Chapter 3

H. Conrad Cunningham

08 April 2022

Contents

3 Object-Based Paradigms 2
  3.1 Chapter Introduction ............................. 2
  3.2 Motivation ...................................... 2
  3.3 Object Model .................................... 3
    3.3.1 Objects .................................. 3
      3.3.1.1 Essential characteristics ............... 3
      3.3.1.2 Important but non-essential characteristics ... 4
    3.3.2 Classes .................................. 5
    3.3.3 Inheritance ................................ 6
    3.3.4 Subtype polymorphism ....................... 10
  3.4 Object-Oriented Paradigm ......................... 12
    3.4.1 Object-oriented Python example ............... 13
    3.4.2 Object-oriented Scala example ............... 15
  3.5 Prototype-based Paradigm ......................... 15
    3.5.1 Prototype concepts .......................... 15
    3.5.2 Lua as an object-based language ............... 16
    3.5.3 Prototype-based Lua example ............... 18
    3.5.4 Observations ................................ 21
  3.6 What Next? .................................. 21
  3.7 Exercises ..................................... 22
  3.8 Acknowledgements .............................. 22
  3.9 Terms and Concepts ............................. 23
  3.10 References .................................... 24

Copyright (C) 2016, 2017, 2018, 2022, H. Conrad Cunningham
Professor of Computer and Information Science
University of Mississippi
Browser Advisory: The HTML version of this textbook requires a browser that supports the display of MathML. A good choice as of April 2022 is a recent version of Firefox from Mozilla.
3 Object-Based Paradigms

3.1 Chapter Introduction

The imperative-declarative taxonomy described in the previous chapter divides programming styles and language features on how they handle state and how they are executed. The previous chapter also mentioned other paradigms such as procedural, modular, object-based, and concurrent.

The dominant paradigm since the early 1990s has been the object-oriented paradigm. Because this paradigm is likely familiar with most readers, it is useful to examine it in more detail.

Thus the goals of this chapter are to examine the characteristics of:

- the object-oriented paradigm
- related paradigms such as the object-based, class-based, and prototype-based paradigms

3.2 Motivation

In contemporary practice, most software engineers approach the design of programs from an object-oriented perspective.

The key idea (notion?) in object orientation is the following: The real world can be accurately described as a collection of objects that interact.

This approach is based on the following assumptions:

1. Describing large, complex systems as interacting objects make them easier to understand than otherwise.
2. The behaviors of real world objects tend to be stable over time.
3. The different kinds of real world objects tend to be stable. (That is, new kinds appear slowly; old kinds disappear slowly.)
4. Changes tend to be localized to a few objects.

Assumption 1 simplifies requirements analysis, software design, and implementation—makes them more reliable.

Assumptions 2 and 3 support reuse of code, prototyping, and incremental development.

Assumption 4 supports design for change.

The object-oriented approach to software development:

- uses the same basic entities (i.e., objects) throughout the software development lifecycle
- identifies the basic objects during analysis
identifies lower-level objects during design, reusing existing object descriptions where appropriate
- implements the objects as software structures (e.g., Java classes)
- maintains the object behaviors

3.3 Object Model

We discuss object orientation in terms of an object model. Our object model includes four basic components:

1. objects (i.e., abstract data structures)
2. classes (i.e., abstract data types)
3. inheritance (hierarchical relationships among abstract data types)
4. subtype polymorphism

Some writers consider dynamic binding a basic component of object orientation. Here we consider it an implementation technique for subtype polymorphism.

Now let’s consider each of four components of the object model.

3.3.1 Objects

For languages in the object-based paradigms, we require that objects exhibit three essential characteristics. Some writers consider one or two other other characteristics as essential. Here we consider these as important but non-essential characteristics of the object model.

3.3.1.1 Essential characteristics An object must exhibit three essential characteristics:

a. state
b. operations
c. identity

An object is a separately identifiable entity that has a set of operations and a state that records the effects of the operations. An object is typically a first-class entity that can be stored in variables and passed to or returned from subprograms.

The state is the collection of information held (i.e., stored) by the object.

- It can change over time.
- It can change as the result of an operation performed on the object.
It cannot change spontaneously.

The various components of the state are sometimes called the **attributes** of the object.

An **operation** is a procedure that takes the state of the object and zero or more arguments and changes the state and/or returns one or more values. Objects permit certain operations and not others.

If an object is **mutable**, then an operation may change the stored state so that a subsequent operation on that object acts upon the modified state; the language is thus imperative.

If an object is **immutable**, then an operation cannot change the stored state; instead the operation returns a new object with the modified state.

