# Introduction to Programming Languages

CSE 307 – Principles of Programming Languages

Stony Brook University

http://www.cs.stonybrook.edu/~cse307

# Introduction

- What makes a language successful?
  - easy to learn (python, BASIC, Pascal, LOGO, Scheme)
  - easy to express things, easy use once fluent, "powerful" (C, Java, Common Lisp, APL, Algol-68, Perl)
  - easy to implement (Javascript, BASIC, Forth)
  - possible to compile to very good (fast/small) code (Fortran, C)
  - backing of a powerful sponsor (Java, Visual Basic, COBOL, PL/1, Ada)
  - wide dissemination at minimal cost (Java, Pascal, Turing, erlang)

# Introduction

- Why do we have programming languages? What is a language for?
  - way of thinking -- way of expressing algorithms
  - languages from the user's point of view
  - abstraction of virtual machine -- way of specifying what you want
  - the hardware to do without getting down into the bits
  - languages from the implementor's point of view

# Why study programming languages?

- Help you choose a language:
  - C vs. C++ for systems programming
  - Matlab vs. Python vs. R for numerical computations
  - Android vs. Java vs. ObjectiveC vs. Javascript for embedded systems
  - Python vs. Ruby vs. Common Lisp vs. Scheme vs. ML for symbolic data manipulation
  - Java RPC (JAX-RPC) vs. C/CORBA for networked PC programs

# Why study programming languages?

- Make it easier to learn new languages
  - some languages are similar: easy to walk down family tree
  - concepts have even more similarity; if you think in terms of iteration, recursion, abstraction (for example), you will find it easier to assimilate the syntax and semantic details of a new language than if you try to pick it up in a vacuum. Think of an analogy to human languages: good grasp of grammar makes it easier to pick up new languages (at least Indo-European).

# Why study programming languages?

- Help you make better use of whatever language you use
  - understand obscure features:
    - In C, help you understand unions, arrays & pointers, separate compilation, catch and throw
    - In Common Lisp, help you understand first-class functions/closures, streams, catch and throw, symbol internals

# Why study programming languages?

- Help you make better use of whatever language you use
  - understand implementation costs: choose between alternative ways of doing things, based on knowledge of what will be done underneath:
    - use simple arithmetic equal (use x*x instead of x**2)
    - use C pointers or Pascal "with" statement to factor address calculations
    - avoid call by value with large data items in Pascal
    - avoid the use of call by name in Algol 60
    - choose between computation and table lookup (e.g. for cardinality operator in C or C++)

# Why study programming languages?

- Help you make better use of whatever language you use
  - figure out how to do things in languages that don't support them explicitly:
    - lack of suitable control structures in Fortran
    - use comments and programmer discipline for control structures
    - lack of recursion in Fortran, CSP, etc.
      - write a recursive algorithm then use mechanical recursion elimination (even for things that aren't quite tail recursive)

# Why study programming languages?

- Help you make better use of whatever language you use
  - figure out how to do things in languages that don't support them explicitly:
    - lack of named constants and enumerations in Fortran
    - use variables that are initialized once, then never changed
    - lack of modules in C and Pascal use comments and programmer discipline

# Classifications

- Many classifications group languages as:
  - imperative
    - von Neumann (Fortran, Pascal, Basic, C)
    - object-oriented (Smalltalk, Eiffel, C++?)
    - scripting languages (Perl, Python, JavaScript, PHP)
  - declarative
    - functional (Scheme, ML, pure Lisp, FP)
    - logic, constraint-based (Prolog, VisiCalc, RPG)
- Many more classifications: scripting languages, markup languages, assembly languages, etc.

# HW1 (part of hw1)

- **Write and test the GCD Program in 4 languages: in C, in XSB Prolog, in SML and in Python:**
  - **In C:**

```
int main() {
        int i = getint(), j = getint();
        while (i != j) {
                if (i > j) i = i - j;
                else j = j - i;
        }
        putint(i);
}
```

Due: Thursday, 9/3 on Blackboard.

  - **In XSB Prolog:**

```
gcd(A,B,G) :- A = B, G = A.
gcd(A,B,G) :- A > B, C is A-B, gcd(C,B,G).
gcd(A,B,G) :- A < B, C is B-A, gcd(C,A,G).
```

  - **In SML:**

```
fun gcd(m,n):int = if m=n then n
= else if m>n then gcd(m-n,n)
= else gcd(m,n-m);
```

- **In Python:**

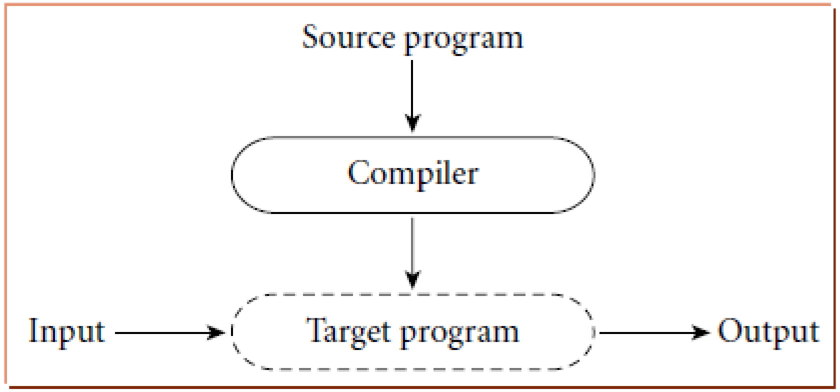
```
def gcd(a, b):
   if a == b:
      return a
   else:
      if a > b:
         return gcd(a-b, b)
      else:
         return gcd(a, b-a)
```

