Lecture #9: Sequences

- The term *sequence* refers generally to a data structure consisting of an *indexed collection of values*.
- That is, there is a first, second, third value (which CS types call #0, #1, #2, etc.
- A sequence may be *finite* (with a length) or *infinite*.
- As an object, it may be *mutable* (elements can change) or *immutable*.
- There are numerous alternative interfaces (i.e., sets of operations) for manipulating it.
- And, of course, numerous alternative implementations.
- Today: immutable, finite sequences, recursively defined.
A Recursive Definition

- A possible definition: A sequence consists of
  - An empty sequence, or
  - A first element and a sequence consisting of the elements of the sequence other than the first—the rest of the sequence or tail.

- The definition is clearly recursive ("a sequence consists of ... a sequence ..."), so let’s call it an rlist for now.

- Suggests the following ADT interface:

```python
empty_rlist = ...
def make_rlist(first, rest = empty_rlist):
    """A recursive list, r, such that first(r) is FIRST and rest(r) is REST, which must be an rlist."""
def first(r):
    """The first item in R."""
def rest(r):
    """The tail of R."""
def isempty(r):
    """True iff R is the empty sequence""
```
Implementation With Pairs

- An obvious implementation uses two-element tuples (pairs), such as those defined in lecture 8.

- The result is called a **linked list**.

```python
empty_rlist = None
def make_rlist(first, rest = empty_rlist):
    return cons(first, rest)
def first(r):
    return left(r)
def rest(r):
    return right(r)
def isempty(r):
    return r is None
```
Implementation With Pairs (II)

- This implementation is rather trivial. Basically, we've done nothing but give new names to the functions in the pair interface defined in lecture 8.

- In fact, we could have defined everything like this:

```python
code
empty_rlist = None
make_rlist = cons
first = left
rest = right
def isempty(r):
    return r is None
```
Box-and-Pointer Diagrams for Linked Lists

• Diagrammatically, one gets structures like this:
  # The sequence containing: 8; the sequence containing 5 and 3;
  # and the empty sequence
  Q = make_rlist(5, make_rlist(3, empty_rlist))
  L = make_rlist(8,
                  make_rlist(Q, make_rlist(empty_rlist, empty_rlist)))
  # or
  # Q = make_rlist(5, make_rlist(3))
  # L = make_rlist(8, make_rlist(Q, make_rlist(empty_rlist)))

L: 8 → Q → 5 → 3
From Recursive Structure to Recursive Algorithm

• The cases in the recursive definition of list often suggest a recursive approach to implementing functions on them.

• Example: length of an rlist:

```python
def len_rlist(s):
    # A sequence is:
    """The length of rlist ‘s’.""
    if isempty(s):
        # Empty or...
        return 0
    else:
        return 1 + len_rlist(rest(s))
        # A first element and
        # the rest of the list
```

• Q: Why do we know the comment is accurate?

• A: Because we assume the comment is accurate! (For “smaller” arguments, that is).

• An example of reasoning by structural induction...

• ...or recursive thinking about data structures.
Another Example: Selection

- Want to extract item \#k from an rlist (number from 0).
- Recursively:

```python
def getitem_rlist(s, i):
    """Return the element at index ‘i’ of recursive list ‘s’."
    >>> L = make_rlist(2, make_rlist(3, make_rlist(4)))
    >>> getitem_rlist(L, 1)
    3"

    if ________:
        return ________
    else:
        return ________
```
getitem_rlist (II)

- Want to extract item \#k from an rlist (number from 0).
- Recursively:

```python
def getitem_rlist(s, i):
    "Return the element at index ‘i’ of recursive list ‘s’."

    if i == 0:
        return first(s)
    else:
        return getitem_rlist(rest(s), i-1)
```
Iterative Version of getitem_rlist

