# COMPILER CONSTRUCTION
# Seminar 01 – TDDB66 2024

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# SEMINARS AND LABS

In the laboratory exercises, you shall complete a compiler for DIESEL – a small Pascal like language, giving you a practical experience of compiler construction

There are 7 separate parts of the compiler to complete in 11x2 laboratory hours and 4x2 seminar hours. You will also have to work during non-scheduled time.

# PURPOSE OF SEMINARS

The purpose of the seminars is to introduce you to the lab

You need to read the introductions, the course book and the lecture notes!

The lab instructions as well as a small collection of exercises are available via the course homepage.

# SEMINARS

Seminar 1 (Today): Lab 1 & 2

Seminar 2: Lab 3 & 4

Seminar 3: Lab 5, 6 & 7

Seminar 4: Exam prep

# RELATING LABS TO THE COURSE

- Building a complete compiler
  - We use a a language that is small enough to be manageable.
  - Scanner, Parser, Semantic Elaboration, Code Generation.
  - Experience in compilation and software engineering.

# LAB EXERCISES

This approach (building a whole compiler) has several advantages and disadvantages:

## Advantages

- Students gains deep knowledge
- Experience with complex code
- Provides a framework for the course
- Success instills confidence

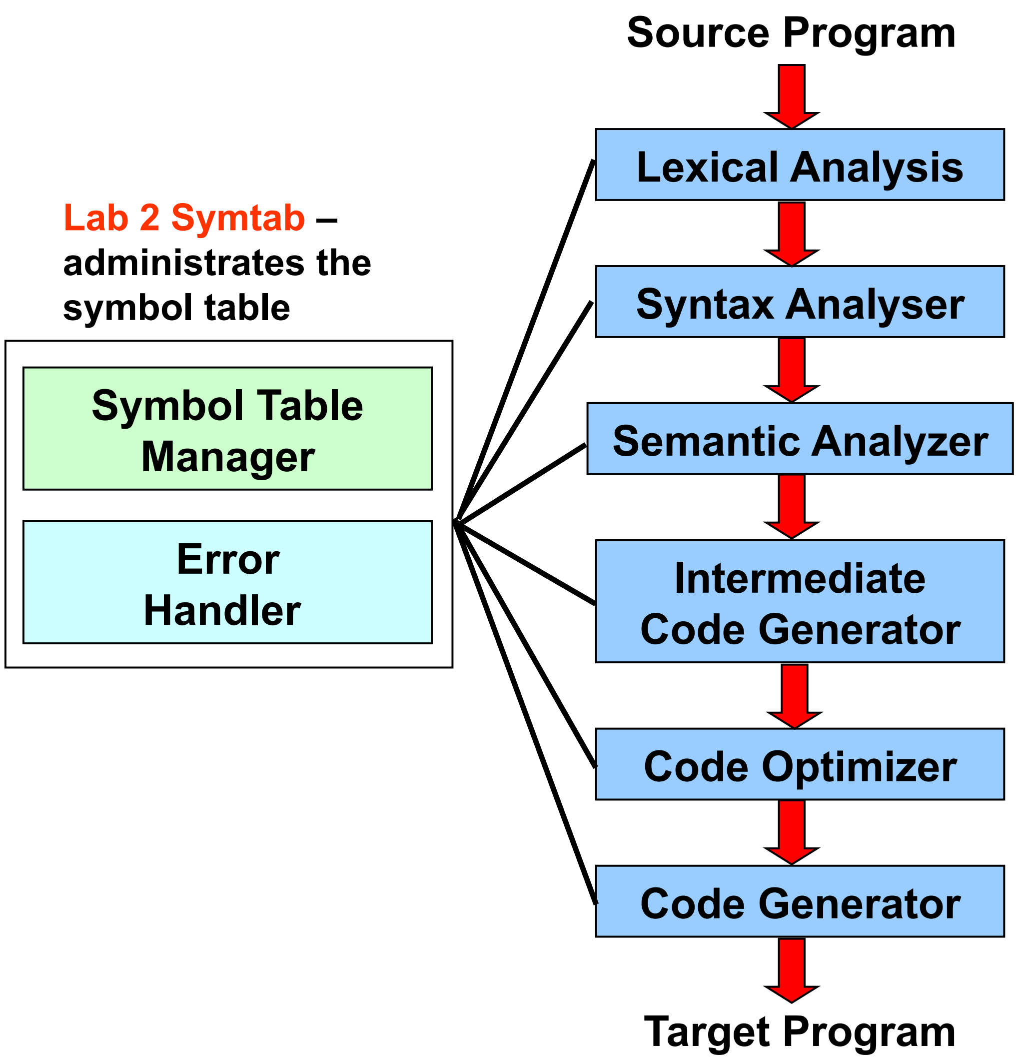
## Disadvantages

- High ratio of programming to thought
- Cumulative nature magnifies early failures
- Many parts are simplified

# LABS

Lab 0 Formal languages and grammars
Lab 1 Creating a scanner using "**flex**"
Lab 2 Symbol tables
Lab 3 LR parsing and abstract syntax tree construction using "**bison**"
Lab 4 Semantic analysis (type checking)
Lab 5 Optimization
Lab 6 Intermediary code generation (quads)
Lab 7 Code generation (assembler) and memory management

# PHASES OF A COMPILER




Lab 2 Symtab – administrates the symbol table

Lab 1 Scanner – manages lexical analysis

Lab 3 Parser – manages syntactic analysis, build internal form

Lab 4 Semantics – checks static semantics

Lab 6 Quads – generates quadruples from the internal form

Lab 5 Optimizer – optimizes the internal form

Lab 7 Codegen – expands quadruples to assembler

# PHASES OF A COMPILER (cont'd)

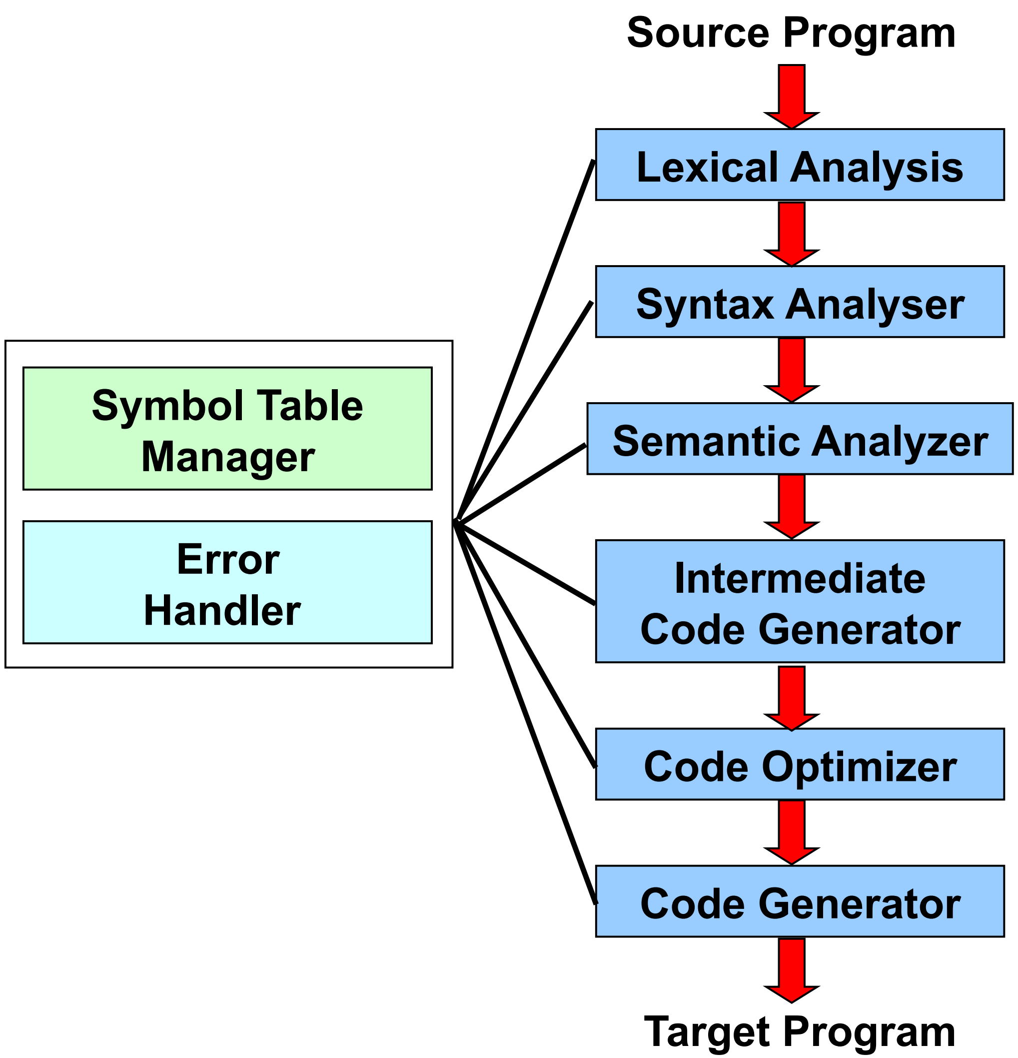
Let's consider this DIESEL program:

```
program example;
const
    PI = 3.14159;
var
    a : real;
    b : real;
begin
    b := a + PI;
end.
```

