Replicating AspectJ Constructs in Python: Limitations and Considerations

Bc. Viktor Modroczký

Institute of Informatics, Information Systems and Software
Engineering
Faculty of Informatics and Information Technologies
Slovak University of Technology in Bratislava

2023

Abstract

AspectJ is a widely adopted aspect-oriented framework known for its extensive set of features. It enables the management of cross-cutting concerns in Java-based applications, without directly modifying their code. Although AspectJ is considered to be one of the best in the field, according to the 2023 Developer Survey conducted by Stack Overflow, Java is dominated by Python in popularity. On account of that, we take a look at what Python has to offer in the context of aspect-oriented software development. Without utilizing any third-party libraries, Python provides features, such as decorators and metaclasses, that can be used to implement aspect-oriented capabilities. However, using Python's decorators and metaclasses to replicate AspectJ advice can pose challenges and limitations that we explore in this paper.

1   Introduction

Aspect-oriented programming offers a way of resolving cross-cutting concerns in applications without the need to modify existing code. AspectJ is the leading framework in the aspect-oriented paradigm of software development, serving as an extension to Java [1]. Its practicality lies in so-called advice that provide means of adding functionality within join points in code execution [2].

In this paper, we discuss the features of Python, namely decorators and metaclasses, which can be utilized to adapt the aspect-oriented paradigm to the language by monkey-patching [3, 4]. Decorators allow one to extend the behavior of existing functions without modifying their source code explicitly. They are syntactic sugar for functions that take another function as a parameter, wrapping it and modifying its behavior [4]. Metaclasses define

1

the creation of other classes and, in addition to that, can manipulate their attributes and methods [4, 5].

Aspects in AspectJ, which comprise pointcuts, `before()` and `after()` advice, as well as `around()` advice, are woven into join points at the byte-code level before execution [6]. In contrast to Java, Python lacks an aspect-oriented extension similar to AspectJ. Python is a dynamic interpreted language; therefore, any decorator and metaclass used for aspect-orientation purposes is evaluated at runtime [7].

Moreover, Python not having an AspectJ-esque extension reduces the complexity of aspect-oriented solutions within the language. Considering how well-established and developed AspectJ is, we set out to explore limitations of using decorators and metaclasses to replicate AspectJ advices in pure Python. These limitations can take various forms, such as performance differences, challenges in implementation, and the scope of AspectJ features, rendering replication of its advices in Python a difficult task.

2   Introduction to AspectJ

Kiczales et al. [8] recognized that object-oriented and procedural programming languages often struggle to clearly capture some of the important design decisions that a program must implement. Consequently, the implementation of such design decisions becomes scattered throughout the codebase, resulting in difficult code maintenance. Properties that are addressed by these design decisions are referred to as aspects that cross-cut the system's core. Kiczales et al. [8, 9] introduced the concept of aspect-oriented programming, which presents a clear expression of aspects in a modular manner and served as the foundation for the development of AspectJ.

2.1   AspectJ Concepts

AspectJ supports two types of cross-cutting implementation, dynamic and static. According to Kiczales et al. [9], dynamic cross-cutting allows additional implementation to run at certain points in the execution of a program, whereas static cross-cutting allows the definition of new operations on existing types. Dynamic cross-cutting constructs are pointcuts and advice, whereas static cross-cutting constructs are inter-type declarations.

The following sections provide an explanation of the essential concepts within the aspect-oriented programming paradigm, as well as AspectJ itself. Descriptions of AOP concepts used in AspectJ are also supplemented with code examples.

2.1.1   Join Points & Pointcuts

Join points are a crucial part of any aspect-oriented language. As stated by Clement et al. [10], the join point is a well-defined point in the execution of a program. Join points are captured by matching pointcuts, allowing for the insertion of advice into captured join points. A single pointcut can capture any number of join points in the program flow.

