Introduction to Programming Languages

CSE 307 – Principles of Programming Languages

Stony Brook University

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

Introduction

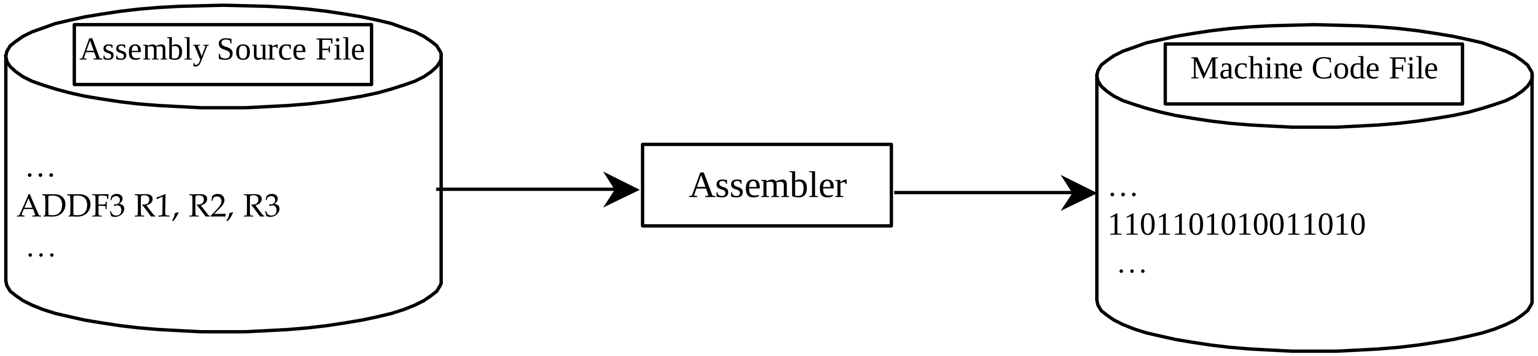
- At the beginning there was only machine language: a sequence of bits that directly controls a processor, causing it to add, compare, move data from one place to another
  - Example: GCD program in x86 machine language:

```
55 89 e5 53  83 ec 04 83  e4 f0 e8 31  00 00 00 89  c3 e8 2a 00
00 00 39 c3  74 10 8d b6  00 00 00 00  39 c3 7e 13  29 c3 39 c3
75 f6 89 1c  24 e8 6e 00  00 00 8b 5d  fc c9 c3 29  d8 eb eb 90
```

Introduction

- Assembly languages were invented to allow operations to be expressed with **mnemonic** abbreviations
  - For example, to add two numbers, you might write an instruction in assembly code like this:

    ADDF3 R1, R2, R3
  - A program called ***assembler*** is used to convert assembly language programs into machine code



Introduction

- Example: GCD program in x86 assembly:

```
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        andl    $-16, %esp
        call    getint
        movl    %eax, %ebx
        call    getint
        cmpl    %eax, %ebx
        je      C
A:      cmpl    %eax, %ebx
        jle     D
        subl    %eax, %ebx
B:      cmpl    %eax, %ebx
        jne     A
C:      movl    %ebx, (%esp)
        call    putint
        movl    -4(%ebp), %ebx
        leave
        ret
D:      subl    %ebx, %eax
        jmp     B
```

Introduction

- Assemblers were eventually augmented with elaborate "***macro expansion***" facilities to permit programmers to define **parameterized** abbreviations **for common sequences of instructions**
- Problem: each different kind of computer had to be programmed in its own assembly language
  - People began to wish for a ***machine-independent languages***
- These wishes led in the mid-1950s to the development of standard ***higher-level languages*** compiled for different architectures by ***compilers***

Introduction

- Today there are thousands of high-level programming languages, and new ones continue to emerge
- Why are there so many?
  - Evolution
  - Special Purposes
  - Personal Preference

Introduction

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

Introduction

- Why do we have programming languages? What is a language for?
  - **way of thinking** -- way of expressing algorithms
  - **way of specifying** what you want
  - **ease of use** - languages from the implementor's point of view
  - **access special features of the hardware**

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 – **<u>same way of doing things:</u>**
    - 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
  - **<u>understand implementation costs:</u>** 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)
    - 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 recursion in Fortran, CSP, etc.
      - write a recursive algorithm then use mechanical recursion elimination (even for things that aren't quite tail recursive)
    - lack of suitable control structures in Fortran
      - use comments and programmer discipline for control structures
        - 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/Turing (Fortran, Pascal, Basic, C)
    - object-oriented imperative (Smalltalk, Eiffel, C++?)
    - scripting languages (Perl, Python, JavaScript, PHP)
  - declarative
    - functional (Scheme, ML, pure Lisp, FP)
    - logic, constraint-based (Prolog, Flora2, ASP clingo)
- Many more classifications: markup languages, assembly languages, etc.

