CS107 / AC207

SYSTEMS DEVELOPMENT FOR COMPUTATIONAL SCIENCE

LECTURE 5

Tuesday, September 21st 2021

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RECAP OF LAST TIME

- More `git` basics
- Remote repositories
- Branching in `git` (today)

You should now have a basic understanding of the core design of `git` and understand some of its internals as well as know how to use its interface to exploit VCS.

OUTLINE

- Python basics (a review)
- Nested environments
- Closures
- Decorators

PYTHON BASICS

PYTHON BASICS

It is assumed that you are familiar with the very basics of `python` and especially its syntax. If you need a refreshment on these basics, a good reference to work through is: https://learnxinyminutes.com/docs/python/. The supplementary notebooks given at https://harvard-iacs.github.io/2021-CS107/lectures/lecture5/ are another option to review.

Topics include:

- `python` types
- Basic data structures including lists, dictionaries and tuples.
- How to write user defined functions including variable numbers of arguments using `*args` and `**kwargs` for positional and keyword arguments.
- Writing `for`-loops and know how to use `enumerate` and `zip` in the loop header.
- Proper syntax for opening files using the `with` syntax.
- Some basic exception handling
- Know a little of `numpy` and `matplotlib`

PYTHON BASICS

`python 2.7` is no longer supported since January 1st, 2020

- If you are still using `python 2.7` please upgrade
- We are using `python 3` in this class
- Here are a few notes on porting code from `python 2` to `python 3`: https://docs.python.org/3/howto/pyporting.html

PYTHON BASICS

Preliminaries: pythontutor

There is a cool tool you should know about. It helps us to visualize `python` code such that we can better understand what is going on *under the hood*. You can find it at https://pythontutor.com/. To visualize your code interactively, you can start here: https://pythontutor.com/visualize.html#mode=edit.

PYTHON BASICS: REFERENCE VARIABLES

- A *variable* in `python` is called a *name*.
- ***Example:*** the assignment `a = 1` declares the *name* `a` to hold an integer value of `1`.

```
>>> a = 1
>>> type(a)
<class 'int'>
```

- The term "*variable*" seems more intuitive and you can call "`a`" a variable too.

PYTHON BASICS: REFERENCE VARIABLES

Important take-away for today:
Variables in `python` are *references* to objects in memory.

- If you heard this the first time now, you should make sure you remember it.
- *It is perfectly valid in `python` that **multiple** references point to the same object.*
- From the `python 3.9.7` Language Reference, Section 3.1:

> *Every object has an identity, a type and a value. An object's identity never changes once it has been created; you may think of it as the object's address in memory. The '`is`' operator compares the identity of two objects; the `id()` function returns an integer representing its identity.*

Reference: https://docs.python.org/3/reference/datamodel.html#objects-values-and-types

PYTHON BASICS: REFERENCE VARIABLES

Let us investigate the following code:

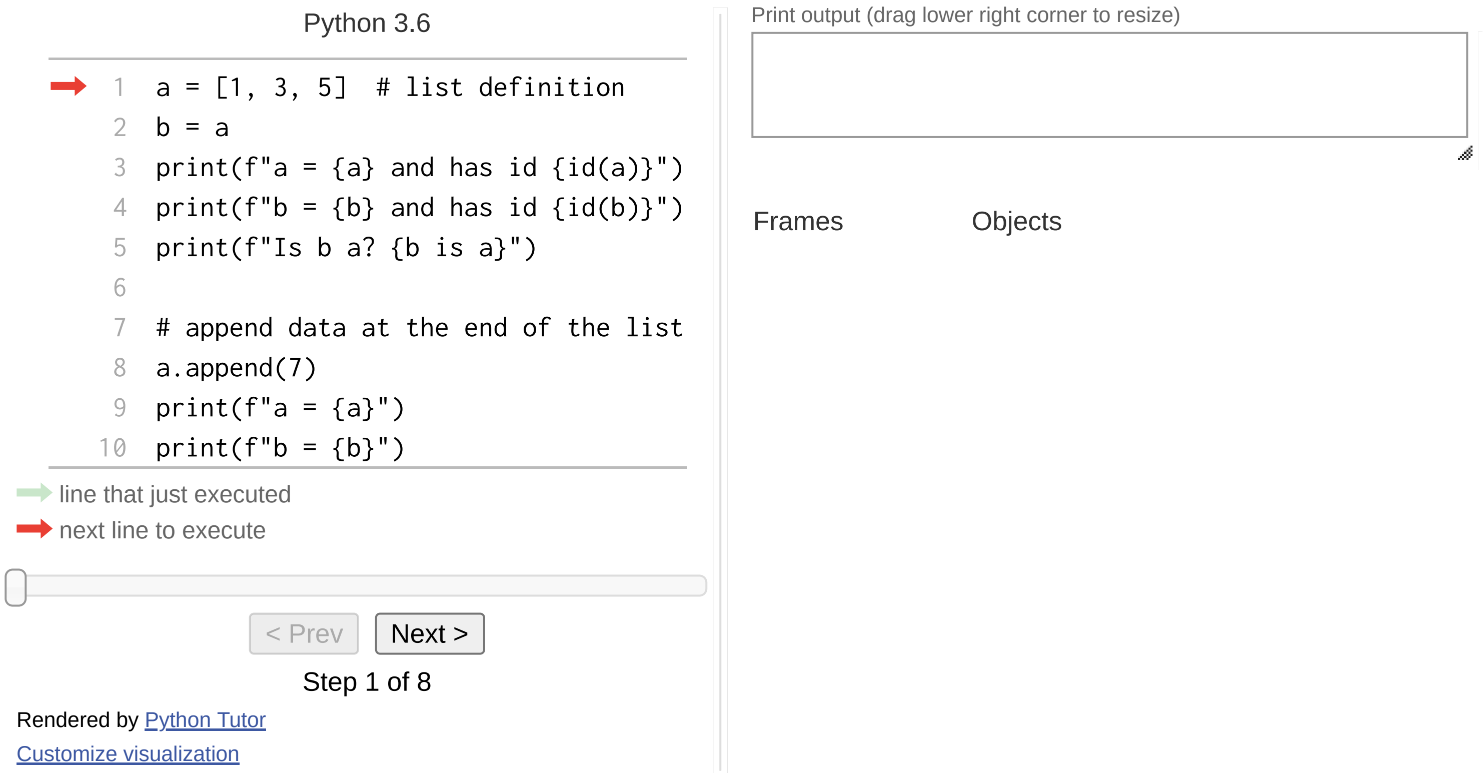
```python
a = [1, 3, 5]  # list definition
b = a
print(f"a = {a} and has id {id(a)}")
print(f"b = {b} and has id {id(b)}")
print(f"Is b a? {b is a}")

# append data at the end of the list
a.append(7)
print(f"a = {a}")
print(f"b = {b}")
```

