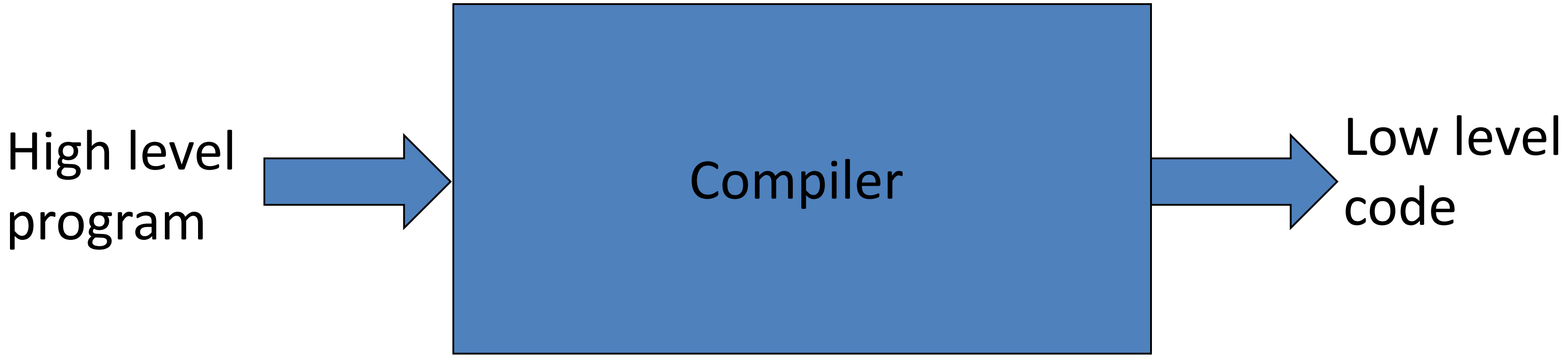
What are Compilers?

- Translates from one representation of the program to another
- Typically from high level source code to low level machine code or object code
- Source code is normally optimized for human readability
  - Expressive: matches our notion of languages (and application?!)
  - Redundant to help avoid programming errors
- Machine code is optimized for hardware
  - Redundancy is reduced
  - Information about the intent is lost



Compiler as a Translator

Goals of translation

- Good compile time performance
- Good performance for the generated code
- Correctness
  - A very important issue.
  - Can compilers be proven to be correct?
    - Tedious even for toy compilers! Undecidable in general.
  - However, the correctness has an implication on the development cost

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
- Intermediate representations should be amenable to program manipulation of various kinds (type checking, optimization, code generation etc.)
- 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.

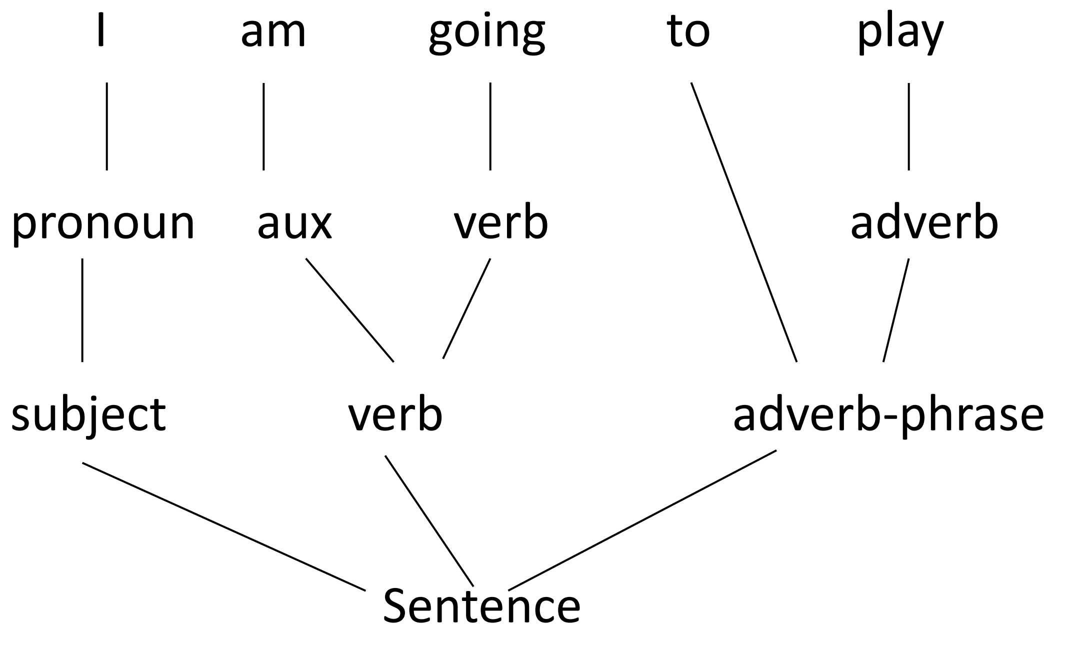
- The lexical analyzer breaks a sentence into a sequence of words or tokens:
  - If a == b then a = 1 ; else a = 2 ;
  - Sequence of words (total 14 words)

    if a == b then a = 1 ; else a = 2 ;