Declarations

Instructions block

# PHASES OF A COMPILER (cont'd)




Lab 1 Scanner – manages lexical analysis

# PHASES OF A COMPILER (SCANNER)

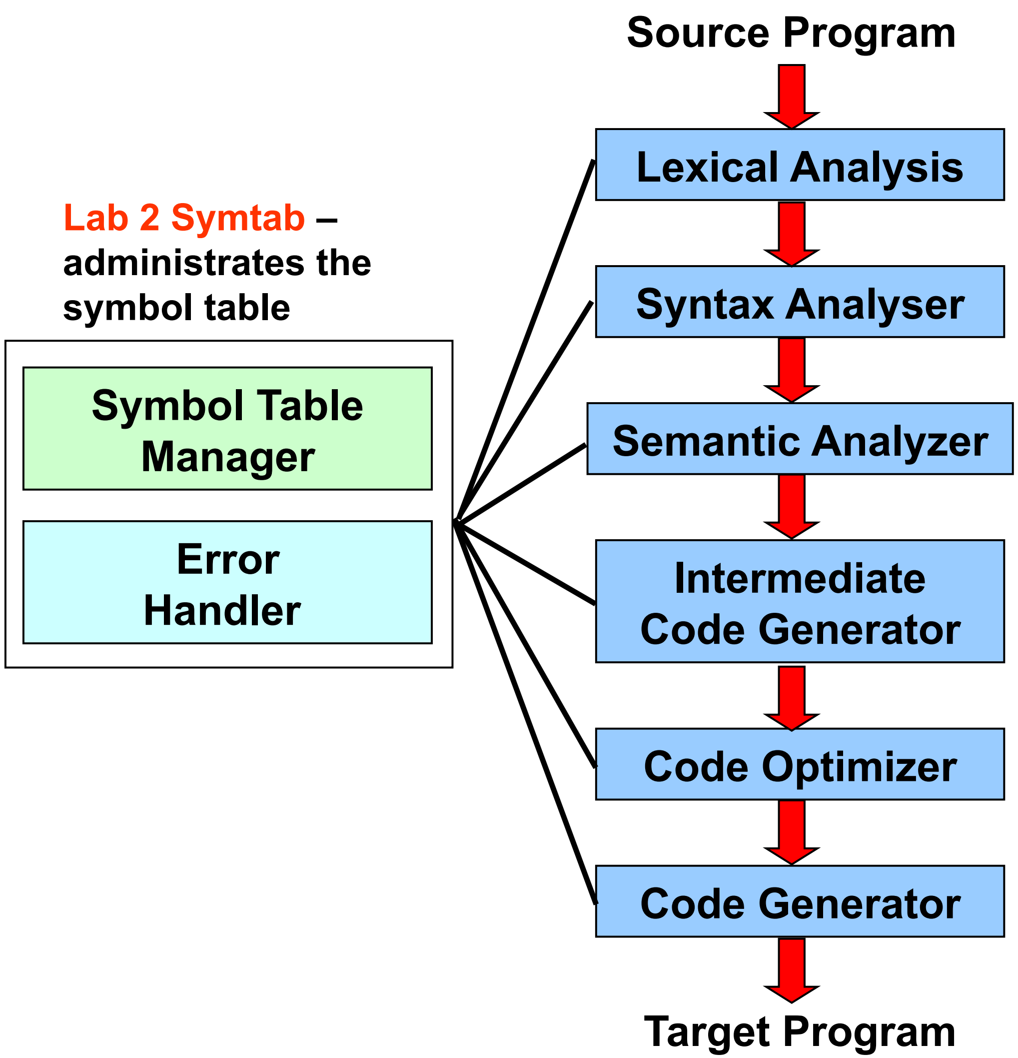
INPUT

```
program example;
const
    PI = 3.14159;
var
    a : real;
    b : real;
begin
    b := a + PI;
end.
```

OUTPUT

| token | pool_p | val | type |
|---|---|---|---|
| T_PROGRAM | | | keyword |
| T_IDENT | EXAMPLE | | identifier |
| T_SEMICOLON | | | separator |
| T_CONST | | | keyword |
| T_IDENT | PI | | identifier |
| T_EQ | | | operator |
| T_REALCONST | | 3.14159 | constant |
| T_SEMICOLON | | | separator |
| T_VAR | | | keyword |
| T_IDENT | A | | identifier |
| T_COLON | | | separator |
| T_IDENT | REAL | | identifier |
| T_SEMICOLON | | | separator |
| T_IDENT | B | | identifier |
| T_COLON | | | separator |
| T_IDENT | REAL | | identifier |
| T_SEMICOLON | | | separator |
| T_BEGIN | | | keyword |
| T_IDENT | B | | identifier |
| T_ASSIGNMENT | | | operator |
| T_IDENT | A | | identifier |
| T_ADD | | | operator |
| T_IDENT | PI | | identifier |
| T_SEMICOLON | | | separator |
| T_END | | | keyword |
| T_DOT | | | separator |

# PHASES OF A COMPILER (cont'd)




**Lab 1 Scanner** – manages lexical analysis

**Lab 2 Symtab** – administrates the symbol table

# PHASES OF A COMPILER (SYMTAB)

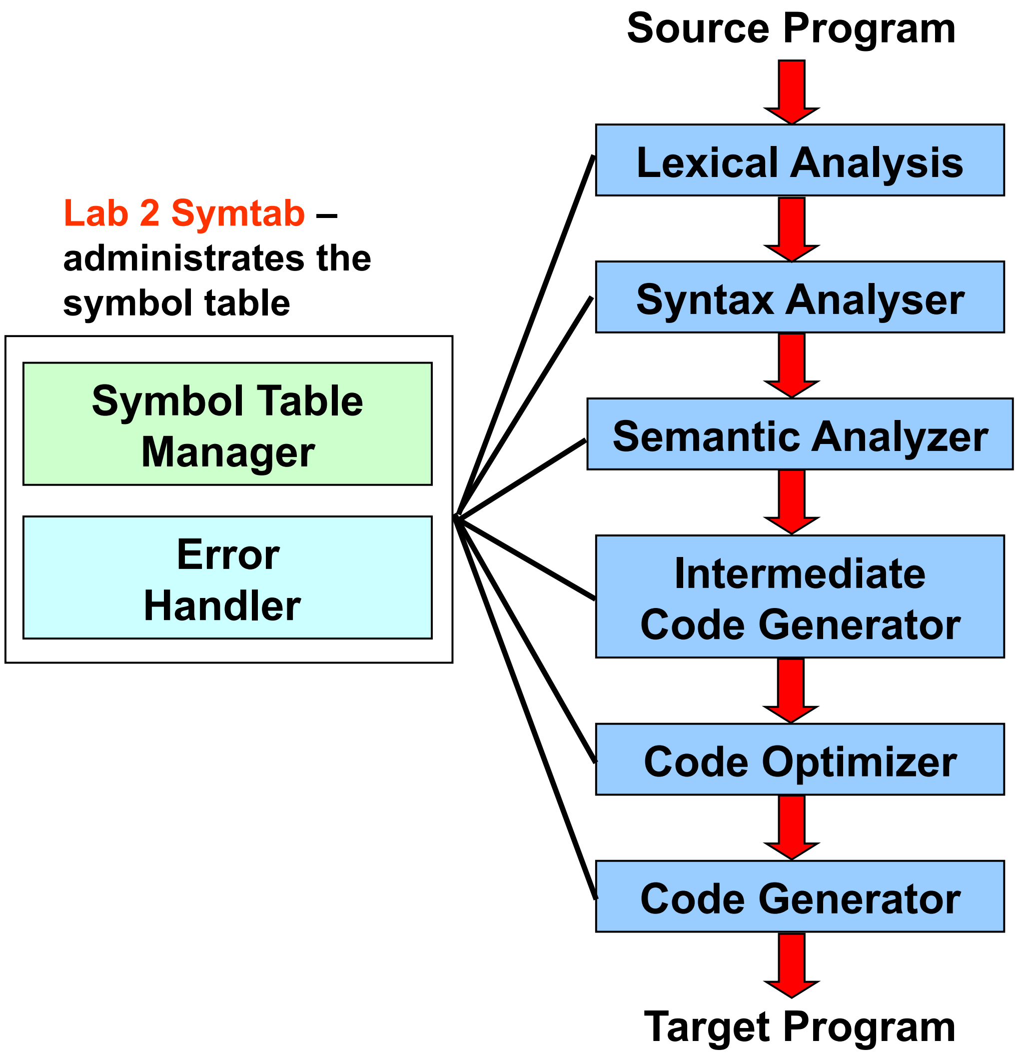
INPUT

```
program example;
const
    PI = 3.14159;
var
    a : real;
    b : real;
begin
    b := a + PI;
end.
```