As specified by Clement et al. [10], AspectJ pointcuts have access to five types of join points:

- Method or constructor call

- Method, constructor, or advice execution

- Access to or update of a field

- Initialization of classes and objects

- Exception handler execution

2.1.2   Advice

Advice are constructs that define what is going to be done when a pointcut matches a join point. There are three types of advice in AspectJ described by The AspectJ Team [11] and Clement et al. [10]:

- `before()` advice that run just as a join point is reached, before the program proceeds with it

- `after()` advice that run after the program proceeds with a join point

- `around()` advice that runs as a join point is reached, but has explicit control whether the program proceeds with a join point, and the ability to change values within the join point, unlike `before()` or `after()` advice

2.1.3   Inter-type Declarations

Inter-type declarations, alternatively referred to as introductions, are described by Laddad [6] as constructs that can be utilized to alter the static structure of classes, interfaces, and aspects in a program. Clement et al. [10] state that aspects using introductions can assume responsibility for certain capabilities on behalf of other types. Introductions can modify a class or a set of classes by adding new attributes and methods to them, and can also influence the class hierarchy within a program, as stated by Gradecki and Lesiecki [12].

2.1.4   Aspects

Aspects in AspectJ are described by Clement et al. [10] as units of modularity, encapsulation, and, through their meaningful naming, abstraction. They are designed to handle cross-cutting concerns by piecing pointcuts, advice, and introductions together.

3   AOP in Python

According to the 2023 Developer Survey conducted by Stack Overflow [13], Python is a more popular language than Java. It is therefore a viable option to explore Python as a language for replicating key AspectJ functionality.

To operate as an aspect-oriented programming language, Python does not require the use of third-party libraries. Its intrinsic features are suitable for managing cross-cutting concerns, although not as fully fledged as in Java-based applications using AspectJ.

Python is a dynamic language by nature, which allows for aspect orientation using a technique called monkey-patching [3]. Ramalho [4] describes monkey-patching as dynamically changing a module, class, or function at runtime, to add features or fix bugs.

3.1   Decorators

Python decorators are based on the decorator pattern, which, as defined by Gamma et al. [14], has the following intent:

> *"Attach additional responsibilities to an object*
> *dynamically. Decorators provide a flexible alternative to*
> *subclassing for extending functionality."*

As explained by Sarcar [15], the decorator pattern is also called the wrapper pattern because in programming we often use wrappers to dynamically add functionalities. A key characteristic of the decorator pattern in the context of aspect-oriented programming is that the existing structure of decorated code remains untouched, and therefore developers do not introduce bugs in existing code.

In Python, everything is an object, according to the official language reference. Therefore, the decorator pattern can be applied to functions, as well as classes and their methods. Van Rossum and the Python Development Team [16] state:

> *"Objects are Python's abstraction for data. All data in a*
> *Python program is represented by objects or by relations*
> *between objects."*

A simple decorator can be defined as follows:

```python
1  def decorator(func):
2      def wrapper():
3          print("Running wrapper().")
4
5      return wrapper
6
7
8  @decorator
9  def decorated():
10     print("Running decorated().")
```

The syntax using the *at* symbol (@) is equivalent to the following explicit call to the decorator:

```python
1  decorated = decorator(decorated)
```

Running `decorated()` will result in the output "Running wrapper().", which means that the decorator replaces the decorated function. To retain what the decorated function does, we need to define the decorator as such:

```python
1  def decorator(func: Callable[..., Any]):
2      def wrapper(*args, **kwargs):
3          print("Running wrapper().")
4          func(*args, **kwargs)
5
6      return wrapper
```

The *args and **kwargs parameters are essential if the decorated function has any arguments or keyword arguments. Running `decorated()` will now result in the following output:

```
1  Running wrapper().
2  Running decorated().
```

However, if we wanted to create parameterized decorators, we would have to define them differently. As noted by Ramalho [4], parameterized decorators are not strictly decorators themselves; they are more like decorator factories that return the actual decorators. The following is an example of such a factory:

```python
1  def decorator_factory(param1: int, param2: None | str = None):
2      def decorator(func: Callable[..., Any]):
3          def wrapper(*args, **kwargs):
4              print("Running wrapper().")
5              print(f"Doing something with {param1} and
               ↪  {param2}.")
6              func(*args, **kwargs)
7
8          return wrapper
9
10     return decorator
11
12
13  @decorator_factory(7)
14  def decorated(x: Any, y=0.1, z="string"):
15      print(f"Running decorated({x}, {y}, {z}).")
```

