Acknowledgements

The slides for this lecture are a modified versions of the offering by **Prof. Sanjeev K Aggarwal**

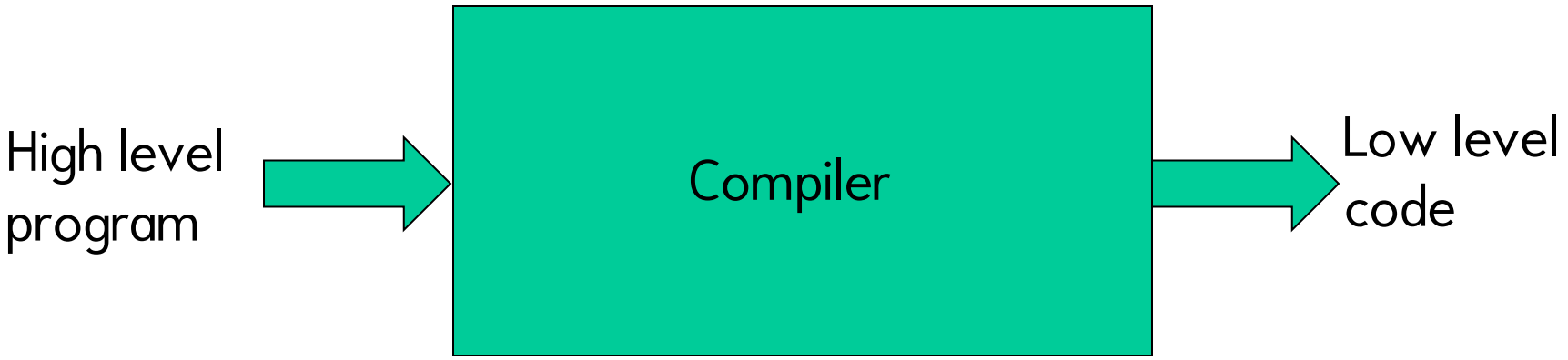
What are Compilers?

Compiler is a program that translates an input program from high level language (source language) to a low level language (target language) *

*For the purpose of this course; in general, a compiler translates from one representation of the program to another

Why?

- 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


High level program
Compiler
Low level code

High Level Language

- Provides "natural" abstractions to express programmer's intent
  - Classes and Functions
  - Unbounded variables
  - Multiple types of branching constructs (if-then, if-then-else, switch statements)
  - Multiple looping constructs (for, while, do-while)
  - Block statements for compound actions
  - List comprehensions and higher order functions

Some HLLs can be "higher" than others if they

Goals of a "good" HLL*

1. Non-ambiguity
2. High level language features (abstractions)
3. Good support of tools (editors, syntax checkers, type checkers, debuggers, memory managers...)
4. Can be compiled down to efficient code
   - (2) and (4) are generally in conflict

*A Crash course in Principles of Programming Languages

Describing a programming language

Syntax + Semantics

Structure of a program

Meaning of a program

Syntax of a language

- Generally described in the BNF (or EBNF syntax)
- Essentially describes a context-free language that all valid program (strings) must adhere to!

- Project check: Check if you can find the BNF description for your language
  - Assignment: Extend the BCF of your language with additional constructs that you want to add

Extended BNF

- Use vertical bars to separate alternatives: eg. 'a | b' stands for "a or b".
- Optional components by square brackets: '[a]' stands for an optional a.
- Repetition represented by curly braces: '{ a }' stands for "epsilon | a | aa | aaa | ..."

(https://www2.cs.arizona.edu/~debray/Teaching/CSc453/DOCS/cminusminusspec.html)

Lexical Rules

letter ::= a | b | … | z | A | … | Z

digit ::= 0 | 1 | … | 9

id ::= letter { letter | digit | _ }

intcon ::= digit { digit }

(https://www2.cs.arizona.edu/~debray/Teaching/CSc453/DOCS/cminusminusspec.html)

Syntax Rules

```
prog  :       { dcl ';'  |  func }
dcl   :       type var_decl { ',' var_decl }
      | [ extern ] type id '(' parm_types ')' { ',' id
'(' parm_types ')' }
 stmt :       if '(' expr ')' stmt [ else stmt ]
      |       while '(' expr ')' stmt
      |       return [ expr ] ';'
      |       assg ';'
      |       id '(' [expr { ',' expr } ] ')' ';'
      |       '{' { stmt } '}'
      |       ';'
```

(https://www2.cs.arizona.edu/~debray/Teaching/CSc453/DOCS/cminusminusspec.html)

Operator Associativities and Precedences

Operator	Associativity
!, – (unary)	right to left
*, /	left to right
+, – (binary)	left to right
<, <=, >, >=	left to right
==, !=	left to right
&&	left to right
||	left to right

(https://www2.cs.arizona.edu/~debray/Teaching/CSc453/DOCS/cminusminusspec.html)

Program Semantics

- Operational semantics
  - How an ideal interpreter should operate!
- Denotational semantics
  - The mathematical meaning of each construct and their compositions!
- Axiomatic semantics
  - The possible states that a program can produce!
- ...

Operational Semantics of Addition

$$\frac{[\Gamma]\ x \rightsquigarrow v_x\ [\Gamma]}{[\Gamma]\ x+y \rightsquigarrow v_x+y\ [\Gamma]}$$

$$\frac{[\Gamma]\ y \rightsquigarrow v_y\ [\Gamma]}{[\Gamma]\ v_x+y \rightsquigarrow v_x+v_y\ [\Gamma]}$$

$$\frac{[\Gamma]\ \neg(Ptr(v_x) \wedge Ptr(v_y))[\Gamma]}{[\Gamma]\ v_x+v_y \rightsquigarrow semadd(v_x, v_y)\ [\Gamma]}$$

