# Compilers and Programming Languages

An Introduction

# How are Languages Implemented?

- Two major strategies:
  - Interpreters (older)
  - Compilers (newer)
  - A Combination

- Interpreters run programs “as is”
  - Little or no preprocessing
- Compilers do extensive preprocessing

# The Structure of a Compiler

1. Lexical Analysis
2. Parsing
3. Semantic Analysis
4. Optimization
5. Code Generation

The first 3, at least, can be understood by analogy to how humans comprehend a natural language.

# Lexical Analysis

- First step: recognize words.
  - Smallest unit above letters
  - This is a sentence.
- Lexical analyzer divides program text into "words" or "tokens"

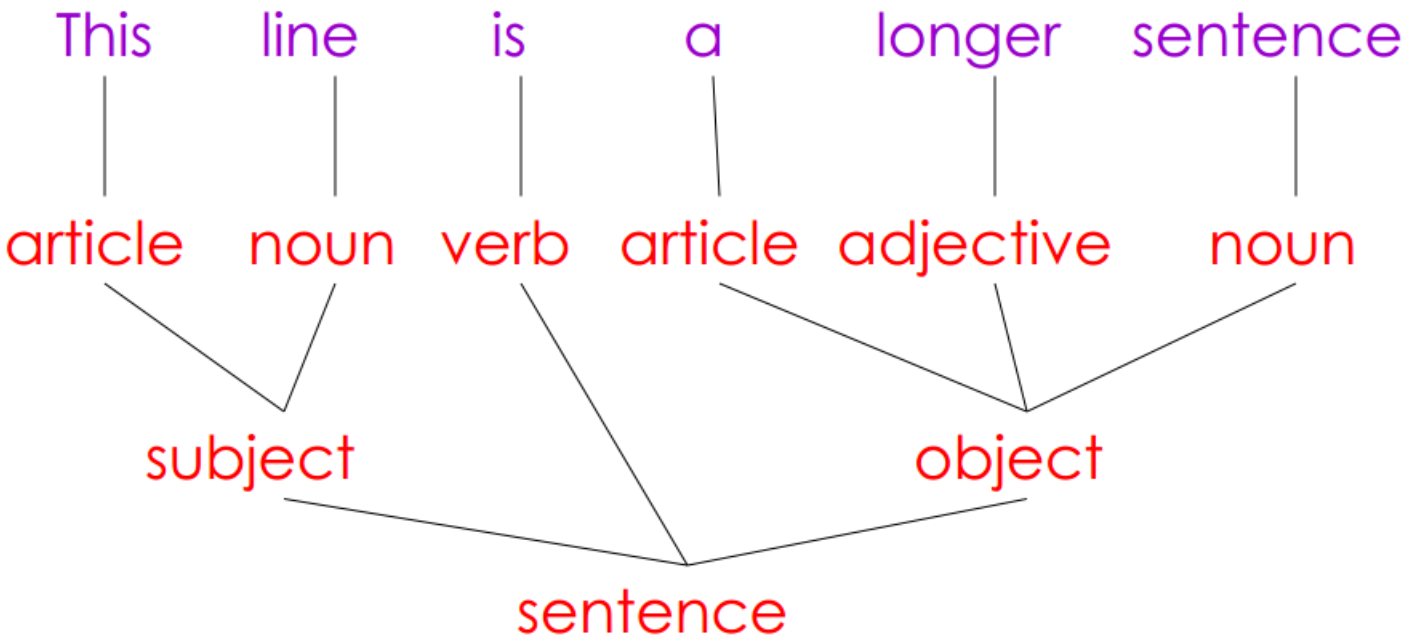
  **If x == y then z = 1; else z = 2;**

# Parsing

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

- Parsing = Diagramming Sentences
  - The diagram is a tree

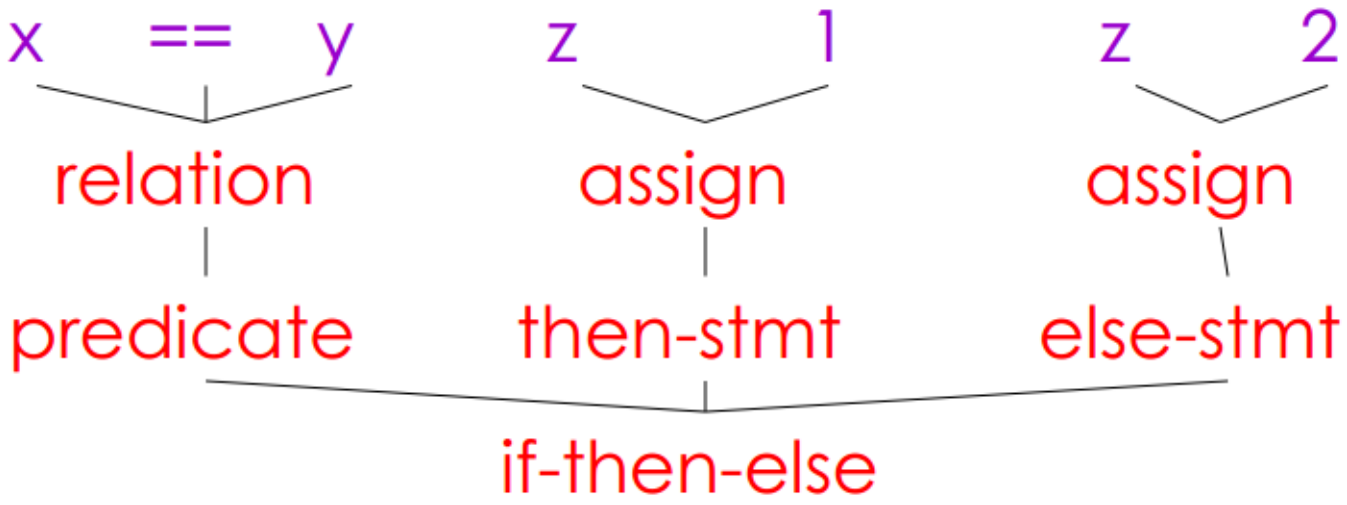
# Diagramming Sentences



# Diagramming Sentences

- Parsing program expressions is the same
- Consider:
  - If x == y then z = 1; else z = 2;

- Diagrammed:



# Semantic Analysis

- Once sentence structure is understood, we can try to understand “meaning”
  - But meaning is too hard for compilers

- Compilers perform limited analysis to catch inconsistencies.

# Semantic Analysis in English

- Example:

  Jack said Jerry left his assignment at home.

  – What does “his” refer to? Jack or Jerry?

- Even worse:

  Jack said Jack left his assignment at home?

  – How many Jacks are there?

  – Which one left the assignment?

# Semantic Analysis in Programming

- Semantic Analysis in Programming

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

# More Semantic Analysis

- Compilers perform many semantic checks besides variable bindings

- Example:

  Jack left her homework at home.

- A “type mismatch” between her and Jack; we know they are different people (Presumably Jack is male).

# Optimization

- No strong counterpart in English, but akin to editing
  - You can express the same idea using fewer words
- Automatically modify programs so that they
  - Run faster
  - Use less memory
  - In general, conserve some resource

# Optimization Example

- X = Y * 0 is the same as X = 0

# Code Generation

- Produces assembly code (usually)
- A translation into another language
  - Analogous to human translation

# Issues

- Compiling is almost this simple, but there are many pitfalls.
- Example: How are erroneous programs handled?
- Language design has big impact on compiler
  - Determines what is easy and hard to compile
  - many trade-offs in language design

# Compilers Today

- The overall structure of almost every compiler adheres to our outline
- The proportions have changed since FORTRAN
  - Early: lexing, parsing most complex, expensive
  - Today: optimization dominates all other phases, lexing and parsing are cheap

