CMSC 330: Organization of Programming Languages

Course Policies

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 (and being able to make your own).

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**

Resources

- Class Website (https://bakalian.cs.umd.edu/330)
  - course information (office hours and discussion info, syllabus, etc)
- Gradescope (https://gradescope.com)
  - Submitting assignments
- Piazza (https://piazza.com)
  - Forum for asking questions
- Github (https://github.com/umd-cmsc330/fall22)
  - Projects and Discussions

Syllabus

- Dynamic/ Scripting languages (Ruby)
- Regular Expressions
- Functional programming (OCaml)
- Regular expressions & finite automata
- Context-free grammars & parsing
- Lambda Calculus and Operational Semantics
- Safe, “zero-cost abstraction” programming (Rust)
- Garbage Collection

Calendar / Course Overview

- Tests
  - 5 quizzes, 2 midterm exams, 1 final exam ALL ONLINE
  - Do not schedule your interviews on exam dates
- Lecture quizzes
  - On Gradescope, due by the end of the day of lecture
- Projects
  - Project 0 - Setup
  - Project 1 – Ruby
  - Project 2-4 – OCaml
  - Project 5 - Rust
    - P1, P2, and P4 are split in two parts
  - Can submit 24 hours late for 10% penalty
  - Get five (5) 12-hour late tokens

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

- 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 gradescope
- See web page for Ruby, OCaml, etc. versions we use, if you want to install at home

Rules and Reminders

- 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
- Cliff's Advice
  - Ask Questions
  - Make Friends
  - Start projects early
  - Feel Emotions
  - Expect to get things wrong

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

Quiz time!

- According to IEEE Spectrum Magazine which is the “top” programming language of 2021?

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

Quiz time!

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A. Java
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D. C++

Rank	Language	Type	Score
1	Python		100.0
2	Java		95.4
3	C		94.7
4	C++		92.4
5	JavaScript		88.1
6	C#		82.4

Inserting my own course overview

What is a “Top” Language?

- What is a language?
  - Practical or Textbook Definition
- How do we use a language?
  - Claim: to express oneself
  - Does the language influence our expressiveness?
- What are the parts of a language?
  - Syntax, semantics, grammar
  - features and paradigms

What is a “Top” Language?

- Syntax, semantics, grammar
  - What does a language look like?
  - What does a idiom mean?
  - What structure does a language has?

- Features and Paradigms
  - Feature: Alphabet (English vs Mandarin)
  - Paradigm: Temporal (Fictional heptapod vs English)

What is a “Top” Language?

- Programming Languages are different
  - Features help express different things
  - Not all languages have all features

- Studying features helps you learn how to approach a problem
  - You will learn about certain features as well as how to implement them

Done my own course overview

The rest is stuff that was originally there. I feel like we can cut the rest

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
    - Lots of ink has been spilt about this mostly useless fact.
- Essentially all general-purpose programming languages are Turing complete
    - I.e., any program can be written in any TC 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

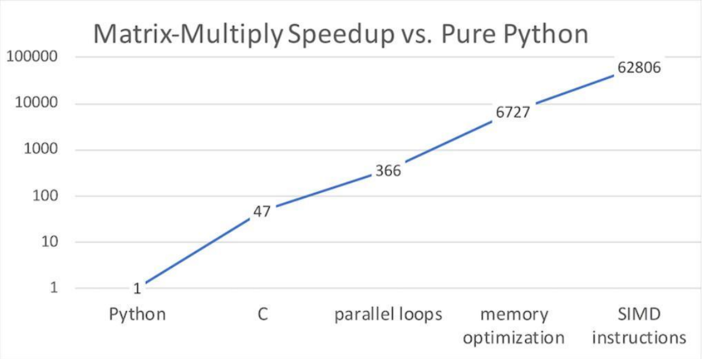
Studying Programming Languages

- 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



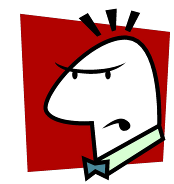
- Today
  - Language features based on design concepts
    - Encapsulation, records, inheritance, functionality, assertions
  - Machines cheap; programmers expensive
    - Scripting languages are slow(er), but run on fast machines
    - They've become very popular because they ease the programming process
  - 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 …



