Compiler Construction

Lecture 1 - An Overview

A few basic definitions

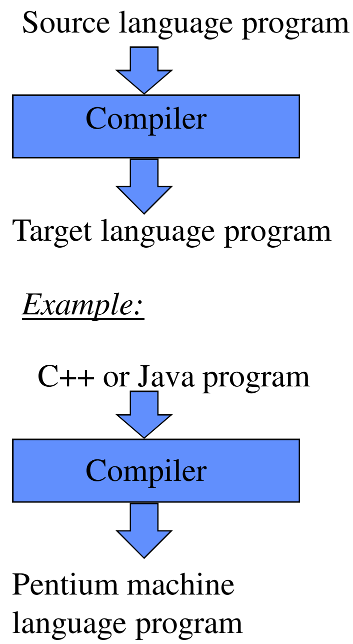
Translate - *v*, a.to turn into one's own language or another. b. to transform or turn from one of symbols into another

Translator - *n*, someone or something that translates.

Compilers are translators that produce object code (machine-runnable version) from source code (human-readable version).

Interpreters are translators that translate only as much as is necessary to run the next statement of the program.

- *Source Language* - the language in which the source code is written
  Target Language - the language in which the object code is written
- *Implementation Language* - Language in which the compiler is written



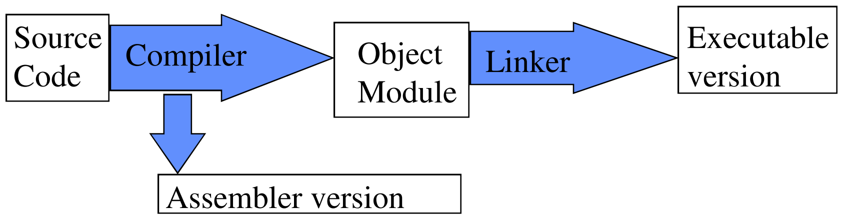
Choice of an Implementation Language

The implementation language for compilers used to be assembly language.

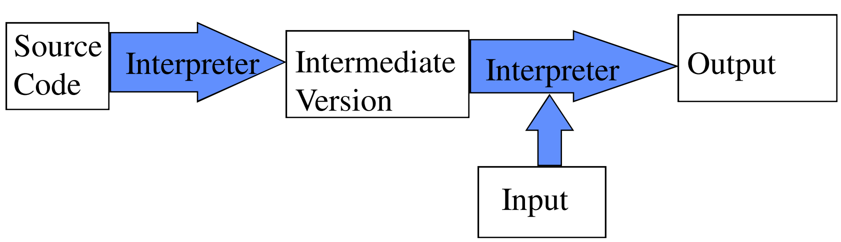
It is now customary to write a compiler in the source language.

Why? The compiler itself can then be used as a sample program to test the compiler's ability to translate complex programs that utilize the various features of the source language.

The Compiling Process



The Interpretation Process



Source language - designed to be machine-translatable ("Context-free grammar")

e.g., FORTRAN, COBOL, Pascal, C, BASIC, LISP

•Portable, i.e., programs can be moved from one computer to another with minimal or no rewriting.

•The Level of Abstraction matches the problem and not the hardware.

•Does not require an intimate knowledge of the computer hardware

Assembly language - machine acronyms for machine language commands.

e.g., mov ax, 3

•Eliminates the worst of the details, but leaves many to be dealt with.

Object Module - a machine language version of the program lacking some necessary references.

e.g., on the Intel 8x86 (in real mode)

1011	1	000	0000 0000 0000 0011
mov (from immediate to register)	16-bit value	AX reg.	the immediate value

Load Module - a machine language version that is complete with addresses of all variables and routines.

Other types of Compilers

There are compilers that do not necessarily follow this model:

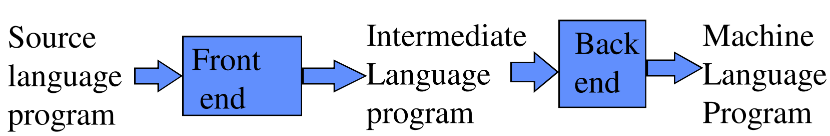
Load-and-go compilers generate executable code without the use of a linker.

