COMPILER CONSTRUCTION

Principles and Practice

Kenneth C. Louden

Content

Main Reference

Book:

Compiler Construction Principles and Practice

Kenneth C. Louden

1. INTRODUCTION

What is a compiler?

- A computer program translates one language to another

Source Program $\longrightarrow$ Compiler $\longrightarrow$ Target Program

- A compiler is a complex program
    - From 10,000 to 1,000,000 lines of codes
- Compilers are used in many forms of computing
    - Command interpreters, interface programs

What is the purpose of this text

- This text is to provide basic knowledge
  - Theoretical techniques, such as automata theory
- This text is to give necessary tools and practical experience
  - A series of simple examples
  - TINY, C-Minus

Main Topics

1.1 Why Compilers? A Brief History [Open]
1.2 Programs Related to Compilers [Open]

1.3 The Translation Process [Open]
1.4 Major Data Structures in a Compiler [Open]

1.5 Other Issues in Compiler Structure [Open]
1.6 Bootstrapping and Porting [Open]

1.7 The TINY Sample Language and Compiler [Open]
1.8 C-Minus: A Language for a Compiler Project [Open]

1.1 Why? A Brief History

Why Compiler

- Writing machine language-numeric codes is time consuming and tedious

C7 06 0000 0002

Mov x, 2

X=2

- The assembly language has a number of defects
  - Not easy to write
  - Difficult to read and understand

Brief History of Compiler

- The first compiler was developed between 1954 and 1957
  - The FORTRAN language and its compiler by a team at IBM led by John Backus
  - The structure of natural language was studied at about the same time by Noam Chomsky

Brief History of Compiler

- The related theories and algorithms in the 1960s and 1970s
  - The classification of language: Chomsky hierarchy
  - The parsing problem was pursued:
    - Context-free language, parsing algorithms
  - The symbolic methods for expressing the structure of the words of a programming language:
    - Finite automata, Regular expressions
  - Methods have been developed for generating efficient object code:
    - Optimization techniques or code, improvement techniques

Brief History of Compiler

- Programs were developed to automate the complier development for parsing
  - Parser generators,
    - such as Yacc by Steve Johnson in 1975 for the Unix system
  - Scanner generators,
    - such as Lex by Mike Lesk for Unix system about same time

Brief History of Compiler

- Projects focused on automating the generation of other parts of a compiler
  - Code generation was undertaken during the late 1970s and early 1980s
  - Less success due to our less than perfect understanding of them

Brief History of Compiler

- Recent advances in compiler design
  - More sophisticated algorithms for inferring and/or simplifying the information contained in program,
    - such as the unification algorithm of Hindley-Milner type checking
  - Window-based Interactive Development Environment,
    - IDE, that includes editors, linkers, debuggers, and project managers.
  - However, the basic of compiler design have not changed much in the last 20 years.

BACK

1.2 Programs related to Compiler

Interpreters

- Execute the source program immediately rather than generating object code
- Examples: BASIC, LISP, used often in educational or development situations
- Speed of execution is slower than compiled code by a factor of 10 or more
- Share many of their operations with compilers

Assemblers

- A translator for the assembly language of a particular computer
- Assembly language is a symbolic form of one machine language
- A compiler may generate assembly language as its target language and an assembler finished the translation into object code

Linkers

- Collect separate object files into a directly executable file
- Connect an object program to the code for standard library functions and to resource supplied by OS
- Becoming one of the principle activities of a compiler, depends on OS and processor

Loaders

- Resolve all re-locatable address relative to a given base
- Make executable code more flexible
- Often as part of the operating environment, rarely as an actual separate program

Preprocessors

- Delete comments, include other files, and perform macro substitutions
- Required by a language (as in C) or can be later add-ons that provide additional facilities

Editors

- Compiler have been bundled together with editor and other programs into an interactive development environment (IDE)
- Oriented toward the format or structure of the programming language, called structure-based
- May include some operations of a compiler, informing some errors

Debuggers

- Used to determine execution error in a compiled program
- Keep tracks of most or all of the source code information
- Halt execution at pre-specified locations called breakpoints
- Must be supplied with appropriate symbolic information by the compiler

Profilers

- Collect statistics on the behavior of an object program during execution
  - Called Times for each procedures
  - Percentage of execution time
- Used to improve the execution speed of the program

Project Managers

- Coordinate the files being worked on by different people, maintain coherent version of a program
- Language-independent or bundled together with a compiler
- Two popular project manager programs on Unix system
  - Sccs (Source code control system)
  - Rcs (revision control system)