The output of running the function `decorated(("X", "Y"), y=0.7)` is then the following:

```
1  Running wrapper().
2  Doing something with 7 and None.
3  Running decorated(('X', 'Y'), 0.7, string).
```

Alternatively, as described by Ramalho [4], we can create a decorator or decorator factory as a class with the `__call__` method implemented, which offers both enhanced readability and conciseness. A class implementing this method has callable instances. The following is a decorator factory implementation using a class:

```python
1  class DecoratorFactory:
2      def __init__(self, param1: int, param2: None | str = None):
3          self.param1 = param1
4          self.param2 = param2
5
6      def __call__(self, func: Callable[..., Any]):
7          def wrapper(*args, **kwargs):
8              print("Running wrapper().")
9              print(f"Doing something with {self.param1} and
               ↪  {self.param2}.")
```

```
10              func(*args, **kwargs)
11
12          return wrapper
13
14
15  @DecoratorFactory(7)
16  def decorated(x: Any, y=0.1, z="string"):
17      print(f"Running decorated({x}, {y}, {z}).")
```

Running `decorated(["a", 0.5, 10], y=7.7, z="another string")` yields the following output:

```
1  Running wrapper().
2  Doing something with 7 and None.
3  Running decorated(['a', 0.5, 10], 7.7, another string).
```

Notice that using both `decorator_factory` and `DecoratorFactory`, we decorated a function with both arguments and keyword arguments, passing them to the original function `func` through the `wrapper` function in the `DecoratorFactory`'s `__call__` method and `decorator_factory`'s `decorator` function using `*args` and `**kwargs`.

3.2 Metaclasses

A metaclass in Python is a class that builds classes. One such class in Python is the `type` class. The `type` class being a metaclass means that every instance of it is a class, as stated by Ramalho [4].

According to Van Rossum and the Python Development Team [16], Python classes are created by the built-in `type` metaclass class if invoked with three arguments `type(name, bases, namespace)`, where `name` is the class name, `bases` is a tuple of base classes and `namespace` is a dictionary of name-value mappings of class methods and attributes.

Consider the following classes:

```
1  class A:
2      pass
3
4  class B(A):
5      text = "abc"
6
7      def double_text(self):
8          return self.text * 2
```

The same two classes can be created using the following `type` class invocations:

```python
A = type("A", (), {})

B = type(
    "B",
    (A,),
    {
        "text": "abc",
        "double_text": lambda self: self.text * 2
    }
)
```

We can use `type` as a base class for custom metaclasses. Consider the following code:

```python
class A(type):
    def __new__(cls, name, bases, namespace):
        def squared(self):
            return self.num**2

        # Alter class, e.g.
        namespace["num"] = 5
        namespace["squared"] = squared

        return super().__new__(cls, name, bases, namespace)


class B(metaclass=A):
    def __init__(self, num):
        self.num = num
```

Now, if we run the following code

```python
b = B(10)

print(f"b.num from B.__init__ is {b.num}")
print(f"Class B has a squared method outputting {b.squared()}")
```

we get the following output:

```
1 b.num from B.__init__ is 10
2 Class B has a squared method outputting 100
```

In this way, we can alter classes that use our custom metaclass, by adding new attributes or methods to them.

4   Related Work

Kiczales et al. [9] proposed the usage of advice as a means of aspect-oriented programming. They introduced the AspectJ extension to Java that implements the proposed concepts. They describe the way in which AspectJ provides support for modular implementation of cross-cutting concerns, called aspects, and its interoperability with Java code. We use their work as a reference for implementing advice in Python.

Spinczyk, Gal, and Schröder-Preikschat [17] introduced an aspect-oriented extension to C++ that takes a similar approach to AOP as AspectJ. It also provides around, before, and after advice, and has pointcut definitions. AspectC++ uses compile-time weaving like AspectJ while introducing little to no run-time or memory overhead to application execution. Run-time overhead only occurs using certain pointcut functions that require runtime type checking.

Mărieș [18] implemented a Python library called aspectlib, which is an aspect-oriented programming library that uses monkey-patching and decorators. It provides a way to change the behavior of existing Python code. The implementation contains an `Aspect` decorator that can be used to decorate generator functions that yield advice. This results in an aspect which can be used to decorate functions whose behavior we desire to change.