Classification

- **GCD Program in different languages, like C, Prolog, SML and 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);
}
```

  - **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:**

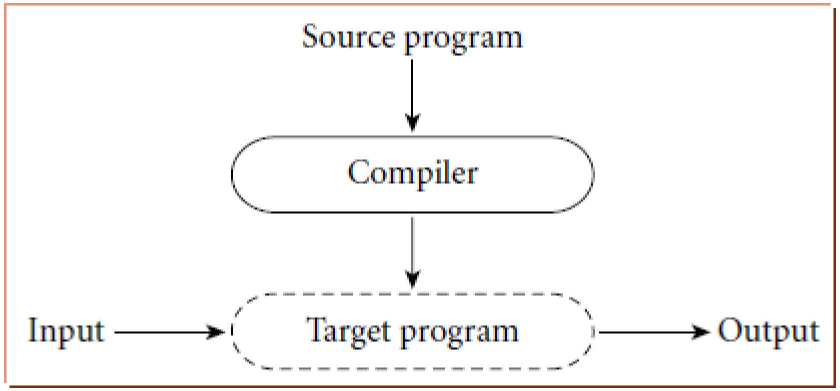
```
fun gcd(m,n):int = if m=n then n
= else if m>n then gcd(m-n,n)
= else gcd(m,n-m);
```

- **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)
```

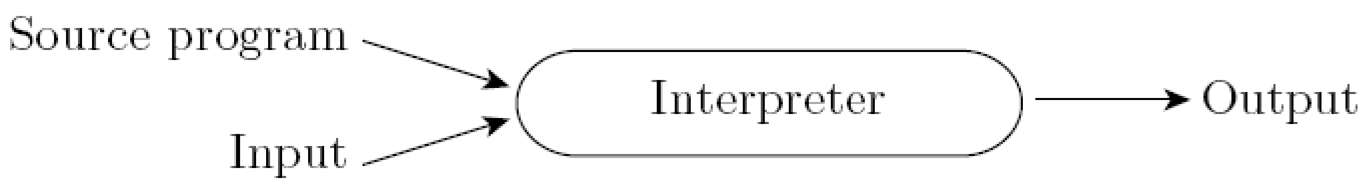
Compilation vs. Interpretation

- 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



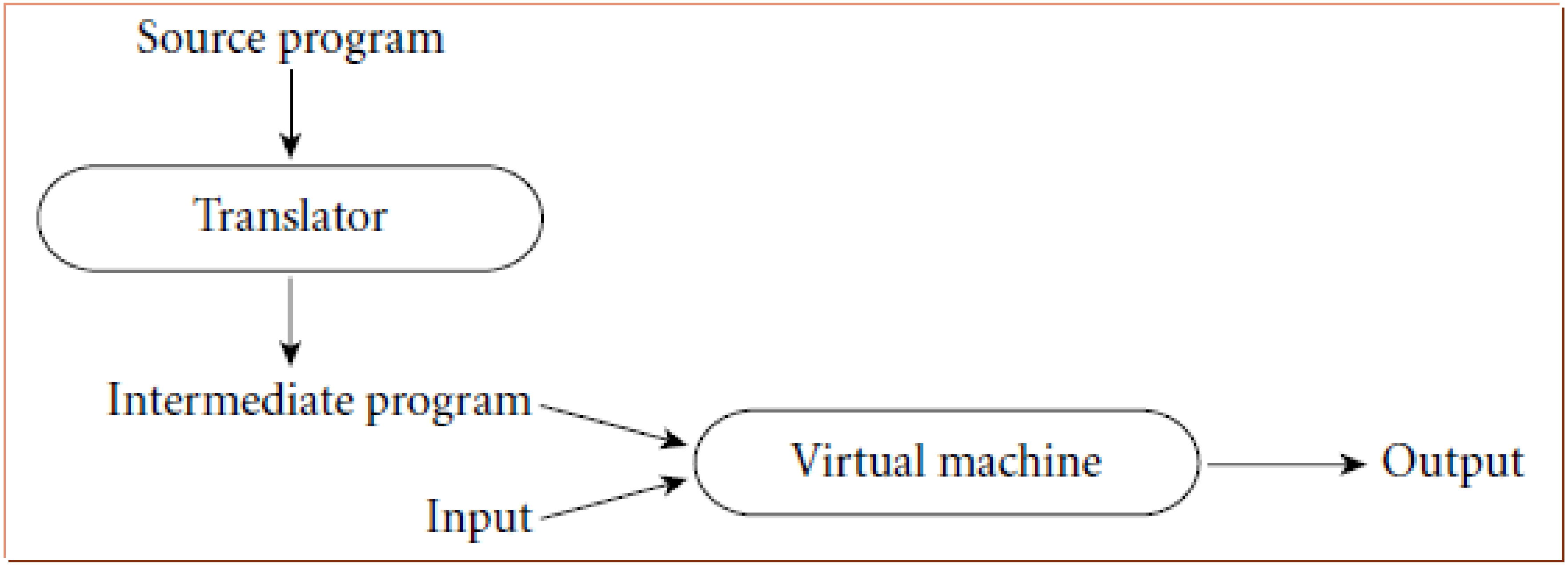
Compilation vs. Interpretation

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

- Compilation
  - Better performance!