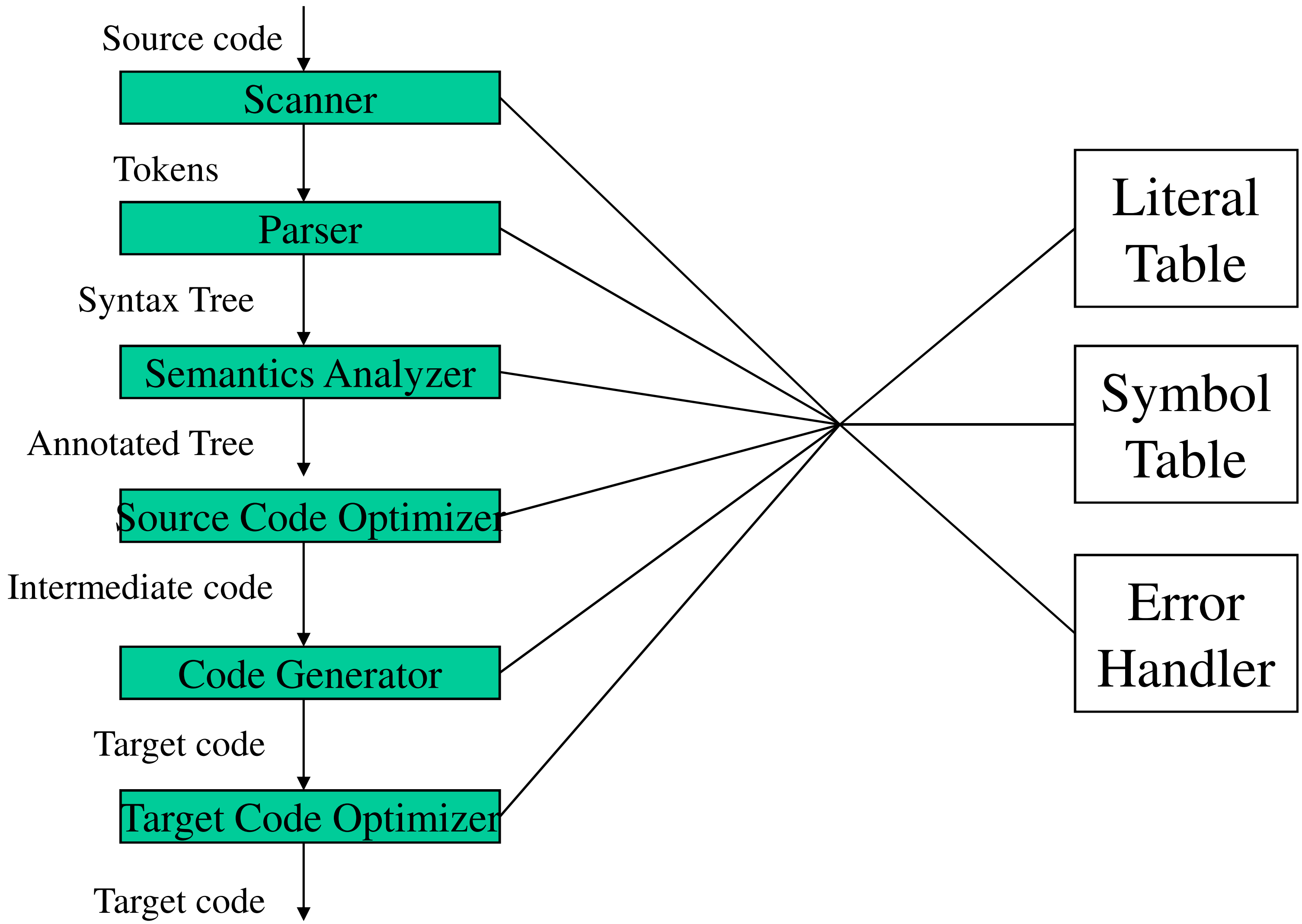
BACK

1.3 The Translation Process

The Phases of a Compiler

- Six phases
  - Scanner
  - Parser
  - Semantic Analyzer
  - Source code optimizer
  - Code generator
  - Target Code Optimizer
- Three auxiliary components
  - Literal table
  - Symbol table
  - Error Handler

