Metaclass Programming with Python

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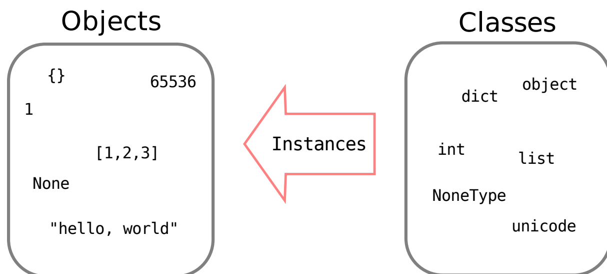
1. The Object Model for Classes
2. Customizing Class Creation
3. Applications of Metaclasses
4. Metaclasses and You

Tiny Little World

Tiny Little World



Classes and Objects

- abstract vs. concrete
- behavior of objects is determined by their classes
- “normal” code works with concrete objects

Classes as Objects

Everything is an Object

- classes live in the same space as their instances
- classes are "normal" objects

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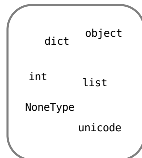
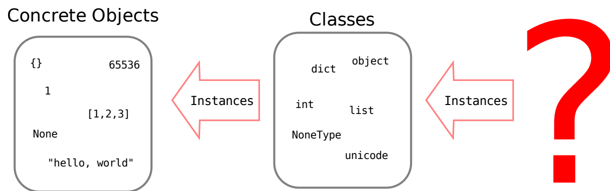
Examples

```
>>> intdict = defaultdict(int)
>>> intdict["abc"]
0
>>> ts = [int, float, str, unicode, list, dict]
>>> [t for t in ts if hasattr(t, "__len__")]
[<type 'str'>, <type 'unicode'>,
 <type 'list'>, <type 'dict'>]
>>> [t() for t in ts]
[0, 0.0, '', u'', [], {}]
```

Classes as Objects II



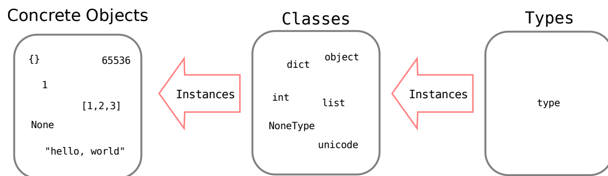
Classes as Objects II



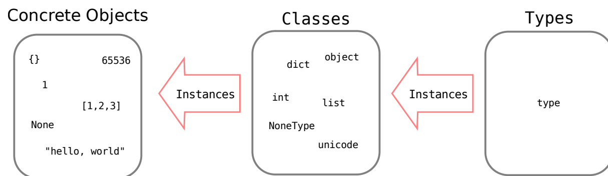
Classes as Objects

- every object has a type, which determines its behavior
- classes must be instances of *something*
- what is the class of a class?

Types/Metaclasses



Types/Metaclasses



Classes of Classes

- Classes are derived from metaclasses/types
- `type` is for classes what `object` is for instances

Instances, everywhere

`type`

- classes are instances of `type`
- `type` is again just an object, living in the same space
- Can we create arbitrary classes at runtime?

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Two Faces of the `type` Builtin

- `type(obj)`: returns the type of an object
  - `isinstance(obj, type(obj)) == True`
- `type(name, bases, dict)`: **returns a new type**

type at Work

Creating Types at Runtime

```
def say(self, msg):
    print msg

Speaker = type("Speaker", (object, ), {"say": say})
s = Speaker()
s.say("Hello World!")
```

Arguments

type at Work

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1. type name
   - Speaker.__class__.__name__

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1. type name
   - `Speaker.__class__.__name__`
2. base classes
   - `Speaker.__class__.__bases__`

type at Work

Creating Types at Runtime

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def say(self, msg):
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```

Arguments

1. type name
   - Speaker.__class__.__name__
2. base classes
   - Speaker.__class__.__bases__
3. class dictionary
   - basis for Speaker.__class__.__dict__

