  

Compiler
編譯器原理

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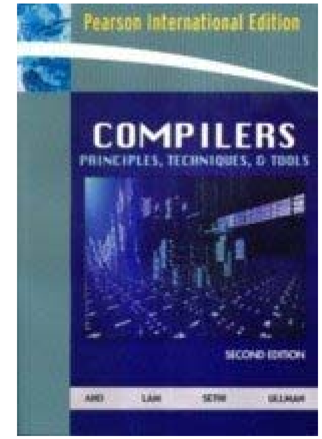
Syllabus



- **授課教師:** 張原豪 (207-2 室、分機 2288)
- **上課時間:** 星期四下午 1:10 – 4:00
- **教室:** 二教 206
- **教科書：**
  - Compilers: Principles, Techniques, and Tools, second edition, 2007
    Authors: Alfred V. Aho, Monica S. Lam, Ravi Sethi, and Jeffrey D. Ullman
    Publisher: Person International Edition
    ISBN: 0-321-49169-6
- **課程網頁:**
  - http://www.ntut.edu.tw/~johnsonchang/ 點 Lecturing 或
  - http://www.ntut.edu.tw/~johnsonchang/courses/Compiler201002/
- **成績評量：**(subject to changes)

  作業: (30%), 期中考(30%), 期末考(30%), 平時表現(10%)
- **需求：**具有 C 或 Java (或其他高階) 程式語言之概念



Overview

- Part 1
  - Introduce motivational material and background issues.
- Part 2
  - Develop a miniature compiler and introduce important concept.
- Part 3
  - Cover lexical analysis, regular expression, finite-state machines, and scanner-generator tools (Lex).
- Part 4
  - Introduce the major parsing methods (top-down LL and bottom-up LR), including the parser generator (Yacc).

Overview (Cont.)

- Part 5
  - Introduce the principal ideas in syntax-directed definition and translation.
- Part 6
  - Use the theory in Part 5 to generate intermediate code.
- Part 7
  - Introduce run-time environment, especially the run-time stack and garbage collection.
- Part 8
  - Object-code generation



Chapter 1
Introduction



Outline

- Language processor
- The structure of a compiler
- The evolution of programming languages
- The science of building a compiler
- Applications of compiler technology
- Programming language basics



Language Processors



Introduction

- Compilers are fundamental to modern computing.
  - The computing world depends on programming languages.
  - Programming languages depend on compilers to translate the source program to target program.
  - The principles and techniques for compiler design are applicable to many other domains.

Source program (e.g., programming language) → Compiler → Target program (e.g., machine language or assembly language)



Language Processors

- Machine-language program as the target program produced by a compiler (faster)

Input → Target program → output

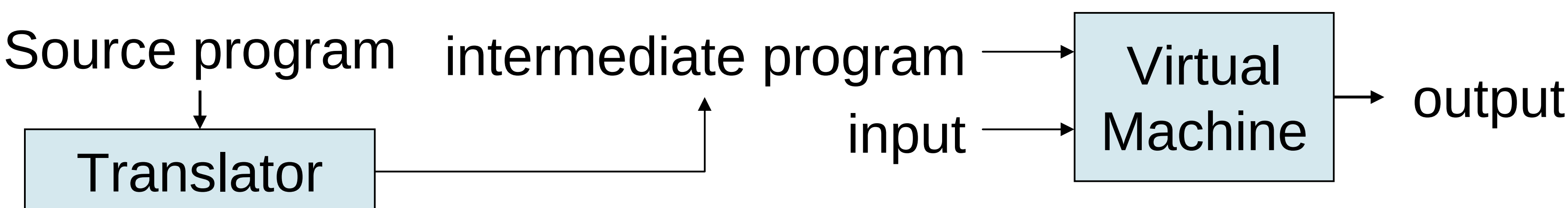
- Another language processor: Interpreter
  - It executes the source program statement by statement (better error diagnostics)