# Why So Many Languages?

- Application domains have distinctive and conflicting needs.
- E.g. For scientific applications you need
  - floating point representation
  - Arrays and operations on arrays
  - Parallism
- For business Applications, you need
  - Persistence (you do not want to loose your data)
  - Report generation
  - Data analysis (i.e. you need to be able to ask questions about your data)
  - ➔ SQL

- System Languages e.g.
  - Embedded systems
  - Operating systems
- For such applications, you need
  - Very low level control over resources
  - Real time constraints, you need to be able to reason about time

# Why are there new programming languages?

- Programmer trainer is the most dominant cost factor for a programming language
- ➔ Widely used languages are slow to change (because any change required educating a large number of people)
- ➔ Easy to start a new language (0 users = 0 training cost to begin with)
  - People will convert to the new language if productivity > training cost
- Languages are developed to fill a void as new technology appears e.g. mobile devices, internet, etc
- New languages look a lot like old languages (to reduce the training cost)

# What is a good programming language?

- There is no universally accepted metric for language design.
- i.e.. people tend to disagree on what makes a good programming language
- 4 criteria

# Language Evaluation Criteria

- **Readability**: maintenance is considered to be the major part of the software lifecycle, **and maintainability is directly related to how easily a program may be read**.

- **Writeability**: this is the measure of **how easily a language may be used to create programs**, and is closely related to readability.

- **Reliability**: a program is reliable if it **performs to its specification under all conditions.**

- **Cost:** the ultimate total cost**.**

# Evaluation Criteria: Readability

- Overall simplicity
  - A manageable set of features and constructs
  - Minimal feature multiplicity (small variety)
  - Minimal operator overloading
- Orthogonality
  - A relatively **small set of primitive constructs** can be combined in a relatively small number of ways to get the desired results.
  - The more orthogonal the design, the fewer exceptions.
  - Example In IBM assembly lang there are two instructions for addition
    - A Reg1, memory_cell
    - AR Reg1, Reg2
  - However in VAX's lang there is one that is more general
    - ADDL operand1, operand2
  - VAX's instruction for addition is more orthogonal than the instructions provided by IBM; hence, it is easier for the programmer to remember (and use) than the one provided by IBM.
  - This makes it easier to learn, read and write programs in a programming language.
  - Every possible combination is legal ➔fewer exceptions

# Evaluation Criteria: Readability

- Data types
  - Adequate predefined data types
- Syntax considerations
  - Identifier forms: flexible composition
  - Special words and methods of forming compound statements
  - Form and meaning: self-descriptive constructs, meaningful keywords

# Evaluation Criteria: Writability

- Simplicity and orthogonality
  - Few constructs, a small number of primitives, a small set of rules for combining them
- Support for abstraction
  - The ability to define and use complex structures or operations in ways that **allow details to be ignored**
- Expressivity
  - A set of relatively convenient ways of specifying operations
  - Strength and number of operators and predefined functions

# Evaluation Criteria: Reliability

- Type checking
  - Testing for type errors
- Exception handling
  - Intercept run-time errors and take corrective measures
- Aliasing
  - Presence of two or more distinct referencing methods for the same memory location
- Readability and writability
  - A language that does not support “natural” ways of expressing an algorithm will require the use of “unnatural” approaches, and hence reduced reliability

# Evaluation Criteria: Cost

- Training programmers to use the language
- Writing programs (closeness to particular applications)
- Compiling programs
- Executing programs
- Language implementation system: availability of free compilers
- Reliability: poor reliability leads to high costs
- Maintaining programs

# Language Design Trade-Offs

- Reliability vs. cost of execution
  - Example: Java demands all references to array elements be checked for proper indexing, which leads to increased execution costs
- Readability vs. writability

  Example: APL provides many powerful operators (and a large number of new symbols), allowing complex computations to be written in a compact program but at the cost of poor readability
- Writability (flexibility) vs. reliability
  - Example: C++ pointers are powerful and very flexible but are unreliable

# Evaluation Criteria: Others

- Portability
  - The ease with which programs can be moved from one implementation to another
- Generality
  - The applicability to a wide range of applications
- Well-definedness
  - The completeness and precision of the language's official definition