Spot the Difference

```
def say(self, msg):
  print msg
Speaker = type("Speaker",
               (object, ),
               {"say": say})
```

```
class Speaker(object):
  def say(self, msg):
    print msg
```

Spot the Difference

```python
def say(self, msg):
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Speaker = type("Speaker",
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```

```python
class Speaker(object):
  def say(self, msg):
    print msg
```

Solution

- There is (close to) none
- `class` statement is *syntactic sugar*
- makes sure namespaces stay clean
- **Important**: class object is created after statement block

Instantiation vs. Inheritance

Two Different Relationships

- Instantiation: between template and concrete object
  - *Bender is an actual bending unit.*
- Inheritance: between general and specific template
  - *A bending unit is a special kind of robot.*

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- `isinstance(1, int)`
- `isinstance(1, object)`
- `issubclass(int, object)`
- `isinstance(int, type)`
- `isinstance(object, type)`

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- `issubclass(object, type)`
- `isinstance(1, type)`

We can create new objects and classes.

Can we also create new **metaclasses**?

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Custom Metaclasses

Changing the Meta Class

- by default, Python uses `type` as a metaclass of a newly-created class
- custom metaclass can be set with the magic attribute `__metaclass__`

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`__metaclass__` Contract

- can be any callable object
- must take three arguments: name, bases and dictionary
- should return a new type that has been created using `type`

Interface Demo

Implementation

```python
def boring_meta(name, bases, dict_):
    print "Name: ", name
    print "Bases: ", bases
    print "Class Dictionary: ", ", ".join(dict_)
    return type(name, bases, dict_)

class SomeClass(object):
    __metaclass__ = boring_meta
    def foo(self): pass
```

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class SomeClass(object):
    __metaclass__ = boring_meta
    def foo(self): pass
```

```
Name:  SomeClass
Bases:  (<type 'object'>,)
Members  __module__, foo, __metaclass__
```

A More “Useful” Example

Problem

- 3rd-party modules that use classes with camel-case-methods
- you happen to dislike camel case (as you should)

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Problem

- 3rd-party modules that use classes with camel-case-methods
- you happen to dislike camel case (as you should)

Solution

- write a metaclass that turns PEP-8 style function names into camel case names
- write your classes according to your style, camel case names are never seen by you

The Camelizer

Implementation

```
import types

def pep8_to_cc(n): ...

def add_camelcase(cls_name, bases, dict_):
  for name, obj in dict_.items():
    if (not name.startswith("_")
        and isinstance(obj, types.FunctionType)):
        dict_[pep8_to_cc(name)] = obj
  return type(cls_name, bases, dict_)
```

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        and isinstance(obj, types.FunctionType)):
       dict_[pep8_to_cc(name)] = obj
  return type(cls_name, bases, dict_)
```

```
>>> class SomeClass(object):
...   __metaclass__ = add_camelcase
...   def say_ni(self): print "Ni!"
>>> SomeClass().sayNi()
```

Something Actually Useful

A Real Problem

- super-class method is overridden in class
- name of super-class method changes, e.g. due to refactoring
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Inspiration from Java

- `@Override` annotation on methods as a hint to the compiler
- if annotated method does not override anything, compilation results in a failure

Compliance Checks in Metaclasses

Application for Metaclasses

- test should be carried out ...
  - as **early** as possible
  - exactly **once**

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Solution Sketch

- method decorator `@override`
- metaclass that checks all decorated methods
- **Warning:** code is not production-ready

Implementation

The Decorator

```
def override(func):
  func._must_override = True
  return func
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Comments

- just stores some metadata on the function
- used similar to Java's annotations
  ...though decorators are much more powerful
- **Important**: class object does not exist at this point, so constraint cannot be checked right away

The Metaclass

```
def get_all_bases(classes):
  return list(
    chain.from_iterable(inspect.getmro(c)
                        for c in classes))

class MethodCheckerType(type):
  def __new__(mcs, cls_name, bases, dict_):
    all_bases = get_all_bases(bases)
    for name, obj in dict_.iteritems():
      if getattr(obj, "_must_override", False):
        assert any(hasattr(base_cls, name)
                   for base_cls in all_bases)

    return type.__new__(mcs, cls_name, bases, dict_)
```