OUTPUT

| token | pool_p | val | type |
|---|---|---|---|
| T_IDENT | VOID | | |
| T_IDENT | INTEGER | | |
| T_IDENT | REAL | | |
| T_IDENT | EXAMPLE | | |
| T_IDENT | PI | 3.14159 | REAL |
| T_IDENT | A | | REAL |
| T_IDENT | B | | REAL |

# PHASES OF A COMPILER (cont'd)




**Lab 2 Symtab** – administrates the symbol table

**Lab 1 Scanner** – manages lexical analysis

**Lab 3 Parser** – manages syntactic analysis, build internal form

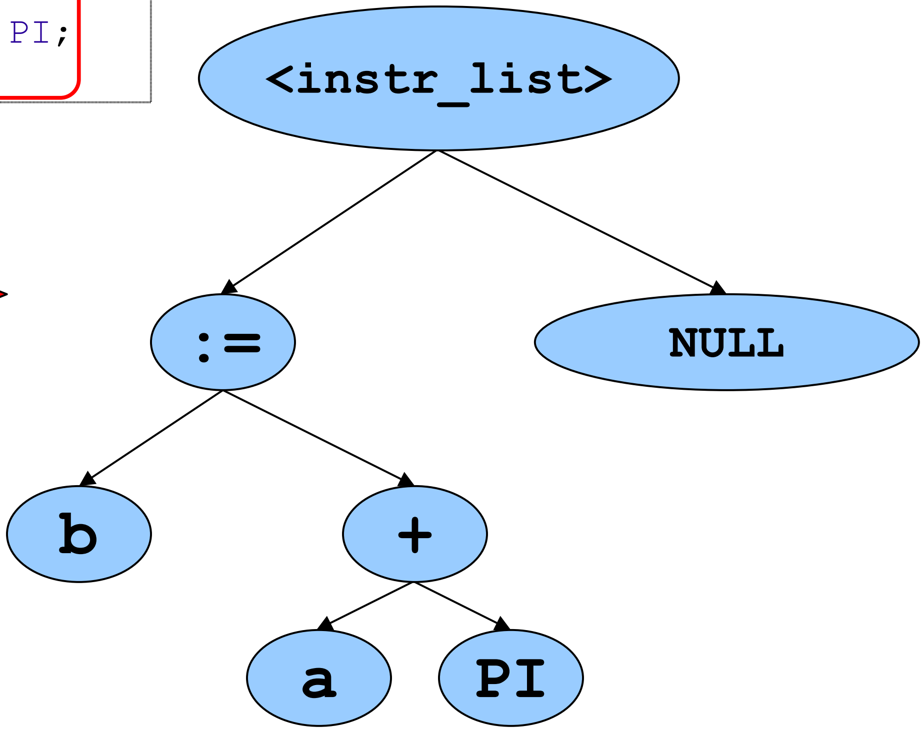
# PHASES OF A COMPILER (PARSER)

## INPUT

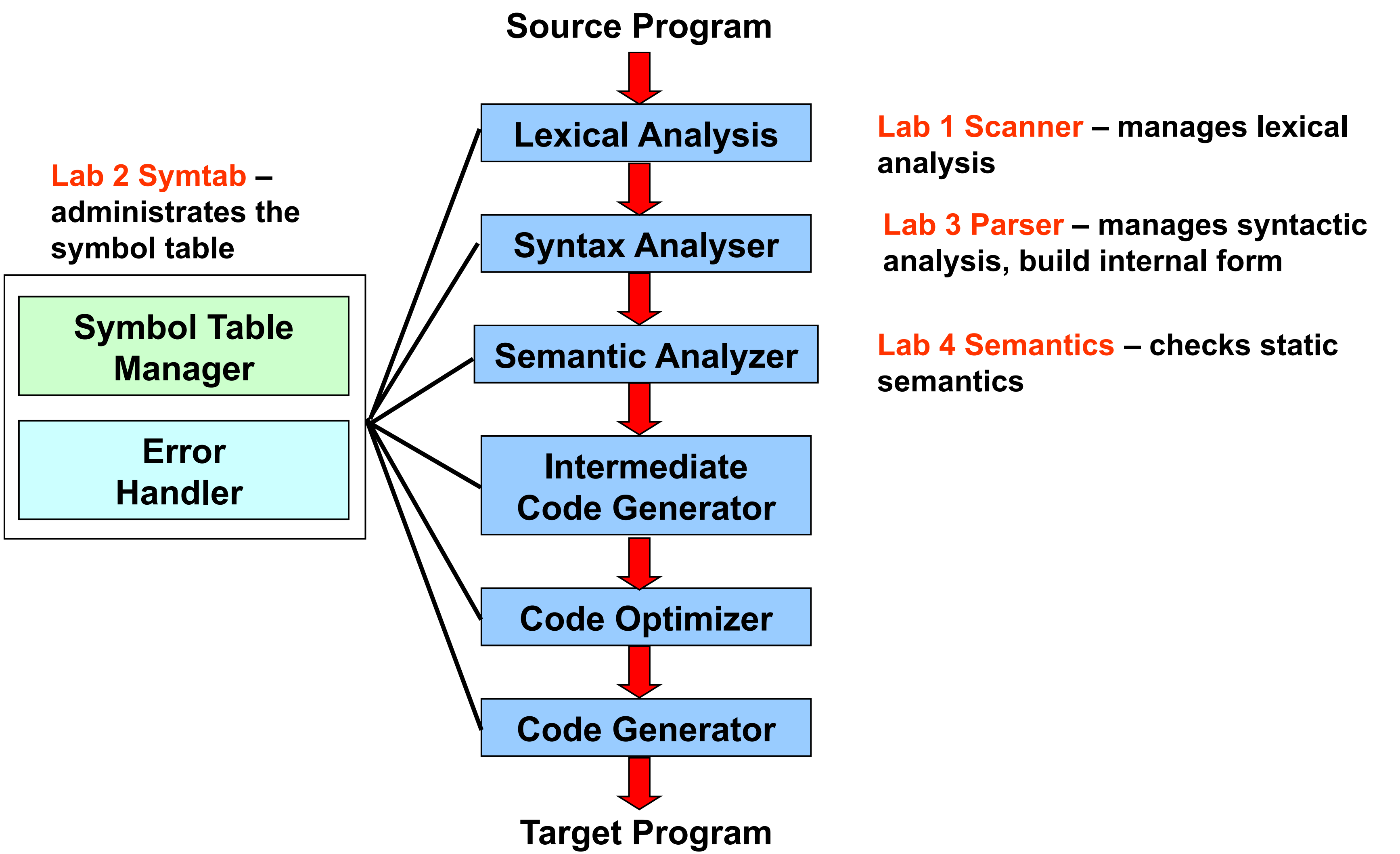
| token | pool_p | val | type |
|---|---|---|---|
| T_PROGRAM | | | keyword |
| T_IDENT | EXAMPLE | | identifier |
| T_SEMICOLON | | | separator |
| T_CONST | | | keyword |
| T_IDENT | PI | | identifier |
| T_EQ | | | operator |
| T_REALCONST | | 3.14159 | constant |
| T_SEMICOLON | | | separator |
| T_VAR | | | keyword |
| T_IDENT | A | | identifier |
| T_COLON | | | separator |
| T_IDENT | REAL | | identifier |
| T_SEMICOLON | | | separator |
| T_IDENT | B | | identifier |
| T_COLON | | | separator |
| T_IDENT | REAL | | identifier |
| T_SEMICOLON | | | separator |
| T_BEGIN | | | keyword |
| T_IDENT | B | | identifier |
| T_ASSIGNMENT | | | operator |
| T_IDENT | A | | identifier |
| T_ADD | | | operator |
| T_IDENT | PI | | identifier |
| T_SEMICOLON | | | separator |
| T_END | | | keyword |
| T_DOT | | | separator |

```
program example;
const
    PI = 3.14159;
var
    a : real;
    b : real;
begin
    b := a + PI;
end.
```

