Lecture #4: Higher-Order Functions

Announcements:

• Theta Tau rush events, starting 1/31. See Piazza post.

• CSUA Unix/Emacs help sessions: Thursday 1/26, Tuesday 1/31, Thursday 2/2 in 310 Soda, 6-8PM.
A Simple Recursion

• The Fibonacci sequence is defined

\[ F_k = \begin{cases} k, & \text{for } k = 0, 1 \\ F_{k-2} + F_{k-1}, & \text{for } k > 1 \end{cases} \]

• …which translates easily into Python:

```python
def fib(n):
    """The Nth Fibonacci number, N>=0."""
    assert n >= 0
    if n <= 1:
        return n
    else:
        return fib(n-2) + fib(n-1)
```

• This definition works, but why is it so slow?
Redundant Calculation

- Consider the computation of fib(10).
- This calls fib(9) and fib(8), but then fib(9) calls fib(8) again and both fib(9) and the two calls to fib(8) call fib(7), so that fib(7) is called 3 times.
- Likewise, fib(6) is called 5 times, fib(7) is called 8 times, and so forth in increasing Fibonacci sequence, interestingly enough.
- Therefore, the time required (proportional to the number of calls) grows exponentially:
- As it turns out, fib(N) requires time roughly proportional to $\Phi^N$, where the golden ratio $\Phi = (1 + \sqrt{5})/2$. 
Avoiding Recalculation

• To compute the next Fibonacci number, we need the preceding two.

• Let’s generalize and consider what it takes to compute \( N \) more:

```python
def fib2(fk1, fk, k, n):
    """Assuming FK1 and FK F[K-1] and F[K] in the Fibonacci sequence numbers and N>=K, return F[N].""
    if n == k:
        return fk
    else:
        return ________________________

def fib(n):
    if n <= 1:
        return n
    else:
        return fib2(0, 1, 1, n)
```
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    """Assuming FK1 and FK F[K-1] and F[K] in the Fibonacci sequence numbers and N>=K, return F[N].""
    if n == k:
        return fk
    else:
        return fib2(fk, fk1+fk, k+1, n)
def fib(n):
    if n <= 1:
        return n
    else:
        return fib2(0, 1, 1, n)
```
Tail Recursion and Repetition

- In this last version, whenever \( \text{fib2} \) is called recursively, the value of that call is immediately returned.

- This property is called \textit{tail recursion}.

```python
def fib2(fk1, fk, k, n):
    if n == k: return fk
    else: return fib2(fk, fk1+fk, k+1, n)
def fib(n):
    if n <= 1: return n
    else: return fib2(0, 1, 1, n)
```

- It is this sort of process that is easily expressed as a repetition.

- Parameters become variables; initial call on \( \text{fib2} \) inside \( \text{fib} \) initializes them; each tail-recursive call updates them. Iterative equivalent:

```python
def fib3(n):
    if n <= 1: return n
    fk1, fk, k = 0, 1, 1
    while n != k:
        fk1, fk, k = fk, fk1+fk, k+1
    return fk
```
Nested Functions

• In the last recursive version, \texttt{fib2} function is an auxiliary function, used only by \texttt{fib}.

• It makes sense to tuck it away inside \texttt{fib}, like this:

```python
def fib(n):
    def fib2(fk1, fk, k):
        if n == k: return fk
        else: return fib2(fk, fk1+fk, k+1)

