CSL302: Compiler Design

Overview of Compiler Design

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Note

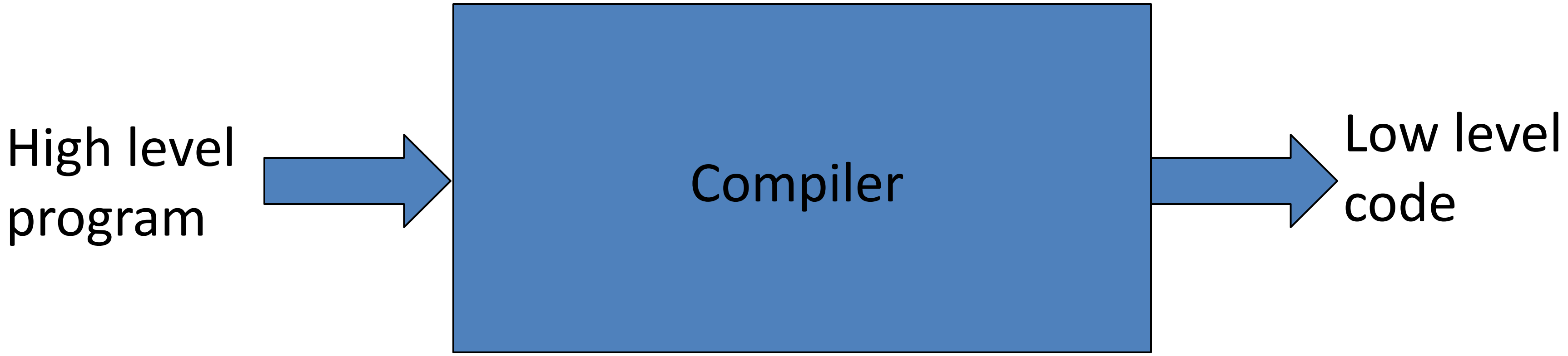
- *Throughout this course, I am preparing/using the lectures notes from various references.*

Acknowledgement

- *References for today's slides:*
  - *lectures notes of Prof. Amey Karkare (Dept of CSE, IIT Kanpur)*
  - *lectures notes of late Prof. Sanjeev K Aggarwal (Dept of CSE, IIT Kanpur)*

Compilers Introduction

- Translates from one representation of the program to another
- Typically from high level source code to low level machine code
- Source code is normally optimized for human readability
  - Expressive: matches our notion of languages
- Machine code is optimized for hardware
  - Redundancy is reduced
  - Information about the intent is lost


High level program
Compiler
Low level code

Goals of translation

- Good compile time performance
- Good performance for the generated code
- Preserve semantics
- Generate meaningful errors

How to translate?

- Direct translation is difficult. Why?

- Source code and machine code mismatch in level of abstraction
  - Variables vs Memory locations/registers
  - Functions vs jump/return
  - Parameter passing
  - structs

- Some languages are farther from machine code than others
  - For example, languages supporting Object Oriented Paradigm

How to translate easily?

- Translate in steps. Each step handles a reasonably simple, logical, and well defined task
- Design a series of program representations
- Representations become more machine specific and less language specific as the translation proceeds

The first few steps

- The first few steps can be understood by analogies to how humans comprehend a natural language
- The first step is recognizing/knowing alphabets of a language. For example
  - English text consists of lower and upper case alphabets, digits, punctuations and white spaces
  - Written programs consist of characters from the ASCII characters set (normally 9-13, 32-126)

The first few steps

- The next step to understand the sentence is recognizing words
  - How to recognize English words?
  - Words found in standard dictionaries
  - Dictionaries are updated regularly

Oxford Dictionaries

ABOUT OXFORD GLOBAL LANGUAGES THE OED PRESS AND NEWS

December 2016 -

Around 500 new words, phrases, and senses have entered the *Oxford English Dictionary* this quarter, including *glam-ma*, *YouTuber*, and *upstander*.