# Imperative languages

- Imperative languages, particularly the von Neumann languages, predominate

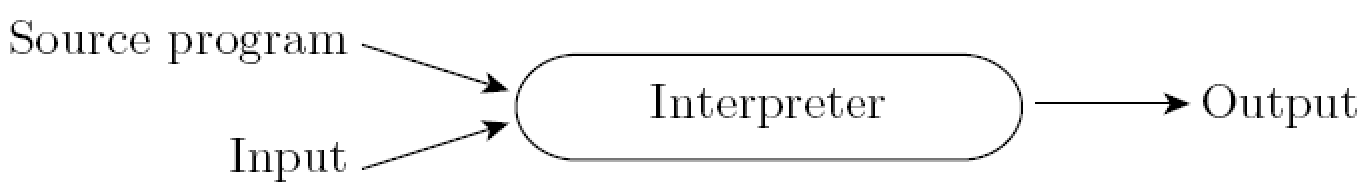
# Compilation vs. Interpretation

- Compilation vs. interpretation
  - not opposites
  - not a clear-cut distinction
- Pure Compilation
  - The compiler translates the high-level source program into an equivalent target program (typically in machine language), and then goes away:



# Compilation vs. Interpretation

- Pure Interpretation
  - Interpreter stays around for the execution of the program
  - Interpreter is the locus of control during execution



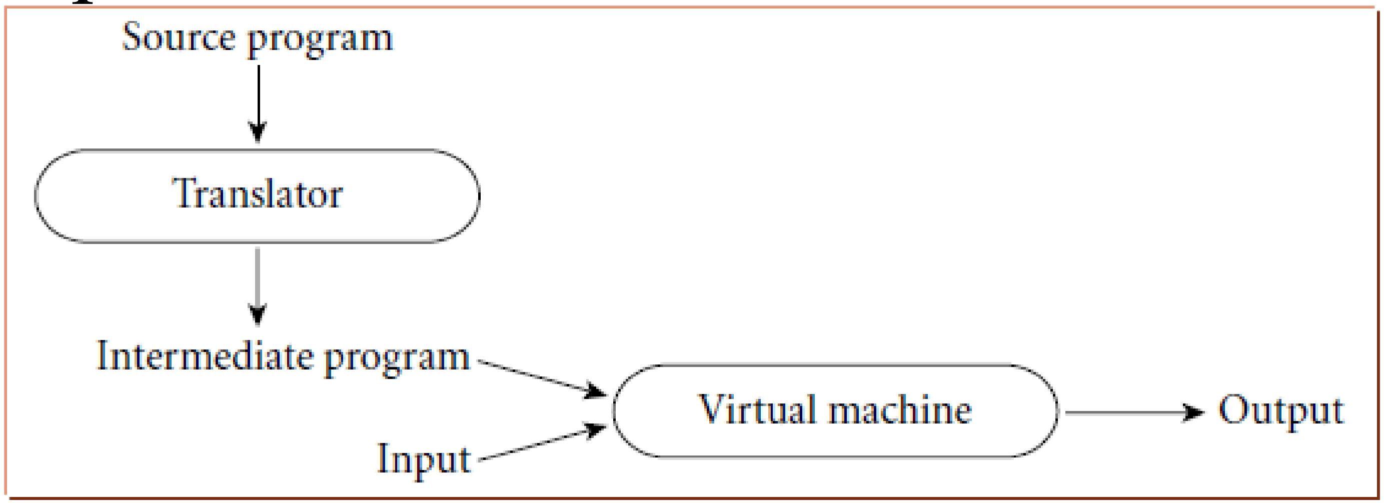
# Compilation vs. Interpretation

- Interpretation:
  - Greater flexibility
  - Better diagnostics (error messages)

- Compilation
  - Better performance!

# Compilation vs. Interpretation

- Common case is compilation or simple pre-processing, followed by interpretation
- Most language implementations include a mixture of both compilation and interpretation



# Compilation vs. Interpretation

- Note that compilation does NOT have to produce machine language for some sort of hardware
- Compilation is translation from one language into another, with full analysis of the meaning of the input
- Compilation entails semantic understanding of what is being processed; pre-processing does not
- A pre-processor will often let errors through. A compiler hides further steps; a pre-processor does not

# Compilation vs. Interpretation

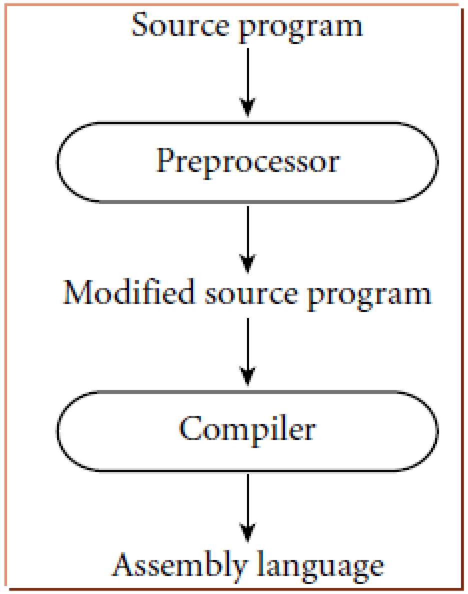
- Many compiled languages have interpreted pieces, e.g., formats in Fortran or C
- Most compiled languages use "virtual instructions"
  - set operations in Pascal
  - string manipulation in Basic
- Some compilers produce nothing but virtual instructions, e.g., Pascal P-code, Java byte code, Microsoft COM+