In Use

```
>>> class BaseClass(object):
...     __metaclass__ = MethodCheckerType
...     def foo(self): pass

>>> class WrongDerivedClass(BaseClass):
...     @override
...     def do_foo(self): pass
AssertionError
```

In Use

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>>> class BaseClass(object):
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Remarks & Extensions

- does not work if annotation is forgotten
- better error message
- should check if superclass object is actually a method
- warn if overridden methods are not annotated

Metaclasses in Python 3.0

Class Decorators

- similar to method decorators, just for classes
- post-processing for classes
- more declarative

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PEP-3115: Rationale

- post-processing can be done by class decorators
- metaclasses come fairly late in the class creation process
- allow the metaclass to provide the dictionary which is used for storing the namespace

Metaclass Changes

Use Cases for Early Involvement

- preserve order of declarations
  - automatic mapping to C structs
- injection of volatile field constructors
- forward references within a class body

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Implementation

- metaclass types can provide a method `__prepare__`
- called with name and bases
- returns a mapping object which is used to store the namespace
- **optional!**

Extended Syntax for Class Definitions

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- metaclass can provide the namespace
- must be known before class body is evaluated
- no way to pass arguments to metaclasses directly

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Extended Syntax

```
class Foo(base1, metaclass=mymeta, private=True):
  ...
```

- `metaclass` to specify the metaclass object
- other keyword arguments are passed to the metaclass

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Before We Begin

Metaclasses and You

- metaclasses are just one way to customize classes
- customization prior to *instantiation* is just one way to have customized classes

The Code Ahead

- real (or almost . . .) examples
- consume responsibly!

Object-Relational Mappers

The Idea

- classes whose attributes can be mapped to tables in relational databases (and back)
- knowledge about attributes needed
  - data type
  - relation to other objects
  - possible constraints
- ideally done in a intuitive & declarative style

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Challenges

- needs extensive compliance checks
- database table must be created from field descriptions
- efficient way to enumerate all fields at runtime
- no leaky abstractions

Example: Django Models

Model Example

```
class Musician(models.Model):
    first_name = models.CharField(max_length=50)
    last_name = models.CharField(max_length=50)
    instrument = models.CharField(max_length=100)

class Album(models.Model):
    artist = models.ForeignKey(Musician)
    name = models.CharField(max_length=100)
    release_date = models.DateField()
```

Taken from http://docs.djangoproject.com/en/dev/topics/db/models/

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Using a model

```
a = Musician(name="Everett",
             first_name="Mark", instrument="Guitar")
a.save()
```

Django Model Guts

`django.models.Model`

- sets the metaclass to `django.models.ModelBase`
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`django.models.ModelBase`

- creates the class
- ensures that data fields are added to the class
- registers models at a central location

Lazy Attribute Lookup

Problem

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- parsing & object setup is always the same
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Solution

- use metaclasses to provide proxy/recording objects when generating code
- all function all and object accesses get recorded
- only instantiation of UI classes needs to be changed, all other code in UI loader is the same
- either runs on recording or actual UI objects

Proxy Namespace

```
>>> class QtCore(ProxyNamespace): pass
>>> str(QtCore.QDate(1, 2, 3))
'QtCore.QDate(1, 2, 3)'
>>> str(qtproxies.QtCore.QDate(1, 2, 3)\
                .toString().length())
'QtCore.QDate(1, 2, 3).toString().length()'
```

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- but can be written as a normal classes

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ProxyType Metaclass

- customized attribute lookup for class objects
- on-the-fly generation of literal objects
- sets namespace information
- not a generic framework, customized for the UI loading use case

Call Dispatch

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- certain methods in a class need to be registered as event handlers
- examples: visitors, parsers
- dispatch dictionary should be known before event dispatch
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Solution

- annotate event handlers via decorators
- create dispatch dictionary in metaclass