$$\frac{[\Gamma]\ lvar(x)\ [\Gamma]}{[\Gamma]\ x:=e\ [\Gamma\{x \mapsto e\}]}$$

No rule for adding pointers

Tasks of a compiler

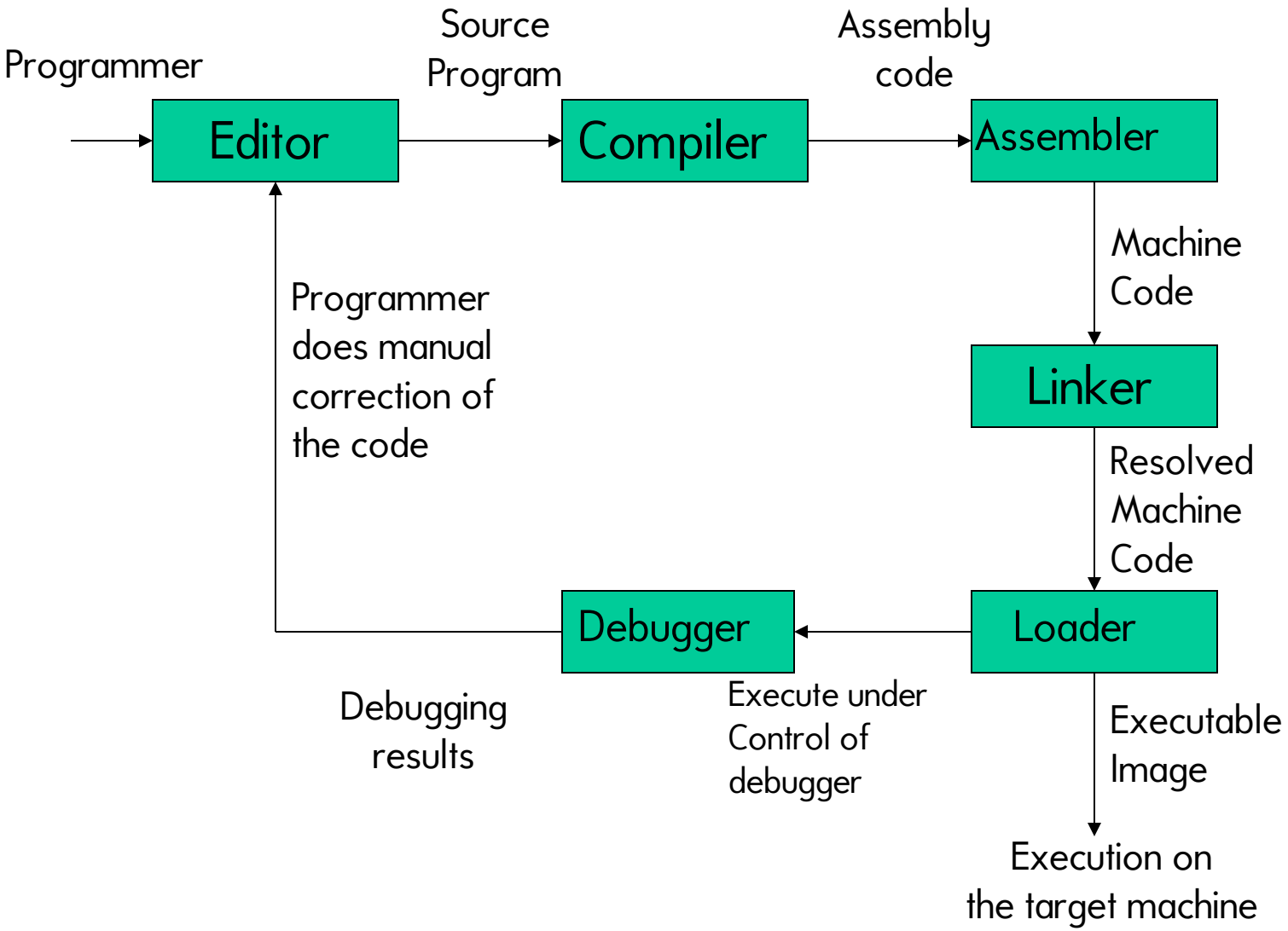
- Check if the program is syntactically correct (Syntax check)
  - It conforms to the provided BNF
- Check if the program is semantically correct (Semantic check)
  - The given program will not get "stuck" or do garbage operations (like adding two addresses)
- Make the program work faster, take less memory, less power... (Optimization)
- Translate the program to low-level language (Translation)

Syntax Check

- Essentially a membership check in a context-free grammar
- How difficult is it? Do you know an algorithm for it?
- CYK algorithm: $O(n^3)$ time and O(???) space
- Typical program sizes:
  - GCC
  - Linux kernel
  - Apache web server
  - Oracle database
- Each line of code has multiple tokens!
- Is it feasible to spend $O(n^3)$ compiling them?

Syntax Check

- To have realistic compilation times, we need an algorithm that works not only in linear time, but only with one scan of the input program
- To have realistic memory footprint, only a small part of the program should have to be buffered at any point in time (overall O(n) space, i.e. size of the program representation AST in memory)
- The compilation process should be modular; it should be possible to compile multiple "modules" separately and then "join" them



Normally end up with error

Semantic Check

- Need to identify programs on which our ideal interpreter would get "stuck"
- For example:
  - adding two addresses does not make sense, so the ideal interpreter should **not** have a rule that adds two addresses
  - If a program forces the interpreter to add two addresses it will get stuck as it has no such rule

Semantic Check: Types to the rescue!

- Type checking rejects all such programs on which the ideal interpreter can get "stuck"
- This problem is undecidable in general: so the type checker may reject programs on which the ideal interpreter will not get stuck (but not vice versa)

$$\frac{\swarrow\ stm\ :\qquad \swarrow\ P\ :}{\swarrow\ \{\ stm\ ;\ P\ \}\ :}\ [\ sequencing\ ]$$

$$\frac{\swarrow\ x\ :\qquad \swarrow\ e\ :}{\swarrow\ \{\ x\ :\ \ e\ \}\ :}\ [\ stm\ \ \{\ x\ :\ \ e\ \}]$$

$$\frac{x\ :}{\swarrow\ x\ :}$$

$$\frac{\swarrow\ e1 : \text{int}\qquad \swarrow\ e\,2 : \text{int}}{\swarrow\ e1\ \ e\,2 : \text{int}}$$

$$\frac{\swarrow\ e1 :\ ptr\qquad \swarrow\ e\,2 :\ ptr}{\swarrow\ e1\ \ e\,2 : error}$$

Expectations from a type system

- **Soundness**: Does the type checker accept any "wrong" program (on which the ideal interpreter can get stuck)?

- **Completeness**: Does the type checker reject any "correct" program?

What is soundness?

(from Wikipedia)

Well-typed programs cannot "go wrong".[Robin Milner]

... type safety is determined by two properties of the semantics of the programming language:

- **(Type-) preservation or subject reduction**

  "Well typedness" ("typability") of programs remains invariant under the transition rules (i.e. evaluation rules or reduction rules) of the language.

- **Progress**

  A well typed (typable) program never gets "stuck", which means the expressions in the program will either be evaluated to a value, or there is a transition rule for it; in other words, the program never gets into an undefined state where no further transitions are possible.

What is soundness?

(from Wikipedia)

These properties do not exist in a vacuum; they are linked to the semantics of the programming language they describe, and there is a large space of varied languages that can fit these criteria, since the notion of "well typed" program is part of the static semantics of the programming language and the notion of "getting stuck" (or "going wrong") is a property of its dynamic semantics.

"*A language is type-safe if the only operations that can be performed on data in the language are those sanctioned by the type of the data.*" [Vijay Saraswat]

Optimizations

- Needs to analyze the program to infer interesting program facts [Control-flow and Dataflow analysis]
  - which variables have no use after a location [variables can be eliminated]
  - which expression computations are redundant [computation can be eliminated]
- Transform the program

Translation to low-level

- Register Allocation
  - map a large number of variables to a small number of variables
  - take care of machine eccentricities: some registers need to be used for specific tasks
- Instruction Scheduling
  - modern superscalar/VLIW processors execute large number of instructions in parallel; how to arrange the instruction so that this parallellism is used to its best
- Instruction Selection
  - what are best instructions for a given job on the given architecture
- Peephole optimizations
  - can we better rewrite small instruction sequences so that they execute faster on the given architecture

Low Level Language

- Essentially about programming the Von Neumann architecture
  - essentially supports load/store, arithmetic and logical actions, and control transfers (jumps/calls)
  - requires explicit memory allocation on bounded number of registers and memory
  - needs to adhere to the eccentricities of the machine architecture
  - some low level languages provide more features (like pseudo instructions) in an attempt be be "higher" on the abstraction ladder

