References and Memory

15-110 – Wednesday 09/30

Learning Goals

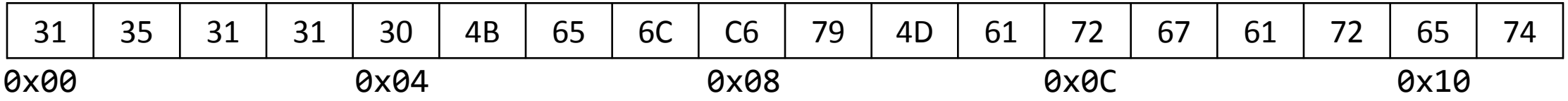
- Recognize whether two values have the same **reference** in **memory**
- Recognize the difference between **mutable** vs **immutable** data types
- Recognize the difference between **destructive** vs. **non-destructive** functions/operations
- Use **aliasing** to write functions that destructively change lists

References and Memory

Computer Memory Holds Data

Recall from the Data Representation lecture that all data on your computer is eventually represented as **bits** (0s and 1s). Your computer's memory is a very long sequence of bytes (8 bits), which are interpreted with different abstractions to become different types. Each byte has its own address.

When you write a Python program, every variable you create is associated with a different segment of memory. The way variables connect to memory becomes more complicated when we use data structures.

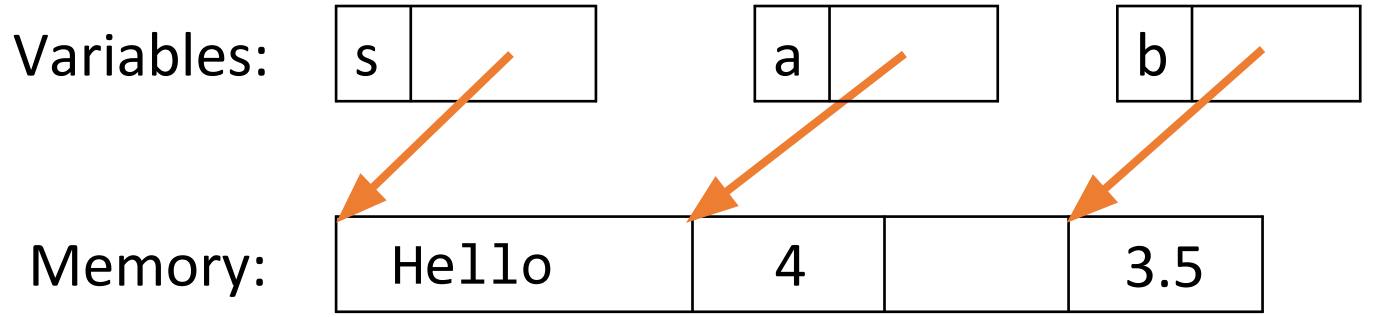


References are Memory Addresses

A **reference** (often called a pointer) is a specific address in memory. References are used to connect variables to their values.

When we set a variable equal to a value, we keep the variable and value **one step apart**. The variable only has access to a reference, which points to the value. If Python goes to the reference's address, it can retrieve the value stored there.

```
s = "Hello"
a = 4
b = 3.5
```



Check References with `id()` and `is`

If you want to check whether two variables share the same reference, you can use a built-in function or an operation. The function `id(var)` takes in a variable and returns the reference ID that Python associates with it.

```
a = "Hello"
b = a
c = "World"

print(id(a)) # some long integer
print(id(b)) # the same number
print(id(c)) # a different number
```

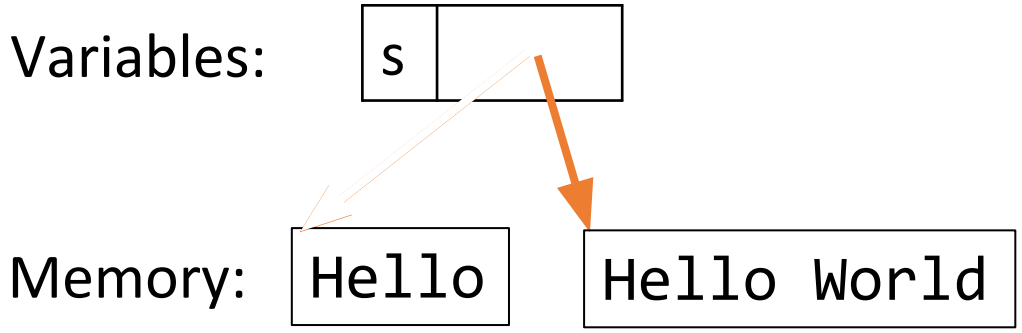
The `is` operation returns `True` if two variables have the same ID, and `False` otherwise.

```
print(a is b) # True
print(a is c) # False
```

