
    public Expr gen() {
        return new Arith(s, expr1.reduce(), expr2.reduce()); }

    public String toString() {
        return expr1.toString() + " " + s + " " +
               expr2.toString();
    }
}
```

Logical.java (logical operator)

```
public class Logical extends Expr {
  public Expr expr1, expr2;
  Logical(String tok, Expr x1, Expr x2) {
    super(tok, null); expr1 = x1; expr2 = x2;
    type = check(expr1.type, expr2.type);
    if (type == null) error("type error");
  }
  public Type check(Type p1, Type p2) {
    if (p1 == Type.Bool && p2 == Type.Bool) return Type.Bool;
    else return null;
  }
  public Expr gen() {
    int f = newlabel(); int a = newlabel();
    Temp temp = new Temp(type);
    this.jumping(0, f);
    emit(temp.toString() + " = true");
    emit("goto L" + a); emitlabel(f);
    emit(temp.toString() + " = false");
    emitlabel(a);
    return temp;
  }
  public String toString(){
    return expr1.toString() + " "+ s + " "+ expr2.toString();
  }
}
```

And.java (logical AND)

```java
public class And extends Logical {
    public And(Expr x1, Expr x2) { super("&&", x1, x2); }

    // Generate jumping code that evaluates expr1,
    // falls through to expr2 if true, and finally sends control
    // to t or f depending on the outcome of expr2.
    public void jumping(int t, int f) {
        int label = f != 0 ? f : newlabel();
        expr1.jumping(0, label);
        expr2.jumping(t, f);
        if (f == 0) emitlabel(label);
    }
}
```

Stmt.java (statements)

```
public class Stmt extends Node {
    public Stmt() {}

    // Single null statement
    public static Stmt Null = new Stmt();

    // Arguments: label immediately before and label immediately after
    public void gen(int b, int a) {}

    int after = 0;  // Label after this statement

    // Current enclosing statement
    public static Stmt Enclosing = Stmt.Null;
}
```

While.java (while loop)

```
public class While extends Stmt {
    Expr expr;   // Predicate
    Stmt stmt;   // Body

    public While() { expr = null; stmt = null; }

    public void init(Expr x, Stmt s) {
        expr = x;
        stmt = s;
        if (expr.type != Type.Bool)
          expr.error("boolean required in while");
    }

    // Generate code that tests the predicate,
    // falls through to the body if true, then
    // jumps back to the expression, otherwise jumps to a.
    public void gen(int b, int a){
        after = a;
        expr.jumping(0, a);
        int label = newlabel();
        emitlabel(label);
        stmt.gen(label, b);
        emit("goto L" + b);
    }
}
```

SymbolTable.java

```
public class SymbolTable {
    private Hashtable table;
    protected SymbolTable outer;    // ST for enclosing scope

    public SymbolTable(SymbolTable st) {
        table = new Hashtable();
        outer = st;
    }

    // Bind a type and the stack offset to an identifier
    public void put(String token, Type t, int b) {
        table.put(token, new Id(token, t, b));
    }

    // Search in this and outer scopes for an identifier
    public Id get(String token) {
        for (SymbolTable tab = this ; tab != null ;
             tab = tab.outer) {
            Id id = (Id)(tab.table.get(token));
            if ( id != null ) return id;
        }
        return null;
    }
}
```

Tree Walker (Program)

```
class MyWalker extends TreeParser;
{
  SymbolTable top = null;
  int used = 0; // Number of bytes in local declarations
}

program returns [Stmt s]
{ s = null; Stmt s1;}
  : #(LBRACE
      { SymbolTable saved_environment = top;
        top = new SymbolTable(top); }
      decls
      s=stmts
      { top = saved_environment; }
    )
  ;
```

Tree Walker (Declarations)

