CSE3302 Programming Languages
CSE5307 Programming Language Concepts

Kenny Q. Zhu

Dept. of Computer Science & Engineering

University of Texas at Arlington

Kenny Q. Zhu

Research Interests:

Artificial Intelligence
- Natural language understanding
- Natural language generation
- Knowledge representation/discovery

Programming Languages
- Domain specific languages
- Data Processing
- Concurrency

Recent Publications:

AAAI, IJCAI, ACL, EMNLP,…

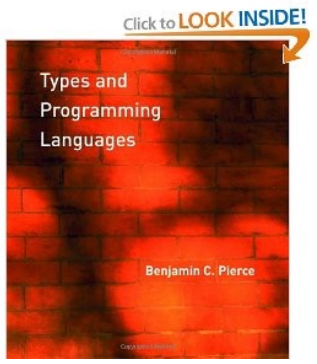
Degrees:	*National University of Singapore (NUS)*
Postdoc:	*Princeton University*
Experiences:	*Microsoft Redmond*
	Microsoft Research Asia
	Shanghai Jiao Tong University
	Joined *UT Arlington* in fall 2023

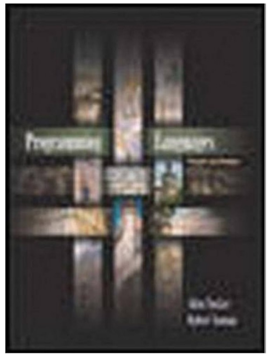
Administrative Info (I)

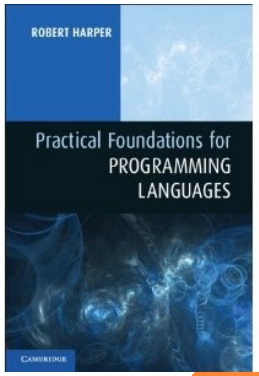
- Hybrid course (both undergrad & graduate)
- Lecturer:
  - Kenny Zhu, ERB-535, kenny.zhu@uta.edu
  - Office hours: Wed 4-5 PM, also by email appointments
- Teaching Assistant:
  - Sinong Wang, ERB-316, sxw7663@mavs.uta.edu
  - Office hours: Tuesday 2-4 PM
- Course Web Page (definitive source!): https://kenzhu2000.github.io/cse3302/
- Materials may be optionally uploaded to Canvas as well

Administrative Info (II)

- Format:
  - 1.5 hour lecture on Monday
  - 0.5 hour lecture and 1 hour tutorial discussion on Wednesday
  - Tutorials are led by TA
- Reference Texts:
  - **Types and Programming Languages** by Benjamin C. Pierce, The MIT Press.
  - **Programming Languages – Principles and Paradigms**, 2nd Edition, by Tucker & Noonan, McGraw Hill
  - **Practical Foundations for Programming Languages** by Robert Harper, Cambridge University Press
- Lecture materials on course web page







Administrative Info (III)

- 3-credit course (16 weeks)
- Modes of Assessment:

In-class quizzes:	10%
Tutorial discussion participation:	5%
Assignments:	30%
Programming Project:	25%
Final Exam:	30%

- Quizzes
  - Given out at random times
  - Usually on-screen **multiple choice questions or short answer questions**
  - Bring piece of paper and a pen every time!
  - Submit answer after class (immediately) to TA or me
- Tutorials
  - Discuss assignment questions, issues in project, other Q&A
  - You will be asked to present your answers
  - Volunteer to win tutorial participation points

Administrative Info (IV)

- Assignments
  - Released (usually) every Wednesday)
  - Due date printed on assignment sheet
  - Submit solutions including code and data on Canvas
  - Late submission: -30% of full score for each additional day
  - Assignment solutions to be discussed at the tutorial on the following week (led by TA)

- Programming Project
  - Individual project
  - Implement an interpreter for a simple language called simPL
  - Be able to run test programs and produce correct evaluation results
  - Produce a report + code + results: due end of semester

Introduction

Why Do we Learn Programming Languages?