Updating a Variable Changes the Reference

When we set a variable to a new value, Python makes a **new data value** and reassigns the variable to reference the new value. It does not change the old value at all.

```
s = "Hello"
s = s + " World"
```



Analogy: Lockers and Nametags

You can think of Python's memory as a series of lockers, each with its own number. The item inside a locker is the data value it holds.

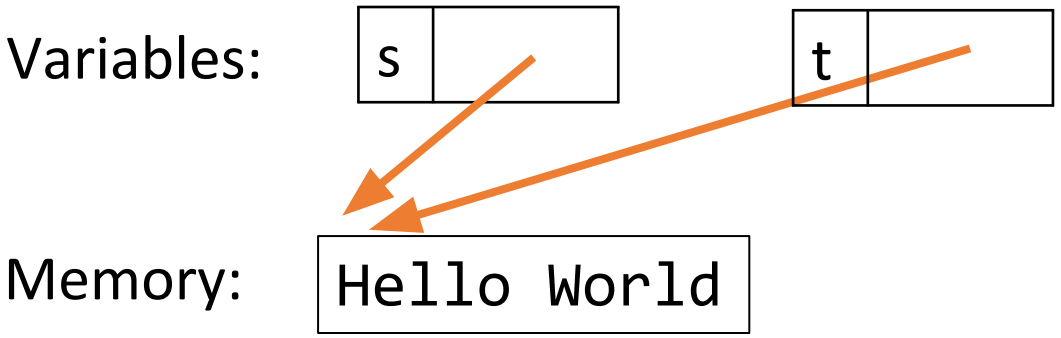
A variable is then a nametag sticker. When you stick a nametag onto a locker, it 'points to' the item in that locker. If you move the nametag onto a different locker, the original locker's contents don't change.

Copying a Variable Copies the Reference

What happens when we set a new variable equal to an old one? We don't need to create a new data value in a new memory address; Python just **copies the reference** instead.

This is like taking a new nametag and putting it on the same locker as another nametag.

```
s = "Hello World"
t = s
```

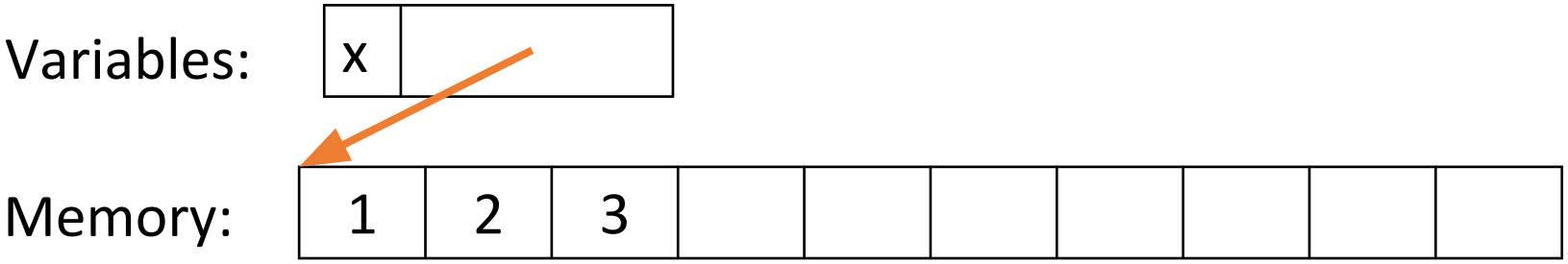


Lists Take Up Adjacent Addresses

When we set a variable to a **list** (or another data structure), Python sets aside a large place in memory for the data values it will hold.

By breaking up that large chunk of memory into parts, Python can assign each value in the list a location, ordered sequentially.

```
x = [1, 2, 3]
```



Analogy: A List is a Locker With Shelves

You can think of the list memory as still being a single locker (the starting reference), but broken up with several shelves.

Each shelf can hold its own item (data value), and has its own reference.

This allows us to change memory in new and interesting ways.

Mutable vs Immutable Values

List Values Can Be Changed

Unlike the previous types we've worked with, the values in a list can be **changed directly** without reassigning the variable. This is what the list methods we saw last time did.