Digression: Projects

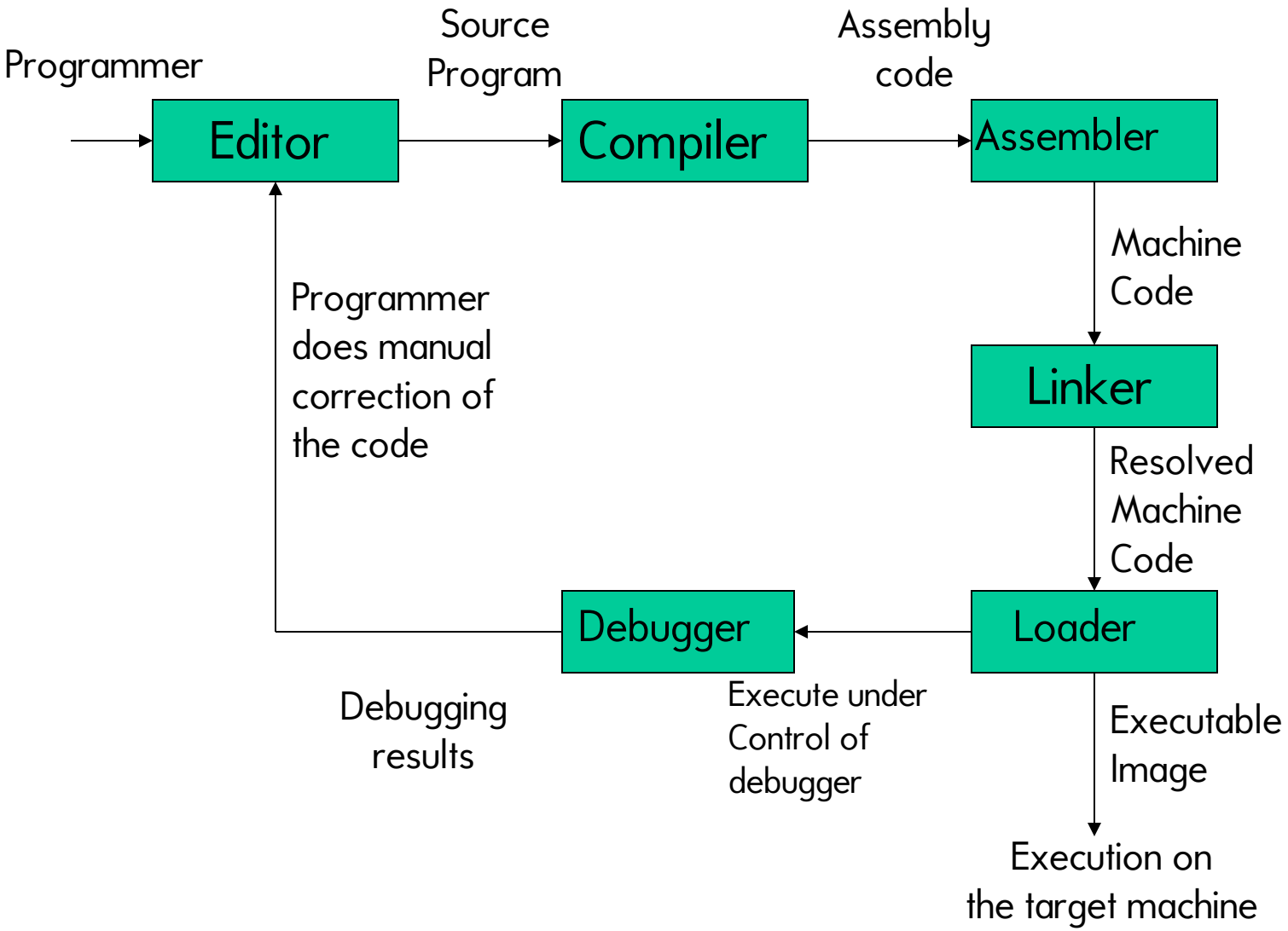
- Your project will be graded on the amount of "abstraction gap" your compiler has bridged; that is
  - how many nice abstractions (language features) your HLL supports --- add new constructs if our base language is poor
  - how challenging was your low-level language
- Your compiler must be able to produce executable code that can be executed on a machine or a simulator
- Languages like HTML are not executable; languages like Cool are not production languages

Goals of translation

- Good performance for the generated code
- Good compile time performance
- Maintainable code
- High level of abstraction within compiler passes
- Correctness ? --- very important issue. Can compilers be proven to be correct? Very tedious!
  - Prove that the translated code is correct (translation validation)
  - Prove that each pass of the compiler is correct and they interface correctly (compiler verification)

The big picture

- Compiler is part of program development environment
- The other typical components of this environment are editor, assembler, linker, loader, debugger, profiler etc.
- The compiler (and all other tools) must support each other for easy program development



Normally end up with error

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 next step to understand the sentence is recognizing words (lexical analysis)
  - English language words can be found in dictionaries
  - Programming languages have a dictionary (keywords etc.) and rules for constructing words (identifiers, numbers etc.)

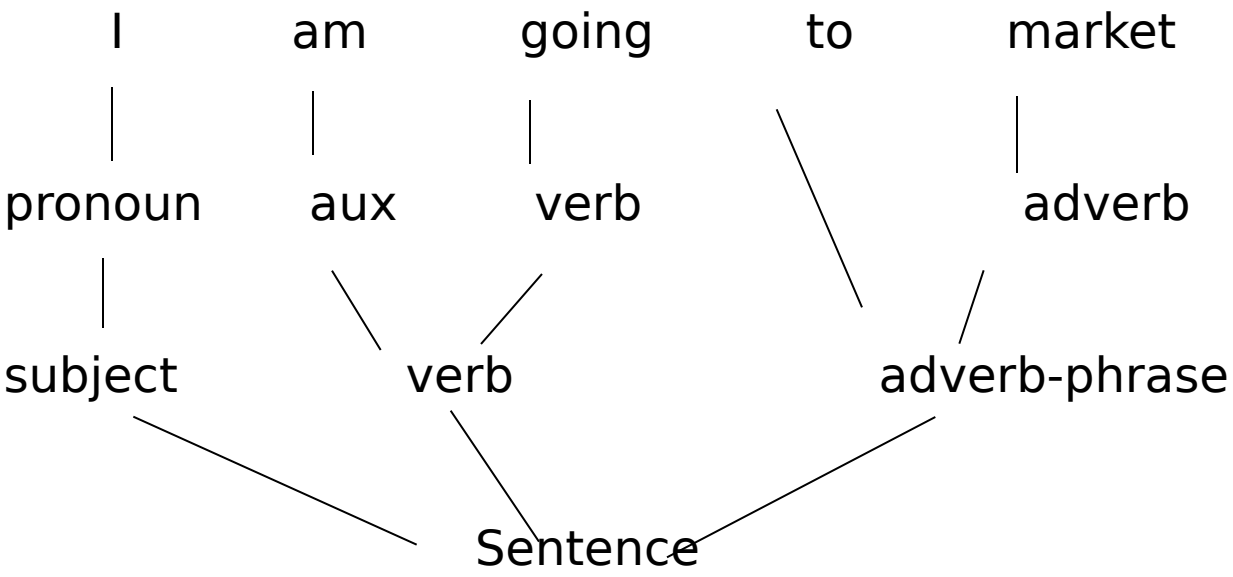
Lexical Analysis

- Recognizing words is not completely trivial. For example:
  ist his ase nte nce?
- Therefore, 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.
- 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