**Identity** means we can distinguish between two distinct objects (even if they have the same state and operations).

As an example, consider an object for a student desk in a simulation of a classroom.

- A student desk is distinct from the other student desks and, hence, has a unique **identity**.
- The relevant **state** might be attributes such as location, orientation, person using, items in the basket, items on top, etc.
- The relevant **operations** might be state-changing operations (called **mutator**, setter, or command operations) such as “move the desk”, “seat student”, or “remove from basket” or might be state-observing operations (called **accessor**, getter, observer, or query operations) such as “is occupied” or “report items on desktop”.

A language is **object-based** if it supports objects as a language feature.

Object-based languages include Ada, Modula, Clu, C++, Java, Scala, C#, Smalltalk, and Python 3.

Pascal (without module extensions), Algol, Fortran, and C are not inherently object-based.

### 3.3.1.2 Important but non-essential characteristics

Some writers require that an object have additional characteristics, but this book considers these as important but **non-essential** characteristics of objects:

- **encapsulation**
- **independent lifecycle**

The state may be **encapsulated** within the object—that is, not be directly visible or accessible from outside the object.
The object may also have an independent lifecycle—that is, the object may exist independently from the program unit that created it. Its lifetime is not determined by the program unit that created it.

We do not include these as essential characteristics because they do not seem required by the object metaphor.

Also, some languages we wish to categorize as object-based do not exhibit one or both of these characteristics. There are languages that use a modularization feature to enforce encapsulation separately from the object (or class) feature. Also, there are languages that may have local “objects” within a function or procedure.

In languages like Python 3, Lua, and Oberon, objects exhibit an independent lifecycle but do not themselves enforce encapsulation. Encapsulation may be supported by the module mechanism (e.g., in Oberon and Lua) or partly by a naming convention (e.g., in Python 3).

In C++, some objects may be local to a function and, hence, be allocated on the runtime stack. These objects are deallocated upon exit from the function. These objects may exhibit encapsulation, but do not exhibit independent lifecycles.

3.3.2 Classes

A class is a template or factory for creating objects.

- A class describes a collection of related objects (i.e., instances of the class).
- Objects of the same class have common operations and a common set of possible states.
- The concept of class is closely related to the concept of type.

A class description includes definitions of:

- operations on objects of the class
- the set of possible states

As an example, again consider a simulation of a classroom. There might be a class `StudentDesk` from which specific instances can be created as needed.

An object-based language is class-based if the concept of class occurs as a language feature and every object has a class.

Class-based languages include Clu, C++, Java, Scala, C#, Smalltalk, Ruby, and Ada 95. Ada 83 and Modula are not class-based.

At their core, JavaScript and Lua are object-based but not class-based.

In statically typed, class-based languages such as Java, Scala, C++, and C# classes are treated as types. Instances of the same class have the same (nominal) type.
However, some dynamically typed languages may have a more general concept of type: If two objects have the same set of operations, then they have the same type regardless of how the object was created. Languages such as Smalltalk and Ruby have this characteristic—sometimes informally called duck typing. (If it walks like a duck and quacks like a duck, then it is a duck.) See Chapter 5 for more discussion of types.

3.3.3 Inheritance

A class \( C \) inherits from class \( P \) if \( C \)'s objects form a subset of \( P \)'s objects.

- Class \( C \)'s objects must support all of the class \( P \)'s operations (but perhaps are carried out in a special way).
- Class \( C \) may support additional operations and an extended state (i.e., more information fields).
- Class \( C \) is called a subclass or a child or derived class.
- Class \( P \) is called a superclass or a parent or base class.
- Class \( P \) is sometimes called a generalization of class \( C \); class \( C \) is a specialization of class \( P \).

The importance of inheritance is that it encourages sharing and reuse of both design information and program code. The shared state and operations can be described and implemented in base classes and shared among the subclasses.

As an example, again consider the student desks in a simulation of a classroom. The \texttt{StudentDesk} class might be derived (i.e., inherit) from a class \texttt{Desk}, which in turn might be derived from a class \texttt{Furniture}. In diagrams, there is a convention to draw arrows (e.g., ←) from the subclass to the superclass.

\[
\text{Furniture} \leftarrow \text{Desk} \leftarrow \text{StudentDesk}
\]

The simulation might also include a \texttt{ComputerDesk} class that also derives from \texttt{Desk}.

\[
\text{Furniture} \leftarrow \text{Desk} \leftarrow \text{ComputerDesk}
\]

We can also picture the above relationships among these classes with a class diagram as shown in Figure 3.1.

