CMSC 330: Organization of Programming Languages

Introduction

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Course Goal

Learn how programming languages work

- Broaden your language horizons
  - Different programming languages
  - Different language features and tradeoffs
    - Useful programming patterns
- Study how languages are described / specified
  - Mathematical formalisms
- Study how languages are implemented
  - What really happens when I write x.foo(…)?

All Languages Are (Kind of) Equivalent

- A language is Turing complete if it can compute any function computable by a Turing Machine
- Essentially all general-purpose programming languages are Turing complete
  - I.e., any program can be written in any programming language
- Therefore this course is useless?!
  - Learn only 1 programming language, always use it

Studying Programming Languages

- Helps you to choose between languages
  - Programming is a human activity
    - Features of a language make it easier or harder to program for a specific application
  - Using the right programming language for a problem may make programming
    - Easier, faster, less error-prone

Studying Programming Languages

- Become better at learning new languages
  - A language not only allows you to express an idea, it also shapes how you think when conceiving it
    - There are some fundamental computational paradigms underlying language designs that take getting used to
  - You may need to learn a new (or old) language
    - Paradigms and fads change quickly in CS
    - Also, may need to support or extend legacy systems

5

Why Study Programming Languages?

- To make you better at learning new languages
  - You may need to add code to a legacy system
    - E.g., FORTRAN (1954), COBOL (1959), …
  - You may need to write code in a new language
    - Your boss says, "From now on, all software will be written in {C++/Java/C#/Python…}"
  - You may think Java is the ultimate language
    - But if you are still programming or managing programmers in 20 years, they probably won't be programming in Java!

6

Studying Programming Languages

- Improve your understanding of languages you are already familiar with
  - Many "design patterns" in Java are functional programming techniques
  - Understanding what a language is good for will help you know when it is appropriate to use
  - The deeper your understanding of a language, the better you will be at using it appropriately

7

Course Subgoals

- Learn some fundamental programming-language concepts
  - Regular expressions
  - Automata theory
  - Context free grammars
  - Computer security
- Improve programming skills
  - Practice learning new programming languages
  - Learn how to program in a new style

8

Syllabus

- Scripting languages (Ruby)
- Regular expressions & finite automata
- Context-free grammars & parsing
- Functional programming (OCaml)
- Scoping, type systems, parameter passing
- Logic programming (Prolog)
- Secure programming
- Comparing language styles; other topics

Calendar / Course Overview

- Tests
  - 4 quizzes, 2 midterms, final exam
- Projects
  - Project 1 – Ruby
  - Project 2-4 – OCaml
  - Project 5 – Prolog
  - Project 6 – Secure programming (Ruby)
- Meet your professor!
  - 1% extra credit : come to chat with your professor during office hours or at a mutually agreed-upon time
  - Conversation need not be long, or technical … but we would like to get to know you!

Discussion Sections

- Lectures introduce the course content
- Discussion sections will deepen understanding
  - These are smaller, and thus can be more interactive
- Oftentimes discussion section will consist of programming exercises
  - Bring your laptop to discussion
  - Be prepared to program: install the language in question on your laptop, or remote shell into Grace
- There will also be be quizzes, and some lecture material in discussion sections

Project Grading

- You have accounts on the Grace cluster
- Projects will be graded using the submit server
  - Software versions on these machines are canonical
- Develop programs on your own machine
  - Generally results will be identical on dept machines
  - Your responsibility to ensure programs run correctly on the grace cluster
- See web page for Ruby, Ocaml, SWI-Prolog versions we use, if you want to install at home

Rules and Reminders

- Use lecture notes as your text
  - Supplement with readings, Internet
  - You will be responsible for everything in the notes, even if it is not directly covered in class!
- Keep ahead of your work
  - Get help as soon as you need it
    - Office hours, Piazza (email as a last resort)
- Don't disturb other students in class
  - Keep cell phones quiet
  - No laptops / tablets in class
    - Except for taking notes (please sit in back of class)

Academic Integrity

- All written work (including projects) must be done on your own
  - Do not copy code from other students
  - Do not copy code from the web
  - Do not post your code on the web
  - We're using Moss; cheaters will be caught
- Work together on high-level project questions
  - Do not look at/describe another student's code
  - If unsure, ask an instructor!
- Work together on practice exam questions