# Compilation vs. Interpretation

- Implementation strategies:
  - Preprocessor
    - Removes comments and white space
    - Groups characters into tokens (keywords, identifiers, numbers, symbols)
    - Expands abbreviations in the style of a macro assembler
    - Identifies higher-level syntactic structures (loops, subroutines)

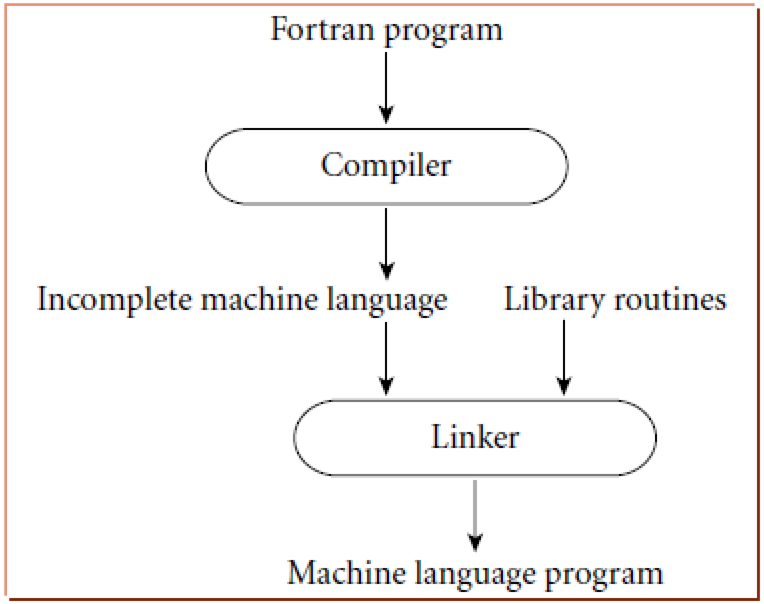
# Compilation vs. Interpretation

- Implementation strategies:
  - The C Preprocessor:
    - removes comments
    - expands macros



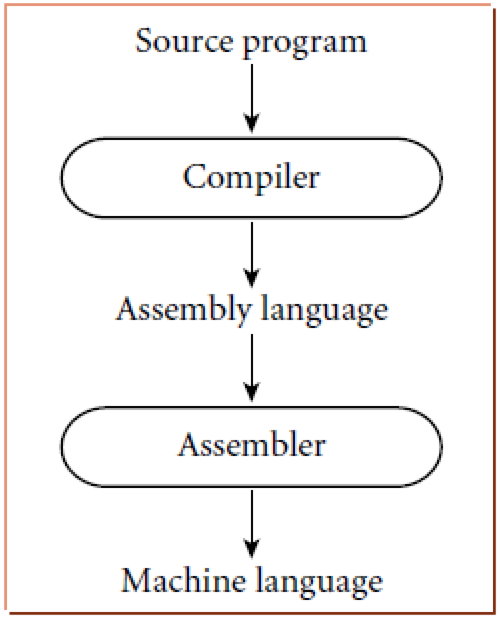
# Compilation vs. Interpretation

- Implementation strategies:
  - Library of Routines and Linking
    - Compiler uses a linker program to merge the appropriate library of subroutines (e.g., math functions such as sin, cos, log, etc.) into the final program:



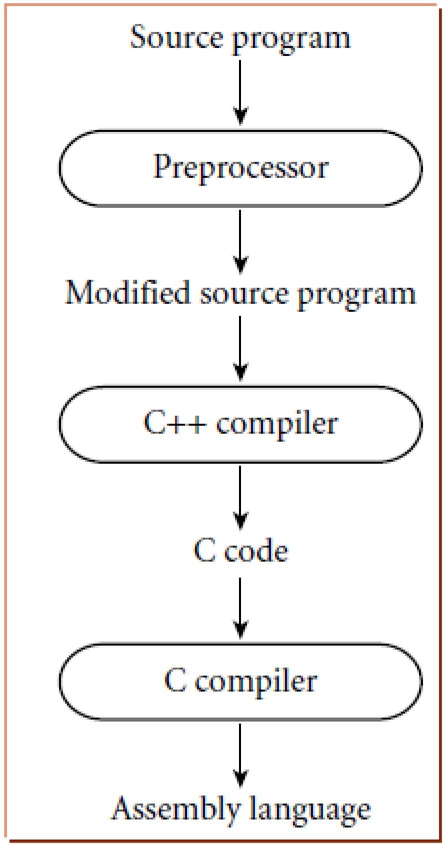
# Compilation vs. Interpretation

- Implementation strategies:
  - Post-compilation Assembly
    - Facilitates debugging (assembly language easier for people to read)
    - Isolates the compiler from changes in the format of machine language files (only assembler must be changed, is shared by many compilers)