Cross compilers run on one type of computer and generate translations for other classes of computers.

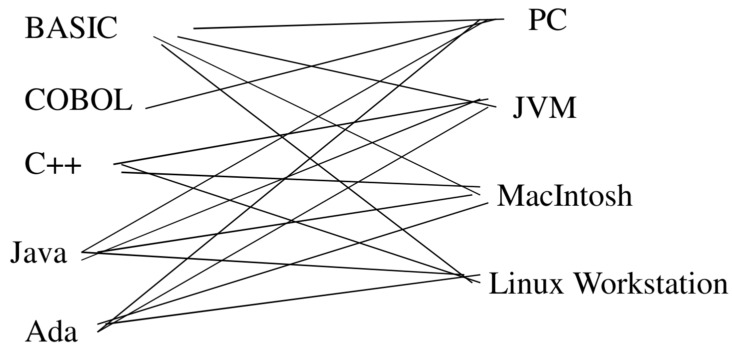
Cross-language compilers translate from one high-level language to another. (e.g., C++ to C)

The organization of a compiler

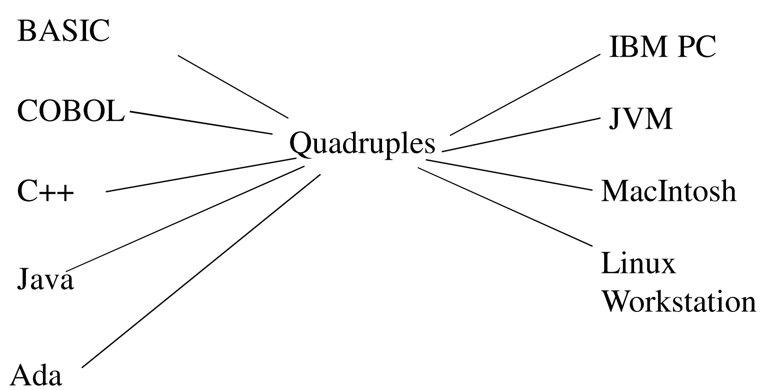
- The various components of a compiler are organized into a ***front end*** and a ***back end***.
- The front end is designed to produce some intermediate representation of a program written in the source language
- The back end is designed to produce a program for a target computer from the intermediate representation.



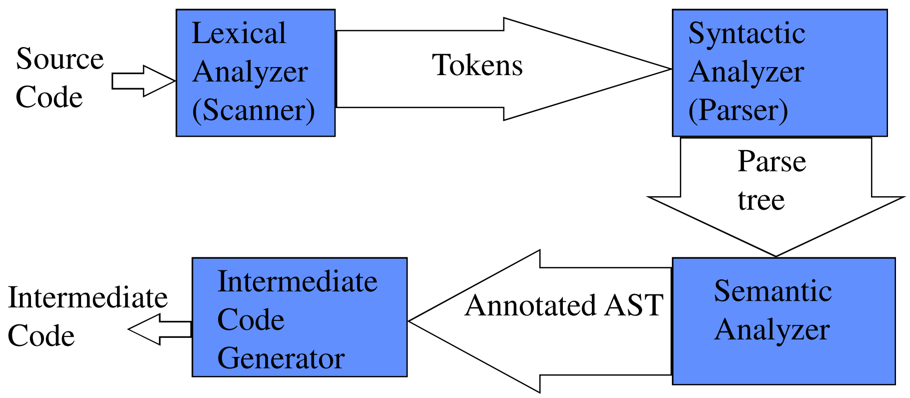
Why Separate Front and Back Ends?