- Want to extract item #k from an rlist (number from 0).
- Recursively:

  ```python
def getitem_rlist(s, i):
    "Return the element at index ‘i’ of recursive list ‘s’."

    if i == 0:
      return first(s)
    else:
      return getitem_rlist(rest(s), i-1)
  ```

  ```python
def getitem_rlist(s, i):
    "Return the element at index ‘i’ of recursive list ‘s’."  
    while ________________:

      ____, ____ = ________________

    return ________________
  ```
Iterative Version of `getitem_rlist` (II)

```python
def getitem_rlist(s, i):
    "Return the element at index ‘i’ of recursive list ‘s’."

    if i == 0:
        return first(s)
    else:
        return getitem_rlist(rest(s), i-1)

def getitem_rlist(s, i):
    "Return the element at index ‘i’ of recursive list ‘s’."

    while i != 0:
        s, i = rest(s), i-1
    return first(s)
```

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On to Higher Orders!

```python
def map_rlist(f, s):
    """The rlist of values F(x) for each element x of rlist S (in the same order.)""
    if ________:
        return ________
    else:
        return ________
```
def map_rlist(f, s):
    """The rlist of values F(x) for each element x of rlist S (in the same order.)""
    if isempty(s):
        return empty_rlist
    else:
        return make_rlist(f(first(s)), map_rlist(f, rest(s)))

- So map_rlist(lambda x:x**2, L) produces a list of squares.
- [Python 3 produces a different kind of result from its map function; we'll get to it.]
- Iterative version not so easy here!
Filtering

• Map unconditionally applies its function argument to elements of a list. It is essentially a loop.

• The analog of applying an if statement to items in a list is called filtering:

```python
def filter_rlist(cond, seq):
    """The rlist consisting of the subsequence of rlist ‘seq’ for which the 1-argument function ‘cond’ returns a true value.""

    if ______: return ______

    elif ______: return ______

    else: return ______
```
def filter_rlist(cond, seq):
    """The rlist consisting of the subsequence of
    rlist 'seq' for which the 1-argument function 'cond'
    returns a true value."""

    if isempty(seq): return empty_rlist

    elif __???__: return ________

    else: return ________
def filter_rlist(cond, seq):
    """The rlist consisting of the subsequence of
    rlist `seq` for which the 1-argument function `cond`
    returns a true value."""

    if isempty(seq): return empty_rlist

    elif cond(first(seq)): return ________

    else: return ________
def filter_rlist(cond, seq):
    """The rlist consisting of the subsequence of
    rlist 'seq' for which the 1-argument function 'cond'
    returns a true value.""

    if isempty(seq): return empty_rlist

    elif cond(first(seq)): ??

    else: return filter_rlist(cond, rest(seq))
Filtering (V)

```python
def filter_rlist(cond, seq):
    """The rlist consisting of the subsequence of rlist `seq' for which the 1-argument function `cond' returns a true value."""

    if isempty(seq):
        return empty_rlist

    elif cond(first(seq)):
        return make_rlist(first(seq),
                          filter_rlist(cond, rest(seq)))

    else:
        return filter_rlist(cond, rest(seq))
```

- Oops! Not tail-recursive. Iteration is problematic (again).
- In fact, until we get to talking about mutable recursive lists, we won't be able to do it iteratively without creating an extra list along the way.
Python’s Sequences

- Rlists are sequences with a particular choice of interface that emphasizes their recursive structure.

- Python has a much different approach to sequences built into its standard data structures, one that emphasizes their iterative characteristics.

- There are several different kinds of sequence embodied in the standard types: tuples, lists, strings, ranges, iterators, and generators.

