During the next few weeks we are going to work with functional programming. Before I can explain to you what FP is, I thought I’d better put things into perspective by talking about other programming paradigms.

Over the last 40 or so years, a number of programming paradigms (a programming paradigm is a way to think about programs and programming) have emerged.

A **programming paradigm**
- is a way to think about programs, programming, and problem solving,
- is supported by one or more programming languages.

Being familiar with several paradigms makes you a better programmer and problem solver. The most popular paradigms:

- **Imperative programming.** Programming with **state**.
- Also known as **procedural programming**. The first to emerge in the 1940s-50s. Still the way most people learn how to program.
  - FORTRAN, Pascal, C, BASIC.

- **Functional programming.** Programming with **values**.
  - Arrived in the late 50s with the LISP language. LISP is still popular and widely used by AI people.
  - LISP, Miranda, Haskell, Gofer.
### Object-Oriented Programming

- Programming with objects that encapsulate data and operations.
- A variant of imperative programming first introduced with the Norwegian language Simula in the mid 60s.
- Simula, Eiffel, Modula-3, C++.

### Logic Programming

- Programming with relations.
- Introduced in the early 70s. Based on predicate calculus. Prolog is popular with Computational Linguists.
- Prolog, Parlog.

### Procedural Programming

The programmer...

- uses control structures (IF, WHILE, ...) to alter the program counter (PC).
- uses assignment statements to alter the store.
- is in charge of memory management, i.e. declaring variables to hold values during the computation.

```plaintext
function fact (n:integer):integer;
  var s, i : integer := 1;
begin
  while i<=n do s:=s*i; i:=i+1; end;
  return s;
end fact.
```

Procedural programming is difficult because:

1. A procedural program can be in a large number of states. (Any combination of variable values and PC locations constitutes a possible state.) The programmer has to keep track of all of them.
2. Any global variable can be changed from any location in the program. (This is particularly true of languages like C & C++ [Why?]).
3. It is difficult to reason mathematically about a procedural program.

We program an abstraction of the Von Neumann Machine, consisting of a store (memory), a program (kept in the store), a CPU and a program counter (PC):

- Computing \( x := x + 1 \)
  1. Compute \( x \)'s address, send it to the store, get \( x \)'s value back.
  2. Add 1 to \( x \)'s value.
  3. Send \( x \)'s address and new value to the store for storage.
  4. Increment PC.
Functional Programming

In contrast to procedural languages, functional programs don’t concern themselves with state and memory locations. Instead, they work exclusively with **values**, and **expressions** and **functions** which compute values.

- **Functional programming is not tied to the von Neumann machine.**
- **It is not necessary to know anything about the underlying hardware when writing a functional program, the way you do when writing an imperative program.**
- **Functional programs are more declarative than procedural ones; i.e. they describe what is to be computed rather than how it should be computed.***

Functional Languages

Common characteristics of functional programming languages:

1. **Simple and concise syntax** and semantics.
2. **Repetition is expressed as recursion** rather than iteration.
3. **Functions are first class objects.** I.e. functions can be manipulated just as easily as integers, floats, etc. in other languages.
4. **Data as functions.** I.e. we can build a function on the fly and then execute it. (Some languages).
5. **Higher-order functions.** I.e. functions can take functions as arguments and return functions as results.
6. **Lazy evaluation.** Expressions are evaluated only when needed. This allows us to build **infinite data structures**, where only the parts we need are actually constructed. (Some languages).
7. **Garbage Collection.** Dynamic memory that is no longer needed is automatically reclaimed by the system. GC is also available in some imperative languages (Modula-3, Eiffel) but not in others (C, C++, Pascal).
Polymorphic types. Functions can work on data of different types. (Some languages).

Functional programs can be more easily manipulated mathematically than procedural programs.

Pure vs. Impure FPL

- Some functional languages are pure, i.e. they contain no imperative features at all. Examples: Haskell, Miranda, Gofer.
- Impure languages may have assignment-statements, goto:s, while-loops, etc. Examples: LISP, ML, Scheme.

What is a function?

- A function maps argument values (inputs) to result values (outputs).
- A function takes argument values from a source set (or domain).
- A function produces result values that lie in a target set (or range).

More on functions

- A function must not map an input value to more than one output value. Example:

  Jenny ➔ IsPretty

  True

  False

  not a function!
More on functions...

- If a function $F$ maps every element in the domain to some element in the range, then $F$ is **total**. I.e. a total function is defined for all arguments.

  ![Diagram](image)

- A function that is undefined for some inputs, is called **partial**.

  ![Diagram](image)

  Divide is partial since $\frac{2}{0}$ is undefined.

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**Specifying functions**

A function can be specified **extensionally** or **intentionally**.

**Extensionally:**

- Enumerate the elements of the (often infinite) set of pairs “(argument, result)” or “Argument $\mapsto$ Result.”
- The extensional view emphasizes the **external behavior** (or **specification**), i.e. **what** the function does, rather than **how** it does it.