```
decls
{ Type t = null; }
  : #(DECLS
       (t=type ID { top.put(#ID.getText(), t, used);
                    used += t.width; } )* )
  ;
type returns [Type t]
{ t = null; }
  : ( "bool"  { t = Type.Bool;  }
    | "char"  { t = Type.Char;  }
    | "int"   { t = Type.Int;   }
    | "float" { t = Type.Float; } )
    (t=dims[t])?
  ;
dims[Type t1] returns [Type t]
{ t = t1; }
  : NUM (t=dims[t])?
    { t = new Array(Integer.parseInt(#NUM.getText()), t); }
  ;
```

Tree Walker (Statements)

```
stmts returns [Stmt s]
{ s = null; Stmt s1; }
  : s=stmt (s1=stmts { s = new Seq(s, s1); } )?
  ;

stmt returns [Stmt s]
{ Expr e1, e2;
  s = null;
  Stmt s1, s2;
}
  : #(ASSIGN e1=expr e2=expr
      { if (e1 instanceof Id) s = new Set((Id) e1, e2);
        else s = new SetElem((Access) e1, e2);
      }
    )
  | #("if" e1=expr s1=stmt
       ( s2=stmt { s = new Else(e1, s1, s2); }
       | /* nothing */ { s = new If(e1, s1); } ))
  | #("while"
       { While whilenode = new While();
         s2 = Stmt.Enclosing;
         Stmt.Enclosing = whilenode; }
       e1=expr
       s1=stmt
       { whilenode.init(e1, s1);
         Stmt.Enclosing = s2;
         s = whilenode; } )
  | #("do"
       { Do donode = new Do();
         s2 = Stmt.Enclosing;
         Stmt.Enclosing = donode; }
       s1=stmt
       e1=expr
       { donode.init(s1, e1);
         Stmt.Enclosing = s2;
         s = donode; } )
  | "break" { s = new Break(); }
  | s=program
  | SEMI { s = Stmt.Null; }
  ;
```

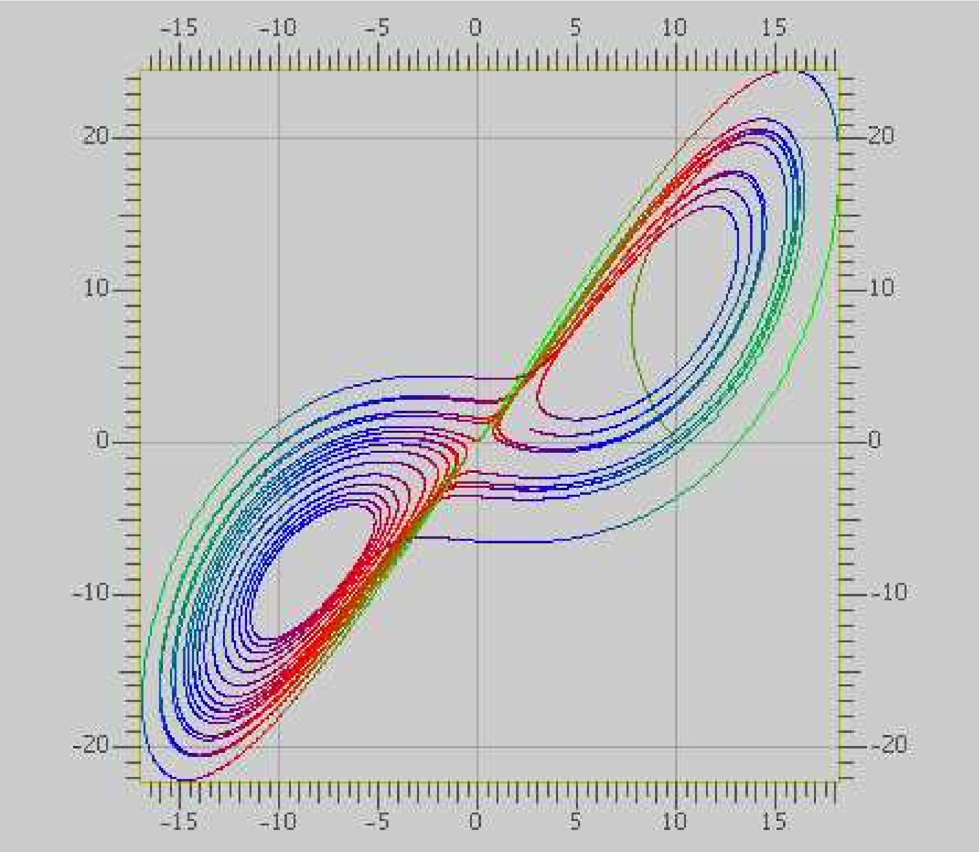
Tree Walker (Expressions)

