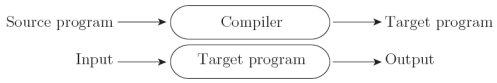
The Design and Implementation of Programming Languages

In Text: Chapter 1

Language Implementation Methods

- Compilation
- Interpretation
- Hybrid

Compilation



- Translate high-level programs to machine code
- Slow translation
- Fast execution

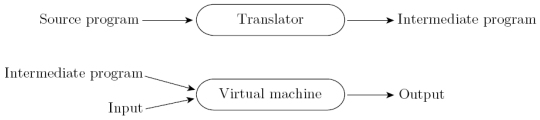
Interpretation

- Interpret one statement and then execute it on a virtual machine
- No translation
- Slow execution
- E.g., Basic

Compilation vs. Interpretation

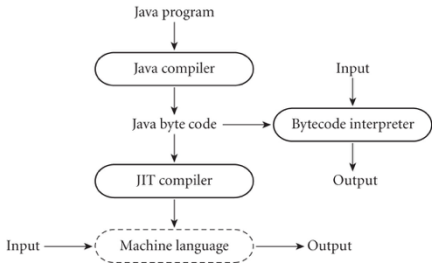
- Compilation
  - Better performance
    - No runtime cost for interpretation
    - Program optimization
- Interpretation
  - Better diagnosis (with excellent source-level debugger)
  - Earlier diagnosis (execute erroneous program)

Hybrid Implementation



- Quick start in "Interpretation" mode
- Compile code on hot paths to speed up
  - E.g., Just-in-Time (JIT) compiler in Java Virtual Machine (JVM)

Hybrid Implementation (Java)



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Implementation Strategies in Practice

- Preprocessing
- Library routines and linking
- Post-compilation assembly
- Source-to-source translation
- Bootstrapping

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Preprocessing (Basic)

- An initial translator
  - to remove comments and white spaces,
  - to group characters together into tokens such as keywords, identifiers, numbers, and symbols,
  - to expand abbreviations in the style of a macro assembler, and
  - to identify higher-level syntactic structures, such as loops and subroutines
- Goal
  - To provide an intermediate form that mirrors the structure of the source, but can be interpreted more efficiently

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Preprocessing (C)

- Conditional compilation
  - Delete portions of code to allow several versions of a program to be built from the same source

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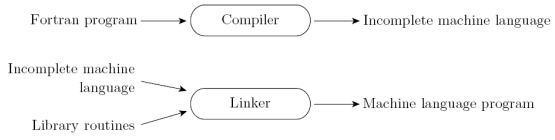
Library routines and linking (Fortran)

- The compilation of source code counts on the existence of a library of subroutines invoked by the program



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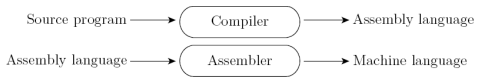
Post-compilation assembly (gcc)

- Source code is first compiled to assembly code, and then the assembler translates it to machine code
  - To facilitate debugging (assembly code is easier to read)
  - To isolate the compiler from changes in the format of machine language files (only the commonly shared assembler must be changed)



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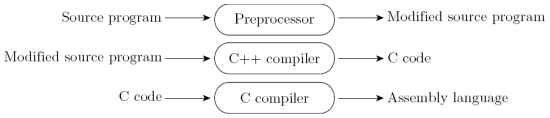
Source-to-Source Translation

- AT&T C++ compiler
  - To translate C++ programs to C programs
  - To facilitate reuse of compilers or language support



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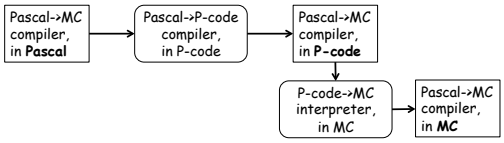
Bootstrapping

- Many compilers are self-hosting:
  - They are written in the language they compile
  - Bootstrapping is used to compile the compiler in the first place



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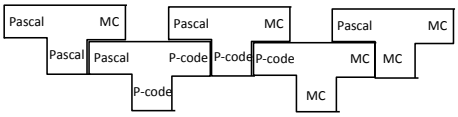

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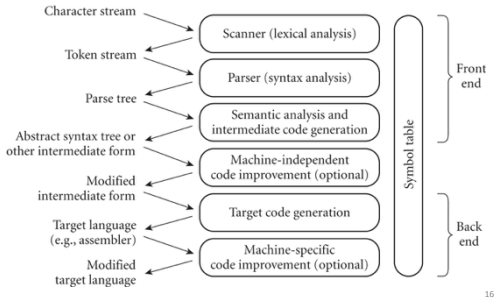
Overview of Compilation