Compilation vs. Interpretation

- Most modern language implementations include a mixture of both compilation and interpretation
  - Compilation followed by 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

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

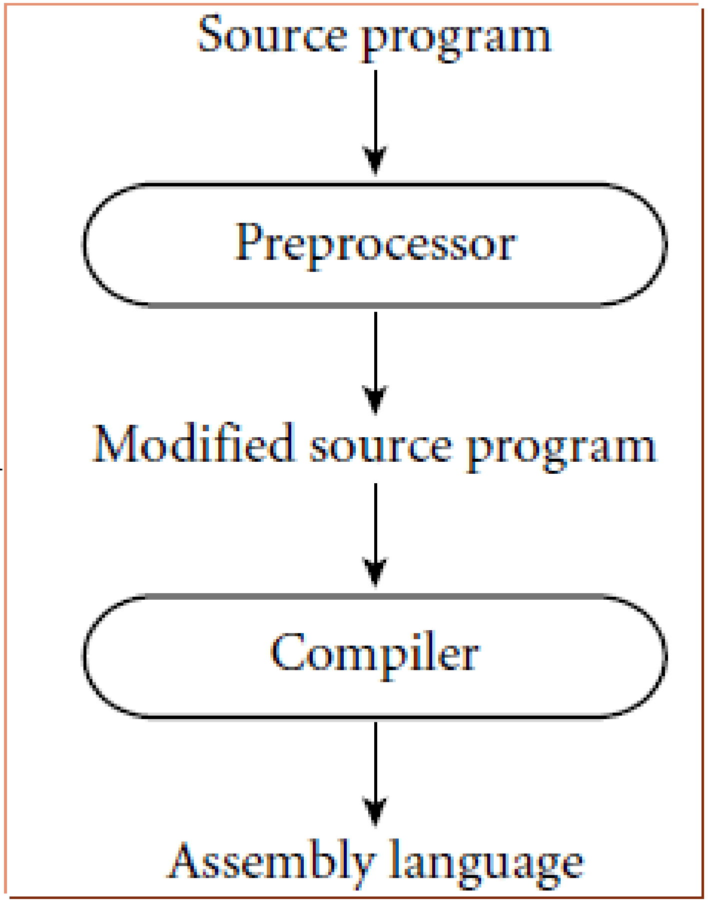
Compilation vs. Interpretation

- 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)
    - Conditional compilation: if-else directives #if, #ifdef, #ifndef, #else, #elif and #endif – example:

```
#ifdef __unix__
# include <unistd.h>
#elif defined _WIN32
# include <windows.h>
#endif
```

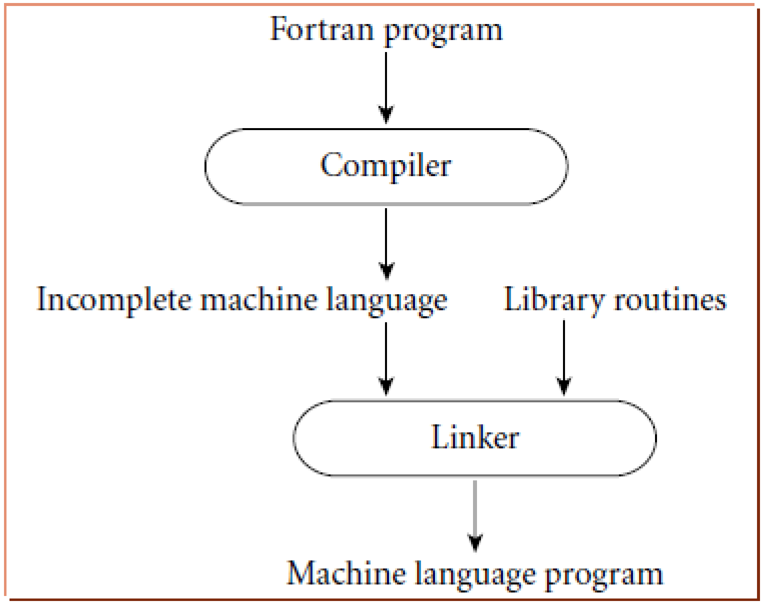
Compilation vs. Interpretation

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



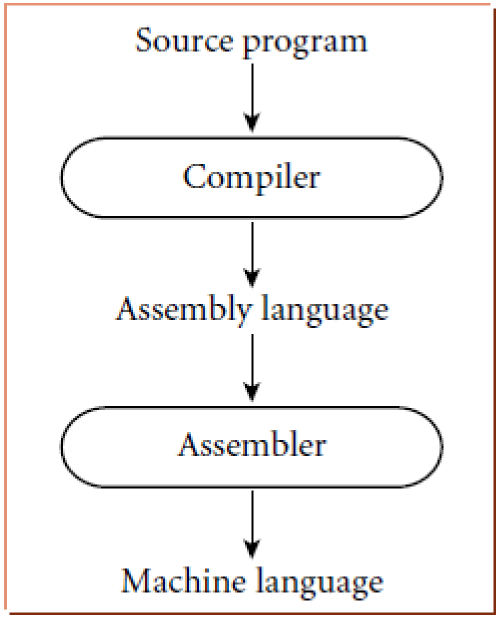
Compilation vs. Interpretation

- 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:



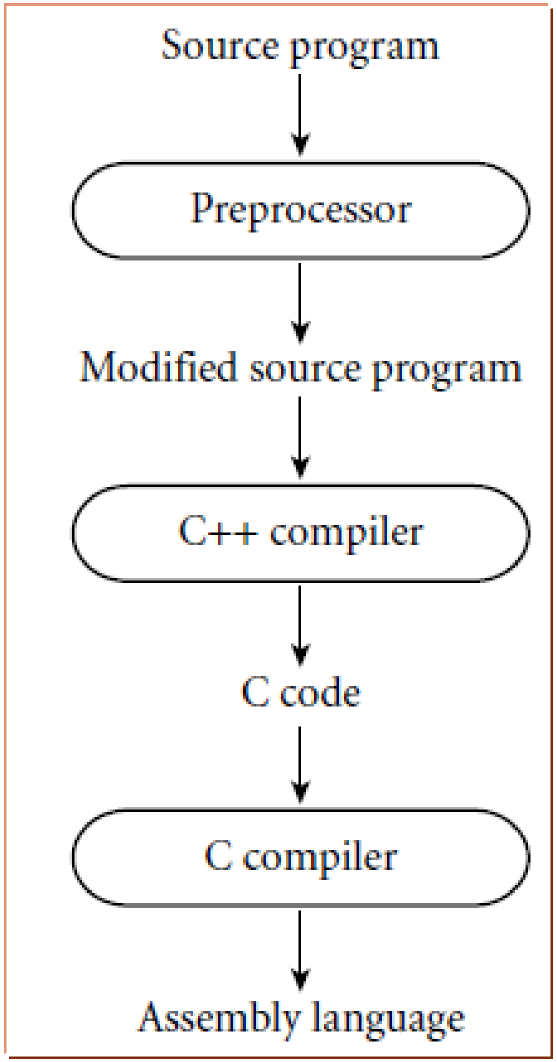
Compilation vs. Interpretation

- 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 (which could be assembly language); successive expanded versions of the compiler are developed using this minimal subset of the language.
    - Assemblers were the first language tools to bootstrap themselves
    - Java is a self-hosting compiler. So are: Basic, C, C++, C#, OCaml, Perl6, python, XSB.
    - It is a form of dogfooding (Using your own product, *Eating your own dog food*)
    - compiler developers and bug reporting part of the community only need to know the language being compiled.
    - Improvements to the compiler's back-end improve not only general-purpose programs but also the compiler itself.
    - It is a comprehensive consistency check as it should be able to reproduce its own object code.

Compilation vs. Interpretation

- Bootstrapping is related to ***self-hosting***:
  - Ken Thompson started development on Unix in 1968 by writing the initial Unix kernel, a command interpreter, an editor, an assembler, and a few utilities on GE-635.
    - Then the Unix operating system became self-hosting: programs could be written and tested on Unix itself.
  - Development of the Linux kernel was initially hosted on a Minix system.
    - When sufficient packages, like GCC, GNU bash and other utilities are ported over, developers can work on new versions of Linux kernel based on older versions of itself (like building kernel 3.21 on a machine running kernel 3.18).

Compilation vs. Interpretation

- Implementation strategies:
  - Compilation of Interpreted Languages (e.g., Prolog, Lisp, Smalltalk, Java, C#):
    - 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

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)

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

- **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)