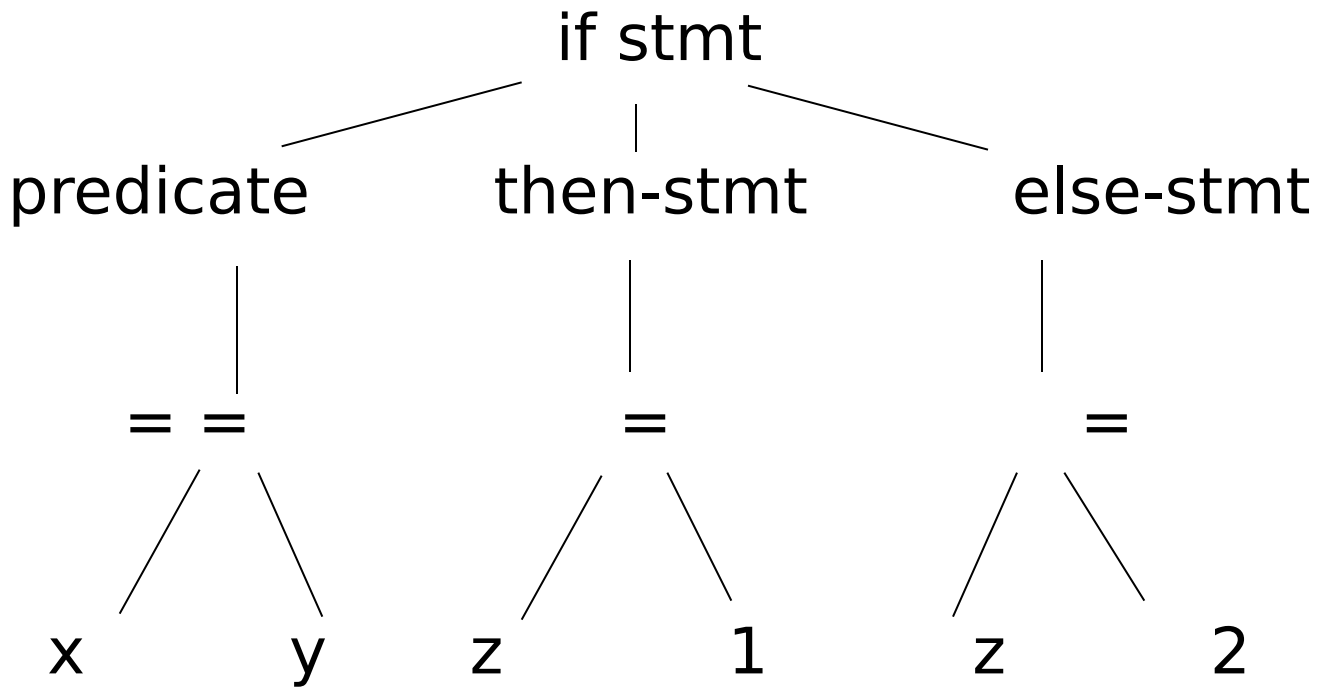
- The process is known as syntax checking or parsing



Parsing

- Parsing a program is exactly the same 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)
- Example:

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

  Amit said Amit left his assignment at home
- How many Amits are there? Which one left the assignment?

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

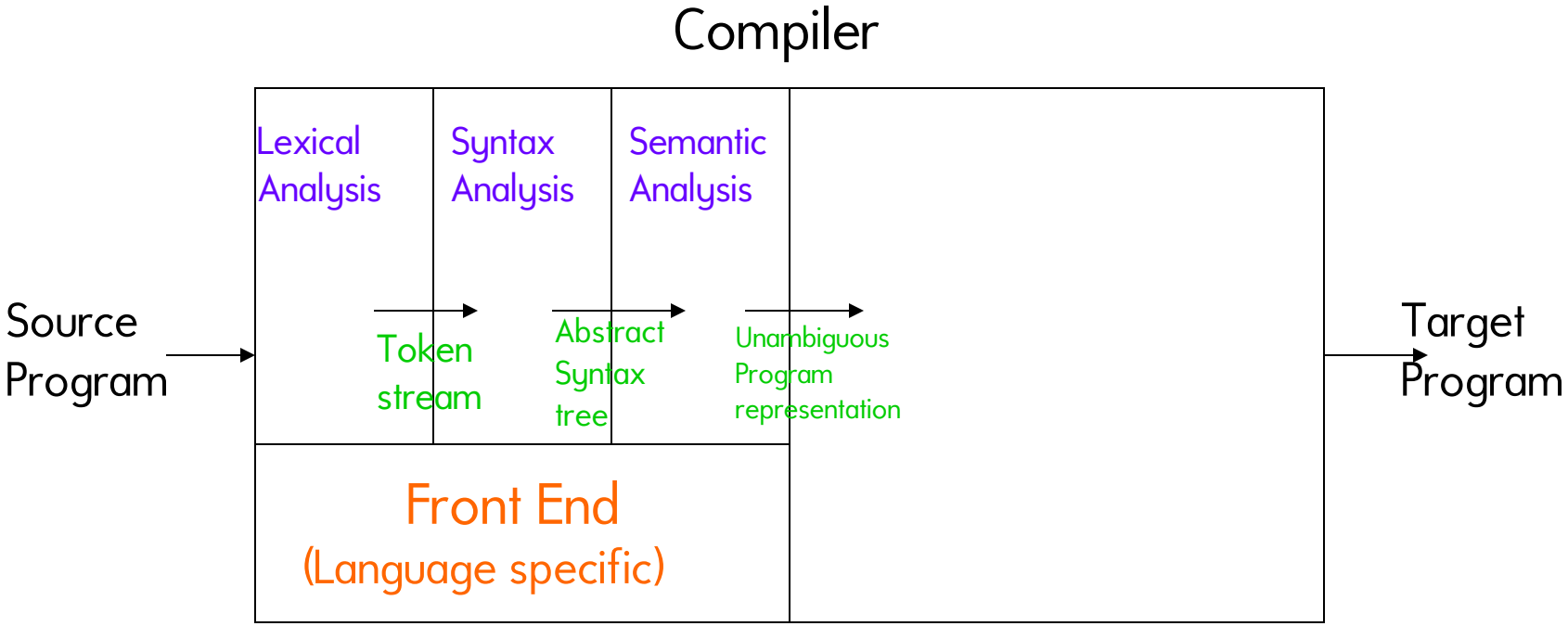
- Type checking

  Amit left her work at home

  Torid/Valdis/Torbjorg left her bag in the car

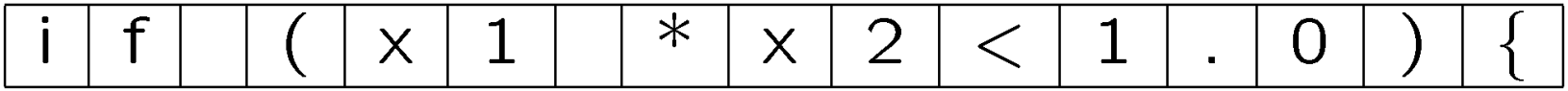
- There is a type mismatch between her and Amit. Presumably Amit is a male. And they are not the same person.

