Elements of Programming Languages

Lecture 0: Introduction and Course Outline

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What is programming?

- Computers are deterministic machines, controlled by low-level (usually binary) machine code instructions.
- A computer **can [only] do whatever we know how to order it to perform** (Ada Lovelace, 1842)
- Programming is **communication**:
  - between a person and a machine, to tell the machine what to do
  - between people, to communicate ideas about algorithms and computation

From machine code to programming languages

- The first programmers wrote all of their code directly in machine instructions
  - ultimately, these are just raw sequences of bits.
- Such programs are extremely difficult to write, debug or understand.
- Simple "assembly languages" were introduced very early (1950's) as a human-readable notation for machine code
- FORTRAN (1957) — one of the first "high-level" languages (procedures, loops, etc.)

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- (HTML is in a gray area — with JavaScript or HTML5 extensions it is a lot more "computational")

Some different languages

```
# Python, Java, SQL
print("Hello, world!")

// Java
public class HelloWorld {
  public static void main(String[] args) {
    System.out.println("Hello, World");
  }
}

-- SQL
SELECT DISTINCT 'Hello world!' AS new_value
  FROM AnyTableWithOneOrMoreRows
 WHERE 1 = 1;
```

Why are there so many?

Many different goals/motivations

- Scientific computation: FORTRAN, R
- Commercial needs/industry backing: COBOL, C, C++, Java, C#, F#, Ruby, JavaScript, Rust, SQL, WebAssembly
- Scripting: Perl, Python, Ruby
- Explore research ideas: LISP, Simula, Smalltalk, Algol, Pascal, Scheme, Racket, ML, OCaml, Haskell, Prolog, Curry

These migrate over time, for example Python now widely used for scientific computation

What do they have in common?

- All (formal) languages have a written form: we call this (concrete) *syntax*
- All (executable) languages can be implemented on computers: e.g. by a *compiler* or *interpreter*
- All programming languages describe computations: they have some *computational meaning*, or *semantics*
- In addition, most languages provide *abstractions* for organizing, decomposing and combining parts of programs to solve larger problems.

What are the differences?

There are many so-called “programming language paradigms”:

- imperative (variables, assignment, if/while/for, procedures)
- object-oriented (classes, inheritance, interfaces, subtyping)
- typed (statically, dynamically, strongly, un/uni-typed)
- functional (λ-calculus, pure, lazy)
- logic/declarative (computation as deduction, query languages)

each representing a (more or less coherent) philosophy of what computation is

Languages, paradigms and elements

- A great deal of effort has been expended trying to find the "best" paradigm, with no winner declared so far.
- In reality, they all have strengths and weaknesses, and almost all languages make compromises or synthesize ideas from several "paradigms".
- This course emphasizes different programming language **features**, or **elements**
  - Analogy: periodic table of the elements in chemistry
- Goal: understand the basic components that appear in a variety of languages, and how they "combine" or "react" with one another.

Applicability

- Major new general-purpose languages come along every decade or so. (C/C++, Java, Python?, Rust?)
  - Hence, few programmers or computer scientists will design a new, widely-used general purpose language, or write a compiler
  - However, domain-specific languages are increasingly used, and the same principles of design apply to them
- Moreover, understanding the principles of language design can help you become a better programmer
  - Learn new languages / recognize new features faster
  - Understand when and when *not* to use a given feature
- Assignments will cover practical aspects of programming languages: *interpreters* and *DSLs/translators*

Course Administration

Staff

- Lecturer: James Cheney <jcheney@inf.ed.ac.uk>, IF 5.29
  - Office hours: by appointment
- TA: Wenhao Tang

Format

- 20 **lectures** (M/Th 1410–1500)
  - 2 intro/review [non-examinable]
  - 2 guest lectures [non-examinable]
  - 16 core material [examinable]
- 1 two-hour **lab session** (September 27, 1210–1400)
- 8 one-hour **tutorial sessions**, starting in week 3 (times and groups TBA)

All of these activities are **part of the course** and may cover examinable material, unless explicitly indicated.

Feedback and Assessment

- Coursework:
  - Assignment 1: **Lab exercise sheet**, available during week 2, due during week 3, worth 0% of final grade
  - Assignment 2: available during week 3, due week 6, worth 0% of final grade.
  - Assignment 3: available during week 6, due week 10, worth 25% of final grade.
  - The first two assignments are marked for formative feedback only, but the third **builds on the first two**.
- One (written) exam: worth 75% of final grade.

Scala

- The main language for this course will be *Scala*
  - Scala offers an interesting combination of ideas from functional and object-oriented programming styles
  - We will use Scala (and other languages) to illustrate key ideas
  - We will also use Scala for the assignments
- However, this is not a "course on Scala"
  - You will be expected to figure out certain things for yourselves (or ask for help)
  - We will not teach every feature of Scala, nor are you expected to learn every dark corner
  - In fact, part of the purpose of the course is to help you recognize such dark corners and avoid them unless you have a good reason...