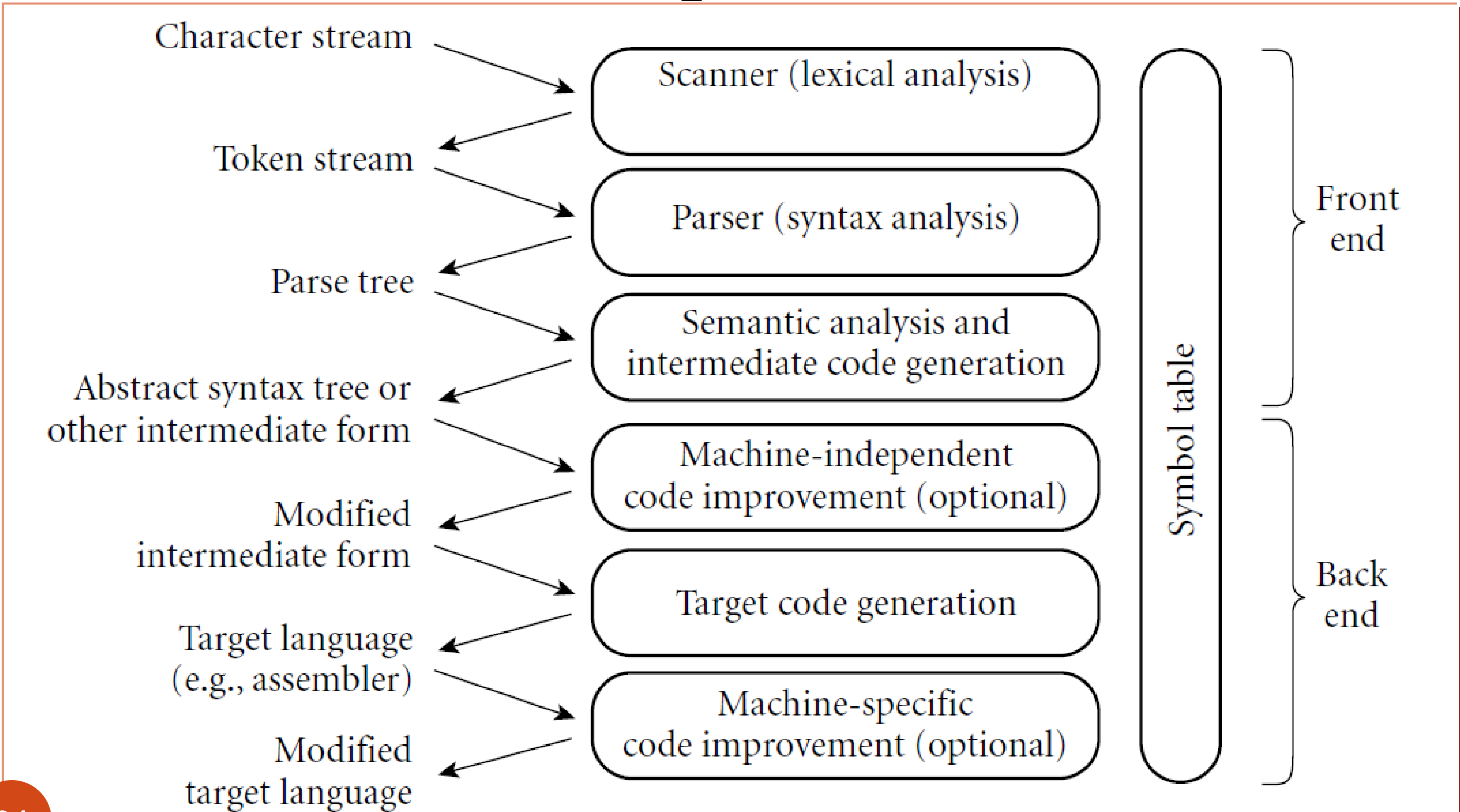
Programming Environment Tools

- 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*** is recognition of a regular language, e.g., via DFA (Deterministic finite automaton)
  - divides the program into "***tokens***", which are the smallest meaningful units; this saves time, since character-by-character processing is slow
  - you can design a parser to take characters instead of tokens as input, but it isn't pretty

An Overview of Compilation

- **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
    - **<u>Scanning</u>** (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

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

An Overview of Compilation

- Context-Free Grammar and Parsing
  - Grammar Example for while loops in C:

while-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 → ϵ

and

block-item-list → *block-item*

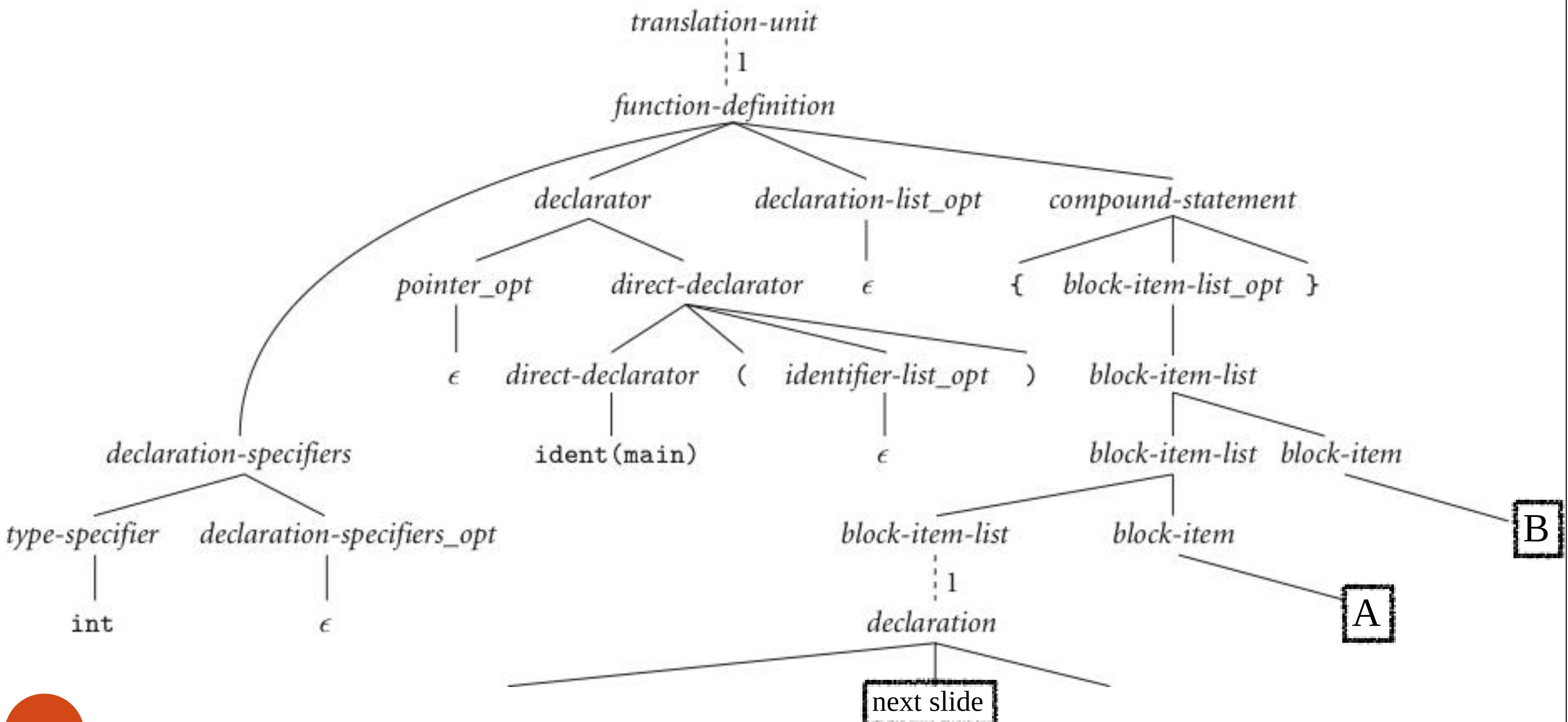
block-item-list → *block-item-list block-item*