We have a selection of release notes this December, each of which takes a closer look at some of our additions. The last few years have seen the emergence of the word *Brexit*, and you can read more about the huge increase in the use of the word, and how we go about defining it, in this article by Craig Leyland,

The first few steps

- How to recognize words in a programming language?
  - a dictionary (of keywords etc.)
  - rules for constructing words (identifiers, numbers etc.)
- This is called lexical analysis
- Recognizing words is not completely trivial. For example:

  w hat ist his se nte nce?

Lexical Analysis: Challenges

- We must know what the word separators are
- The language must define rules for breaking a sentence into a sequence of words.
- Normally white spaces and punctuations are word separators in languages.

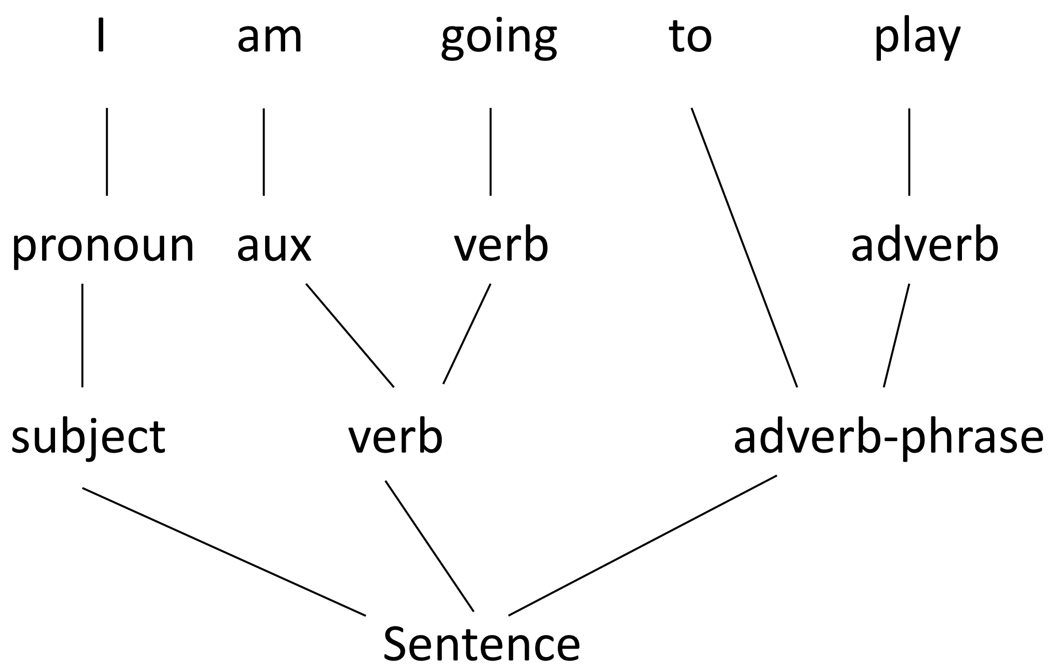
Lexical Analysis: Challenges

- In programming languages a character from a different class may also be treated as word separator.

- The lexical analyzer breaks a sentence into a sequence of words or tokens:
  - If a == b then a = 1 ; else a = 2 ;
  - Sequence of words (total how many words?)