Two Misconceptions about This Course

- “This course about programming.” ✗
- “This is another compiler course.” ✗

Programming is about mastering the use of a language.
Compiler is about implementing a system that can parse a program in a high-level language into an intermediate form and then generate machine code. The focus is practical issues such as time and space complexity, code redundancy, and optimization.

What This Course is About

- *Theoretical aspects* of the design and implementation of all programming languages.

- The commonalities and differences between various *paradigms* and *languages*.

- So you can:
  - Pick the right language for a project;
  - Design your own language (features);
  - Do programming language research.

Outline of Today's Lecture

- Principles
- Paradigms
- Special Topics
- A Brief History
- On Language Design
- Compilers and Virtual Machines
- Roadmap of This Course

The Factorial Program

- n! = 1 * 2 * … * n
- Or $n! = \prod_{i=1}^{n} i$

Two different mathematical languages

In computing, there are many more ways to do this …

The Factorial Program

C:

```
int factorial(int n) {
  int x = 1;
  while (n>1) {
            x = x * n;
            n = n -1;
  }
  return x;
}
```

Java:

```
class Factorial
{
   public static int fact(int n) {
      int c, fact = 1;
      if ( n < 0 )
       System.out.println(“Wrong Input!");
      else {
         for ( c = 1 ; c <= n ; c++ )
            fact = fact*c;
         return fact;
      }
   }
}
```

The Factorial Program

Scheme:

```
(define (factorial n)
    (if (< n 1) 1
    (* n (factorial (- n 1)))
))
```

Prolog:

```
factorial(0, 1).
factorial(N, Result) :-
            N > 0, M is N - 1,
            factorial(M, SubRes),
Result is N * SubRes.
```

Principles

Programming languages have four properties:

- Syntax
- Names
- Types
- Semantics

For any language:

- Its designers must define these properties
- Its programmers must master these properties

SYNTAX

The *syntax* of a programming language is a precise description of all its grammatically correct programs.

When studying syntax, we ask questions like:

- What is the basic vocabulary?
- What is the grammar for the language?
- How are syntax errors detected?

Syntax

```
class Factorial
{
  public static int fact(int n) {
    int c, fact = 1;
    if ( n < 0 )
      System.out.println(“Wrong Input!");
    else {
      for ( c = 1 ; c <= n ; c++ )
        fact = fact*c;
      return fact;
    }
  }
}
```

Vocabulary of Tokens:

- Literal (constant)
- Identifier
- Operator
- Separator(punctuation)
- **Reserved keyword**

Names

Various kinds of entities in a program have names: *variables, types, functions, parameters, classes, objects, …*

An entity is bound to a name (identifier) within the context of:

- Scope (static/dynamic)
- Visibility (part of scope that is visible)
- Lifetime (dynamic and runtime)
- Type

NAMES

```
class Factorial
{
   public static int fact(int n) {
      int c, fact = 1;
      if ( n < 0 )
         System.out.println("Wrong Input!");
      else {
         for ( c = 1 ; c <= n ; c++ )
            fact = fact*c;
         return fact;
      }
   }
}
```

Types

A ***type*** is a collection of values and a collection of legal operations on those values.

- Simple types
  - numbers, characters, booleans, …
- Structured types
  - Strings, lists, trees, hash tables, …
- Function types
  - Simple operations like +, -, *, /
  - More complex/general function: int → int
- Generic types (polymorphism): α
- A language's *type system* can help:
  - Determine legal operations
  - Detect type errors

Types

int→int

```
class Factorial
{
  public static int fact(int n) {
    int c, fact = 1;
    if ( n < 0 )
     System.out.println(“Wrong Input!");
    else {
      for ( c = 1 ; c <= n ; c++ )
        fact = fact*c;
      return fact;
    }
  }
}
```

SEMANTICS

The meaning of a program is called its *semantics*.

In studying semantics, we ask questions like:

- When a program is running, what happens to the values of the variables? (operational semantics)
- What does each expression/statement mean? (static semantics)
- What underlying model governs run-time behavior, such as function call? (dynamic semantics)
- How are objects allocated to memory at run-time?

