

CMSC 330: Organization of Programming Languages

Introduction

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Course Goal

Learn how programming languages work

- Languages you know
- Why are there so many programming languages?

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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(...)`?

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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

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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

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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

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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!

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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

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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

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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

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Calendar / Course Overview

- ▶ Tests
 - 4 quizzes, 1 midterm, final exam
- ▶ Projects
 - Project 1 – Ruby
 - Project 2-4 – OCaml
 - Project 5 – Prolog
- ▶ 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!

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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 quizzes, and some lecture material in discussion sections

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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

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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)

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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

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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

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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

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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)

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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)

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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)

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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

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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 = ()
```

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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

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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”

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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).

?- 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

Query

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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)

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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
- ```

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

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

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## 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!)

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## 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
```

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## 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

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## 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)

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## 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

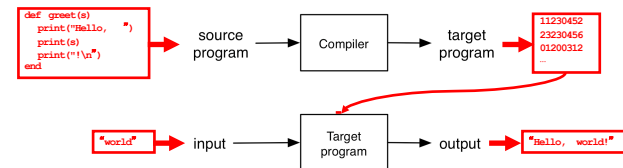
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## Program Execution

- 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**

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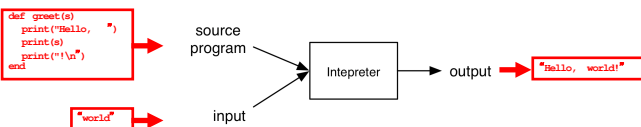
## Compilation



- 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)

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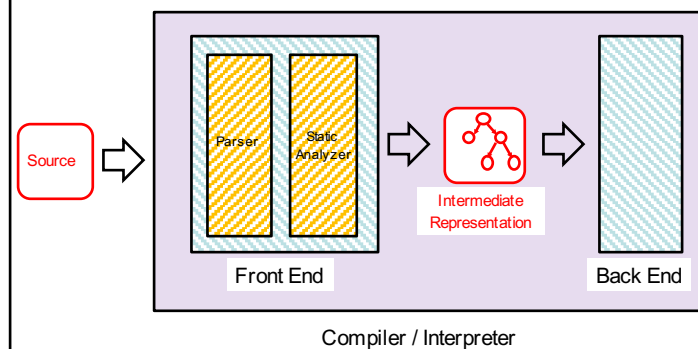
## Interpretation



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

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## Architecture of Compilers, Interpreters



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## 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

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## Compiler or Interpreter?

- ▶ 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

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## 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

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## 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

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## 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

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## 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, ...

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## 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

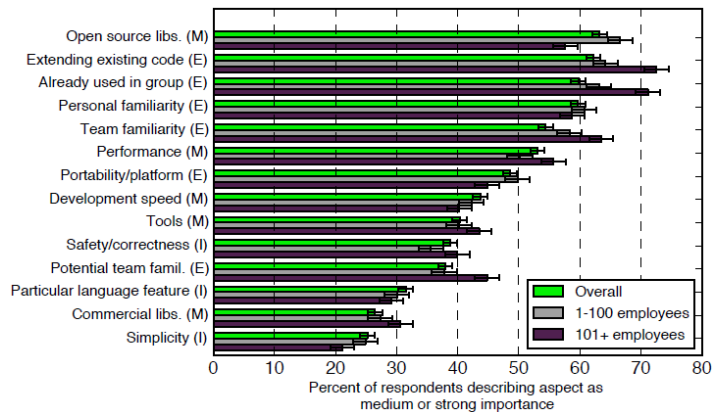
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## Attributes of a Good Language

- 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?

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## What Programmers Want In a PL



Meyerovitch & Rabin, "Empirical analysis of programming language adoption", OOPSLA'13#5

## 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

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