The next step

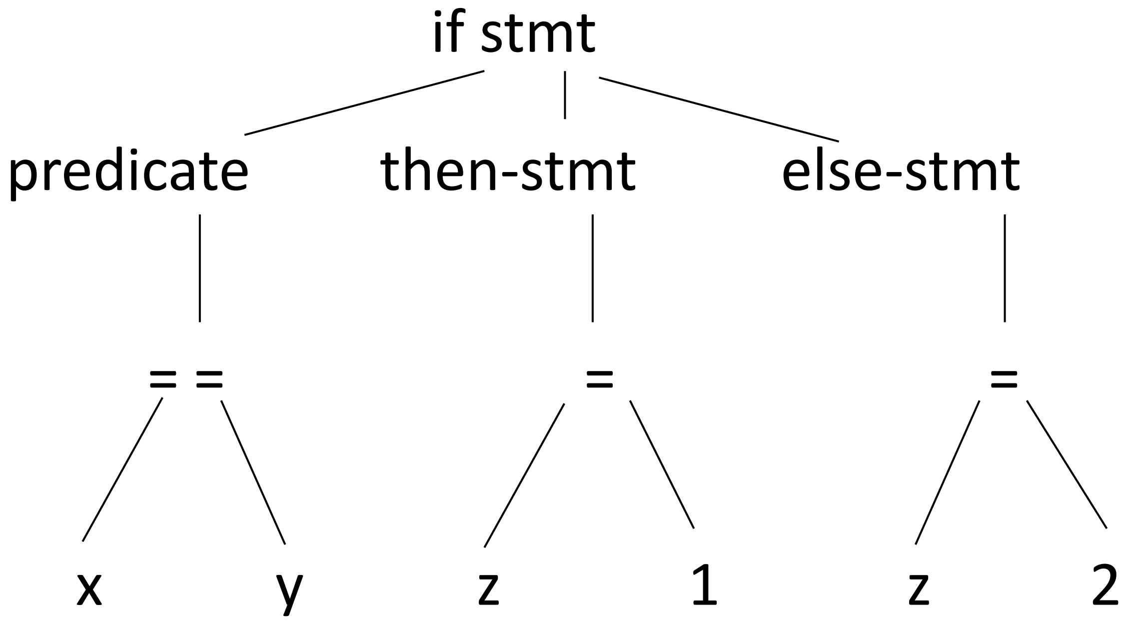
- Once the words are understood, the next step is to understand the structure of the sentence

- 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.