- Python goes to some lengths to provide a uniform interface to all the various sequence types, as well as to its other collection types, including sets and dictionaries.
Sequence Features

- For now, we emphasize computation by *construction* rather than *modification*. The interesting characteristics include:

  - **Explicit Construction:**
    
    ```python
    t = (2, 0, 9, 10, 11)  # Tuple
    L = [2, 0, 9, 10, 11]  # List
    R = range(2, 13)       # Integers 2-12.
    R0 = range(13)         # Integers 0-12.
    E = range(2, 13, 2)    # Even integers 2-12.
    S = "Hello, world!"   # Strings (sequences of characters)
    ```

  - **Indexing:**
    
    ```python
    t[-1] == t[len(t)-1] == 11
    S[1] == "e"
    ```

  - **Slicing:**
    
    ```python
    t[1:4] == (t[1], t[2], t[3]) == (0, 9, 10),
    t[2:] == t[2:len(t)] == (9, 10, 11)
    t[::2] == t[0:len(t):2] == (2, 9, 11),  t[:::-1] == (11, 10, 9, 0, 2)
    ```
Sequence Combination and Conversion

- Sequence types can be converted into each other where needed:
  
  ```
  list((1, 2, 3)) == [1, 2, 3],  
tuple([1, 2, 3]) == (1, 2, 3)
  list(range(2, 10, 2)) == [2, 4, 6, 8]
  list("ABCD") = ['A', 'B', 'C', 'D']
  ```

- One can construct certain sequences (tuples, lists, strings) from smaller ones:
  
  ```
  A = [1, 2, 3, 4]  
  B = [7, 8, 9]  
  A + B == [1, 2, 3, 4, 7, 8, 9]  
  A[1:3] + B[1:] = [1, 2, 3, 8, 9]  
  (1, 2, 3, 4) + (7, 8, 9) = (1, 2, 3, 4, 7, 8, 9)
  "Hello," + " " + "world" = "Hello, world"
  (1, 2, 3, 4) + 3  ERROR (why?)
  ```
Sequence Iteration: For Loops

- We can write more compact and clear versions of `while` loops:

  ```python
  >>> t = (2, 0, 9, 10, 11)
  >>> s = 0
  >>> for x in t:
  >>>     s += x
  >>> print(s)
  32
  ```

- Iteration over numbers is really the same, conceptually:

  ```python
  >>> s = 0
  >>> for i in range(1, 10):
  >>>     s += i
  >>> print(s)
  45
  ```
Higher-Order Manipulation of Sequences

- Python 3 defines `map` (just as on rlists), as well as `accumulate` (called `reduce` in the module `functools`), and `filter`, just as we did on rlists.

- So to compute the sum of the even Fibonacci numbers among the first 12 numbers of that sequence, we could proceed like this:

  First 20 integers:
  
  0 1 2 3 4 5 6 7 8 9 10 11

  Map fib:

  0 1 1 2 3 5 8 13 21 34 55 89

  Filter to get even numbers:

  0 2 8 34

  Reduce to get sum:

  44

  ... or:

  reduce(add, filter(iseven, map(fib, range(12)))) # or
  sum(filter(iseven, map(fib, range(12)))) # Specialized reduction

- Why is this important? Sequences are amenable to parallelization.
List Comprehensions

• In fact, one doesn't often need `map` and `filter` because Python has a succinct syntax for expressing their application: the list comprehension.

• Full form:

\[
[\text{ <expression> for <var> in <sequence expression> if <boolean expression>} ]
\]

• Example: Squares of the prime numbers up to 100.

\[
[ x^2 \text{ for } x \text{ in range}(101) \text{ if isprime}(x) ]
\]

• A different variety is the `generator`, which can be useful in reductions:

\[
\text{sum}( ( x^2 \text{ for } x \text{ in range}(101) \text{ if isprime}(x) ) )
\]

...because it does not actually construct the list. More on generators later.
An aside: Sequences in Unix

- Many Unix utilities operate on *streams of characters*, which are sequences.
- With the help of pipes, one can do amazing things. One of my favorites:

```
tr -c -s ’[:alpha:]’ ’[\n*]’ < FILE | \
  sort | \
  uniq -c | \
  sort -n -r -k 1,1 | \
  sed 20q
```

which prints the 20 most frequently occurring words in FILE, with their frequencies, most frequent first.