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Front end & back end

- Front end
  - To analyze the source code in order to build an internal representation (IR) of the program
  - It includes: lexical analysis, syntactic analysis, and semantic analysis
- Back end
  - To gather and analyze program information from IR, to optimize the code, and to generate machine code
  - It includes: optimization and code generation

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Scanning (Lexical Analysis)

- Break the program into "tokens"—the smallest meaningful units
  - This can save time, since character-by-character processing is slow
- We can tune the scanner better
  - E.g., remove spaces & comments
- A scanner uses a Deterministic Finite Automaton (DFA) to recognize tokens

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A running example: Greatest Common Divisor (GCD)

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

Token sequence:

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

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Parsing

- Organize tokens into a parse tree that represents higher-level constructs (statements, expressions, subroutines)
  - Each construct is a node in the tree
  - Each construct's constituents are its children

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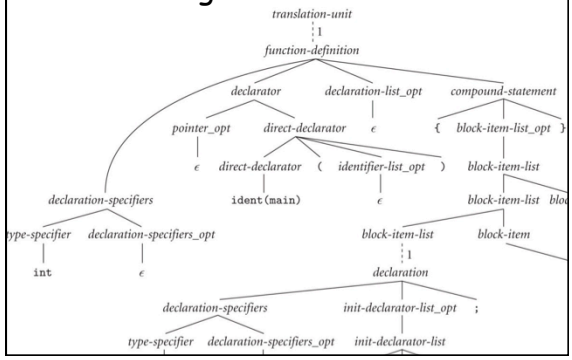
GCD Parsing Tree



Semantic Analysis

- Determine the meaning of a program
- A semantic analyzer builds and maintains a symbol table data structure that maps each identifier to the information known about it, such as the identifier's type, internal structure, and scope

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Semantic Analysis

- With the symbol table, the semantic analyzer can enforce a large variety of rules to check for errors
- Sample rules:
  - Each identifier is declared before it is used
  - Any function with a non-void return type returns a value explicitly
  - Subroutine calls provide the correct number and types of arguments

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Semantic Analysis

- Static semantics
  - Rules that can be checked at compile time
- Dynamic semantics
  - Rules that must be checked at run time, such as
    - Variables should never be used in an expression unless they have been given a value
    - Pointers should never be dereferenced unless they refer to a valid object

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Syntax Tree

- A parse tree is known as a **concrete syntax tree**
  - It demonstrates concretely, how a particular sequence of tokens can be derived under the rule of the context-free grammar
- However, much of the information in a concrete syntax tree is irrelevant
  - E.g., ε under some branches

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Syntax Tree

- In the process of checking static semantic rules, a semantic analyzer transforms the parse tree into an **abstract syntax tree (AST, or syntax tree)** by
  - removing "unimportant" nodes, and
  - annotating remaining nodes with information like pointers from identifiers to their symbol table entries

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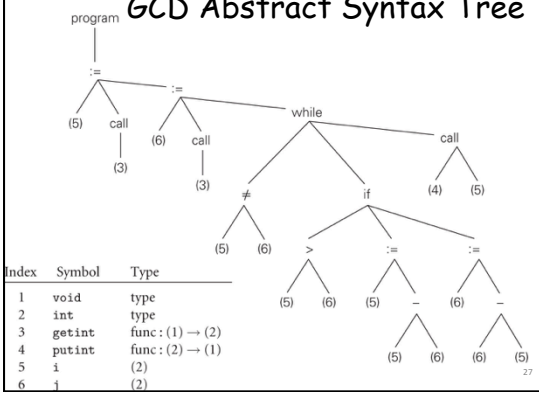
GCD Abstract Syntax Tree



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)

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Intermediate Form (IF)

- Generated after semantic analysis
  - In many compilers, an **AST** is passed as IF from the front end to the back end
  - In other compilers, a **control flow graph** is passed as IF

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Optimization [1]

- High-level optimization
  - Goal: perform high-level analysis and optimization of programs
  - Input: AST + symbol table
  - Output: low-level program representation, such as 3-address code(TAC)
  - Tasks:
    - Procedure/method inlining
    - Array/pointer dependence analysis
    - Loop transformations: unrolling, permutation, …

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Optimization [1]

- Low-level optimization
  - Goal: perform low-level analysis and optimizations
  - Input: low-level representation of programs, such as 3-address code
  - Output: optimized low-level representation, and additional information, such as def-use chains
  - Tasks:
    - Dataflow analysis: live variables, reaching definitions, …
    - Scalar optimizations: constant propagation, partial redundancy elimination, …

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Code Generator [1]

- Goal: produce assembly/machine code from optimized low-level representation of programs
- Tasks:
  - Register allocation
  - Instruction selection

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Reference

[1] Keshav Pingali, Advanced Topics in Compilers, https://www.cs.utexas.edu/~pingali/CS380C/2013/lectures/intro.pdf

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