Source program →
input → Interpreter → output



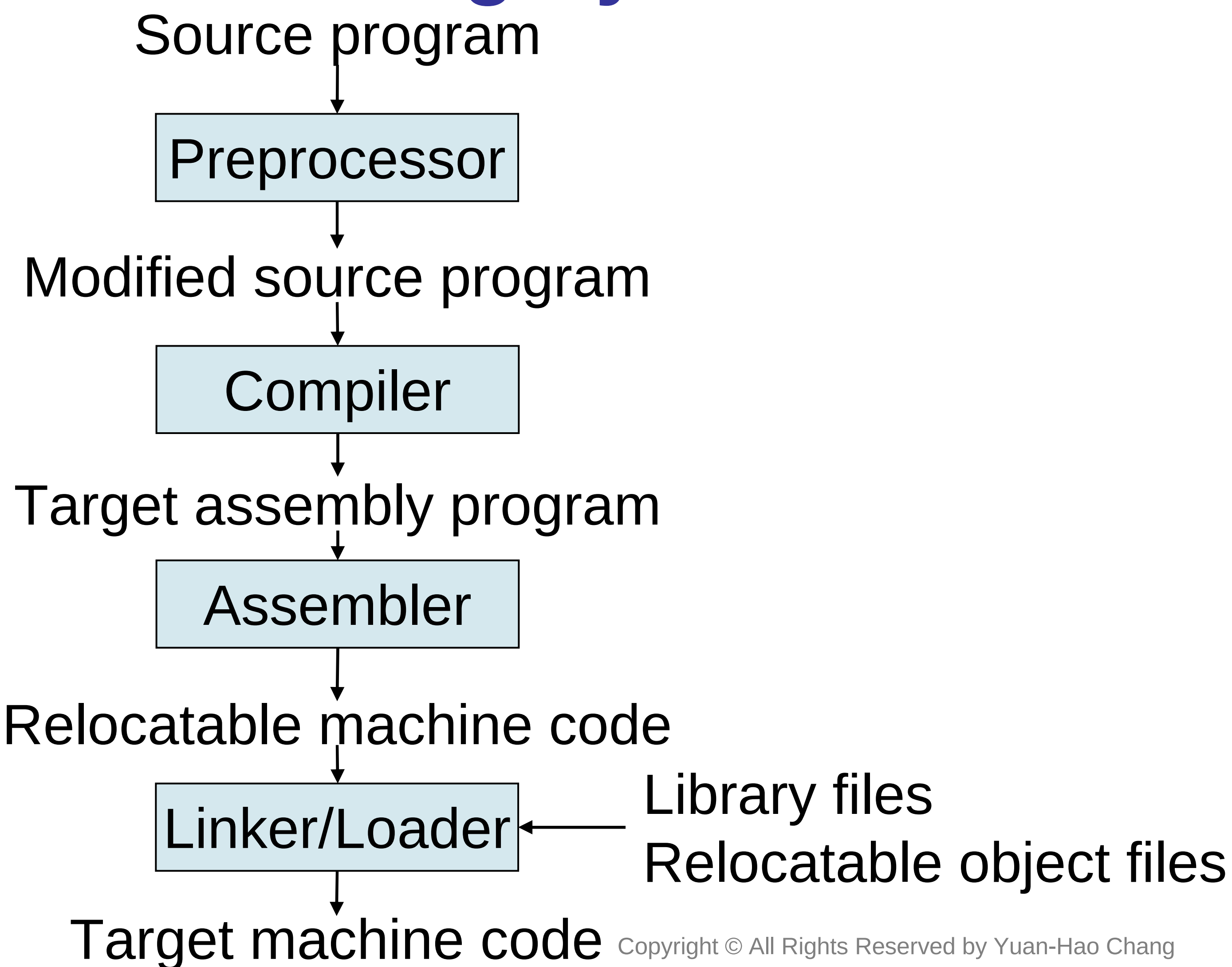
Language Processors (Cont.)

- Hybrid compiler
  - Combine compilation and interpretation
  - E.g., Java language processor
    - Java source program is first compiled into an intermediate form called *bytecodes*.
    - The bytecodes are then interpreted by a virtual machine.
  - High portability (cross platform)
    - Bytecodes compiled on one machine can be interpreted on another machine.





Language Processing System



Language Processing System (Cont.)

- Preprocessor
  - Collect source programs
  - Expand macros
- Compiler
  - It usually produces assembly-language program because assembly language is easier to produce and to debug.
- Assembler
  - Produce relocatable machine code
- Linker
  - Link pieces of a large program together
  - Resolve external memory addresses
- Loader
  - Put all of the executable object files into memory for execution



The Structure of a Compiler

The Structure of a Compiler

Lexeme: 語彙
Syntax: 語法
Semantic: 語意

- A compiler consists of two major parts
  - Analysis part (front end)
    - Break the source program into pieces with the grammatical structure.
    - Provide informative messages when syntactically ill formed or semantically unsound.
    - Collect and organize information from source program to the symbol table, which is passed to the synthesis part.
    - Generate the intermediate representation.
  - Synthesis part (back end)
    - Construct the target program from the intermediate representation and the symbol table.

Phases of a Compiler

Character stream

↓

Lexical Analyzer (scanner)

↓

Token stream

↓

Syntax Analyzer (parser)

↓

Syntax tree

↓

Semantic Analyzer

↓

Syntax tree

↓

Intermediate Code Generator

↓

Intermediate representation

Analysis part

Symbol Table

Used by all phases of the compiler

Machine-Independent Code Optimizer (optional)

↓

Intermediate representation

↓

Code Generator

↓

Target-machine code

↓

Machine-Dependent Code Optimizer

↓

Target-machine code

Synthesis part



Lexical Analysis - Scanning (語彙分析)

- The lexical analyzer
  - Read the source program
  - Group the characters into meaningful sequences called lexemes
  - Output each lexeme as a token as the following form: *<token-name, attribute-value>*
    - token-name: an abstract symbol used in syntax analysis
    - attribute-value: point to the entry in the symbol table for this token
  - Tokens in the symbol table are needed for semantic analysis and code generation.

Lexical Analysis (Cont.)