Matusiak [19] in their work described various techniques and strategies of aspect-oriented programming in Python. They discussed the use of built-in Python features, such as decorators and metaclasses, for AOP. In addition to that, they listed and discussed libraries that use the aspect-oriented paradigm in Python. At the time of writing this paper, the aforementioned libraries are no longer available or maintained.

5   Implementation

In the previous sections, we clearly saw the aspect-oriented nature of Python's intrinsic features. Can we use them to recreate AspectJ constructs though? What are their limitations in this context?

To answer these questions, we will explore how these features can be leveraged to replicate key AspectJ constructs. Furthermore, we will identify and discuss the practical limitations and challenges that may arise when attempting to implement such constructs.

However, AspectJ's feature set is vast, so to manage the scope of our analysis, we will need to focus on a specific subset of features that are most relevant to our exploration of aspect-oriented programming in Python. We select a subset that only contains basic AspectJ features, such as simple `before()`, `after()` `returning`, `after()` `throwing`, and `around()` advice using simple pointcuts.

To implement these constructs, we utilize the latest Python release, which is version 3.12.0 at the time of writing. We choose the previously described features of Python, decorators, and metaclasses for implementation. We propose an implementation that uses monkey-patching, which is used to alter application execution during run-time, as a weaving technique. The implementation is available publicly on GitHub[1].

5.1   AspectJ Advice in Python

To implement AspectJ advice in Python, we used classes as decorator factories that take various parameters. The implemented advice are the following Python classes:

- `Before`

- `AfterReturning`

- `AfterThrowing`

- `Around`

5.1.1   Before

The `Before` class is the Python implementation of the `before()` advice. The constructor of this class takes the following parameters:

- `params_update` which is either a dictionary of key-value pairs, where the key is the name of the parameter to update and the value is the value of the new parameter, or `None`, if no update is desired. This dictionary is used to update positional and keyword arguments by their name. If the key is not the name of an argument, the given key-value pair is ignored.

- `action` which is the function to run before the advised function.

---

[1] `https://github.com/vktr274/aspectpy`

- action_args which are the positional arguments of the action.

- action_kwargs which are the keyword arguments of the action.

```python
class Before:
    def __init__(
        self,
        params_update: dict[str, Any] | None,
        action: Callable[..., Any],
        *action_args,
        **action_kwargs,
    ):
        self.params_update = params_update
        self.action = action
        self.action_args = action_args
        self.action_kwargs = action_kwargs

    def __call__(self, func: Callable[..., Any]):
        @wraps(func)
        def wrapper(*args, **kwargs):
            args, kwargs = mutate_params(
                args, kwargs, self.params_update,
                ↪  signature(func)
            )
            self.action(*self.action_args,
            ↪  **self.action_kwargs)
            return func(*args, **kwargs)

        return wrapper
```

5.1.2   After Advice

The AfterReturning class is the Python implementation of the after() returning advice. The constructor of this class takes the following parameters:

- params_update

- action which is the function to run after the advised function returns. The action must have a parameter named _RETURNED_VAL_ that represents the value returned from the advised function. The action must be decorated using @validate_after_returning_action which checks whether the action follows the requirement.

- `action_args`

- `action_kwargs`

```python
1  class AfterReturning:
2      def __init__(
3          self,
4          params_update: dict[str, Any] | None,
5          action: Callable[..., Any],
6          *action_args,
7          **action_kwargs,
8      ):
9          if not getattr(action, FLAG_VALIDATED, False):
10             raise ValueError(
11                 f"{action.__qualname__} is not decorated "
12                 + f"with
                       ↪  @{validate_after_returning_action.__name__}",
13             )
14         self.params_update = params_update
15         self.action = action
16         self.action_args = action_args
17         self.action_kwargs = action_kwargs
18
19     def __call__(self, func: Callable[..., Any]):
20         @wraps(func)
21         def wrapper(*args, **kwargs):
22             args, kwargs = mutate_params(
23                 args, kwargs, self.params_update,
                       ↪  signature(func)
24             )
25             result = func(*args, **kwargs)
26             return self.action(result, *self.action_args,
                       ↪  **self.action_kwargs)
27
28         return wrapper
```

The `AfterThrowing` class is the Python implementation of the `after()` `throwing` advice. The constructor of this class takes the following parameters:

- `params_update`

- `exceptions` which can be a class that inherits from the `Exception`

class or a tuple of these classes or `None`. If it is `None`, all exceptions are caught.