```
expr returns [Expr e]
{
  Expr a, b;
  e = null;
}
  : #(OR     a=expr b=expr { e = new Or(a, b); } )
  | #(AND    a=expr b=expr { e = new And(a, b); } )
  | #(EQ     a=expr b=expr { e = new Rel("==", a, b); } )
  | #(NE     a=expr b=expr { e = new Rel("!=", a, b); } )
  | #(LT     a=expr b=expr { e = new Rel("<", a, b); } )
  | #(LE     a=expr b=expr { e = new Rel("<=", a, b); } )
  | #(GT     a=expr b=expr { e = new Rel(">", a, b); } )
  | #(GE     a=expr b=expr { e = new Rel(">=", a, b); } )
  | #(PLUS   a=expr b=expr { e = new Arith("+", a, b); } )
  | #(MINUS  a=expr b=expr { e = new Arith("-", a, b); } )
  | #(MUL    a=expr b=expr { e = new Arith("*", a, b); } )
  | #(DIV    a=expr b=expr { e = new Arith("/", a, b); } )
  | #(NOT    a=expr        { e = new Not(a); } )
  | #(NEGATE a=expr        { e = new Unary("-", a); } )
  | NUM  { e = new Constant(#NUM.getText(), Type.Int); }
  | REAL { e = new Constant(#REAL.getText(), Type.Float); }
| "true"                 { e = Constant.True; }
| "false"                { e = Constant.False; }
| #(ID
     { Id i = top.get(#ID.getText());
       if (i == null)
         System.out.println(#ID.getText() + " undeclared");
       e = i;
     }
     ( a=expr
       { Type type = e.type;
         type = ((Array)type).of;
         Expr w = new Constant(type.width);
         Expr loc = new Arith("*", a, w);
       }
       ( a=expr
         { type = ((Array)type).of;
           w = new Constant(type.width);
           loc = new Arith("+", loc, new Arith("*", a, w));
         }
       )*
       { e = new Access(i, loc, type); }
     )?
   )
;
```

Statistics

File	Role	# lines
grammar.g	Scanner/Parser/Walker	190
Main.java	main() procedure	27
SymbolTable.java	Symbol table	20
Type.java	Basic types	19
Array.java	Array type	10
Node.java	Statements and Expressions	7
Stmt.java	A node	7
Break.java	break statement	10
Do.java	do-while statement	17
Else.java	if-else statement	17
If.java	if statement	14
Seq.java	statement sequences	15
SetElem.java	assign to array	22
Set.java	assign to scalar	19
While.java	while statement	18
Expr.java	A node	16
Constant.java	constant expression	11
Id.java	variable identifier	4
Temp.java	temporary variable	6
Op.java	operator (expression)	9
Access.java	array index	10
Arith.java	arithmetic expression	12
Unary.java	unary negation	10
Logical.java	logical operator (expression)	27
And.java	logical AND	9
Not.java	logical NOT	5
Or.java	logical OR	9
Rel.java	$<$, =, etc.	14
total		550

Mx



Mx

A Programming Langauge for Scientific Computation

Resembles Matlab, Octave, Mathematica, etc.

Project from Spring 2003

Authors:

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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;
}
```