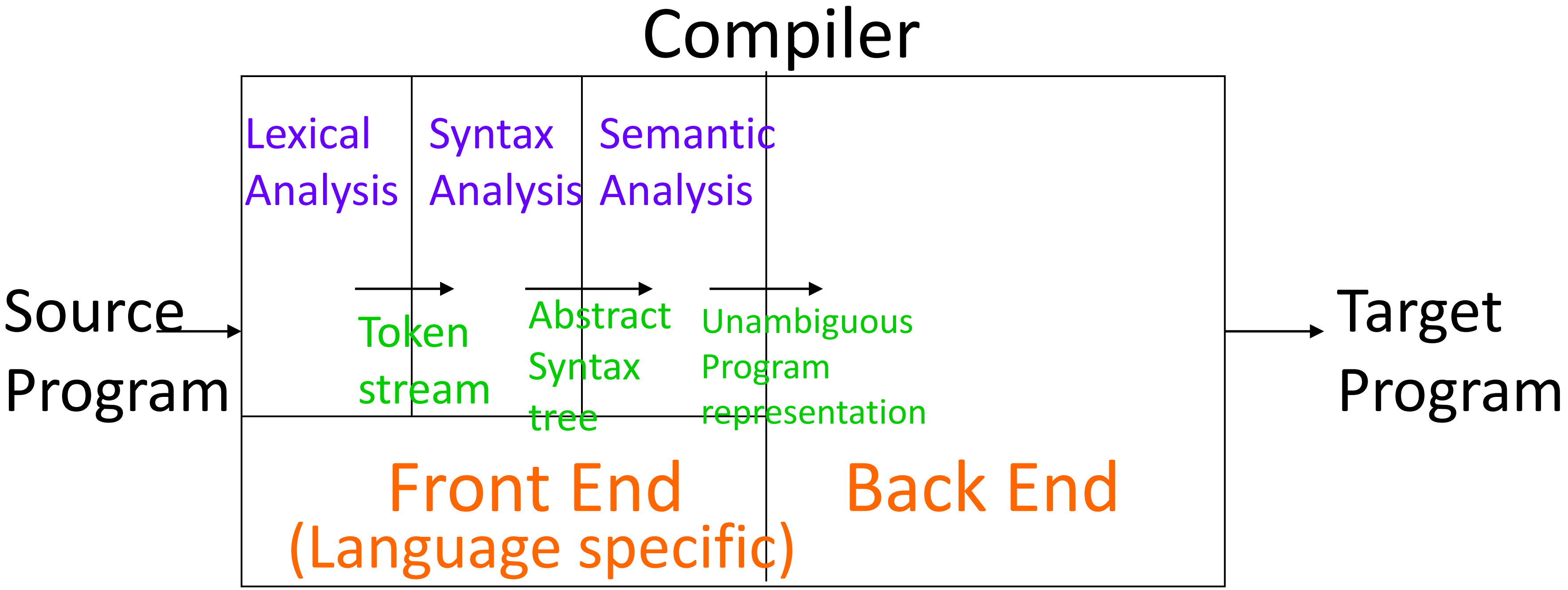
Example from Mahabharat

अश्वथामा हत: इति   नरो वा कुञ्जरो वा

“Ashwathama hathaha iti, narova kunjarova”

Ashwathama is dead. But, I am not certain whether it was a human or an elephant

Compiler structure once again




Back End
SWIFT

Code Optimization

- No strong counter part with English, but is similar to editing/précis writing

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

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

<u>A : assignment   M : multiplication   D : division   E : exponent</u>

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

- 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

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

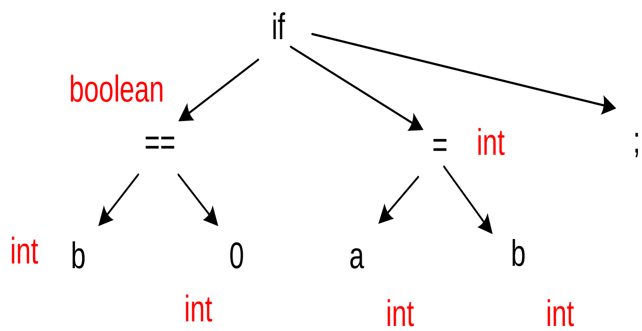
Post translation Optimizations

- 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 (always?)

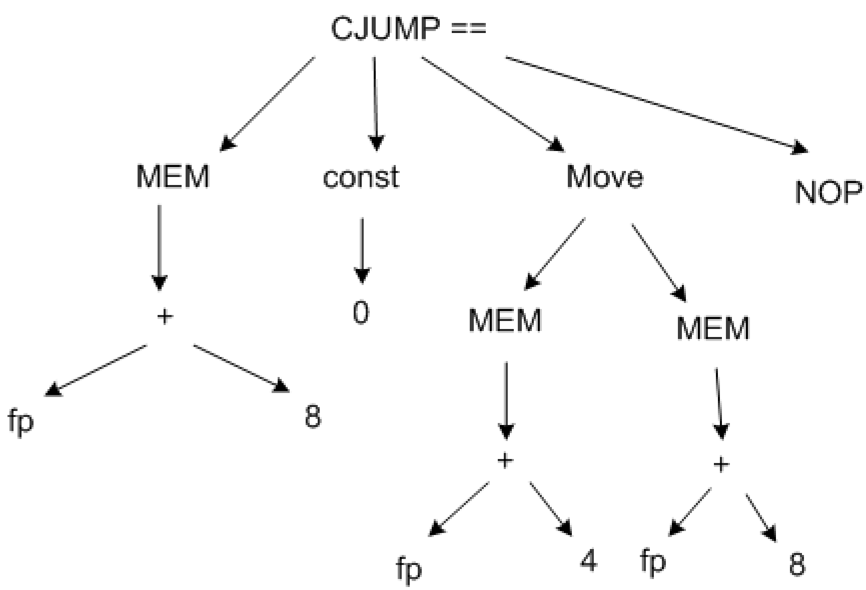
Post translation Optimizations

Instruction selection

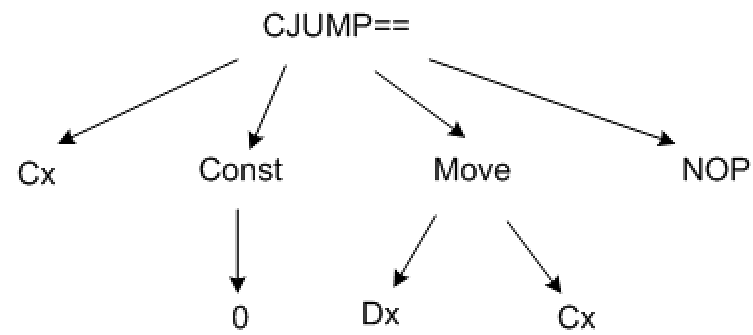
- Addressing mode selection
- Opcode selection
- Peephole optimization