Compiler structure once again

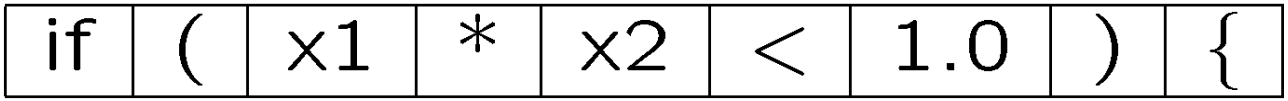


Front End Phases

- Lexical Analysis
  - Recognize tokens and ignore white spaces, comments



Generates token stream

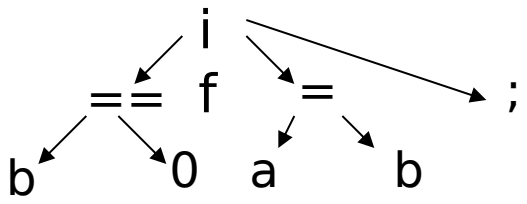


  - Error reporting
  - Model using regular expressions
  - Recognize using Finite State Automata

Syntax Analysis

- Check syntax and construct abstract syntax tree

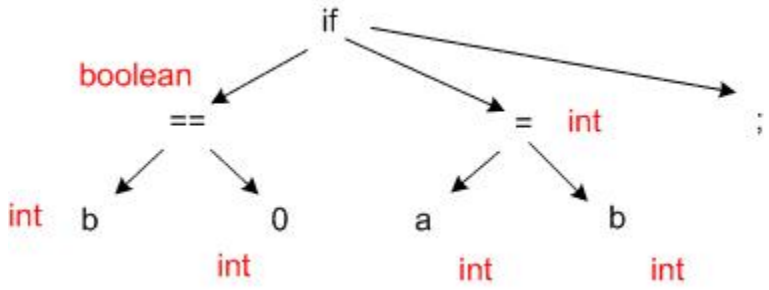
if	(	b	==	0	)	a	=	b	;



- Error reporting and recovery
- Model using context free grammars
- Recognize using Push down automata/Table Driven Parsers

Semantic Analysis

- Check semantics
- Error reporting
- Disambiguate overloaded operators
- Type coercion
- Static checking
  - Type checking
  - Control flow checking
  - Unique ness checking
  - Name checks



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.)
- 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

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

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

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
- Most compilers perform translation between successive intermediate representations
- Intermediate languages are generally ordered in decreasing level of abstraction from highest (source) to lowest (machine)
- However, typically the one after the intermediate code generation is the most important

Intermediate Code Generation

- Abstraction 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

Intermediate 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
- Convert conditionals and iterations to a test/jump or compare instructions

Intermediate Code Generation ...

- Layout parameter passing protocols: locations for parameters, return values, layout of activations frame etc.

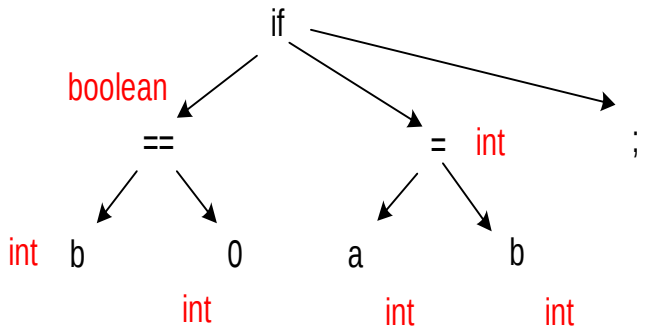
- Interface calls to library, runtime system, operating systems

Post translation Optimizations

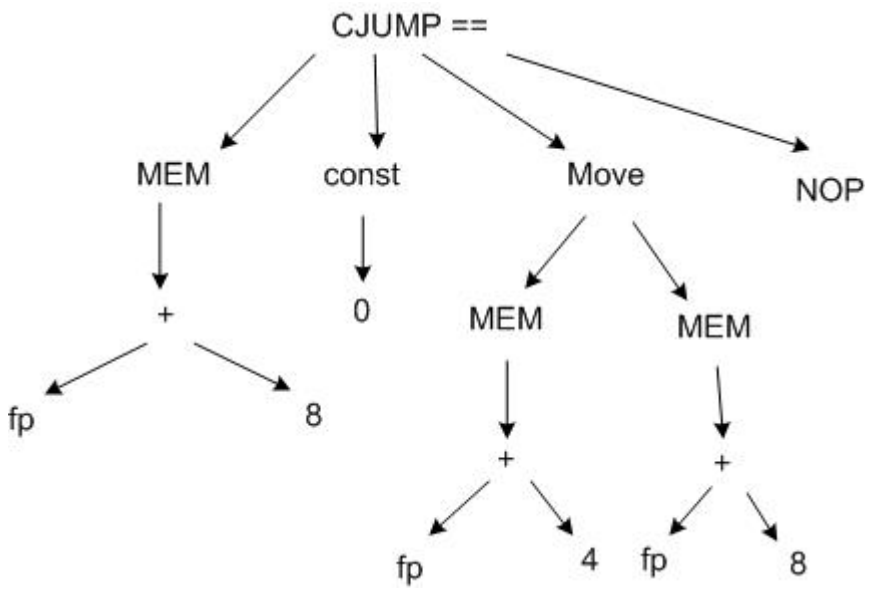
- Algebraic transformations and re-ordering
  - Remove/simplify operations like
    - Multiplication by 1
    - Multiplication by 0
    - Addition with 0
  - Reorder instructions based on
    - Commutative properties of operators
    - For example x+y is same as y+x (always?)

Instruction selection

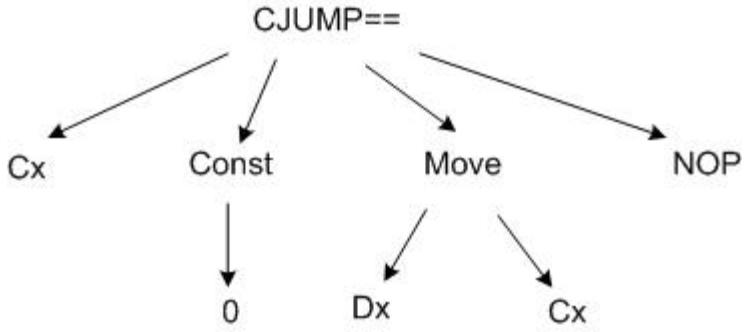
- Addressing mode selection
- Opcode selection
- Peephole optimization