We can also change a list by setting a list index to a new value, like how we would set a variable to a value.

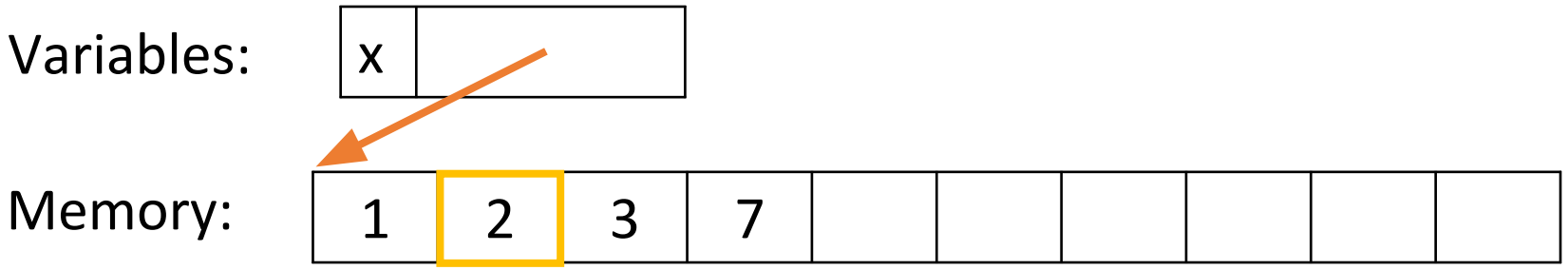
```
lst = [ "a", "b", "c" ]
lst[1] = "foo"
print(lst) # [ "a", "foo", "c" ]
```

Modifying Lists in Memory

How does this work? The large space set aside for the list values allows Python to add and remove values from the list without running out of room or needing to add a new set of data values. It's like having a large number of empty shelves in the locker, and putting the item on one of them.

This makes it easy (and fast!) to locate a specific value based on its index.

```
x = [1, 2, 3]
x.append(7)
print(x[1])
```



Lists are Mutable; Strings are Immutable

We call data types that can be modified without reassignment this way **mutable**. Data types that cannot be modified directly are called **immutable**.

All the other data types we've learned about so far – integers, floats, Booleans, and strings – are immutable. In fact, if we try to set a string index to a new character, we'll get an error. We have to set the entire variable equal to a new value if we want to change the string.

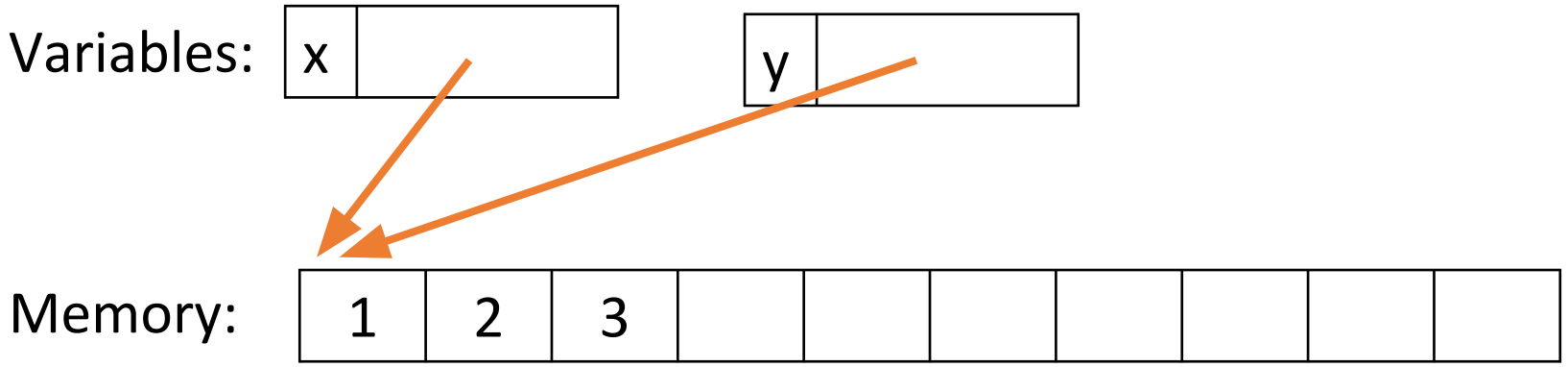
```
s = "abc"
s[1] = "z" # TypeError
s = s[:1] + "z" + s[2:]
```

Copying Lists in Memory

Before, we showed that when we copy a variable into a new variable, the **reference** is copied, not the value.