In Java and Scala, we can express the above inheritance relationships using the \texttt{extends} keyword as follows.

```java
class Furniture // extends cosmic root class for references
{   ...   } // (java.lang.Object, scala.AnyRef)

class Desk extends Furniture
{   ...   }
```
Figure 3.1: Classroom simulation inheritance hierarchy.
class StudentDesk extends Desk
{   ...   }

class ComputerDesk extends Desk
{    ...    }

Both StudentDesk and ComputerDesk objects will need operations to simulate a move of the entity in physical space. The move operation can thus be implemented in the Desk class and shared by objects of both classes.

Invocation of operations to move either a StudentDesk or a ComputerDesk will be bound to the general move in the Desk class.

The StudentDesk class might inherit from a Chair class as well as the Desk class.

Furniture ← Chair ← StudentDesk

Some languages support multiple inheritance as shown in Figure 3.2 for StudentDesk (e.g., C++, Eiffel, Python 3). Other languages only support a single inheritance hierarchy.

---

Figure 3.2: Classroom simulation with multiple inheritance.

Because multiple inheritance is both difficult to use correctly and to implement in a compiler, the designers of Java and Scala did not include multiple inheritance
of classes as features. Java has a single inheritance hierarchy with a top-level class named `Object` from which all other classes derive (directly or indirectly). Scala is similar, with the corresponding top-level class named `AnyRef`.

```java
class StudentDesk extends Desk, Chair // NOT VALID in Java
{
    ...
}
```

To see some of the problems in implementing multiple inheritance, consider the above example. Class `StudentDesk` inherits from class `Furniture` through two different paths. Do the data fields of the class `Furniture` occur once or twice? What happens if the intermediate classes `Desk` and `Chair` have conflicting definitions for a data field or operation with the same name?

The difficulties with multiple inheritance are greatly decreased if we restrict ourselves to inheritance of class `interfaces` (i.e., the signatures of a set of operations) rather than a supporting the inheritance of the class `implementations` (i.e., the instance data fields and operation implementations). Since interface inheritance can be very useful in design and programming, the Java designers introduced a separate mechanism for that type of inheritance.

The Java `interface` construct can be used to define an interface for classes separately from the classes themselves. A Java `interface` may inherit from (i.e., `extend`) zero or more other `interface` definitions.

```java
interface Location3D
{
    ...
}

interface HumanHolder
{
    ...
}

interface Seat extends Location3D, HumanHolder
{
    ...
}
```

A Java `class` may inherit from (i.e., `implement`) zero or more interfaces as well as inherit from (i.e., `extend`) exactly one other `class`.

```java
interface BookHolder
{
    ...
}

interface BookBasket extends Location3D, BookHolder
{
    ...
}

class StudentDesk extends Desk implements Seat, BookBasket
{
    ...
}
```

Figure 3.3 shows this interface-based inheritance hierarchy for the classroom simulation example. The dashed lines represent the `implements` relationship.

This definition requires the `StudentDesk` class to provide actual implementations for all the operations from the `Location3D`, `HumanHolder`, `BookHolder`, `Seat`, `Desk`, and `Chair` interfaces.
Figure 3.3: Classroom simulation with interfaces.

and BookBasket interfaces. The Location3D operations will, of course, need to be implemented in such a way that they make sense as part of both the HumanHolder and BookHolder abstractions.

The Scala trait provides a more powerful, and more complex, mechanism than Java’s original interface. In addition to signatures, a trait can define method implementations and data fields. These traits can be added to a class in a controlled, linearized manner to avoid the semantic and implementation problems associated with multiple inheritance of classes. This is called mixin inheritance.

Java 8+ generalizes interfaces to allow default implementations of methods.

Most statically typed languages treat subclasses as subtypes. That is, if C is a subclass of P, then the objects of type C are also of type P. We can substitute a C object for a P object in all cases.

However, the inheritance mechanism in languages in most class-based languages (e.g., Java) does not automatically preserve substitutability. For example, a subclass can change an operation in the subclass to do something totally different from the corresponding operation in the parent class.

3.3.4 Subtype polymorphism

The concept of polymorphism (literally “many forms”) means the ability to hide different implementations behind a common interface. Polymorphism appears in several forms in programming languages. We will discuss these more later.

Subtype polymorphism (sometimes called polymorphism by inheritance, inclusion polymorphism, or subtyping) means the association of an operation invocation (i.e., procedure or function call) with the appropriate operation implementation in an inheritance (subtype) hierarchy.
This form of polymorphism is usually carried out at run time. That implementation is called *dynamic binding*. Given an object (i.e., class instance) to which an operation is applied, the system will first search for an implementation of the operation associated with the object’s class. If no implementation is found in that class, the system will check the superclass, and so forth up the hierarchy until an appropriate implementation is found. Implementations of the operation may appear at several levels of the hierarchy.

