Programming Paradigms

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28 September 2020

Overview

- Lecture 1: Programming Paradigms (PPs): Monday 14:15 – 15:25
- Lecture 2: Design Patterns (DPs): Tuesday 14:00 – 15:10
- Exercise consultation time: Thursday 17:00 – 17:30

All material at: github.com/klieret/icsc-paradigms-and-patterns

The goal of this course

- This course does not try to make you a better programmer
- But it **does** convey basic concepts and vocabulary to make your design decisions more **consciously**
- Thinking while coding + reflecting your decisions after coding $\longrightarrow$ Experience $\longrightarrow$ Great code!

Programming Paradigms

What **is** a programming paradigm?

- A classification of programming languages based on their features (but most popular languages support multiple paradigms)
- A programming style or way programming/thinking
- Example: Object Oriented Programming (thinking in terms of objects which contain data and code)
- Many common languages support (to some extent) multiple paradigms (C++, python, ...)

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Why should I care?

- Discover new ways of thinking $\longrightarrow$ challenge your current believes about how to code
- Choose the right paradigm for the right problem or pick the best of many worlds

Programming Paradigms

Some problems

- Too formal definitions can be hard to grasp and sometimes impractical, too loose definitions can be meaningless
- Comparing different paradigms requires experience and knowledge in both
  (if all you [know] is a hammer, everything looks like a nail)
- A perfect programmer might write great software using any PP

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My personal approach

- Rather than asking "How to define paradigm X?", ask "How would I approach my problems in X?".
- Try out "academic languages" that enforce a certain paradigm
  $\longrightarrow$ How does it *feel* to program in X
- Get back to your daily programming and rethink your design decisions

Good code: Objectives

Key objectives

- Testability: Make it easy to ensure the software is working correctly
- Maintainability: Make it easy to keep the software working (debugging, readability, ...)
- Extendibility: Make it easy to add new functionality
- Flexibility: Make it easy to adapt to new requirements
- Reusability: Make it easy to reuse code in other projects

$\longrightarrow$ How do I achieve all this?

Modularity

Perhaps the most important principle of good software

Split up code into parts, e.g. functions, classes, modules, packages, ...

You have done **well** if the parts are

- independent of each other
- have clear responsibilities

You have done **badly** if the parts

- are very dependent on each other (changes in one part require changes in many others)

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This has benefits for almost all of your goals:

- Easier and more complete testability by using unit tests, better debugging
- Confidence from unit tests allows for better maintainability and flexibility
- Allowing to split responsibilities for different "modules" enhances collaboration and thereby maintainability
- Code reusability (obvious)

Modularity

Perhaps the most important principle of good software

A related principle: Isolate what changes!

- Which parts of your code will likely have to change in the future?
  - $\longrightarrow$ These parts should be isolated (you should be able to change them in one place, without having to change anything else)
- This also leads to the concept of a separation of
  - interface (used by other "modules", stays untouched) and
  - implementation (only used by the module itself, can change easily)

Complex vs Complicated

From the Zen of python:

Simple is better than complex.
Complex is better than complicated.

- The more *complicated* something is, the harder it is to understand
- The more *complex* something is, the more parts it has

- Complicated problems might not have simple solutions
- But it is often still possible to modularize to have several simple components

- For example, using classes and objects will make your code more *complex*, but still easier to understand

OOP: Idea

- Before OOP: Two **separate** entities: *data* and *functions* (logic)
- Inspiration: In the real world, objects have a "state" (data) and "behaviors" (functions)

OOP

- **Think** in terms of *objects* that contain data and offer *methods* (functions that operate on objects) $\longrightarrow$ Data and functions form a unit
- **Focus** on object structure rather than manipulation logic
- **Organize** your code in *classes* (blueprints for objects): Every object is *instance* of its class

A basic class in python

```
1 class Rectangle:
2     def __init__(self, width, height):  # <-- constructor
3         # 'self' represents the instance of the class
4         self.width = width               # <-- attribute = internal variable
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        return self.width * self.height
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r1 = Rectangle(1, 2)          # <-- object (instance of the class)
print(r1.calculate_area())    # <-- call method of object
print(r1.width)               # <-- get attribute of object
r1.width = 5                  # <-- set attribute of object
```

