Big Ideas for CS 251
~~Theory of Programming Languages~~
Principles of Programming Languages

SOLUTIONS

CS251 Programming Languages
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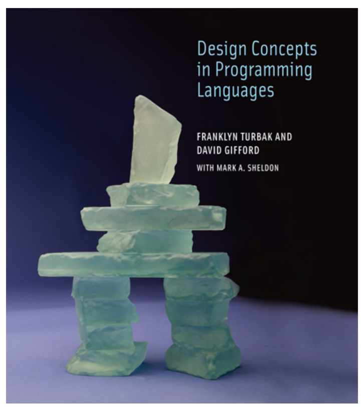
Programming Languages

- What is a PL?
- Why are new PLs created?
  - What are they used for?
  - Why are there so many?
- Why are certain PLs popular?
- What goes into the design of a PL?
  - What features must/should it contain?
  - What are the design dimensions?
  - What are design decisions that must be made?
- Why should you take this course? What will you learn?

PL is my passion!



- First PL project in 1982 as intern at Xerox PARC
- Created visual PL for 1986 MIT masters thesis
- 1994 MIT PhD on PL feature (synchronized lazy aggregates)
- 1996 – 2006: worked on types as member of Church project
- 1988 – 2008: *Design Concepts in Programming Languages*
- 2011 – current: lead TinkerBlocks research team at Wellesley
- 2012 – current: member of App Inventor development team

General Purpose PLs

Java Python Perl
Fortran ML JavaScript
Racket Haskell
C/C++ Ruby C#
Scala CommonLisp

Domain Specific PLs (DSLs)

Excel HTML CSS

OpenGL LaTeX

Matlab

Digital Amati R

JINJA

Swift PostScript IDL

Programming Languages: Mechanical View

A computer is a machine. Our aim is to make the machine perform some specified actions. With some machines we might express our intentions by depressing keys, pushing buttons, rotating knobs, etc. For a computer, we construct a sequence of instructions (this is a ``program'') and present this sequence to the machine.

– *Laurence Atkinson, Pascal Programming*

Programming Languages: Linguistic View

A computer language … is a novel formal medium for expressing ideas about methodology, not just a way to get a computer to perform operations. Programs are written for people to read, and only incidentally for machines to execute.

– *Harold Abelson and Gerald J. Sussman*

"Religious" Views

The use of COBOL cripples the mind; its teaching should, therefore, be regarded as a criminal offense. – *Edsger Dijkstra*

It is practically impossible to teach good programming to students that have had a prior exposure to BASIC: as potential programmers they are mentally mutilated beyond hope of regeneration. – *Edsger Dijstra*

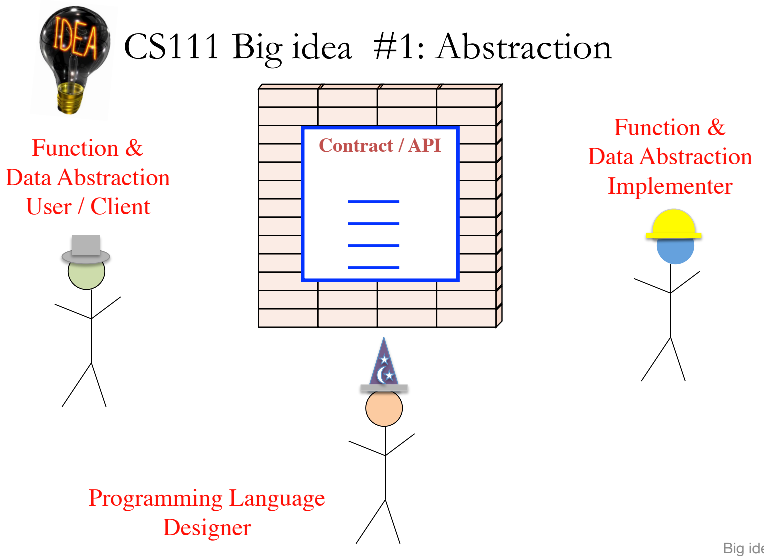
You're introducing your students to programming in C? You might as well give them a frontal lobotomy! – *A colleague of mine*

