Object orientation is in many ways a natural style of programming whose techniques are reinvented constantly by every programmer (Copljen 1992). Object notation consolidates these techniques so that much of the tedious programming necessary to use them is automatically handled by the interpreter. An object can be thought of as an abstract data type that is very useful in separating the idea of *what a thing does* from the details of *the way it goes about doing it*. Support for objects in hoc came late to NEURON, after the notion of cable sections, and as a consequence there are several types of variables (e.g. sections, mechanisms, range variables) that are clearly treated as objects from a conceptual point of view but grew up without a uniform syntax.

In hoc, an object is a collection of functions, procedures, and data, where the data defines the state of the object. There is just enough extra syntax in hoc to support a subset of the object-oriented programming paradigm: specifically, it supports information hiding and polymorphism, but not inheritance. Yet this subset is sufficient to greatly increase the user's ability to maintain conceptual control of complex programs. This immediately provides all the power of data structures of languages such as C or Pascal, and most of the power of modules.

**Object vs. class**

First let's clarify the distinction between *object* and *class*. You're close to the mark if you think of a class as a cookie cutter that cuts out objects called cookies. A class is a general type, whereas an object of the class is a specific instance of the type. The idea of a class as a template motivated the keyword that signals the definition of classes in hoc: one surrounds a collection of functions, procedures, and variables with the keywords `begininstance` and `endinstance`.

From the user's point of view it is necessary to discuss how to create and destroy objects; what is an object reference; how to call an object's methods or access its data; and how to pass objects to functions. From the programmer's point of view it is necessary to discuss how to define a class. Before we plunge into these details, a general overview of objects in hoc will be useful.

**The object model in hoc**

The object model used by hoc manipulates references to objects, never the objects themselves. An object reference is equivalent to a pointer, and can be regarded as a label or alias for the actual object. Thus the assignment
\( \text{ob1} = \text{ob2} \)

means that \( \text{ob1} \) refers to the same object referred to by \( \text{ob2} \), NOT that a new object is cloned from \( \text{ob2} \) and pointed to by \( \text{ob1} \). Thus if \( \text{ob2}' \)s object contains a variable called \( \text{data} \) and that value is changed by the statement

\( \text{ob2}.\text{data} = 5 \)

then

\( \text{ob1}.\text{data} \)

will print the value

5

It quickly becomes tedious to always talk about "the object referred to by \( \text{xxx} \)" so we often shorten the phrase to "\( \text{xxx} \)", always recalling that \( \text{xxx} \) is only a label for that object--in fact, \( \text{xxx} \) is only one of possibly many labels for the object that it points to. In the next few paragraphs we'll strictly maintain the distinction between object reference and object, but be aware that we don't always exert such discipline.

### Objects and object references

#### Declaring an object reference

Just as it is often convenient to deal with variables that can take on different numeric values (algebra is more powerful than arithmetic), it is often convenient to deal with object references that can refer to different objects at different times. Object references are declared with

\[
\text{objref name1, name2, name3, ...}
\]

After an object reference has been declared, it refers to the \text{NULLobject} until it is associated with some other object (see below).

Once a variable has been declared to be an object reference, it cannot be redefined as a scalar, double, or string. The \text{objref} keyword can appear within a compound statement, but the names must originally have been declared outside any \text{func} or \text{proc} before they can be redeclared (as \text{objrefs}) in a procedure.

#### Creating and destroying an object

You create an object with the \text{new} keyword. Thus

\[
\text{objref g}
\]

\[
g = \text{new Graph()}
\]
uses the Graph template to create one Graph object that we can refer to as g. We'll talk about where the templates come from later. Executing these two statements will create one graph window on the screen.

Several object references can refer to the same object. Continuing with the present example,

```c
objref h
h = g
```

does not create a second graph but merely associates h with the same Graph object as g. The "reference count" of an object is the number of object references that point to it. We would say that this Graph object has a reference count of 2.