## OUTPUT



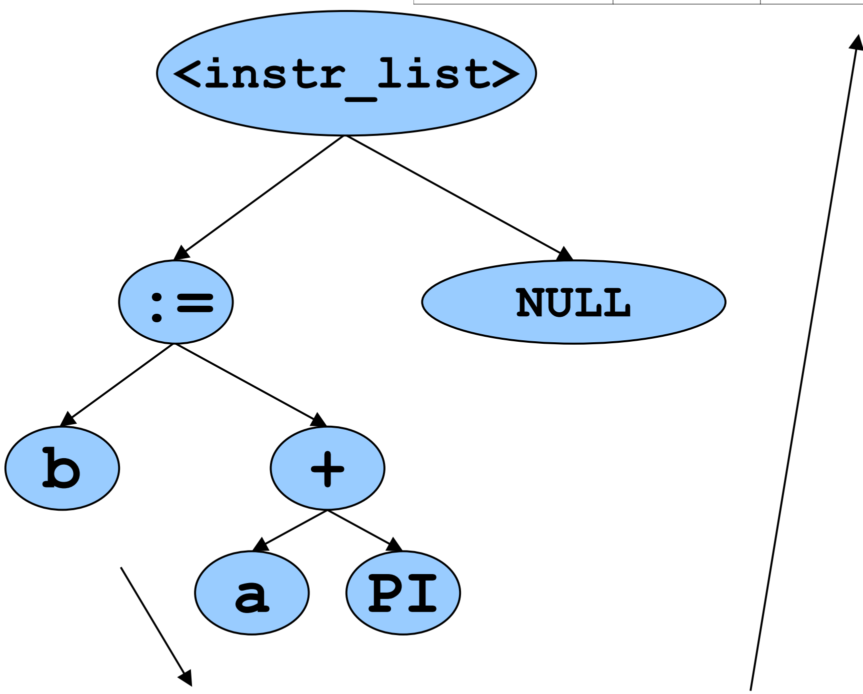
# PHASES OF A COMPILER (cont'd)



# PHASES OF A COMPILER (SEMANTICS)

INPUT

| token | pool_p | val | type |
|---|---|---|---|
| T_IDENT | VOID | | |
| T_IDENT | INTEGER | | |
| T_IDENT | REAL | | |
| T_IDENT | EXAMPLE | | |
| T_IDENT | PI | 3.14159 | REAL |
| T_IDENT | A | | REAL |
| T_IDENT | B | | REAL |

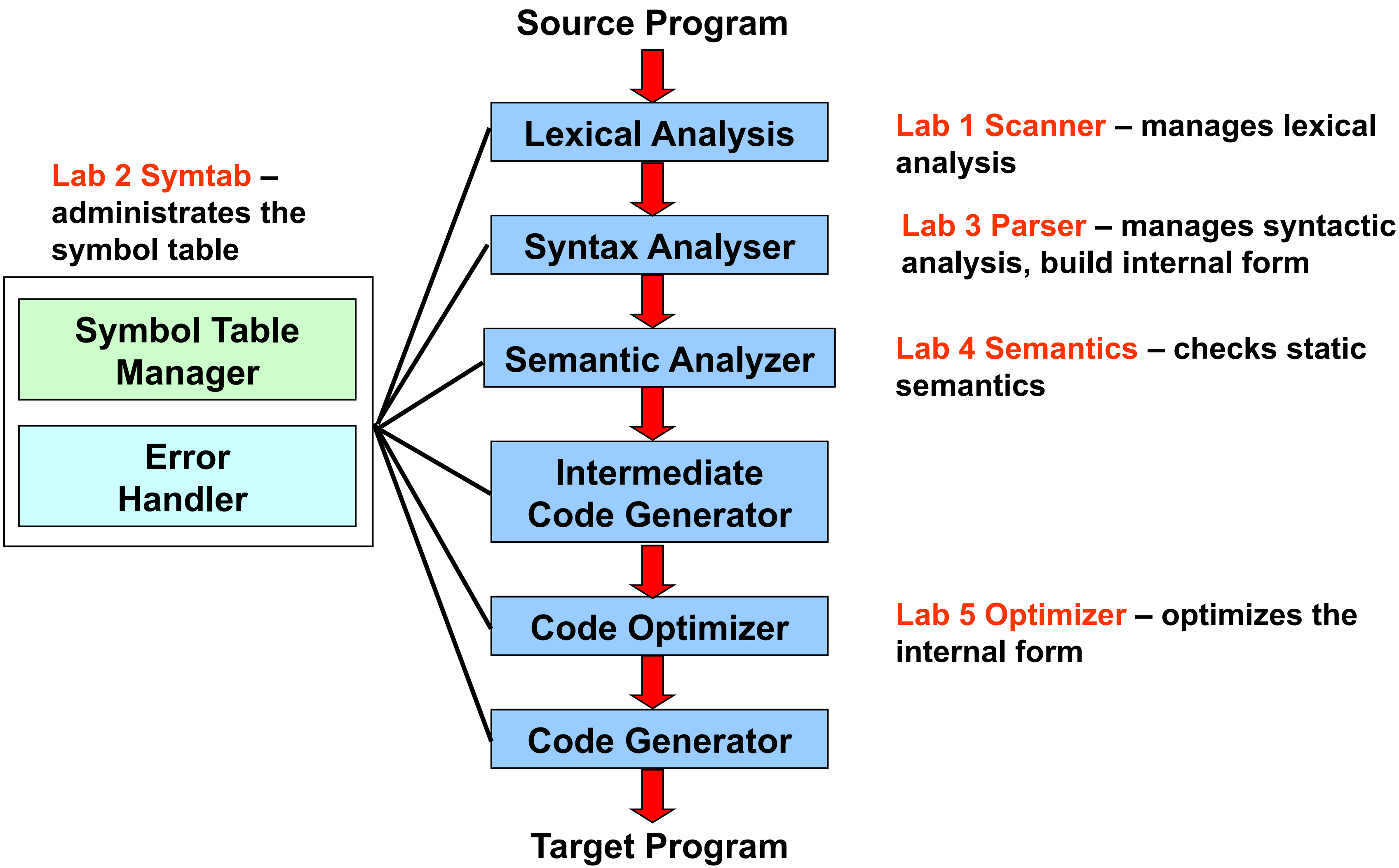



type(a) == type(b) == type(PI) ?

