# CSE401: Introduction to Compiler Construction

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Slides by Chambers, Eggers, Notkin, Ruzzo, and others

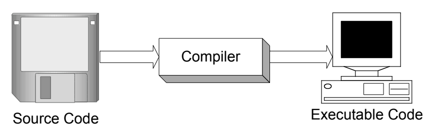

## Today's objectives

- Administrative details
- Define compilers and why we study them
- Define the high-level structure of compilers
- Associate specific tasks, theories, and technologies with achieving the different structural elements of a compiler
  - And build some initial intuition about why these are needed

## Administrative Details

- Course Web:
  http://www.cs.washington.edu/401
- Grading
  - Homeworks ~20%
  - Project ~40%
  - Midterm ~15%
  - Final ~25%
- Project: toy compiler → an (almost) real one. Staged. Optional teams of 2-3 people.

## What is a compiler?




- A software tool that translates
  - a program in source code form to
  - an equivalent program in an executable (target) form
- Converts from a form good for people to a form good for computers

## Examples

- Source languages
  - Java
  - C
  - C++
  - LISP
  - ML
  - COBOL
  - …
- Target architectures
  - MIPS
  - x86
  - SPARC
  - Alpha
  - …
  - C

## Why study compilers?

## CSE401's project-oriented approach

- Start with a compiler for PL/0, written in C++
- We define additional language features
  - Such as comments, arrays, call-by-reference parameters, result-returning procedures, for loops, etc.
- You modify the compiler to translate the extended PL/0 language
  - Project completed in well-defined stages

## More on the project

- Strongly recommended that you work in two-person teams for the quarter
- Grading based on
  - correctness
  - clarity of design and implementation
  - quality of testing
- Provides experience with object-oriented design and with C++
- Provides experience with working in a team

## What's hard about compiling

- I will present a small program to you, character by character
- Identify problems that you can see that you will encounter in compiling this program
- Here's an example problem
  - When we see a character `'1'` followed by a character `'7'`, we have to convert it to the integer 17.

## Example

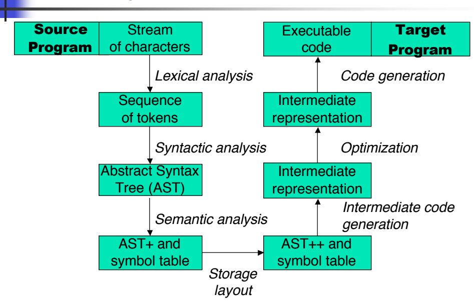
| | | | | | |
|---|---|---|---|---|---|
| 1. | `i` | 11. | `1` | 21. | `i` |
| 2. | `n` | 12. | `7` | 22. | `*` |
| 3. | `t` | 13. | `_` | 23. | `i` |
| 4. | `_` | 14. | `;` | 24. | `+` |
| 5. | `i` | 15. | `p` | 25. | `2` |
| 6. | `;` | 16. | `r` | 26. | `)` |
| 7. | `_` | 17. | `i` | 27. | `;` |
| 8. | `i` | 18. | `n` | | |
| 9. | `:` | 19. | `t` | | |
| 10. | `=` | 20. | `(` | | |

- _ is the space character
- This is not a PL/0 program!

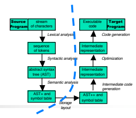
## Structure of compilers

- A common compiler structure has been defined
  - Years and years of deep, difficult research intermixed with building of thousands of compilers
- Actual compilers often differ from this prototype
  - Primary differences are the ordering and clarity with which the pieces are actually separated
  - But the model is still extremely useful
- You will see the structure — to a large degree — in the PL/0 compiler

## Prototype compiler structure



# Front- and back-end



- These parts are often lumped into two categories
- The front-end
  - Focuses on (repeated) analysis
  - Determines what the program is
- The back-end
  - Focuses on synthesis
  - Produces target program equivalent to source program

# An example compilation

```
module main;
  var x:int, result: int;
  procedure square(n:int);
  begin
    result := n*n;
  end square;
begin
  x := input;
  while x <> 0 do
    square(x);
    output := result;
    x := input;
  end;
end main.
```

- A real PL/0 program
- We'll step through
  - Lexical analysis
  - Syntactic analysis
  - Semantic analysis
  - Storage layout
  - Code generation

# Lexical analysis
## (AKA scanning and tokenizing)

- Read in characters and clump them into **tokens**
  - Also strip out white space and comments
- Specify tokens with regular expressions
- Use finite state machines to scan
- Remember the connection between regular expressions and finite state machines

```
Ident    ::= Letter AlphaNum*
Integer  ::= Digit+
AlphaNum ::= Letter | Digit
Letter   ::= 'a' |…|'z' |…|
             'A' |…|'Z'
Digit    ::= '0' |…|'9'
```

E.g.:

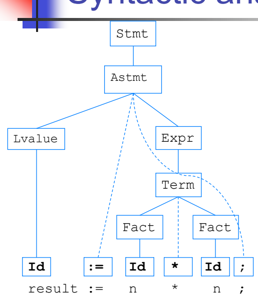
| While | x | <> | 0 | do |
|---|---|---|---|---|
| keywd | id | op | int | keywd |