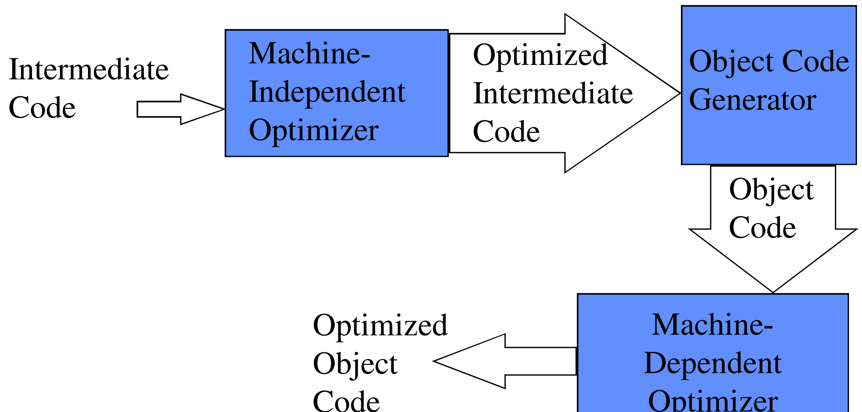
Why Generate Intermediate Code?



Components of a Compiler - The Front End



Components of a Compiler - The Back End



Lexical Analysis

- The lexical analyzer (or ***scanner***) breaks up the stream of text into a stream of strings called "***<u>lexemes</u>***" (or token strings)
- The scanner checks one character at a time until it determines that it has found a character which does not belong in the lexeme.
- The scanner looks it up in the ***symbol table*** (inserting it if necessary) and determines the token associated with that lexeme.

Lexical Analysis (continued)

- ***<u>Token</u>*** - the language component that the character string read represents.
- Scanners usually reads the text of the program either a line or a block at a time. (File I/O is rather inefficient compared to other operations within the compiler.

Syntactic Analysis

- A syntactic analyzer (or ***parser***) takes the stream of tokens determines the syntactic structure of the program.
- The parser creates a structure called a ***parse tree***. The parser usually does not store the parse in memory or on disk, but it does formally recognize program's the grammatical structure

Syntactic Analysis (continued)

The grammar of a language is expressed formally as

G = (T, N, S, P) where

T is a set of ***terminals*** (the basic, atomic symbols of a language).

N is a set of ***nonterminals*** (symbols which denote particular arrangements of terminals).

S is the ***start symbol*** (a special nonterminal which denotes the program as a whole).

P is the set of ***productions*** (rules showing how terminals and nonterminal can be arranged to form other nonterminals.

Syntactic Analysis (continued)

- An example of ***terminal*** would be **PROGRAM**, **ID**, and **:=**.
- An example of a ***nonterminal*** would be *Program*, *Block* and *Statement*.
- The ***start symbol*** in most cases would be *Program*
- An example of a ***production*** would be

  Block ::= **BEGIN** *Statements* **END**

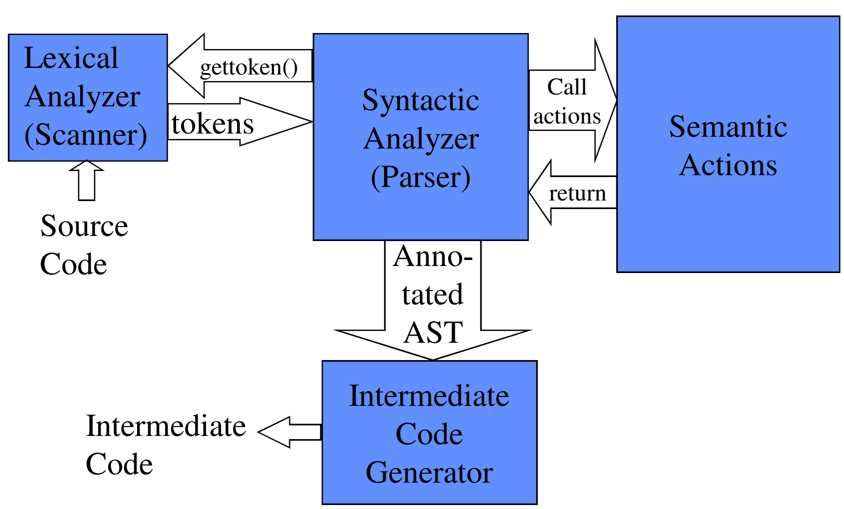
Semantic Analysis

- Semantic analysis involves ensuring that the semantics (or meaning) of the program is correct.
- It is quite possible for a program to be correct syntactically and to be correct semantically.
- Semantic analysis usually means making sure that the data types and control structures of a program are used correctly.