- `action` which is the function to run after the advice catches an exception based on the `exceptions` parameter.

- `action_args`

- `action_kwargs`

```python
class AfterThrowing:
    def __init__(
        self,
        params_update: dict[str, Any] | None,
        exceptions: tuple[Type[Exception], ...] |
        ↪  Type[Exception] | None,
        action: Callable[..., Any],
        *action_args,
        **action_kwargs,
    ):
        self.params_update = params_update
        self.exceptions = exceptions or Exception
        self.action = action
        self.action_args = action_args
        self.action_kwargs = action_kwargs

    def __call__(self, func: Callable[..., Any]):
        @wraps(func)
        def wrapper(*args, **kwargs):
            args, kwargs = mutate_params(
                args, kwargs, self.params_update,
                ↪  signature(func)
            )
            try:
                return func(*args, **kwargs)
            except self.exceptions:
                return self.action(*self.action_args,
                ↪  **self.action_kwargs)

        return wrapper
```

5.1.3   Around Advice

The `Around` class is the Python implementation of the `around()` advice. The constructor of this class takes the following parameters:

- `params_update`

- `proceed` which can be a boolean of a function returning a boolean. This function should take a callable as a parameter, the advised function, so the advice can evaluate whether to proceed or not based on the signature or attributes of the advised function.

- `action` which is the function to run if the advised function does not proceed.

- `action_args`

- `action_kwargs`

```python
class Around:
    def __init__(
        self,
        params_update: dict[str, Any] | None,
        proceed: bool | Callable[[Callable[..., Any]], bool],
        action: Callable[..., Any],
        *action_args,
        **action_kwargs,
    ):
        self.params_update = params_update
        self.proceed = proceed
        self.action = action
        self.action_args = action_args
        self.action_kwargs = action_kwargs

    def __call__(self, func: Callable[..., Any]):
        @wraps(func)
        def wrapper(*args, **kwargs):
            proceed = self.proceed
            if callable(proceed):
                proceed = proceed(func)
            if isinstance(proceed, bool) and proceed:
                args, kwargs = mutate_params(
                    args, kwargs, self.params_update,
                    ↪  signature(func)
                )
```

```
26              return func(*args, **kwargs)
27          return self.action(*self.action_args,
   ↪     **self.action_kwargs)
28
29      return wrapper
```

5.2   Using the Implemented Advice in an Aspect

The following is an example of an aspect implementation in Python:

```
1  class Aspect(type):
2      # Regular expression used as the pointcut
3      before_regexp = re.compile(r"^test[1,2]$")
4
5      def __new__(cls, name, bases, namespace):
6          print(f"Modifying the namespace: {namespace}\n")
7          for attr_name, attr_value in namespace.items():
8              if not callable(attr_value):
9                  continue
10
11             if attr_name == "__init__":
12                 # Explicitly calling the decorator instance
13                 namespace[attr_name] = Before(
14                     {"example": "modified_example"},
   ↪     cls.action, "before __init__", 1, 2
15                 )(
16                     attr_value
17                 )
18
19             elif cls.before_regexp.match(attr_name):
20                 # Explicitly calling the decorator instance
21                 namespace[attr_name] = Before(None, cls.action,
   ↪     f"before {attr_name}", 1, 2)(
22                     attr_value
23                 )
24
25         return super().__new__(cls, name, bases, namespace)
26
27     @staticmethod
28     def action(arg1: Any, arg2: Any, arg3: Any) -> None:
29         print(f"Doing something {arg1} with args: '{arg2}' and
   ↪     '{arg3}'")
```

`Aspect` is a metaclass that implements the `__new__` method to customize the creation of classes. As you can see, in the `__new__` method, we loop over the namespace of the class, which is being created by the `Aspect` metaclass. Essentially, we loop over the namespace of any class that uses this class as its metaclass. We `continue` the loop if we encounter an attribute that is not `callable`. If the `__init__` method is encountered. Next, only methods that match the regular expression `before_regexp` are decorated.