Intermediate code generation



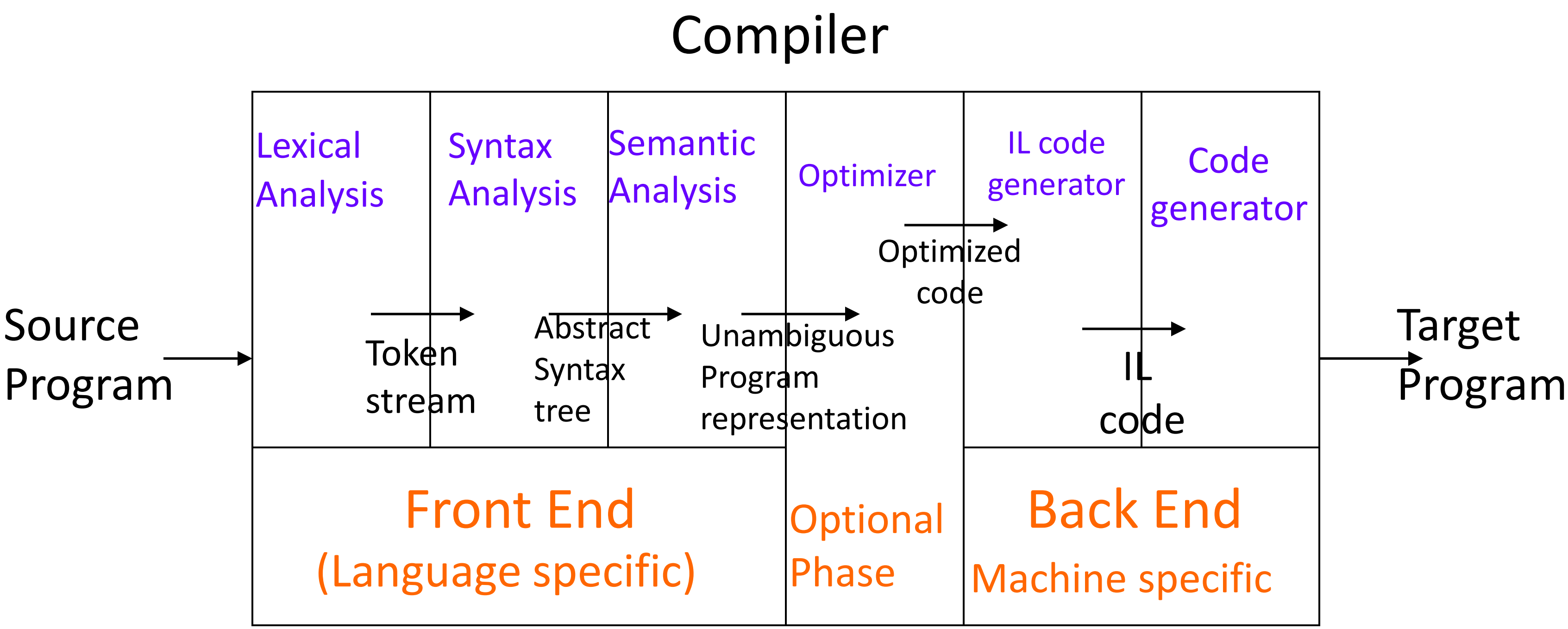
Optimization



Code Generation

```
CMP Cx, 0
CMOVZ  Dx,Cx
```

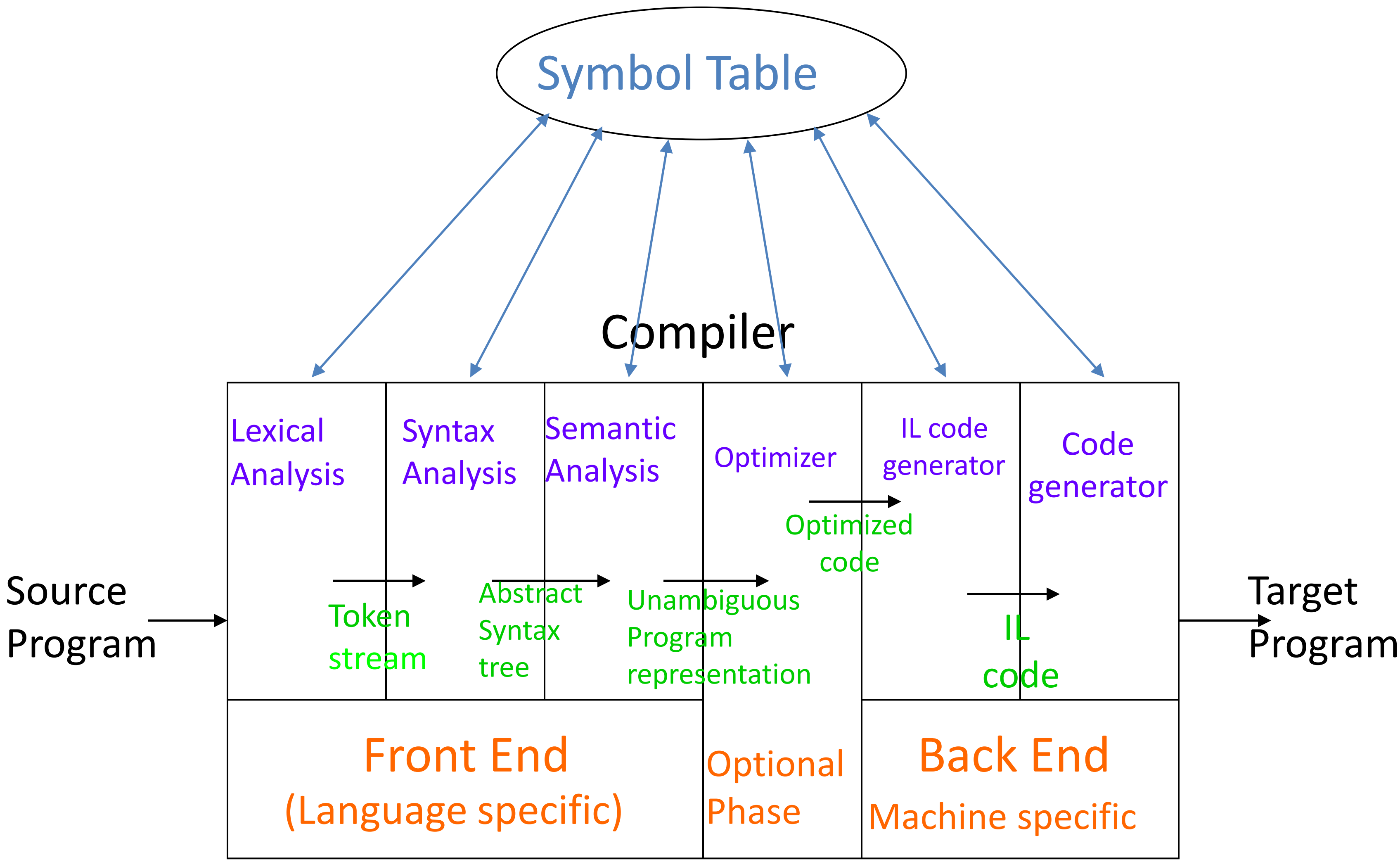
Compiler structure



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 (has obvious problems)
  - At a central repository and every phase refers to the repository whenever information is required
- Normally the second approach is preferred
  - 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