The next step

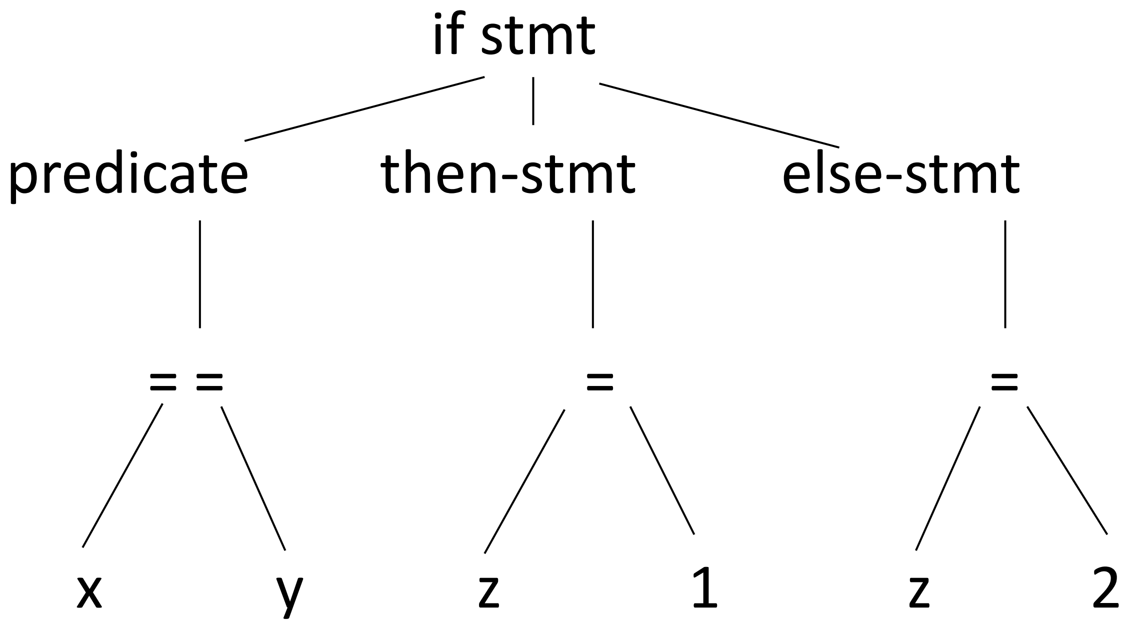
- Once the words are understood, the next step is to understand the structure of the sentence
- The process is known as *syntax checking* or *parsing*



Parsing

- Parsing a program is exactly the same process as shown in previous slide.
- Consider an expression

  if x == y then z = 1 else z = 2



Understanding the meaning

- Once the sentence structure is understood we try to understand the meaning of the sentence (semantic analysis)
- A challenging task
- Example:

  Prateek said Nitin left his assignment at home
- What does his refer to? Prateek or Nitin?

Understanding the meaning

- Worse case

Amit said Amit left his assignment at home

- Even worse

Amit said Amit left Amit's assignment at home

- How many Amits are there?
  Which one left the assignment?
  Whose assignment got left?

Semantic Analysis

- Too hard for compilers. They do not have capabilities similar to human understanding
- However, compilers do perform analysis to understand the meaning and catch inconsistencies
- Programming languages define strict rules to avoid such ambiguities

