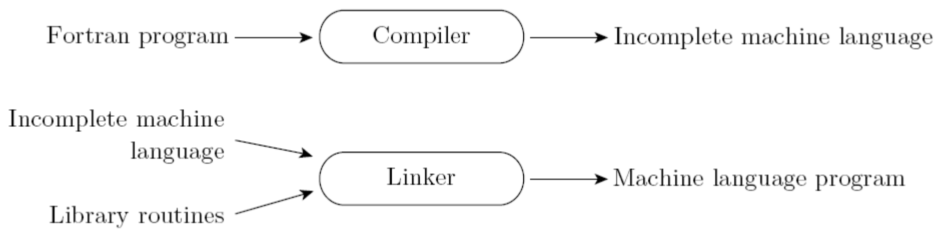
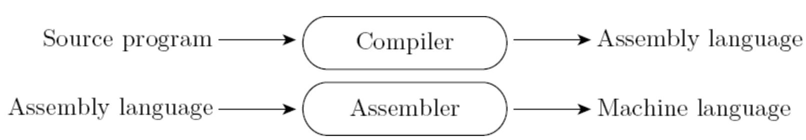
Library routines and linking (Fortran)

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



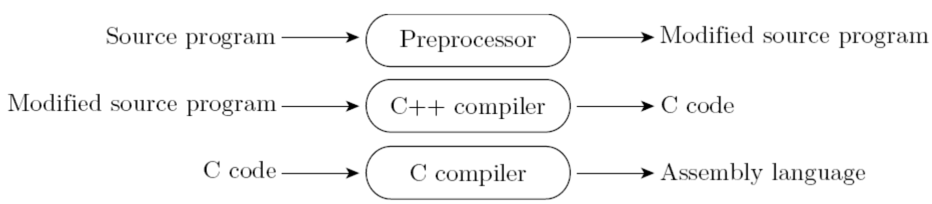
Post-compilation assembly (gcc)

- 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)



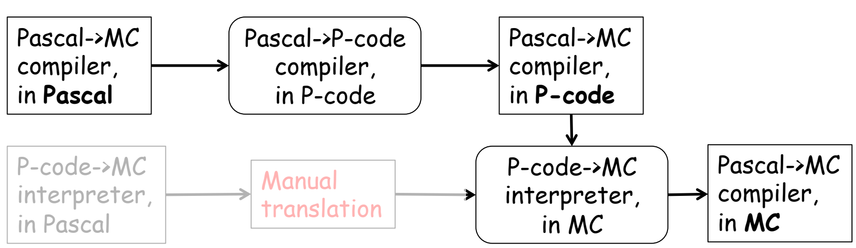
Source-to-Source Translation

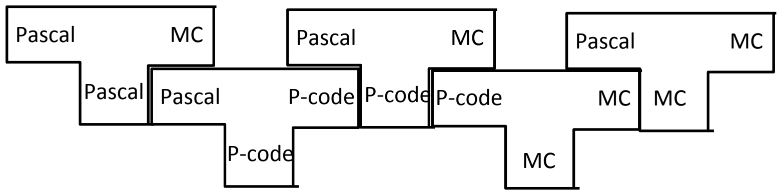
- AT&T C++ compiler
  - To translate C++ programs to C programs
  - To facilitate reuse of compilers or language support



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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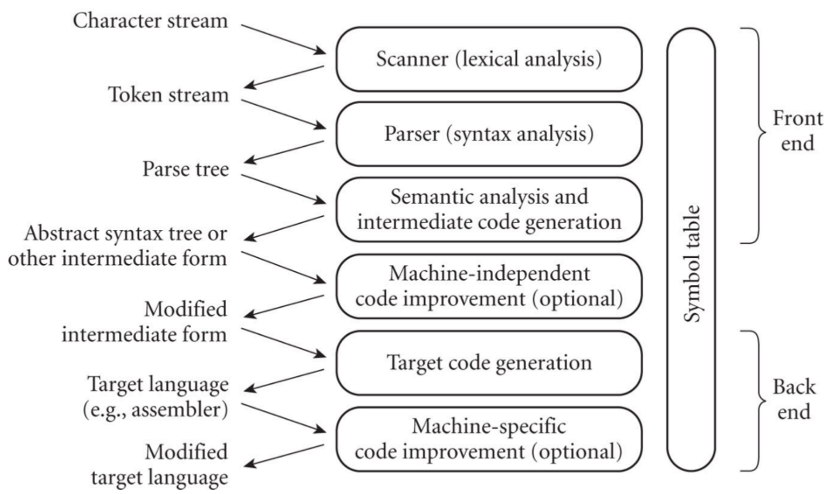
Overview of Compilation