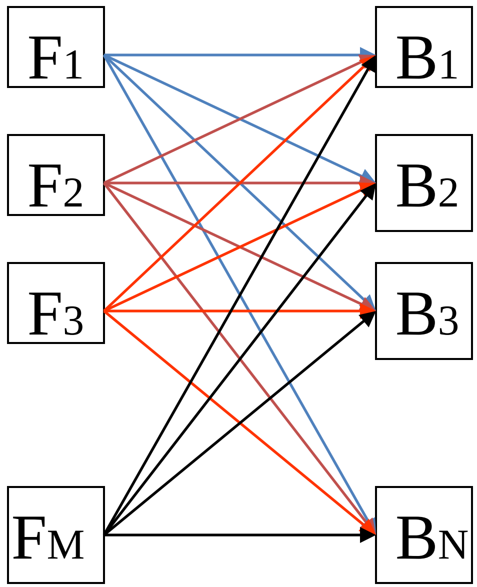
Advantages of the model …

- Compiler is re-targetable
- Source and machine independent code optimization is possible.
- Optimization phase can be inserted after the front and back end phases have been developed and deployed

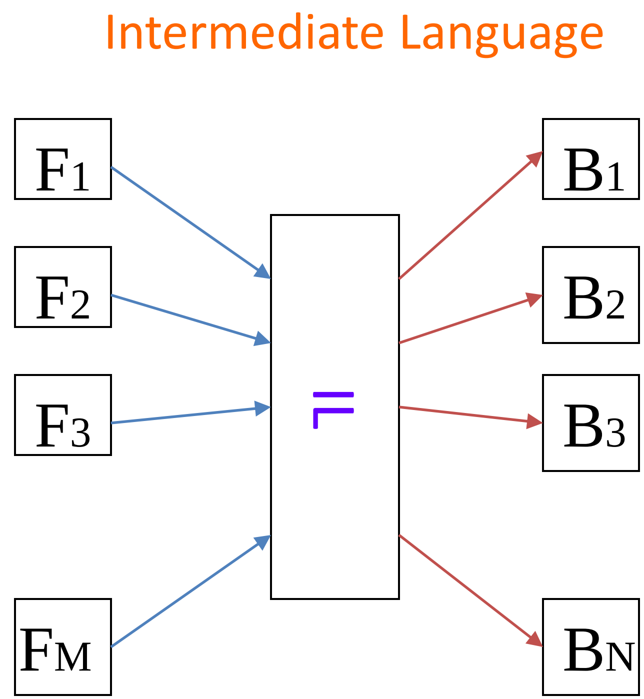
Issues in Compiler Design

- 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



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

How do we know compilers generate correct code?