Semantic Analysis (continued)

- The various semantic analysis routines are usually incorporated into the parser and do not usually comprise a separate phase of the compiling process.
- The process of generating an intermediate representation (usually an abstract syntax tree) is usually directed by the parsing of the program.

A More Realistic View of the Front End



Error detection in Source Programs

- All the previous stages analyze the program, looking for potential errors.

```
FOR i != 1 TO n DO WriteLn;
```

Lexical error

```
IF x > N THEN Y := -3; ELSE Y := 3;
```

Syntactic error

Error Detection in Source Programs

```
PROGRAM Average;
  VAR Average : Integer;
      Sum, Val1, Val2, Val3 : Real;
  BEGIN
    Val1 := 6.0;
    Val2 := 4;
    Val3 := 37.5;
    Sum := Val1 + Val2 + Val3;
    Average := (Val1 + Val2 + Val3) DIV 3
  END.  { Average }
```

Mixed-typed assignment

Semantic error

Intermediate Code Generation

- The intermediate code generator creates a version of the program in some machine-independent language that is far closer to the target language than to the source language.
- The abstract syntax tree may serve as an intermediate representation.

Object Code Generation

- The object code generator creates a version of the program in the target machine's own language.
- The process is significantly different from intermediate code generation.
- It may create an assembly language version of the program, although this is not the usual case.

An example of the compiling process

```
int    main()
{
  float      average;
  int        x[3];
  int        i, sum;

  x[0] = 3;
  x[1] = 6;
  x[2] = 10;
  sum = 0;
  for  (i = 0;  i < 3;  i++)
      sum += x[i];
  average = sum/3;
  return(0);
}
```

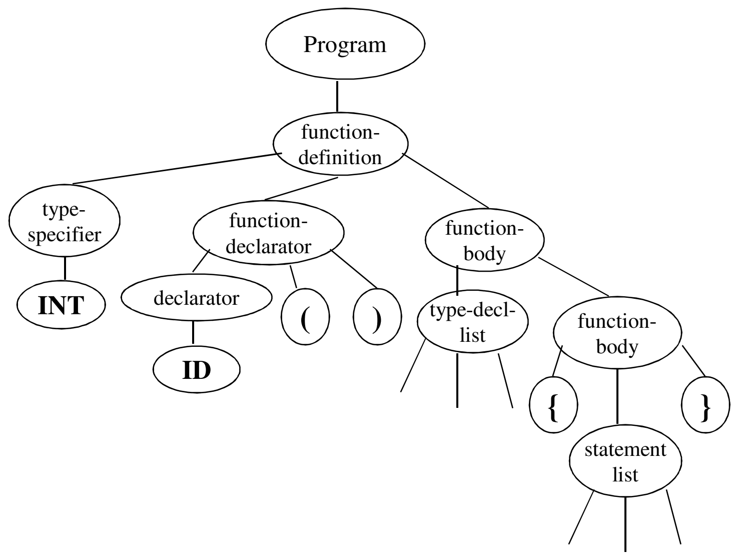
An example of Lexical Analysis

The tokens are:

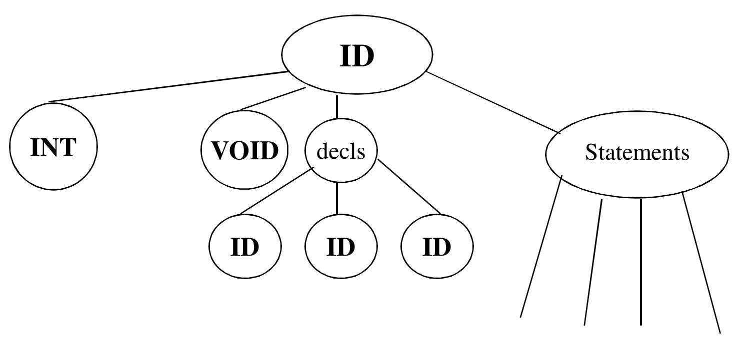
INT	**ID**	**(**	**)**	**{**	**FLOAT**	
ID	**;**	**INT**		**ID**	**[**	
NUMLITERAL		**]**	**;**		**INT**	**ID**
,	**ID**	**;**	**ID**		**[**	
NUMLITERAL		**]**	**=**			
NUMLITERAL		**;**				