We use regular expressions in concatenation with conditional statements as a way of implementing pointcuts. An alternative to regular expressions is the `fnmatchcase` function of the `fnmatch` Python module. This function allows matching strings with strings that contain Unix-style wildcard characters, although it was originally meant to be used for matching filenames.

If more control over the pointcuts is desired, it is also possible to include only methods with a signature having certain parameter types or a certain return value. The signature can be inspected using the `signature` function in the `inspect` Python module. However, such granularity of control over pointcuts requires methods to be type-annotated.

An example use of the `Aspect` metaclass could be the following:

```python
class MyClass(metaclass=Aspect):
    def __init__(self, example):
        self.example = example
        print(f"INIT: Initializing MyClass with example =
            ↪  '{self.example}'")

    def test1(self):
        print("TEST 1: Doing something")
        return 1

    def test2(self):
        print("TEST 2: Doing something")
        return 2

    def another_method(self):
        print("ANOTHER_METHOD: Doing something")
        return 3
```

Then we can create an instance of `MyClass` and call its methods:

```python
my_class = MyClass("example")
print(f"Return value: {my_class.test1()}\n")
```

```
3 print(f"Return value: {my_class.test2()}\n")
4 print(f"Return value: {my_class.another_method()}")
```

Creating the instance and calling its methods yields the following output:

```
1 Modifying the namespace: {'__module__': '__main__',
  ↪  '__qualname__': 'MyClass', '__init__': <function
  ↪  MyClass.__init__ at 0x0000024C32435620>, 'test1': <function
  ↪  MyClass.test1 at 0x0000024C324356C0>, 'test2': <function
  ↪  MyClass.test2 at 0x0000024C32435760>, 'another_method':
  ↪  <function MyClass.another_method at 0x0000024C32435800>}
2
3 Doing something before __init__ with args: '1' and '2'
4 INIT: Initializing MyClass with example = 'modified_example'
5 Doing something before test1 with args: '1' and '2'
6 TEST 1: Doing something
7 Return value: 1
8
9 Doing something before test2 with args: '1' and '2'
10 TEST 2: Doing something
11 Return value: 2
12
13 ANOTHER_METHOD: Doing something
14 Return value: 3
```

On line 1, you can see that the namespace of `MyClass` contains its attributes, including methods. We skip the decoration of any method not conforming to the `before_regexp` regular expression in the metaclass and therefore the `action` static method of `Aspect` is not executed before it. We can see that the initialization method has also been decorated and the `example` member variable has been modified using the dictionary from the first argument of the `Before` advice.

Note that using metaclasses is a way of automating the process of decorating class methods as opposed to manual decoration using the syntax with the *at* symbol.

5.3   Limitations of AOP in Python

During implementation, we discovered several limitations of using Python within the aspect-oriented paradigm. One of the most limiting factors of Python in this context is its dynamic typing. Therefore, it is up to the developer to include type annotations using the `typing` module. If functions

do not have annotations, using function signatures for pointcut definition is not possible.

Another limitation is the fact that using an aspect-oriented solution like ours in Python relies on direct modification of original source code files, where we need to include the metaclass `metaclass` keyword argument in definitions of classes in which we want to modify the methods or add decorators to functions directly. This implies that the metaclasses of the aspects, utilizing advice from our solution, must be imported into the module housing the classes that we aim to modify. However, the implementations of functions or class methods are not explicitly modified, implying that any new bugs might arise solely within the aspects or advice actions themselves. Assuming the absence of bugs in the original code, eliminating these aspects or advice actions from the code should resolve the issues encountered.

If a behavior change in class methods is desired, updating class definitions with the `metaclass` keyword argument is necessary for every class intended for this change, even if each class is set to employ the same aspect metaclass. This is a limitation that could lead to code maintainability issues. To overcome this limitation, a different strategy of applying aspects is necessary. A solution to consider in this case could be defining every class with the aspect metaclass and dealing with advice application in the aspect itself based on class names. For such a solution, the use of the `name` argument of the `__new__(cls, name, bases, namespace)` method of the metaclass is required to make decisions whether to apply aspects to the method of a class or not.