Intermediate code generation



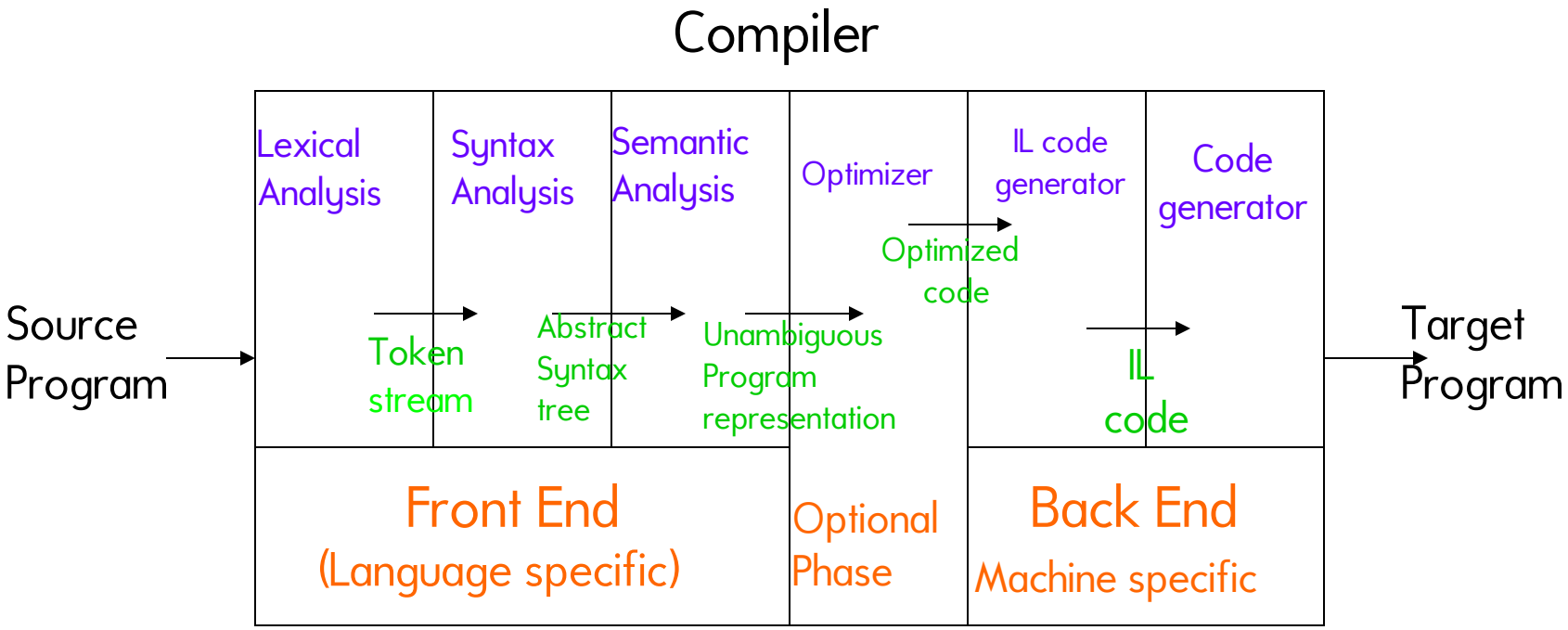
Optimization



Code Generation

CMP Cx, 0
CMOVZ Dx,Cx

Compiler structure

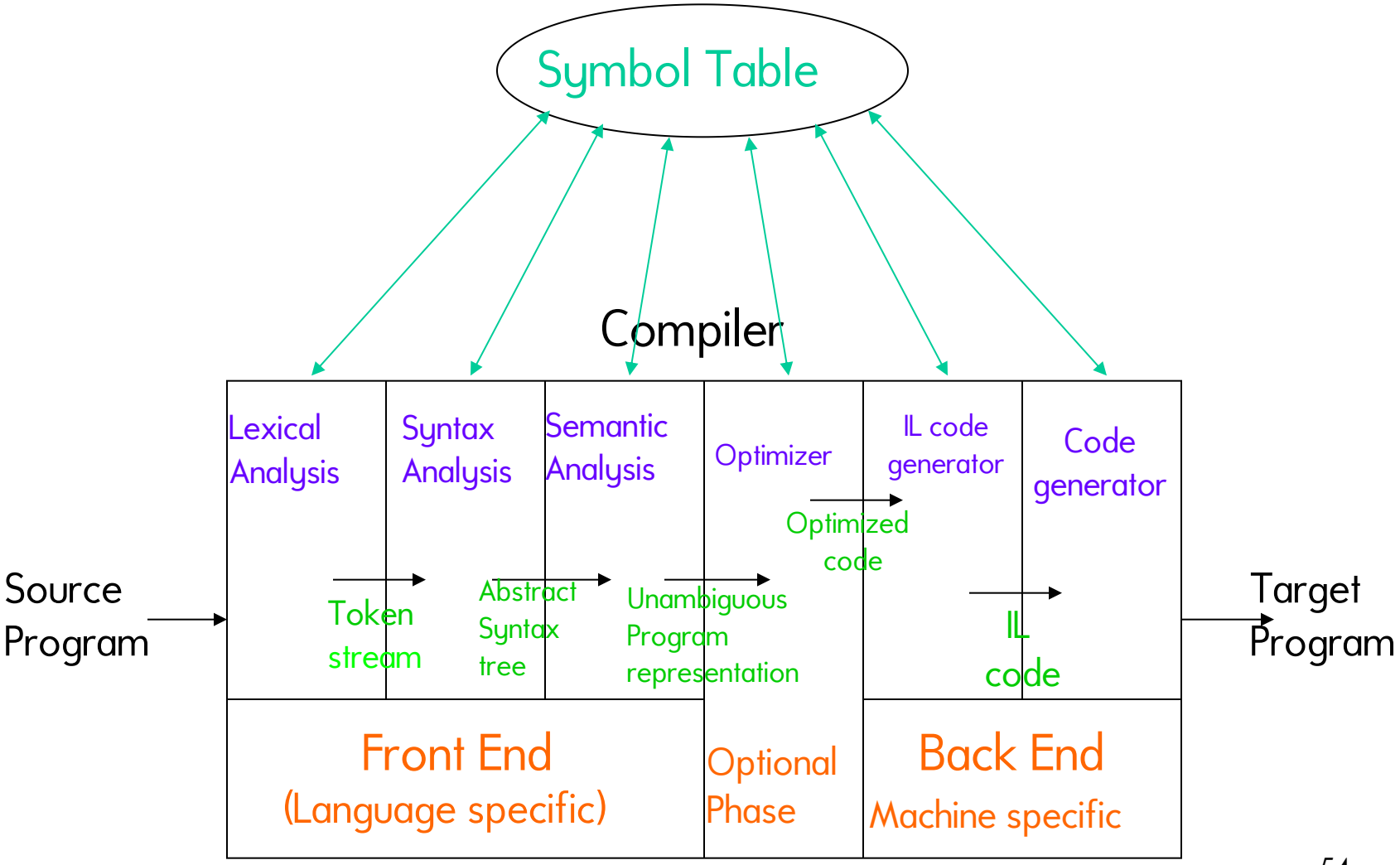


- Information required about the program variables during compilation
  - Class of variable: keyword, identifier etc.
  - Type of variable: integer, float, array, function etc.
  - Amount of storage required
  - Address in the memory
  - Scope information

- 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 ...

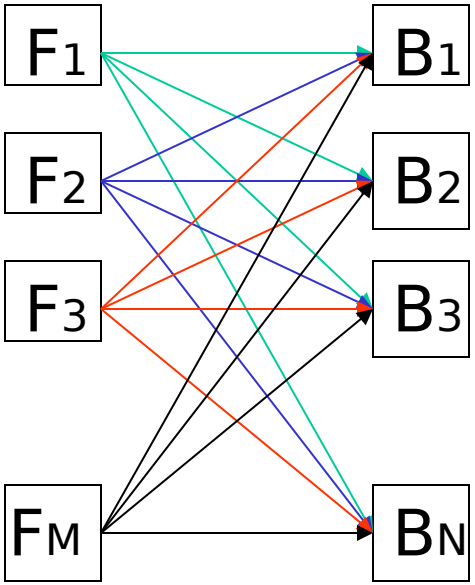
- Compiler is re-targetable
- Source and machine independent code optimization is possible.
- Optimization phase can be inserted after the front and back end phases have been developed and deployed

Issues in Compiler Design

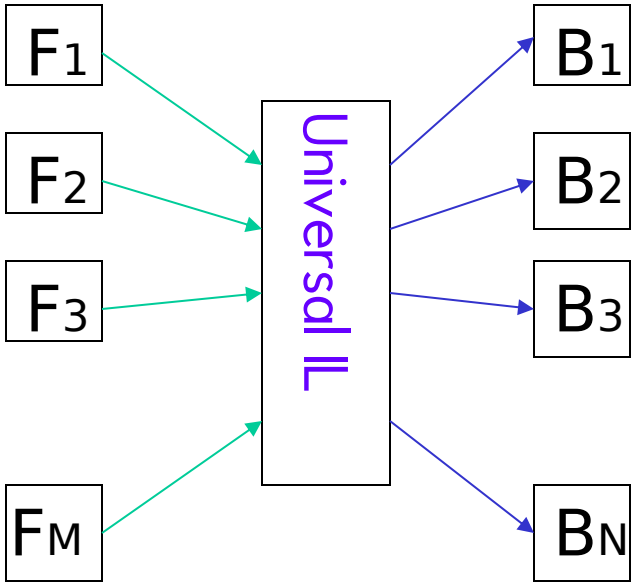
- Compilation appears to be very simple, but there are many pitfalls
- How are erroneous programs handled?
- Design of programming languages and architectures have a big impact on the complexity of the compiler
- M*N vs. M+N problem
  - Compilers are required for all the languages and all the machines
  - 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

Universal Intermediate Language



Requires M*N compilers



Requires M front ends
And N back ends

Universal Intermediate Language

- Universal Computer/Compiler Oriented Language (UNCOL)
  - a vast demand for different compilers, as potentially one would require separate compilers for each combination of source language and target architecture. To counteract the anticipated combinatorial explosion, the idea of a linguistic switchbox materialized in 1958
  - UNCOL (UNiversal COmputer Language) is an intermediate language, which was proposed in 1958 to reduce the developmental effort of compiling many different languages to different architectures

Universal Intermediate Language ...