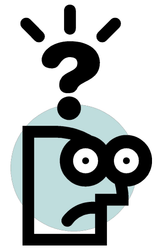
  - Differences initially jarring; overcome with experience

- 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)

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

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
  - E.g., used by WebAssembly

https://webassembly.github.io/spec/core/exec/conventions.html#formal-notation

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 - Resource-controlled (zero-cost)
  - Functional - 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

A Small OCaml Example

intro.ml:

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

```
$ ocaml
        OCaml version 4.07.1

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

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

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
```

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

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

Object-Oriented Languages

- Programs are built from objects
  - Objects combine functions and data
    - Often into "classes" which can inherit

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

- "Base" may be either imperative or functional
  - Smalltalk (1969)
  - C++ (1986)
  - OCaml (1987)
  - Ruby (1993)
  - Java (1995)

Other Languages

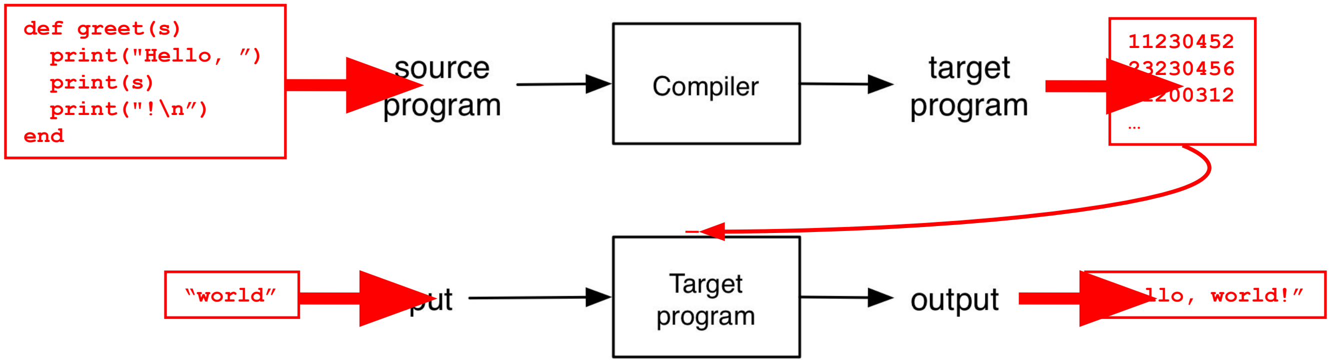
- There are lots of other languages w/ various features
  - COBOL (1959) – Business applications
    - Imperative, rich file structure
  - BASIC (1964) – MS Visual Basic
    - Originally designed for simplicity (as the name implies)
    - Now it is object-oriented and event-driven, widely used for UIs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

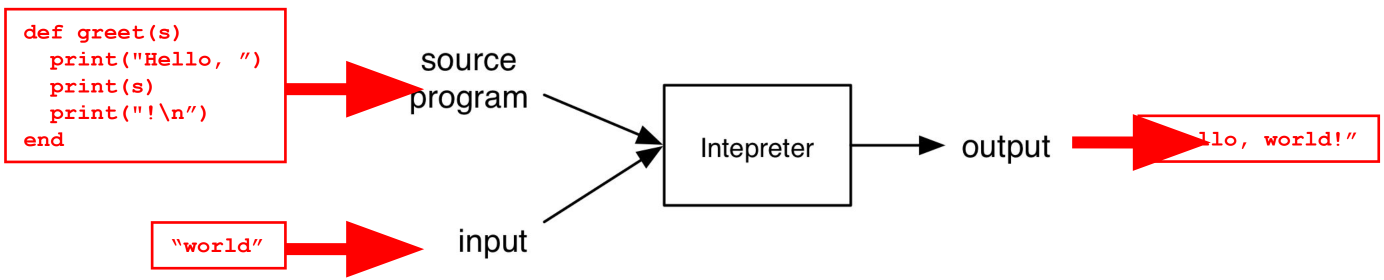
- Two broad ways
  - Compilation
  - Interpretation

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?