SEMANTICS

```
class Factorial
{
  public static int fact(int n) {
    int c, fact = 1;
    if ( n < 0 )
     System.out.println("Wrong Input!");
    else {
      for ( c = 1 ; c <= n ; c++ )
        fact = fact*c;
      return fact;
    }
  }
```

Static Semantics

Operational Semantics

value

reference

Paradigms

- A programming *paradigm* is a pattern of problem-solving thought that underlies a particular *genre* of programs and languages.

a category of artistic composition, as in music or literature, characterized by similarities in form, style, or subject matter.

- There are four main programming paradigms:
  - Imperative
  - Object-oriented
  - Functional
  - Logic (declarative)

Imperative Paradigm

- Follows the classic von Neumann-Eckert model:
  - Program and data are indistinguishable in memory
  - Program = a sequence of commands
  - State = values of all variables when program runs
  - Large programs use procedural abstraction
- Example imperative languages:
  - Cobol, Fortran, C, Ada, Perl, …

The von Neumann-Eckert Model

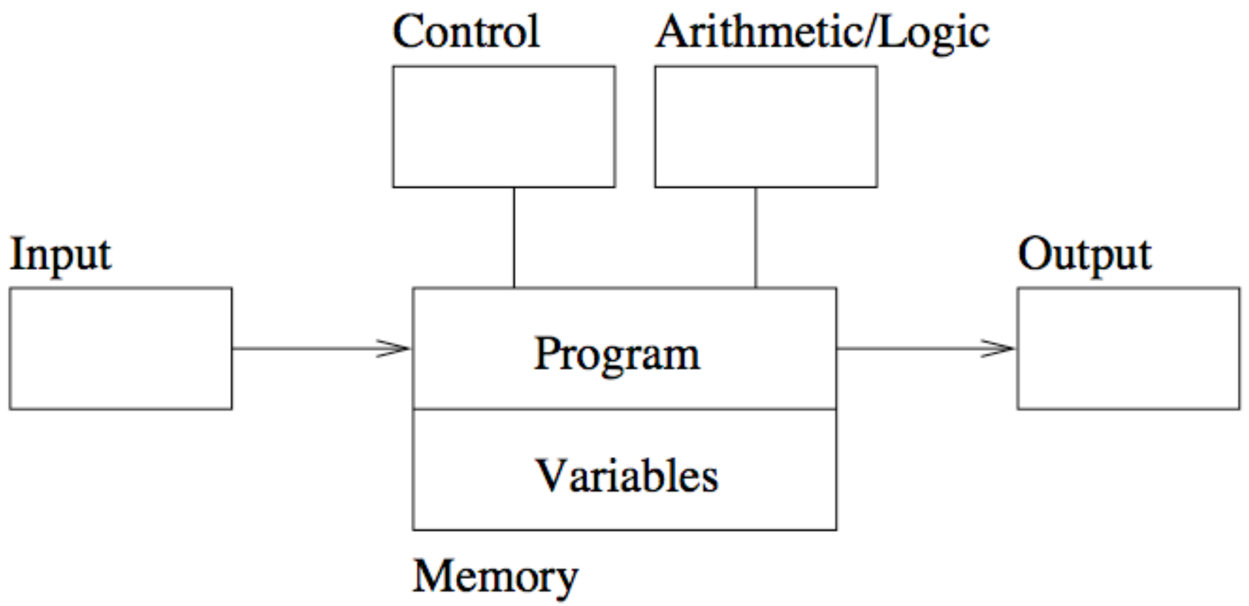


Figure 1.1: The von Neumann-Eckert Computer Model

Object-oriented (OO) Paradigm

- An OO Program is a collection of objects that interact by passing messages that transform the state.