# Assessment characteristics

| | | Criteria | |
|---|---|---|---|
| Characteristic | Readability | Writeability | Reliability |
| Simplicity/orthogonality | • | • | • |
| Control structures | • | • | • |
| Data types and structures | • | • | • |
| Syntax design | • | • | • |
| Support for abstraction | | • | • |
| Expressivity | | • | • |
| Type checking | | | • |
| Exception handling | | | • |
| Restricted aliasing | | | • |

# Influences on Language Design

- Computer Architecture
  - Languages are developed around the prevalent computer architecture, known as the *von Neumann* architecture
- Programming Methodologies
  - New software development methodologies (e.g., object-oriented software development) led to new programming paradigms and by extension, new programming languages

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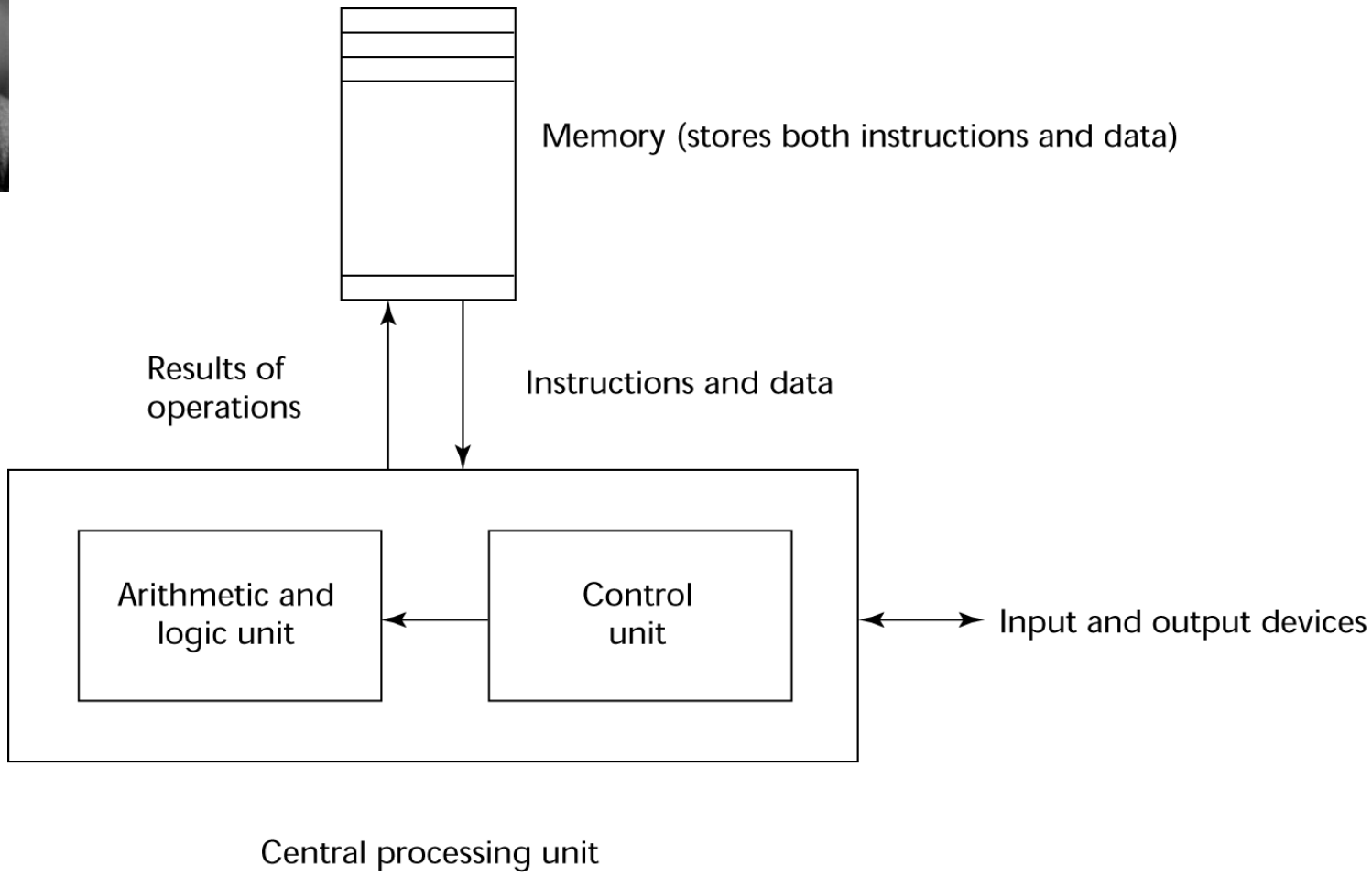
# Computer Architecture Influence