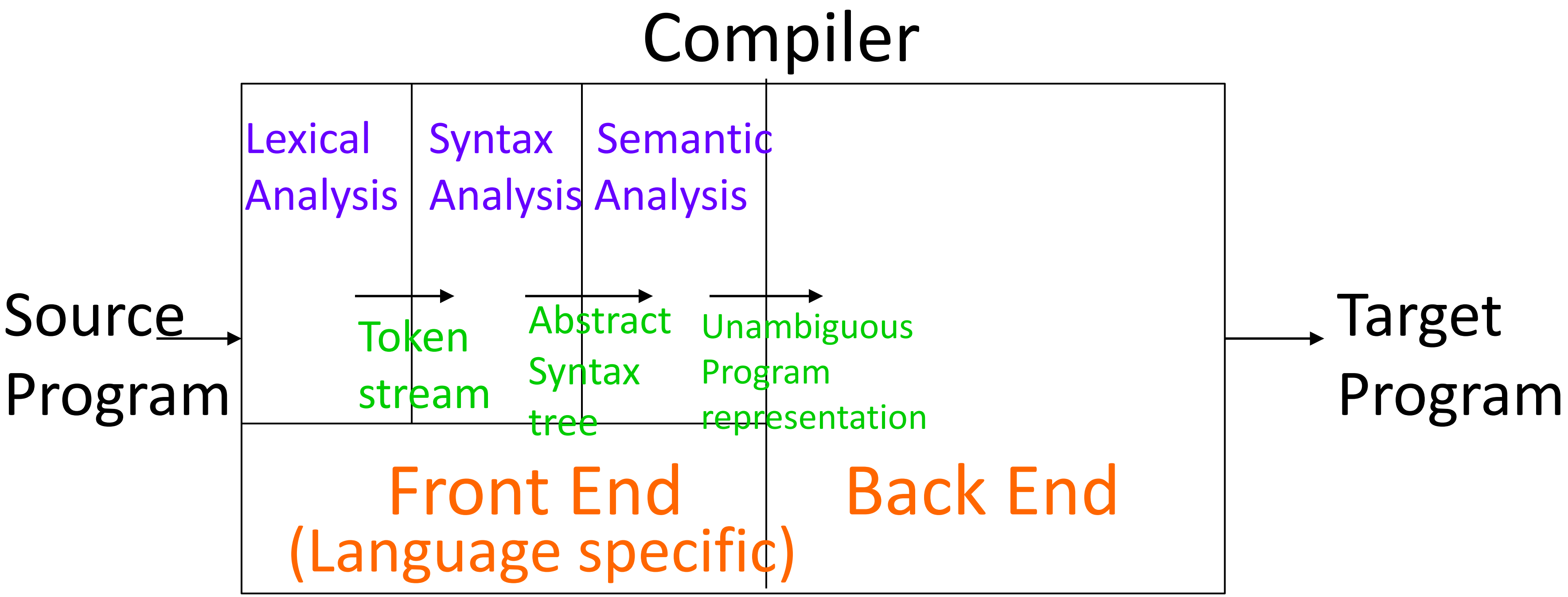
```
{ int Amit = 3;
     { int Amit = 4;
        cout << Amit;
     }
 }
```

More on Semantic Analysis

- Compilers perform many other checks besides variable bindings
- Type checking

  Amit left her work at home
- There is a type mismatch between her and Amit. Presumably Amit is a male. And they are not the same person.

Compiler structure once again



Back End
SWIFT
SWIFT
VXI

Code Generation

- Usually a two step process
  - Generate intermediate code from the semantic representation of the program
  - Generate machine code from the intermediate code

- The advantage is that each phase is simple
- Requires design of intermediate language

Example

Expression: $a = b * -c + b * c$

Intermediate code:

$t_1 = -c$

$t_2 = b * t_1$

$t_3 = b * c$

$t_4 = t_2 + t_3$

$a = t_4$

Intermediate Code Optimization

- Automatically modify programs so that they
  - Run faster
  - Use less resources (memory, registers, space, fewer fetches etc.)

Intermediate Code Optimization

- Some common optimizations
  - Common sub-expression elimination
  - Copy propagation
  - Dead code elimination
  - Code motion
  - Strength reduction
  - Constant folding

- Example: x = 15 * 3 is transformed to x = 45

Example of Optimizations

A : assignment M : multiplication D : division E : exponent

```
PI = 3.14159
Area = 4 * PI * R^2
Volume = (4/3) * PI * R^3                 3A+4M+1D+2E
---------------------
X = 3.14159 * R * R
Area = 4 * X
Volume = 1.33 * X * R                     3A+5M
---------------------
Area = 4 * 3.14159 * R * R
Volume = ( Area / 3 ) * R                 2A+4M+1D
---------------------
Area = 12.56636 * R * R
Volume = ( Area /3 ) * R                  2A+3M+1D
---------------------
X = R * R
Area = 12.56636 * X
Volume = 4.18879 * X * R                  3A+4M
```

Code Generation

- Most compilers perform translation between successive intermediate representations

- Intermediate languages are generally ordered in decreasing level of abstraction from highest (source) to lowest (machine)

Code Generation

- Abstractions at the source level

  identifiers, operators, expressions, statements, conditionals, iteration, functions (user defined, system defined or libraries)

- Abstraction at the target level

  memory locations, registers, stack, opcodes, addressing modes, system libraries, interface to the operating systems

- Code generation is mapping from source level abstractions to target machine abstractions