Changing Language Goals

- 1950s-60s – Compile programs to execute efficiently
  - Language features based on hardware concepts
    - Integers, reals, goto statements
  - Programmers cheap; machines expensive
    - Computation was the primary constrained resource
    - Programs had to be efficient because machines weren't
      - Note: this still happens today, just not as pervasively

Changing Language Goals

- Today
  - Language features based on design concepts
    - Encapsulation, records, inheritance, functionality, assertions
  - Machines cheap; programmers expensive
    - Scripting languages are slow(er), but run on fast machines
    - They've become very popular because they ease the programming process
  - The constrained resource changes frequently
    - Communication, effort, power, privacy, …
    - Future systems and developers will have to be nimble

Language Attributes to Consider

- Syntax
  - What a program looks like
- Semantics
  - What a program means (mathematically)
- Implementation
  - How a program executes (on a real machine)

17

Imperative Languages

- Also called procedural or von Neumann
- Building blocks are procedures and statements
  - Programs that write to memory are the norm

```
int x = 0;
while (x < y) x = x + 1;
```

  - FORTRAN (1954)
  - Pascal (1970)
  - C (1971)

18

Functional Languages

- Also called applicative languages
- Less explicit map to underlying memory
  - Functions are higher-order

```
let rec map f = function [] -> []
                | x::l -> (f x)::(map f l)
```

  - LISP (1958)
  - ML (1973)
  - Scheme (1975)
  - Haskell (1987)
  - OCaml (1987)

19

OCaml

- A mostly-functional language
  - Has objects, but won't discuss (much)
  - Developed in 1987 at INRIA in France
  - Dialect of ML (1973)
- Natural support for *pattern matching*
  - Generalizes `switch`/`if-then-else` – very elegant
- Has full featured module system
  - Much richer than interfaces in Java or headers in C
- Includes type inference
  - Ensures compile-time type safety, no annotations

20

A Small OCaml Example

intro.ml:

```
let greet s =
  List.iter (fun x -> print_string x)
    ["hello, "; s; "!\n"]
```

```
$ ocaml
        Objective Caml version 3.12.1

# #use "intro.ml";;
val greet : string -> unit = <fun>
# greet "world";;
Hello, world!
- : unit = ()
```


Logic-Programming Languages

- Also called rule-based or constraint-based
- Program rules constrain possible results
  - Evaluation = constraint satisfaction = search
  - "A :- B" – If B holds, then A holds ("B *implies* A")
    - `append([], L2, L2).`
    - `append([X|Xs],Ys,[X|Zs]) :- append(Xs,Ys,Zs).`
  - PROLOG (1970)
  - Datalog (1977)
  - Various expert systems

Prolog

- A logic programming language
  - 1972, University of Aix-Marseille
  - Original goal: Natural language processing
- Rule based
  - Rules resemble pattern matching and recursive functions in Ocaml, but more general
- Execution = search
  - Rules specify relationships among data
    - Lists, records, "atoms", integers, etc.
  - Programs are queries over these relationships
    - The query will "fill in the blanks"

A Small Prolog Example

```
/* A small Prolog program */

female(alice).
male(bob).
male(charlie).
father(bob, charlie).
mother(alice, charlie).

% "X is a son of Y"
son(X, Y) :- father(Y, X), male(X).
son(X, Y) :- mother(Y, X), male(X).
```

Query

```
?- son(X,Y).
X = charlie,
Y = bob;
X = charlie,
Y = alice.
```

- Lowercase logically terminates
- Program consists of facts and rules
- Uppercase denotes variables
- User types ; to request additional answer
- Multiple answers
- User types return to complete request

Object-Oriented Languages

- Programs are built from objects
  - Objects combine functions and data
    - Often into "classes" which can inherit
  - "Base" may be either imperative or functional

```
class C { int x; int getX() {return x;} … }
class D extends C { … }
```

  - Smalltalk (1969)
  - C++ (1986)
  - OCaml (1987)
  - Ruby (1993)
  - Java (1995)

Scripting Languages

- Rapid prototyping languages for common tasks
  - Traditionally: text processing and system interaction
- "Scripting" is a broad genre of languages
  - "Base" may be imperative, functional, OO…
- Increasing use due to higher-layer abstractions
  - Not just for text processing anymore

  - sh (1971)
  - perl (1987)
  - Python (1991)
  - Ruby (1993)

```
#!/usr/bin/ruby
while line = gets do
   csvs = line.split /,/
   if(csvs[0] == "330") then
   ...
```


Ruby

- An imperative, object-oriented scripting language
  - Created in 1993 by Yukihiro Matsumoto (Matz)
  - "Ruby is designed to make programmers happy"
  - Core of Ruby on Rails web programming framework (a key to its popularity)
  - Similar in flavor to many other scripting languages
  - Much cleaner than perl
  - Full object-orientation (even primitives are objects!)

