#4-2: References and Memory

CS SCHOLARS – PROGRAMMING

Learning Goals

Recognize whether two values have the same **reference** in **memory**

Recognize the difference between **destructive** vs. **non-destructive** functions/operations

Use **aliasing** to write functions that destructively change lists

Read and write code using **2D lists**

References and Memory

Computer Memory Holds Data

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 in different ways 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.

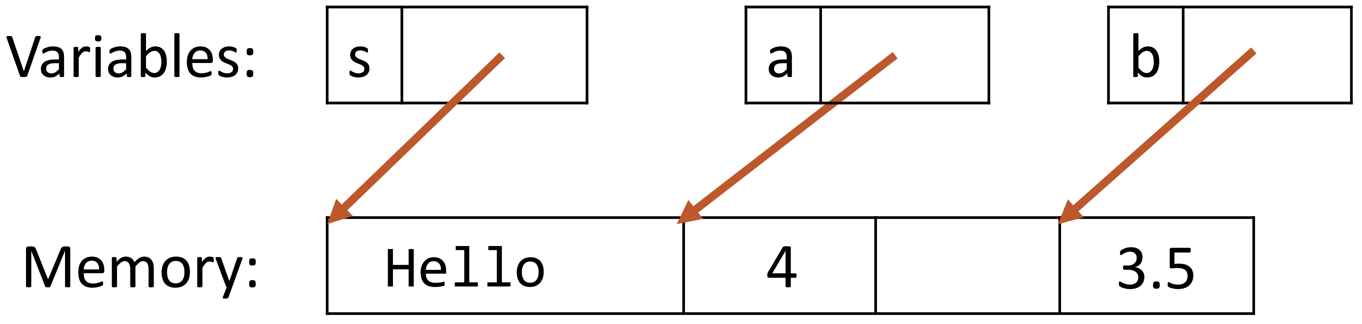
31	35	31	31	30	4B	65	6C	C6	79	4D	61	72	67	61	72	65	74
0000				0004				0008				0012				0016	

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.

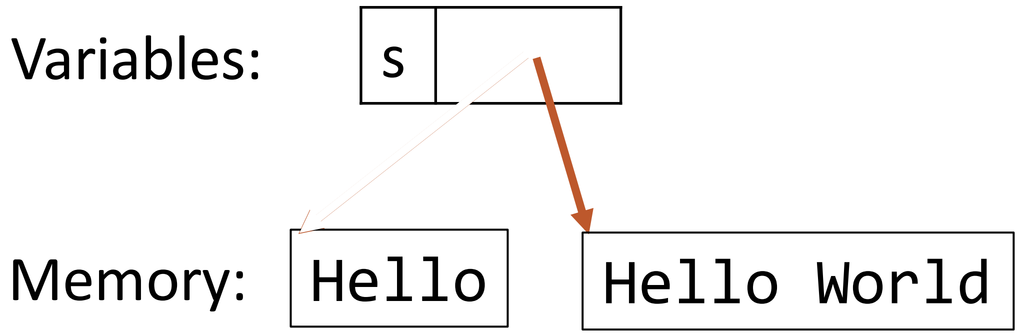
```
s = "Hello"
a = 4
b = 3.5
```



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 in memory 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.

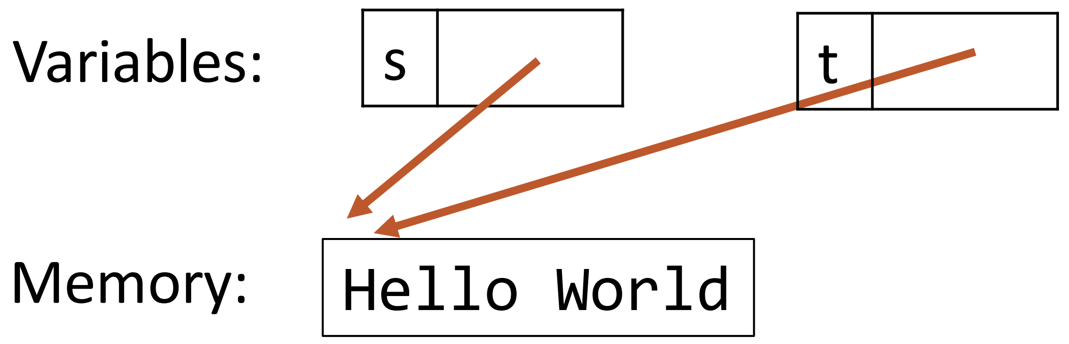
A variable is then a nametag sticker. When you stick a nametag onto a locker, it 'points to' the item in that locker. If you move the nametag onto a different locker, the original locker's contents don't change.