This is true for lists as well; an example is shown below.

```
x = [1, 2, 3]
y = x
```



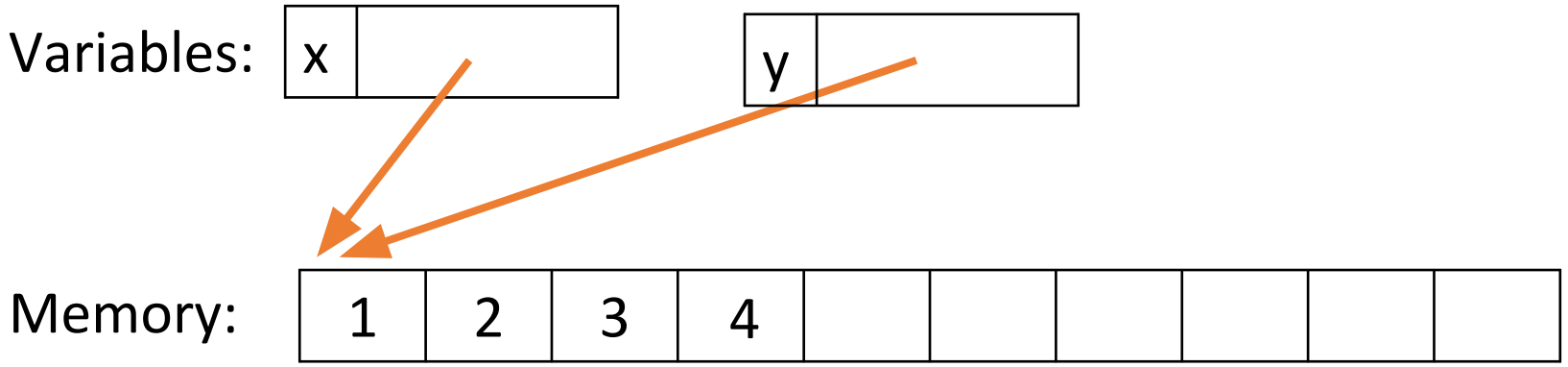
You do: what happens to the values in `x` and `y` if we add the line `y.append(4)` to the end of this code snippet?

Reference-Sharing Lists Share Changes

When a direct action is done on a list, that action affects the **data values,** not the variable. Any lists that share a reference with the original list will see the same changes!

We call lists that share a reference this way **aliased**.

```
x = [1, 2, 3]
y = x
y.append(4)
```

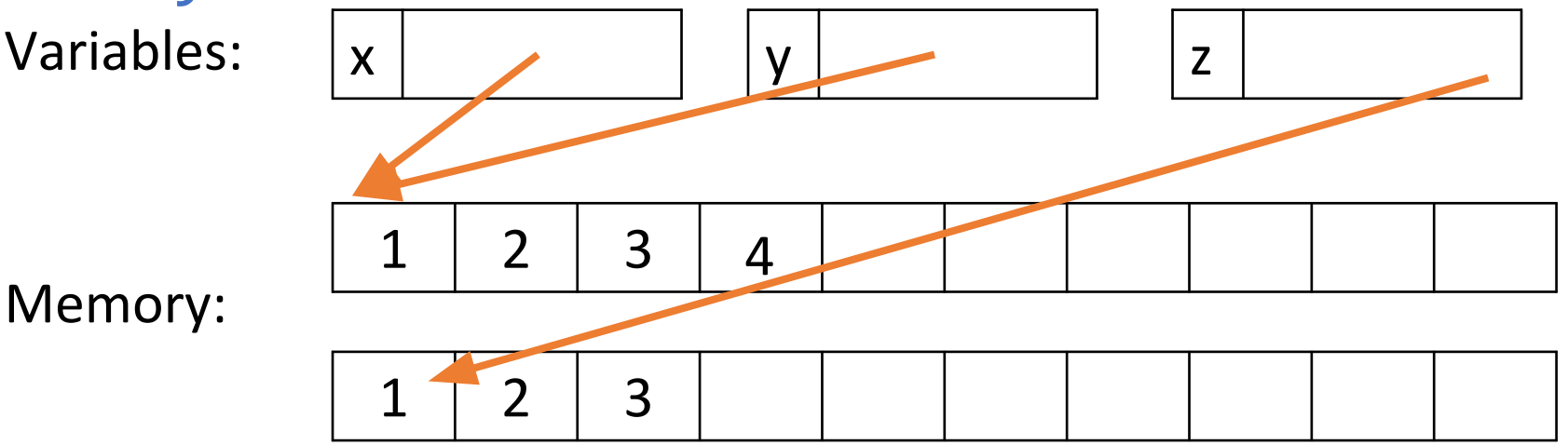


Copying Variables vs. Copying Values

Two variables won't be aliased just because they contain the same values. Their references need to point to the same place for them to be aliased.