Code Generation

- Map identifiers to locations (memory/storage allocation)
- Explicate variable accesses (change identifier reference to relocatable/absolute address
- Map source operators to opcodes or a sequence of opcodes

Code Generation

- Convert conditionals and iterations to a test/jump or compare instructions
- Layout parameter passing protocols: locations for parameters, return values, layout of activations frame etc.
- Interface calls to library, runtime system, operating systems

Post translation Optimizations

- Algebraic transformations and reordering
  - Remove/simplify operations like
    - Multiplication by 1
    - Multiplication by 0
    - Addition with 0
  - Reorder instructions based on
    - Commutative properties of operators
    - For example x+y is same as y+x

Post translation Optimizations

Instruction selection

- Addressing mode selection
- Opcode selection
- Peephole optimization

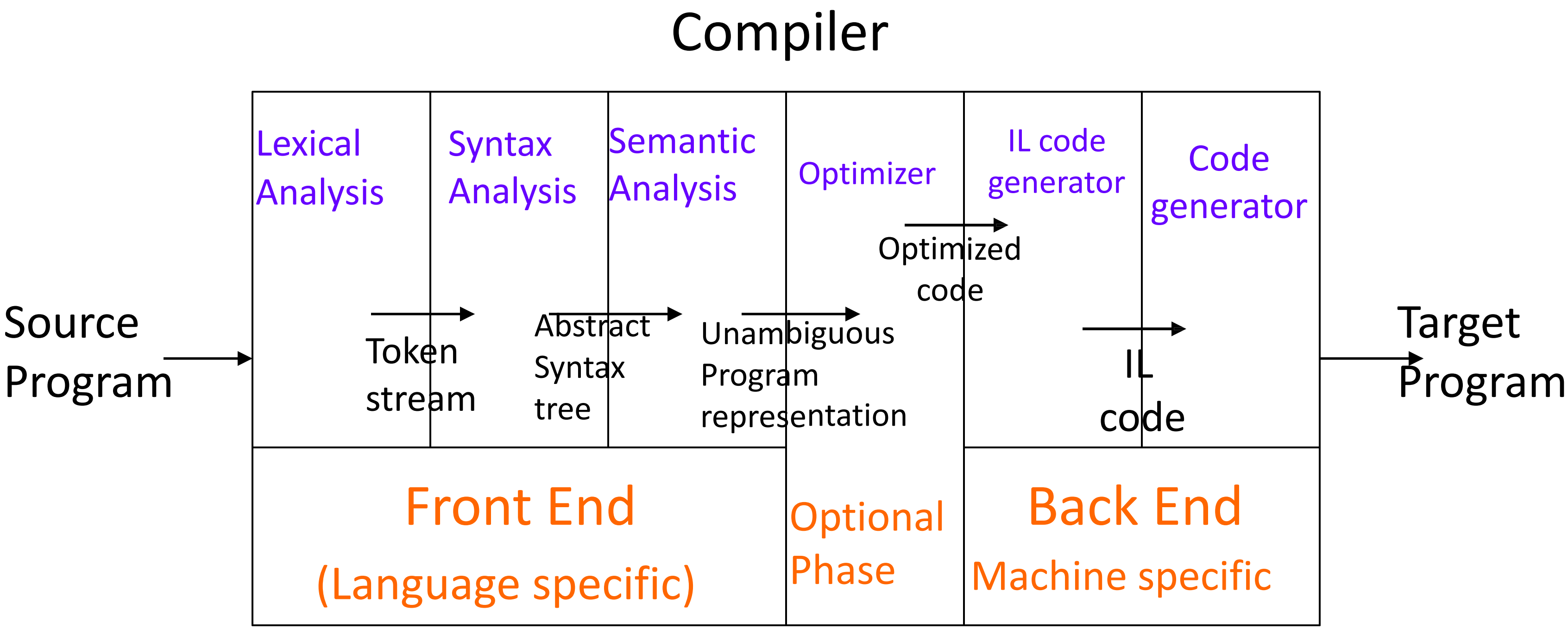
Instruction Selection

```
x=x+1
```

```
LD R0, x          //R0=x
ADD R0, R0, #1    //R0=R0+1
ST x, R0          //x=R0
```

```
INC x
```