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
```



Check References with `is`

If you want to check whether two variables share the same reference, you can use the `is` operator. It returns `True` if two variables reference the same memory and `False` otherwise.

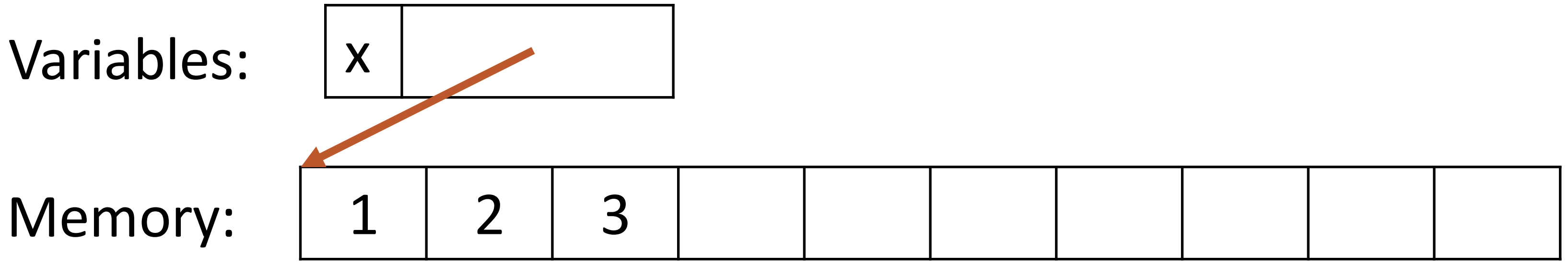
```
a = "Hello"
b = a
c = "World"

a is b # True
a is c # False
```

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]
```



Technically each index also holds a reference to a new location, but that's out of scope for this course

Analogy: A List is a Locker With Shelves

You can think of the list memory as a single locker (the starting reference) 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.

Activity: Same Reference?

You do: after the code is set up as shown here, for each of the following variable pairs, do they share the same reference or not?

```
a = 123
b = a
c = a
a = a * 2

a is b

a is c

b is c
```

List Modification

List Values Can Be Changed

Because of how lists are stored in memory, the values in a list can be **changed directly** without reassigning the variable.

We can 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"
lst # [ "a", "foo", "c" ]
```

Some List Methods Change the List

We can also modify a list directly, to add or remove elements from it, using some **list methods**. These methods change the list **without using variable assignment at all**.

```
lst = [ 1, 2, "a" ]
lst.append("b") # adds the element to the end of the list
lst # [ 1, 2, "a", "b" ]
```

Note that we do not set `lst = lst.append`; the list is changed **in place**. In fact, the `append` method returns `None`, not a list.

Example: getFactors(n)

Let's write a function that takes an integer and returns a list of all the factors of that integer.

```
def getFactors(n):
    factors = [ ]
    for num in range(1, n+1): # n is a possible factor
        if n % num == 0:
            factors.append(num)
    return factors
```

Additional List Methods

Here are a few other useful list methods that change the list in place:

```
lst = [ 1, 2, "a" ]
lst.insert(1, "foo") # inserts 2nd param into 1st param index
lst.remove("a") # removes the given element from the list once
lst.pop(0) # removes the element at given index from the list
```

Activity: `longWordsOnly(words)`

Write a function `longWordsOnly(words)` that takes a list of words (strings) and returns a new list that only contains words that were longer than 4 characters.

For example, `longWordsOnly(["What", "a", "fabulous", "day", "it", "is", "today"])` would return `["fabulous", "today"]`.

Try using the **append** method to set up the new list instead of using list concatenation!

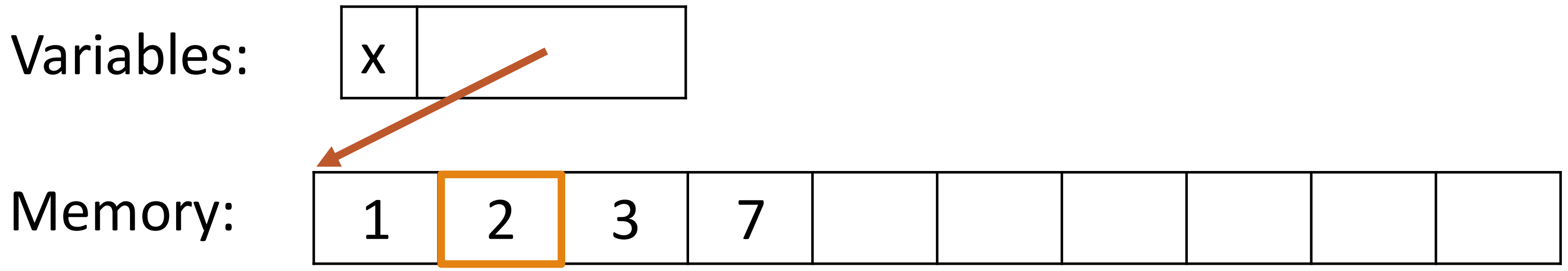
Mutable vs Immutable Values

Modifying Lists in Memory

How do these methods 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 in memory**. It's like having tons 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.

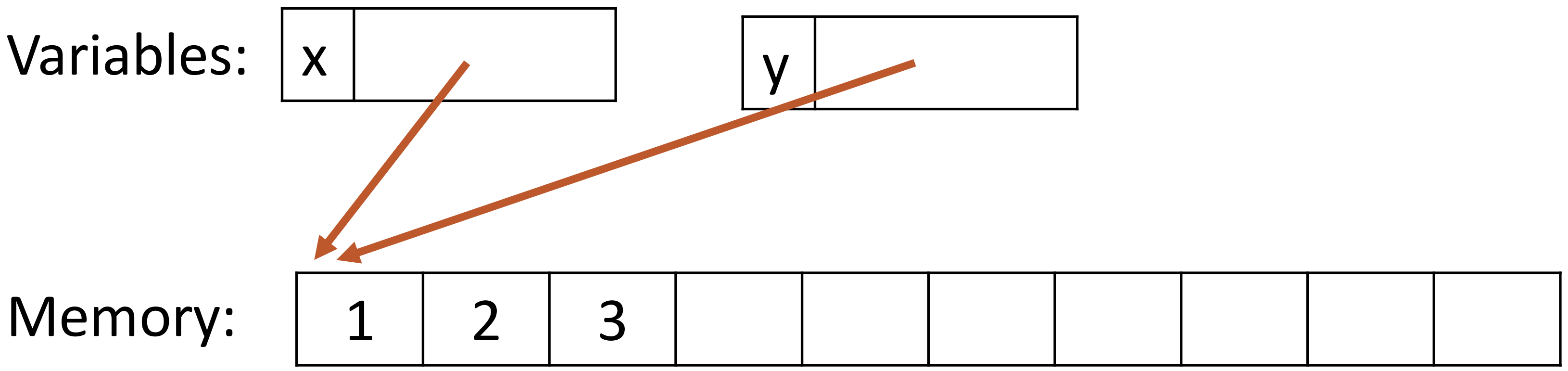
```
s = "abc"
s[1] = "z" # TypeError
s = s[:1] + "z" + s[2:]
```

Copying Lists in Memory

We showed before 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
```