In the following example, the lack of a **reference copy** keeps the list z from being aliased to x and y.

```
x = [1, 2, 3]
y = x
z = [1, 2, 3]
x.append(4)
```



Destructive vs. Non-destructive

Two Ways of Modifying Lists

Whenever we want to modify a list (by changing a value, adding a value, or removing a value), we can choose to do so **destructively** or **non-destructively**.

Destructive approaches change the data values without changing the variable reference. Any aliases of the variable will see the change as well, since they refer to the same list.

Non-destructive approaches make a new list, giving it a **new reference**. This 'breaks' the alias, and doesn't change the previously-aliased variables.

Destructive Methods are Efficient

Why would we ever want to use a destructive approach, instead of a simpler non-destructive approach?

Destructive approaches are **more efficient.** Instead of needing to copy all of the values into a new place in memory, you only change a small part of the existing memory. This saves both space in memory and time.

We'll discuss efficiency in more detail next week.

Two Ways to Add Values

How do we add a value to a list **destructively**? Use append, insert, or +=.

```
lst = [1, 2, 3]
lst.append(5)
lst.insert(1, "foo")
lst += [10, 20] # Annoyingly different from lst = lst + [10, 20]
```

How do we add a value to a list **non-destructively**? Use variable assignment with list concatenation.

```
lst = [1, 2, 3]
lst = lst + [5] # note that 5 needs to be in its own list
lst = [lst[0]] + ["foo"] + lst[1:]
lst = lst + [10, 20]
```

Two Ways to Remove Values

How do we remove a value from a list **destructively**? Use remove or pop.

```
lst = [1, 2, 3]
lst.remove(2)  # remove the value 2
lst.pop(1)     # remove the value at index 1
```

How do we remove a value from a list **non-destructively**? Use variable assignment with list slicing.

```
lst = [1, 2, 3]
lst = lst[:1] + lst[2:]
lst = lst[:1]
```

Break an Alias with Concatenation

If you have two variables that are aliased, and you don't want them to be aliased, you need to 'break' the alias between them. This is done by setting one of the variable equal to a new data value with the same values as the original list.

The easiest way to do this is to concatenate the empty list to the original list. Python doesn't recognize that the second list is empty, so it will create an entirely new list in memory.

```
a = [1, 2, 3]
b = a # a and b are aliased
a = a + [ ] # a now has a new reference, but the same values
```

Activity: Which Lists are Aliased?

At the end of this set of operations, which lists will be aliased? What values will each variable hold?

```
a = [ 1, 2, "x", "y" ]
b = a
c = [ 1, 2, "x", "y" ]
d = c
a.pop(2)
b = b + [ "woah" ]
c[0] = 42
d.insert(3, "yowza")
```

Writing Destructive Functions

Function Arguments are Aliased

When you call a function with a mutable value as one of the arguments, that argument is **aliased**. The same reference is used for the original argument and the parameter that the function uses.