block-item → *declaration*

block-item → *statement*

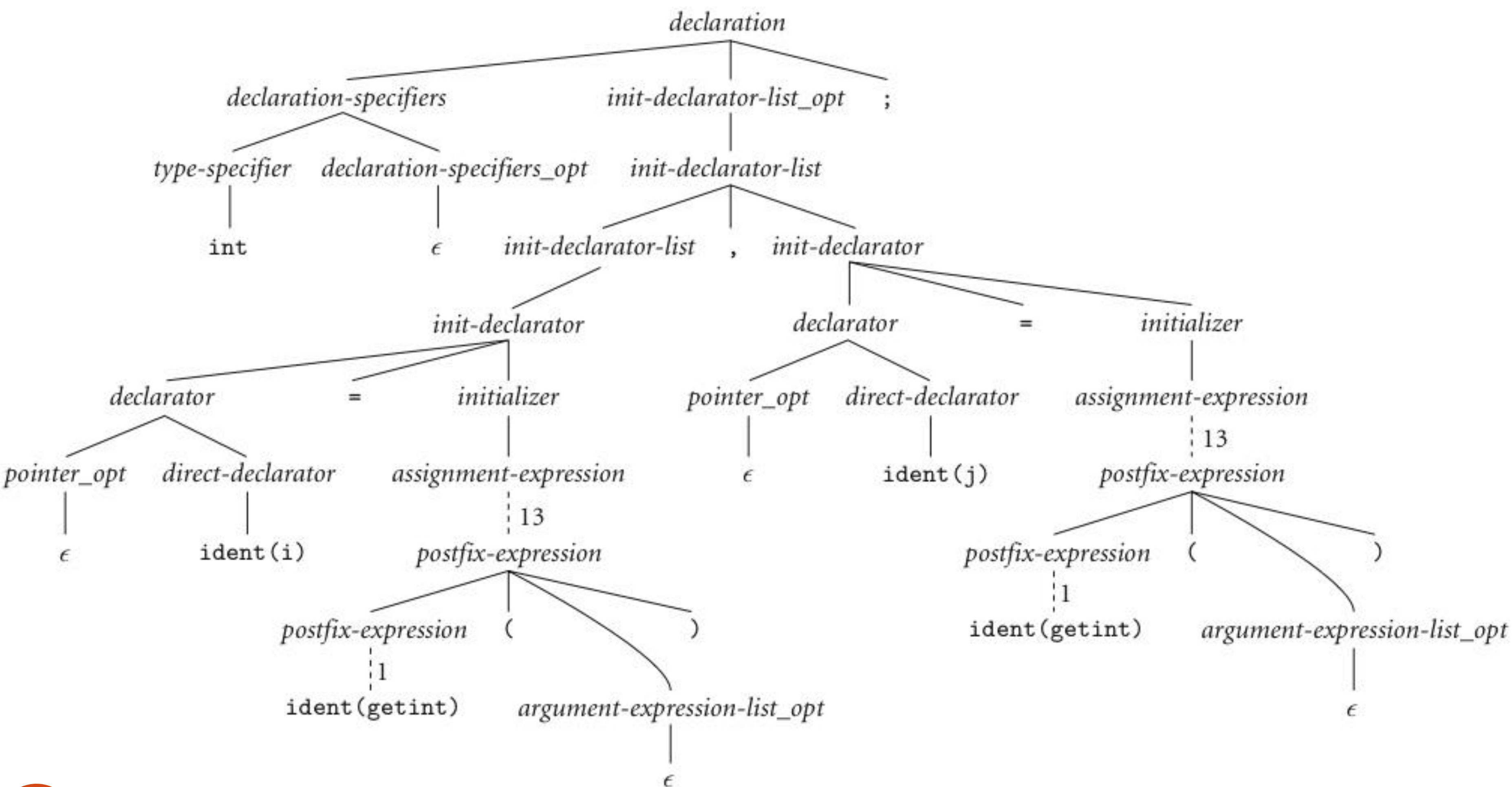
An Overview of Compilation

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



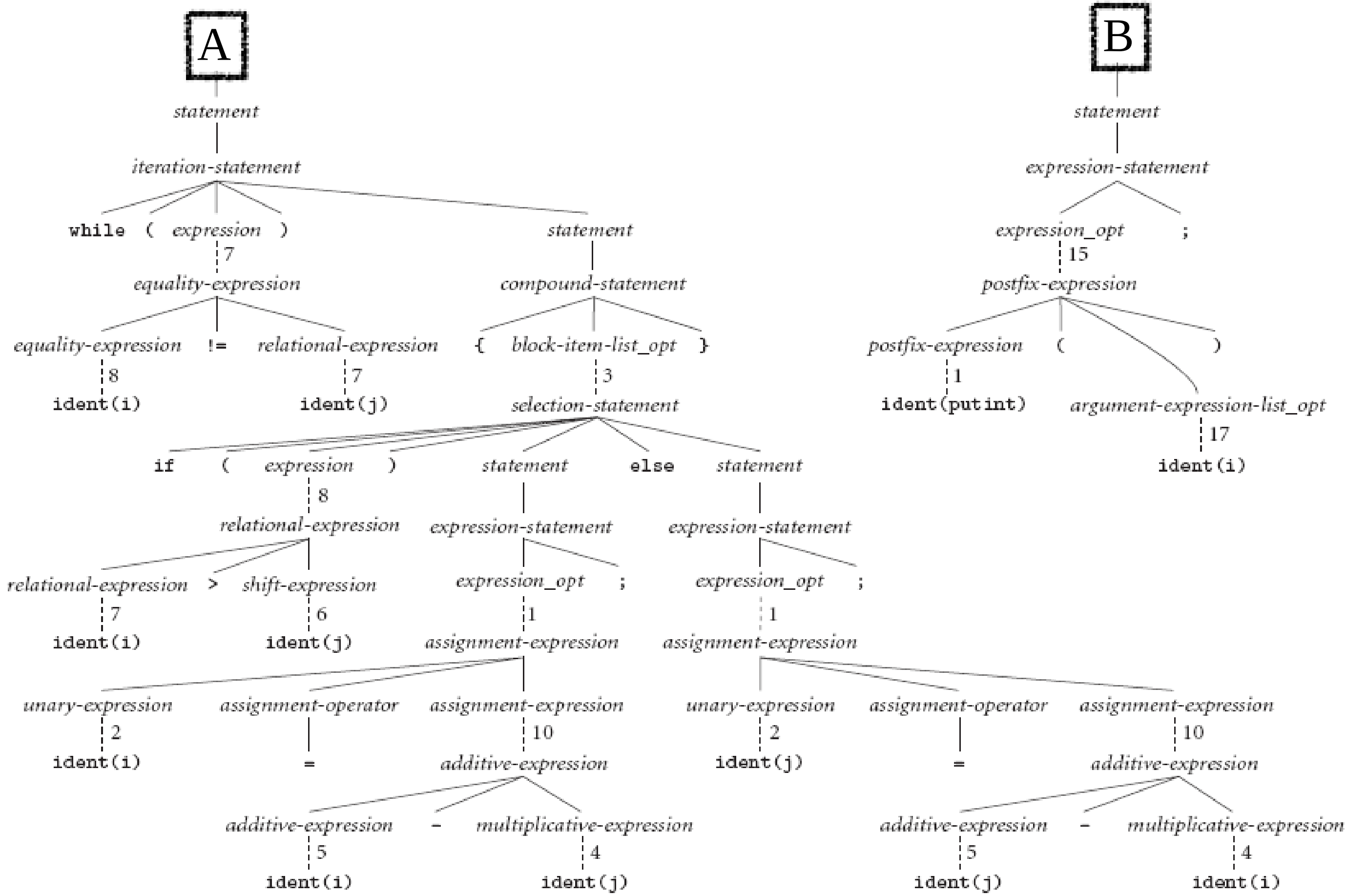
An Overview of Compilation

- Context-Free Grammar and Parsing (continued)



An Overview of Compilation

- Context-Free Grammar and Parsing (continued)



An Overview of Compilation

- ***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

- **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

- **Semantic Analysis and Intermediate Code Generation**
  - Semantic analysis is the discovery of meaning in a program
    - tracks the types of both identifiers and expressions
      - builds and maintains a *symbol table* data structure that maps each identifier to the information known about it
    - context checking
      - Every identifier is declared before it is used
      - No identifier is used in an inappropriate context (e.g., adding a string to an integer)
      - Subroutine calls provide the correct number and types of arguments.
      - Labels on the arms of a switch statement are distinct constants.
      - Any function with a non-void return type returns a value explicitly