Python does not allow multiple metaclasses to be used by a single class. This means that developers cannot use multiple aspects proposed in this work for a single class. Only one aspect metaclass can be used for a chosen class, which could make the aspect metaclass cluttered and difficult to maintain over time. Another challenge may arise when applying AOP in Python to alter the execution of methods within a class that already employs a metaclass. In these scenarios, a workaround involves bypassing the suggested aspects entirely. Instead, we manually apply decorators to the specific methods we intend to modify using the *at* syntax.

6   Evaluation

The solution proposed for AOP in Python was largely inspired by AspectJ and its way of defining aspects and advice within them. It allows us to define advice, such as before, after returning, after throwing, and around, and where to apply them, providing functionality similar to pointcuts in AspectJ.

Similarly to AspectJ, pointcuts can be defined using wildcard characters thanks to the `fnmatch` module in Python. A more flexible approach is using

regular expression. However, these could be more error-prone, for example, by defining them incorrectly or making a mistake in their definition, if more complex regular expressions are used.

The implementation allows you to easily change the values of the arguments of the methods or functions. It also provides a way of defining which exceptions are to be caught by the after throwing advice. In the around advice, it allows customizing whether to proceed with the advised function or not, similar to AspectJ. Initialization methods are also customizable by applying advice; therefore, AspectJ's ability to define pointcuts for constructor executions is also present in our Python solution.

The implementation conforms to both properties of AOP, quantification and obliviousness [20]. In accordance to the quantification property, it allows performing some actions in programs whenever required conditions arise, e.g. where to apply advice, whether to proceed with a function or do a different action instead using the around advice or catch a certain type of exception. The solution can be used to extend existing code with new requirements to the software, in accordance with the obliviousness property.

Considering that AspectC++ implements the same constructs for C++ as AspectJ does for Java, our Python solution also shared similarities with the C++ implementation. However, looking at the aspectlib library written in Python, there are some key differences.

This library does not explicitly provide before, after returning, after throwing, and around advice, but rather provides a decorator named `Aspect`, which can be used to decorate generators. These generators are also decorators that can be used to provide additional functionality to existing functions. The additional functionality is accomplished by using the library's own version of advice - `Return`, `Proceed` or raising an exception by the `raise` keyword. This

Another key difference between aspectlib and our solution is the weaving mechanism. The aspectlib library has a custom weaver function that needs to be run in order to apply aspects to objects. This approach differs from our usage of metaclasses to implement a run-time weaving mechanism.

7 Conclusion

In this paper, we discussed the usage of decorators and metaclasses in Python for aspect-oriented programming. We used them to replicate the constructs that can be found in AspectJ and AspectC++. The chosen constructs were the before, after returning, after throwing and around advice.

These advice were implemented as decorator factories that provide all of the basic features found in AspectJ. Metaclasses were proposed as a way to define aspects, similar to aspects in AspectJ. The solution allows for the use of AOP in Python to add functionality to any function or method, including

dunder methods, e.g. `__init__`.

Metaclasses were used to create aspects that implement different advice based on pointcuts. Pointcuts were defined using regular expressions or wildcard characters. Furthermore, pointcuts can be extended using the `name` argument of the `__new__` method in metaclasses.

The limitations of aspect-oriented programming in Python were evaluated in comparison with the state-of-the-art language, AspectJ. Alternative approaches to using our solution were also considered as ways to overcome limitations. The proposed solution lacks the advanced features present in AspectJ. However, the implemented advice could be useful to extend existing code with new requirements to the software.

Acronyms

AOP   aspect-oriented programming

References

[1] Heba A Kurdi. "Review on Aspect Oriented Programming". In: *International Journal of Advanced Computer Science and Applications*. Vol. 4. 9. The Science and Information Organization. 2013, pp. 22–27. URL: https://thesai.org/Downloads/IJACSA_Volume4No9.pdf.

[2] Massood Khaari and Raman Ramsin. "Process Patterns for Aspect-Oriented Software Development". In: *2010 17th IEEE International Conference and Workshops on Engineering of Computer Based Systems*. IEEE. 2010, pp. 241–250. DOI: 10.1109/ECBS.2010.33.