- E.g., (for example)

  position = initial + rate * 60 (1.1)

  - position: a lexeme mapped to the token <id, 1>, where
    - id: an abstract symbol standing for *identifier*
    - 1: the entry for "position" in the symbol table to hold information about the identifier, such as its name and type.
  - Assignment symbol =: a lexeme mapped into the token <=>
    - No attribute-value so that it can be omitted
  - initial: a lexeme mapped to the token <id, 2>
  - +: a lexeme mapped to the token <+>
  - rate: a lexeme mapped to the token <id, 3>
  - *: a lexeme mapped to the token <*>
  - 60: a lexeme mapped to the token <60>

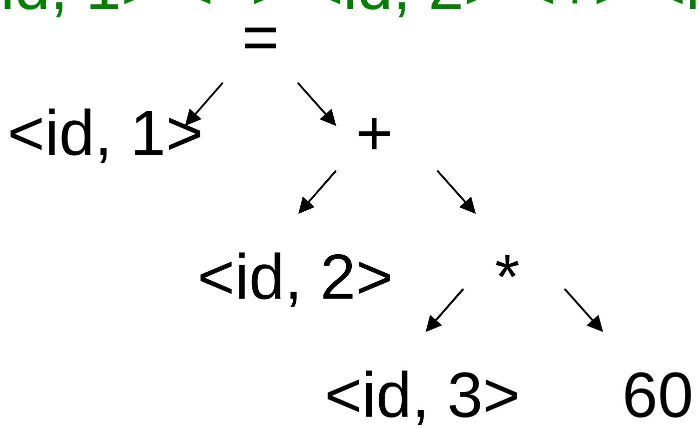
1	position	…
2	initial	…
3	rate	…

Symbol Table

<id, 1> <=> <id, 2> <+> <id, 3> <*> <60> (1.2)

Syntax Analysis – Parsing (語法分析)

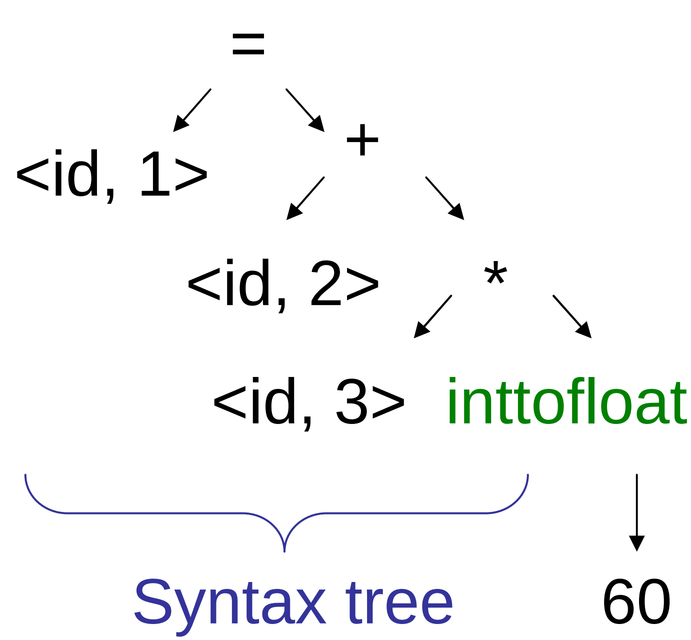
- Syntax analyzer uses tokens produced by lexical analyzer to create syntax trees that are usually used in syntax and semantic analysis)
  - Interior node
    - It represents an operation.
    - Its children represent the arguments of the operation.
  - E.g., <id, 1> <=> <id, 2> <+> <id, 3> <*> <60>



Syntax tree

Semantic Analysis (語義分析)

- Semantic analyzer uses the syntax tree and the symbol table to check the semantic consistency, and then update the syntax tree and symbol table.
  - Type checking
    - E.g., an array index should an integer.
  - Type conversion (coercion)
    - E.g., 3.5 + 5 (The compiler converts the integer into a floating-point number)





Intermediate Code Generation

- Important properties of intermediate representation:
  - Easy to produce
  - Easy to translate into the target machine.
- Three-address code (a commonly used intermediate form)
  - Consist of a sequence of assembly-like instructions with three operands, each of which acts like a register.
    E.g., <id, 1> <=> <id, 2> <+> <id, 3> <*> <60>

```
t1 = inttoflota(60)
t2 = id3 * t1                    (1.3)
t3 = id2 + t2
id1 = t3
```



Intermediate Code Generation (Cont.)

- Three-address code
  - There is at most one operator on the right side.
  - The compiler must generate a temporary name to hold the value computed by a three-address instruction.
  - An instruction might have fewer than three operands.

```
t1 = inttoflota(60)
t2 = id3 * t1                    (1.3)
t3 = id2 + t2
id1 = t3
```

Code Optimization

- Machine-independent code-optimization is to improve the intermediate code.
  - E.g., faster, shorter code, target code consuming less power
- Code optimization might slow down the compilation.

```
t1 = inttoflota(60)
t2 = id3 * t1          (1.3)
t3 = id2 + t2
id1 = t3
```

```
t1 = id3 * 60.0        (1.4)
id1 = id2 + t1
```

- Convert 60 to 60.0 automatically
- t3 is used only once.