Recommended reading

- There is no official textbook for the course that we will follow exactly
- However, the following are recommended readings to complement the course material:
  - Practical Foundations for Programming Languages, second edition, (PFPL2), by Robert Harper. Available online from the author's webpage and through the University Library's ebook access.
  - Concepts in Programming Languages (CPL), by John Mitchell. Available through the University Library's ebook access.
- **Slides** available on web page, **lecture notes** available in Piazza

Course Outline

Wadler's Law

In any language design, the total time spent discussing a feature in this list is proportional to two raised to the power of its position.

0. Semantics
1. Syntax
2. Lexical syntax
3. Lexical syntax of comments

The number of people who feel qualified to comment on an issue is inversely proportional to the expertise required to understand it
Few languages are well-designed because few people know what good language design is. Let's change that.

Syntax

- This course is primarily about language design and semantics.
- As a foundation for this, we will necessarily spend some time on abstract syntax trees (and programming with them in Scala)
- We will cover: Name-binding, substitution, static vs. dynamic scope
- We will not cover: Concrete syntax, lexing, parsing, precedence (Compiling Techniques does some of this)

Interpreters, Compilers and Virtual Machines

- Suppose we have a *source* programming language L_S, a *target* language L_T, and an *implementation* language L_I
  - An *interpreter* for L_S is an L_I program that executes L_S programs.
  - When both L_S and L_I are low-level (e.g. L_S = JVM, L_I = x86), an interpreter for L is called a *virtual machine*.
  - A *translator* from L_S to L_T is an L_I program that translates programs in L_S to “equivalent” programs in L_T.
  - When L_T is low-level, a translator to L_T is usually called a *compiler*.
- In this course, we will use interpreters to explore different language features.

Semantics

- How can we understand the meaning of a language/feature, or compare different languages/features?
- Three basic approaches:
  - *Operational semantics* defines the meaning of a program in terms of "rules" that explain the step-by-step execution of the program
  - *Denotational semantics* defines the meaning of a program by interpreting it in a mathematical structure
  - *Axiomatic semantics* defines the meaning of a program via logical specifications and laws
- All three have strengths and weaknesses
- We will focus on operational semantics in this course: it is the most accessible and flexible approach.

Abstraction, abstraction, abstraction

- The three most important considerations for programming language design are:
  - (Data) Abstraction
  - (Control) Abstraction
  - (Modular) Abstraction
- We will investigate different language elements that address the need for these abstractions, and how different design choices interact.
- In particular, we will see how **types** offer a fundamental organizing principle for programming language features.

Data Structures and Abstractions

- **Data structures** provide ways of organizing data:
  - option types vs. null values
  - pairs/record types;
  - variant/union types;
  - lists/recursive types;
  - pointers/references
- **Data abstractions** make it possible to hide data structure choices:
  - overloading (ad hoc polymorphism)
  - generics (parametric polymorphism)
  - subtyping
  - abstract data types

Control Structures and Abstractions

- **Control structures** allow us to express flow of control:
  - goto
  - for/while loops
  - case/switch
  - exceptions
- **Control abstractions** make it possible to hide implementation details:
  - procedure call/return
  - function types/higher-order functions
  - continuations

Design dimensions and modularity

- Programming “in the large” requires considering several cross-cutting **design dimensions**:
  - eager vs. lazy evaluation
  - purity vs. side-effects
  - static vs. dynamic typing
- and **modularity** features
  - modules, namespaces
  - objects, classes, inheritance
  - interfaces, information hiding

The art and science of language design

- Language design is both an art and a science
- The most popular languages are often not the ones with the cleanest foundations (and vice versa)
- This course teaches the science: formalisms and semantics
- Aesthetics and "good design" are hard to teach (and hard to assess), but one of the assignments will give you an opportunity to experiment with domain-specific language design

Course goals

By the end of this course, you should be able to:

1. Investigate the design and behaviour of programming languages by studying implementations in an interpreter
2. Employ abstract syntax and inference rules to understand and compare programming language features
3. Design and implement a domain-specific language capturing a problem domain
4. Understand the design space of programming languages, including common elements of current languages and how they are combined to construct language designs
5. Critically evaluate the programming languages in current use, acquire and use language features quickly, recognise problematic programming language features, and avoid their (mis)use.

Relationship to other UG3 courses

- **Compiling Techniques** (S2)
  - covers complementary aspects of PL implementation, such as lexical analysis and parsin, compilation of imperative programs to machine code
- **Introduction to Theoretical Computer Science** (S1)
  - covers formal models of computation (Turing machines, etc.) as well as some λ-calculus and type theory
- **Modelling Concurrent Systems** (S1)
  - covers formal models of *concurrency* including operational techniques
- In this course, we focus on *interpreters*, *operational semantics*, and *types* to understand programming language features.
- There is relatively little overlap with CT, MCS, or ITCS.

Summary

- Today we covered:
  - Background and motivation for the course
  - Course administration
  - Outline of course topics
- Next time:
  - Concrete and abstract syntax
  - Programming with abstract syntax trees (ASTs)