The combination of dynamic binding with a well-chosen inheritance hierarchy allows the possibility of an instance of one subclass being substituted for an instance of a different subclass during execution. Of course, this can only be done when none of the extended operations of the subclass are being used.

As an example, again consider the simulation of a classroom. As in our discussion of inheritance, suppose that the *StudentDesk* and *ComputerDesk* classes are derived from the *Desk* class and that a general *move* operation is implemented as a part of the *Desk* class. This could be expressed in Java as follows:

```java
class Desk extends Furniture
{
    ... 
    public void move(...)
    ...
}

class StudentDesk extends Desk
{
    ... 
    // no move(...) operation here
    ...
}

class ComputerDesk extends Desk
{
    ... 
    // no move(...) operation here
    ...
}
```

As we noted before, invocation of operations to *move* either a *StudentDesk* or a *ComputerDesk* instance will be bound to the general *move* in the *Desk* class.

Extending the example, suppose that we need a special version of the *move* operation for *ComputerDesk* objects. For instance, we need to make sure that the computer is shut down and the power is disconnected before the entity is moved.

To do this, we can define this special version of the *move* operation and associate it with the *ComputerDesk* class. Now a call to *move* a *ComputerDesk* object will be bound to the special *move* operation, but a call to *move* a *StudentDesk* object will still be bound to the general *move* operation in the *Desk* class.
The definition of move in the ComputerDesk class is said to override the definition in the Desk class.

In Java, this can be expressed as follows:

```java
class Desk extends Furniture {
    ... 
    public void move(...) 
    ... 
}

class StudentDesk extends Desk {
    ... 
    // no move(...) operation here 
    ... 
}

class ComputerDesk extends Desk {
    ... 
    public void move(...) 
    ... 
}
```

A class-based language is object-oriented if class hierarchies can be incrementally defined by an inheritance mechanism and the language supports polymorphism by inheritance along these class hierarchies.

Object-oriented languages include C++, Java, Scala, C#, Smalltalk, and Ada 95. The language Chu is class-based, but it does not include an inheritance facility.

Other object-oriented languages include Objective C, Object Pascal, Eiffel, and Oberon 2.

### 3.4 Object-Oriented Paradigm

Now let’s consider the object-oriented paradigm more concretely. First, let’s review what we mean by an object-oriented language. A language is:

- **object-based** if it supports objects that satisfy the three essential characteristics (state, operations, and identity) as a language feature
- **class-based** if it is object-based, has the concept of class as a language feature, and assigns every object to a class
- **object-oriented** if it is class-based, can define class hierarchies incrementally using an inheritance mechanism, and supports polymorphism by inheritance along these class hierarchies

A class-based language is object-oriented if class hierarchies can be incrementally defined by an inheritance mechanism and the language supports polymorphism
by inheritance along these class hierarchies.

### 3.4.1 Object-oriented Python example

TODO: This example mostly illustrates class-based Python. It needs to be extended to show effective use of inheritance and subtyping. Possibly create two different subclasses to override the hook methods or leave them abstract and make concrete in subclass—as in Arith and Geom modules for the modular examples.

Python 3 is a dynamically typed language with support for imperative, procedural, modular, object-oriented, and (to a limited extent) functional programming styles [28]. It’s object model supports state, operations, identity, and an independent lifecycle. It provides some support for encapsulation. It has classes, single and multiple inheritance, and subtype polymorphism.

Let’s again examine the counting problem from Chapter 2 from the standpoint of object-oriented programming in Python 3. The following code defines a class named `CountingOO`. It defines four instance methods and two instance variables.

Note: By *instance variable* and *instance method* we mean variables and instances associated with an object, an instance of a class.

```python
class CountingOO:
    # (1)
    def __init__(self, c, m):
        # (2, 3)
        self.count = c
        # (4)
        self.maxc = m

    def has_more(self, c, m):
        # (5)
        return c <= m

    def adv(self):
        # (6)
        self.count = self.count + 1

    def counter(self):
        # (7)
        while self.has_more(self.count, self.maxc):
            print(self.count)  # (8)
            self.adv()
```

The following notes explain the numbered items in the above code.

1. By default, a Python 3 class inherits from the cosmic root class `object`. If a class inherits from some other class, then we place the parent class’s name in parenthesis after the class name, as with class `Times2` below. (Python 3 supports multiple inheritance, so there can be multiple class names separated by commas.)

2. Python 3 classes do not normally have explicit constructors, but we often
define an initialization method which has the special name `__init__`.