If an object is no longer referenced, i.e. when its reference count is 0, it is destroyed and the memory that held its data becomes available for any other purpose. In this example, we can break the association between g and the Graph object by redeclaring g

```c
objref g
```

so that g once again points to the NULLobject. However, the graph will persist on our screen because it is still referenced by h. To get rid of the graph we have to break this final reference, e.g. with the statement

```c
h = g
```

**Using an object reference**

The object reference g should be thought of as pointing to an actual object located in the computer. This object has "members" which consist of variables that describe its state, plus "methods" (functions and procedures) that do things to itself and to the outside world. Some of these members are hidden from the outside world (i.e. "private"), but others are visible ("public") and can be accessed from outside the object. The syntax for using the public members of an object employs a "dot" notation that is reminiscent of how one accesses an element of a structure in C. For example, the Graph class has a method called erase() that erases graph lines, so if g is an objref that points to a Graph object, the statement

```c
    g.erase()
```

will erase the lines in the Graph.

**Passing objrefs (and objects) to functions**

As mentioned in Chapter 12 (see Arguments under Functions and procedures), objref arguments are passed using call by reference. This has two consequences: the called func or proc can change which object the objref argument points to, and also that it can change the object itself. As a rather artificial example of the first consequence, let us define a proc that swaps the objects that two objrefs point to.

```c
objref otmp   // so it can be used as an objref in a proc
```
proc oswap() {
  otmp = $01
  $01 = $02
  $02 = otmp  // destroy link between otmp and $02
}

Suppose a and b are objrefs that point to a Graph and a Vector, respectively, so that
print "a is ", a, ", b is ", b
returns
    a is Graph[0] , b is Vector[3]
If we call
  oswap(a, b)
and then repeat
        print "a is ", a, ", b is ", b
we now see
    a is Vector[3] , b is Graph[0]
In other words, oswap() made these objrefs point to different objects.

For an even more artificial example of the second consequence, consider
proc foo() {   // expects a Vector argument with size >= 2
  $01.x[1] = PI
}

Suppose we declare
    objref data
data = new Vector(3)
data.indgen()
which makes data point to a Vector with three elements whose values are 0,1, and 2,
so that data.printf() returns
        0 1 2
Calling foo(data) and then trying data.printf() once more gives us
        0 3.14159 2
i.e. foo() changed the object itself. In passing we note that call by reference also applies
to the rare situations in which it might be useful to pass an actual object name (as distinct
from an objref--see Object references vs. object names below) to a proc or func.

Defining an object class

A new object class can be defined by writing hoc code that specifies the properties of
the class. This code is called a template, and once the hoc interpreter has parsed the code
in a template, the class that it defines is fixed for that session. This means that any
changes to a template require exiting NEURON and restarting.
The syntax for writing a template is

\begin{verbatim}
begin template classname
  public name1, name2, name3, ...
  external variable1, string2, function3, template4, ...
  ... hoc code ...
end template classname
\end{verbatim}

where \texttt{classname} is the name of the class that the template defines. The \texttt{hoc} code can be almost anything you like, but generally it consists of declarations of variables and definitions of procedures and functions. As noted above, a function or procedure that is defined in a class is also called a \textit{method}.

By default, every variable, \texttt{proc}, and \texttt{func} that belongs to an object will be hidden from the outside. To make something visible from the outside, you must declare that it is \texttt{public}. Inside the template you cannot refer to any \textit{user-defined} global variables or functions except those that appear in an \texttt{external} statement. However, you can execute built-in functions such as \texttt{printf()} and \texttt{exp()}, and you can also create objects from any externally-defined template.

**Direct commands**

Direct commands within a template, e.g.

\begin{verbatim}
begin template Foo
  public a
  a = 5 // this is a direct command
end template Foo
\end{verbatim}

are executed once when the template is interpreted. This means that declarations such as \texttt{double}, \texttt{strdef}, \texttt{func}, \texttt{xopen(file)}, etc., that need to be executed only once \textit{and not for each object} are useful as direct commands. However, direct commands such as \texttt{a = 5} are less useful, since the value of \texttt{a} is lost when an actual object is created, because the assignment statement is not executed at that time. Thus if we create a new object of class \texttt{Foo} named \texttt{footest}

\begin{verbatim}
oc>objref footest
ocz>footest = new Foo()
oc>footest.a 0
ocz>
\end{verbatim}

we see that the value of \texttt{footest.a} is 0, not 5.