A Small Ruby Example

intro.rb:

```
def greet(s)
  3.times { print "Hello, " }
  print "#{s}!\n"
end
```

```
% irb      # you'll usually use "ruby" instead
irb(main):001:0> require "intro.rb"
=> true
irb(main):002:0> greet("world")
Hello, Hello, Hello, world!
=> nil
```

Concurrent / Parallel Languages

- Traditional languages had one thread of control
  - Processor executes one instruction at a time
- Newer languages support many threads
  - Thread execution conceptually independent
  - Means to create and communicate among threads
- Concurrency may help/harm
  - Readability, performance, expressiveness
- Won't cover in this class
  - Threads covered in 132 and 216; more in 412, 433

Supporting secure execution

- Security is a big issue today
- Features of the language can help (or hurt)
  - C/C++ lack of memory safety leaves them open for many vulnerabilities: buffer overruns, use-after-free errors, data races, etc.
  - Type safety is a big help, but so are abstraction and isolation facilities, to help enforce security policies, and limit the damage of possible attacks
- Additional ecosystem support also useful
  - Fuzz testing, static analysis, dynamic analysis (e.g., taint tracking)

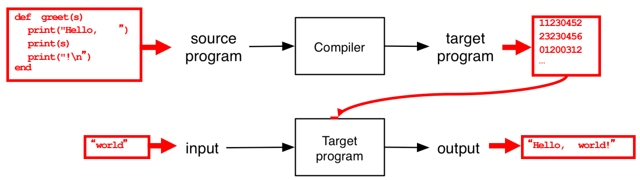
Other Languages

- There are lots of other languages w/ various features
  - COBOL (1959) – Business applications
    - Imperative, rich file structure
  - BASIC (1964) – MS Visual Basic
    - Originally designed for simplicity (as the name implies)
    - Now it is object-oriented and event-driven, widely used for UIs
  - Logo (1968) – Introduction to programming
  - Forth (1969) – Mac Open Firmware
    - Extremely simple stack-based language for PDP-8
  - Ada (1979) – The DoD language
    - Real-time
  - Postscript (1982) – Printers- Based on Forth

Program Execution

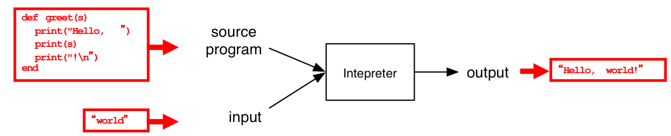
- Suppose we have a program P written in a high-level language (i.e., not machine code)
- There are two main ways to run P
  1. Compilation
  2. Interpretation

Compilation



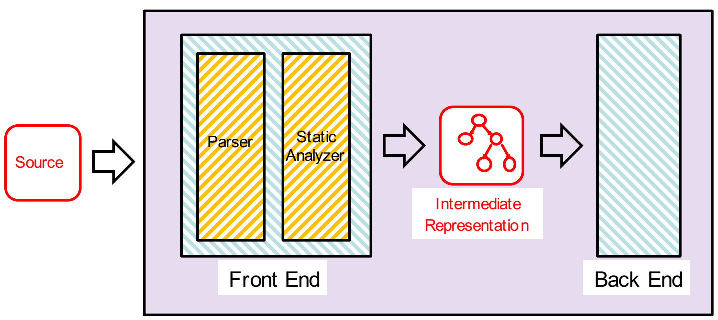
- Source program translated ("compiled") to another language
  - Traditionally: directly executable machine code
  - Generating code from a higher level "interface" is also common (e.g., JSON, RPC IDL)

Interpretation



- Interpreter executes each instruction in source program one step at a time
  - No separate executable

Architecture of Compilers, Interpreters



Compiler / Interpreter

Front Ends and Back Ends

- Front ends handle syntactic analysis
  - Parser converts source code into intermediate format ("parse tree") reflecting program structure
  - Static analyzer checks parse tree for errors (e.g. types), may also modify it
  - What goes into static analyzer is language-dependent!
- Back ends handle "semantics"
  - Compiler: back end ("code generator") translates intermediate representation into "object language"
  - Interpreter: back end executes intermediate representation directly

Compiler or Intepreter?