- C
- Python
- Java
- 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

- C
- Python
- Java
- **All of the above**

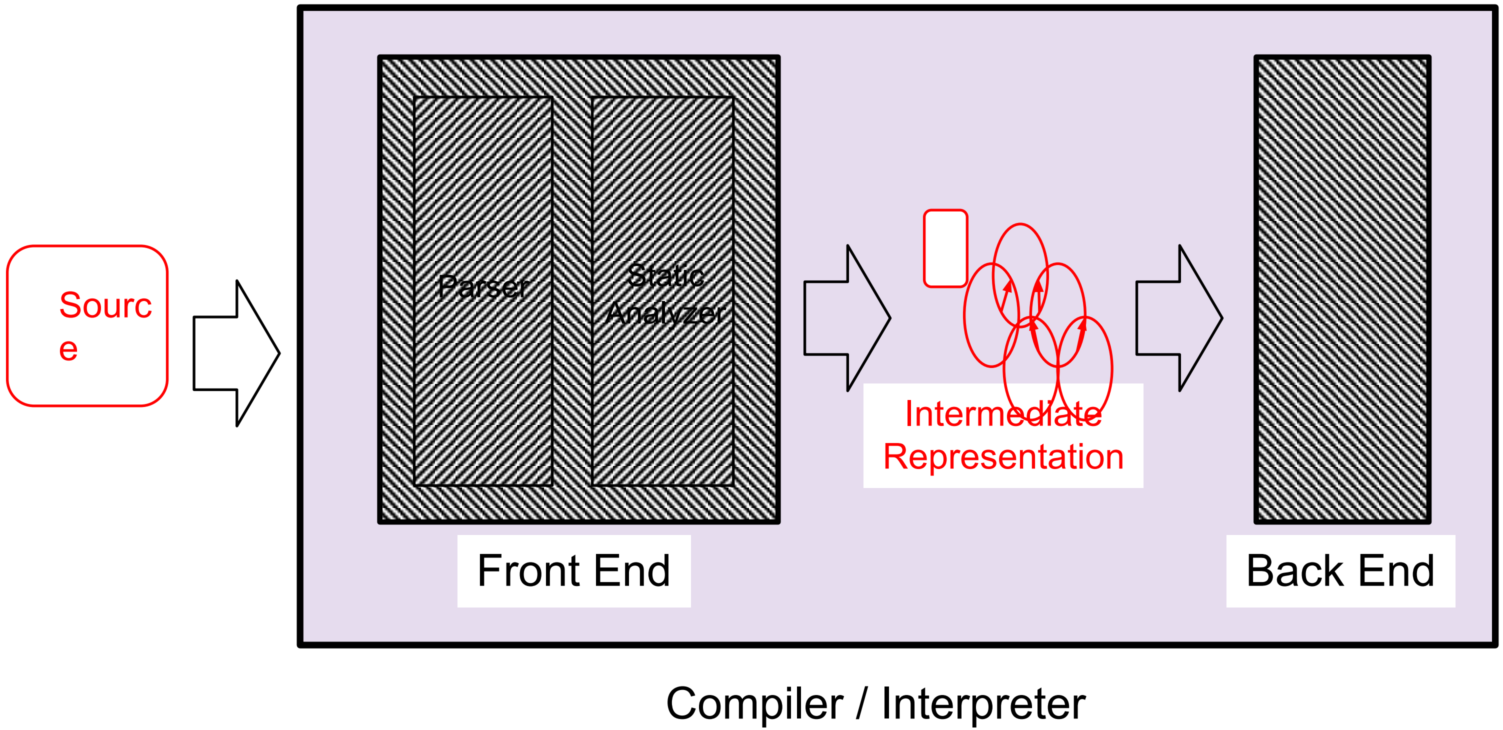
Defining Paradigm: Elements of PLs

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

- Declarations
  - Explicit
  - Implicit

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

Architecture of Compilers, Interpreters



Front Ends and Back Ends

- Front ends handle syntax
  - Parser converts source code into intermediate format (“parse tree”) reflecting program structure
  - Static analyzer checks parse tree for errors (e.g., erroneous use of 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
  - Fast start time (no compilation), slow execution time
- In practice
  - “General-purpose” programming languages (e.g., C, Java) are often compiled, although debuggers provide interpreter support
  - Scripting languages languages are often interpreted, even if general-purpose