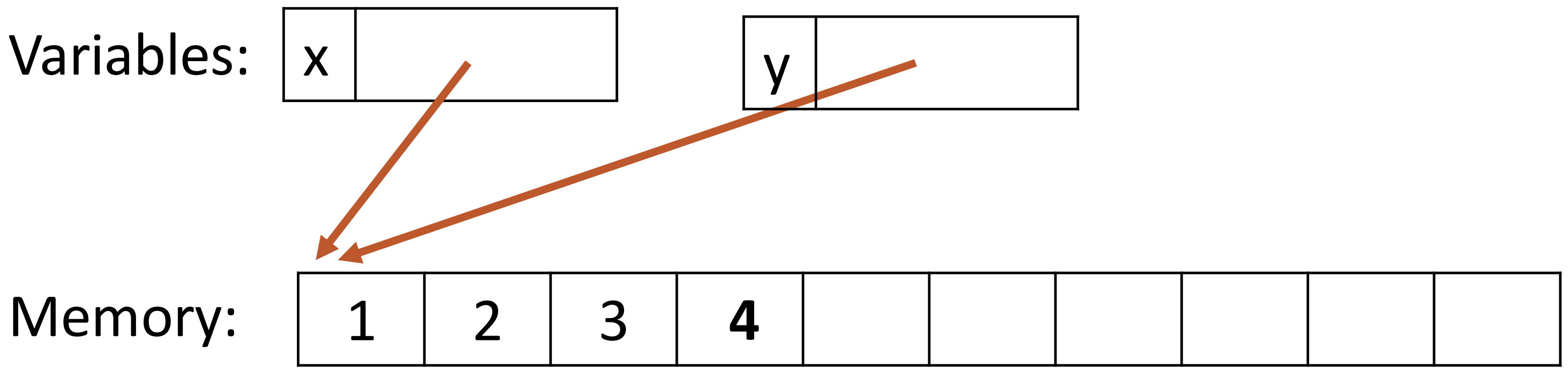
You do: what happens to the values in `x` and `y` if we add the line `y.append(4)` to the end of this code snippet?

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)
```

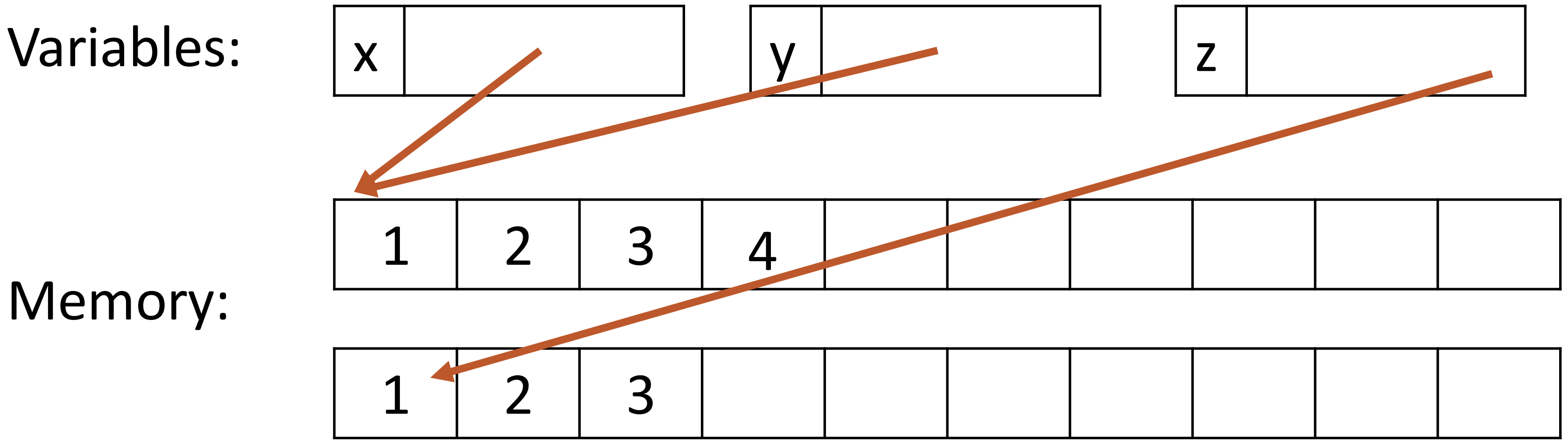


Copying Variables vs. Copying Values

Two list 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 the values into a new place in memory, you only change a small part of the existing memory. This saves time *and* space in memory.

Two Ways to Add Values

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

```
lst = ["A", "B", "C"]
lst.append("E")
lst.insert(0, "foo") # specifies where to add the value
lst += ["F", "G"] # Annoyingly different from lst = lst + ["F", "G"]
```

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

```
lst = ["A", "B", "C"]
lst = lst + ["E"] # note that "E" needs to be in its own list
lst = lst[:len(lst)//2] + ["F"] + lst[len(lst)//2:]
newLst = ["A", "B", "C"]
newLst.append("bar") # destructive, but to a different list
```

Two Ways to Remove Values

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