- gcc
  - Compiler – C code translated to object code, executed directly on hardware (as a separate step)
- javac
  - Compiler – Java source code translated to Java byte code
- java
  - Interpreter – Java byte code executed by virtual machine
- sh/csh/tcsh/bash
  - Interpreter – commands executed by shell program

Compilers vs. Interpreters

- Compilers
  - Generated code more efficient
  - "Heavy"
- Interpreters
  - Great for debugging
  - Slow
- In practice
  - "General-purpose" programming languages (e.g. C, Java) are often compiled, although debuggers provide interpreter support
  - Scripting languages and other special-purpose languages are interpreted, even if general purpose

Formal (Mathematical) Semantics

- What do my programs mean?

```
let rec fact n =
  if n = 0 then 1
  else n * (fact n-1)
```

```
let fact n =
  let rec aux i j =
    if i = 0 then j
    else aux (i-1) (j*i) in
  aux n 1
```

- Both OCaml functions implement "the factorial function." How do I know this? Can I prove it?
  - Key ingredient: a mathematical way of specifying what programs do, i.e., their semantics
  - Doing so depends on the semantics of the language

Semantic styles

- Textual language definitions are often incomplete and ambiguous
- A formal semantics is basically a mathematical definition of what programs do. Two flavors:
  - Denotational semantics (compiler/translator)
    - Meaning defined in terms of another language (incl. math)
    - If we know what C means, then we can define Ruby by translation to C
  - Operational semantics (interpreter)
    - Meaning defined as rules that simulate program execution
    - Show what Ruby programs do directly, using an abstract "machine," more high-level than real hardware

Attributes of a Good Language

- Cost of use
  - Program execution (run time), program translation, program creation, and program maintenance
- Portability of programs
  - Develop on one computer system, run on another
- Programming environment
  - External support for the language
  - Libraries, documentation, community, IDEs, …

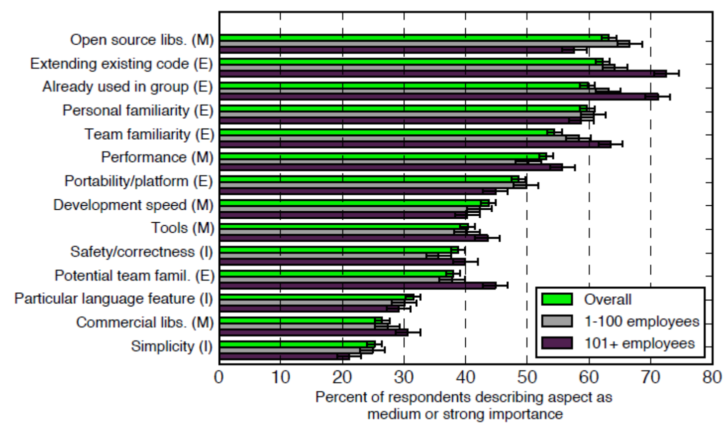
Attributes of a Good Language

- Clarity, simplicity, and unity
  - Provides both a framework for thinking about algorithms and a means of expressing those algorithms
- Orthogonality
  - Every combination of features is meaningful
  - Features work independently
- Naturalness for the application
  - Program structure reflects the logical structure of algorithm

Attributes of a Good Language

- Support for abstraction
  - Hide details where you don't need them
  - Program data reflects the problem you're solving
- Security & safety
  - Should be very difficult to write unsafe programs
- Ease of program verification
  - Does a program correctly perform its required function?

What Programmers Want In a PL



Meyerovitch & Rabin, "Empirical analysis of programming language adoption", OOPSLA'13

Summary

- Many types of programming languages
  - Imperative, functional, logical, OO, scripting, ...
- Many programming language attributes
  - Clear, natural, low cost, verifiable, secure, ...
- Programming language implementation
  - Compiled, interpreted
- Programming language semantics
  - Proving your program operates correctly