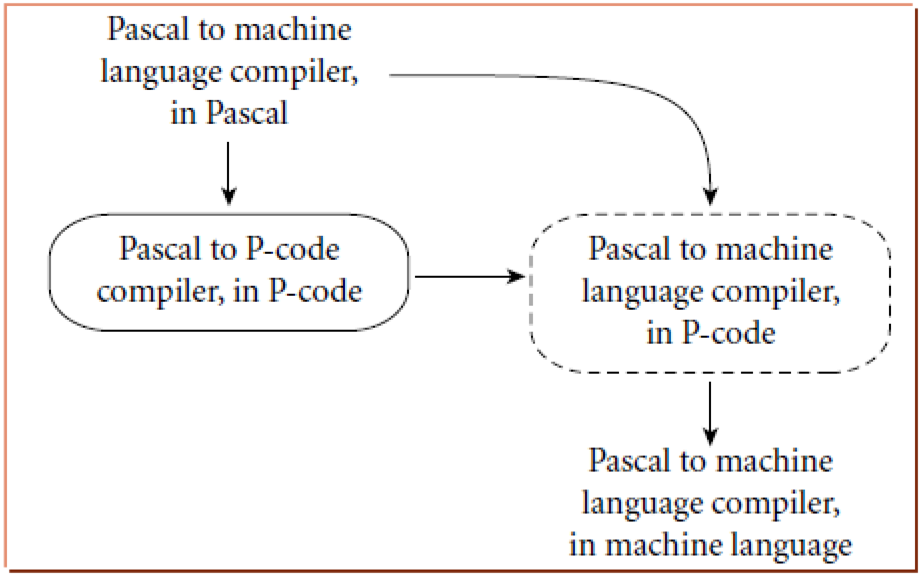
# Compilation vs. Interpretation

- Implementation strategies:
  - Source-to-Source Translation
    - C++ implementations based on the early AT&T compiler generated an intermediate program in C, instead of an assembly language



# Compilation vs. Interpretation

- Implementation strategies:
  - Bootstrapping: many compilers are self-hosting: they are written in the language they compile
    - How does one compile the compiler in the first place?
    - Response: one starts with a simple implementation—often an interpreter—and uses it to build progressively more sophisticated versions



# Compilation vs. Interpretation

- Implementation strategies:
  - Compilation of Interpreted Languages (e.g., Prolog, Lisp, Smalltalk, Java, C#):
    - The compiler generates code that makes assumptions about decisions that won't be finalized until runtime. If these assumptions are valid, the code runs very fast. If not, a dynamic check will revert to the interpreter.
    - Permit a lot of late binding .
    - Are traditionally interpreted.

# Compilation vs. Interpretation

- Implementation strategies:
  - Dynamic and Just-in-Time Compilation
    - In some cases a programming system may deliberately delay compilation until the last possible moment.
      - Lisp or Prolog invoke the compiler on the fly, to translate newly created source into machine language, or to **optimize the code for a particular input set** (e.g., dynamic indexing in Prolog).
      - The Java language definition defines a machine-independent intermediate form known as byte code. Bytecode is the standard format for distribution of Java programs:
        - it allows programs to be transferred easily over the Internet, and then run on any platform
      - The main C# compiler produces .NET Common Intermediate Language (CIL), which is then translated into machine code immediately prior to execution.

# Compilation vs. Interpretation

- Implementation strategies:
  - Microcode
    - **Assembly-level instruction set is not implemented in hardware**; it runs on an interpreter.
    - **The interpreter is written in low-level instructions (microcode or firmware)**, which are stored in read-only memory and executed by the hardware.

# Compilation vs. Interpretation

- Compilers exist for some interpreted languages, but they aren't pure:
  - selective compilation of compilable pieces and extra-sophisticated pre-processing of remaining source.
  - Interpretation is still necessary.
    - E.g., XSB Prolog is compiled into .wam (Warren Abstract Machine) files and then executed by the interpreter
- **Unconventional compilers:**
  - text formatters: TEX and troff are actually compilers
  - silicon compilers: laser printers themselves incorporate interpreters for the Postscript page description language
  - query language processors for database systems are also compilers: translate languages like SQL into primitive operations (e.g., tuple relational calculus and domain relational calculus)