```
lst = ["A", "B", "C"]
lst.remove("A") # remove the value "A"
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 = ["A", "B", "C"]
lst = lst[1:]
lst = lst[:len(lst)-1]
```

Break an Alias with List 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 variables 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 = ["A", "B", "C"]
b = a # a and b are aliased
a = a + [ ] # a now has a new reference, but the same values
a is b # False
```

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")
```

Destructive Looping: `for` vs. `while`

It is a **very bad idea** to destructively add or remove elements in a list while looping over it with a for loop.

This will often lead to unexpected and bad behavior because the range is only calculated once.

```
lst = ["a", "a", "c", "d", "e"]
for i in range(len(lst)):
    if lst[i] == "a" or \
       lst[i] == "e":
        lst.pop(i)
```

Instead, use a **while loop** if you're planning to destructively change the list length. The list length is reevaluated when the while condition is checked each iteration.

```
lst = ["a", "a", "c", "d", "e"]
i = 0
while i < len(lst):
    if lst[i] == "a" or \
       lst[i] == "e":
        lst.pop(i)
    else:
        i = i + 1
```

Destructive Looping: `break` to exit early

What if you want to destructively remove exactly one element from a list, then exit the loop immediately before you remove any others?

It's possible to design a loop control variable to do this, but it's often easier to use the `break` statement instead. As soon as the code reaches a `break`, it immediately exits the loop. (If loops are nested, it only exits the innermost loop).

```
lst = ["a", "a", "c", "d", "e"]
for i in range(len(lst)):
    if lst[i] == "a":
        lst.pop(i)
        break # exits immediately, only removes one "a"
```

Writing Destructive Functions

Function Arguments/Parameters are Aliased

When you call a function with a mutable value as one of the arguments, that argument is **aliased** to the function's parameter variable. 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 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"
```

Destructive Functions Use Mutable Methods

When writing a destructive function, use index assignment and the mutable methods (`append`, `insert`, `pop`, and `remove`) on the **parameter 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 `lst` because the parameter `lst` and the argument `x` **refer to the same values**. We usually have destructive functions return None as an indicator that they're destructive.

```
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

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.

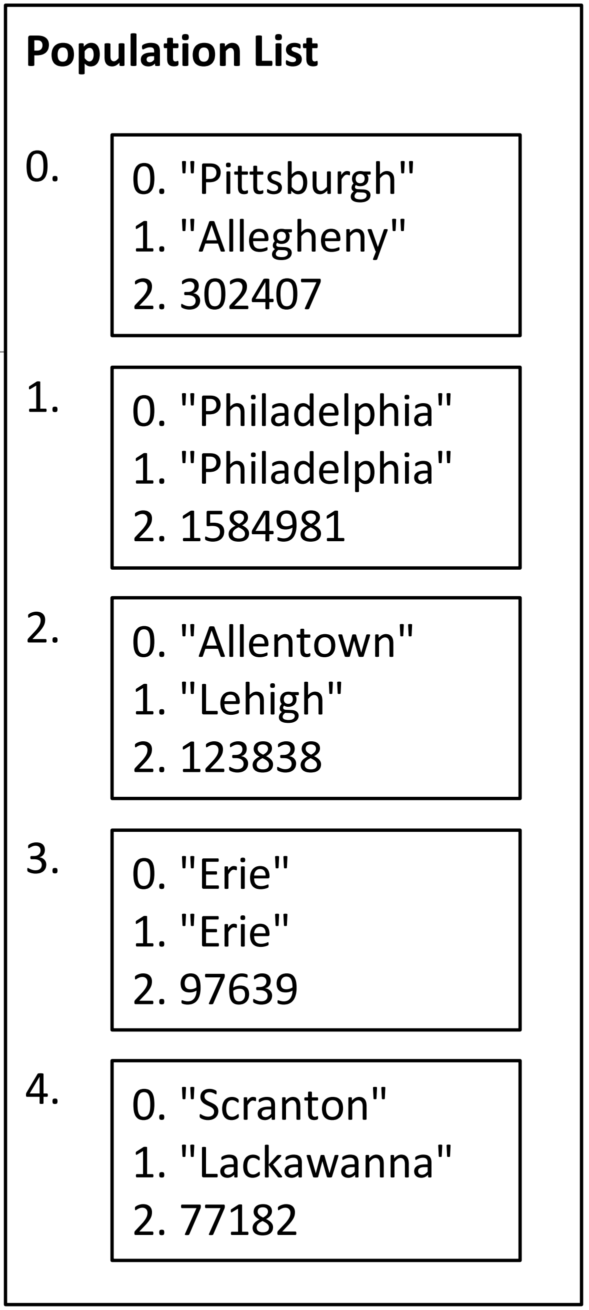
```
def makePositive(lst):
    result = [ ]
    for i in range(len(lst)):
        if lst[i] < 0:
            result.append(lst[i] * -1)
        else:
            result.append(lst[i])
    return result
```

2D Lists

2D Lists are Lists of Lists

We often need to work with data that is **two-dimensional**, such as the coordinates on a grid, values in a spreadsheet, or pixels on a screen. We can store this type of data in a **2D list**, which is just a list that contains other lists.

For example, the 2D list to the right holds population data, where each population datapoint itself contains multiple data values (city, county, and population).



Population List

0.
   0. "Pittsburgh"
   1. "Allegheny"
   2. 302407

1.
   0. "Philadelphia"
   1. "Philadelphia"
   2. 1584981

2.
   0. "Allentown"
   1. "Lehigh"
   2. 123838

3.
   0. "Erie"
   1. "Erie"
   2. 97639

4.
   0. "Scranton"
   1. "Lackawanna"
   2. 77182

Syntax of 2D Lists

Setting up a 2D list is no different than setting up a 1D list; each inner list is one data value.