Encapsulation and data hiding

- Do not expose object internals that may change in the future $\longrightarrow$ Make certain attributes and methods private (*data hiding*)
- Rephrased: Separate interface (won't be touched because it's used by others) from implementation (might change)
- In some languages this is "enforced" (e.g. using the `private` keyword), in others it is denoted by naming conventions (e.g. leading underscore)

Subclasses and Inheritance

Subclasses are specializations of a class

- inherit attributes/methods of their superclass
- can introduce new attributes/methods
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1 class Person:
2     def __init__(self, name):
3         self.name = name
4 
5     def greet(self):
6         print(f"Hello, I'm {self.name}")
```

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- inherit attributes/methods of their superclass
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    def __init__(self, name):
        self.name = name

    def greet(self):
        print(f"Hello, I'm {self.name}")


class Child(Person):
    def __init__(self, name, school):
        super().__init__(name)
        self.school = school

    def learn(self):
        print(f"I'm learning a lot at {self.school}")


c1 = Child("john", "iCSC20")
c1.greet()
c1.learn()
```

Abstract methods

- An *abstract method* is a method that has to be implemented by a subclass
- An *abstract class* (*abstract type*) is a class that cannot be instantiated directly but it might have *concrete subclasses* that can
- Use abstract classes to enforce interfaces for the concrete classes

```
1  from abc import ABC, abstractmethod
2
3
4  class Shape(ABC):
5      @abstractmethod
6      def calculate_area(self):
7          pass
8
9      @abstractmethod
10     def draw(self):
11         pass
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Strenghts and Weaknesses

Strengths

- Easy to read and understand if done well (very natural way of thinking if classes model real world objects)
- Natural way to structure large projects (e.g. taking classes as components)
- Very wide spread way of thinking
- Especially applicable to problems that center around data and bookkeeping with logic that is strongly tied to the data

Weaknesses

- Wrong abstractions can lead to less code reusability
- Lasagna code: Too many layers of classes can be hard to understand
- Can be hard to parallelize if many entangled and interdependent classes with shared mutable states are involved ($\longrightarrow$ if required, should be design requirement from the start; *parallel patterns* address some difficulties)

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Functional programming

Functional programming

- expresses its computations in the style of mathematical functions
- emphasizes
  - expressions ("is" something: a series of identifiers, literals and operators that reduces to a value)

  over
  - statements ("does" something, e.g. stores value, etc.)

  $\longrightarrow$ declarative nature
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Examples

Languages made for FP (picture book examples):

- `Lisp` and derivatives: `Common Lisp`, `Clojure`, ...
- `Haskell`
- `OCaml`
- `F#`
- `Wolfram Language` (Mathematica etc.)
- ...

With emphasis on FP:

- `JavaScript`
- `R`
- ...

Not designed for, but offering strong support for FP:

- `C++` (from `C++11` on)
- `Perl`
- `Python` (?) ($\longrightarrow$ You might also want to check out the `coconut` language)
- ...

Pure functions

A function is called pure if

1. Same arguments $\Longrightarrow$ same return value $(x = y \implies f(x) = f(y))$
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def f1(x):
    return x**2


def f2(x):
    print(x)
    return x**2


global y = 0


def f3(x):
    y += 1
    return x + y
```

```python
def f4():
    return int(input()) + 1


def f5(lst: List):
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Answer: `f1` is pure; `f2`, `f3`, `f5` violate rule 2; `f4`, `f3` violate rule 1.

Non strict evaluation

- Some functional programming languages use *non-strict evaluation*: The arguments of a function are *only* evaluated once the function is called.
- But `Python` actually has something similar in the concept of `generators`:

```
%time a = range(int(1e8))
>>> Wall time: 7.63 µs

%time b = list(a)
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- This allows for infinite data structures (which can be more practical than it sounds)

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  Example: `print(sqrt(sin(a**2)))`

  In a strict language (e.g. `Python`, `C++`), we evaluate inside out:

  $$a \longmapsto a^2 \longmapsto \sin a^2 \longmapsto \sqrt{\sin a^2}$$

  In a non-strict language, the evaluation of the inner part is **deferred**, until it is actually needed.

