Functional Programming

& why it’s relevant for HEP computing

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About me

Doctoral student @ CERN and University of Twente (NL)

Working on ROOT, **RNTuple** to be exact

Today, I program almost exclusively in **C++**

Programming languages I've used before include Python, **Haskell**, C, Java, Ruby, JavaScript (& more)

Why talk about functional programming?

I like it (but am by no means an expert)

It requires a different (mental) approach to the computing problem at hand

It's becoming more and more relevant in our modern computing landscape
→ This includes HEP computing!

Lecture outline

What is functional programming?

The essentials of functional programming

Functional thinking in the real world

Wrap-up

N.B., There will be an opportunity to see what we will discuss today in action during tomorrow's exercise session

What is functional programming?

Declarative vs. imperative programming

Functional programming is a **declarative programming paradigm**

A declarative program describes **what** should be computed, rather than **how**

This is the opposite[1] of **imperative** programs (written in e.g. C++ or Python)

[1] Many (modern) languages draw inspiration from both paradigms, as we will see today

(Pure) functional programming

A functional program is a **function** which takes an **input** as its arguments and produces an **output**

This function is defined in terms of other functions or **primitives** (e.g., literals)

Purely functional programs have no **side effects**. This means that:

- Data is immutable, the global program state cannot be altered
- The order of execution of independent items is irrelevant

In other words, functional programming separates **data** from **behaviour**

The ingredients that give power to FP

Besides the absence of side effects, there are 4 more (interrelated) ingredients that make functional programming extremely powerful:

1. **Recursion** is considered a first-class citizen, and enables looping over data in a pure manner
2. Functions don’t have explicit return types, which allows for **partial application**
3. Functions themselves are types, which gives rise to **higher-order functions**
4. Functions are evaluated **lazily**, which means computation only happens when the result is needed

The essentials of functional programming

Haskell

Haskell is a **purely functional** language

It has several implementations, with **GHC** being the most widely used

Programs can be **compiled** or **interpreted** interactively

It is mostly used in **academic** settings, but also has found its way into **industry** applications from (among others) GitHub and Facebook

A Haskell function

A Haskell function consists of two parts: the **type declaration** and **function definition**

```haskell
add :: Int -> Int -> Int
add x y = x + y
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Function definition

Recursion

Recursive functions are functions are defined in terms of themselves

For example, we can compute $n!$ recursively as follows:

$$\textbf{factorial}\,n = \begin{cases} 1 & \text{if } n = 0 \\ n \cdot \textbf{factorial}\,(n-1) & \text{otherwise} \end{cases}$$

$$\text{e.g., } \textbf{factorial}\,3 = 3 \cdot \textbf{factorial}\,(2 \cdot \textbf{factorial}\,(1 \cdot \textbf{factorial}\,0)) = 6$$

A recursive function must have one or more **base cases** to prevent infinite loops!

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The Haskell implementation of **factorial** is left as an exercise to the reader ;)

Partial application

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```haskell
add_42 :: Int -> Int
add_42 x = add 42 x
```

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```
add :: Int -> Int -> Int
add x y = x + y
```

```
add_42 :: Int -> Int
add_42 = add 42 -- We can omit trailing arguments!
```

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add :: Int -> Int -> Int
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add_42 = add 42 -- We can omit trailing arguments!
```

This allows us to build functions **"on the fly"**

Higher-order functions

Functions can act as types themselves, and can be provided as function arguments

```
apply_operator :: Num a => (a -> a -> a) -> a -> a -> a
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```
λ> apply_operator add 9 1
10
```

These functions can be defined and provided in-place with **lambda function**:

```
λ> apply_operator (\ x y -> x - y) 9 1
8
```

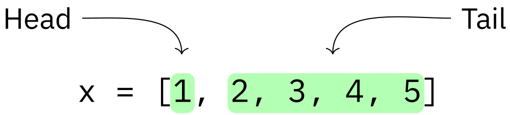
Intermezzo: lists

A **list** with elements of type α is recursively defined as follows:

$$\textbf{listof}\ \alpha = [\,] \mid \alpha : (\textbf{listof}\ \alpha)$$

e.g., $[1, 2, 3, 4, 5] = 1 : (2 : (3 : (4 : (5 : [\,]))))$

The first element in a list is referred to as the **head**, and the remaining elements as the **tail**



Lazy evaluation

Lazy evaluation means the evaluation of an expression is only performed when the results are **needed by another computation**

This property, together with the previously mentioned properties, gives us powerful ways to evaluate data

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filter_odds :: [Int] -> [Int]
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→ What happens when we call `filter_odds [1..]` ?

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```
λ> filter_odds [1..5]
[1, 3, 5]
```

→ What happens when we call `filter_odds [1..]` ?

→ What happens when we call `take 5 (filter_odds [1..])` ?

Functional thinking in the real world

Parallel, concurrent and distributed computing

Moore's law states that the number of transistors in a microchip doubles every year (with the costs remaining constant)

Need more **performance**? Buy new **hardware**!

However, we are running into several limits:

1. The **power wall**: higher clock rates could lead to overheating
2. The **ILP wall**: a single clock cycle can only take on so many instructions at once
3. The **memory wall**: memory performance has lagged behind CPU performance

Instead, we have to increase performance through **parallelism**, **concurrency** and the **distribution** of tasks over multiple resources

Challenges in parallel programming

Parallel computing does not come for free

Two important questions to consider:

- How to make sure one task cannot alter the data used in another task?
- What if task A finishes before task B?

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Now, recall what we mentioned about purely functional programs and the lack of **side effects**

Challenges in parallel programming

Parallel computing does not come for free

Two important questions to consider:

- How to make sure one task cannot alter the data used in another task?
  - **Data is immutable, so the global program state cannot be altered**
- What if task A finishes before task B?
  - **The order of execution of independent items is irrelevant**

Now, recall what we mentioned about purely functional programs and the lack of **side effects**

A pioneer in functional parallelism: MapReduce

Originally presented by Google, **MapReduce** is a programming model for **parallel** and **distributed** data processing

It is based on two fundamental functions: `map` and `reduce`