**Initializing variables in an object**

All variables that are declared in a template start off with a value of 0 by default. To initialize variables to something other than 0, the template must contain an \texttt{init()} procedure. This procedure will be executed automatically every time a new object is created. If \texttt{init()} appears in the \texttt{public} list, you can execute it explicitly as well. For example, if we define a new class \texttt{Foo2} as
begintemplate Foo2
   public init, a
   proc init() {
      a = 5
   }
endtemplate Foo2

and then create a new object of this class

oc>objref foo2test
oc>foo2test = new Foo2()

now we find that foo2test.a has the nonzero value that we wanted

oc>foo2test.a
   5
oc>

Furthermore, if we assign a different value to foo2test.a

oc>foo2test.a = 6
oc>foo2test.a
   6
oc>

we can restore the original value by invoking foo2test.init()

oc>foo2test.init()
   0
oc>foo2test.a
   5
oc>

Keyword names

One restriction on templates is that hoc keywords cannot be redefined. This is an
artifact of the order in which symbol tables are searched. For an example of how this
affects programming, suppose we wanted to add a method to our Stack class that would
print the name of every object in the stack. It might seem reasonable do this by inserting

proc print() { local cnt, i
   cnt = list.count()
   if (cnt == 0) {
      print "stack is empty"
   } else {
      for i=0,cnt-1 print list.object(i)
   }
}

into the body of the template and adding print to the public statement. This would
allow us to call our new method with the highly mnemonic statement stack.print().
But when the interpreter tried to translate this to intermediate code, it would issue the
error message

nrvn: parse error in stack3.hoc near line 2
   public push, pop, print
^

and we would have to change the name of the method to something else, e.g.
printnames.
Object references vs. object names

Up to this point we have been using object references to refer to objects, emphasizing the difference between an object itself and what we call it. Actually, each object does have a unique name that can be used anywhere a reference to the object is used. However, these unique names are primarily intended for use by the library routines that construct NEURON's graphical interface. While it may occasionally be useful to employ these unique names in user-written code (e.g. for diagnostic or didactic purposes), this should never be done in ordinary programming. Object names are not guaranteed to be the same between different sessions of NEURON unless the sequence of creation and destruction of objects of the same type is identical. This is because the object name is defined as classname[index], where the "index" is automatically incremented every time a new instance of that class is created. Index numbers are not reused after objects are deleted except when there are no existing objects of that type; then the index starts over again at 0.

The reason why unique object names are allowed at all is because some objects, such as the PointProcessManager, should be destroyed when their window is dismissed. This could not happen if the interpreter had an objref to that object, since an object is destroyed only when its reference count goes to 0. Thus the idiom is to cause the VBox window itself to increment the reference count for the object (and decrement it when the window is dismissed, using the VBox's ref() or dismiss_action() method). Now the hoc objref that holds the reference can safely discard it, and the object will not be immediately destroyed. But the consequence is that there is now no way to get to the object (or the objects it created) from the interpreter except to use the object name, e.g. there is no other way to graph one of the point process variables in the PointProcessManager.

An example of the didactic use of object names

The name of an object can be used in any context in which a string is expected, e.g. a print objref statement. For example, if we execute the statements

``` hoc
objref g, h
g = new Graph()
h = g
```
then we see a graph on the computer screen, and

``` hoc
print g, h
```
returns

```
Graph[0] Graph[0]
```
because both g and h refer to the same Graph object. At this point if we type the command print Graph[0] we also get Graph[0].

After redeclaring g

``` hoc
objref g
```
we find that print g, h gives us
NULLObject Graph[0]

Since one object reference (h) still points to Graph[0], the graph is still visible, and print Graph[0] still produces Graph[0].

Now asserting

\[ h = g \]

discards the last reference to Graph[0], destroying this object. Consequently the graph disappears from the screen, and print g, h produces

\[ \text{NULLobject NULLobject} \]

Any lingering doubts concerning the fate of Graph[0] are dispelled when we find that print Graph[0] generates the message

\[ \text{nrvniv: Object ID doesn't exist: Graph[0]} \]

near line 11

print Graph[0] ^

Using objects to solve programming problems

Dealing with collections or sets

Most, if not all, nontrivial programming problems seem to involve the notion of a set or collection of objects. \texttt{hoc} can represent the concept of "more than one" in several ways, but the workhorses are the array of objects and the list of objects. The array is the most efficient but requires a prior knowledge of the number of objects to be stored. The list can store any number of objects at any time; this fact makes \texttt{List} the most often used class.