Code Generation

- Map the intermediate representation to the target language.
  - E.g., if the target is machine code,
    - Registers or memory locations are selected for each variable used in the program.
    - Then the intermediate representation is translated into machine instructions.

```
t1 = id3 * 60.0      (1.4)
id1 = id2 + t1
```

dest.

Immediate constant

```
LDF   R2,  id3
MULF  R2,  R2, #60.0
LDF   R1,  id2              (1.5)
ADDF  R1,  R1, R2
STF   id1, R1
```

- F stands for for floating point.
- LD(load)/ST(store) are used to access memory.
- The issue of storage allocation is ignored here.

Translation of An Assignment Statement

Character stream ↓

Lexical Analyzer (scanner) ↓

Token stream ↓

Syntax Analyzer (parser) ↓

Syntax tree ↓

Semantic Analyzer ↓

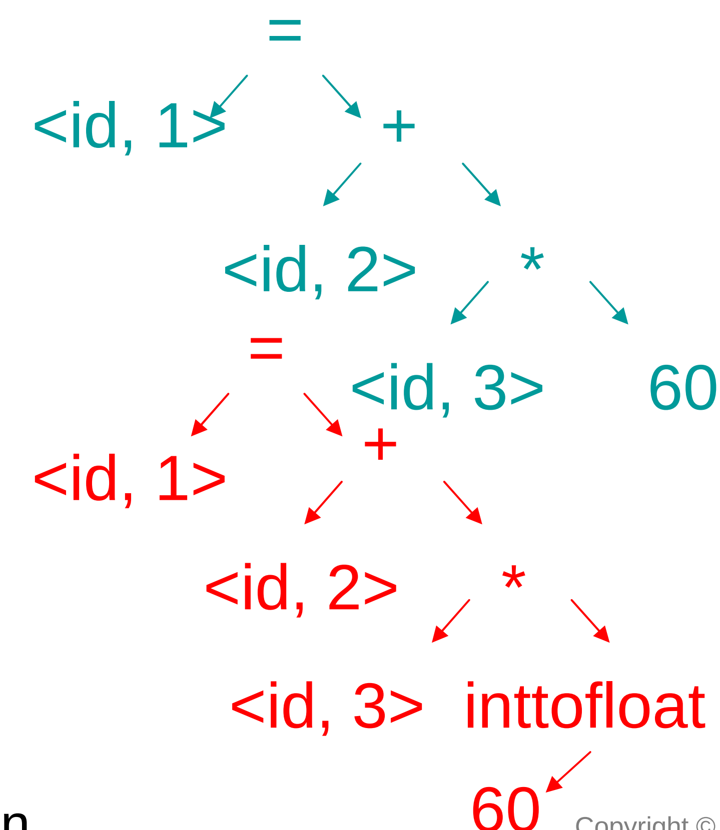
Syntax tree ↓

Intermediate Code Generator ↓

Intermediate representation

position = initial + rate * 60

<id, 1> <=> <id, 2> <+> <id, 3> <*> <60>



1	position	…
2	initial	…
3	rate	…

Symbol Table

t1 = inttoflota(60)
t2 = id3 * t1
t3 = id2 + t2
id1 = t3

Translation of An Assignment Statement (Cont.)

1	position	…
2	initial	…
3	rate	…

Symbol Table

```
t1 = inttoflota(60)
t2 = id3 * t1
t3 = id2 + t2
id1 = t3
```

```
t1 = id3 * 60.0
id1 = id2 + t1
```

```
LDF  R2,  id3
MULF R2,  R2, #60.0
LDF  R1,  id2
ADDF R1,  R1, R2
STF  id1, R1
```

Intermediate representation

Machine-Independent Code Optimizer (optional)

Intermediate representation

Code Generator

Target-machine code

Machine-Dependent Code Optimizer

Target-machine code

Symbol-Table Management

- The symbol table
  - is a data structure containing a record for each variable name (e.g., *identifiers* and *keywords*) with fields for the attributes of the name.
  - Should be designed to allow the compiler
    - To find the record for each name quickly and
    - To store or retrieve data from that record quickly.

Grouping of Phases into Passes

- A pass
  - Groups several phases together and
  - Reads an input file and writes an output file.
- E.g.,
  - Pass 1 consists of the front-end (analysis) phases:
    - Lexical analysis, syntax analysis, semantic analysis, and intermediate code generation
  - Pass 2 consists of the back-end (synthesis) phase:
    - Code generation for a particular target machine

Note: code optimization might be an optional pass.



Grouping of Phases into Passes (Cont.)

- Benefits
  - Combine different front ends with the back end for a target machine.
  - Combine a front end with back ends for different target machines. (e.g., gcc for different processors)



Compiler-Construction Tools

- Scanner generators (e.g., Lex) :
  - Produce lexical analyzers from a regular-expression description of the tokens of a language.
- Parser generators (e.g., Yacc):
  - Automatically produce syntax analyzers from a grammatical description of a programming language.
- Syntax-directed translation engines:
  - Produce collections of routines for walking a parse tree and generating intermediate code.
- Code-generator generators:
  - Produce a code generator from a collection of rules for translating the intermediate language.