```
map :: (a -> b) -> [a] -> [b]
map f []     = []
map f (x:xs) = f x : map f xs
```

```
λ> map (* 2) [1..5]
[2, 4, 6, 8, 10]
```

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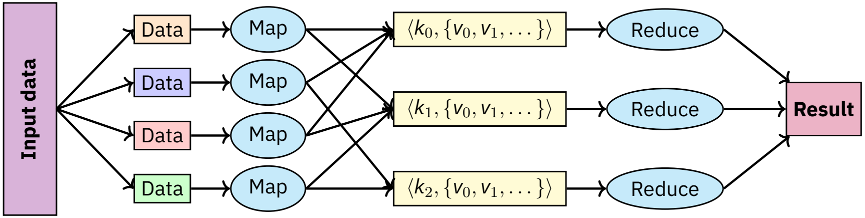
```
reduce :: (a -> b -> b) -> b -> [a] -> b
reduce _ acc []     = acc
reduce f acc (x:xs) = f x (reduce f acc xs)
```

```
λ> reduce (*) 1 [1..5]
120
```

MapReduce in a nutshell

1. The input data set is split and distributed over *n* computation units
2. A **mapper** transforms each data element into a key-value pair
3. The key-value pairs are grouped by key
4. The **reducer** merges each value belonging to a key to a single, final value



Functional patterns in other languages

Many of the concepts we've seen today have been adopted by imperative languages

This includes **C++** and **Python**

Other noteworthy examples include Rust, Scala and Julia

In general, languages are shifting from **single-paradigm** to **multi-paradigm**

Functional patterns in C++

C++11 introduced **lambda functions** to the language:

```cpp
auto add = [](int x, int y){ return x + y; }
```

We can use these with the **`algorithms`** STL library

```cpp
std::vector<int> xs = {1, 2, 3, 4, 5};
std::vector<int> ys = {0, 0, 0, 0, 0};
std::transform(xs.begin(), xs.end(), ys.begin(),
               [](int x){ return x * 2; });
```

→ What is the value of `ys`?

Functional patterns in C++ (2)

Variables and function arguments are not immutable by default

In fact, immutability can become tricky in a language that heavily relies on passing-by-reference

Clever use of `const` qualifiers is necessary!

With these ingredients, we can start building concurrent and parallel programs using C++'s built-in **`thread`** library or third-party tools such as Intel's **oneTBB**

Functional patterns in Python (1)

Similar to C++, Python has the notion of **lambda functions**

```
add = lambda x, y: x + y
```

Some functions, like `map` and `filter` are built in

More functions are provided with the **`functools`** library

```
functools.reduce(lambda acc, x: acc * x,
                 [1, 2, 3, 4, 5],
                 1)
```

Functional patterns in Python (2)

In Python, lazy evaluation can be achieved with **generators**

```python
def gen_fibonacci():
    a, b = 0, 1
    while True:
        yield a
        a, b = b, a + b
```

```
>>> fibonacci = gen_fibonacci()
>>> [next(fibonacci) for _ in range(10)]
[0, 1, 1, 2, 3, 5, 8, 13, 21, 34]
```

Functional thinking in HEP: RDataFrame

ROOT's **RDataFrame** enables the creation of physics analysis using functional patterns

```
ROOT::RDataFrame df("myEvents", "data.root");
auto hist =
  df.Filter("charge1 * charge2 == -1")
    .Define("invMass",
            "sqrt(2 * pt1 * pt2"
            "  * (cosh(eta1 - eta2) - cos(phi1 - phi2)))")
    .Histo1D("invMass");
hist->Draw();
```

Functional thinking in HEP: RDataFrame

ROOT’s **RDataFrame** enables the creation of physics analysis using functional patterns

Besides providing interfaces that resemble functional patterns, RDataFrame evaluates data **lazily**

This is achieved by first creating a **computation graph**, and only executing this when results are requested

By first constructing the full computation graph, **parallel scheduling of the tasks** becomes possible

Wrap-up

What we’ve discussed today

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These ingredients give rise to patterns highly suitable for **parallel**, **distributed** and **concurrent** computing

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Functional programming is a programming paradigm where **data** is separated from **behaviour**

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Other powerful features of functional programming include **recursion**, **partial application** of functions, **higher-order functions** and **lazy evaluation**

These ingredients give rise to patterns highly suitable for **parallel**, **distributed** and **concurrent** computing

Because of this, **functional thinking** is applied more and more outside of pure functional programming

Exercises

Your chance to apply what we have discussed in practice!

Tomorrow (Tuesday 16/04) from 13:45-15:45 in 513/1-024

Materials can be found on Indico

No special setup needed, just your **laptop** and **an internet connection**

Come say hi :D

Further learning

For more functional programming theory:

- *Why Functional Programming Matters* (paper)
- *How Functional Programming Mattered* (paper)

For more Haskell:

- Learn You a Haskell for Great Good!
- Real World Haskell
- Monday Morning Haskell

Thank you!

& a special thanks to my mentor, Sebastien Ponce :)