PYTHON BASICS: REFERENCE VARIABLES

Let's have a look in pythontutor:

- Note that `b` points to the same object in memory
- The memory address of what `a` and `b` points to is *identical*



Python 3.6

```python
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# append data at the end of the list
a.append(7)
print(f"a = {a}")
print(f"b = {b}")
```
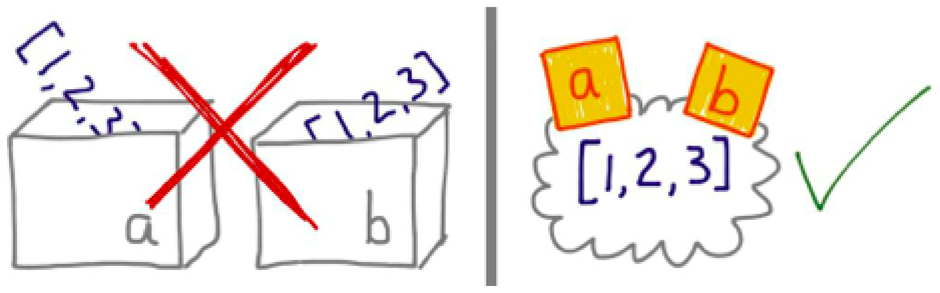

PYTHON BASICS: REFERENCE VARIABLES

A corresponding illustration from *Fluent Python: Clear, Concise, and Effective Programming* by Luciano Ramalho (O'Reilly Media, 2015):