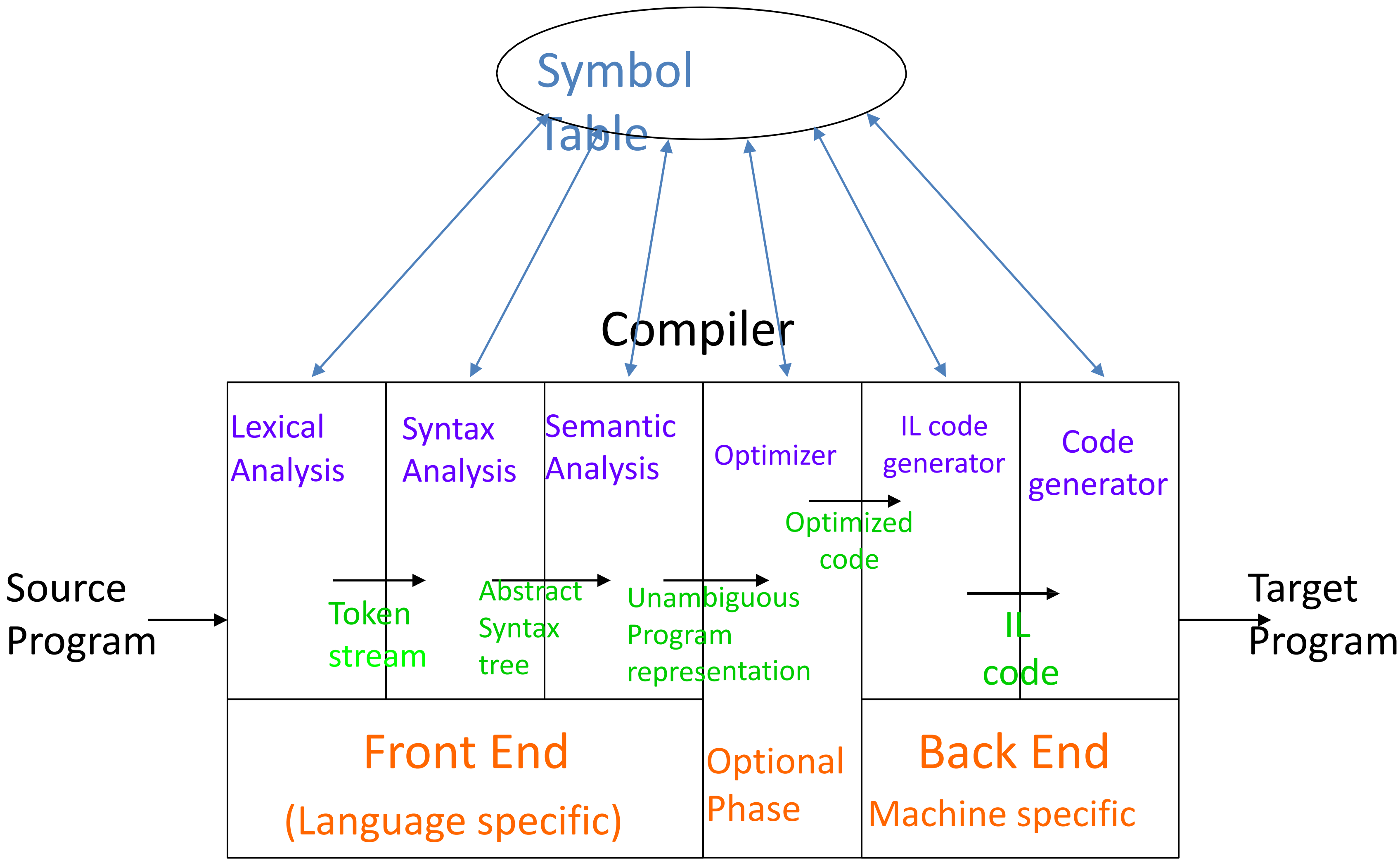
Compiler structure



Something is missing

- Information required about the program variables during compilation
  - Class of variable: keyword, identifier etc.
  - Type of variable: integer, float, array, function etc.
  - Amount of storage required
  - Address in the memory
  - Scope information
- Location to store this information
  - Attributes with the variable
  - At a central repository and every phase refers to the repository whenever information is required
  - Use a data structure called symbol table

