CMSC 330: Organization of Programming Languages

Administrivia

Course Goals

- Describe and compare programming language features
  - And understand how language designs have evolved
- Choose the right language for the job
- Write better code
  - Code that is shorter, more efficient, with fewer bugs

- In short:
  - Become a better programmer with a better understanding of your tools.

Course Activities

- Learn different **types of languages**
- Learn different **language features** and tradeoffs
  - Programming patterns repeat between languages
- Study how languages are **specified**
  - **Syntax**, **Semantics** — mathematical formalisms
- Study how languages are **implemented**
  - Parsing via **regular expressions** (automata theory) and **context free grammars**
  - Mechanisms such as **closures**, **tail recursion**, **lazy evaluation**, **garbage collection**, …
- Language impact on **computer security**

Syllabus

- Dynamic/ Scripting languages (Ruby)
- Functional programming (OCaml)
- Regular expressions & finite automata
- Context-free grammars & parsing
- Lambda Calculus and Operational Semantics
- Safe, “zero-cost abstraction” programming (Rust)
- Secure programming
- Scoping, type systems, parameter passing, comparing language styles; other topics

Calendar / Course Overview

- Tests
  - 4 quizzes, 2 midterm exams, 1 final exam
  - Do not schedule your interviews on exam dates
- Clicker quizzes
  - ~~In class, graded~~, during the lectures
- Projects
  - Project 1 – Ruby
  - Project 2-5 – OCaml (and parsing, automata)
  - Project 6 – Security
    - P1, P2, and P4 are split in two parts

Clickers

- Turning Technology subscription is free
  - See course syllabus for link to sign up

- In class clicker questions are not graded. Instead, clicker quizzes will be grade on ELMS.

Quiz time!

- According to IEEE Spectrum Magazine which is the “top” programming language of 2019?

  A. Java
  B. R
  C. Python
  D. C++

session ID: **cmsc**

Discussion Sections

- Discussions will be in-person
- Discussion sections will deepen understanding of concepts introduced in lecture
- Oftentimes discussion section will consist of programming exercises
- There will also be be quizzes, and some lecture material in discussion section

Project Grading

- You have accounts on the Grace cluster
- Projects will be graded using the Gradescope
  - Software versions on these machines are canonical
- Develop programs on your own machine
  - Your responsibility to ensure programs run correctly on the grace cluster
- See web page for Ruby, OCaml, etc. versions we use, if you want to install at home
  - Linux VM or Docker

Rules and Reminders

- Use lecture notes as your text
  - Videos of lectures will be recorded for later reference
  - 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)
- Avoid distractions, to yourself and your classmates
  - Keep cell phones quiet
  - ~~No laptops / tablets in class~~
    - ~~Prefer hand-written notes (else, sit in back of class)~~

Academic Integrity

- All written work (including projects) 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
- Cheaters are caught by auto-comparing code
- Work together on *high-level* project questions
  - Discuss approach, pointers to resources: OK
  - Do not look at/describe another student's code
  - If unsure, ask an instructor!
- Work together on practice exam questions

CMSC 330: Organization of Programming Languages

Overview

Plethora of programming languages

- LISP:
```
(defun double (x) (* x 2))
```
- Prolog:
```
size([],0).
size([H|T],N) :-
size(T,N1), N is N1+1.
```
- OCaml:
```
List.iter (fun x -> print_string x)
                ["hello, "; s; "!\n"]
```
- Smalltalk:
```
( #( 1 2 3 4 5 ) select:[:i | i even ] )
```

All Languages are (sort 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 one programming language, always use it

Studying Programming Languages

- Will make you a better programmer
  - Programming is a human activity
    - Features of a language make it easier or harder to program for a specific application
  - Ideas or features from one language translate to, or are later incorporated by, another
    - Many "design patterns" in Java are functional programming techniques
  - Using the right programming language or style for a problem may make programming
    - Easier, faster, less error-prone