The Phases of a Compiler



The Scanner

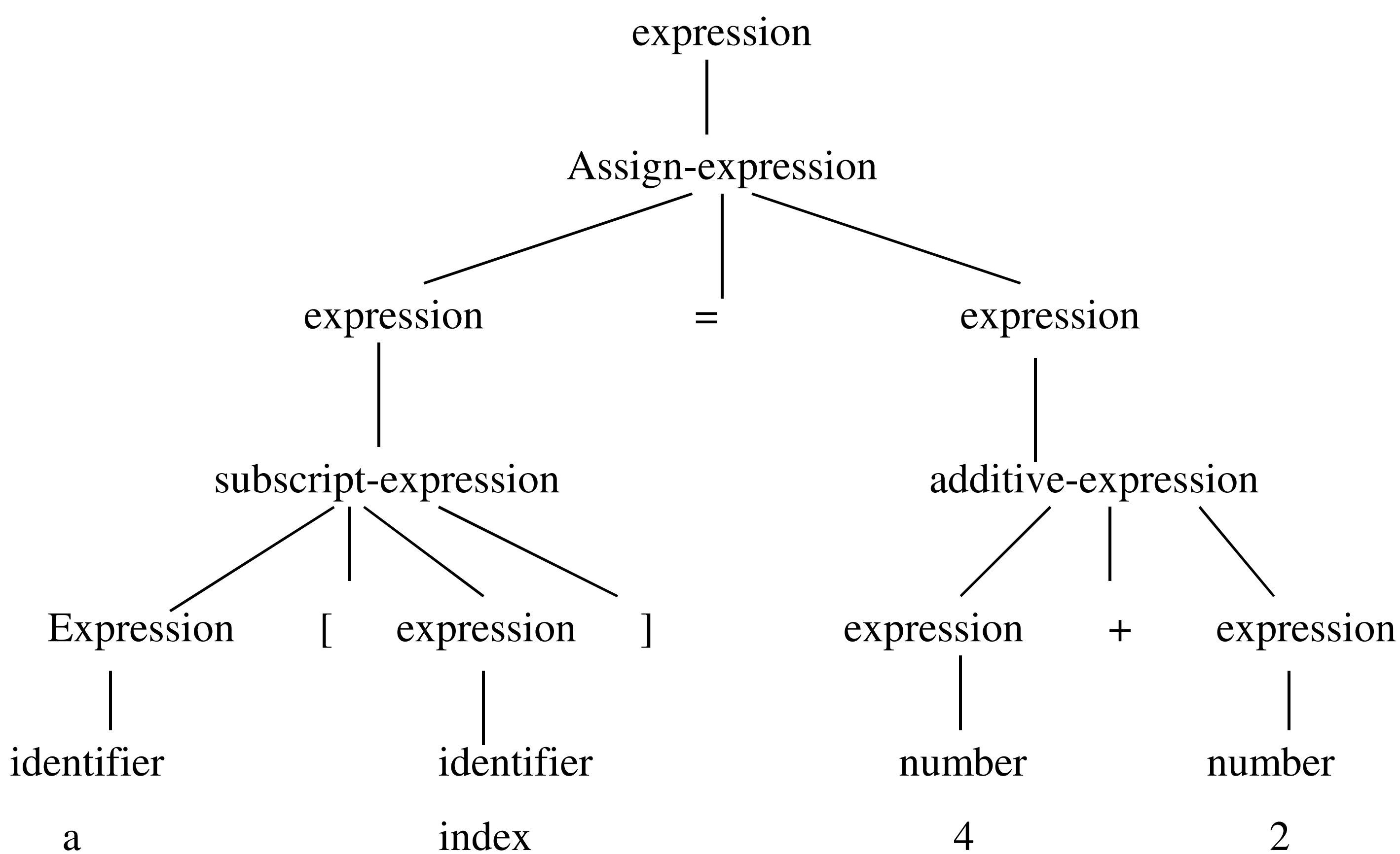
- Lexical analysis: it collects sequences of characters into meaningful units called tokens
- An example: a[index]=4+2
  - a — identifier
  - [— left bracket
  - index — identifier
  -] — right bracket
  - = — assignment
  - 4 — number
  - + — plus sign
  - 2 — number
- Other operations: it may enter literals into the literal table