A LISP programmer knows the value of everything, but the cost of nothing. - *Alan Perlis*

I have never met a student who cut their teeth in any of these languages and did not come away profoundly damaged and unable to cope. … I mean this reads to me very similarly to teaching someone to be a carpenter by starting them off with plastic toy tools and telling them to go sculpt sand on the beach. - *John Haugeland, on blocks languages*

A language that doesn't affect the way you think about programming, is not worth knowing. - *Alan Perlis*

Which Programming/PL Hat do You Wear?



Programming Paradigms

- ***Imperative*** *(e.g. C, Python)*: Computation is step-by-step execution on a stateful abstract machine involving memory slots and mutable data structures.
- ***Functional, function-oriented*** *(e.g Racket, ML, Haskell)*: Computation is expressed by composing functions that manipulate immutable data.
- ***Object-oriented*** *(e.g. Simula, Smalltalk, Java)*: Computation is expressed in terms of stateful objects that communicate by passing messages to one another.
- ***Logic-oriented*** *(e.g. Prolog)*: Computation is expressed in terms of declarative relationships.

Note: In practice, most PLs involve multiple paradigms. E.g.

- Python supports functional features (map, filter, list comprehensions) and objects
- Racket and ML have imperative features.

Paradigm Example: Quicksort

```
void qsort(int a[], int lo, int hi) {
  int h, l, p, t;

  if (lo < hi) {
    l = lo;
    h = hi;
    p = a[hi];

    do {
      while ((l < h) && (a[l] <= p))
          l = l+1;
      while ((h > l) && (a[h] >= p))
          h = h-1;
      if (l < h) {
          t = a[l];
          a[l] = a[h];
          a[h] = t;
      }
    } while (l < h);

    a[hi] = a[l];
    a[l] = p;

    qsort( a, lo, l-1 );
    qsort( a, l+1, hi );
  }
}
```

```
quicksort :: Ord a => [a] -> [a]
quicksort []     = []
quicksort (p:xs) =
        (quicksort lesser)
        ++ [p]
        ++ (quicksort greater)
    where
        lesser  = filter (< p) xs
        greater = filter (>= p) xs
```

Functional Style (in Haskell)

Imperative Style
(in C; Java would be similar)

PL Dimensions

PLs differ based on decisions language designers make in many dimensions. E.g.:

- ***First-class values****:* what values can be named, passed as arguments to functions, returned as values from functions, stored in data structures. Which of these are first-class in your favorite PL: arrays, functions, variables?
- ***Naming***: Do variables/parameters name expressions, the values resulting from evaluating expressions, or mutable slots holding the values from evaluating expressions? How are names declared and referenced? What determines their scope?
- ***State***: What is mutable and immutable; i.e., what entities in the language (variables, data structures, objects) can change over time.
- ***Control***: What constructs are there for control flow in the language, e.g. conditionals, loops, non-local exits, exception handling, continuations?
- ***Data***: What kinds of data structures are supported in the language, including products (arrays, tuples, records, dictionaries), sums (options, oneofs, variants), sum-of-products, and objects.
- ***Types***: Are programs statically or dynamically typed? What types are expressible?

Why *study* PL?

- Crossroads of CS
- Approach problems as a *language designer.*
  - *"A good programming language is a conceptual universe for thinking about programming"* -- Alan Perlis
  - Evaluate, compare, and choose languages
  - Become better at learning new languages
  - Become a better programmer by leveraging powerful features (first-class functions, tree recursion, sum-of-product datatypes, pattern matching)
  - You probably won't design a general-purpose PL, but might design a DSL
  - view API design as language design
- Ask:
  - Why are PLs are the way they are?
  - How could they (or couldn't they) be better?
  - What is the cost-convenience trade-off for feature X?