3. Unlike object-oriented languages such as Java, Python 3 requires that the receiver object be passed explicitly as the first parameter of instance methods. By convention, this is a parameter named `self`.

4. An instance of the class `CountingOO` has two instance variables, `count` and `maxc`. Typically, we create these dynamically by explicitly assigning a value to the name. We can access these values in expressions (e.g., `self.count`).

5. Method `has_more()` is a function that takes the receiver object and values for the current count and maximum values and returns `True` if and only if there are additional values to generate. (Although an instance method, it does not access the instance's state.)

6. Method `adv()` is a procedure that accesses and modifies the state (i.e., the instance variables), setting `self.count` to a new value closer to the maximum value `self.maxc`.

7. Method `counter()` is a procedure intended as the primary public interface to an instance of the class. It uses function method `has_more()` to determine when to stop the iteration, procedure method `adv()` to advance the variable `count` from one value to the next value, and the `print` function to display the value on the standard output device.

8. Expression `f'{self.count}'` is a Python 3.7 interpolated string.

In terms of the Template Method design pattern [17], `counter` is intended as a template method that encodes the primary algorithm and is not intended to be overridden. Methods `has_more()` and `adv()` are intended as hook methods that are often overridden to give different behaviors to the class.

Consider the following fragment of code.

```python
ctr = CountingOO(0,10)
ctr.counter()
```

The first line above creates an instance of the `CountingOO` class, initializes its instance variables `count` and `maxc` to 0 and 10, and stores the reference in variable `ctr`. The call `ctr.counter()` thus prints the values 0 to 10, one per line, as do the programs from Chapter 2.

However, we can create a subclass that overrides the definitions of the hook methods `has_more()` and `adv()` to give quite different behavior without modifying class `CountingOO`.

```python
class Times2(CountingOO):  # inherits from CountingOO
    def has_more(self,c,m):  # overrides
        return c != 0 and abs(c) <= abs(m)
```

15
def adv(self):  # overrides
    self.count = self.count * 2

Now consider the following code fragment.

ctr2 = Times2(-1,10)
ctr2.counter()

This generates the sequence of values -1, -2, -4, and -8, printed one per line.

The call to any method on an instance of class Times2 is polymorphic. The system dynamically searches up the class hierarchy from Times2 to find the appropriate function. It finds has_more() and adv() in Times2 and counter() in parent class CountingOO.

The code for this section is in source file CountingOO.py.

3.4.2 Object-oriented Scala example

The program CountingOO.scala is an object-oriented Scala [27,30] program similar to the Python version given above.

3.5 Prototype-based Paradigm

Classes and inheritance are not the only way to support relationships among objects in object-based languages. Another approach of growing importance is the use of prototypes.

3.5.1 Prototype concepts

A prototype-based language does not have the concept of class as defined above. It just has objects. Instead of using a class to instantiate a new object, a program copies (or clones) an existing object—the prototype—and modifies the copy to have the needed attributes and operations.

Each prototype consists of a collection of slots. Each slot is filled with either a data attribute or an operation.

This cloning approach is more flexible than the class-based approach.

In a class-based language, we need to define a new class or subclass to create a variation of an existing type. For example, we may have a Student class. If we want to have students who play chess, then we would need to create a new class, say ChessPlayingStudent, to add the needed data attributes and operations.

Aside: Should Student be the parent ChessPlayingStudent? or should ChessPlayer be the parent? Or should we have fields of ChessPlayingStudent that hold Student and ChessPlayer objects?

In a class-based language, the boundaries among categories of objects specified by classes should be crisply defined. That is, an object is in a particular class or
it is not. Sometimes this crispness may be unnatural.

In a prototype-based language, we simply clone a student object and add new slots for the added data and operations. This new object can be a prototype for further objects.

In a prototype-based language, the boundaries between categories of objects created by cloning may be fuzzy. One category of objects may tend to blend into others. Sometimes this fuzziness may be more natural.

Consider categories of people associated with a university. These categories may include Faculty, Staff, Student, and Alumnus. Consider a student who gets a BSCS degree, then accepts a staff position as a programmer and stays a student by starting an MS program part-time, and then later teaches a course as a graduate student. The same person who started as a student thus evolves into someone who is in several categories later. And he or she may also be a chess player.

Instead of static, class-based inheritance and polymorphism, some languages exhibit prototype-based delegation. If the appropriate operation cannot be found on the current object, the operation can be delegated to its prototype, or perhaps to some other related, object. This allows dynamic relationships along several dimensions. It also means that the “copying” or “cloning” may be partly logical rather than physical.

Prototypes and delegation are more basic mechanisms than inheritance and polymorphism. The latter can often be implemented (or perhaps “simulated”) using the former.