    if n <= 1: return n
    else: return fib2(0, 1, 1)
```

• I've taken the liberty here of removing the parameter \texttt{n} from \texttt{fib2}: it's always the same as the outer \texttt{n} and never changes.

• But to explain how this works, we'll have to extend the environment model just a bit.
Nested Functions and Environments

\[ \text{fib(n)} \]

\[ \text{fib2(fk1, fk, k)} \]

\[ \text{fk1: 1} \]
\[ \text{fk: 1} \]
\[ \text{k: 2} \]

\[ \text{fk1: 0} \]
\[ \text{fk: 1} \]
\[ \text{k: 1} \]
Defining Environments

- Each function value is attached to the environment frame in which the `def` statement that created it was evaluated.

- Since the `def` for `fib` was evaluated in the global frame, the resulting function value bound to `fib` is attached to the global frame.

- Since the `def` for `fib2` was evaluated in the local frame of an execution of `fib`, the resulting function value is attached to that local frame.

- When a user-defined function value is called, the local frame that is created for that call is attached to the defining frame of the function.
Do You Understand the Machinery? (I)

What is printed (0, 1, or error) and why?

def f():
    return 0

def g():
    print(f())

def h():
    def f():
        return 1
    g()

h()
Answer (I)

The program prints 0. At the point that \( f \) is called, we are in the situation shown below:

So we evaluate \( f \) in an environment (B) where it is bound to a function that returns 0.
Do You Understand the Machinery? (II)

What is printed (0, 1, or error) and why?

```python
def f():
    return 0

g = f

def f():
    return 1

print(g())
```
The program prints 0 again:

At the time we evaluate $f$ to assign it to $g$, it has the value indicated by the crossed-out dotted line, so that is the value $g$ gets. The fact that we change $f$’s value later is irrelevant, just as $x = 3; y = x; x = 4; \text{print}(y)$ prints 3 even though $x$ changes: $y$ doesn’t remember where its value came from.
Do You Understand the Machinery? (III)

What is printed (0, 1, or error) and why?

```python
def f():
    return 0

def g():
    print(f())

def f():
    return 1

g()
```
Answer (III)

This time, the program prints 1. When $g$ is executed, it evaluates the name 'f'. At the time that happens, f's value has been changed (by the third def), and that new value is therefore the one the program uses.
Functions As Templates

- If we think of a function body as a template for a computation, parameters are "blanks" in that template.

- For example:

```python
def sum_squares(N):
    k, sum = 0, 0
    while k <= N:
        sum, k = sum+k**2, k+1
    return sum
```

is a template for an infinite set of computations that add squares of numbers up to 0, 1, 2, 3, \ldots, in place of the \( N \).
Functions on Functions

• Likewise, function parameters allow us to have templates with slots for computations:

```python
def summation(N, f):
    k, sum = 1, 0
    while k <= N:
        sum, k = sum+f(k), k+1
    return sum
```

• Generalizes sum_squares. We can write `sum_squares(5)` as:

```python
def square(x): return x*x
summation(5, square)
```

• or (if we don't really need a “square” function elsewhere), we can create the function argument anonymously on the fly:

```python
summation(5, lambda x: x*x)
```
Lambda

- In Python, `lambda` is just an abbreviation.
- Writing `lambda PARAMS: EXPRESSION` is the same as writing `NAME`, where `NAME` is a name that appears nowhere else in the program and is defined by

  ```python
def NAME(PARAMS):
    return EXPRESSION
  ```

  evaluated in the same environment in which the original `lambda` was.
- Now we can write any number of summations succinctly:

  ```python
summation(10, lambda x: x**3)  # Sum of cubes
summation(10, lambda x: 1 / x)  # Harmonic series
summation(10, lambda k: x**(k-1) / factorial(k-1))  # Approximate e**x
  ```
Functions that Produce Functions

- Functions are first-class values, meaning that we can assign them to variables, pass them to functions, and return them from functions.

- Example:

```python
def add_func(f, g):
    """Return function that returns f(x)+g(x) for argument x.""
    def adder(x):
        return f(x) + g(x)  # or return lambda x: f(x) + g(x)
    return adder

h = add_func(abs, lambda x: -x)
>>> print(h(-5))
10
```

- Generalize the example:

```python
def combine_funcs(op, f, g):
    return lambda x: op(f(x), g(x))
# Now add_func = ____________________________
```

- What do the environments look like here?
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    return adder

h = add_func(abs, lambda x: -x)
>>> print(h(-5))
10
```

- Generalize the example:

  ```python
def combine_funcs(op, f, g):
    return lambda x: op(f(x), g(x))
# Now add_func = lambda f, g: combine_funcs(sum, f, g)
```

- What do the environments look like here?