Administrivia

- Schedule, psets, quizzes, lateness policy, etc.: see http://cs.wellesley.edu/~cs251/.
- Do (most of) PS0 tonight
  - Fill out "get to know you" Introze introduction.
  - Review course syllabus and policies (we'll go over these tomorrow)
  - Read Wed slides on "big-step semantics" of Racket
  - Install Dr. Racket
- PS1 is available; due next Friday. Start it this week!
- Credit/non is a **bad idea** for 251. Talk to me first!
- Visit me in office hours before next Friday!

PL Parts

Syntax: *form* of a PL

- What a P in a given L look like as symbols?
- Concrete syntax vs abstract syntax trees (ASTs)

Semantics: *meaning* of a PL

- *Dynamic Semantics*: What is the behavior of P? What actions does it perform? What values does it produce?
  - Evaluation rules: what is the result or effect of evaluating each language fragment and how are these composed?
- *Static Semantics:* What can we tell about P before running it?
  - Scope rules: to which declaration does a variable reference refer?
  - Type rules: which programs are well-typed (and therefore legal)?

Pragmatics: *implementation* of a PL (and PL environment)

- How can we evaluate programs in the language on a computer?
- How can we optimize the performance of program execution?

Syntax (Form) vs. Semantics (Meaning) in Natural Language

Furiously sleep ideas green colorless.

Colorless green ideas sleep furiously.

Little white rabbits sleep soundly.

Concrete Syntax: Absolute Value Function

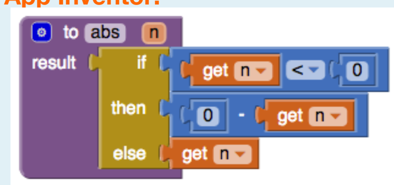
Logo: to abs :n ifelse :n < 0 [output (0 - :n)] [output :n] end

Javascript: function abs (n) {if (n < 0) return -n; else return n;}

Java: public static int abs (int n) {if (n < 0) return -n; else return n;}

Python:
```
def abs(n):
  if n < 0:
    return -n
  else:
    return n
```

App Inventor:

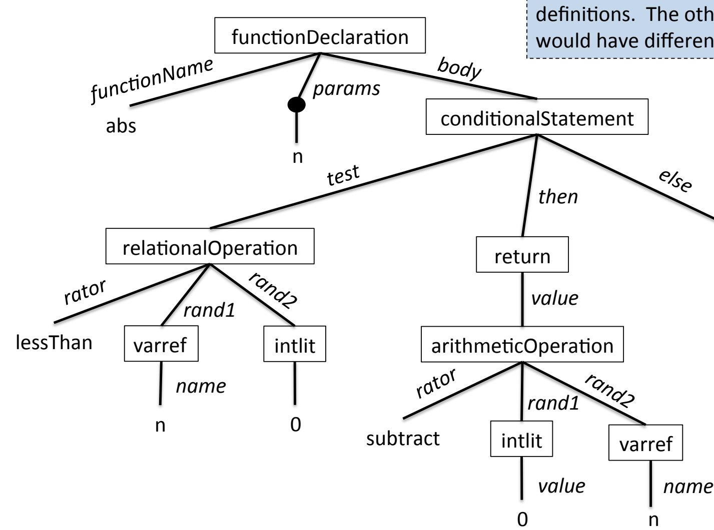


Scheme/Racket: (define abs (lambda (n) (if (< n 0) (- n) n)))

PostScript: /abs {dup 0 lt {0 swap sub} if} def

Abstract Syntax Tree (AST): Absolute Value Function

This AST abstracts over the concrete syntax for the Logo, JavaScript, and Python definitions. The other definitions would have different ASTs.