# Syntactic analysis
## (AKA parsing)

- Turn token stream into tree based on the program's syntactic structure
- Define syntax using context free grammar (CFG)
  - EBNF is a common notation for defining *concrete syntax*
    - Cares about semi-colons, parens, and such
  - Parser usually constructs AST representing *abstract syntax*
    - Cares about statement structures, precedence and such

```
Stmt   ::= Astmt | IfStmt | …
Astmt  ::= Lvalue := Expr ;
Lvalue ::= Id
IfStmt ::= if Test then Stmt
           [else Stmt] ;
Test   ::= Expr = Expr |
           Expr < Expr | …
Expr   ::= Term + Term |
           Term - Term | Term
Term   ::= Factor * Factor |
           … | Factor
Factor ::= - Factor | Id |
           Int | ( Expr )
```

# Syntactic analysis example




```
Stmt   ::= Astmt | IfStmt | …
Astmt  ::= Lvalue := Expr ;
Lvalue ::= Id
IfStmt ::= if Test then Stmt
           [else Stmt] ;
Test   ::= Expr = Expr |
           Expr < Expr | …
Expr   ::= Term + Term |
           Term - Term | Term
Term   ::= Factor * Factor |
           … | Factor
Factor ::= - Factor | Id |
           Int | ( Expr )
```

# Semantic analysis
## (Name resolution and type checking)

- Given AST
  - figure out what declaration each name refers to
  - perform **static** consistency checks
- Key data structure: *symbol table*
  - maps names to information about name derived from declaration
- Semantic analysis steps
  - Process each scope, top down
  - Process declarations in each scope into symbol table for scope
  - Process body of each scope in context of symbol table

## Semantic analysis example

```
int x;
int y(void);
int main(void) {
    double x,y;
    x = x + 5;
    printf("x is %d",x);
    x = y();
    return 1/2 ;
}
```

- Which var with which decl?
- What type?
- Operators legal on those types?
- Coercion?
- Function arg & return types too?
- Overloading?
- Goto/case labels unique?

## Storage layout

- Given symbol table, determine how and where variables will be stored at runtime
- What representation is used for each kind of data?
- How much space does each variable require?
- In what kind of memory should it be placed?
  - static, global memory
  - stack memory
  - heap memory
- Where in memory should it be placed?
  - e.g., what stack offset?

## Storage layout example

```
int x;
int y(void);
int main(void) {
    double x,y;
    x = x + 5;
    printf("x is %d",x);
    x = y();
    return 1/2 ;
}
```

- Outer x: 4 bytes, static
- Inner x,y: 8 bytes each on stack
- What address?
- How does printf find its parameters?
- How does main return a value?

## Code generation

- Given annotated AST and symbol table, produce target code
- Often done as three steps
  - Produce machine-independent low-level representation of the program (*intermediate representation* or *IR*)
  - Perform machine-independent optimizations (optional)
  - Translate IR into machine-specific target instructions
    - Instruction selection
    - Register allocation

## Codegen example

```
x = x + y;        t42 ← x               lw   $2, 48($fp)
                  t43 ← y               lw   $3, 52($fp)
                  t44 ← t42 + t43       add  $2, $2, $3
                  x ← t44               sw   $2, 48($fp)
x = x * 2;t45 ← x                 lw   $2, 48($fp)
                  t46 ← 2               li   $3, 2
                  t47 ← t45 * t46       mul  $2, $2, $3
                  x ← t47               sw   $2, 48($fp)
x += y;           t48 ← x               lw   $2, 48($fp)
                  t49 ← y               lw   $3, 52($fp)
                  t50 ← t48 + t49       add  $2, $2, $3
                  x ← t50               sw   $2, 48($fp)
```

## Optimization

- Can you see simple changes that would streamline the code above?
- How could you find them automatically?

## Does this structure work well?

- FORTRAN I Compiler (circa 1954-56)
  - 18 person years
- PL/0 Compiler
  - By the end of the quarter, you'll have a working compiler that's way better than FORTRAN I in most respects
    (key exception: optimization)

## Compilers vs. interpreters

- Compilers implement languages by translation
- Interpreters implement languages directly
- Note: the line is not always crystal-clear
- Compilers and interpreters have tradeoffs
  - Execution speed of program
  - Start-up overhead, turn-around time
  - Ease of implementation
  - Programming environment facilities
  - Conceptual clarity

## Compiler engineering issues

- Portability
  - Ideal is multiple front-ends and multiple back-ends with a shared intermediate language
- Sequencing phases of compilation
  - Stream-based vs. syntax-directed
- Multiple, separate passes vs. fewer, integrated passes
- How to avoid compiler bugs?

## Objectives: next lecture

- Define overall theory and practical structure of lexical analysis
- Briefly recap regular expressions, finite state machines, and their relationship
  - Even briefer recap of the language hierarchy
- Show how to define tokens with regular expressions
- Show how to leverage this style of token definition in implementing a lexer