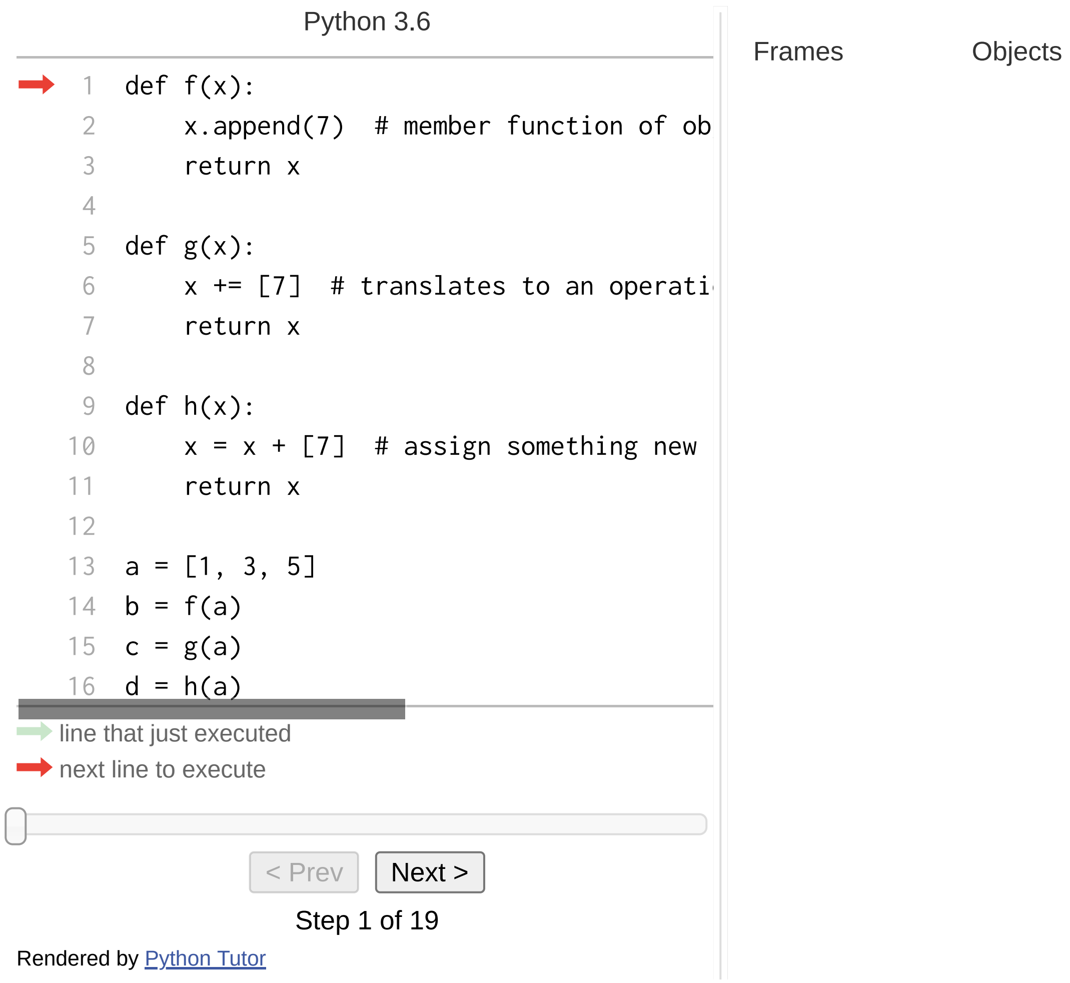
PYTHON BASICS: REFERENCE VARIABLES

But be careful when working with functions. Variables inside functions may become new objects depending on the operators you use:

```python
def f(x):
    x.append(7)  # member function of object x
    return x

def g(x):
    x += [7]  # translates to an operation on object x
    return x

def h(x):
    x = x + [7]  # assign something new to x (it is now local to the function)
    return x

a = [1, 3, 5]
b = f(a)
c = g(a)
d = h(a)
```

PYTHON BASICS: REFERENCE VARIABLES

See what is going on in pythontutor:



Python 3.6

```
def f(x):
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    return x

def h(x):
    x = x + [7]  # assign something new
    return x

a = [1, 3, 5]
b = f(a)
c = g(a)
d = h(a)
```

PYTHON BASICS: TYPES

- Every variable in `python` has a *type* (e.g. `float`, `string`, `int`, etc.)
- `python` is a *strongly typed* language
- `python` is also *dynamically typed*:
  - Types are assigned at *runtime* rather than compile time (for example as in `C`)
  - This implies a performance penalty (slower execution) as type interpretation is not for free
  - But it makes your life (a bit) easier when writing code since you do not need to worry (too much) about it.
  - When the program starts, it is *undefined* what that variable will point to (same for *uninitialized* variables in `C`)

In `python`:

```python
a = 1      # interpreted as an integer (int)
a = 1.1    # a is now a float of value 1.1
           # (a different type!)
```

In `C`:

```c
int a = 1;   // defined as an integer (int)
a = 1.1;     // a is still an integer,
             // its value will be 1
```

PYTHON BASICS: TYPES

From *Fluent Python: Clear, Concise, and Effective Programming* by Luciano Ramalho (O'Reilly Media, 2015), Chapter 11:

STRONG VERSUS WEAK TYPING

If the language rarely performs *implicit* conversion of types, it is considered *strongly typed*; if it often does, it is *weakly typed*. `Java`, `C/C++` and `python` are strongly typed. `php`, `JavaScript` and `perl` are weakly typed.

STATIC VERSUS DYNAMIC TYPING

If type-checking is performed at *compile time*, the language is *statically typed*; if it happens at *runtime*, it is *dynamically typed*. Static typing requires type declarations (some modern languages use type inference to avoid some of that). `Fortran` and `Lisp` are the two oldest programming languages still alive. They use static and dynamic typing, respectively.

ASIDE ON COMPILERS

We came across the word *"compile"*. For our purposes, the meaning of "compiling code" is to *transform* human-readable code (written by you) into machine-readable form (instructions that the CPU knows how to *execute*).

- Compiler technology is really amazing!
- Compiler developers and standardization committees of programming languages (e.g. `C++`) are often not best friends.
- The part of a compiler that tries to make syntactic sense of the source code involves a *parser generator*. **A popular parser generator is called `yacc` . Can you guess where it was developed?**
- `C/C++` are compiled languages, you must *build* the code first before you can run it.
- `python` has tools for *just-in-time* (JIT) compilation. See the numba project.

Some complementary references for this topic:

- https://gcc.gnu.org/
- https://llvm.org/
- https://cs.lmu.edu/~ray/notes/introcompilers/

PYTHON BASICS: FRAMES

You may have noticed the two columns in the pythontutor examples we were discussing before. So far we have been talking about *objects* which are instances in memory that can have *one or more references* to it.

The evaluation of any expression requires *knowledge of the context in which the expression is being evaluated*. This context is called a ***frame***. Recall the pythontutor example from before where we entered a new frame every time we were executing a function call.

An ***environment*** is a *sequence of frames*, with each frame or context having a bunch of labels, or bindings, associating variables with values. The first frame in an environment is called *global* frame, which contains the bindings for imports, built-ins, etc.