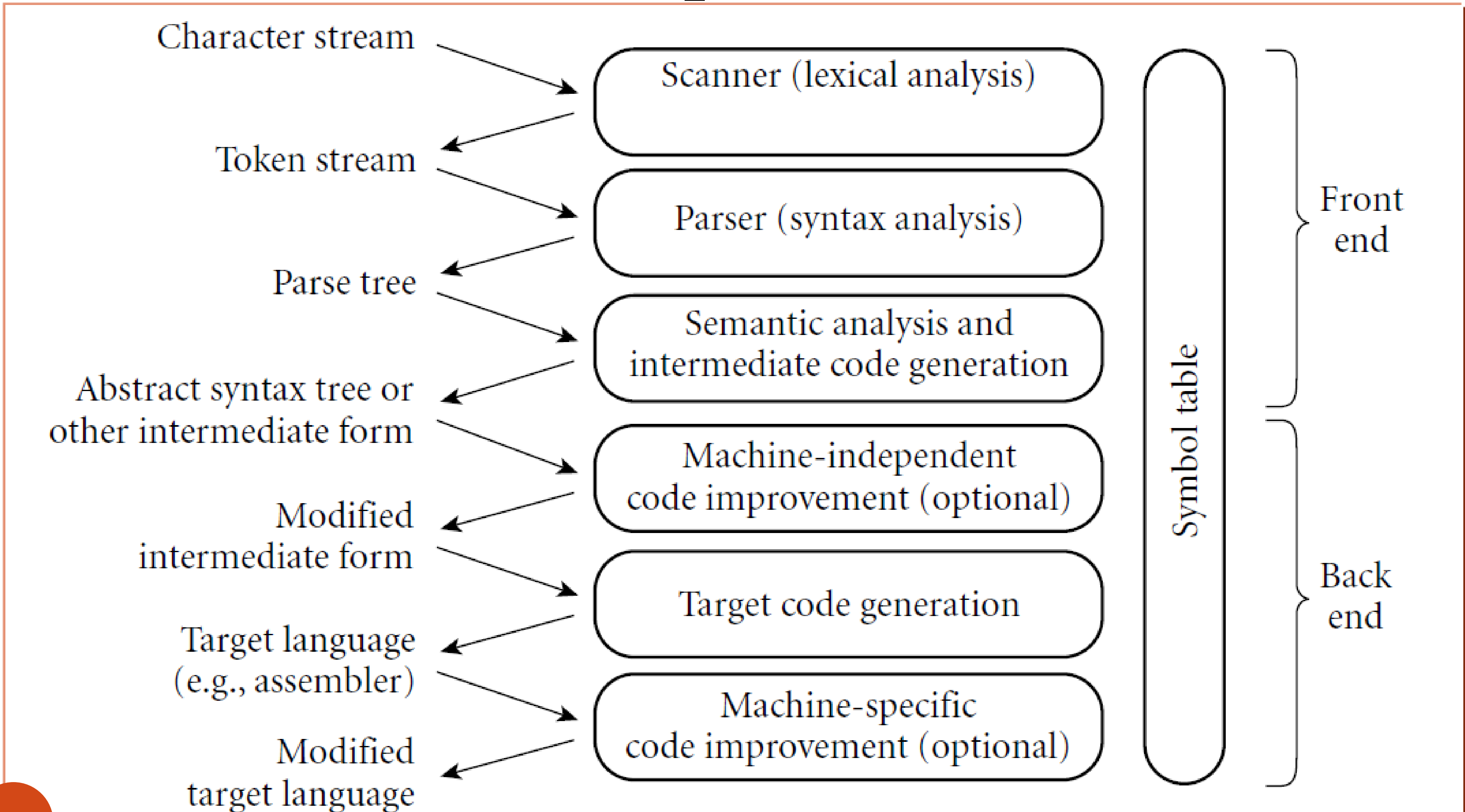
# Programming Environment Tools

- Tools/IDEs:
  - Compilers and interpreters do not exist in isolation
  - Programmers are assisted by tools and IDEs

| Type | Unix examples |
|---|---|
| Editors | vi, emacs |
| Pretty printers | cb, indent |
| Pre-processors (esp. macros) | cpp, m4, watfor |
| Debuggers | adb, sdb, dbx, gdb |
| Style checkers | lint, purify |
| Module management | make |
| Version management | sccs, rcs |
| Assemblers | as |
| Link editors, loaders | Id, Id-so |
| Perusal tools | More, less, od, nm |
| Program cross-reference | ctags |

# An Overview of Compilation

- Phases of Compilation



# An Overview of Compilation

- Scanning:
  - divides the program into "tokens", which are the smallest meaningful units; this saves time, since character-by-character processing is slow
  - we can tune the scanner better if its job is simple; it also saves complexity (lots of it) for later stages
  - you can design a parser to take characters instead of tokens as input, but it isn't pretty
  - scanning is recognition of a regular language, e.g., via DFA

# An Overview of Compilation

- Parsing is recognition of a context-free language, e.g., via PDA
  - Parsing discovers the "context free" structure of the program
  - Informally, it finds the structure you can describe with syntax diagrams (the "circles and arrows" in a Pascal manual)

# An Overview of Compilation

- Semantic analysis is the discovery of meaning in the program
  - The compiler actually does what is called STATIC semantic analysis. That's the meaning that can be figured out at compile time
  - Some things (e.g., array subscript out of bounds) can't be figured out until run time. Things like that are part of the program's DYNAMIC semantics

# An Overview of Compilation

- Intermediate form (IF) done after semantic analysis (if the program passes all checks)
  - IFs are often chosen for machine independence, ease of optimization, or compactness (these are somewhat contradictory)
  - They often resemble machine code for some imaginary idealized machine; e.g. a stack machine, or a machine with arbitrarily many registers
  - Many compilers actually move the code through more than one IF

# An Overview of Compilation

- Optimization takes an intermediate-code program and produces another one that does the same thing faster, or in less space
  - The term is a misnomer; we just improve code
  - The optimization phase is optional
- Code generation phase produces assembly language or (sometime) relocatable machine language

# An Overview of Compilation

- Certain machine-specific optimizations (use of special instructions or addressing modes, etc.) may be performed during or after target code generation
- Symbol table: all phases rely on a symbol table that keeps track of all the identifiers in the program and what the compiler knows about them
  - This symbol table may be retained (in some form) for use by a debugger, even after compilation has completed

# An Overview of Compilation

- Lexical and Syntax Analysis
  - For example, take the GCD Program (in C):

```
int main() {
  int i = getint(), j = getint();
   while (i != j) {
    if (i > j) i = i - j;
    else j = j - i;
  }
  putint(i);
}
```

# An Overview of Compilation

- Lexical and Syntax Analysis
  - GCD Program Tokens
    - Scanning (lexical analysis) and parsing recognize the structure of the program, groups characters into tokens, the smallest meaningful units of the program

```
int      main    (    )         {
int      i       =    getint    (    )  ,  j   =   getint  (  )  ;
while    (       i    !=        j    )   {
if       (       i    >         j    )   i   =   i   -        j   ;
else     j       =    j         -    i   ;
}
putint   (       i    )         ;
}
```