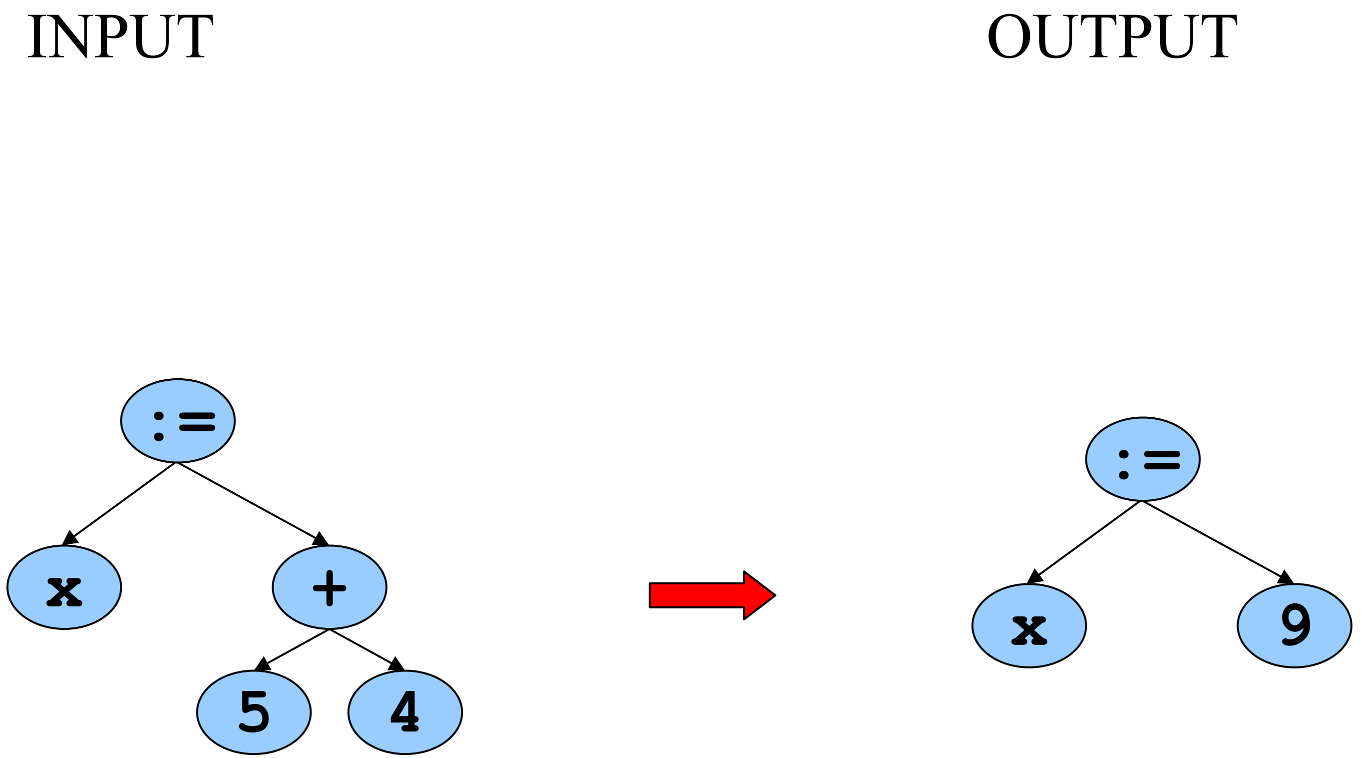
OUTPUT

**YES**

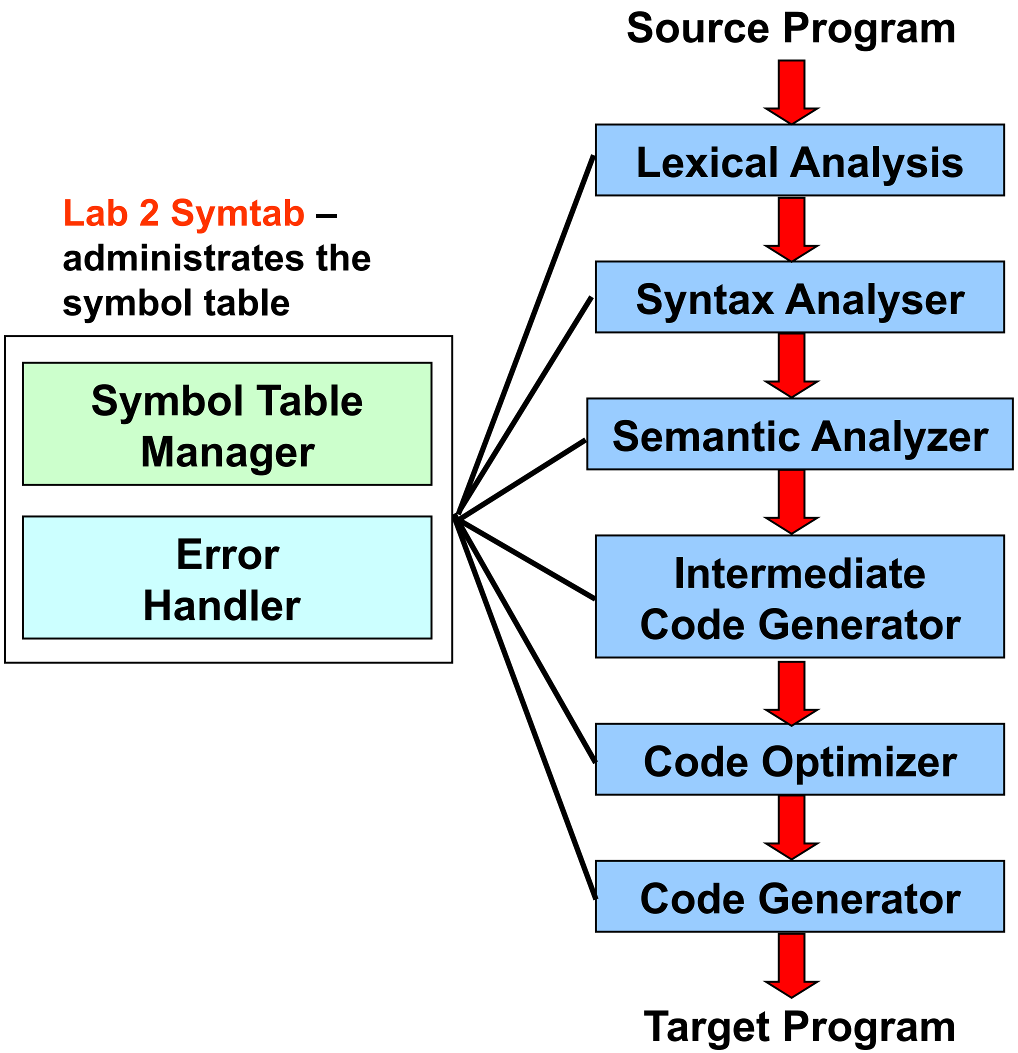
# PHASES OF A COMPILER (cont'd)



# PHASES OF A COMPILER (OPTIMIZER)



# PHASES OF A COMPILER (cont'd)




**Lab 2 Symtab** – administrates the symbol table

**Lab 1 Scanner** – manages lexical analysis

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**Lab 4 Semantics** – checks static semantics