RETURN

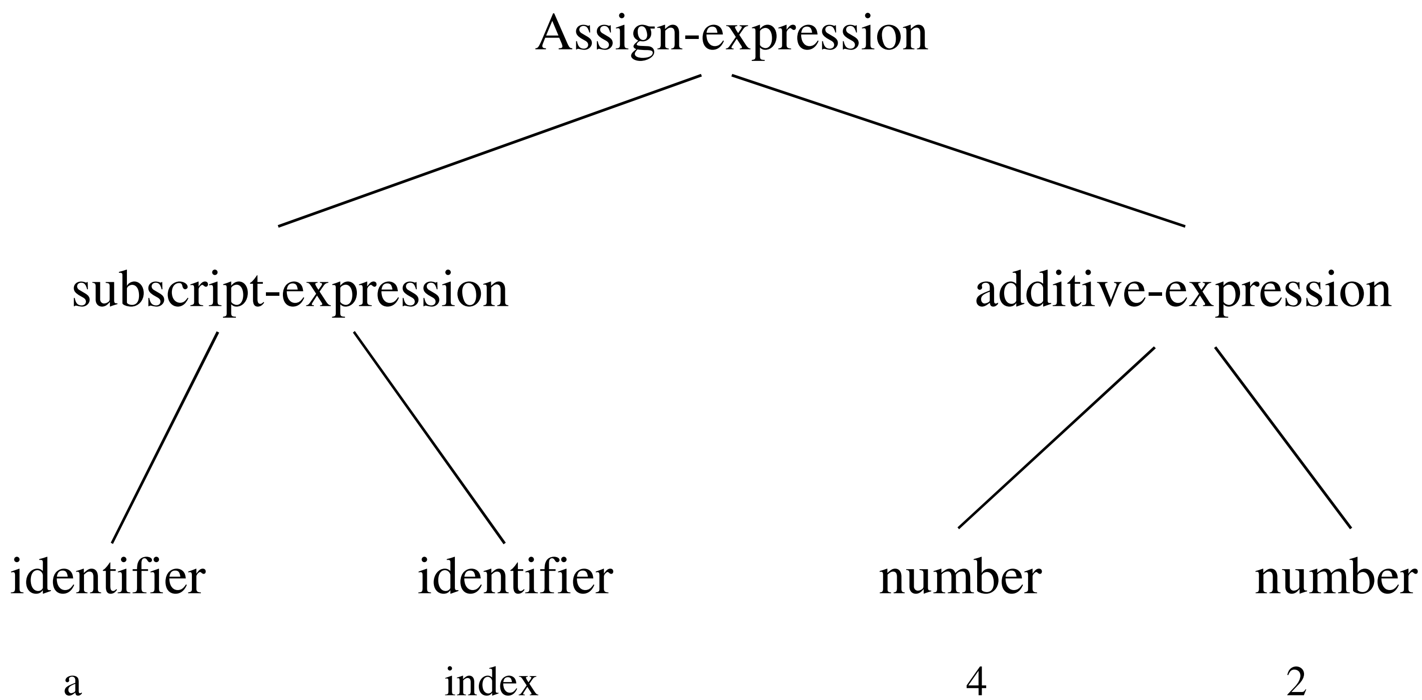
The Parser

- Syntax analysis: it determines the structure of the program
- The results of syntax analysis are a parse tree or a syntax tree
- An example: a[index]=4+2
  - Parse tree
  - Syntax tree (abstract syntax tree)

The Parse Tree



The Syntax Tree

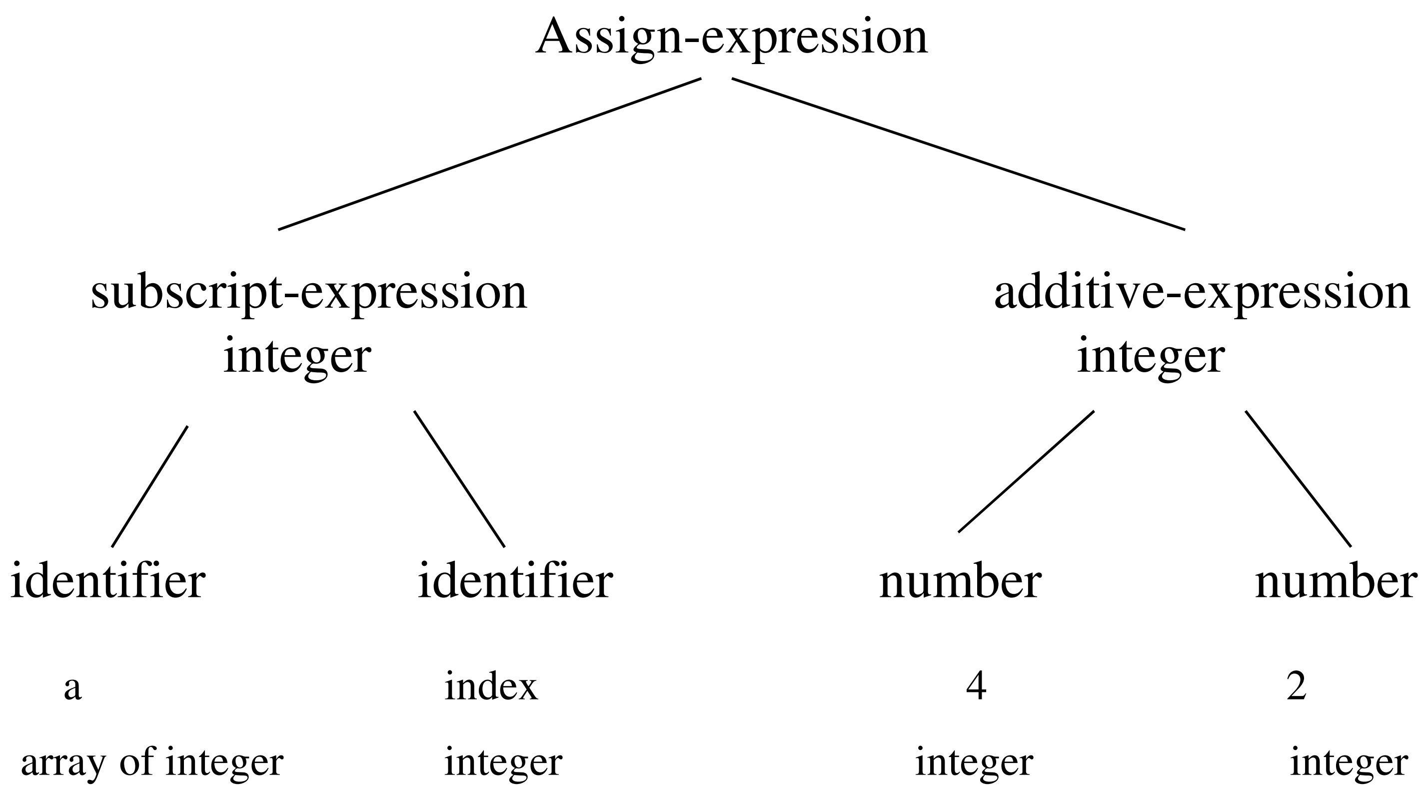


RETURN

The Semantic Analyzer

- The semantics of a program are its “meaning”, as opposed to its syntax, or structure, that
  - determines some of its running time behaviors prior to execution.
- Static semantics: declarations and type checking
- Attributes: The extra pieces of information computed by semantic analyzer
- An example: a[index]=4+2
  - The syntax tree annotated with attributes