Compiler-Construction Tools (Cont.)

- Data-flow analysis engines:
  - Help gather information on value transmission from one part of a program to the other part.
  - Data-flow analysis is a key part of code optimization.
- Compiler-construction toolkits:
  - Provide an integrated set of routines for constructing various phases of a compiler



The Evolution of Programming Languages & The Science of Compilers



The Move to High-Level Languages

- In the 1940's:
  - The first electronic computer appeared and programmed in machine language by sequences of 0's and 1's.
- In the early 1950's:
  - Development of mnemonic assembly languages
    - Instructions for mnemonic representation of machine instructions
    - Macro instruction for frequently used sequences of machines instructions with parameters.
- In the late 1950's:
  - Development of higher-level languages
    - Fortran (for scientific computing), Cobol (for business data processing), and Lisp (for symbolic computation)
- In the following decades:
  - Thousands of high-level programming languages are developed.



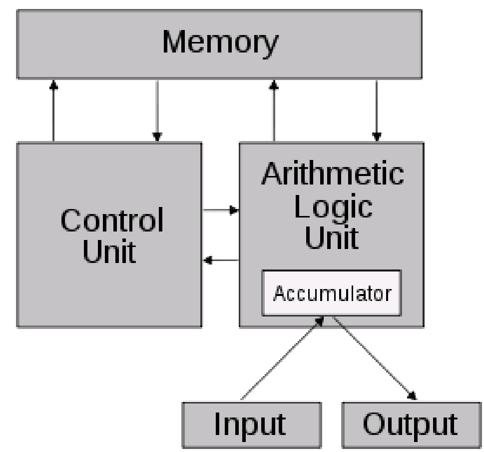
Classification of Programming Languages

- By Generation:
  - First generation: machine languages
  - Second generation: assembly languages
  - Third generation: higher-level languages
    - E.g., Fortran, Cobol, Lisp, C, C++, C#, and Java
  - Fourth generation: languages for specific applications
    - E.g., SQL for database queries, and Postscript for text formatting
  - Fifth generation: logic- and constraint-based languages
    - E.g., Prolog and OPS5



Classification of Programming Languages (Cont.)

- Imperative (命令) / Declarative (陳述)
  - Imperative language: specify how a computation is to be done.
    - E.g., C, C++, C#, and Java
  - Declarative language: specify what computation is to be done.
    - E.g., Functional languages such as ML and Haskell, and constraint logic languages such as Prolog
- *von Neumann* language
  - Based on the von Neumann architecture
    - E.g., Fortran, and C



- Object-oriented language
  - A program consists of a collection of objects.
  - E.g., Smalltalk, C++, C#, and Java
- Scripting language
  - Interpreted languages called scripts, such as JavaScript, Perl, and PHP, Phthon, and Tcl

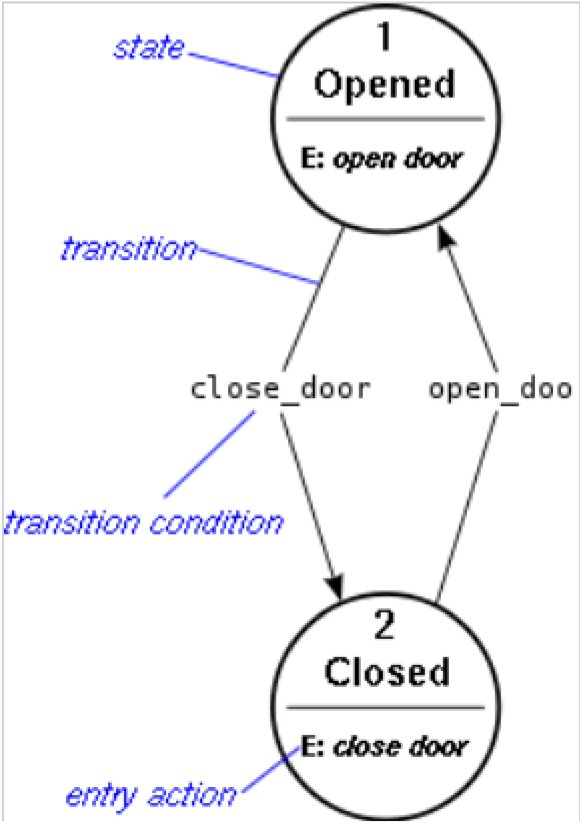


Impacts on Compilers

- Compilers and programming languages are closely related.
  - Compiler can help reduce overhead of programs.
  - Compilers are critical in making high-performance computer architecture effective on user applications.
- Compiler writing is challenging.
  - A compiler itself is a large program. (參考書:人月神話)
- A compiler must translate correctly.
- The problem of generating the optimal target code is undecidable. (NP-hard problem)

Modeling in Compiler Design

- Fundamental models:
  - finite-state machines and regular expressions are useful for describing lexical units of programs.
    - Finite-state machine is a model of behavior composed of a finite number of states, transitions between those states, and actions.
    - Regular expressions provide a concise and flexible means for matching strings of text.
  - Context-free grammars are used to describe the syntactic structure such as the nesting of parentheses or control constructs.