and so on

A sample parse tree

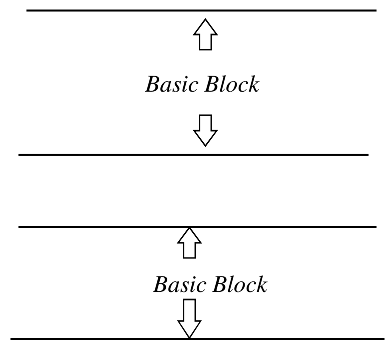


The corresponding Abstract Syntax Tree



The intermediate code for the example

```
main:
    x[0] = 3
    x[1]  = 6
    x[2]  = 10
    sum = 0
    i  =0
t1:
    if i >= 3 goto t2:
    t3 : = x[i]
    Sum : = Sum + t3
    goto t1
t2:
    Average := Sum / 3
```



The assembler code for the example

_main PROC NEAR ; COMDAT
; File C:\MyFiles\Source\avg3\avg3.c
; Line 4

```
    push ebp
    mov  ebp, esp
    sub  esp, 88
    push ebx
    push esi
    push edi
    … … ..
    mov  DWORD PTR _x$[ebp], 3
    mov  DWORD PTR _x$[ebp+4], 6
    mov  DWORD PTR _x$[ebp+8], 10
    mov  DWORD PTR _sum$[ebp], 0
    … … …
```

The Symbol Table

- The symbol table tracks all symbols used in a given program.
- This includes:
  - Key words
  - Standard identifiers
  - Numeric, character and other literals
  - User-defined data types
  - User-defined variables

The Symbol Table (continued)

- Symbol tables must contain:
  - Token class
  - Lexemes
  - Scope
  - Types
  - Pointers to other symbol table entries (as necessary)

“Shaper” - an example of a translator

- Shaper is a “microscopic” language which draws rectangles, square and right isosceles triangles on the screen.
- Shaper has three statements:
  - **RECTANGLE** *{***WIDE** *or* **LONG***} Number* **BY** *Number*
  - **SQUARE SIZE** *Number*
  - **TRIANGLE SIZE** *Number*
- Example
  - **RECTANGLE LONG 6 by 5**
  - **RECTANGLE WIDE 15 BY 30**
  - **SQUARE SIZE 9**
  - **TRIANGLE SIZE 5**