Event-based Parsing with ElementTree

```
class HtmlParser(IterParseHandler):
  @element("p")
  def _handle_paragraph(self, elem):
    ...

  @element("div")
  @element("span")
  def _handle_neutral(self, elem):
    ...

hp = HtmlParser()
with open("some_file", "r") as f:
  hp.parse(f)
```

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hp = HtmlParser()
with open("some_file", "r") as f:
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```

Remarks

- use schema to enforce that all elements are handled

Modified Classes

Far-reaching Changes

- metaclasses allow heavy modifications
- modified attribute lookup
- changed object instantiation behavior
- magic methods for class objects

Java, again: Enums

Yes, I did program a lot of Java

```
public enum Planet {
    public static final double G = 6.67300e-11;
    VENUS   (4.869e+24, 6.0518e+6),
    EARTH   (5.976e+24, 6.37814e+6),
    MARS    (6.421e+23, 3.3972e+6),
    ...
    private final double mass;   // in kilograms
    private final double radius; // in meters
    Planet(double mass, double radius) {
        this.mass = mass;
        this.radius = radius;
    }
    public double mass()   { return mass; }
    public double radius() { return radius; }
    public double surfaceGravity() {
        return G * mass / (radius * radius);
    }
}
```

Adapted from http://java.sun.com/j2se/1.5.0/docs/guide/language/enums.html

Enums, Adapted

Adaptation

- Java code is still quite verbose
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```
import enum

class Planet(enum.Enum):
    G = 6.67300e-11;

    __fields__ = ["mass", "radius"]

    VENUS = enum.member(4.869e+24, 6.0518e+6)
    EARTH = enum.member(5.976e+24, 6.37814e+6)
    MARS  = enum.member(6.421e+23, 3.3972e+6)

    @property
    def surface_gravity(self):
        return self.G * self.mass / self.radius**2
```

Enum's Inner Workings

`enum.Enum`: base class

- sets the metaclass
- provides equality tests, `__repr__`

Enum's Inner Workings

enum.Enum: base class

- sets the metaclass
- provides equality tests, `__repr__`

enum._EnumType: the metaclass

- creates the instances, correct number of fields etc.
- ensures immutability
- creates property objects for all fields
- provides methods for iterating over all enum members
- each enum class object (**not instance**) is a sequence

Enums.v3

Putting New Metaclasses to Use

```
import enum3

class Planet(enum3.Enum, fields=["mass", "radius"]):
    G = 6.67300e-11;

    VENUS = Planet(4.869e+24, 6.0518e+6)
    EARTH = Planet(5.976e+24, 6.37814e+6)
    MARS  = Planet(6.421e+23, 3.3972e+6)

    @property
    def surface_gravity(self):
        return self.G * self.mass / self.radius**2
```

- even possible to define fields in class body

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Clever Code

> *Debugging is twice as hard as writing the code in the first place. Therefore, if you write the code as cleverly as possible, you are, by definition, not smart enough to debug it.*
>
> — Brian W. Kernighan

How to Use Metaclasses

Hide Metaclasses

- do not expose directly
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Where to Use

- tool for library/framework writers
- overkill for one-off situations

Don't Use Metaclasses

Technical Problems

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- conflicts with other metaclasses
- hard-to-find/strange bugs
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Social/Philosophical Problems

- other programmers likely won't understand your code
- break default assumptions on code
    - ...it's what they are there for, after all

Alternatives to Metaclasses

Concrete Problems

- modified attribute access
    - `__getattr__`, descriptors
- post-processing (adding extra functions, registering)
    - explicit function calls
    - class decorators

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Other Techniques

- mixins
- descriptors
- code generation

A Summary, In Questions

Do I Need to Know About Metaclasses?

Deliberately **avoiding knowledge** won't make you a better programmer.

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Should I Use Metaclasses?

Make your own mistakes, **but learn from them**.

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What Do I Gain From Metaclasses?

Elegant & intuitive code in **classes** through complex code in **metaclasses** and loss of explicitness.

The End

Thanks a lot for your attention!

Questions? Comments?