An Example of Finite-State Machine



Objectives of Compiler Code Optimization

- The optimization must be correct.
- The optimization must improve the performance of many programs.
  - E.g., Speed, code size in embedded system, and power in mobile devices
- The compilation time must be kept reasonable.
- The engineering effort required must be manageable.



Applications of Compiler Technology

Compiler Technology for High-Level Programming Languages

- Register keyword (in C language):
  - Let programmers to control registers.
- Data-flow optimization
  - E.g., reduce redundant load-store operation to variables.
- Procedure inlining
  - Replacement a procedure call by the body of the procedure
- Development trend: increase levels of abstraction to handle things for programmers.
  - We use Java as an example:
    - Type-safe: an object can only be used in related types.
    - Boundary checks for arrays
    - No pointers
    - Built-in garbage collection

Optimization for Computer Architectures

- The evolution of computer architectures has led to new demand for new compiler technology.
- E.g., high performance systems usually adopt:
  - Parallelism:
    - Instruction level: Multiple instructions are executed simultaneously.
      - E.g., VLIW (Very Long Instruction Word) such as Intel IA64 to process a vector of data at the same time. (Compilers could adopt the instruction set.)
    - Processor level: Different threads of the same application are run on different processors.
      - Compilers could translate sequential program into multiprocessor code.
  - Memory hierarchies:
    - Registers (B), caches (KB), physical memory (MB~GB), secondary storage (GB~TB) ~ two to three orders of magnitude
    - Compilers can change
      - The order of instructions and layout of data to improve the effectiveness of memory hierarchy. (especially data caches)
      - The layout of code to improve the effectiveness of instruction caches.

Optimization for Computer Architectures (Cont.)

```
for (i=0;i<2;i++) {
   for (j=0;j<2;j++) {
      a[ j ][ i ] = 0;
   }
}
```

```
for (i=0;i<2;i++) {
   for (j=0;j<2;j++) {
      a[ i ][ j ] = 0;
   }
}
```

a[0][0]	a[1][0]	a[2][0]	a[0][1]	a[1][1]	a[2][1]	a[0][2]	a[1][2]	a[2][2]

a[0][0]	a[0][1]	a[0][2]	a[1][0]	a[1][1]	a[1][2]	a[2][0]	a[2][1]	a[2][2]

Layout of data

Design of New Computer Architectures

- Compilers are now developed in the processor-design stage to evaluate the HW architecture.
- Some HW architectures:
  - RISC (Reduced Instruction-Set Computer)
    - Compilers can use small number of simple instructions to reduce the redundancies in complex instructions. (Optimization issue) (Note: CISC: Complex Instruction-Set Computer)
    - E.g., PowerPC, MIPS (Note: x86 is with CISC but adopts many design ideas of RISC)
  - Specialized architecture
    - E.g., Data-flow machine, VLIW, SIMD (Single instruction multiple data) array of processors, multiprocessors with shared/distributed memory, systolic arrays



Program Translation Assisted by Compilers

- Binary Translation
  - Translate the binary code for one machine to the other.
- Hardware Synthesis
  - Hardware designs are now described in high-level languages like Verilog, VHDL (Very high-speed integrated circuit Hardware Description Language)
  - Hardware designs are typically designed at the register transfer level (RTL):
    - Variables represent registers.
    - Expressions represent combinational logic.
  - Hardware-synthesis tools translate RTL into gates automatically. (circuit optimization takes hours.)
- Database Query Interpreters
  - SQL (Structured Query Language) that can be interpreted or compiled
- Compiled Simulation (Emulation)
  - Instead of writing a simulator that interprets the design, it is faster to compile the design to produce machine code that simulates the particular design.



Software Productivity Tools

- Testing is the primary technique for locating errors so as to improve software productivity.
- Finding all program errors is undecidable. (NP-hard)
  - Practical error detectors are often neither sound nor complete. (Reported errors are not all real errors, and only partial errors are found.)
- Some detection techniques
  - Type checking
  - Bounds checking
    - E.g., data flow analysis to detect buffer overflow.
  - Memory-management tools
    - E.g., garbage collection to prevent memory leaks



Programming Language Basics

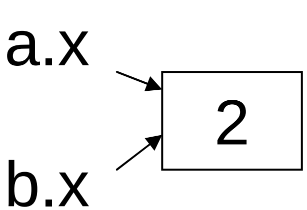
The Static / Dynamic Distinction

- Policies
  - Static policy:
    - A decision allowed to be made at compile time
  - Dynamic policy:
    - A decision allowed to be made at run time
- Scope:
  - The scope of a declaration of *x* is the region of the program in which uses of *x* refer to this declaration.
    - Static scope (or lexical scope): based on space
      - Determine the scope of a declaration by looking only at the program.
      - E.g., C and Java, and most languages
    - Dynamic scope: based on time
      - The same use of *x* could refer to any of several different declarations of *x*.