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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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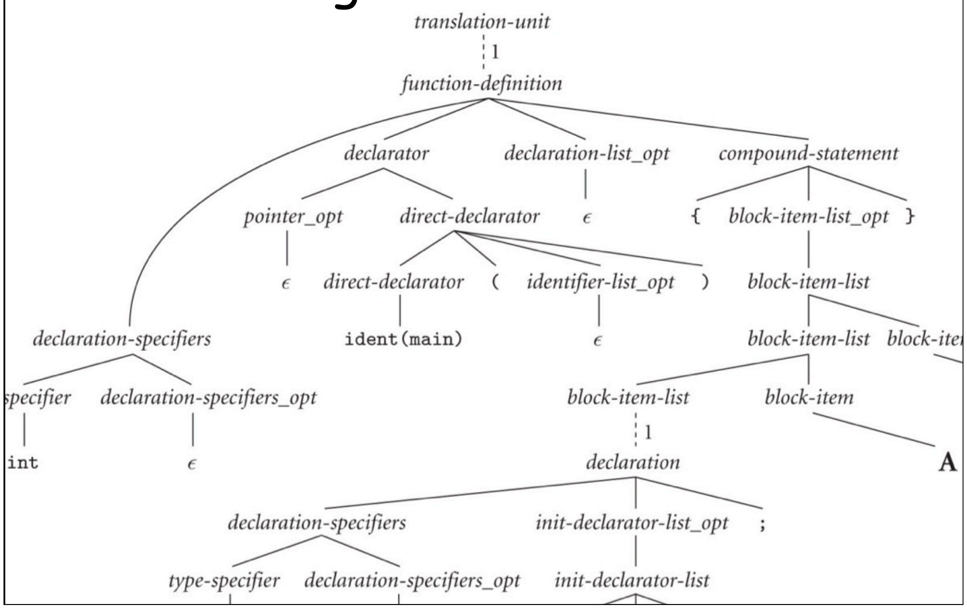
GCD Parsing Tree



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 are never used in an expression unless they have been given a value
    - Pointers are never dereferenced unless they refer to a valid object

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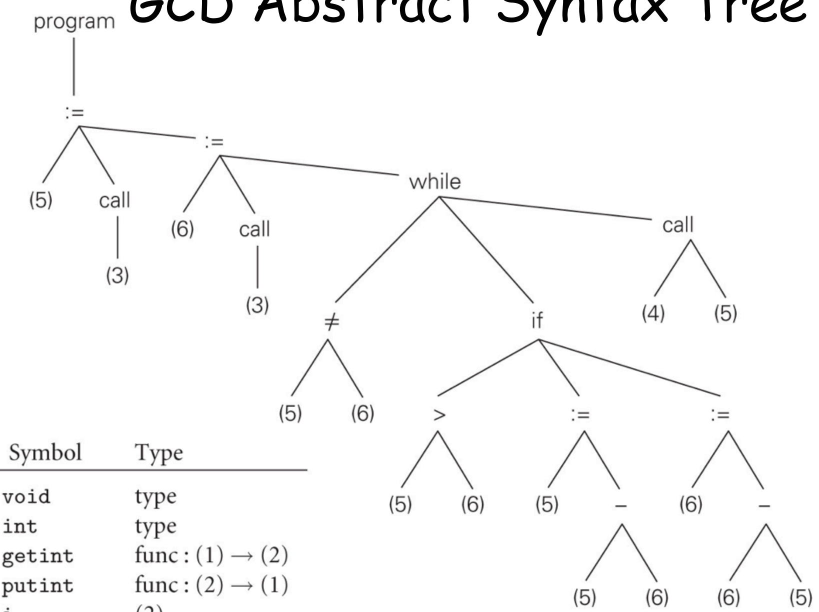
Syntax Tree

- 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

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

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
  - 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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Programming Language Syntax

In Text: Chapter 2

Outline

- Basic concepts
  - Programming language, regular expression, context-free grammars
- Lexical analysis
  - Scanner, Deterministic finite automaton (DFA)
- Syntactic analysis
  - Parser

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What is a "Language"?

- A language is a set of strings of symbols that are constrained by rules
- A **sentence** is a string of symbols
- **Syntax** (Grammar)
  - To describe the structure of a language
- **Semantics**
  - To describe the meaning or sentences, phrases, or words

Natural languages are ambiguous

- "I saw a man on a hill with a telescope"
- Programming languages should be precise and unambiguous
  - Both programmers and computers can tell what a program is supposed to do