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```
1  import time
2  from functools import lru_cache
3
4
5  @lru_cache()
6  def expensive(x):
7      time.sleep(1)
8      return x+42
9
10
11 %time expensive(2)
12 >>> Wall time: 1 s
13
14 % time expensive(2)
15 >>> Wall time: 6.2 µs
```

Higher order functions

A *higher order function* does one of the following:

- returns a function
- takes a function as an argument

Opposite: *first-order function*.

Mathematical examples (usually called *operators* or *functionals*): differential operator, integration, ...

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Classic example of a higher order function: `map` (applies function to all elements in list):

```
1 def map(function, iterator):
2     """ Our own version of map (returns a list rather than a generator) """
3     return [function(item) for item in iterator]
4
5
6 map(lambda x: x**2, [1, 2, 3])
7 >>> [1, 4, 9]
```

Higher order functions II

A function that also returns a function:

```
1  def get_map_function(function):
2      """ Takes a function f and returns the function map(f, *) """
3      def _map_function(iterator):
4          return map(function, iterator)
5
6      return _map_function
7
8
9  mf1 = get_map_function(lambda x: x**2)
10 mf2 = get_map_function(lambda x: x+1)
11
12 mf2(mf1([1, 2, 3]))
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12 mf2(mf1([1, 2, 3]))
13 >>> [2, 5, 10]
```

Type systems

Types:

- In OOP, type and class are often used interchangeably (e.g. `"abc"` is of type *string* = is an instance of the `str` class)
- In FP we talk about *type*s
- Complex types can be built from built in types
  (e.g. `List[Tuple[str, int]]`, we can also use `structs`)
- In many languages, types of variables, arguments, etc. have to be declared
  (e.g. `def len(List[float]) -> int`)
- Real FP languages usually have very powerful type systems

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Single/multiple dispatch/ad hoc polymorphism:

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Type classes:

- Define a "type" by what functions it has to support (e.g. define `Duck` as anything that allows me to call the `quack` function on it)
- Similar to a class with only abstract methods (=*interface*) and no encapsulated data

Looping in functional programming

Let's consider a function that calculates $\sum_{i=0}^{N} i^2$:

```
1 def sum_squares_to(n):
2     result = 0
3     for i in range(n+1):
4         result += i^2
5     return result
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How to change this?

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1 def sum_squares_to(n):
2     result = 0
3     for i in range(n+1):
4         result += i^2
5     return result
```

This is a function, but does not follow the FP paradigm:

- More statements (assignments, loops, ...) than expressions
- The for loop segment is not free of side effects (value of `result` changes)
- Repeated reassignments of `result` are frowned upon (or impossible)

How to change this? $\longrightarrow$ Use recursion

```
1 def sum_squares_to(n):
2     return 0 if n == 0 else n^2 + sum_squares_to(n-1)
```

Looping in functional programming

The previous example is called a head recursion (recursion before computation); using a tail recursion (recursion after computation) is preferable due to better compiler optimization:

```
1 def sum_squares_to(n, partial_sum=0):
2     return partial_sum if n == 0 else sum_squares_to(n-1, partial_sum + n^2)
```

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```

Another FP way is to use the higher level functions `map` and `reduce` together with anonymous functions (lambda):