An Overview of Compilation

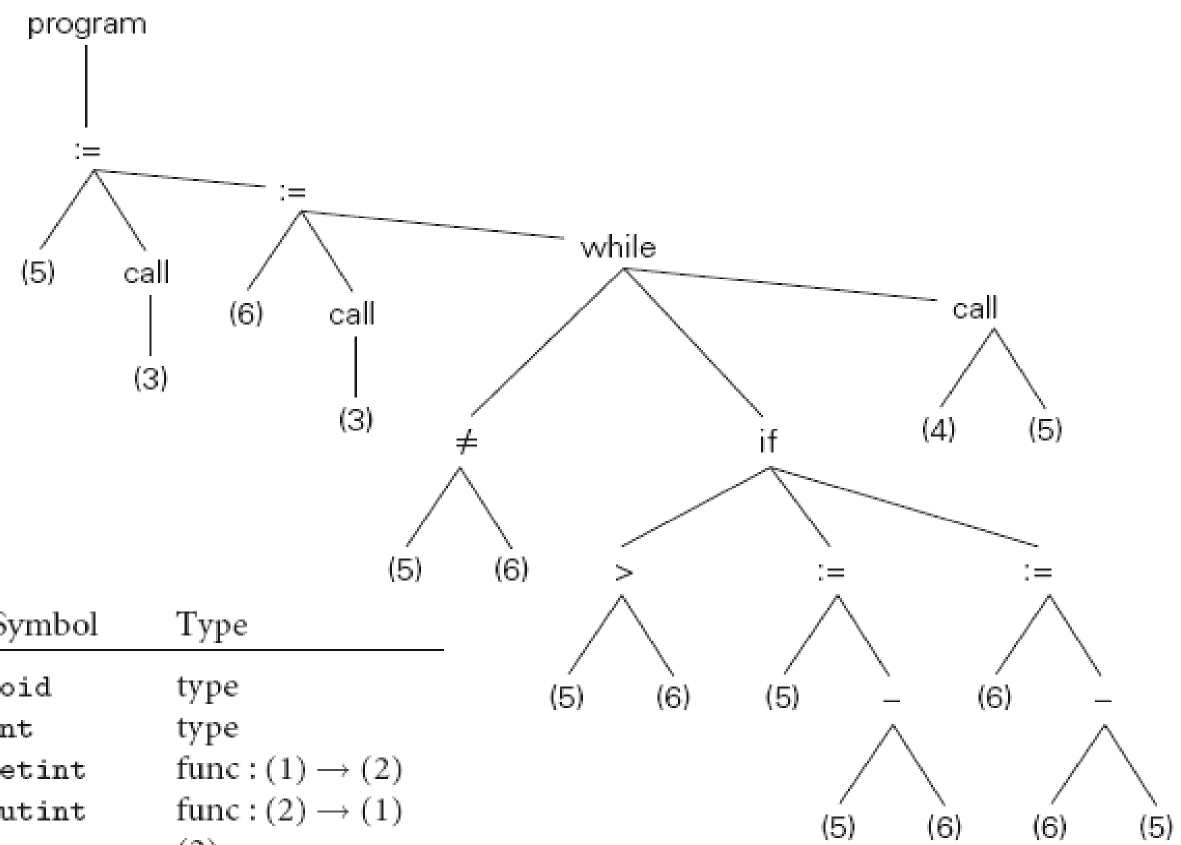
- **Semantic analysis implementation**
  - *semantic action routines* are invoked by the parser when it realizes that it has reached a particular point within a grammar rule.
- Not all semantic rules can be checked at compile time: only the *static semantics* of the language
  - the *dynamic semantics* of the language must be checked at run time
    - Array subscript expressions lie within the bounds of the array
    - Arithmetic operations do not overflow

An Overview of Compilation

- Semantic Analysis and Intermediate Code Generation
  - **The parse tree is very verbose**: once we know that a token sequence is valid, **much of the information in the parse tree is irrelevant to further phases of compilation**
  - The semantic analyzer typically transforms the parse tree into an ***abstract syntax tree*** (***AST*** or simply a ***syntax tree***) by removing most of the "artificial" nodes in the tree's interior
  - The semantic analyzer also ***annotates*** the remaining nodes with useful information, such as pointers from identifiers to their symbol table entries
    - The annotations attached to a particular node are known as its *attributes*

An Overview of Compilation

- GCD Syntax Tree (AST)



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)

An Overview of Compilation

- In many compilers, the annotated syntax tree constitutes the ***intermediate form*** that is passed from the front end to the back end.
- In other compilers, semantic analysis ends with a **traversal** of the tree that generates some other intermediate form
  - One common such form consists of a control flow graph whose nodes resemble fragments of assembly language for a simple idealized machine

An Overview of Compilation

- ***Intermediate Form*** (IF) is 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 <u>**resemble machine code for some imaginary idealized machine**</u>; 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

- **Target Code Generation:**
  - The code generation phase of a compiler translates the intermediate form into the target language
  - To generate assembly or machine language, the code generator traverses the symbol table to assign locations to variables, and then traverses the intermediate representation of the program, generating loads and stores for variable references, interspersed with appropriate arithmetic operations, tests, and branches

An Overview of Compilation

- Target Code Generation:
  - Naive x86 assembly language for the GCD program

```
        pushl   %ebp                # \
        movl    %esp, %ebp          #  ) reserve space for local variables
        subl    $16, %esp           # /
        call    getint              # read
        movl    %eax, -8(%ebp)      # store i
        call    getint              # read
        movl    %eax, -12(%ebp)     # store j
A:      movl    -8(%ebp), %edi      # load i
        movl    -12(%ebp), %ebx     # load j
        cmpl    %ebx, %edi          # compare
        je      D                   # jump if i == j
        movl    -8(%ebp), %edi      # load i
        movl    -12(%ebp), %ebx     # load j
        cmpl    %ebx, %edi          # compare
        jle     B                   # jump if i < j
        movl    -8(%ebp), %edi      # load i
        movl    -12(%ebp), %ebx     # load j
        subl    %ebx, %edi          # i = i - j
        movl    %edi, -8(%ebp)      # store i
        jmp     C
B:      movl    -12(%ebp), %edi     # load j
        movl    -8(%ebp), %ebx      # load i
        subl    %ebx, %edi          # j = j - i
        movl    %edi, -12(%ebp)     # store j
C:      jmp     A
D:      movl    -8(%ebp), %ebx      # load i
        push    %ebx                # push i (pass to putint)
        call    putint              # write
        addl    $4, %esp            # pop i
        leave                       # deallocate space for local variables
        mov     $0, %eax            # exit status for program
        ret                         # return to operating system
```

An Overview of Compilation

- Some improvements are machine independent
- Other improvements require an understanding of the target machine
- Code improvement often appears as two phases of compilation, one immediately after semantic analysis and intermediate code generation, <u>the other immediately after target code generation</u>