The Annotated Syntax Tree

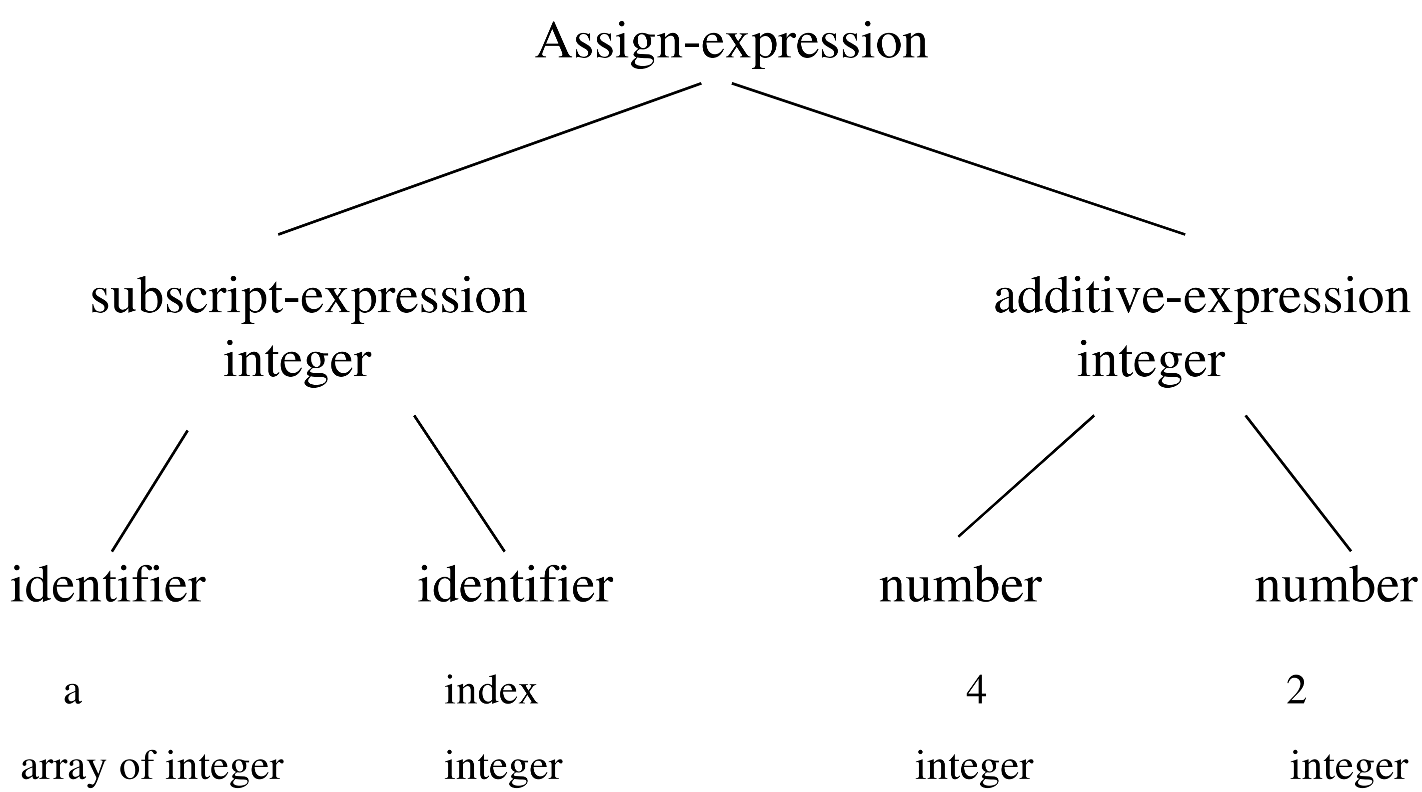


RETURN

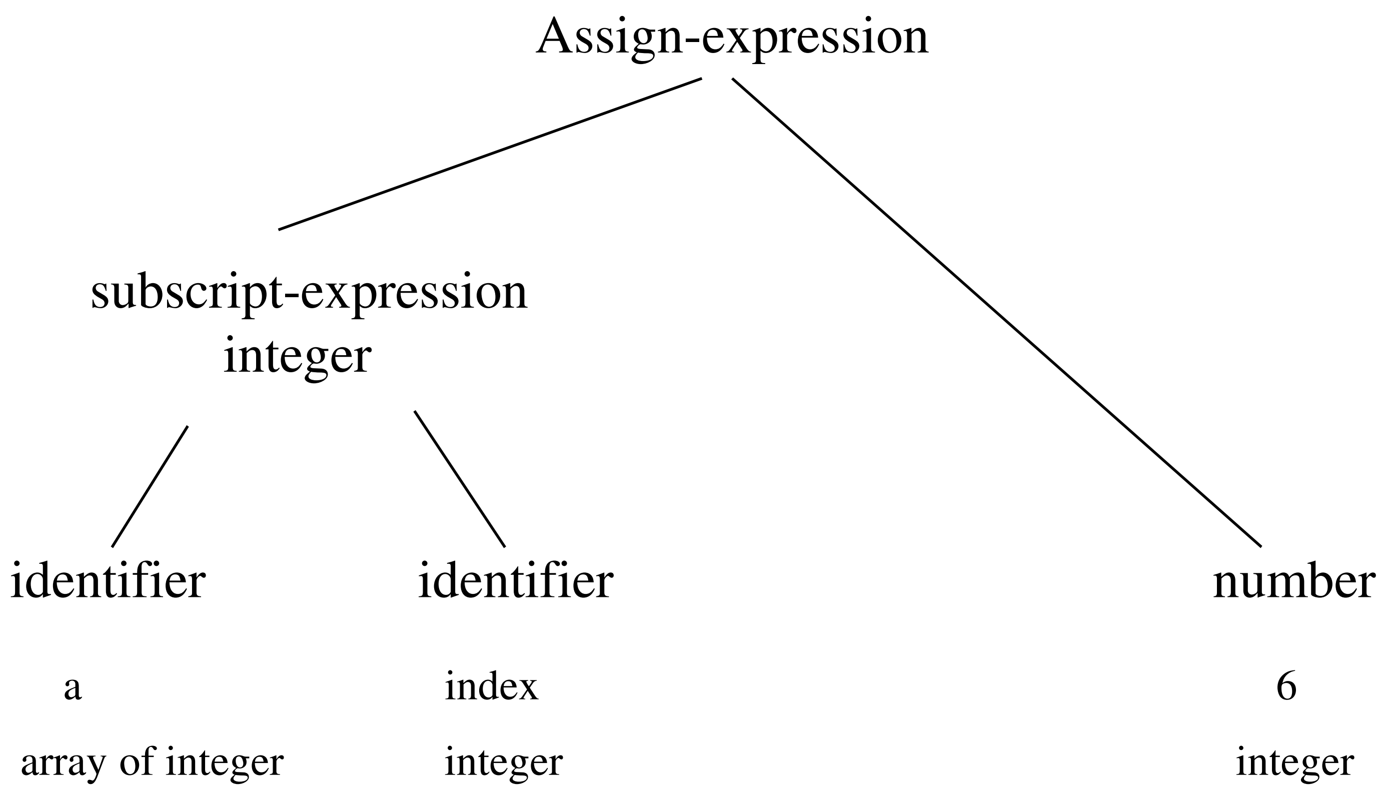
The Source Code Optimizer

- The earliest point of most optimization steps is just after semantic analysis
- The code improvement depends only on the source code, and as a separate phase
- Individual compilers exhibit a wide variation in optimization kinds as well as placement
- An example: a[index]=4+2
  - Constant folding performed directly on annotated tree
  - Using intermediate code: three-address code, p-code

Optimizations on Annotated Tree



Optimizations on Annotated Tree



Optimization on Intermediate Code

```
t = 4 + 2
a[index]=t
```

↓

```
t = 6
a[index]=t
```

↓

```
a[index]=6
```

RETURN

The Code Generate

- It takes the intermediate code or IR and generates code for target machine
- The properties of the target machine become the major factor:
  - Using instructions and representation of data
- An example: a[index]=4+2
  - Code sequence in a hypothetical assembly language

A possible code sequence

a[index]=6

```
MOV R0, index
MUL R0,2
MOV R1,&a
ADD R1,R0
MOV *R1,6
```

RETURN

The Target Code Optimizer

- It improves the target code generated by the code generator:
  - Address modes choosing
  - Instructions replacing
  - As well as redundant eliminating

```
MOV R0, index
MUL R0,2
MOV R1,&a
ADD R1,R0
MOV *R1,6
```

→

```
MOV R0, index
SHL R0
MOV &a[R0],6
```

BACK

1.4 Major Data Structure in a Compiler

Principle Data Structure for Communication among Phases

- TOKENS
  - A scanner collects characters into a token, as a value of an enumerated data type for tokens
  - May also preserve the string of characters or other derived information, such as name of identifier, value of a number token
  - A single global variable or an array of tokens
- THE SYNTAX TREE
  - A standard pointer-based structure generated by parser
  - Each node represents information collect by parser or later, which maybe dynamically allocated or stored in symbol table
  - The node requires different attributes depending on kind of language structure, which may be represented as variable record.