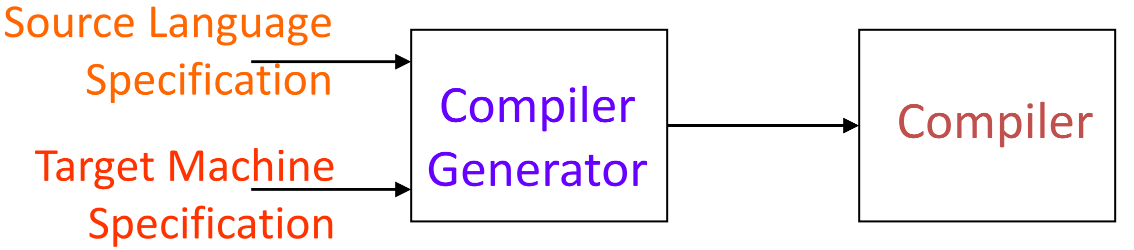
- Prove that the compiler is correct.
- However, program proving techniques do not exist at a level where large and complex programs like compilers can be proven to be correct
- In practice do a systematic testing to increase confidence level

- Regression testing
  - Maintain a suite of test programs
  - Expected behavior of each program is documented
  - All the test programs are compiled using the compiler and deviations are reported to the compiler writer

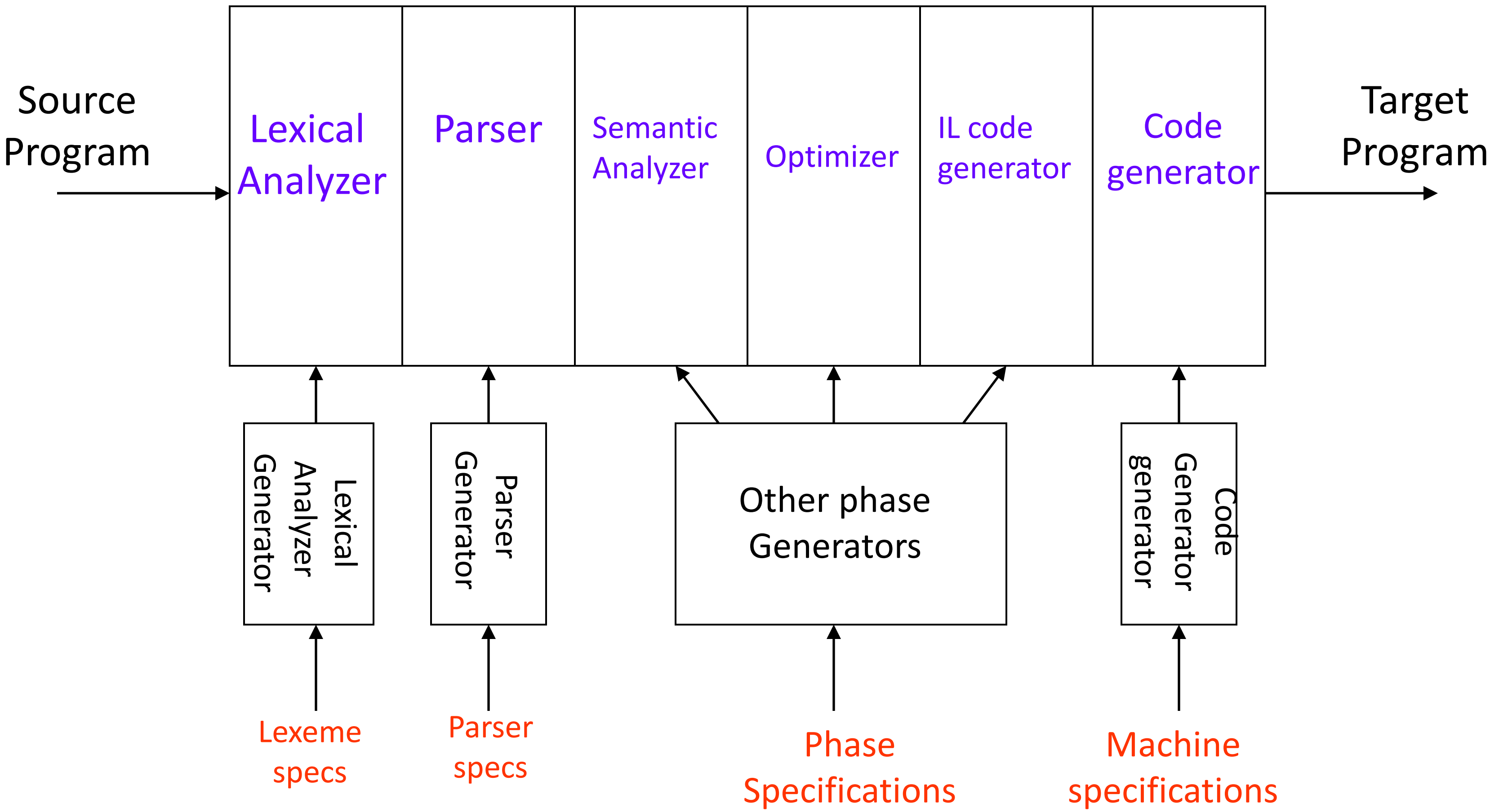
- Design of test suite
  - Test programs should exercise every statement of the compiler at least once
  - Usually requires great ingenuity to design such a test suite
  - Exhaustive test suites have been constructed for some languages