- Well-known computer architecture: Von Neumann
- Imperative languages, most dominant, because of von Neumann computers
  - Data and programs stored in memory
  - Memory is separate from CPU
  - Instructions and data are piped from memory to CPU
  - Basis for imperative languages
    - Variables model memory cells
    - Assignment statements model piping
    - Iteration is efficient

# The von Neumann Architecture



# The von Neumann Architecture

- Fetch-execute-cycle (on a von Neumann architecture computer)

```
initialize the program counter
repeat forever
  fetch the instruction pointed by the counter
  increment the counter
  decode the instruction
  execute the instruction
end repeat
```

# Programming Methodologies Influences

- 1950s and early 1960s: Simple applications; worry about machine efficiency
- Late 1960s: People efficiency became important; readability, better control structures
  - structured programming
  - top-down design and step-wise refinement
- Late 1970s: Process-oriented to data-oriented
  - data abstraction
- Middle 1980s: Object-oriented programming
  - Data abstraction + inheritance + polymorphism

# Language Categories

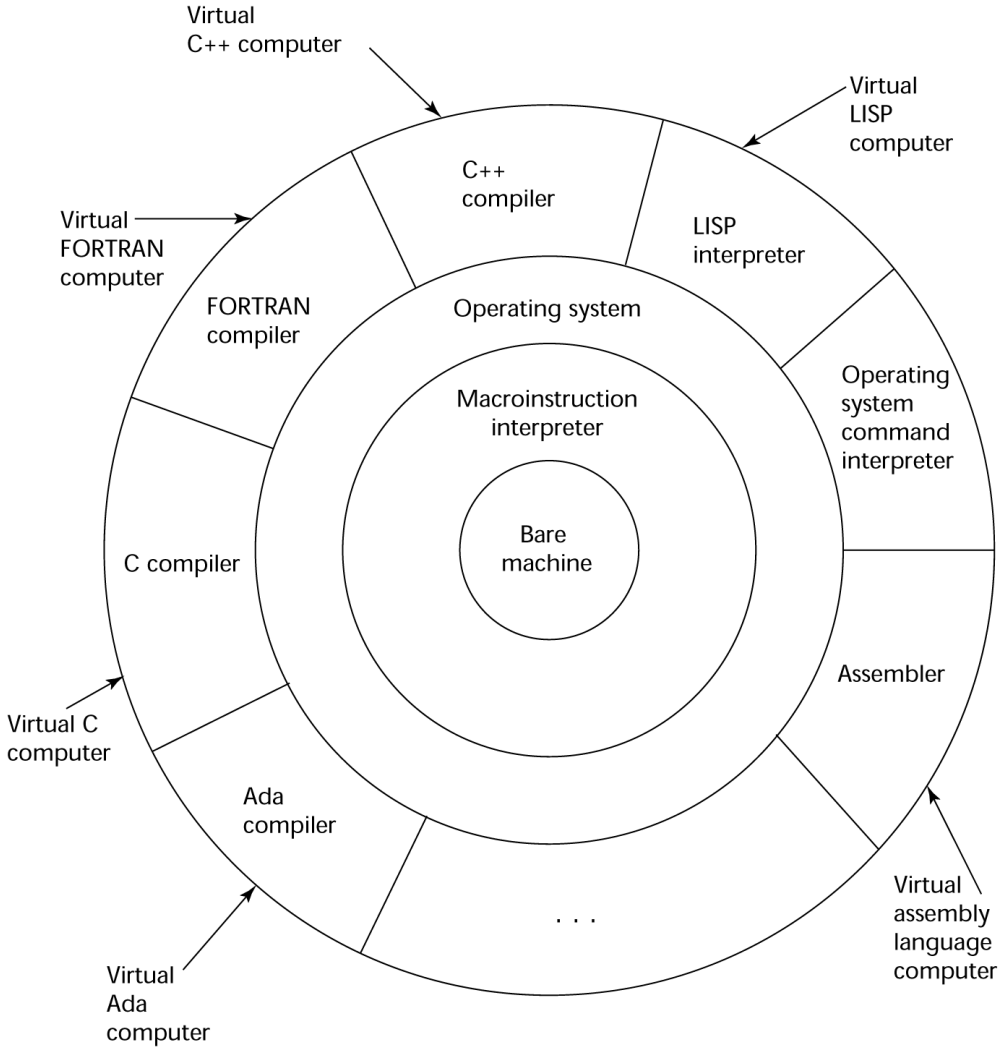
- Imperative
  - Central features are variables, assignment statements, and iteration
  - Include languages that support object-oriented programming
  - Include scripting languages
  - Include the visual languages
  - Examples: C, Java, Perl, JavaScript, Visual BASIC .NET, C++
- Functional
  - Main means of making computations is by applying functions to given parameters
  - Examples: LISP, Scheme
- Logic
  - Rule-based (rules are specified in no particular order)
  - Example: Prolog
- Markup/programming hybrid
  - Markup languages extended to support some programming
  - Examples: JSTL, XSLT (a language for transforming XML documents into other XML documents, or other objects such as HTML for web pages, plain text or into XSL Formatting Objects which can then be converted to PDF, PostScript and PNG.[2]