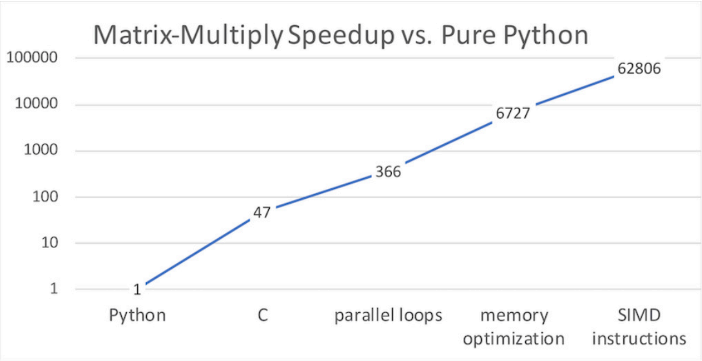
Studying Programming Languages

- 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
  - 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

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), i.e., what it computes
- Paradigm and Pragmatics
  - How programs tend to be expressed in the language
- Implementation
  - How a program executes (on a real machine)

Syntax

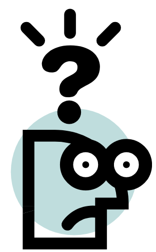
- The keywords, formatting expectations, and structure of the language
  - Differences between languages usually superficial
    - C / Java if (x == 1) { … } else { … }
    - Ruby if x == 1 … else … end
    - OCaml if (x = 1) then … else …

  - Differences initially jarring; overcome with experience
- Concepts such as **regular expressions**, **context-free grammars**, and **parsing** handle language syntax

Semantics

- What does a program *mean*? What does it *compute*?
  - Same syntax may have different semantics in different languages!

	Physical Equality	Structural Equality
Java	a == b	a.equals(b)
C	a == b	*a == *b
Ruby	a.equal?(b)	a == b
OCaml	a == b	a = b



- Can specify semantics informally (in prose) or formally (in mathematics)

Why **Formal** Semantics?

- Textual language definitions are often incomplete and ambiguous
  - Leads to two different implementations running the same program and getting a different result!
- A formal semantics is a mathematical definition of what programs compute
  - Benefits: concise, unambiguous, basis for proof
- We will consider operational semantics
  - Consists of rules that define program execution
  - Basis for implementation, and proofs of program correctness

Paradigm

- There are many ways to compute something
  - Some differences are superficial
    - For loop vs. while loop
  - Some are more fundamental
    - Recursion vs. looping
    - Mutation vs. functional update
    - Manual vs. automatic memory management
- Language's paradigm favors some computing methods over others. This class:

  - Imperative
  - Functional
  - Resource-controlled (zero-cost)
  - Scripting/dynamic

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)

Functional (Applicative) Languages

- Favors immutability
  - Variables are never re-defined
  - New variables a function of old ones (exploits recursion)
- Functions are higher-order
  - Passed as arguments, returned as results

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

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

Dynamic (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
  - Originally for text processing; now, much more

  - 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
  - Full object-orientation (even primitives are objects!)
  - And functional-style programming paradigms
  - Dynamic typing (types hidden, checked at run-time)
  - Similar in flavor to other scripting languages (Python)
- 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 Ruby's popularity

Theme: Software Security

- 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, to help enforce security policies, and limit the damage of possible attacks
- Secure development requires vigilance
  - Do not trust inputs – unanticipated inputs can effect surprising results! Therefore: verify and sanitize

Zero-cost Abstractions in Rust

- A key motivator for writing code in C and C++ is the low (or zero) cost of the abstractions use
  - Data is represented minimally; no metadata required
  - Stack-allocated memory can be freed quickly
  - Malloc/free maximizes control – no GC or mechanisms to support it are needed
- But no-cost abstractions in C/C++ are insecure
- Rust language has safe, zero-cost abstractions
  - Type system enforces use of ownership and lifetimes
  - Used to build real applications – web browsers, etc.

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

Other Language Paradigms

- We are not covering them all in CMSC330!
- Parallel/concurrent/distributed programming
  - Cilk, Fortress, Erlang, MPI (extension), Hadoop (extension); more on these in CMSC 433
- Logic programming
  - Prolog, λ-prolog, CLP, Minikanren, Datalog
- Object-oriented programming
  - Simula, Smalltalk, C++, Java, Scala
- Many other languages over the years, adopting various styles