The “Shaper” Translator

```
#include    <iostream.h>
#include    <fstream.h>
#include    <ctype.h>
#include    <stdlib.h>
#include    <string.h>

enum  tokentype   {tokby, tokeof, tokerror,
                  toklong, toknumber,
                  tokrectangle, toksize,
                  toksquare, toktriangle,
                  tokwide};

char  *tokenname[] = {"by","eof", "error",
                  "long", "number", "rectangle",
                  "size","square", "triangle",
                  "wide"};
```

```
const int   filenamesize = 40,
            tokenstringlength = 15,
            numtokens = 10;

int   wordsearch(char *test, char *words[],
                  int len);

class scanner     {
public:
  scanner(int argcount, char  *arg[]);
  scanner(void);
  ~scanner(void);
  tokentype scan(char tokenstring[]);
private:
  tokentype scanword(char c, char tokenstring[]);
  tokentype scannum(char c, char tokenstring[]);
  ifstream  infile;
};
```

```
scanner::scanner(int argcount, char *arg[])
{
  char      filename[filenamesize];

  //  If there is only one argument, it must be
  //  the program file for Shaper.  That means
  //  that we need the source file.
  //  If there are two arguments, we have it
  //  already as the second argument.  If there
  //  are more, there must be a mistake.

  if  (argcount == 1)   {
      cout << "Enter program file name\t?";
        cin >> filename;
  }
  else if (argcount == 2)
      strcpy(filename, arg[1]);
```

```
  else      {
      cerr << "Usage: Shaper <filename>\n";
      exit(1);
  }

  infile.open(filename, ios::in);
  if (!infile)    {
      cerr << "Cannot open " << filename << endl;
      exit(1);
  }
}
```

```
// scanner() -    Default constructor for the
//                scanner
scanner::scanner(void)
{
  char      filename[filenamesize];

  cout << "Enter program file name\t?";
  cin >> filename;

  // Open the input file
  infile.open(filename, ios::in);
  if (!infile)    {
      cerr << "Cannot open " << filename << endl;
      exit(1);
  }
}
```

```
scanner::~scanner(void)
{
  infile.close();
}
```

```
//scan() -  Scan out the words of the language
tokentype   scanner::scan(char tokenstring[])
{
  char      c;

  //  Skip the white space in the program
  while (!infile.eof() &&
            isspace(c=infile.get()))
      ;

  //  If this is the end of the file, send the
  //              token that indicates this
  if (infile.eof())
            return(tokeof);
```

```
//If it begins with a letter, it is a word.  If
//begins with a digit, it is a number. Otherwise,
//it is an error.
  if (isalpha(c))
      return(scanword(c, tokenstring));
  else if (isdigit(c))
      return(scannum(c, tokenstring));
  else
      return(tokerror);
}
```

```
//scanword() -    Scan until you encounter
//                something other than a letter.
//                It uses a binary search to find
//                the appropriate token in the
//                table.
tokentype   scanner::scanword(char c,
                              char tokenstring[])
{
  int             i = 0;
  tokentype tokenclass;

  //  Build the string one character at a time.
  //  It keep scanning until either the end of
  // file or until it encounters a non-letter
  tokenstring[i++] = c;
```

```
  while  (!infile.eof() &&
                 isalpha(c = infile.get()))
      tokenstring[i++] = c;
  tokenstring[i] ='\0';

    //      Push back the last character
  infile.putback(c);

  //  Is this one of the legal keywords for
  //  Shaper?  If not, it's an error
  if ((tokenclass =
            (tokentype)wordsearch(tokenstring,
  tokenname, numtokens))
                 == -1)
      return(tokerror);
  else
      return(tokenclass);
}
```

```
//scannum() -     It returns the token toknumber.
//                The parser will receive the
//                number as a string and is
//                responsible for converting it
//                into numerical form.
tokentype   scanner::scannum(char c,
                              char tokenstring[])
{
  int i = 0;

  //  Scan until you encounter something that
  //  cannot be part of a number or the end of
  //  file
  tokenstring[i++] = c;
```

```
  while  (!infile.eof() &&
                 isdigit(c = infile.get()))
      tokenstring[i++] = c;

  tokenstring[i] = '\0';

  //  Push back the last character
  infile.putback(c);
  return(toknumber);
}
```

Managing the "Symbol Table"

```
//wordsearch() -  A basic binary search to find a
//                string in an array of strings
int   wordsearch(char *test, char *words[],
                       int len)
{
  int low = 0, mid, high = len - 1;

  //  Keep searching as long as we haven't
  //  searched the whole array
  while (low <= high)   {
      mid = (low + high)/2;
      if (strcmp(test,words[mid]) < 0)
            //    search the lower half
            high = mid - 1;
```

```
      else if (strcmp(test,words[mid]) > 0)
            //    search the upper half
            low = mid + 1;
      else
            //    We found it!!
            return(mid);
   }
   // It isn't there
   return(-1);
}
```