Self [32,36], NewtonScript [24,26], JavaScript [1,40], Lua [20,22,34], and Io [9,15,33] are prototype-based languages. (Package prototype.py can also make Python behave in a prototype-based manner.)

Let’s look at Lua as a prototype-based language.

Note: The two most widely used prototype languages are JavaScript and Lua. I choose Lua here because it is simpler and can also execute conveniently from the command line. I have also used Lua extensively in the past and have not yet used JavaScript extensively.

### 3.5.2 Lua as an object-based language

Lua is a dynamically typed, multiparadigm language [20,22]. The language designers stress the following design principles [23]:

- portability
- embeddability
- efficiency
- simplicity

To realize these principles, the core language implementation:
• can only use standard C and the standard C library
• must be efficient in use of memory and processor time (i.e., keep the interpreter small and fast)
• must support interoperability with C programs in both directions (i.e., can call or be called by C programs)

C is ubiquitous, likely being the first higher-level language implemented for any new machine, whether a small microcontroller or a large multiprocessor. So this implementation approach supports the portability, embeddability, and efficiency design goals.

Because of Lua’s strict adherence to the above design principles, it has become a popular language for extending other applications with user-written scripts or templates. For example, it is used for this purpose in some computer games and by Wikipedia. Also, Pandoc, the document conversion tool used in production of this textbook, enables scripts to be written in Lua. (The Pandoc program itself is written in Haskell.)

The desire for a simple but powerful language led the designers to adopt an approach that separates mechanisms from policy. As noted on the Lua website [23]:

A fundamental concept in the design of Lua is to provide meta-mechanisms for implementing features, instead of providing a host of features directly in the language. For example, although Lua is not a pure object-oriented language, it does provide meta-mechanisms for implementing classes and inheritance. Lua’s meta-mechanisms bring an economy of concepts and keep the language small, while allowing the semantics to be extended in unconventional ways.

Lua provides a small set of quite powerful primitives. For example, it includes only one data structure—the table (dictionary, map, or object in other languages)—but ensures that it is efficient and flexible for a wide range of uses.

Lua’s tables are objects as described in Section 3.3. Each object has its own:

• state (i.e., values associated with keys)
• identity independent of state
• lifecycle independent of the code that created it

In addition, a table can have its own operations by associating function closures with keys.

Note: By function closure, we mean the function’s definition plus aspects of its environment necessary (e.g., variables variables outside the function) necessary for the function to be executed.

So a key in the table represents a slot in the object. The slot can be occupied by either a data attribute’s value or the function closure associated with an operation.
Lua tables do not directly support *encapsulation*, but there are ways to build structures that encapsulate key data or operations.

Lua’s *metatable* mechanism, particularly the *__index* metamethod, enables an access to an undefined key to be delegated to another table (or to result in a call of a specified function).

Thus tables and metatables enable the prototype-based paradigm as illustrated in the next section.

As in Python 3, Lua requires that the *receiver* object be passed as an argument to object-based function and procedure calls. By convention, it is passed as the first argument, as shown below.

```
obj.method(obj, other_arguments)
```

Lua has a bit of *syntactic sugar*—the : operator—to make this more convenient. The following Lua expression is equivalent to the above.

```
obj:method(other_arguments)
```

The Lua interpreter evaluates the expression `obj` to get the receiver object (i.e., table), then retrieves the function closure associated with the key named `method` from the receiver object, then calls the function, passing the receiver object as its first parameter. In the body of the function definition, the receiver object can be referenced by parameter name `self`.

We can use a similar notation to define functions to be methods associated with objects (tables).

### 3.5.3 Prototype-based Lua example

The Lua code below, from file CountingPB.lua, implements a Lua module similar to the Python 3 *CountingOO* class given in Section 3.4.1. It illustrates how to define Lua modules as well as prototypes.

```lua
-- File CountingPB.lua
local CountingPB = {count = 1, maxc = 0} -- (1)

function CountingPB:new(mixin) -- (2)
    mixin = mixin or {}
    local obj = { __index = self } -- (4)
    for k, v in pairs(mixin) do -- (5)
        if k ~= "__index" then
            obj[k] = v
        end
    end
    return setmetatable(obj, obj) -- (6,7)
end
```

19
function CountingPB:has_more(c,m)    -- (2)
    return c <= m
end

function CountingPB:adv()    -- (2)
    self.count = self.count + 1
end

function CountingPB:counter()    -- (2)
    while self:has_more(self.count,self.maxc) do
        print(self.count)
        self:adv()
    end
end

return CountingPB    -- (3)

The following notes explain the numbered steps in the above code.