- When studying OO, we learn about:
  - Sending Messages → objects are active
  - Inheritance
  - Polymorphism

- Example OO languages:
  - *Smalltalk, Java, C++, C#, and Python*

Functional Paradigm

- Functional programming models a computation as a collection of mathematical functions.
  - Set of all inputs = domain
  - Set of all outputs = range

- Functional languages are characterized by:
  - Functional composition
  - Recursion
  - No state changes: no variable assignments
    - x := x + 1 (wrong!)
  - Mathematically: output results instantly

- Example functional languages:
  - Lisp, Scheme, ML, Haskell, …

Logic Paradigm

- Logic programming declares *what* outcome the program should accomplish, rather than *how* it should be accomplished.

```
    parent(X, Y) :- father(X, Y).
    parent(X, Y) :- mother(X, Y).
    grandparent(X, Y) :- parent(X, Z), parent(Z, Y).
?- grandparent(X, jim).
```

  - Declarative!

- When studying logic programming we see:
  - Programs as sets of constraints on a problem
  - Programs that achieve all possible solutions
  - Programs that are nondeterministic

- Example logic programming languages:
  - Prolog, CLP

Modern Languages are Multi-paradigm

- Haskell (F + I)
- Scala (F + I + O)
- OCaml (F + I + O)
- F Sharp (F + I + O)
- Python (O + I + F)
- …

Special Topics

- Concurrency
  - E.g., Client-server programs
- Event handling
  - E.g., GUIs, home security systems
- Correctness
  - How can we prove that a program does what it is supposed to do under all circumstances?
  - Why is this important???

A Brief History

How and when did programming languages evolve?

What communities have developed and used them?

- Artificial Intelligence – Prolog, CLP, (Python)
- Computer Science Education – Pascal, Logo
- Science and Engineering – Fortran, Ada, ML, Haskell
- Information Systems – Cobol, SQL
- Systems and Networks – C, C++, Perl, Python
- World Wide Web – HTML, Java, Javascript, PHP