Array of objects

Storage for an array of objects is declared with

\[ \text{objref array[size]} \]

Only rarely is the size known when the program is written, so it is common practice to separate the declaration from the size definition, specifying the latter just after the point in execution when the size is finally known, as in

\[ \text{objref array[1]} \]

\[ \text{// size must be declared even if wrong} \]

\[ \text{proc set_size() \{} \]

\[ \text{objref array[$1]} \]

\[ \text{\} } \]

After the size is set, it can no longer be changed without redeclaring the entire array, which discards the references to any objects referenced by its previous incarnation. When an array is declared or redeclared, all of its elements reference the \texttt{NULLObject}. 
An array is a random access object because its individual elements can easily be retrieved in any sequence, just specifying the corresponding index. For example an array of five graphs can be created with

```haskell
    objref graphs[5]
    for i=0, 4 { graphs[i] = new Graph() }
```

The internal name of each item in the array can be printed in reverse order with

```haskell
    for (i=4; i >= 0; i -= 1) { print graphs[i] }
```

Suppose we wanted to destroy the third (index = 2) graph. We can't simply say

```haskell
    objref graphs[2]
```

because this would discard the entire array, throwing away all of our graphs and creating a new array whose elements all point to the NULLobject. Instead, the way to make the reference count for the third graph become 0 is

```haskell
    objref nil     // nil points to NULLobject
```

**Example: emulating an "array of strings"**

Even very simple templates have their uses. There is no such thing in hoc as an array of strings, but consider

```haskell
    begin template String
        public s
        strdef s
    endtemplate String
```

Now an array of objects can be used to get the functionality of an array of strings.

```haskell
    objref s[3]
    for i=0,2 s[i] = new String()    // they all start out empty
    s[0].s = "hello"
    s[2].s = "goodbye"
```

It is important to realize that there is no conflict between the use of s as the name of a strdef inside the template and the use of s as the name of an object reference outside the template.

We must mention that NEURON comes with a very similar implementation of the String class (see stdlib.hoc in nrn-x.x/share/lib/hoc/ (UNIX/Linux) or c:\nrnxx\lib\hoc\ (MSWindows)). This is automatically available after nrngui.hoc has been loaded.

**List of objects**

A list of objects uses the List class

```haskell
    objref list
    list = new List()
```

Objects are added to the list with the append() method, as in

```haskell
    for i=0, 4 { list.append(new Graph()) }
```
Notice that we do not have to know how many items will be added to the list before we start adding them. One can print the names of the objects in a list with the statement,

```plaintext
for i=0, list.count - 1 { print list.object(i) }
```

The List class’s `count()` method always returns the number of objects in the list, and the `object()` method returns the item.

Iteration over a list is one of the most commonly used programming idioms. This allows processing of each item in the list, as in

```plaintext
objref tobj
for i=0, list.count - 1 {
    tobj = list.object(i)
    // do something to the object referenced by tobj
}
```

Notice how a temporary `objref` is employed to refer to each object in turn.

**Example: a stack of objects**

This template defines a class that can be used to create stacks of objects.

```plaintext
begin template Stack
  public push, pop
  objref list

  proc init() {
    list = new List()
  }

  proc push() {
    list.append($o1)
  }

  proc pop() { local cnt
    cnt = list.count()
    if (cnt == 0) {
      print "stack underflow"
      stop
    }
    $o1 = list.object(cnt-1)
    list.remove(cnt-1)
  }
end template Stack
```

After `hoc` parses this template, the statements

```plaintext
objref stack
stack = new Stack()
```

create an object that functions as a stack. At the time this new object is created, its `init()` procedure is executed, which creates an empty list for use by the `push()` and `pop()` procedures. Notice that `push()` and `pop()` are public, but the internal list is private.

Suppose we already have three `Graph` objects `g[0]`, `g[1]`, and `g[2]` (see **Creating an object** under **Objects and object references** above). Then `stack.push(g[1])`
adds a reference to the second Graph at the end of the Stack object's internal list.  

\texttt{stack.pop(g[2])} would cause \texttt{g[2]} to reference the same object as \texttt{g[1]} and remove it from the stack.