Parsing A “Shaper” Program

```
class parser : scanner  {
public:
  parser(int argcount, char   *args[]);
  parser(void);
  void      ProcProgram(void);
private:
  void      ProcRectangle(void);
  void      ProcSquare(void);
  void      ProcTriangle(void);
  tokentype tokenclass;
  char      tokenstring[tokenstringlength];
};
```

```
// parser() -     A constructor that passes
//                initial values to the base
//                class
parser::parser(int argcount, char   *args[])
            : scanner (argcount,args)
{
      // Get the first token
      tokenclass = scan(tokenstring);
}

// parser() -     A default constructor
parser::parser(void)
{
      // Get the first token
      tokenclass = scan(tokenstring);
}
```

```
void  parser::ProcProgram(void)
{
  //  Get a token and depending on that token's
  //  value, parse the statement.
  while (tokenclass  != tokeof)
      switch(tokenclass)      {
      case tokrectangle:
                  ProcRectangle();
                  tokenclass = scan(tokenstring);
                  break;

      case toksquare:
                  ProcSquare();
                  tokenclass = scan(tokenstring);
                  break;
```

```
        case toktriangle:
                    ProcTriangle();
                    tokenclass = scan(tokenstring);
                    break;

        default:    cerr << tokenstring
                          << " is not a legal"
                          << " statement\n"
                          << endl;
                    exit(3);
        }
}
```

```
//ProcRectangle() -     Parse the rectangle
//                      command and if there
//                      are no errors, it will
/                       produce a rectangle
//                      on the whose dimensions
//                      are set by the
//                      rectangle statement.
void  parser::ProcRectangle(void)
{
  int       shape, columns, rows;
  char      tokenstring[tokenstringlength];

  //  The next word should be wide or long to
  //  indicate whether there are more rows or
  //  columns.  This is not really necessary for
  //  the statement to work correctly, but is a
  //  good simple illustration of how type
  //  checking works.
```

```
if ((tokenclass = scan(tokenstring)) != tokwide
        && tokenclass != toklong)           {
    cerr << "Expected \"wide\" or \"long\"”
        << “ instead of " << tokenstring
        << endl;
    exit(4);
}

//  Get the number of columns and if it is a
//  number
if ((tokenclass = scan(tokenstring)) !=
toknumber)      {
    cerr << "Expected number instead of "
        << tokenstring << endl;
    exit(5);
}
```

```
//  The token by is simply a separator but the
//        grammar requires it.
if ((tokenclass = scan(tokenstring)) != tokby){
    cerr << "Expected \"by\" instead of "
        << tokenstring << endl;
}

//  Get the number of rows and if it is a
//  number
if ((tokenclass = scan(tokenstring))
                    != toknumber)     {
    cerr << "Expected number instead of "
        << tokenstring << endl;
    exit(5);
}
}
```

Adding the Semantic Actions to ProcRectangle

```
void   parser::ProcRectangle(void)
{
   int        shape, columns, rows;
   chartokenstring[tokenstringlength];

   //  The next word should be wide or long to indicate
   //  whether there are more rows or columns.  This is
   //  not really necessary for the statement to work
   //  correctly, but is a good simple illustration of
   //  how type checking works.
   if ((tokenclass = scan(tokenstring)) != tokwide
                            && tokenclass != toklong)  {
       cerr << "Expected \"wide\" or \"long\" instead"
               <<  of " << tokenstring << endl;
       exit(4);
   }
```

```
   //  The shape is indicated by whether this
   //  token was wide or long
   shape = tokenclass;

   //  Get the number of columns and if it is a number,
   //  convert the character string into an integer
   if ((tokenclass = scan(tokenstring)) != toknumber) {
       cerr << "Expected number instead of "
               << tokenstring << endl;
       exit(5);
   }
   columns = atoi(tokenstring);
   //  The token by is simply a separator but the
   //          grammar requires it.
   if ((tokenclass = scan(tokenstring)) != tokby){
       cerr << "Expected \"by\" instead of "
               << tokenstring << endl;
   }
```

```
//  Get the number of rows and if it is a
//  number, convert the character string into
//  an integer.
if ((tokenclass = scan(tokenstring)) != toknumber) {
    cerr << "Expected number instead of "
           << tokenstring << endl;
    exit(5);
}
rows = atoi(tokenstring);

//  A long rectangle should have more rows than
//  columns and a wide rectangle will have the
//  opposite.  This illustrates how type
//  checking works on a facile level.
```

```
    if (shape == toklong && columns < rows
          || shape == tokwide
                       && columns > rows)      {
    cerr << "A " << tokenname[shape]
          << " rectangle cannot be " << columns
          << " by " << rows << endl;
    exit(6);
  }
  DrawRectangle(columns, rows);
}
```