Dynamic Semantics Example 1

What is the meaning of the following expression?

```
(1 + 11) * 10
```

Some possible answers:

- 120 (regular interpretation of numbers, operators)
- 1000 (binary numbers, regular operators)
- 0 (“+” means “minus”, “*” means “plus”)
- 111…1 (30 1s; “+” means “convert to string and concatenate”; * means “repeated concatenation”)
- 13 (number of characters in string)
- 5 (number of nodes in AST)
- 3 (number of leaves in AST)

Dynamic Semantics Example 2

What is printed by the following program?

```
a = 1;
b = a + 20;
print(b);
a = 300
print(b);
count = 0;
fun inc() { count = count + 1; return count; }
fun dbl(ignore, x) { return x + x; }
print(dbl(inc(), inc())
```

Here are some possible answers. What execution models give rise to these answers?

21	21	21	21
21	21	320	320
4	2	3	2

Semantics Example 3 **Solutions**

Suppose a is an array (or list) containing the three integer values 10, 20, and 30 in the following languages. What is the meaning of the following expressions/ statements in various languages (the syntax might differ from what's shown).

	`a[1]`	`a[3]`	`a[2] = "foo"`	`a[3] = 17`
Java	20	dynamic index out of bounds error	static type error	dynamic index out of bounds error
C	20	returns value in memory slot after a[2]	static type error	Stores 17 in memory slot after a[2]
Python	20	dynamic list index out of range error	stores "foo" in third slot of a	dynamic list index out of range error
JavaScript	20	"undefined" value	stores "foo" in third slot of a	Stores 17 in a[3]
Pascal	20	static index out of bounds error	static type error	static index out of bounds error
App Inventor	10	30	stores "foo" in second slot of a	Stores 17 in third slot of a

How do you determine the answers? **Try in implementation; consult documentation**

Static Semantics Example 1: Type Checking **Solutions**

Which of the following Java examples can be well-typed (i.e., pass the type checker)? How do you know? What assumptions are you making?

Green indicates statically well-typed; Red indicates static type error.

A
```
2 * (3 + 4)
```

B
```
2 < (3 + 4)
```

C
```
2 < True
```

D Assume a,b,c are ints
```
if (a < b) {
   c = a + b;
} else {
   c = a * b;
}
```

E Assume a,b are ints; can't find type for c
```
if (a < b) {
   c = a + b;
} else {
   c = a > b;
}
```

F A can't both be bool for test and int for +/*
```
if (a) {
   c = a + b;
} else {
   c = a * b;
}
```

G
```
public boolean f(int i, boolean b) {
   return b && (i > 0);
}
```

H
```
public int g(int i, boolean b) {
   return i * (b ? 1 : -1);
}
```

I
```
public int p(int w) {
   if (w > 0) { return 2*w; }
}
```
No else clause, so no return of in when w <= 0

J Return type needs to be boolean, not int
```
public int q(int x) { return x > 0; }
```

K Assume g has type from above: g : (int, boolean) -> int
```
public int r(int y) { return g(y, y>0); }
```

L If f has type (int, boolean) -> boolean, not well-typed; But *would* be well typed if f : (int) -> boolean
```
public boolean s(int z) { return f(z); }
```


Static Semantics Example 2: Detecting Loops **Solutions**

Which of these Python programs has inputs for which it loops forever?

```
def f(x):
  return x+1
```
No ∞ loop on any input

```
def g(x):
  while True:
    pass
  return x
```
∞ loop on all inputs

```
def h(x):
  while x > 0:
    x = x+1
  return x
```
No ∞ loop for x <= 0. ∞ loop for x > 0, assuming arbitrarily large numbers. In practice, will either run out of memory when x gets too big, or will wrap to negative and halt.

```
def g2(x):
  return g2(x)
```
∞ recursion on all inputs. In practice, runs out of stack space in Python. Similar Racket program is true ∞ loop due to proper tail recursion.

```
def h2(x):
  if x <= 0:
     return x
  else:
     return h2(x+1)
```
No ∞ loop for x <= 0. ∞ recursion for x > 0. In practice, runs out of stack space in Python. Similar Racket program will loop, but run out memory when x gets too big.

```
def collatz(x):
  while x != 1:
    if (x % 2) == 0:
      x = x/2
    else:
      x = 3*x + 1
  return 1
```
Although this terminates for all x > 0 that have been tested, no one knows the answer for all x. This a famous open problem in mathematics. Solve it and win a Fields medal!