1. Create module object CountingPB as a Lua table with default values for data attributes count and maxc. This object is also the top-level prototype object.

2. Define methods (i.e., functions) new(), has_more(), adv(), and counter() and add them to the CountingPB table. The key is the function’s name and the value is the function’s closure.

   Method new() is the constructor for clones.

3. Return CountingPB when the module file CountingPB.lua is imported with a require call in another Lua module or script file.

   Method new is what constructs the clones. This method:

4. Creates the clone initially as a table with only the __index set to the object that called new (i.e., the receiver object self).

5. Copies the method new’s parameter mixin’s table entries into the clone. This enables existing data and method attributes of the receiver object self to be redefined and new data and method attributes to be added to the clone.

   If parameter mixin is undefined or an empty table, then no changes are made to the clone.

6. Sets the clone’s metatable to be the clone’s table itself. In step 4, we had set its metamethod __index to be the receiver object self.

7. Returns the clone object (a table) as is the convention for Lua modules.

If a Lua program accesses an undefined key of a table (or object), then the interpreter checks to see whether the table has a metatable defined.
• If no metatable is set, then the result of the access is a `nil` (meaning undefined).

• If a metatable is set, then the interpreter uses the `__index` metamethod to determine what to do. If `__index` is a table, then the access is delegated to that table. If `__index` is set a function closure, then the interpreter calls that function. If there is no `__index`, then it returns a `nil`.

We can load the `CountingPB.lua` module as follows:

```lua
local CountingPB = require "CountingPB"
```

Now consider the Lua assignment below:

```lua
x = CountingPB:new({count = 0, maxc = 10})
```

This creates a clone of object `CountingPB` and stores it in variable `x`. This clone has its own data attributes `count` and `maxc`, but it delegates method calls back to object `CountingPB`.

If we execute the call `x:counter()`, we get the following output:

```
0
1
2
3
4
5
6
7
8
9
10
```

Now consider the Lua assignment:

```lua
y = x:new({count = 10, maxc = 15})
```

This creates a clone of object in `x` and stores the clone in variable `y`. The `y` object has different values for `count` and `maxc`, but it delegates the method calls to `x`, which, in turn, delegates them on to `CountingPB`.

If we execute the call `y:counter()`, we get the following output:

```
10
11
12
13
14
15
```

Now, consider the following Lua assignment:
This creates a clone of object \( y \) that keeps \( x \)'s current value of \texttt{count} \( (\text{which is 16 after executing } y:counter()) \), sets a new value of \texttt{maxc}, overrides the definitions of methods \texttt{has\_more()} \ and \texttt{adv()}, \ and defines new method \texttt{bye()} \ and new data attribute \texttt{msg}.

If we execute the call \( z:counter() \) followed by \( z:bye() \), we get the following output:

\[
\begin{align*}
16 \\
32 \\
64 \\
128 \\
256 \\
\text{Good-Bye!}
\end{align*}
\]

The Lua source code for this example is in file \texttt{CountingPB.lua}. The example calls are in file \texttt{CountingPB\_Test.lua}.

### 3.5.4 Observations

How does the prototype-based (PB) paradigm compare with the object-oriented (OO) paradigm?

- The OO paradigm as implemented in a language usually enforces a particular discipline or policy and provides syntactic and semantic support for that policy. However, it makes programming outside the policy difficult.

- The PB paradigm is more flexible. It provides lower-level mechanisms and little or no direct support for a particular discipline or policy. It allows programmers to define their own policies, simple or complex policies depending on the needs. These policies can be implemented in libraries and reused. However, PB can result in different programmers or different software development shops using incompatible approaches.

Whatever paradigm we use (OO, PB, procedural, functional, etc.), we should be careful and be consistent in how we design and implement programs.

### 3.6 What Next?

In Chapters 2 and 3 (this chapter), we explored various programming paradigms.
In Chapter 4, we begin examining Haskell, looking at our first simple programs and how to execute those programs with the interactive interpreter.

In subsequent chapters, we look more closely at the concepts of type introduced in this chapter and abstraction introduced in the previous chapter.

### 3.7 Exercises

1. This chapter used Python 3 to illustrate the object-oriented paradigm. Choose a language such as Java, C++, or C#. Describe how it can be used to write programs in the object-oriented paradigm. Show the `CountingOO` example in the chosen language.

2. C is a primarily procedural language. Describe how C can be used to implement object-based programs. Show the `CountingOO` example in the chosen language.