# An Overview of Compilation

- Lexical and Syntax Analysis
  - Context-Free Grammar and Parsing
    - Parsing organizes tokens into a parse tree that represents higher-level constructs in terms of their constituents
    - Potentially recursive rules known as context-free grammar define the ways in which these constituents combine

# An Overview of Compilation

- Context-Free Grammar and Parsing
  - Example (while loop in C):

*iteration-statement* → *while ( expression ) statement*

statement, in turn, is often a list enclosed in braces:

*statement* → *compound-statement*

*compound-statement* → *{ block-item-list opt }*

where

*block-item-list opt* → *block-item-list*

or

*block-item-list opt* → $\epsilon$

and

*block-item-list* → *block-item*

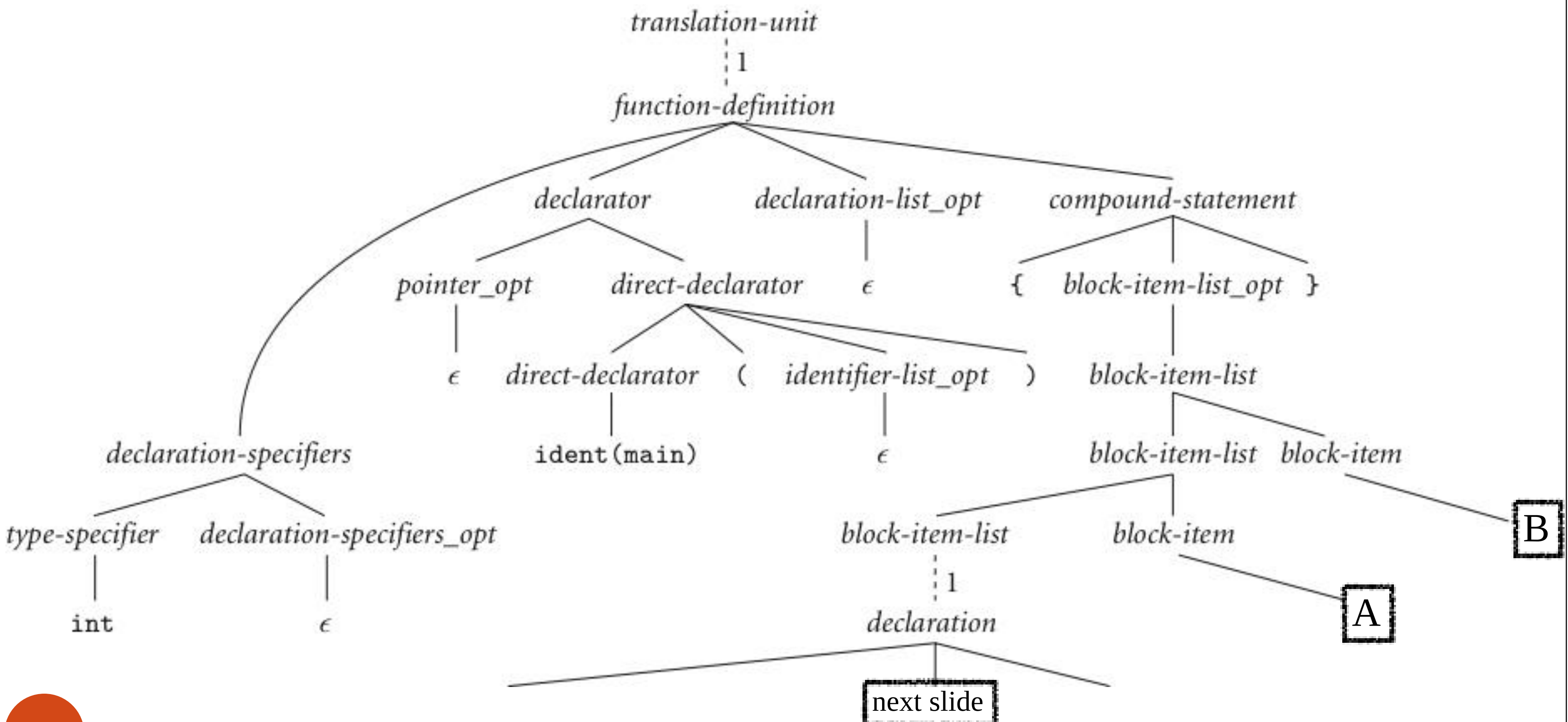
*block-item-list* → *block-item-list block-item*