**Lab 6 Quads** – generates quadruples from the internal form

**Lab 5 Optimizer** – optimizes the internal form

# PHASES OF A COMPILER (QUADS)

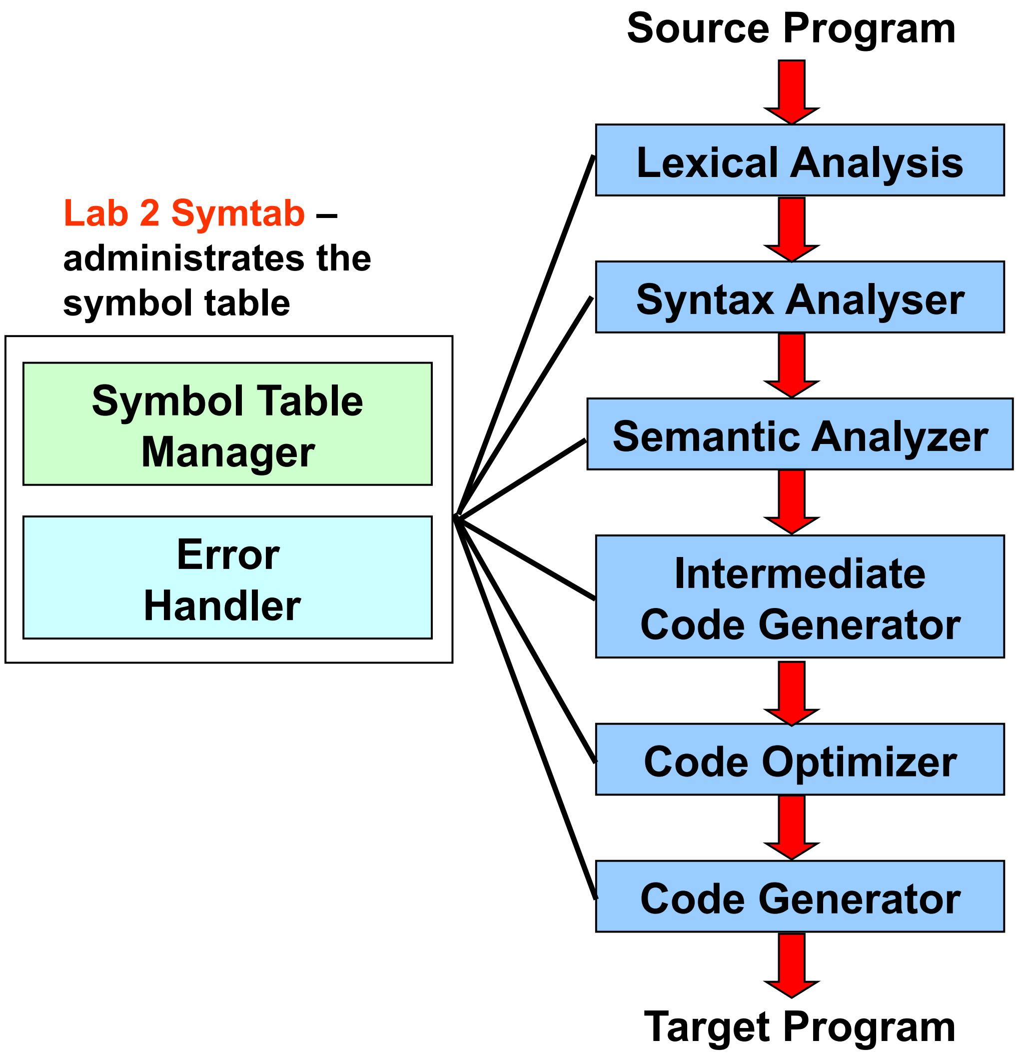
INPUT

OUTPUT

```
program example;
const
   PI = 3.14159;
var
   a : real;
   b : real;
begin
   b := a + PI;
end.
```

```
q_rplus     A    PI   $1
q_rassign   $1   -    B
q_labl      4    -    -
```

# PHASES OF A COMPILER (cont'd)

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**Lab 7 Codegen** – expands quadruples to assembler

# PHASES OF A COMPILER (CODEGEN)

INPUT

```
program example;
const
    PI = 3.14159;
var
    a : real;
    b : real;
begin
    b := a + PI;
end.
```

```
q_rplus     A    PI   $1
q_rassign   $1   -    B
q_labl      4    -    -
```

OUTPUT

```
L3:             # EXAMPLE
        push    rbp
        mov     rcx, rsp
        push    rcx
        mov     rbp, rcx
        sub     rsp, 24
        mov     rcx, [rbp-8]
        fld     qword ptr [rcx-16]
        mov     rcx, 4614256650576692846
        sub     rsp, 8
        mov     [rsp], rcx
        fld     qword ptr [rsp]
        add     rsp, 8
        faddp
        mov     rcx, [rbp-8]
        fstp    qword ptr [rcx-32]
        mov     rcx, [rbp-8]
        mov     rax, [rcx-32]
        mov     rcx, [rbp-8]
        mov     [rcx-24], rax
L4:
        leave
        ret
```

# LAB SKELETON

- `TDDE66.git`
  - `/code`
    - `/scan`
      - Contains all the necessary files to complete the first lab
    - `/symtab`
      - Contains all the necessary files to complete the second lab
    - `/remaining`
      - Contains all the necessary files to complete the rest of the labs
    - `/testpgm`
      - Diesel programs for testing the implementation

# INSTALLATION

- Take the following steps in order to install the lab skeleton on your system:
  - Fork the gitlab repository to a private repository on gitlab.liu.se
  - More information in the Lab Compendium

# HOW TO COMPILE

- To compile:
  - Execute `make` in the proper source directory

- To run:
  - Call the `diesel` script with the proper flags
  - The Lab Compendium specifies, for each lab, what test programs to run, and what flags to use.

- To test:
  - Execute for example `make lab3` in the proper source directory
  - Running the test target checks that your output matches that of the /trace subdirectory

# HANDING IN LABS

- Demonstrate the working solutions to your lab assistant during scheduled time. Then send a link to your git branch containing your modified files to the same assistant (put *TDDE66 <Name of the assignment*> in the topic field). One e-mail per group.

- You should get a webreg notification that the source code was received, when it is approved, and if the code needs to be revised

- You should get a webreg notification within 24 hours of an approved demonstration of the lab

# DEADLINE

- Deadline for all the assignments is the end of HT2 study period (you will get 3 extra points on the final exam if you finish on time!)

- Note: Check with your lab assistant for handing in solutions after the last scheduled lab

# DIESEL EXAMPLE

```
program circle;
const
   PI = 3.14159;
var
   o : real;
   r : real;
procedure init;
begin
   r := 17;
end;
function circumference(radius : real) : real;
   function diameter(radius : real) : real;
   begin
      return 2 * radius;
   end;
begin
   return diameter(radius) * PI;
end;
begin
   init();
   o := circumference(r);
end.
```

# LAB 1
# THE SCANNER

# SCANNING

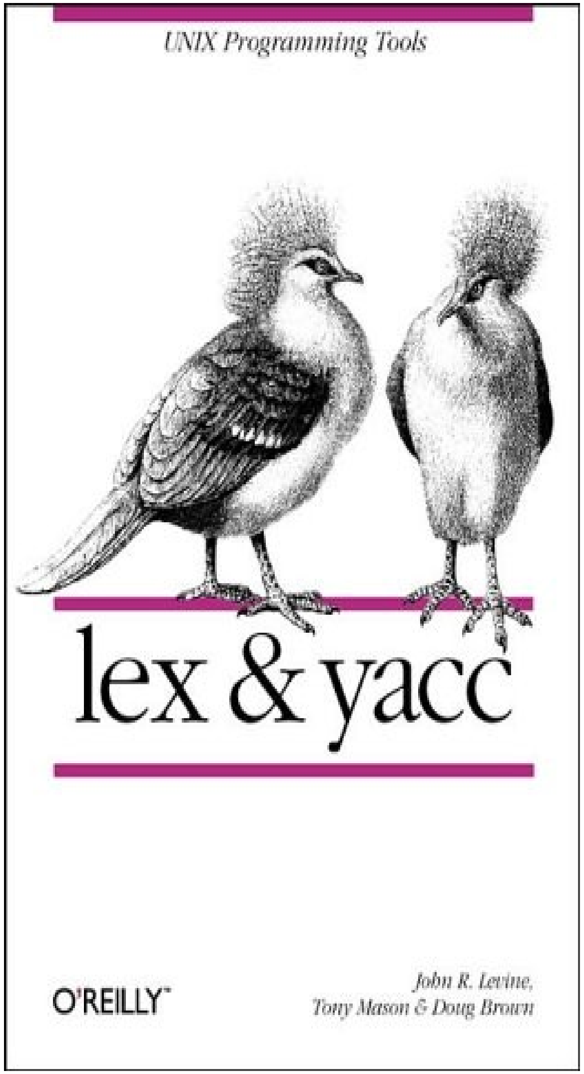
**Scanners are programs that recognize lexical patterns in text**

- Its **input** is text written in some language
- Its **output** is a sequence of tokens from that text. The tokens are chosen according with the language
- Building a scanner manually is hard
- We know that the mapping from regular expressions to FSM (Finite-State Machine) is straightforward, so why not we automate the process?
- Then we just have to type in regular expressions and get the code to implement a scanner back

# SCANNER GENERATORS

- Automate is exactly what `flex` does!
- `flex` is a fast lexical analyzer generator, a tool for generating programs that perform pattern matching on text
- `flex` is a free implementation (started 1987) of the well-known `lex` program (~1977)