  - `double = {⋯, (1,2), (5,10), ⋯}`
  - `even = {⋯, (0,True), (1,False), ⋯}`
  - `double = {⋯, 1↦2, 5↦10, ⋯}`  
  - `isHandsome={Chris↦True,Hugh↦False}`

**Intentionally:**

- Give a **rule** (i.e. **algorithm**) that computes the result from the arguments.
- The intentional view emphasizes the **process** (or algorithm) that is used to compute the result from the arguments.

  - `double x = 2 * x`
  - `even x = x mod 2 == 0`
  - `isHandsome x = if isBald x then True else False`
Specifying functions...

**Function Application**

- The most important operation in a functional program is **function application**, i.e. applying a function to its argument(s), and retrieving the result:

  double \( x = 2 \times x \)

  even \( x = x \mod 2 == 0 \)

  double 5 \( \Rightarrow \) 10

  even 6 \( \Rightarrow \) True

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**Function Composition**

- **Function composition** makes the result of one function application the input to another application:

  double \( x = 2 \times x \)

  even \( x = x \mod 2 == 0 \)

  even (double 5) \( \Rightarrow \) even 10 \( \Rightarrow \) True

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**Function Definition — Example**

Example: How many numbers are there between \( m \) and \( n \), inclusive?

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**Extensional Definition:**

\[
\text{sumbetween } m \ n = \{ \cdots (1,1) \mapsto 1, (1,2) \mapsto 2, \cdots, (2,10) \mapsto 9 \}
\]

**Intentional Definition:**

\[
\text{sumbetween } m \ n = ((m + n) \times (\text{abs} (m-n) + 1)) \div 2
\]

---

**Graphical Definition:**

\[
\begin{align*}
\text{sumbetween} & \quad \text{abs} & \quad \div & \quad m \\
\text{m} & \quad \text{n} & \quad \text{abs} & \quad \text{div} & \quad \text{sumbetween}
\end{align*}
\]
Function Signatures

To define a function we must specify the types of the input and output sets (domain and range, i.e. the function’s signature), and an algorithm that maps inputs to outputs.

What’s so Good About FP?

Referential Transparency

- The most important concept of functional programming is referential transparency. Consider the expression
  
  \[(2 \times 3) + 5 \times (2 \times 3)\]

- \((2 \times 3)\) occurs twice in the expression, but it has the same meaning (6) both times.

- RT means that the value of a particular expression (or sub-expression) is always the same, regardless of where it occurs.

- This concept occurs naturally in mathematics, but is broken by imperative programming languages.

- RT makes functional programs easier to reason about mathematically.

Referential Transparency...

- Consider this Java expression:

  \[
  f() + f()
  \]

- Could we replace it by the expression

  \[
  2 * f()
  \]

- If this was mathematics, we could! But, in Java...
Referential Transparency...

- If our definition of \( f() \) was

```java
int f() {
    return 5;
}
```

then \( f()+f() \) and \( 2*f() \) both mean the same.

- But, if \( f() \) is

```java
int x=5;
int f() {
    x++; // Side-effect
    return x;
}
```

then \( f()+f()=6+7=13 \) and \( 2*f()=2*6=12 \)!

Referential Transparency...

- What about these two Java expression:

```java
f() + g()
```

and

```java
g() + f()
```

- Are they equivalent? In math they are...

Referential Transparency...

- But, Java isn’t math:

```java
int x=5;
int f() {
    x++; // Side-effect
    return x;
}
int g() {
    return x;
}
```

then \( f()+g()=6+6=12 \) and \( g()+f()=5+6=11 \)!

Referential Transparency...

- Because of such side-effects, Java isn’t referentially transparent.

- The same is true of any procedural language (Pascal, C, Modula-2, etc) and object-oriented language (Java, C++, C#).
Pure functional programming languages are referentially transparent.
This means that it is easy to find the meaning (value) of an expression.
We can evaluate it by substitution. I.e. we can replace a function application by the function definition itself.

Evaluate $\text{even (double 5)}$:

\begin{align*}
double x &= 2 \times x \\
even x &= x \mod 2 == 0
\end{align*}

$\text{even (double 5)}$ ⇒ $\text{even (2 \times 5)}$ ⇒ $\text{even 10}$ ⇒ $10 \mod 2 == 0$ ⇒ $0 == 0$ ⇒ True

In a pure functional language

- Expressions and sub-expressions always have the same value, regardless of the environment in which they’re evaluated.
- The order in which sub-expressions are evaluated doesn’t effect the final result.
- Functions have no side-effects.
- There are no global variables.

Variables are similar to variables in mathematics: they hold a value, but they can’t be updated.
Variables aren’t (updatable) containers the way they are imperative languages.
Hence, functional languages are much more like mathematics than imperative languages. Functional programs can be treated as mathematical text, and manipulated using common algebraic laws.
Here is a mathematical definition of the combinatorial function \( \binom{n}{r} \) “n choose r”, which computes the number of ways to pick \( r \) objects from \( n \):

\[
\binom{n}{r} = \frac{n!}{r! \cdot (n-r)!}
\]

Give an extensional, intentional, and graphical definition of the combinatorial function, using the notations suggested in this lecture.

You may want to start by defining an auxiliary function to compute the factorial function, \( n! = 1 \cdot 2 \cdot \cdots \cdot n \).