*block-item* → *declaration*

*block-item* → *statement*

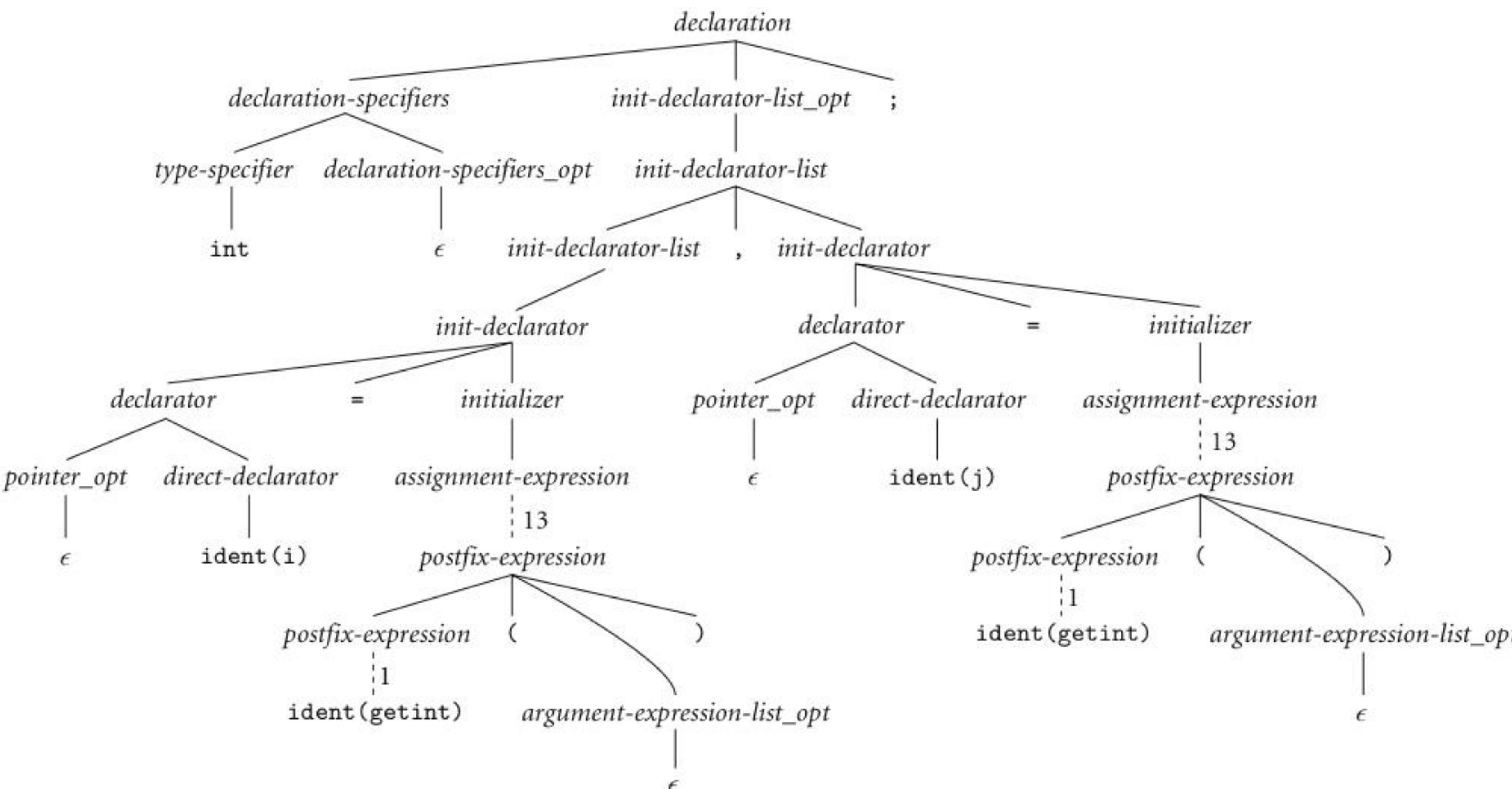
# An Overview of Compilation

- Context-Free Grammar and Parsing
  - GCD Program Parse Tree:



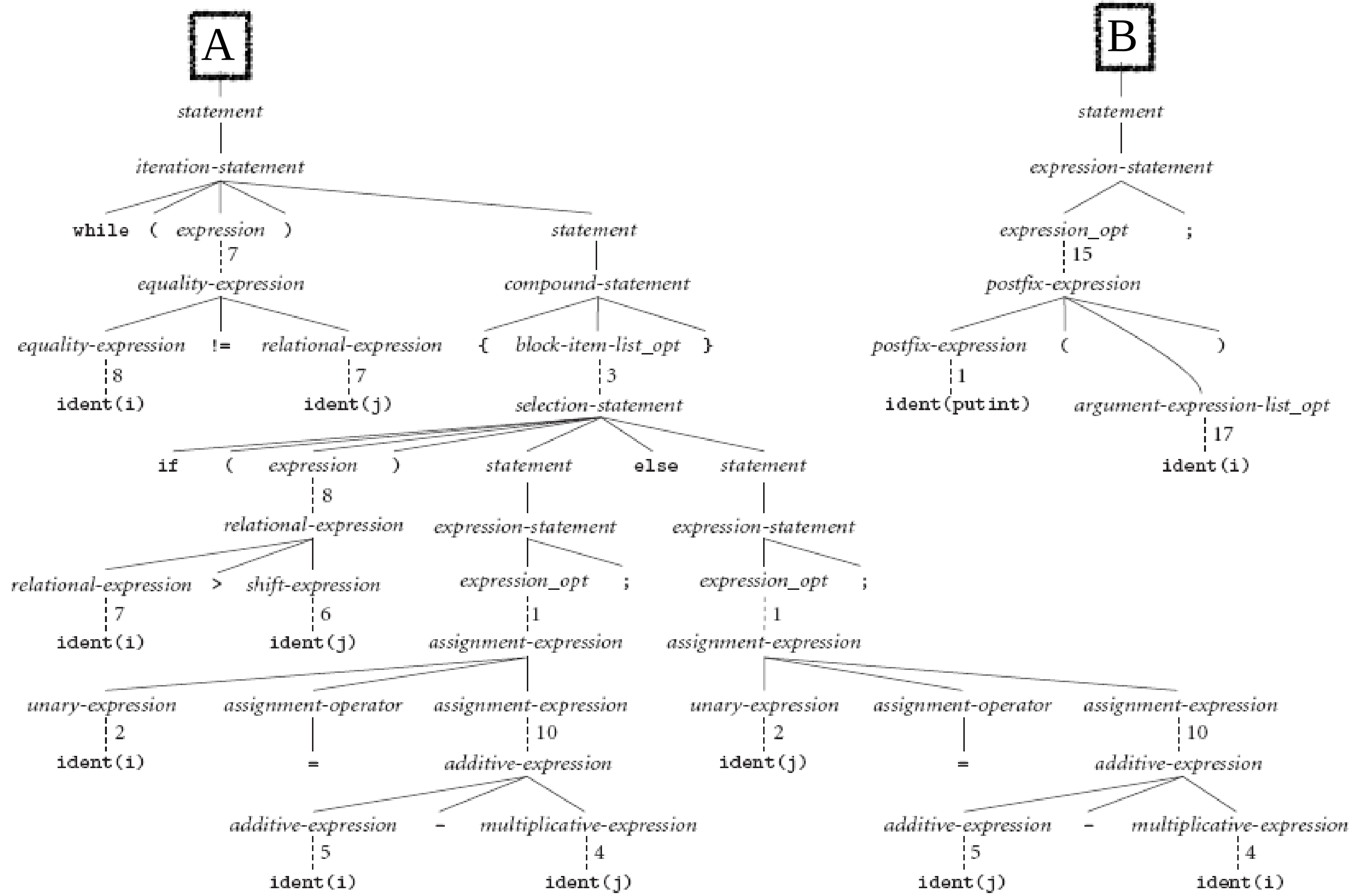
# An Overview of Compilation

- Context-Free Grammar and Parsing (continued)



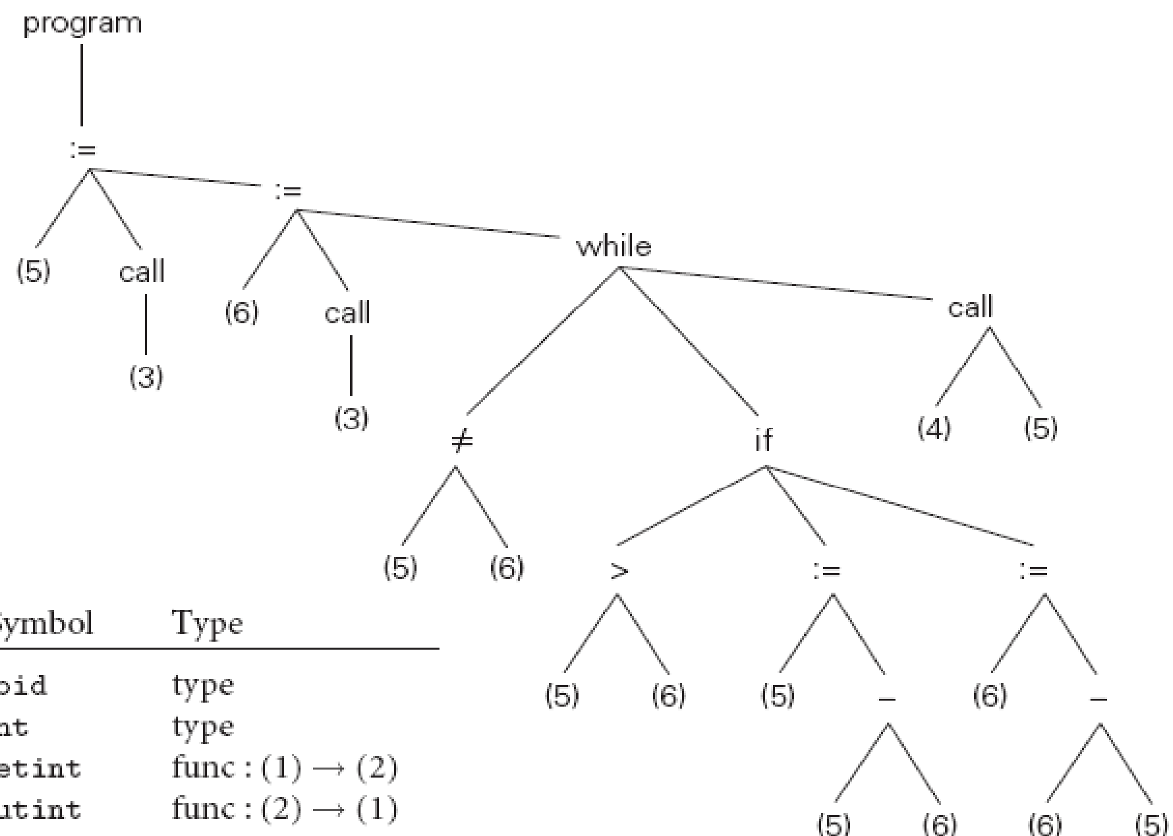
# An Overview of Compilation

- Context-Free Grammar and Parsing (continued)



# An Overview of Compilation

- Syntax Tree
  - GCD Program Parse Tree




| Index | Symbol | Type |
|---|---|---|
| 1 | `void` | type |
| 2 | `int` | type |
| 3 | `getint` | func : (1) → (2) |
| 4 | `putint` | func : (2) → (1) |
| 5 | `i` | (2) |
| 6 | `j` | (2) |