- The first intermediate language UNCOL (UNiversal Computer Oriented Language) was proposed in 1961 for use in compilers to reduce the development effort of compiling many different languages to many different architectures

- the IR semantics should ideally be independent of both the source and target language (i.e. the target processor) Accordingly, already in the 1950s many researchers tried to define a single universal IR language, traditionally referred to as UNCOL (UNiversal Computer Oriented Language)

  - it is next to 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

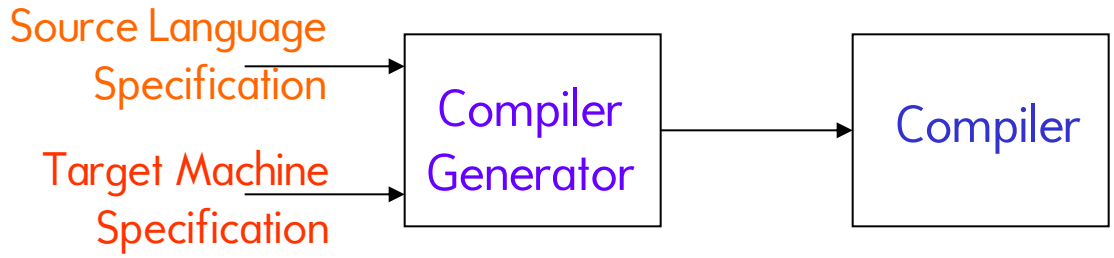
How do we know compilers generate correct code?

- 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?

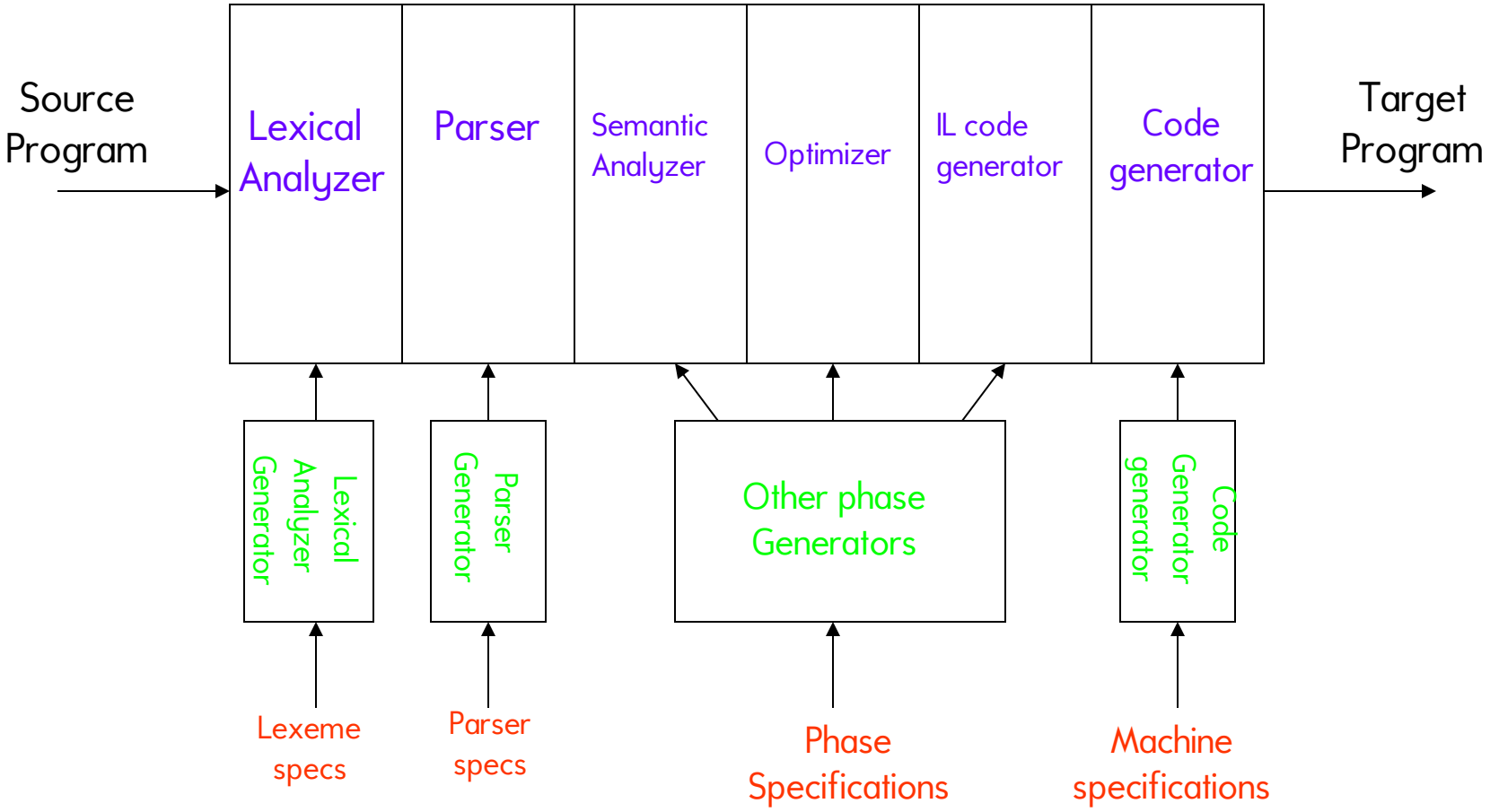
- DO NOT WRITE COMPILERS
- GENERATE compilers
- A compiler generator should be able to “generate” compiler from the source language and target machine specifications



Specifications and Compiler Generator

- How to write specifications of the source language and the target machine?
  - Language is broken into sub components like lexemes, structure, semantics etc.
  - Each component can be specified separately. For example, an identifier may be specified as
    - A string of characters that has at least one alphabet
    - starts with an alphabet followed by alphanumeric
    - letter (letter|digit)*
  - Similarly syntax and semantics can be described
- Can target machine be described using specifications?

Tool based Compiler Development



How to Retarget Compilers?