Static Semantics and Uncomputability

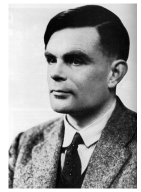
It is generally **impossible** to answer any interesting question about static program analysis!

This is a consequence of **Rice's Theorem** (see CS235).

For example, will this program ever:

- halt on certain inputs
- encounter an array index out of bounds error?
- throw a NullPointerException?
- access a given object again?
- send sensitive information over the network?
- divide by 0?
- run out of memory, starting with a given amount available?
- try to treat an integer as an array?

The Church-Turing Thesis and Turing-Completeness



- **Church-Turing Thesis**: Computability is the common spirit embodied by this collection of formalisms.
- This thesis is a claim that is widely believed about the intuitive notions of algorithm and effective computation. It is not a theorem that can be proved.
- Because of their similarity to later computer hardware, Turing machines (CS235) have become the gold standard for effectively computable.
- We' ll see in CS251 that Church's lambda-calculus formalism is the foundation of modern programming languages.
- A consequence: programming languages all have the "same" computational "power" in term of what they can express. All such languages are said to be **Turing-complete**.

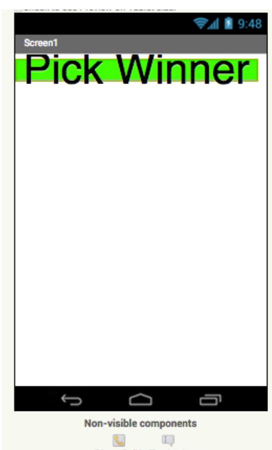
Expressiveness and Power

- About:
  - ease
  - elegance
  - clarity
  - modularity
  - abstraction
  - ...
- Not about: computability
- Different problems, different languages
  - Facebook or web browser in assembly language?

Pragmatics: Raffle App In App Inventor

http://ai2.appinventor.mit.edu

Designer Window



Blocks Editor

To enter the raffle, text me now with an empty message: **339-225-0287**

How hard is this to do in more traditional development environments for Android/iOS?

Pragmatics: Metaprogramming

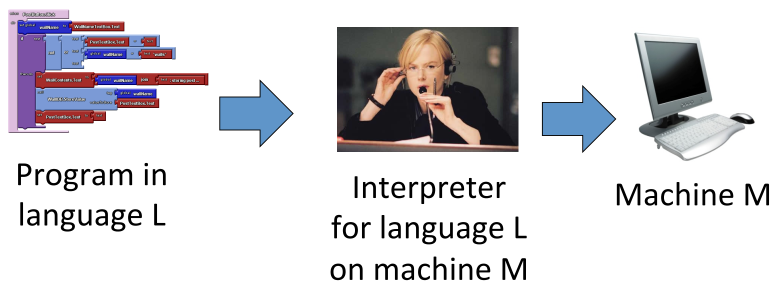
PLs are implemented in terms of **metaprogams** = programs that manipulate other programs.

This may sound weird, but programs are just trees (ASTs), so a metaprogram is just a program that manipulates trees (think a more complex version of CS230 binary tree programs).