PYTHON BASICS: FRAMES

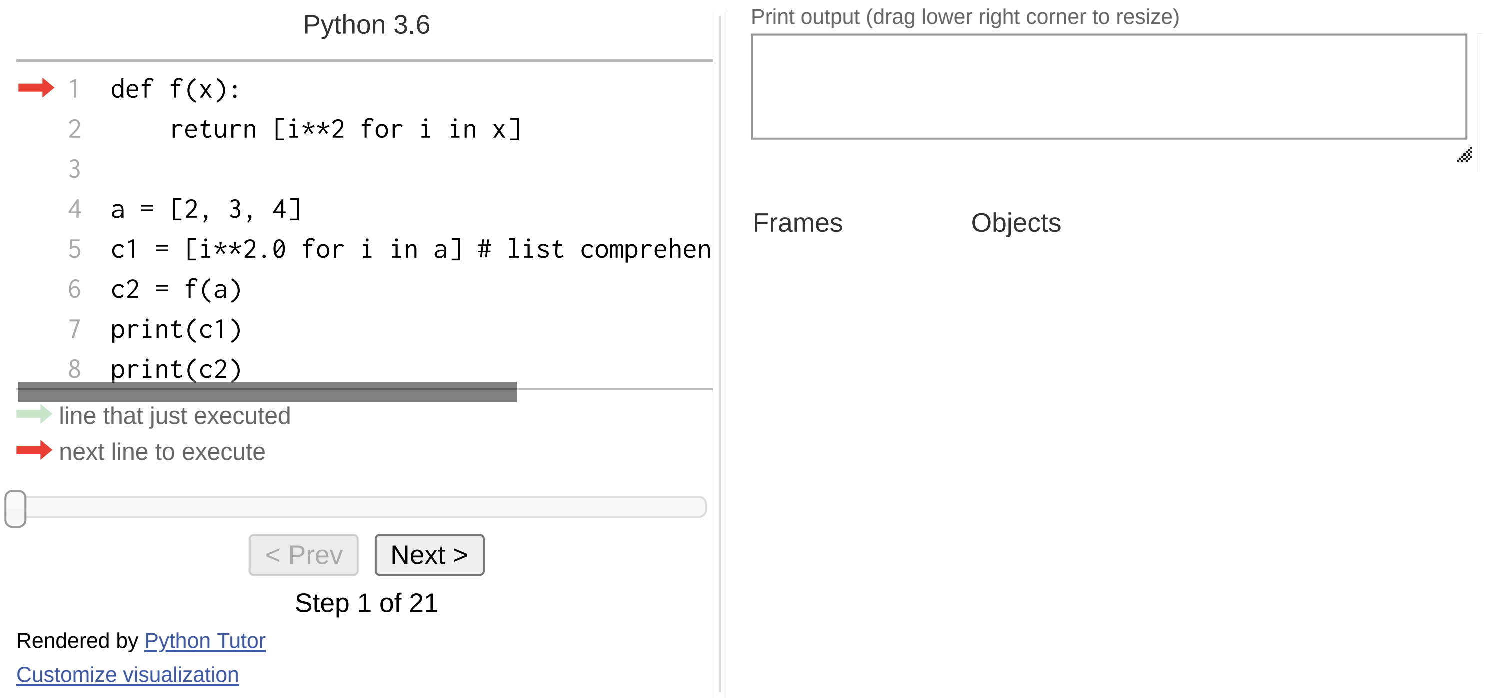
Example to study frames in `python`:

```python
def f(x):
    return [i**2 for i in x]

a = [2, 3, 4]
c1 = [i**2.0 for i in a] # list comprehension, very pythonic
c2 = f(a)
print(c1)
print(c2)
```

PYTHON BASICS: FRAMES

Example to study frames in `python`: analyze in pythontutor



Python 3.6

```
def f(x):
    return [i**2 for i in x]

a = [2, 3, 4]
c1 = [i**2.0 for i in a] # list comprehen
c2 = f(a)
print(c1)
print(c2)
```

PYTHON BASICS: FUNCTIONS AND ENVIRONMENTS

Functions are *first class objects* in `python`. If this term is fuzzy to you please review the supplementary notes for this lecture.

Let's look at another code example:

```python
s = 'The lost world...' # a string
len_of_s = len(s)       # len() is a built-in function for the length of an iterable
my_len = len            # What are we doing here? (assign a function to a name)
my_len_of_s = my_len(s)
```

PYTHON BASICS: FUNCTIONS AND ENVIRONMENTS

Let's look at another code example:

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len_of_s = len(s)       # len() is a built-in function for the length of an iterable
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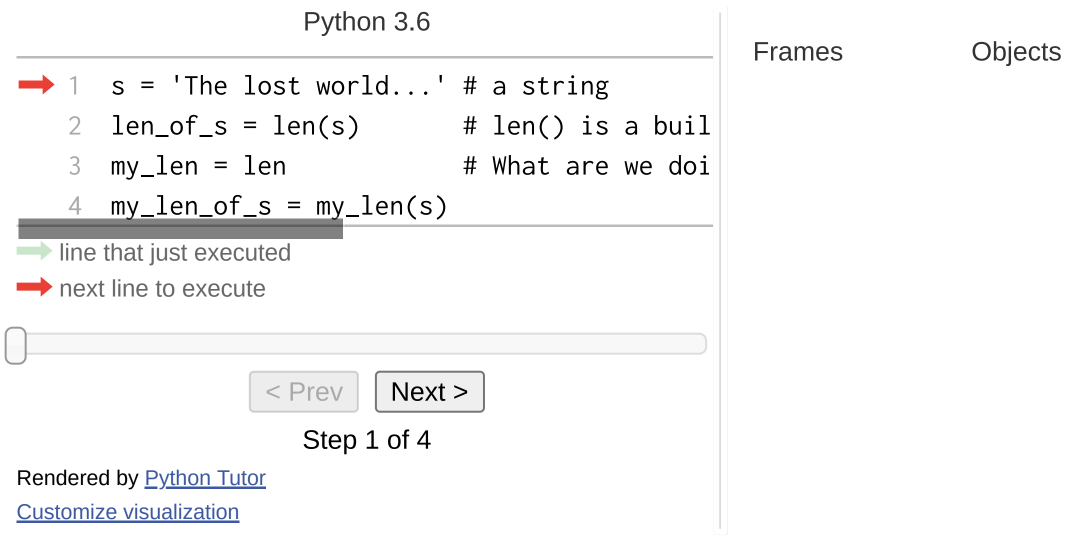
my_len_of_s = my_len(s)
```

Click here for example on pythontutor


Python 3.6