How to reduce development and testing effort?

- DO NOT WRITE COMPILERS
- GENERATE compilers
- A compiler generator should be able to "generate" compiler from the source language and target machine specifications



Tool based Compiler Development



Bootstrapping

- Compiler is a complex program and should not be written in assembly language
- How to write compiler for a language in the same language (first time!)?
- First time this experiment was done for Lisp
- Initially, Lisp was used as a notation for writing functions.
- Functions were then hand translated into assembly language and executed
- McCarthy wrote a function eval[e] in Lisp that took a Lisp expression e as an argument
- The function was later hand translated and it became an interpreter for Lisp

Bootstrap

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Bootstrapping: Example

- Lets solve a simpler problem first
- Existing architecture and C compiler:
  - gcc-x86 compiles C language to x86
- New architecture:
  - x335
- How to develop cc-x335?
  - runs on x335, generates code for x335

Bootstrapping: Example

- How to develop cc-x335?
- Write a C compiler in C that emits x335 code
- Compile using gcc-x86 on x86 machine
- We have a C compiler that emits x335 code
  - –But runs on x86, not x355 ☹

Bootstrapping: Example

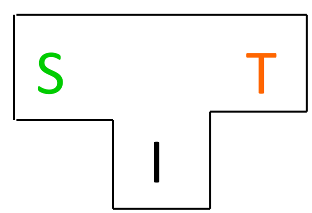
- We have cc-x86-x335
  - Compiler runs on x86, generated code runs on x355
- Compile the source code of C compiler with cc-x86-x335
- There it is
  - the output is a binary that runs on x335
  - this binary is the desired compiler : cc-x335

Bootstrapping …

- A compiler can be characterized by three languages: the source language (S), the target language (T), and the implementation language (I)

- The three language S, I, and T can be quite different. Such a compiler is called cross-compiler

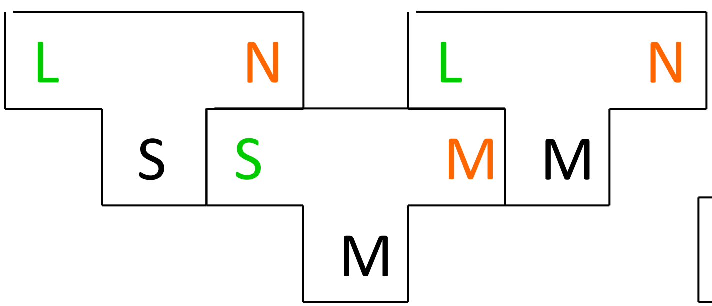
- This is represented by a T-diagram as:

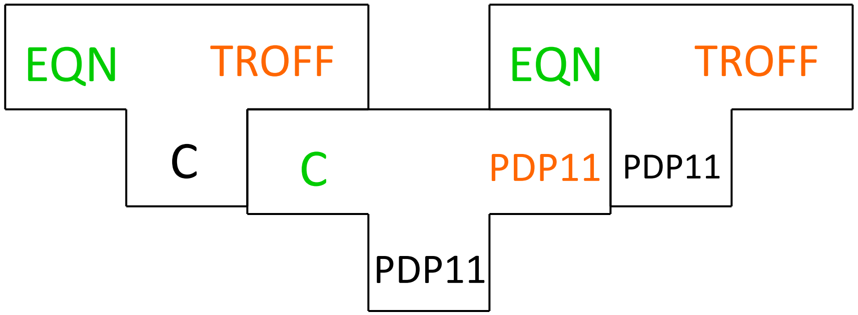


- In textual form this can be represented as

$S_I T$

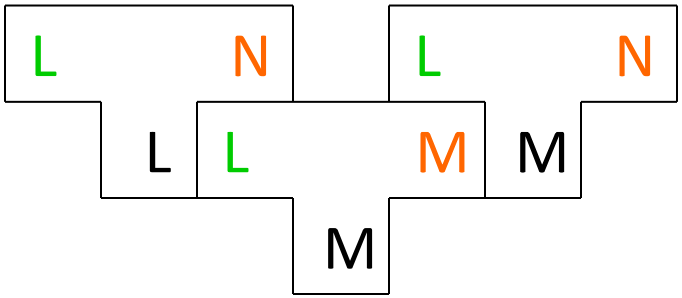
- Write a cross compiler for a language L in implementation language S to generate code for machine N
- Existing compiler for S runs on a different machine M and generates code for M
- When Compiler $L_S N$ is run through $S_M M$ we get compiler $L_M N$