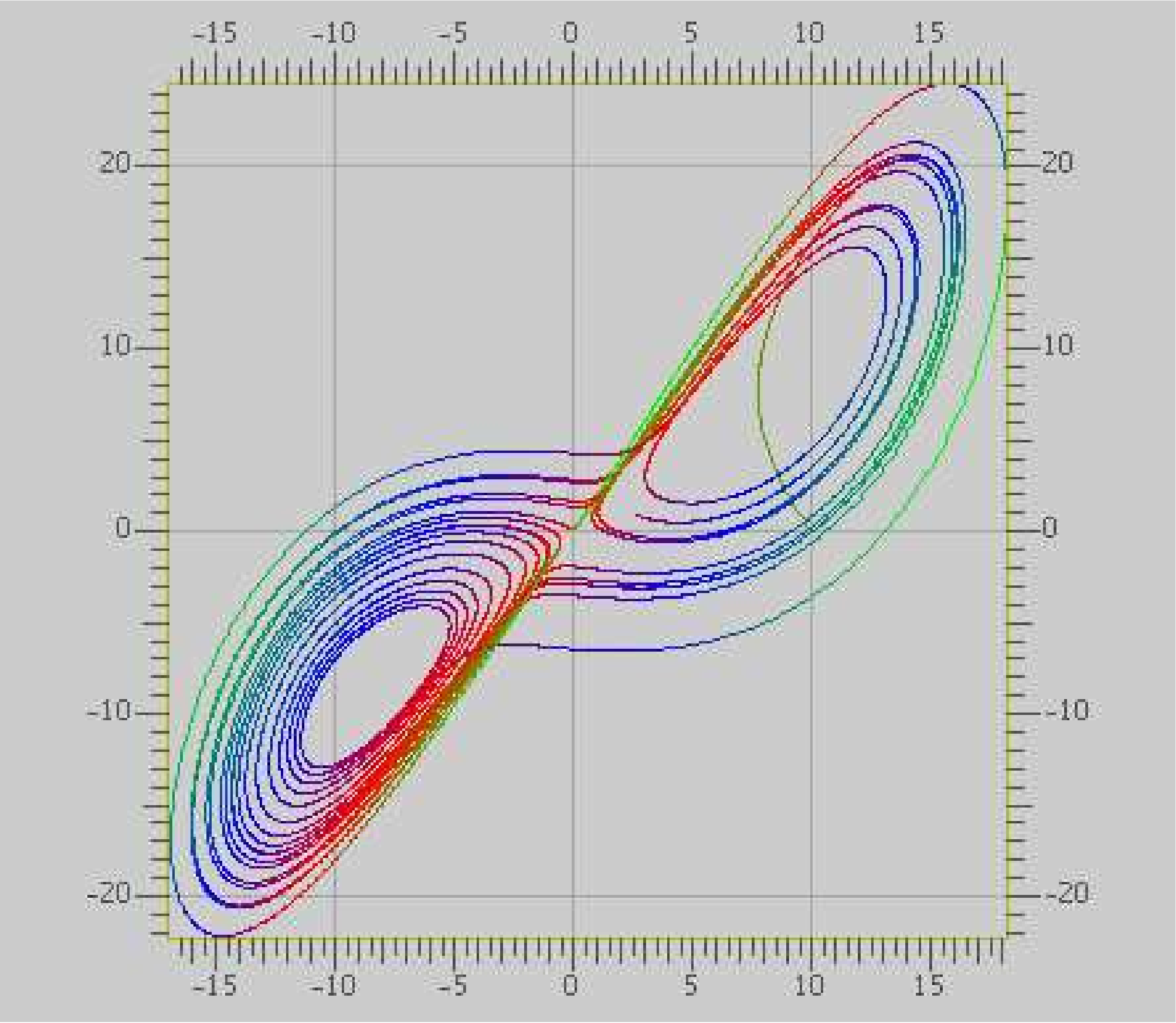
Mx source part 2

```
/* 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 ); }
  ;
```