```python
s = 'The lost world...' # a string
len_of_s = len(s)       # len() is a buil
my_len = len            # What are we doi
my_len_of_s = my_len(s)
```

Step 1 of 4

Rendered by Python Tutor

Customize visualization

PYTHON BASICS: FUNCTIONS AND ENVIRONMENTS

By now we are aware that whenever we execute a user defined function we are pushed onto a new frame and execute the statements in the function body in that new frame.

We have also figured out that function arguments are *passed by reference* initially (the argument is a *copy of the reference* but they point to the same object in memory). The correct terminology in `python` is "pass by assignment".

PYTHON BASICS: FUNCTIONS AND ENVIRONMENTS

There are two types of objects in `python`:

1. ***mutable:*** You can mutate the state of the object. *If you **rebind** a mutable object in a function, the outer scope (outside the function) will **not** be aware of it.*
2. ***immutable:*** You can not mutate such an object (they are constant) nor can you *rebind* it inside a function body.

PYTHON BASICS: FUNCTIONS AND ENVIRONMENTS

Example: `list` is *mutable*, `tuple` is *immutable*

```python
def mutate(x):
    x[0] = 1  # mutate first element
    return x

def rebind(x):
    x = x[:]  # rebind by assignment (overwrite old reference)
    return x

l = [4, 3, 2]  # list:  mutable object
t = (4, 3, 2)  # tuple: immutable object

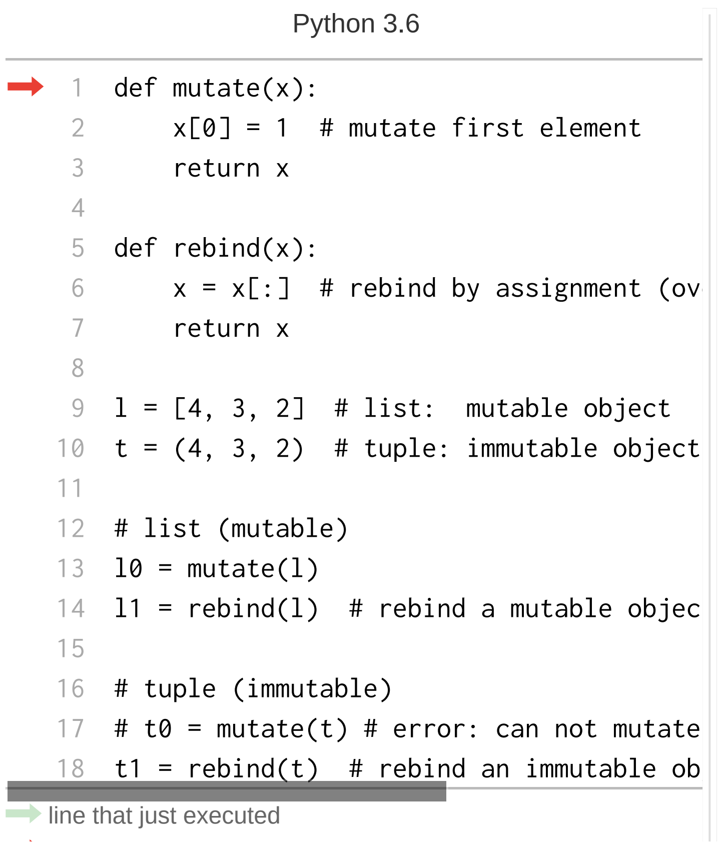
# list (mutable)
l0 = mutate(l)
l1 = rebind(l)  # rebind a mutable object creates a new object

# tuple (immutable)
# t0 = mutate(t) # error: can not mutate immutable!
t1 = rebind(t)  # rebind an immutable object maintains the reference
```

PYTHON BASICS: FUNCTIONS AND ENVIRONMENTS

Example: `list` is *mutable*, `tuple` is *immutable*

Pay attention to this example!



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# tuple (immutable)
# t0 = mutate(t) # error: can not mutate
t1 = rebind(t)  # rebind an immutable ob
```

PYTHON BASICS: EXECUTION MODEL

A *code block* is executed in an *execution frame*. A frame contains some administrative information (used for debugging) and determines where and how execution continues after the code block's execution has completed. *A Python program is constructed from code blocks. A block is a piece of Python code that is executed as a unit*. Code blocks are among the following:

- modules
- function bodies
- class definitions
- commands typed interactively
- a script file (what you pass to `python` as an argument)
- See `python` execution model for the remaining

PYTHON BASICS: NAME (VARIABLE) BINDING

Names (or variables) refer to objects. Names are introduced by name binding operations. The following constructs bind names:

- Formal parameters to functions
- `import` statements
- `class` and `function` definitions (these bind the class or function name in the defining block)
- Targets that are identifiers if occurring in an assignment (what we did in the function body of `rebind(x)` before)
- `for` -loop headers
- after the `as` keyword in a `with` statement or the `expect` clause

The `import` statement of the form `from ... import *` binds *all* names defined in the imported module, *except those beginning with an underscore*. This form may only be used at the module level.

PYTHON BASICS: NAME (VARIABLE) LOOKUP

A ***scope*** defines the visibility of a name within a block. If a local variable is defined in a block, its scope includes that block. *If the definition occurs in a function block, the scope extends to any blocks contained within the defining one, unless a contained block introduces a different binding for the name (what we did in the `rebind(x)` function before)*.

When a name is used in a code block, it is resolved using the *nearest enclosing scope*. The set of all such scopes visible to a code block is called the block's ***environment***.