# Implementation Methods

- Compilation
  - Programs are translated into machine language
- Pure Interpretation
  - Programs are interpreted by another program known as an interpreter
- Hybrid Implementation Systems
  - A compromise between compilers and pure interpreters

# Layered View of Computer

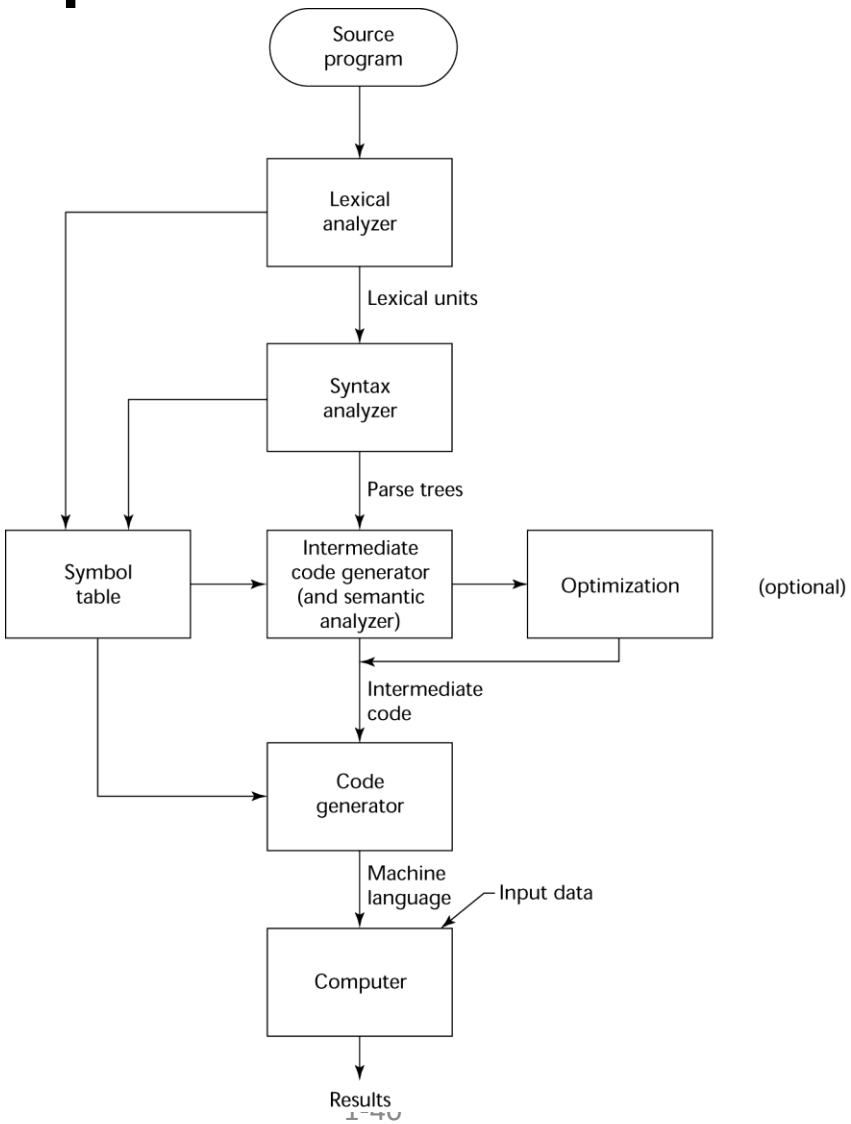
The operating system and language implementation are layered over machine interface of a computer