### 3.8 Acknowledgements

Beginning in Summer 2016 and continuing through Fall 2018, I adapted and revised much of this chapter from my previous course materials:

- I adapted the Object-Oriented programming paradigm section from my notes *Introduction to Object Orientation* [14], which I wrote originally for the first C++ (CSci 490) and Java-based (CSci 211) classes at UM in 1996 but expanded and adapted for other courses. These notes—and my approach to object-oriented design and programming in general—were influenced by my study of works by Horstmann [18,19], Budd [6,7], Meyer [25], Thomas [35], Wirfs-Brock [38,39], Beck [4], Bellin [5], the “Gang of Four” [17], Buschmann [8], Fishwick [16], Johnson [21], Schmid [31]; Schmid1999a, and many other sources (lost in the mists of time).

  Note: In particular, chapters 3-6 of Horstmann’s C++ book [18]—on “Implementing Classes”, “Interfaces”, “Object-Oriented Design”, and “Invariants”—considerably influenced my views on object-oriented design and programming as I was learning the approach. Similarly, the first edition of Horstmann and Cornell’s *Core Java* [19] influenced my approach to OOP in Java.

- I expanded the Prototype-based programming paradigm section from my 2016 draft notes [12] and Lua example [13] on that topic. These notes and example were influenced by Craig [10], Jerusalimschy [20], Ungar [36], and other sources (e.g., the Lua website [22] and the Wikipedia article “Prototype-based Programming” [37]) and by my experiences developing and my teaching Lua-based courses.

  Note: I chose Lua instead of Javascript because the former is simpler and “cleaner” and could easily execute from the command line. I also had considerably more Lua programming experience. I had used it in my
Software Language Engineering (CSci 658) course in the Fall 2013 and the Fall 2014 and Fall 2016 offerings of Organization of Programming Languages (CSci 450). (Initially, I planned to use Lua as the programming language for the interpreters in this textbook. However, my experiences with CSci 450 in Fall 2016 suggested that I needed more mature teaching materials for the Fall 2017 class. I decided to instead expand my relatively mature Notes on Functional Programming with Haskell [11] and redesign the interpreters to use Haskell.)

TODO: Perhaps add citation for 2013 CSCI 658 course materials? Also identify which Javascript book had influence on my thinking?

In 2017, I incorporated this material into Chapter 1, Fundamentals, of my 2017 Haskell-based programming languages textbook.

In 2018 I reorganized and expanded the previous Fundamentals chapter into four chapters for the 2018 version of the textbook, now titled Exploring Languages with Interpreters and Functional Programming (ELIFP). These are Chapter 1, Evolution of Programming Languages; Chapter 2, Programming Paradigms; Chapter 3, Object-Based Paradigms (this chapter); and Chapter 80, Review of Relevant Mathematics.

In 2018, I added the new Python 3 [28] examples in ELIFP Chapters 2 and 3. My approach to Python 3 programming are influenced by Beazley [2], Ramalho [29], and other sources and by my experiences developing and teaching two graduate courses that used Python 3 in 2018.

In 2018, I also revised the discussion of the Lua example and incorporated it into this chapter.

I used Chapter 2 in CSci 450 in Fall 2018 but not this chapter. However, I used both chapters in my Python-based Multiparadigm Programming (CSci 556) course in Fall 2018.

I retired from the full-time faculty in May 2019. As one of my post-retirement projects, I am continuing work on this textbook. In January 2022, I began refining the existing content, integrating additional separately developed materials, reformattting the document (e.g., using CSS), constructing a bibliography (e.g., using citeproc), and improving the build workflow and use of Pandoc.

I maintain this chapter as text in Pandoc’s dialect of Markdown using embedded LaTeX markup for the mathematical formulas and then translate the document to HTML, PDF, and other forms as needed.

### 3.9 Terms and Concepts

Object (state, operations, identity, encapsulation, independent lifecycle, mutable, immutable), object-based language, class, type, class-based language, inheritance, subtype, interface, polymorphism, subtype polymorphism (subtyping,
inclusion polymorphism, polymorphism by inheritance), dynamic binding, object-oriented language, prototype, clone, slot, delegation, prototype-based language, embeddability, Lua tables, metatables, and metamethods, function closure.

3.10 References


[33] Bruce Tate. 2010. *Seven languages in seven weeks: A pragmatic guide to learning programming languages*. Pragmatic Bookshelf, Raleigh, North Carolina, USA.

[34] Bruce Tate, Ian Dees, Frederic Daoud, and Jack Moffitt. 2014. *Seven more languages in seven weeks: Languages that are shaping the future*. Pragmatic Bookshelf, Raleigh, North Carolina, USA.


[38] Rebecca Wirfs-Brock and Alan McKean. 2003. *Object design: Roles, responsibilities, and collaborations*. Addison-Wesley, Boston, Massachusetts, USA.