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, …

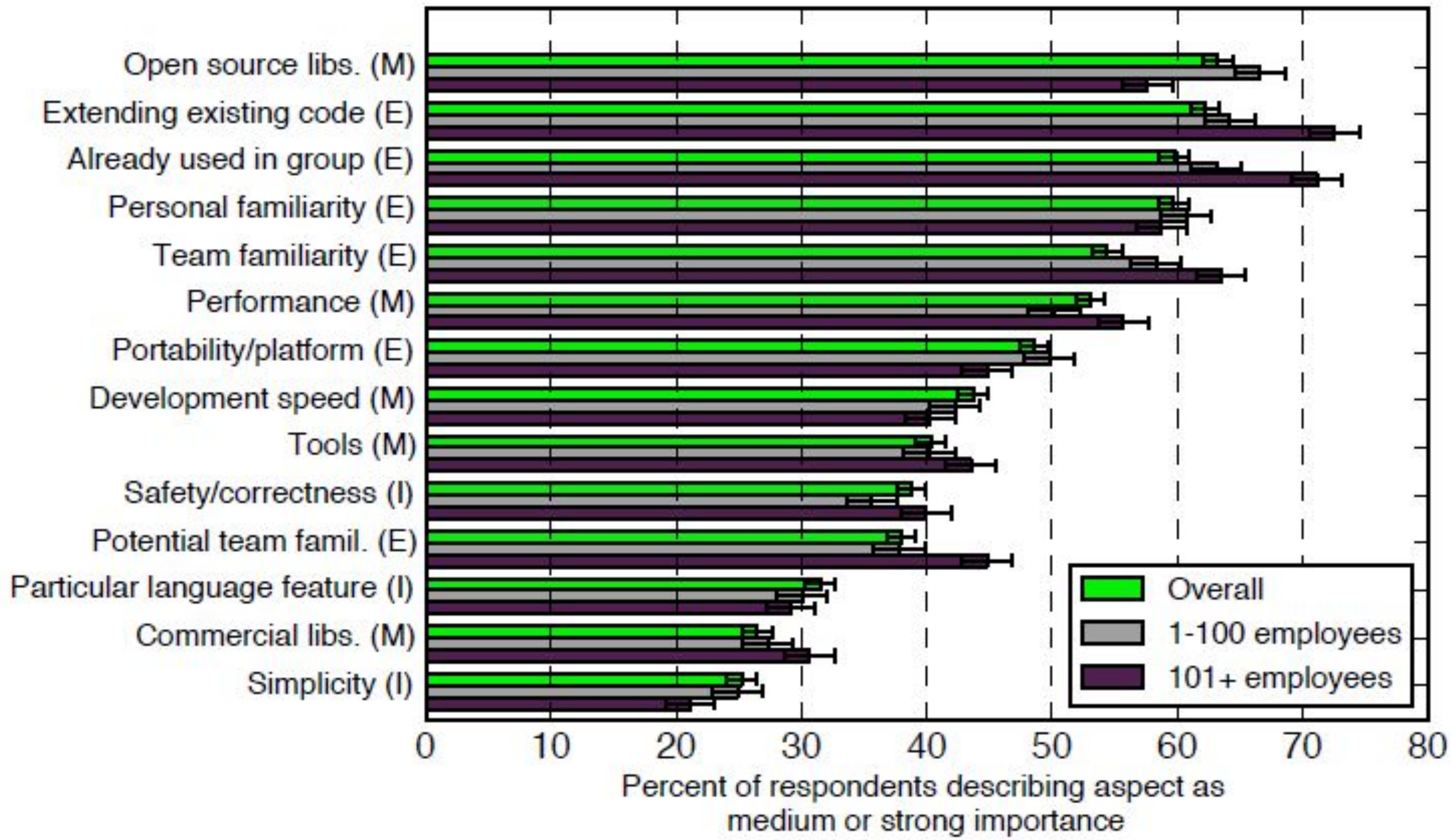
Attributes of a Good Language

- 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



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

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