PYTHON BASICS: NAME (VARIABLE) LOOKUP

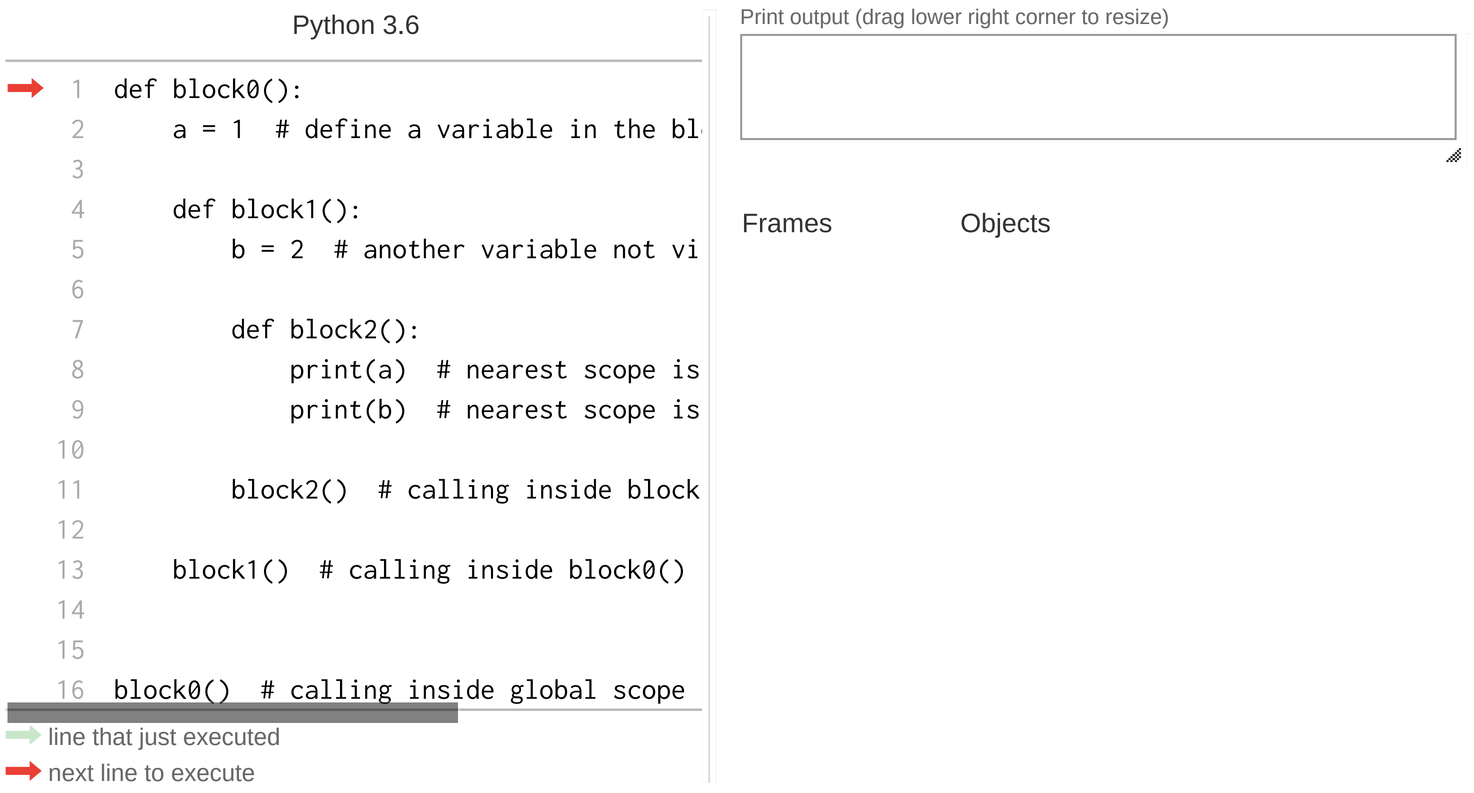
Example: nested function blocks

```python
def block0():
    a = 1  # define a variable in the block0 scope (function body)

    def block1():
        b = 2  # another variable not visible to block0 scope

        def block2():
            print(a)  # nearest scope is block0
            print(b)  # nearest scope is block1

        block2()  # calling inside block1()

    block1()  # calling inside block0()


block0()  # calling inside global scope
```

PYTHON BASICS: NAME (VARIABLE) LOOKUP

Example: nested function blocks

pythontutor



Python 3.6

```
def block0():
    a = 1  # define a variable in the bl
    
    def block1():
        b = 2  # another variable not vi
        
        def block2():
            print(a)  # nearest scope is
            print(b)  # nearest scope is
            
        block2()  # calling inside block
        
    block1()  # calling inside block0()
    
    
block0()  # calling inside global scope
```

➡ line that just executed

➡ next line to execute

Print output (drag lower right corner to resize)

Frames

Objects

NESTED ENVIRONMENTS

NESTED ENVIRONMENTS

- The previous example showed that you can *nest the definitions of functions* (something you *can not* do in `C` for example).
- When you do this, the *inner* function definitions are not even evaluated until the outer function is called.
- We also found that these inner functions have automatic access to the name bindings (or variables) in the *scope* of the outer function.

NESTED ENVIRONMENTS

Example: nested function that is partially completed

```python
def set_partial_value(partial):
    """Return a function to be called later with captured `partial` argument"""
    def set_final_value(final):
        """Combine the `partial` name from the outer scope with the `final` name"""
        return ' '.join((partial, final))
    return set_final_value  # we return a function here

# recall: functions in python are first class objects
i_am = set_partial_value('Hi, my name is')
print(type(i_am))

# we can call the function i_am like any other function
print(i_am('Alice'))
print(i_am('Bob'))
```

Output when we run this program:

```
<class 'function'>
Hi, my name is Alice
Hi, my name is Bob
```

NESTED ENVIRONMENTS

Example: nested function that is partially completed

```python
def set_partial_value(partial):
    """Return a function to be called later with captured `partial` argument"""
    def set_final_value(final):
        """Combine the `partial` name from the outer scope with the `final` name"""
        return ' '.join((partial, final))
    return set_final_value  # we return a function here

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print(type(i_am))

# we can call the function i_am like any other function
print(i_am('Alice'))
print(i_am('Bob'))
```

- In the `set_partial_value` function, both, `partial` and `set_final_value` (a function) will be defined.
- In `python` functions are first class objects and are treated like variables (or names)
- Inside `set_final_value` you have access to `partial` which is defined in the scope of the outer function.