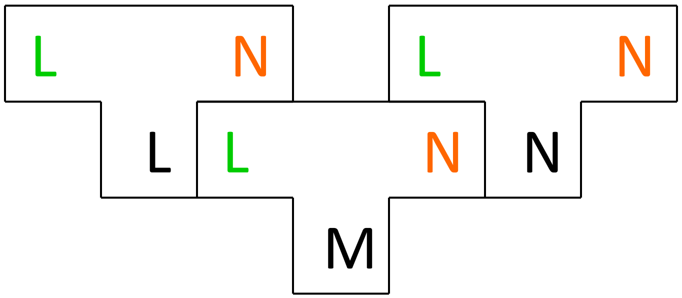


Bootstrapping a Compiler

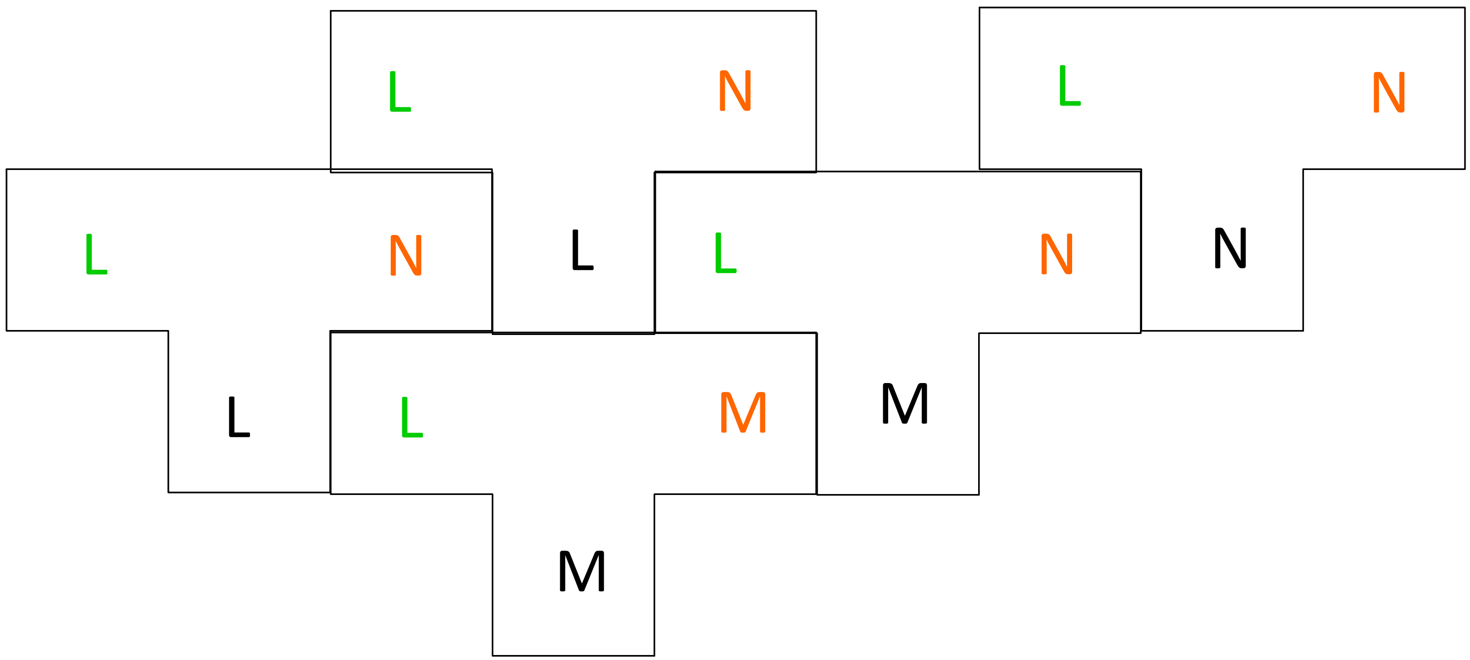
- Suppose $L_N N$ is to be developed on a machine M where $L_M M$ is available



- Compile $L_L N$ second time using the generated compiler



Bootstrapping a Compiler: the Complete picture



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