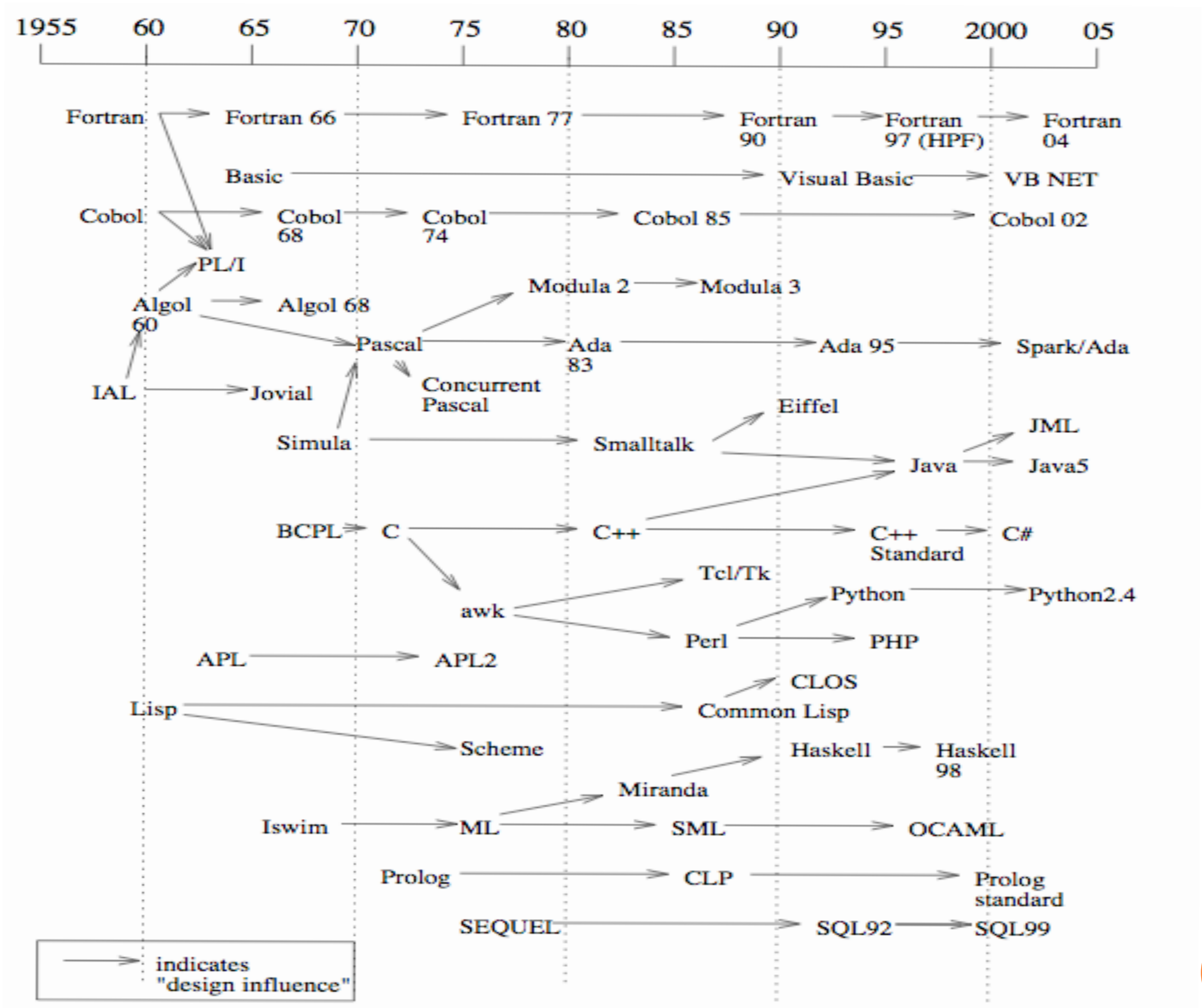


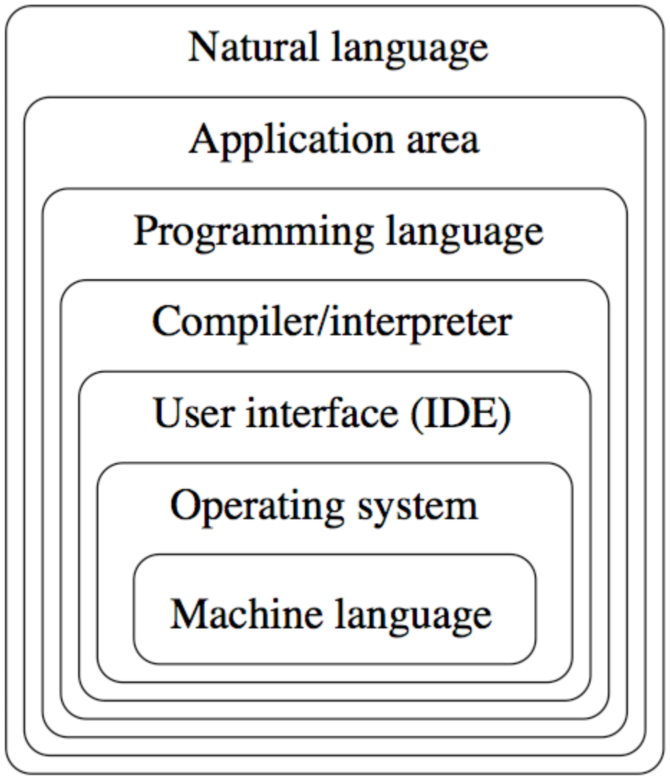
Figure 1.2: A Snapshot of Programming Language History

On Language Design

Design Constraints

- Computer architecture
- Technical setting
- Standards
- Legacy systems

Design Outcomes and Goals



Levels of abstraction in computing

What makes a successful language?

Key characteristics:

- Simplicity and readability
- Clarity about binding
- Reliability
- Support
- Abstraction
- Orthogonality
- Efficient implementation

Simplicity and Readability

- Small instruction set
  - E.g., Java vs. Scheme
- Simple syntax
  - E.g., C/C++/Java vs. Python
- Benefits:
  - Ease of learning
  - Ease of programming

Clarity about Binding

- A language element is ***bound*** to a property at the time that property is defined for it.
- So a *binding* is the association between an object and a property of that object
  - Examples:
    - a variable and its type
    - a variable and its value
  - Early binding takes place at compile-time
  - Late binding takes place at run time

Reliability

A language is *reliable* if:

- Program behaviour is the same on different platforms
  - E.g., early versions of Fortran
- Type errors are detected
  - E.g., C vs. Haskell
- Semantic errors are properly trapped
  - E.g., C vs. C++
- Memory leaks are prevented
  - E.g., C vs. Java

Language Support

- Accessible (public domain) compilers/interpreters
  - Java (open) vs. C# (closed)
- Good texts and tutorials
- Wide community of users
- Integrated with development environments (IDEs)
  - Jupyter Notebook vs. vim
  - Visual Studio vs. Emacs

Abstraction in Programming

- Data
  - Programmer-defined types/classes
  - Class libraries
- Procedural
  - Programmer-defined functions
  - Standard function libraries

Orthogonality

- A language is *orthogonal* if its features are built upon a small, ***mutually independent*** set of primitive operations.
  - **while** loop vs. **for** loop in C
- Fewer exceptional rules = conceptual simplicity
  - E.g., our tutorials are "usually" on Monday except the last week of each month or when the TA is busy with his research on text generation…
  - E.g., restricting types of arguments to a function
- Tradeoffs with efficiency

Efficient implementation

- Embedded systems
  - Real-time responsiveness (e.g., navigation)
  - Failures of early Ada implementations
- Web applications
  - Responsiveness to users (e.g., Google search)
- Corporate database applications
  - Efficient search and updating
- AI applications
  - Modeling human behaviors

Compilers and Interpreters

- Compiler – produces machine code
- Interpreter – executes instructions on a virtual machine
- Example compiled languages:
  - Fortran, Cobol, C, C++
- Example interpreted languages:
  - Scheme, Haskell, Python, Perl
- Hybrid compilation/interpretation
  - The Java Virtual Machine (JVM)
    - .java → .class
    - .class executes on JVM