NESTED ENVIRONMENTS

Example: nested function that is partially completed

An explanation in words: in `line 9` we call the function `set_partial_value('Hi, my name is')` and bind its return value to the name `i_am`. The returned value is the inner function defined inside `set_partial_value` which has access to the `'Hi, my name is'` argument that we have passed to the outer function call in `line 9`. Because functions are first class objects in `python` we can now use the name `i_am` (note that here "name" is likely more intuitive than "variable") just like any other function. The call to `i_am` will finalize the `tuple` that we could only define partially when we defined the outer function `set_partial_value`.

NESTED ENVIRONMENTS

The reason this works is that in addition to the environment in which a *user-defined* function is running, that function has access to a second environment: the environment in which the function was *defined*. Here the inner function `set_final_value` has access to the environment spanned by `set_partial_value`, which is its parent environment.

This enables two properties:

1. Names inside the inner functions (or the outer ones for that matter) *do not interfere* with names in the global scope. Inside the inner and outer functions, the names that *are nearest* to them are the ones that matter.
2. An inner function can access the environment of its enclosing (outer) function.

CLOSURES

CLOSURES

Since the inner functions can *capture* names from an outer function's environment, the inner function is sometimes called a ***closure***.

```python
def set_partial_value(partial):
    def set_final_value(final):
        return ' '.join((partial, final))
    return set_final_value
```

- Once `partial` is captured by the inner function, *it cannot be changed anymore.*
- This *inability to access data directly* is called ***data encapsulation*** and is one of the foundations in Object Oriented Programming (OOP), next to inheritance and polymorphism.

CLOSURES

The concept of closures in `python` is useful to *augment* functions. Because functions are first class objects, passing them around as arguments to other functions and capturing them in a closure turns out to be useful. For example, you can augment a function with call information or ***wrap*** a timer around them.

CLOSURES

Example: wrap a timer around a function `f` to obtain profiling information

```python
import time

def timer(f):
    """Augment arbitrary function f with profiling information"""
    def inner(*args, **kwargs):
        t0 = time.time()
        retval = f(*args, **kwargs) # here we call the captured function
        elapsed = time.time() - t0
        print(f"{f.__name__}: elapsed time {elapsed:e} seconds")
        return retval
    return inner
```

- The function `inner` accepts a *variable* list of ***positional*** and ***keyword*** arguments.
- It *wraps* the arbitrary function `f` in between an execution timer.
- We assume an *unknown* argument list for `f`, abstracted by `*args` (positional arguments) and `**kwargs` (keyword arguments). See section `4. Functions` in https://learnxinyminutes.com/docs/python/ to refresh these.

CLOSURES

Example: wrap a timer around a function `f` to obtain profiling information

Test with a sleep function:

```python
import time

def sleep(x):  # one positional argument x
    """Sleep for x seconds"""
    time.sleep(x)

timed_sleep = timer(sleep) # augment sleep with the timer from previous slide
timed_sleep(2) # sleep for 2 seconds
```

Output

```
sleep: elapsed time 2.002061e+00 seconds
```

DECORATORS

(also called *wrappers*)

Optional reading: *Decorators* in Chapter 4 of *Design Patterns: Elements of Reusable Object-Oriented Software* by E. Gamma, R. Helm, R. Johnson and J. Vlissides, Addison Wesley Professional, 1995.

DECORATORS

Let's recap what we did before:

- We wrote a function called `timer` to augment or ***decorate*** any function of interest, we called this arbitrary function `f` in our code.
- Our intention was to *wrap* an execution timer around the function `f`.
- Such a wrapper may be useful if you need to profile your function calls to find *bottlenecks* in your code. There are many more useful decorations.
- We performed the following steps after we wrote the `timer` function:
  1. Write a function `f` for a problem you are working on.
  2. To make use of the decorations in `timer`, we had to call the `timer` function with our target function `f` as an argument.
  3. We received a new (decorated) function which we called subsequently in our code.

DECORATORS

Decorator = *outer function* + *closure* (that wraps code around the captured function `f`)

```python
def timer(f):
    def inner(*args, **kwargs):
        t0 = time.time()
        retval = f(*args, **kwargs) # here we call the captured function
        elapsed = time.time() - t0
        print(f"{f.__name__}: elapsed time {elapsed:e} seconds")
        return retval
    return inner
```

Usage:

```python
# a function that performs useful work (with required and optional arguments)
def target(a, b, method='linear', log=True):
    pass

decorated_target = timer(target)        # decorate it
return_value = decorated_target(a, b)  # use in code (assume a and b are defined)
```

DECORATORS

Because the decorator pattern is so useful, `python` provides a special syntax for it to reduce code bloat and make code more readable.

- What we did so far (*not* pythonic):

```python
def target():
    pass

decorated_target = decorator(target)
```

- The correct (pythonic) way:

```python
@decorator
def target():
    pass
```

DECORATORS

Our `sleep` function decorated with the `timer` function correctly done:

```python
import time

@timer  # the timer decorator was defined previously (code not repeated here)
def sleep(x):
    """Sleep for x seconds"""
    time.sleep(x)

sleep(2) # sleep for 2 seconds
```

Output:

```
sleep: elapsed time 2.002102e+00 seconds
```

- Be sure you understand the decorator pattern
- It can be useful at many places in your code
- The `@timer` syntax is often called "syntactic sugar". It hides all of what we have done in the previous discussion in one line of code.
- Note that we can also use the decorated function by the name we give it when we define it.