In this example, we have exploited an existing object class (List) to create a new object class (Stack) that can be used to hold a stack of objects of any class we like--not just objects of any of NEURON's built-in classes, but also objects of any other classes that we might dream up in the future! Note the use of the List class's \texttt{count()} and \texttt{remove()} methods to find the object at the end of the list and to remove this reference from the list.

**Encapsulating code**

Suppose you have a hoc file that works perfectly all by itself (when nothing else is loaded) and does something meaningful when you type \texttt{run()} at the \texttt{oc>} prompt. Also suppose the file has no direct commands except declarations (if it does have direct commands, just collect them into an \texttt{init()} procedure). Then, if you put the these lines at the beginning of the file

\begin{verbatim}
begin-template F1
public run
\end-template F1
\end{verbatim}

and this line at the end of the file

\begin{verbatim}
end-template F1
\end{verbatim}

you have an object template. You can use this template to create an object and run it, like this

\begin{verbatim}
objref f1
f1 = new(F1)
f1.run()
\end{verbatim}

and you will get identical behavior as before. What's been gained? Well, you can do this to a bunch of files and load them all together and never worry about variable or function name clashes between files because nothing (except the object templates and specific object names) is global.

Don't forget that the default initialization of variables declared in a template is 0. It is a good idea to include an \texttt{init()} procedure that uses explicit assignment statements to make sure that variables will start off with the proper values. It is possible to declare a variable with an assignment statement in procedure \texttt{P1}, and then use it in a \texttt{public} procedure \texttt{P2}, but be mindful of the possibility that someone may execute \texttt{P2} before executing \texttt{P1}. If this happens, the variable will have a value of 0.

**Polymorphism and inheritance**

A language supports polymorphism when it automatically does the right thing whether a function is called on the base class or on an object of a subclass. Since an object reference can refer to any type of object, hoc's object model is polymorphic. Thus, if \texttt{A} and \texttt{B} are different classes but happen to have a method with the same name, e.g.
foo(), then if oref refers to an instance of either A or B, we can say oref.foo() and the method of the particular object type will be called.

For a concrete example, suppose we have defined several different classes of objects that generate specialized graphs called BodePlot, PowerSpect, and CrossCorr, and that each of these classes has its own plot() and erase() method. We can easily automate plotting and erasing if we declare

    proc plotall() { local i
        for i = 0, glist.count()-1 glist.object(i).plot()
    }

    proc eraseall() { local i
        for i = 0, glist.count()-1 glist.object(i).erase()
    }

and, every time we spawn a new instance of one of these classes, we append it to a List object, e.g.

    objref mygraflist
    glist = new List()
    ...

    objref bp, ps, cc
    bp = new BodePlot()
    glist.append(bp)
    ps = new PowerSpect()
    glist.append(ps)
    cc = new CrossCorr()
    glist.append(cc)

Now we can take care of all of these graphs at once by invoking plotall() or eraseall().

Inheritance allows us to define many kinds of subclasses starting from a more abstract base class. It is useful in capturing the "IS A" relationship, and is most effective when the subtype "IS A" kind of base type, i.e. whenever a program uses an object of the base type then it would also make sense if it used an object of the subtype. People often (ab)use inheritance when the IS A relationship does not hold, in order to conveniently reuse a portion of the base class. When one class is "ALMOST LIKE" another, and that other is ready and waiting to be used, it is tempting to inherit the whole behavior and replace only the parts that are different. It's best to avoid this practice and instead factor out the behavior common to both classes, placing that in a base class which can be inherited by both classes.

In **h**ocl, inheritance can only be emulated by having the "subclass" instance create its "superclass" instance during initialization and supply stub methods for calling the public methods of the superclass. For example, consider the trivial Base class
begintemplate Base
public a, b
objref this

proc a()
{
    printf("inside %s.a()\n", this)
}

proc b()
{
    printf("inside %s.b()\n", this)
}
endtemplate Base

Then the following will look like a subclass of Base, where we provide our own implementation of a and "inherit" the method b:

begintemplate Sub
public a, b
objref this, base

proc init()
{
    base = new Base()
}

proc a()
{
    printf("inside %s.a\n", this)
}

proc b()
{
    base.b()
}
endtemplate Sub

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