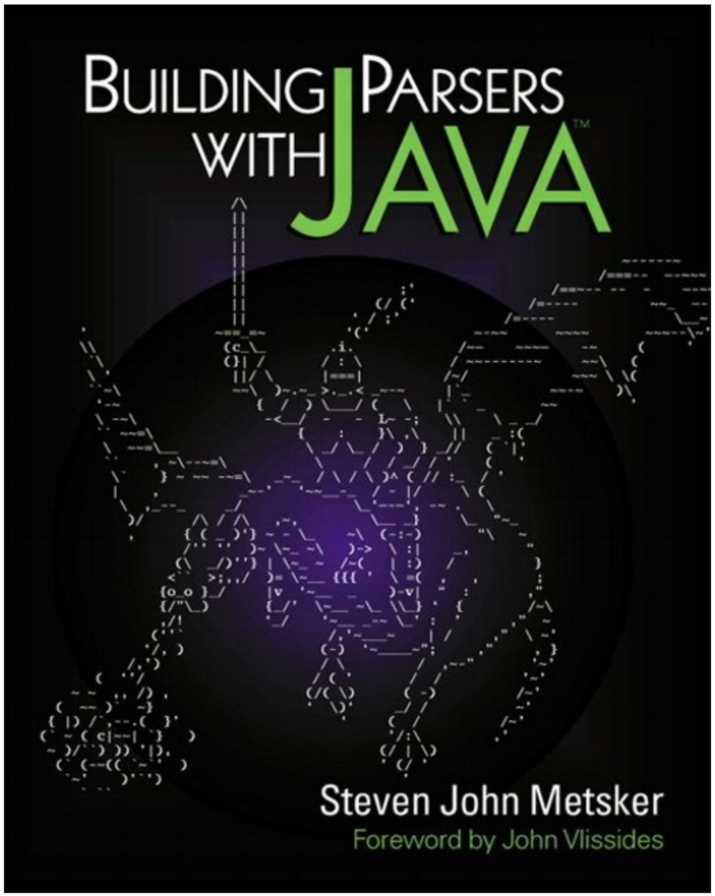
# MORE ON LEX/BISON




If you'll use flex/bison in the future…

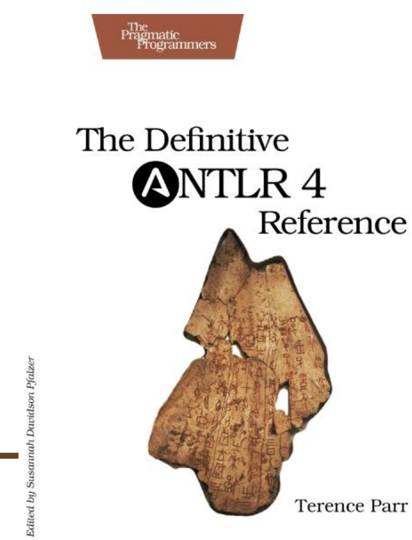
Lex & Yacc, 2nd ed
By, John R Levine, Tony Mason & Doug Brown
O'Reilly & Associates
ISBN: 1565920007

# MORE REFERENCES




For those who would like to learn more about parsers by using Java.

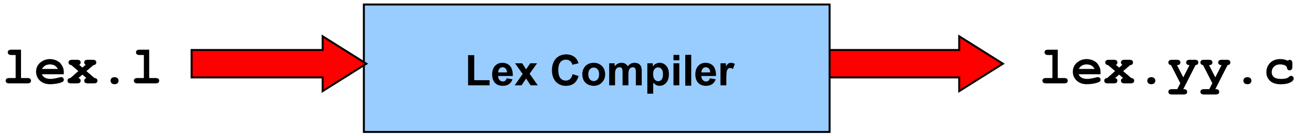
See also ANTLR:
https://www.antlr.org/



# HOW IT WORKS

**flex** generates at output a **C** source file **lex.yy.c** which defines a routine **yylex()**

```
>> flex lex.l
```

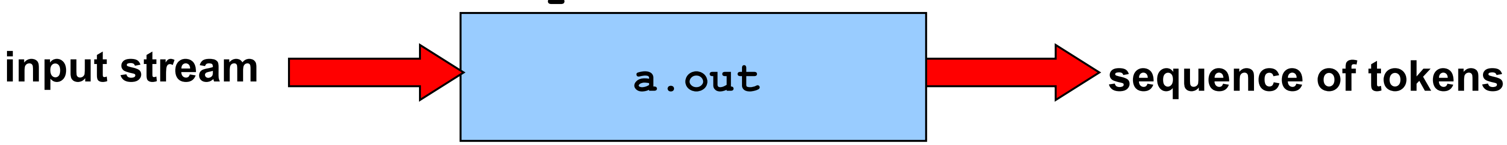


# HOW IT WORKS

**`lex.yy.c`** is compiled and linked with the **`-lfl`** library to produce an executable, which is the scanner

```
>> g++ lex.yy.c -lfl
```


```
>> a.out < input.txt
```



# FLEX SPECIFICATIONS

Lex programs are divided into three components

```
/* Definitions - name definitions
 *             - variables defined
 *             - include files specified
 *             - etc
 */

%%

/* Translation rules - pattern actions {C/C++statements} */

%%

/* User code - supports routines for the above C/C++
 *             statements
 */
```

# NAME DEFINITIONS

- *Name definition* are intended to simplify the scanner specification and have the form:

```
name     definition
```

- Subsequently the definition can be referred to by `{name}`, witch then will expand to the `definition`.
- Example:

```
DIGIT    [0-9]
{DIGIT}+"."{DIGIT}*
```

is identical/will be expanded to:

```
([0-9])+"."([0-9])*
```

# PATTERN ACTIONS

- The *transformation rules* section of the **lex**/**flex** input, contains a series of rules of the form:

```
pattern    action
```

- Example:

```
[0-9]*     { printf ("%s is a number", yytext); }
```

# Simple Patterns

Match only one specific character

- `x` The character '**`x`**'
- `.` Any character except newline

# CHARACTER CLASS PATTERNS

Match any character within the class

`[xyz]` The pattern matches either '**x**', '**y**', or '**z**'

`[abj-o]` This pattern spans over a range of characters and matches '**a**', '**b**', or any letter ranging from '**j**' to '**o**'

# NEGATED PATTERNS

Match any character not in the class

`[^z]` This pattern matches any character EXCEPT '**z**'

`[^A-Z]` This pattern matches any character EXCEPT an uppercase letter

`[^A-Z\n]` This pattern matches any character EXCEPT an uppercase letter or a newline

# SOME USEFUL PATTERNS

| | |
|---|---|
| `r*` | Zero or more '`r`', '`r`' is any regular expr. |
| `\\0` | **`NULL`** character (ASCII code 0) |
| `\123` | Character with octal value **`123`** |
| `\x2a` | Character with hexadecimal value **`2a`** |
| `p\|s` | Either '`p`' or '`s`' |
| `p/s` | '`p`' but only if it is followed by an '`s`', which is not part of the matched text |
| `^p` | '`p`' at the beginning of a line |
| `p$` | '`p`' at the end of a line, equivalent to '`p/\n`' |

# FLEX USER CODE

Finally, the user code section is simply copied to `lex.yy.c` verbatim

It is used for companion routines which call, or are called by the scanner

The presence of this user code is optional, if you don't have it there's no need for the second `%%`

# FLEX PROGRAM VARIABLES

**`yytext`** Whenever the scanner matches a token, the text of the token is stored in the null terminated string **`yytext`**

**`yyleng`** The length of the string **`yytext`**

**`yylex()`** The scanner created by the Lex has the entry point **`yylex()`**, which can be called to start or resume scanning. If **`lex`** action returns a value to a program, the next call to **`yylex()`** will continue from the point of that return

# A SIMPLE FLEX PROGRAM

## Recognition of verbs

*.l

Mary has a little lamb

```
%{
/* includes and defines should be stated in this section */
%}

%%

[\t]+                  /* ignore white space */

do|does|did|done|has { printf ("%s: is a verb\n", yytext); }
[a-zA-Z]+              { printf ("%s: is not a verb\n",yytext); }
.|\n                   { ECHO; /* normal default anyway */ }

%%

main()                 { yylex(); }
```

# A SIMPLE FLEX PROGRAM

A scanner that counts the number of characters and lines in its input

```
int num_lines = 0, num_chars = 0; /* Variables */

%%

\n   { ++num_lines; ++num_chars; } /* Take care of newline */
.    { ++num_chars; }        /* Take care of everything else */

%%
main() { yylex();
      printf("lines: %d, chars: %d\n", num_lines, num_chars );
    }
```

The output is the result

# A PASCAL SCANNER

```
%{
   #include <math.h>
%}
DIGIT     [0-9]
ID        [a-z][a-z0-9]*

%%

{DIGIT}+  { printf("An integer: %s (%d)\n", yytext,  atoi( yytext ));
          }

{DIGIT}+"."{DIGIT}*
          { printf("A float: %s (%g)\n", yytext, atof( yytext )); }

if|then|begin|end|procedure|function
      { printf("A keyword: %s\n", yytext); }

{ID}      { printf("An identifier: %s\n", yytext); }
```