# Compilation

- Translate high-level program (source language) into machine code (machine language)
- Slow translation, fast execution
- Compilation process has several phases:
  - lexical analysis: converts characters in the source program into lexical units
  - syntax analysis: transforms lexical units into *parse trees* which represent the syntactic structure of program
  - Semantics analysis: generate intermediate code
  - code generation: machine code is generated

# The Compilation Process



# Additional Compilation Terminologies

- **Load module** (executable image): the user and system code together
- **Linking and loading**: the process of collecting system program units and linking them to a user program

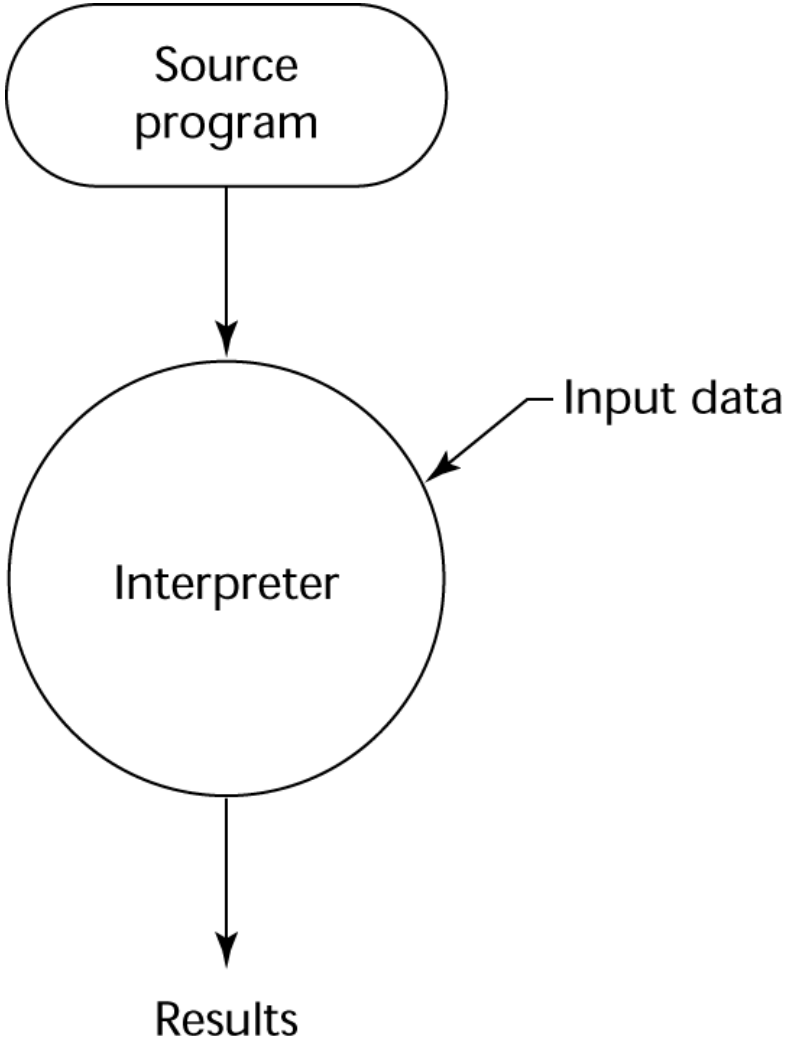
# Von Neumann Bottleneck

- Connection speed between a computer's memory and its processor determines the speed of a computer
- Program **instructions often can be executed much faster than the speed of the connection**; the connection speed thus results in a *bottleneck*
- Known as the *von Neumann bottleneck*; it is the **primary limiting factor** in the speed of computers

# Pure Interpretation

- No translation
- Easier implementation of programs (run-time errors can easily and immediately be displayed)
- Slower execution (10 to 100 times slower than compiled programs)
- Often requires more space
- Now rare for traditional high-level languages