- Changing specifications of a phase can lead to a new compiler
  - If machine specifications are changed then compiler can generate code for a different machine without changing any other phase
  - If front end specifications are changed then we can get compiler for a new language
- Tool based compiler development cuts down development/maintenance time by almost 30-40%
- Tool development/testing is one time effort
- Compiler performance can be improved by improving a tool and/or specification for a particular phase

Bootstrapping

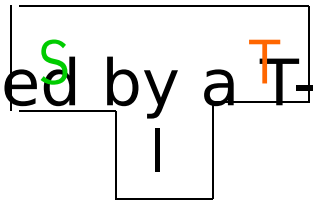
- Compiler is a complex program and should not be written in assembly language
- How to write compiler for a language in the same language (first time!)?
- First time this experiment was done for Lisp
- Initially, Lisp was used as a notation for writing functions.
- Functions were then hand translated 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

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

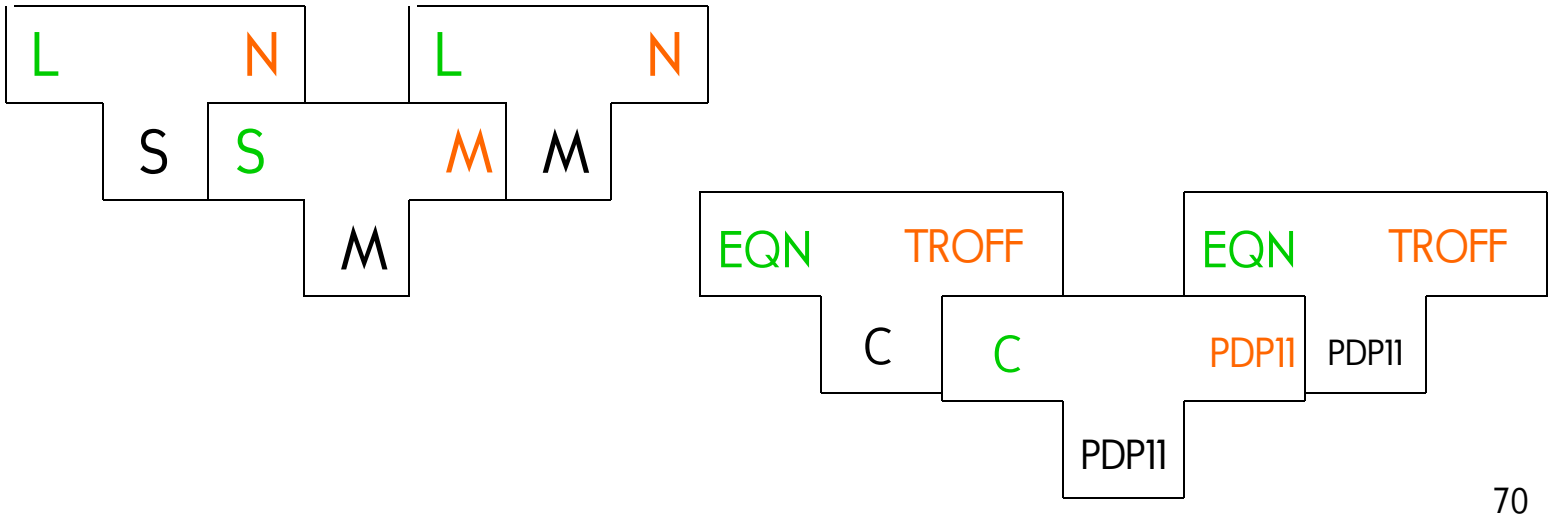
- This is represented by a T-diagram as:



- In textual form this can be represented as

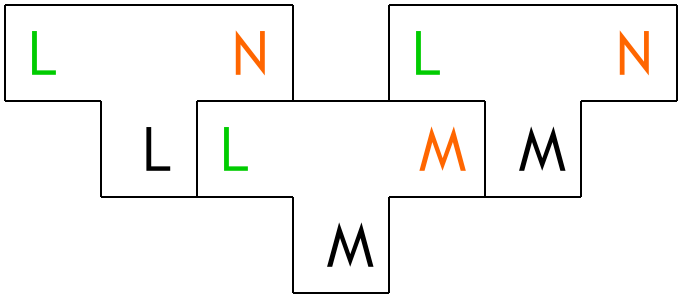
$$S_I T$$

- 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 $L_M N$

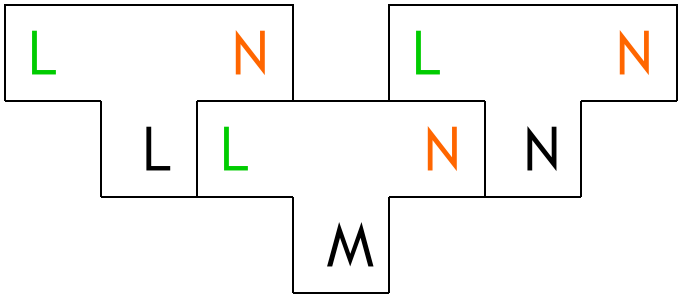


Bootstrapping a Compiler

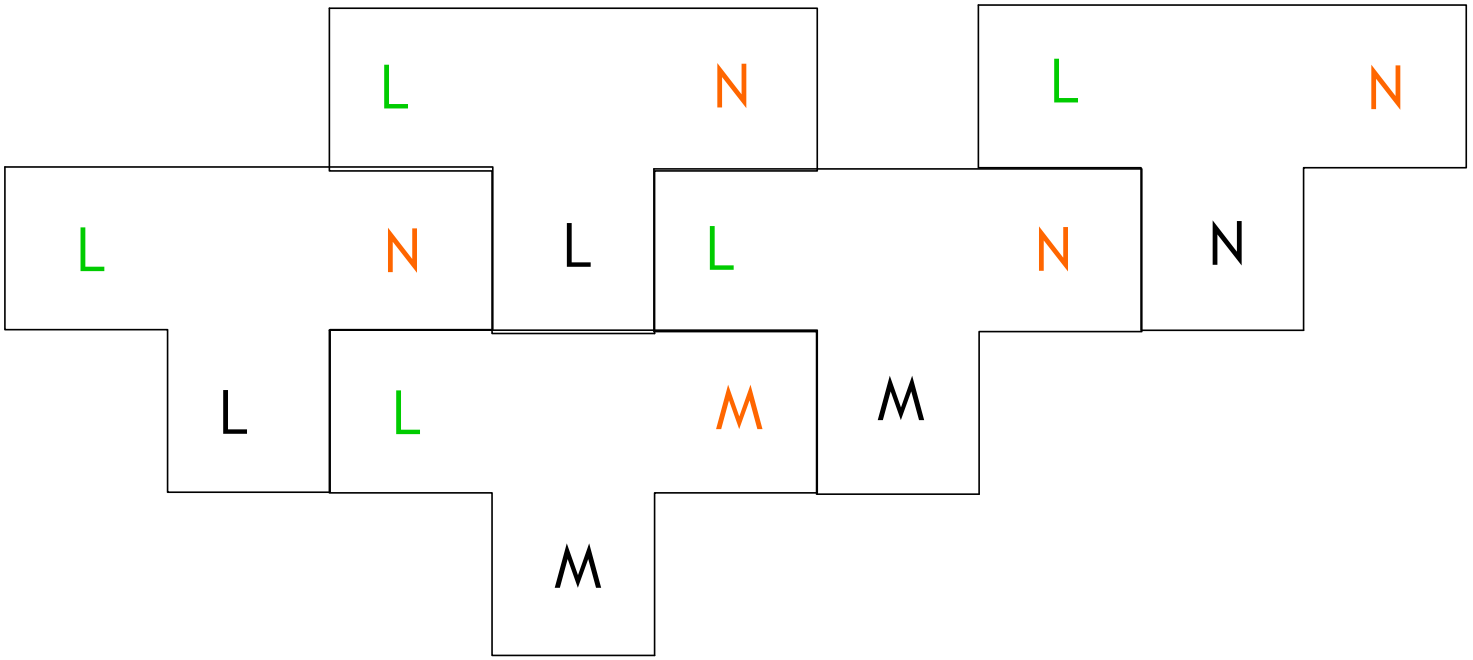
- Suppose $L_L N$ is to be developed on a machine M where $L_M M$ is available



- 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