# A PASCAL SCANNER

```
"+"|"-"|"*"|"/"          { printf("An operator: %s\n", yytext); }


"{" [^}\n]* "}"          /* eat up one-line comments */

[\t\n]+                  /* eat up whitespace */

.                        { printf("Unknown character: %s\n", yytext );}

%%

main(argc, argv) {
    ++argv, --argc;  /* skip over program name */
    if ( argc > 0 )  yyin = fopen( argv[0], "r" );
    else  yyin = stdin;
    yylex();
}
```

# FILES OF INTEREST

- Files you will need to modify:
  - **`scanner.l`** : is the **`flex`** input file, which you're going to complete. This is the only file you will need to edit in this lab.
- Other files of interest
  - **`scanner.hh`** : is a temporary include file used for scanner testing.
  - **`scantest.cc`** : is an interactive test program for your scanner.
  - **`symtab.hh`** : contains symbol table information, including string pool methods.
  - **`symbol.cc`** : contains symbol implementations (will be edited in lab 2).
  - **`symtab.cc`** : contains the symbol table implementation.
  - **`error.hh`** and **`error.cc`** contain debug and error message routines.

# LAB2
# THE SYMBOL TABLE

# SYMBOL TABLES

A Symbol table contains all the information that must be passed between different phases of a compiler/interpreter

A symbol (or token) has at least the following attributes:

- Symbol Name
- Symbol Type (int, real, char, ....)
- Symbol Class (static, automatic, cons...)

# SYMBOL TABLES

In a compiler we also need:

- Address (where is the information stored?)
- Other information due to used data structures

Symbol tables are typically implemented using hashing schemes because good efficiency for the lookup is needed

# SYMBOL TABLES

The symbol table primarily helps ...

… in checking the program's semantic correctness (type checking, etc.)

… in generating code (keep track of memory requirements for various variables, etc.)

# SIMPLE SYMBOL TABLES

We classify symbol tables as:

- Simple
- Scoped

Simple symbol tables have…
… only one scope
... only “global” variables

Simple symbol tables may be found in BASIC and FORTRAN compilers

# SCOPED SYMBOL TABLES

Complication in simple tables involves languages that permit multiple scopes

C permits at the simplest level two scopes: global and local (it is also possible to have nested scopes in C)

# WHY SCOPES?

The importance of considering the scopes are shown in these two C programs

```
int a=10; //global variable

main(){
   changeA();
   printf("Value of a=%d\n,a);
}

void changeA(){
   int a;  //local variable
   a=5;
}
```

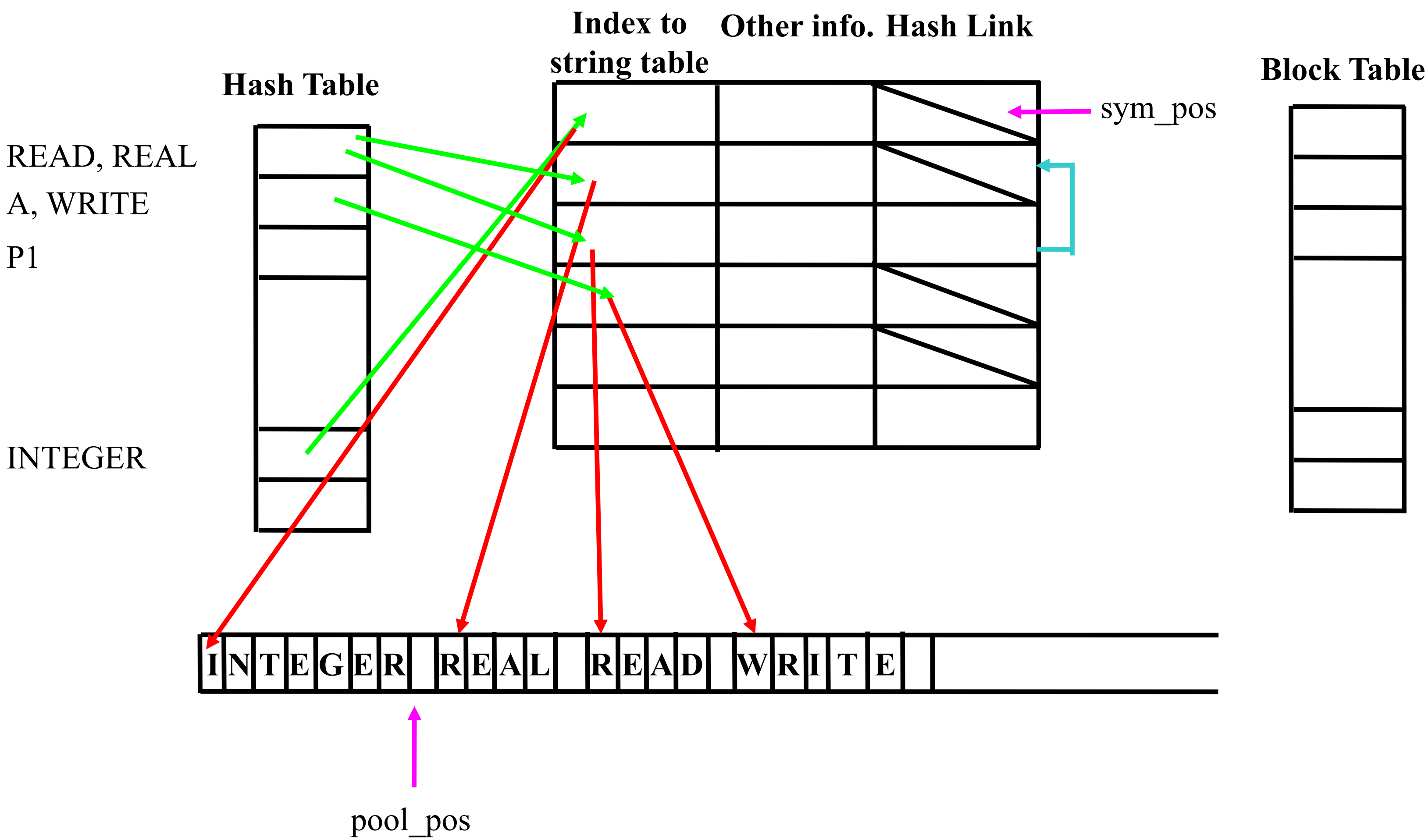
```
int a=10; //global variable

main(){
   changeA();
   printf("Value of a=%d\n,a);
}

void changeA(){
   a=5;
}
```

# SCOPED SYMBOL TABLES

Operations that must be supported by the symbol table in order to handle scoping:

- Lookup in any scope – search the most recently created scope first
- Enter a new symbol in the symbol table
- Modify information about a symbol in a "visible" scope
- Create a new scope
- Delete the most recently scope

# HOW IT WORKS



Index to string table
Other info.
Hash Link
Block Table
Hash Table
sym_pos
READ, REAL
A, WRITE
P1
INTEGER
I N T E G E R R E A L R E A D W R I T E
pool_pos

# A SMALL PROGRAM

```
program prog;
var
    a : integer;
    b : integer;
    c : integer;

procedure p1;
var
    a : integer;
begin
    c := b + a;
end;

begin
    c := b + a;
end.
```

# YOUR TASK

- Implement the methods *open_scope()* and *close_scope()*, called when entering and leaving an environment.
- Implement the method *lookup_symbol()*, it should search for a symbol in open environments.
- Implement the method *install_symbol()*, it should install a symbol in the symbol table.
- Implement the method *enter_procedure()*.

# FILES OF INTEREST

- Files you will need to modify
  - **symtab.cc** : contains the symbol table implementation.
  - **scanner.l** : minor changes.
- Other files of interest

*(Other than the Makefile, use the same files you were given in the first lab.)*

  - **symtab.hh** : contains all definitions concerning symbols and the symbol table.
  - **symbol.cc** : contains the symbol class implementations.
  - **error.hh** and **error.cc** : contain debug and error message routine
  - **symtabtest.cc** : used for testing. Edit this file to simulate various calls to the symbol table.
  - **Makefile** : not the same as in the first lab!

# DEBUGGING

- All symbols can be sent directly to cout. The entire symbol table can be printed using the *print()* method with various arguments.