The Compiling Process

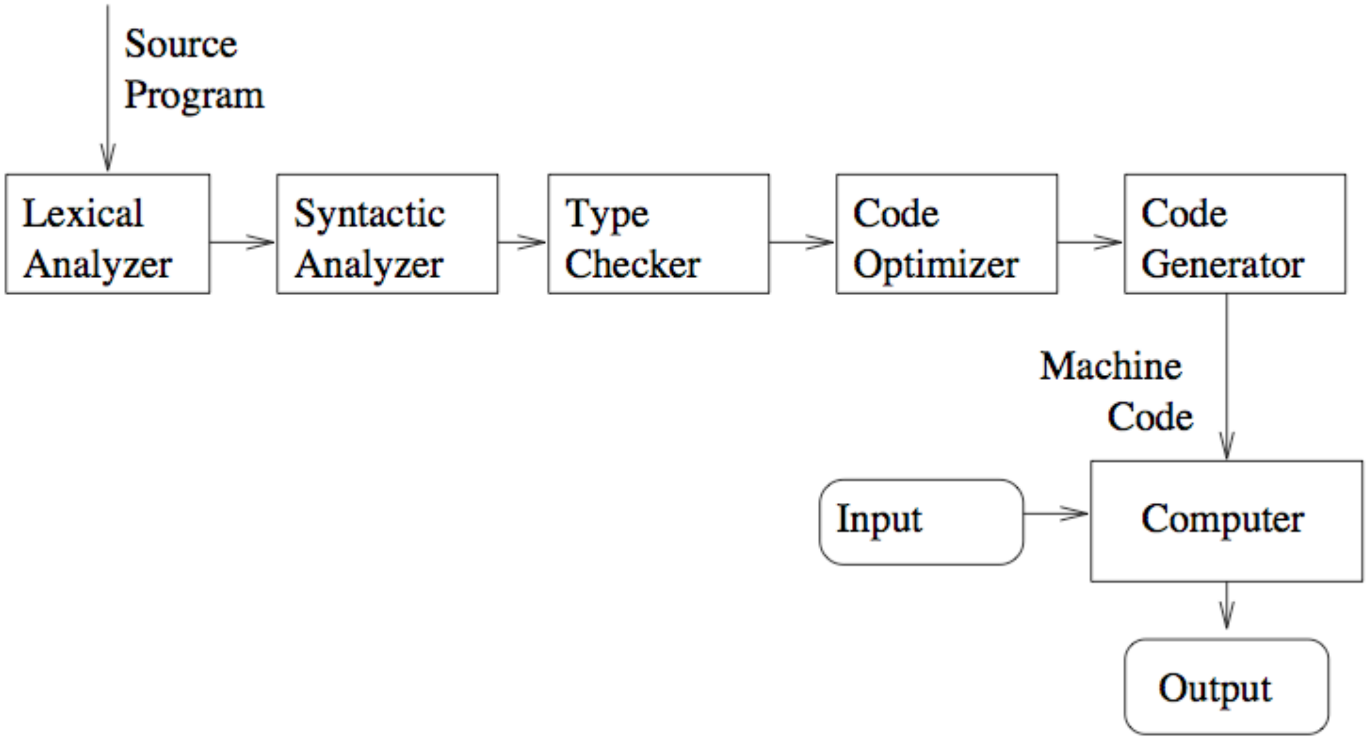


Figure 1.4: The Compile-and-Run Process

The Interpreting Process

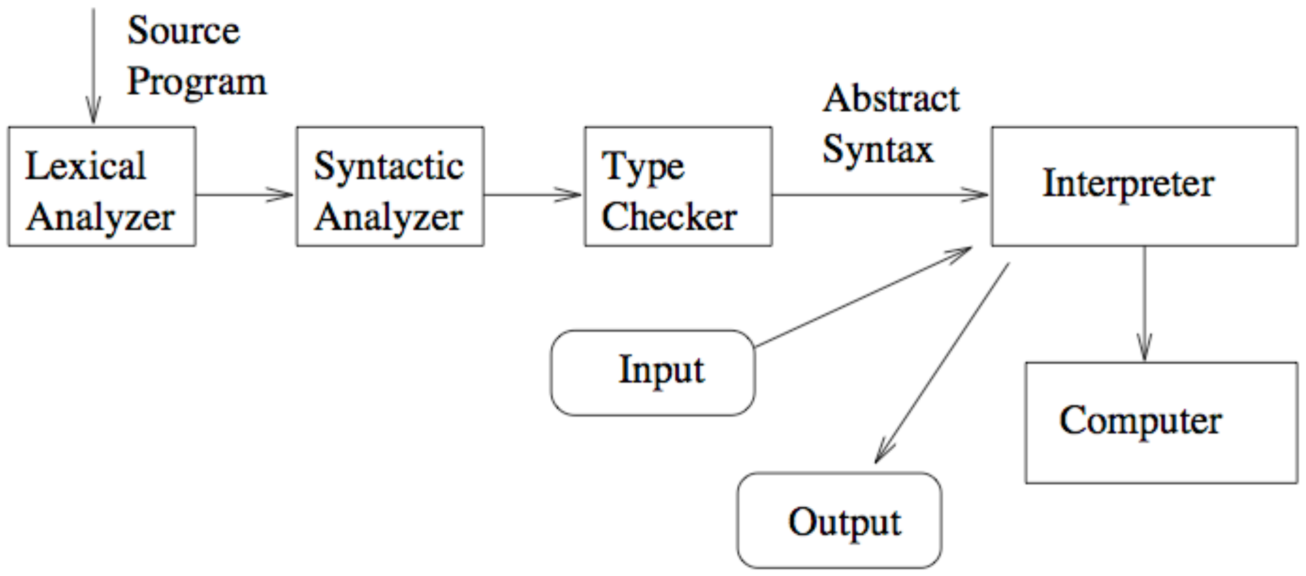


Figure 1.5: Virtual Machines and Interpreters

Course Roadmap

- Mathematic foundation – inductive definition and inductive proofs
- Untyped Lambda Calculus
- Simply-typed Lambda Calculus
- Extensions to Simply-typed Lambda Calculus
- Going Imperative
- Memory Management
- Subtyping
- Type Inference

- Case Study: Logic Programming (Prolog)
- Case Study: Functional Programming (OCaml)

Finally, Enjoy This Video!

“The most popular programming languages 1965-2021”

https://youtu.be/qQXXI5QFUfw