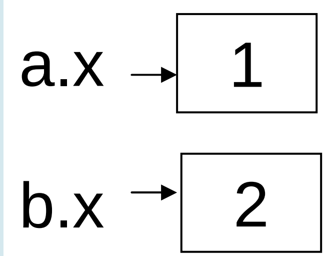
Static Variable in Java

- A variable is a *name* for a *location* in memory to hold a data *value*.
  - In Java, a “static” (class) variable means that all the instances of the class share the same copy of the variable.
  - E.g.,



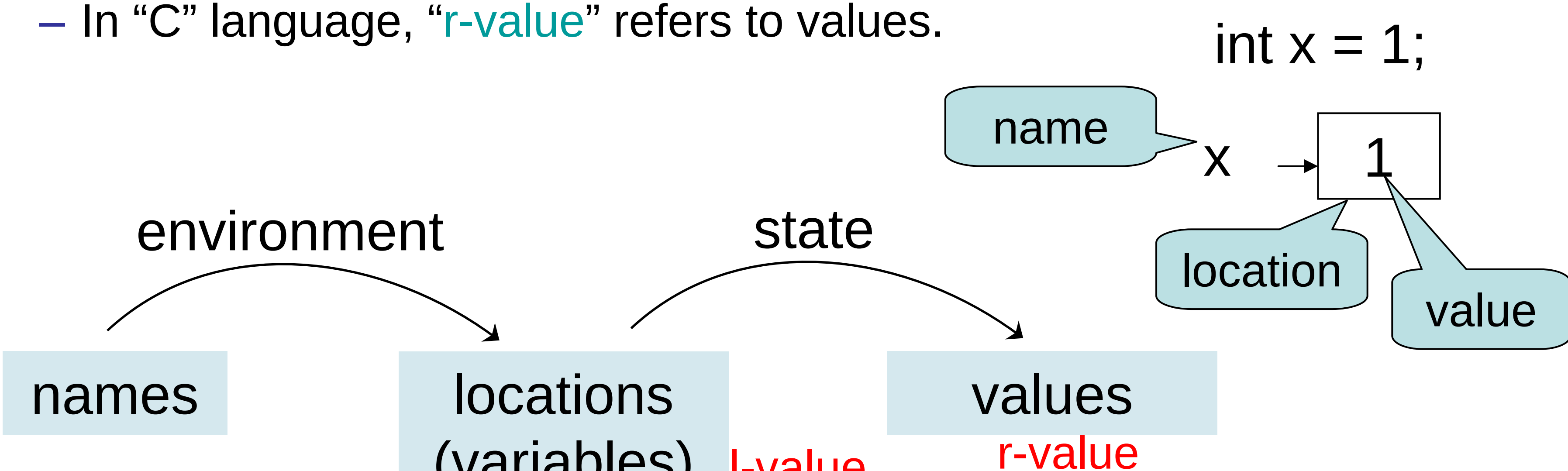

```
class stcla {
    public static int x;
    …
}
…
a = new stcla();
b = new stcla();
a.x = 1;
b.x = 2;
System.out.write(a.x); // 2
```

```
class stcla {
    public int x;
    …
}
…
a = new stcla();
b = new stcla();
a.x = 1;
b.x = 2;
System.out.write(a.x); // 1
```



Two-State Mapping from Names to Values

- Environment:
  - A mapping from names to locations in the store or memory.
  - In “C” language, “l-values” refers to the locations.
- State:
  - A mapping from locations in the store to their values.
  - In “C” language, “r-value” refers to values.



Two Declarations of the Name i

- The *local i* is local to function *f*.
- The *local i* is given a place on the run-time stack.
- Declarations in C must precede their use.
  - The function *g* can access neither local i nor global i.
  - The function *h* can't access local i, but can access global i.

```
g() {…}
…
int i;             /* global i */
…
void f(…) {
    int i;         /* local i */
    …
    i = 3;         /* use of local i */
    …
}
…
x = i + 1;         /* use of global I */
…
h() {…}
```

Binding

- Static / dynamic binding of names to locations:
  - Most binding of names to locations is dynamic.
  - E.g., in the previous example, local i is dynamic binding, but the global i is static binding.
    (Here the relocation issue is ignored since the loader and the operating system will handle it.)
- Static / dynamic binding of locations to values:
  - Most binding of locations to values is dynamic.
  - The value in a location could be changed from time to time.
  - Exception: constants
    - E.g., #define ARRAYSIZE 1000 /* C language */

Names, Identifiers, and Variables

- Identifier: a string of characters to identify an entity
  - All identifiers are names, but not all names are identifiers.
  - E.g., x.y → x, y, and x.y are names, but only x and y are identifiers.
- Variable: a particular location of the store
  - An identifier could be declared more than once, and each declaration introduces a new variable.
  - E.g., an identifier (or a name) local to a recursive procedure will refer to different locations of the store at different times. (e.g., recursion to solve **Fibonacci series: 1, 1, 2, 3, 5, ….**)



Static Scope and Block Structure

- Most languages adopts static scope.
  - The scope of a declaration is determined *implicitly* by where the declaration appears.
  - C++, Java, and C# provide *explicit* control over scopes through keywords, such as ***public***, ***private***, and ***protected***.
- Block structure
  - Block is a grouping of declarations and statements, and can be used to define a static scope.
    - E.g., “C” uses { }, Pascal uses “begin” and “end”.
  - Block structure allows blocks to be nested inside each other.
    - A declaration D belongs to a block B if B is the most closely nested block containing D. → That is, D is located within B, not within any block within B.