Other Languages

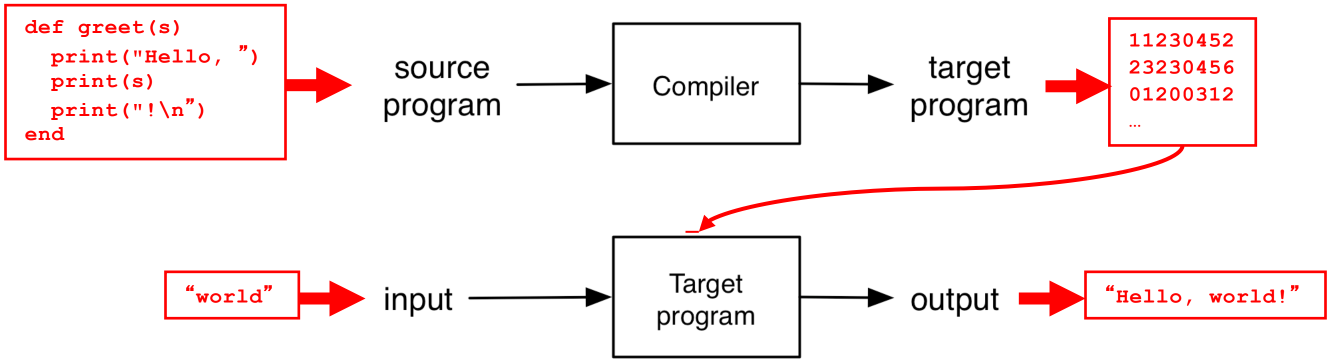
- There are lots of other languages w/ various features
  - COBOL (1959) – Business applications
    - Imperative, rich file structure
  - BASIC (1964) – MS Visual Basic
    - Originally designed for simplicity (as the name implies)
    - Now it is object-oriented and event-driven, widely used for UIs
  - 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

Implementation

- How do we implement a programming language?
  - Put another way: How do we get program P in some language L to run?

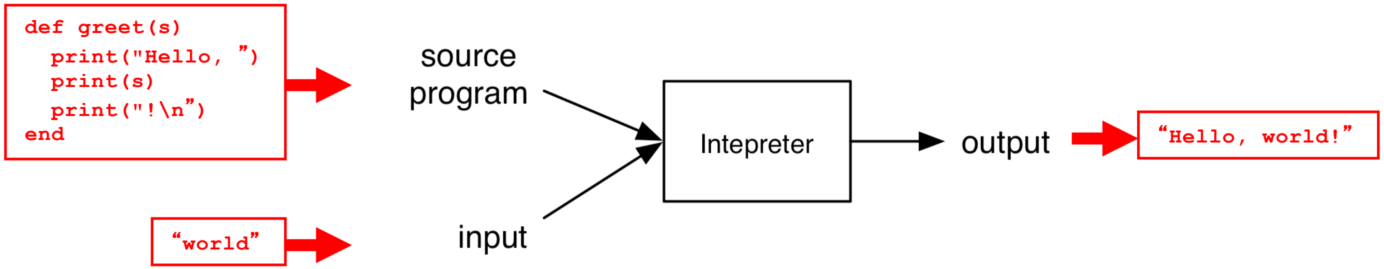
- Two broad ways
  - Compilation
  - Interpretation

Compilation



- Source program translated ("compiled") to another language
  - Traditionally: directly executable machine code
    - gcc, clang
  - Bytecode, Portable Code
    - Javac

Interpretation



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

Quiz: What do you think?

- Which of the following languages has implementations as a compiler *and* an interpreter?

a) C
b) Python
c) Java
d) All of the above

Quiz: What do you think?

- Which of the following languages has implementations as a compiler *and* an interpreter?

A language often has a canonical kind of implementation, but there can be others

a) C

b) Python

c) Java

d) All of the above

Defining Paradigm: Elements of PLs

- Important features
  - Regular expression handling
  - Objects
    - Inheritance
  - Closures/code blocks
  - Immutability
  - Tail recursion
  - Pattern matching
    - Unification
  - Abstract types
  - Garbage collection

- Declarations
  - Explicit
  - Implicit

- Type system
  - Static
    - Polymorphism
    - Inference
  - Dynamic
  - Type safety

Summary

- Programming languages vary in their
  - Syntax
  - Semantics
  - Style/paradigm and pragmatics
  - Implementation
- They are designed for different purposes
  - And goals change as the computing landscape changes, e.g., as programmer time becomes more valuable than machine time
- Ideas from one language appear in others