```
cities = [ ["Pittsburgh", "Allegheny", 302407],
           ["Philadelphia", "Philadelphia", 1584981],
           ["Allentown", "Lehigh", 123838],
           ["Erie", "Erie", 97639],
           ["Scranton", "Lackawanna", 77182] ]
```

When indexing into a 2D list, the first square brackets index into a row and the second index into a column. The length of a 2D list is the number of lists in the outer list.

```
cities[2]    # [ "Allentown", "Lehigh", 123838 ]
cities[2][1] # "Lehigh"
len(cities)  # 5
```

Looping Over 2D Lists

We can loop over a 2D list the same way we loop over a list. Indexing into a list once will produce an **inner list**. We'll need to index a second time to get a value.

```
def getCounty(cities, cityName):
    for i in range(len(cities)):
        entry = cities[i] # entry is a list
        if entry[0] == cityName:
            return entry[1]
    return None # city not found
```

Looping Over All 2D List Elements

When you loop over a 2D list and want to access *every* element, you need to use **nested for loops**. Often, the outer loop iterates over the indexes of the outer list (**rows**) and the inner loop iterates over the indexes of the inner list (**columns**).

```
gameBoard = [ ["X", " ", "O"], [" ", "X", " "], [" ", " ", "O"] ]
for row in range(len(gameBoard)): # each row is a list
    boardString = ""
    for col in range(len(gameBoard[row])): # each col is a string
        boardString = boardString + gameBoard[row][col]
    print(boardString) # separate rows on separate lines
```

Looping Over All 2D List Elements

We could have done this by looping directly over the board as well! This works because we don't need to know **where** the icons are on the board- they get added to the string regardless.

```
gameBoard = [ ["X", " ", "O"], [" ", "X", " "], [" ", " ", "O"] ]
for boardRow in gameBoard: # boardRow is a list
    boardString = ""
    for icon in boardRow: # icon is "X", "O", or " "
        boardString = boardString + icon
    print(boardString) # separate rows on separate lines
```

Activity: getTotalPopulation(cities)

Write the function `getTotalPopulation(cities)` that takes the city-information 2D list from before and finds the total population of all cities in the list. Here's a list to test with:

```
cities = [ ["Pittsburgh", "Allegheny", 302407],
           ["Philadelphia", "Philadelphia", 1584981],
           ["Allentown", "Lehigh", 123838],
           ["Erie", "Erie", 97639],
           ["Scranton", "Lackawanna", 77182] ]
```

Hint: note that the population is in the third column. What index corresponds to that?

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Read and write code using **2D lists**