Introduction to Programming Languages

CSE 307 – Principles of Programming Languages
Stony Brook University
http://www.cs.stonybrook.edu/~cse307
What makes a language successful?

- easy to learn (python, BASIC, Pascal, LOGO, Scheme)
- easy to express things, easy use once fluent, "powerful" (C, Java, Common Lisp, APL, Algol-68, Perl)
- easy to implement (Javascript, BASIC, Forth)
- possible to compile to very good (fast/small) code (Fortran, C)
- backing of a powerful sponsor (Java, Visual Basic, COBOL, PL/1, Ada)
- wide dissemination at minimal cost (Java, Pascal, Turing, erlang)
Introduction

• Why do we have programming languages? What is a language for?
  • way of thinking -- way of expressing algorithms
  • languages from the user's point of view
  • abstraction of virtual machine -- way of specifying what you want
  • the hardware to do without getting down into the bits
  • languages from the implementor's point of view
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
  - 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
• understand implementation costs: choose between alternative ways of doing things, based on knowledge of what will be done underneath:
  • use simple arithmetic equal (use $x^2$ instead of $x^{**2}$)
  • use C pointers or Pascal "with" statement to factor address calculations
  • 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 suitable control structures in Fortran
    • use comments and programmer discipline for control structures
    • 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)
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 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 (Fortran, Pascal, Basic, C)
    - object-oriented (Smalltalk, Eiffel, C++?)
    - scripting languages (Perl, Python, JavaScript, PHP)
  - declarative
    - functional (Scheme, ML, pure Lisp, FP)
    - logic, constraint-based (Prolog, VisiCalc, RPG)
- Many more classifications: markup languages, assembly languages, etc.
HW1 (part of hw1)

- Write and test the GCD Program in 4 languages: in C, in XSB Prolog, in SML and in Python:
  - In C:
    ```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:
    ```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:
    ```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:
    ```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)
    ```

Due: next Thursday on Blackboard.
Imperative languages

- Imperative languages, particularly the von Neumann languages, predominate in industry
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

- Common case is compilation or simple pre-processing, followed by interpretation
- Most modern language implementations include a mixture of both compilation and 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
- Some compilers produce nothing but virtual instructions, e.g., Java byte code, Pascal P-code, Microsoft COM+ (.net)
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)
Compilation vs. Interpretation

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

![Diagram of compilation process]

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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—and uses it to build progressively more sophisticated versions
Compilation vs. Interpretation

• Implementation strategies:
  • Compilation of Interpreted Languages (e.g., Prolog, Lisp, Smalltalk, Java, C#):
    • The compiler generates code that makes assumptions about decisions that won’t be finalized until runtime. If these assumptions are valid, the code runs very fast. If not, a dynamic check will revert to the interpreter.
    • Permit a lot of late binding.
    • Are traditionally interpreted.
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).
- The Java language definition defines a machine-independent intermediate form known as byte code. Bytecode is the standard format for distribution of Java programs:
  - it allows programs to be transferred easily over the Internet, and then run on any platform
- The main C# compiler produces .NET Common Intermediate Language (CIL), which is then translated into machine code immediately prior to execution.
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

- 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

- **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

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An Overview of Compilation

Phases of Compilation

- Character stream
  - Token stream
    - Parse tree
      - Abstract syntax tree or other intermediate form
        - Modified intermediate form
          - Target language (e.g., assembler)
            - Modified target language
          - Machine-independent code improvement (optional)
        - Target code generation
      - Semantic analysis and intermediate code generation
    - Parser (syntax analysis)
  - Scanner (lexical analysis)

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An Overview of Compilation

- Scanning:
  - divides the program into "tokens", which are the smallest meaningful units; this saves time, since character-by-character processing is slow
  - we can tune the scanner better if its job is simple; it also saves complexity (lots of it) for later stages
  - you can design a parser to take characters instead of tokens as input, but it isn't pretty
  - scanning is recognition of a regular language, e.g., via DFA (Deterministic finite automaton)
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

- 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.
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 resemble machine code for some imaginary idealized machine; 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

- Optimization takes an intermediate-code program and produces another one that does the same thing faster, or in less space
- The term is a misnomer; we just improve code
- The optimization phase is optional
An Overview of Compilation

- Code generation phase produces assembly language or (sometimes) relocatable machine language
An Overview of Compilation

• Certain machine-specific optimizations (use of special instructions or addressing modes, etc.) may be performed during or after target code generation

• **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
Lexical and Syntax Analysis

For example, take the GCD Program (in C):

```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**
    - Scanning (lexical analysis) and parsing recognize the structure of the program, groups characters into tokens, the smallest meaningful units of the program

```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
- Context-Free Grammar and Parsing
  - Parsing organizes tokens into a parse tree that represents higher-level constructs in terms of their constituents
  - Potentially recursive rules known as context-free grammar define the ways in which these constituents combine
An Overview of Compilation

• Context-Free Grammar and Parsing

• Example (while loop in C):

\[
\begin{align*}
\text{iteration-statement} & \rightarrow \text{while ( expression ) statement} \\
\text{statement, in turn, is often a list enclosed in braces:} \\
\text{statement} & \rightarrow \text{compound-statement} \\
\text{compound-statement} & \rightarrow \{ \text{block-item-list opt} \} \\
\text{where} & \\
\text{block-item-list opt} & \rightarrow \text{block-item-list} \\
\text{or} & \\
\text{block-item-list opt} & \rightarrow \epsilon \\
\text{and} & \\
\text{block-item-list} & \rightarrow \text{block-item} \\
\text{block-item-list} & \rightarrow \text{block-item-list block-item} \\
\text{block-item} & \rightarrow \text{declaration} \\
\text{block-item} & \rightarrow \text{statement}
\end{align*}
\]
An Overview of Compilation

- Context-Free Grammar and Parsing
- GCD Program Parse Tree:
An Overview of Compilation

- Context-Free Grammar and Parsing (continued)

```
declaration
  declaration-specifiers  init-declarator-list_opt ;
    type-specifier  declaration-specifiers_opt  init-declarator-list
      int  ε  init-declarator-list , init-declarator

init-declarator
  declarator = initializer
    pointer_opt  direct-declarator assignment-expression
      ε  ident(j)  postfix-expression
        ε  ident(getint) argument-expression-list_opt
          ε
```
An Overview of Compilation

- Context-Free Grammar and Parsing (continued)
An Overview ofCompilation

- Syntax Tree
- GCD Program Parse Tree

```
program
  :=
    (5) call
    (3)
    :=
    (6) call
    (3)
  while
    ≠
    (5) (6)
    if
    ≠
    (5) (6)
    :=
    (5)
    :=
    :=
    (5)
    :=
    :=
    (5)
    :=
    :=
    (5)
  call
  (4)
  (5)
```

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