```
1 from functools import map, reduce
2
3
4 def sum_squares_to(n):
5     return reduce(
6         lambda x, y: x+y,
7         map(lambda x: x**2, range(n+1))
8     )
```

This also opens the door for concurrency ($\longrightarrow$ parallel versions of `map` and `reduce`)

Strengths and Weaknesses

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- Proving things mathematically (referential transparency, ...)
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- Easy debugging (no hidden states)
- Can be very short and concise $\longrightarrow$ easy to verify
- Sophisticated logical abstractions (using high level functions) $\longrightarrow$ modularity, code reuse
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- Structuring code in terms of objects can feel more intuitive if logic (methods) are strongly tied to data
- Imperative algorithms might be easier to read and feel more natural than declarative notation
- FP might have a steeper learning curve (e.g. recursions instead of loops, ...)
- Performance issues: Immutable data types and recursion can lead to performance problems (speed and RAM), whereas many mutable data structures are very performant on modern hardware
- Pure FP has still only a small user base outside of academia, but FP support more and more wide spread in common languages

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Object oriented vs functional programming

Some key aspects to keep in mind:

- FP $\neq$ OOP – classes
- FP is **not** the opposite of OOP: Both paradigms take opposite stances in several aspects: declarative vs imperative, mutable vs immutable, ... $\Longrightarrow$ Not everything can be classified into one of these categories
- Rather: Two different ways to think and to approach problems $\longrightarrow$ see caveats at the beginning

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For example:

- Many complicated class structures implementing manipulations can be made more flexible with a system of high level functions, anonymous functions etc. (`pandas.DataFrame.apply`)

Declarative vs imperative programming

Declarative programming:

- Program describes logic rather than control flow
- Program describes "what" rather than "how"
- Aims for correspondence with mathematical logic
- FP is usually considered a subcategory

Declarative vs imperative programming

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Opposite: imperative programming:

- Algorithms as a sequence of steps
- Often used synonymously: procedural programming (emphasizing the concept of using procedure calls (functions) to structure the program in a modular fashion)
- OOP is usually considered a subcategory

Examples

"Pure" declarative languages:

- SQL (Structured Query Language – language to interact with databases):

```
SELECT * FROM Customers WHERE Country='Mexico';
```

- Markup languages, like HTML, CSS (Cascading Style Sheets – language to describe styling of e.g. HTML pages), ...

```
<h1 style="color:blue;">This is a Blue Heading</h1>
```

- Functional programming languages like Haskell (even though they allow some "encapsulated" imperative parts)
- ...

Powerful backends I

Idea:

- Split up your code into application/analysis specific code (describing the problem) and a backend/library (implementing solution strategies)
- The application specific code starts to *feel* very declarative
- The backend can use different strategies depending on the nature/scale of the problem

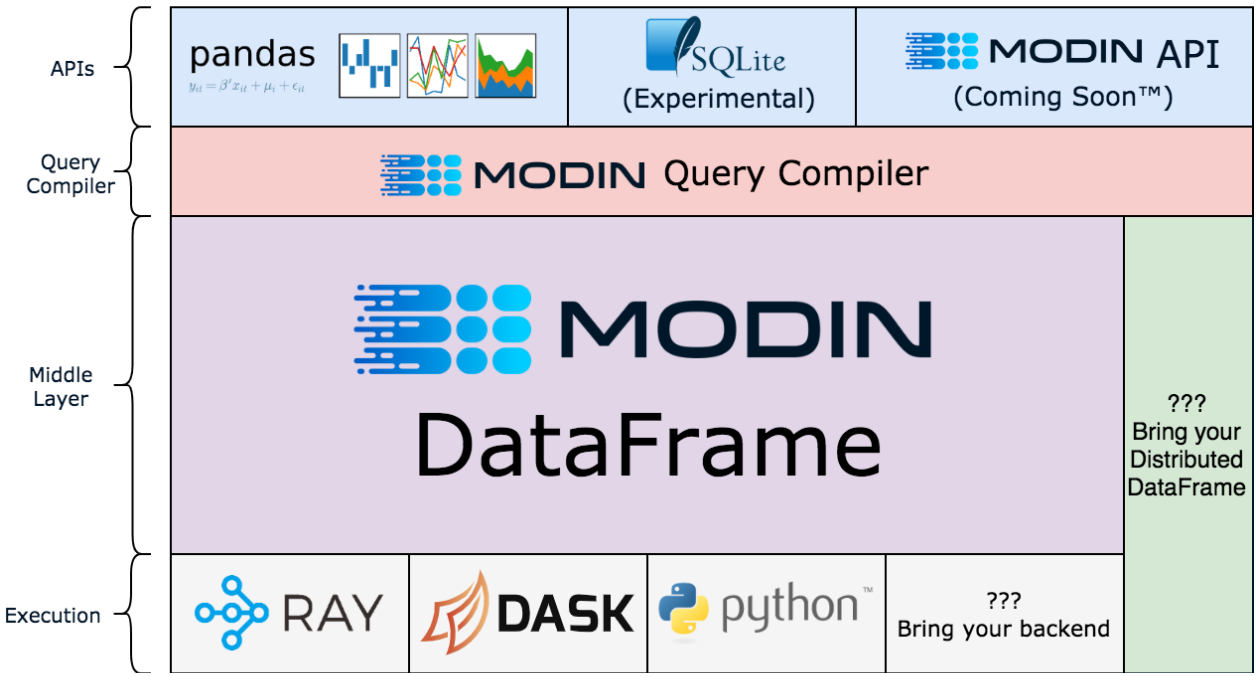
Powerful backends II

Example:

```python
# "Chi2 distance" using plain python
def chi2(data, theory, error):
    err_sum = 0
    for i in range(len(data)):
        if data[i] == theory[i] and error[i] == 0:
            continue
        err_sum += (data[i] - theory[i])**2 / (error[i]**2)
    return err_sum


# Using DataFrames: Table contains columns experiment, theory, error

# ROOT RDataFrame example:
chi2 = ROOT.ROOT.RDataFrame(...)  # initialize
        .Filter("!(data==theory & error==0.)")  # filter rows
        .Define("sqd", "pow(data-theory, 2) / pow(error, 2)")  # new col
        .Sum("sqd").GetValue()  # sum it up

# Pandas example:
chi2 = pd.DataFrame(...)  # initialize
_df = df.query("~(data==theory & error==0)")  # filter
chi2 = (_df["data"] - _df["theory"]).pow(2) / _df["error"].pow(2)).sum()
```

Powerful backends III

- We might want even more of our backend, e.g. delayed or distributed execution
- `pandas` can also be viewed as a "declarative language" describing the problem $\longrightarrow$ have a more sophisticated backend handle all operations $\longrightarrow$ `modin pandas`



Powerful backends IV

Belle II steering file:

```
path = create_path()

# Load data
inputMdstList("default", "/path/to/input/file", path=path)

# Get final state particles

# Fill 'pi+:loose' particle list with all particles that have pion ID > 0.01:
fillParticleList("pi+:loose", "piid > 0.01", path=path)
# Fill 'mu+:loose' particle list with all particles that have muon ID > 0.01:
fillParticleList("mu+:loose", "piid > 0.01", path=path)

# Reconstruct decay
# Fill 'K_S0:pipi' particle list with combinations of our pions and muons
reconstructDecay(
    "K_S0:pipi -> pi+:loose pi-:loose", "0.4 < M < 0.6", path=path
)
```

Powerful backends V

Many more high level tools available:

- LINQtoROOT: Uses C# with LINQ (SQL like) queries to describe problem

```
events
  .Select(e => e.Data.eventWeight)
  .FuturePlot("event_weights", "Sample EventWeights",100, 0.0, 1000.0)
  .Save(hdir);
```

- The FAST HEP toolkit: Uses yaml config files to describe problem; using pandas, numpy, etc. in the backend

```
stages:
 - BasicVars: Define
 - DiMuons: cms_hep_tutorial.DiObjectMass
 - NumberMuons: fast_carpenter.BinnedDataframe
 - EventSelection: CutFlow
 - DiMuonMass: BinnedDataframe
```

- Many more...

Other paradigms

- Logic programming (LP) (subset of declarative programming): Automatic reasoning by applying inference rules
  - LP languages: `Prolog`, `Datalog`
  - LP can be made available with libraries, e.g. for `Python`: `Pyke` (inspired by `prolog`), `pyDatalog` (inspired by `Datalog`)
  - Example:

```
% X, Y are siblings if they share a parent
sibling(X, Y)      :- parent_child(Z, X), parent_child(Z, Y).

% Father, mother implies parent
parent_child(X, Y) :- father_child(X, Y).
parent_child(X, Y) :- mother_child(X, Y).

% Introduce some people
father_child(tom, sally).
father_child(tom, erica).

% Ask:
?- sibling(sally, erica).
Yes
```

- Symbolic programming
- Differentiable programming

Outlook

Next lecture: Software design patterns

- Focus on OOP
- Introduce some "golden rules" of OOP
- Patterns: Reusable solutions to common problems

Discussion on mattermost:
mattermost.web.cern.ch/csc/channels/programming-paradigms

Get the exercises at github.com/klieret/icsc-paradigms-and-patterns