- Significant comeback with some Web scripting languages (e.g., JavaScript, PHP)

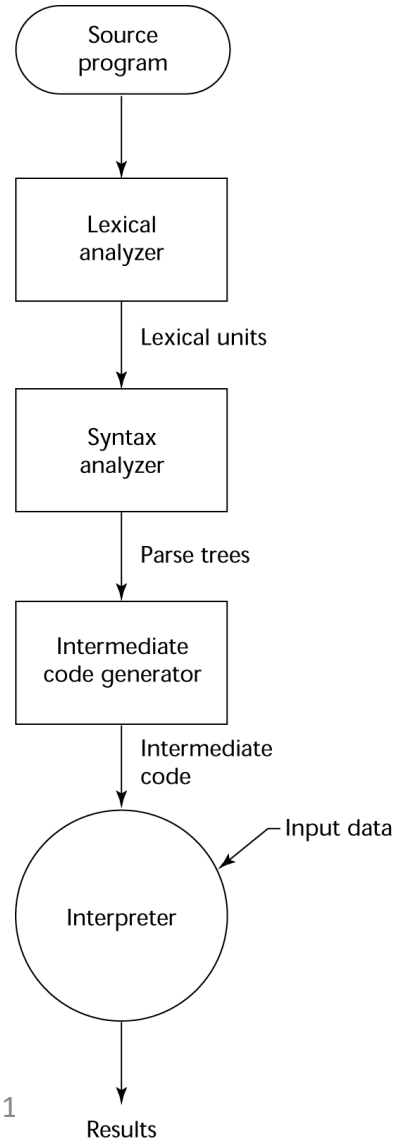
# Pure Interpretation Process



# Hybrid Implementation Systems

- **A compromise** between compilers and pure interpreters
- A high-level language program is translated to an **intermediate language** that allows easy interpretation
- **Faster than pure interpretation**
- Examples
  - Perl programs are partially compiled to detect errors before interpretation
  - Initial implementations of Java were hybrid; the intermediate form, *byte code*, provides portability to any machine that has a byte code interpreter and a run-time system (together, these are called *Java Virtual Machine*)

# Hybrid Implementation Process



# Just-in-Time Implementation Systems

- Initially translate programs to an **intermediate language**
- Then **compile the intermediate language of the subprograms** into machine code when they are called
- **Machine code version is kept for subsequent calls**
- JIT systems are widely used **for Java programs**
- **.NET languages** are implemented with a JIT system

# Why Study Languages and Compilers ?

1. **Increase capacity of expression**
2. Improve **understanding of program behavior**
3. Increase ability to **learn new languages**
4. Learn to **build a large and reliable** system
5. See many **basic CS concepts** a