[3] Arne Bachmann, Henning Bergmeyer, and Andreas Schreiber. "Evaluation of Aspect-Oriented Frameworks in Python for Extending a Project With Provenance Documentation Features". In: *The Python Papers* 6.3 (2011), p. 3. URL: https://core.ac.uk/download/pdf/230920601.pdf.

[4] Luciano Ramalho. *Fluent Python 2nd Edition*. O'Reilly Media, Inc., 2022. ISBN: 978-1-492-05635-5.

[5] Anand Rathore. *MetaClasses in Python*. May 2023. URL: https://codesarray.com/view/MetaClasses-in-Python (visited on 10/16/2023).

[6] Ramnivas Laddad. *AspectJ in Action Second Edition*. Manning Publications Co., 2010. ISBN: 978-1-933988-05-4.

[7] TJ O'Connor. *Violent Python: A Cookbook for Hackers, Forensic Analysts, Penetration Testers and Security Engineers*. Syngress, 2013. ISBN: 978-1-59749-957-6.

[8] Gregor Kiczales et al. "Aspect-oriented Programming". In: *ECOOP'97 Object-Oriented Programming: 11th European Conference Jyväskylä, Finland, June 9–13, 1997 Proceedings 11*. Springer. 1997, pp. 220–242. DOI: 10.1007/BFb0053381.

[9] Gregor Kiczales et al. "An overview of AspectJ". In: *ECOOP 2001 Object-Oriented Programming: 15th European Conference Budapest, Hungary, June 18–22, 2001 Proceedings 15*. Springer. 2001, pp. 327–354. DOI: 10.1007/3-540-45337-7_18.

[10] Andy Clement et al. *Eclipse AspectJ: Aspect Oriented Programming With AspectJ and the Eclipse AspectJ Development Tools*. Addison-Wesley Professional, 2005. ISBN: 0-32-124587-3.

[11] The AspectJ Team. *The AspectJ Programming Guide*. Palo Alto Research Center, Incorporated, 2003. URL: https://eclipse.dev/aspectj/doc/released/progguide/index.html (visited on 10/30/2023).

[12] Joseph D Gradecki and Nicholas Lesiecki. *Mastering AspectJ: Aspect-oriented Programming in Java*. John Wiley & Sons, 2003. ISBN: 0-471-43104-4.

[13] Stack Overflow. *2023 Developer Survey*. 2023. URL: `https://survey.stackoverflow.co/2023` (visited on 10/31/2023).

[14] Erich Gamma et al. *Design Patterns Elements of Reusable Object-Oriented Software*. Addison-Wesley Pub Co., 1995. ISBN: 0201633612.

[15] Vaskaran Sarcar. *Java Design Patterns: A Hands-On Experience with Real-World Examples, Third Edition*. Apress Berkeley, CA, May 2022. ISBN: 978-1-4842-7971-7.

[16] Guido Van Rossum and the Python Development Team. *The Python Language Reference*. 2023. URL: `https://docs.python.org/3.12/reference/` (visited on 10/31/2023).

[17] Olaf Spinczyk, Andreas Gal, and Wolfgang Schröder-Preikschat. "AspectC++: An Aspect-Oriented Extension to the C++ Programming Language". In: *Proceedings of the Fortieth International Conference on Tools Pacific: Objects for internet, mobile and embedded applications*. 2002, pp. 53–60.

[18] Ionel Cristian Mărieș. *Aspectlib Documentation*. Nov. 2018. URL: `https://python-aspectlib.readthedocs.io/` (visited on 12/04/2023).

[19] Martin Matusiak. *Strategies for aspect oriented programming in Python*. May 2009. URL: `https://matusiak.eu/media/uploads/aop_strategies.pdf`.

[20] Robert E Filman, Daniel P Friedman, and Peter Norvig. "Aspect-Oriented Programming is Quantification and Obliviousness". In: *Workshop on Advanced Separation of Concerns*. RIACS, 2000. URL: `https://homepages.cwi.nl/~storm/teaching/reader/FilmanFriedman00.pdf`.