A Block Example with C++

```
Main () {
    int a = 1;                          B1
    int b = 1;
    {
        int b = 2;                      B2
        {
            int a = 3;                  B3
            cout << a << b; // 3 2
        }
        {
            int b = 4;                  B4
            cout << a << b;  // 1 4
        }
        cout << a << b;  // 1 2
    }
    cout << a << b;  // 1 1
}
```

Declaration	Scope
int a = 1;	B_1 - B_3
int b = 1;	B_1 - B_2
Int b = 2;	B_2 - B_4
int a = 3;	B_3
int b = 4;	B_4

Note: B_1 - B_3 stands for B_1 exclusive B_3

Explicit Access Control

- Java and C++ provide explicit control with the keywords "**private**", "**protected**", and "**public**" so as to support *encapsulation*.
  - Private names gives a scope within that class and its friend classes (in C++ term).
  - Protected names are accessible to subclasses (or the same package in Java).
  - Public names are accessible from outside the class.

Explicit Access Control (Cont.)

- An example with Java

```
package P1;        // cla_a.java
public class cla_a {
    public int x;
    protected int y;
    private int z;
    …
}
package P2;        // cla_b.java
public class cla_b extends cla_a {
    public test() {
        x = 1; // accessible
        y = 1; // accessible
        z = 1; // not accessible
    }
    …
}
```

Program entry

```
import P1.*;        // Main.java
import P2.*;
class Main {
    static void main(String[] args) {
        cla_a a = new cla_a();
        cla_b b = new cla_b();
        a.x = 1; // accessible
        a.y = 1; // not accessible
        a.z = 1; // not accessible
        b.test();
    }
}
```



Dynamic Scope

- Dynamic scope
  - It is based on factors that can be known only when the program executes.
  - A use of a name *x* refers to the declaration of *x* in the most recently called procedure with such a declaration.
    - E.g.:
      - Method resolution (in object-oriented programming)

Notes:

- In C, procedures are implemented as functions that returns value, where procedures don't return any value.
- In object-oriented languages, procedures of a class are also implemented as function called methods, and variables of a class are called attributes.



Dynamic Scope Resolution

- Essentials for polymorphic procedures.
  - A procedure that has two or more definitions depends only on the types of the arguments.

E.g.:

1. There is a class C with a method named m().
2. D is a subclass of C, and D has its own method named m().
3. There is a use of m of the form x.m(), where x is an object of class C.

→ Normally, it is impossible to tell at compile time where x will be of class C or D.

Dynamic Scope Resolution (Cont.)

```
public class cla_a {  // cla_a.java
    public void m() {
        System.out.println("a");
    }
}
// cla_b.java
public class cla_b extends cla_a {
 public void m() {
        System.out.println("b");
    }
}
```

```
public class cla_c {  // cla_c.java
    public void test(cla_a x) {
        x.m();
    }
}

class Main {        // Main.java
    static void main(String[] args) {
    cla_a a = new cla_a();
    cla_b b = new cla_b();
    cla_c c = new cla_c();
    c.test(a); // "a"
    c.test(b); // "b"
    }
}
```



Declarations (宣告) and Definitions (定義)

- Declarations / Definitions
  - Declarations tell us about the types of things.
    - E.g., int i;
  - Definitions tell us about their values or contents.
    - E.g., i = 1;
- For example:
  - In C++, a method is declared in a class definition.
  - It is common to define a C function in one file and declare it in other files where the function is used.

```
// definition
int Callee() {      // Callee.c
    …
}
```

```
int Callee(); // declaration
int CallerA() {     // CallerA.c
    Callee();
    …
}
```

```
int Callee();   // declaration
int CallerB() {     // CallerB.c
    Callee();
    …
}
```



Parameter Passing

- Parameters
  - Actual parameters: used in the call of a procedure
  - Formal parameters: used in the procedure definition
- Mechanisms
  - Call-by-value
    - The value of the actual parameter is passed to the callee.
  - Call-by-reference
    - The address of the actual parameter is passed to the callee, and the corresponding formal parameters can't point to any other address.
  - Call-by-address(/pointer)
    - The address of the actual parameter is passed to the callee, and the corresponding formal parameters can point to other addresses.
  - Call-by-name
    - The actual parameter literally substitutes the formal parameter in the callee (similar to a macro).



Aliasing

- Aliasing is that two formal parameters refer to the same location.

```
void q(char *x, char *y) {
    x[10] = 2;
    printf("%d\n", y[10]); // 2
}

void p () {
    char a[20];
    q(a, a);
}
```

The formal variables *x* and *y* are aliasing to each other. (C language)