Principle Data Structure for Communication among Phases

- THE SYMBOL TABLE
  - Keeps information associated with identifiers: function, variable, constants, and data types
  - Interacts with almost every phase of compiler.
  - Access operation need to be constant-time
  - One or several hash tables are often used,
- THE LITERAL TABLE
  - Stores constants and strings, reducing size of program
  - Quick insertion and lookup are essential

Principle Data Structure for Communication among Phases

- INTERMEDIATE CODE
  - Kept as an array of text string, a temporary text, or a linked list of structures, depending on kind of intermediate code (e.g. three-address code and p-code)
  - Should be easy for reorganization
- TEMPORARY FILES
  - Holds the product of intermediate steps during compiling
  - Solve the problem of memory constraints or back-patch addressed during code generation

BACK

1.5 Other Issues in Compiler Structure

The Structure of Compiler

- Multiple views from different angles
  - Logical Structure
  - Physical Structure
  - Sequencing of the operations
- A major impact of the structure
  - Reliability, efficiency
  - Usefulness, maintainability

Analysis and Synthesis

- The analysis part of the compiler analyzes the source program to compute its properties
  - Lexical analysis, syntax analysis and semantics analysis, as well as optimization
  - More mathematical and better understood
- The synthesis part of the compiler produces the translated codes
  - Code generation, as well as optimization
  - More specialized
- The two parts can be changed independently of the other

Front End and Back End

- The operations of the front end depend on the source language
  - The scanner, parser, and semantic analyzer, as well as intermediate code synthesis
- The operations of the back end depend on the target language
  - Code generation, as well as some optimization analysis
- The intermediate representation is the medium of communication between them
- This structure is important for compiler portability

Passes

- The repetitions to process the entire source program before generating code are referred as passes.
- Passes may or may not correspond to phases
  - A pass often consists of several phases
  - A compiler can be one pass, which results in efficient compilation but less efficient target code
  - Most compilers with optimization use more than one pass
    - One Pass for scanning and parsing
    - One Pass for semantic analysis and source-level optimization
    - The third Pass for code generation and target-level optimization

Language Definition and compilers

- The lexical and syntactic structure of a programming language
  - regular expressions
  - context-free grammar
- The semantics of a programming language in English descriptions
  - language reference manual, or language definition.

Language Definition and compilers

- A language definition and a compiler are often developed simultaneously
  - The techniques have a major impact on definition
  - The definition has a major impact on the techniques
- The language to be implemented is well known and has an existing definition
  - This is not an easy task

Language Definition and compilers

- A language occasionally has it semantics given by a formal definition in mathematical term
  - So-called denotational semantics in function programming community
  - Given a mathematical proof that a compiler conforms to the definition
- The structure and behavior of the runtime environment affect the compiler construction
  - Static runtime environment
  - Semi-dynamic or stack-based environment
  - Fully-dynamic or heap-based environment

Compiler options and interfaces

- Mechanisms for interfacing with the operation system
  - Input and output facilities
  - Access to the file system of the target machine
- Options to the user for various purposes
  - Specification of listing characteristic
  - Code optimization options

Error Handling

- Static (or compile-time) errors must be reported by a compiler
  - Generate meaningful error messages and resume compilation after each error
  - Each phase of a compiler needs different kind of error handing
- Exception handling
  - Generate extra code to perform suitable runtime tests to guarantee all such errors to cause an appropriate event during execution.

BACK

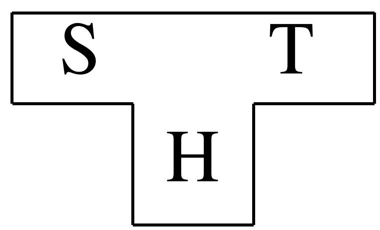
1.6 Bootstrapping and Porting

Third Language for Compiler Construction

- Machine language
  - compiler to execute immediately;
- Another language with existed compiler on the same target machine : (First Scenario)
  - Compile the new compiler with existing compiler
- Another language with existed compiler on different machine : (Second Scenario)
  - Compilation produce a cross compiler

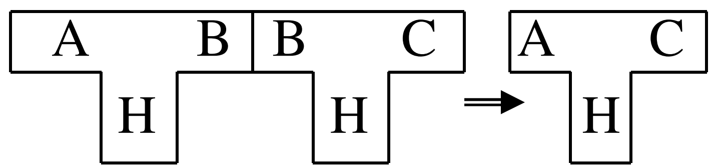
T-Diagram Describing Complex Situation

- A compiler written in language H that translates language S into language T.



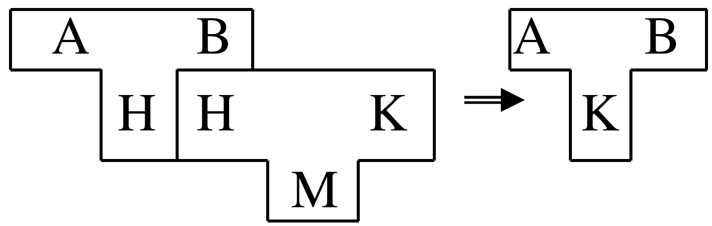
- T-Diagram can be combined in two basic ways.