Final Compiler structure



Advantages of the model

- Also known as Analysis-Synthesis model of compilation
  - Front end phases are known as analysis phases
  - Back end phases are known as synthesis phases
- Each phase has a well defined work
- Each phase handles a logical activity in the process of compilation

Issues in Compiler Design

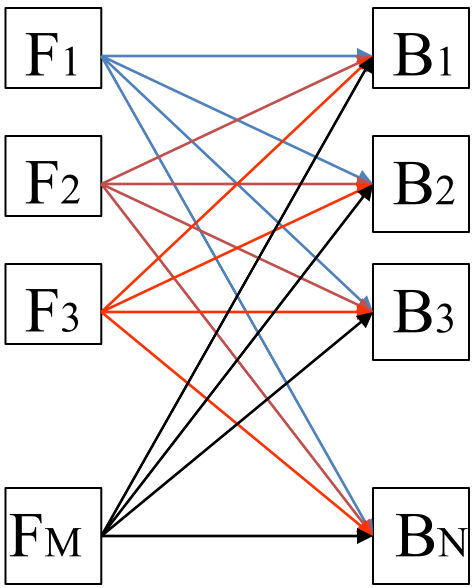
- Compilation appears to be very simple, but there are many pitfalls

- How are erroneous programs handled?

- Design of programming languages has a big impact on the complexity of the compiler

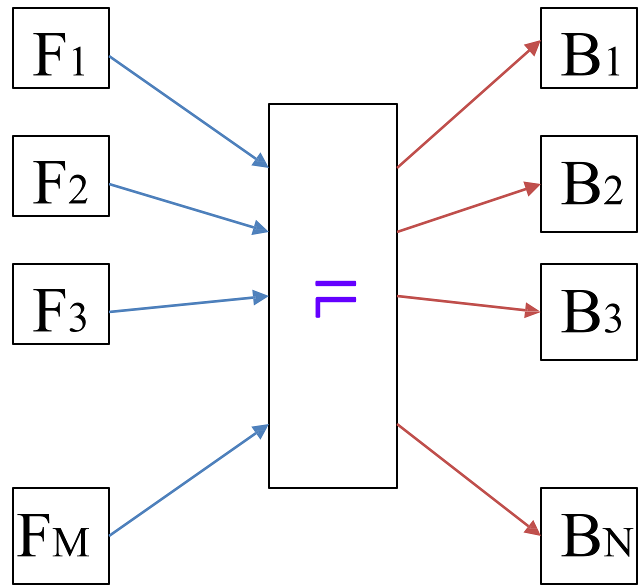
- M*N vs. M+N problem
  - Compilers are required for all the languages and all the machines
  - For M languages and N machines we need to develop M*N compilers
  - However, there is lot of repetition of work because of similar activities in the front ends and back ends
  - Can we design only M front ends and N back ends, and some how link them to get all M*N compilers?

M*N vs M+N Problem



Requires M*N compilers

Intermediate Language



Requires M front ends
And N back ends

Universal Intermediate Language

- Impossible to design a single intermediate language to accommodate all programming languages
  - Mythical universal intermediate language sought since mid 1950s (Aho, Sethi, Ullman)
- However, common IRs for *similar languages*, and *similar machines* have been designed, and are used for compiler development

Compilers of the 21st Century

- Overall structure of almost all the compilers is similar to the structure we have discussed
- The proportions of the effort have changed since the early days of compilation
- Earlier front end phases were the most complex and expensive parts.
- Today back end phases and optimization dominate all other phases. Front end phases are typically a smaller fraction of the total time