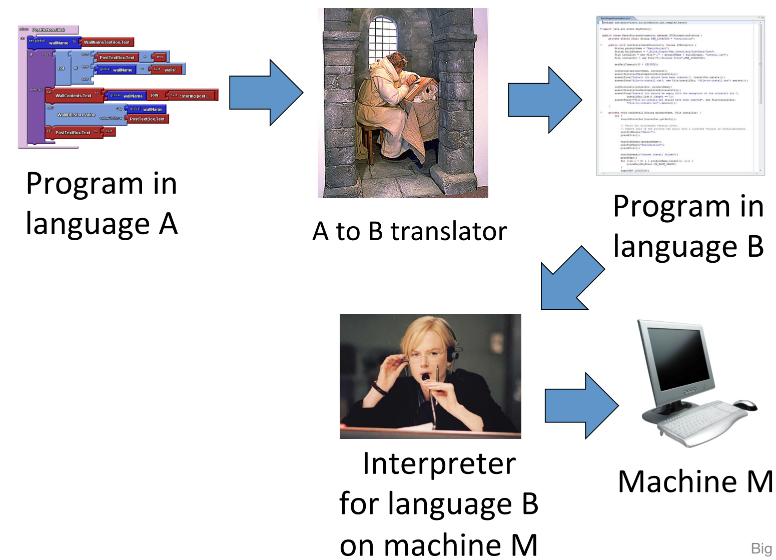
Implementation strategies:

- ***Interpretation***: interpret a program P in a source language S in terms of an implementation language I.
- ***Translation (compilation)***: translate a program P in a source language S to a program P' in a target language T using a translator written in implementation language I.
- **Embedding**: express program P in source language S in terms of data structures and functions in implementation language I.

Metaprogramming: Interpretation



Metaprogramming: Translation



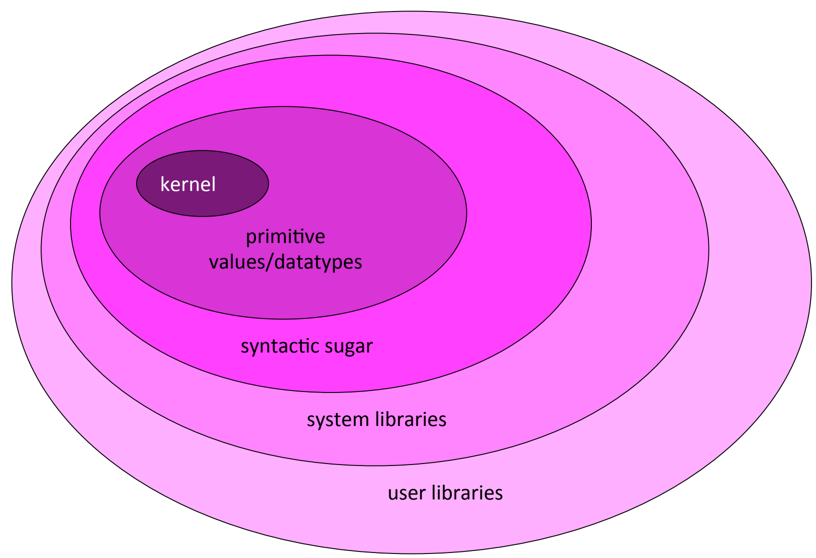
Metaprogramming: Bootstrapping Puzzles

How can a Racket interpreter be written in Racket?

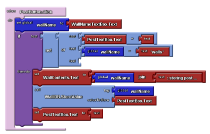
How can a Java compiler be written in Java?

How can gcc (a C-to-x86 compiler) be written in C?

Metaprogramming: Programming Language Layers



Metaprogramming: Embedding



Program in language A embedded in language B

Interpreter for language B on machine M

Machine M

Programming Language Essentials

Primitives

Means of Combination

Means of Abstraction

Think of the languages you know. What means of abstraction do they have?

Why? Who? When? Where? Design and Application

- Historical context
- Motivating applications
  - Lisp: symbolic computation, logic, AI, experimental programming
  - ML: theorem-proving, case analysis, type system
  - C: Unix operating system
  - Simula: simulation of physical phenomena, operations, objects
  - Smalltalk: communicating objects, user-programmer, pervasiveness
- Design goals, implementation constraints
  - performance, productivity, reliability, modularity, abstraction, extensibility, strong guarantees, …
- Well-suited to what sorts of problems?