The First T-diagram Combination



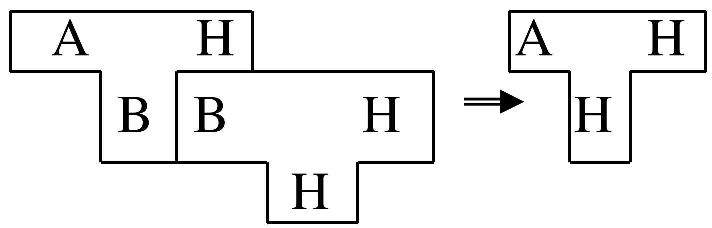
- Two compilers run on the same machine H
  - First from A to B
  - Second from B to C
  - Result from A to C on H

The Second T-diagram Combination



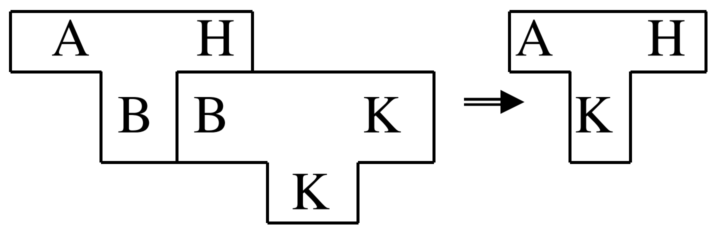
- Translate implementation language of a compiler from H to K
- Use another compiler from H to K

The First Scenario



- Translate a compiler from A to H written in B
  - Use an existing compiler for language B on machine H

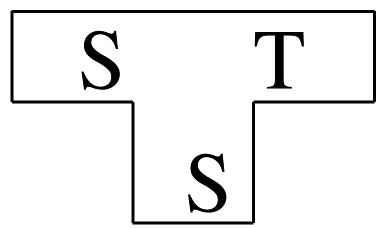
The Second Scenario



- Use an existing compiler for language B on different machine K
  - Result in a cross compiler

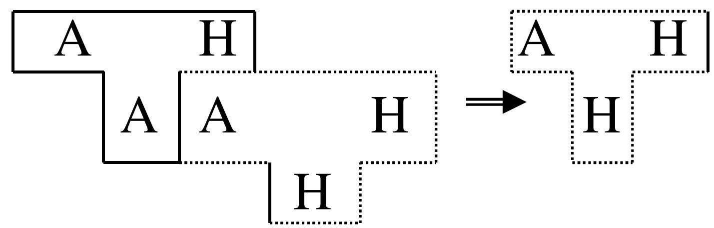
Process of Bootstrapping

- Write a compiler in the same language



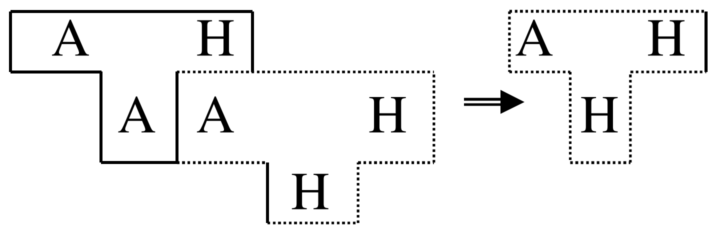
- No compiler for source language yet
- Porting to a new host machine

The First step in bootstrap



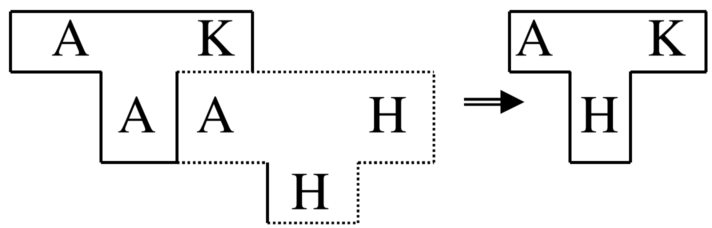
- “quick and dirty” compiler written in machine language H
- Compiler written in its own language A
- Result in running but inefficient compiler

The Second step in bootstrap



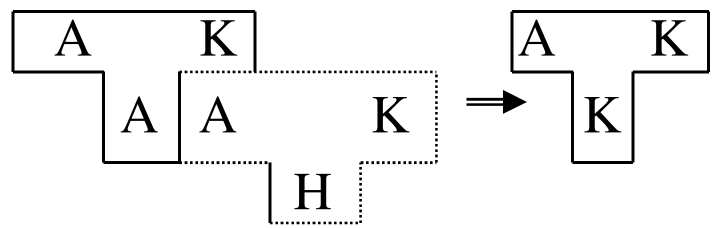
- Running but inefficient compiler
- Compiler written in its own language A
- Result in final version of the compiler

The step 1 in porting



- Original compiler
- Compiler source code retargeted to K
- Result in Cross Compiler

The step 2 in porting



- Cross compiler
- Compiler source code retargeted to K
- Result in Retargeted Compiler

BACK

1.7 The TINY Sample Language and Compiler

Reading this part of text as homework

1.8 C-Minus: A Language for A Compiler Project

Reading this part of text as homework)

End of Chapter One

Thanks