DECORATORS

Be aware that a decorator ***is run right after*** you defined the decorated function and not at the time you call the decorated function. Therefore, if you have decorated code in a *module*, the code of the decorating function will be executed at the time you `import` the module.

```python
def decorator(f):
    print(f'{f.__name__}: start decoration')
    def closure(*args, **kwargs):
        print(f'running closure for {f.__name__}')
        f(*args, **kwargs)
    print(f'{f.__name__}: end decoration')
    return closure

@decorator
def my_func():
    print('inside function body of my_func')

print('RUNNING my_func NOW:')
my_func()
```

DECORATORS

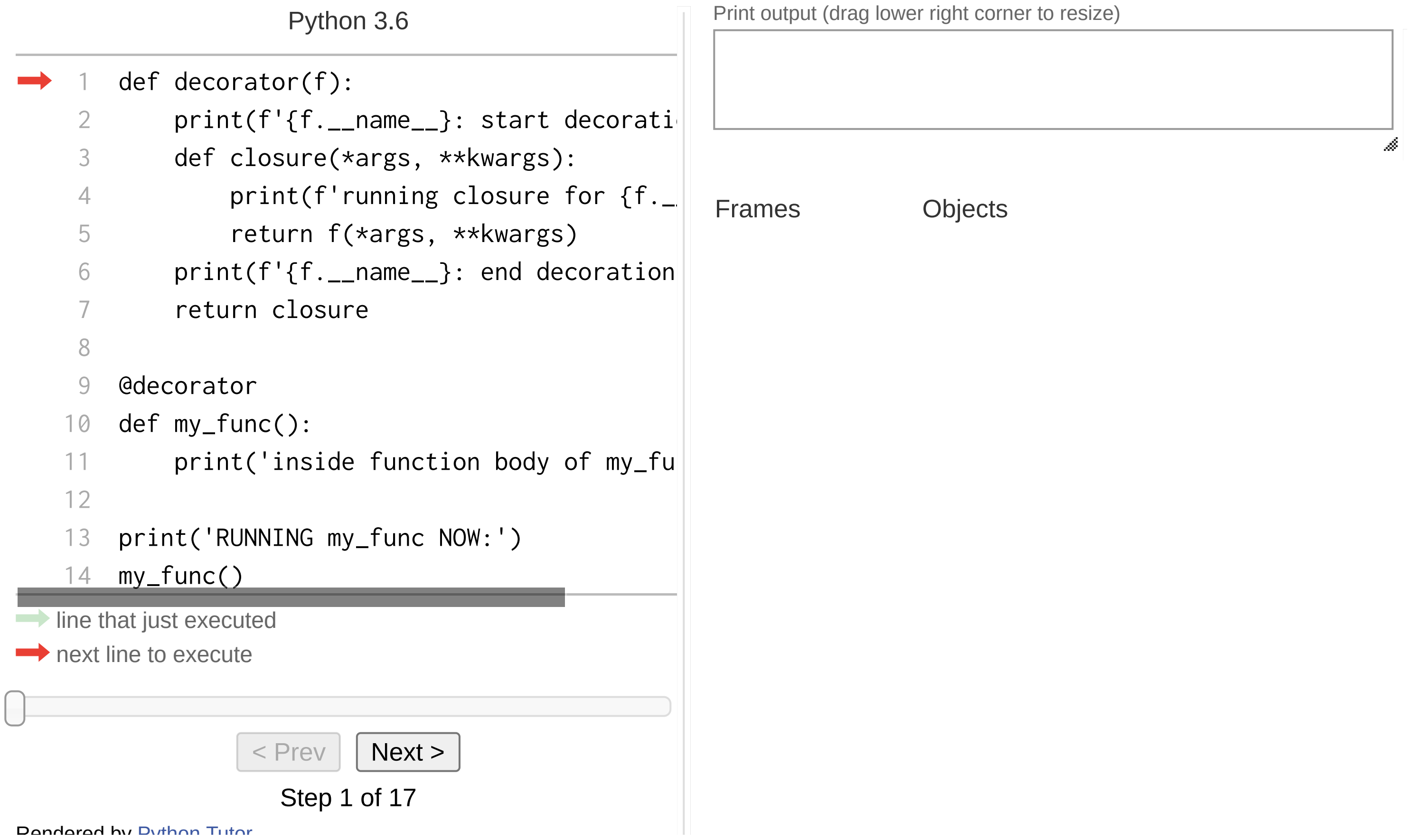
```python
def decorator(f):
    print(f'{f.__name__}: start decoration')
    def closure(*args, **kwargs):
        print(f'running closure for {f.__name__}')
        return f(*args, **kwargs)
    print(f'{f.__name__}: end decoration')
    return closure

@decorator
def my_func():
    print('inside function body of my_func')

print('RUNNING my_func NOW:')
my_func()
```

Output:

```
my_func: start decoration
my_func: end decoration
RUNNING my_func NOW:
running closure for my_func
inside function body of my_func
```

DECORATORS

Step-by-step on pythontutor



```
def decorator(f):
    print(f'{f.__name__}: start decorati
    def closure(*args, **kwargs):
        print(f'running closure for {f._
        return f(*args, **kwargs)
    print(f'{f.__name__}: end decoration
    return closure

@decorator
def my_func():
    print('inside function body of my_fu

print('RUNNING my_func NOW:')
my_func()
```

RECAP

- Python basics (references to objects, frames, environments, functions, https://pythontutor.com/)
- Nested environments
- Closures
- Decorators

REFERENCES

I highly recommend to spend a few minutes on these references:

- `python` programming FAQ
- Learn `python` in X minutes