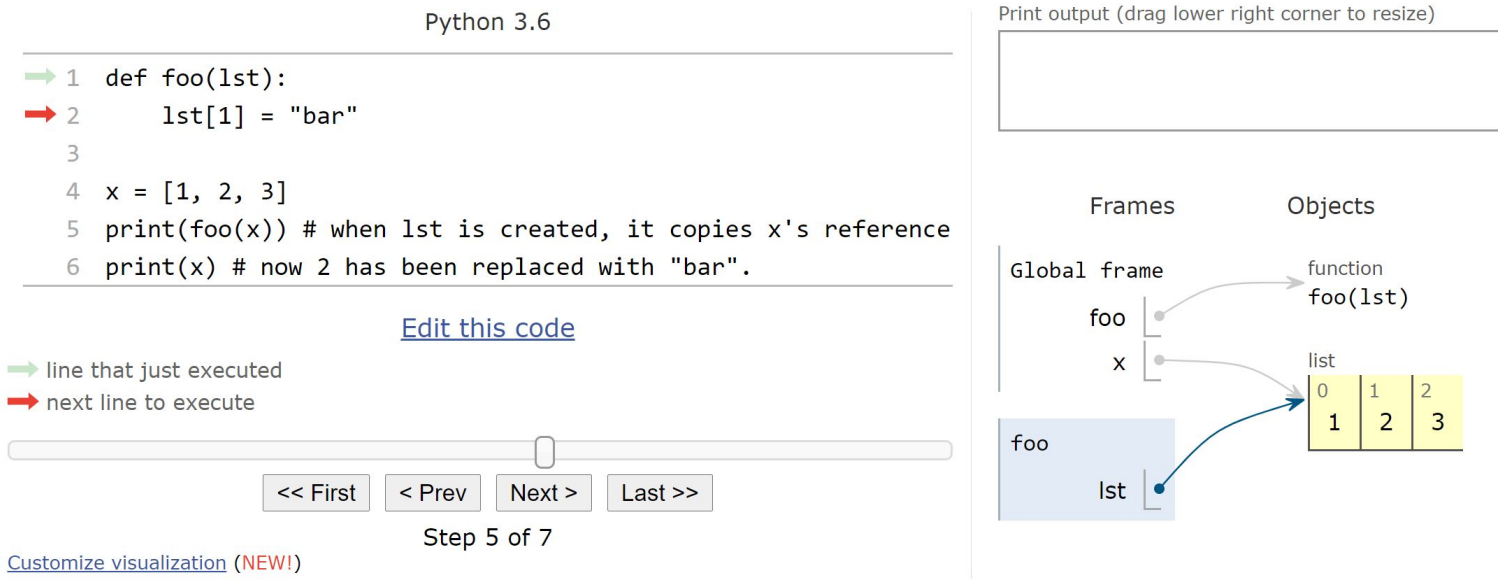
This means that we can write our own functions that behave **destructively**, changing the data values in the given list directly instead of making a new list. This is valuable when we work with large datasets, as we usually don't want to copy all of the values every time we make a change.

```
def foo(lst):
    lst[1] = "bar"

x = [1, 2, 3]
print(foo(x)) # when lst is created, it copies x's reference
print(x) # now 2 has been replaced with "bar".
```

Sidebar: PythonTutor Helps Trace Aliases

If you're having trouble tracing code that uses aliases, it may help to use PythonTutor (http://pythontutor.com/). This website lets you walk through your code's execution step-by-step, and also shows you which variables share references and which don't.



Destructive Functions Use Mutable Methods

When writing a destructive function, use index assignment and the mutable methods (append, insert, pop, and remove) on the input list to change it as needed.

For example, the following code **destructively** doubles all the values in the given list of integers. Note that the function need not return anything, because the parameter `lst` and the argument `x` **refer to the same list**.

```
def destructiveDouble(lst):
    for i in range(len(lst)):
        lst[i] = lst[i] * 2

x = [1, 2, 3]
destructiveDouble(x)
print(x)
```

Non-Destructive Functions Make New Lists

On the other hand, if you want to make a function that is not destructive, you should instead set up a new list and fill it with the appropriate values. To be non-destructive, the parameters must **not** be changed.

The following code **non-destructively** creates a new list of all the doubles of values in the original list. This function **does** need to return the result, as the parameter is not changed. After the call to the function, the variable `x` will not have changed; `y` refers to the new list with all the values doubled.

```
def nonDestructiveDouble(lst):
    result = [ ]
    for i in range(len(lst)):
        result.append(lst[i] * 2)
    return result

x = [1, 2, 3]
y = nonDestructiveDouble(x)
print(x, y)
```

Activity: makePositive(lst)

The following non-destructive function takes a list of integers and turns any negative values in the list into their positive counterparts. Change the function so that it is destructive instead.

```
def makePositive(lst):
    result = [ ]
    for i in range(len(lst)):
        if lst[i] < 0:
            result.append(lst[i] * -1)
        else:
            result.append(lst[i])
    return result
```

Learning Goals

- Recognize whether two values have the same **reference** in **memory**
- Recognize the difference between **mutable** vs **immutable** data types
- Recognize the difference between **destructive** vs. **non-destructive** functions/operations
- Use **aliasing** to write functions that destructively change lists
- **Feedback: https://bit.ly/110-feedback**