Lab Instructions - session 1

Introduction to numpy and matplotlib

A review of numpy arrays and matrices + matplotlib

Open an interactive Python environment (python shell, ipython shell, Jupyter notebook, Google Colab), run the following commands, and see the output. Do not close the environment

Creating numpy arrays

```
>>> l = [1,2,3]
>>> l
>>> import numpy
>>> a = numpy.array(l)
>>> a
>>> a[2] = 300
>>> a

>>> type(l)
>>> type(a)

>>> import numpy as np
>>> a = np.array(l)
>>> a

>>> a = np.zeros(10)
>>> a
>>> a.dtype
>>> a[2] = 4
>>> a

>>> a = np.zeros(10, dtype=np.int64)
>>> a
>>> a.dtype
>>> a = np.ones(10)
>>> a
>>> a = np.ones(10) * -20
>>> a
>>> np.full(10, 222)
>>> a = np.arange(10)
>>> a
>>> 2**a
```

Numpy array basic properties

```
>>>  a = np.ones(10000)
>>>  len(a)
>>>  a.shape
>>>  type(a)
>>>  a.size
>>>  a.ndim
>>>  a.dtype
>>>  a.nbytes
>>>  a.itemsize

>>>  import sys
>>>  sys.getsizeof(a)
```

- Why are the outputs of `a.nbytes` and `sys.getsizeof(a)` different?

Lists vs. numpy arrays

```
>>>  l1 = [1,2,3]
>>>  l2 = [4,5,6]
>>>  a1 = np.array(l1)
>>>  a2 = np.array(l2)
>>>  l1+l2
>>>  a1+a2
```

Data types

```
>>>  a = np.array([1,2,3,4,5,6,7,8,9,10], dtype=np.int64)
>>>  b = np.array([1,2,3,4,5,6,7,8,9,10], dtype=np.int32)
>>>  c = np.array([1,2,3,4,5,6,7,8,9,10], dtype=np.int16)
>>>  d = np.array([1,2,3,4,5,6,7,8,9,10], dtype=np.int8)
>>>  e = np.array([1,2,3,4,5,6,7,8,9,10], dtype=np.uint8)
>>>  print(a.itemsize, b.itemsize, c.itemsize, d.itemsize, e.itemsize)
>>>  print(a.nbytes, b.nbytes, c.nbytes, d.nbytes, e.nbytes)

>>>  d-4
>>>  e-4

>>>  f = np.array([1,2,3,4,5,6,7,8,9,10], dtype=np.float32)
>>>  g = np.array([1,2,3,4,5,6,7,8,9,10], dtype=np.float64)
>>>  h = np.array([1,2,3,4,5,6,7,8,9,10], dtype=np.float128)
>>>  print(f.nbytes, g.nbytes, h.nbytes)

>>>  l = np.array([False, True, True])
>>>  l.dtype
```

```
>>>  l = np.array([0, 1, 1], dtype=np.bool)
>>>  l.dtype
>>>  l.nbytes
```

Basic operations

```
>>>  a = np.array([1,2,3])
>>>  b = np.array([4,5,6])
>>>  a+b
>>>  a-b
>>>  a*b
>>>  b**a
>>>  a + 4
>>>  a * 2
>>>  a ** 2
>>>  a.dtype
>>>  a/b       # different in pythons 2.x and 3.x
>>>  a//b

>>>  a = np.array([1.0,2,3])
>>>  a
>>>  a.dtype
>>>  a / b
>>>  a//b    # different in pythons 2.x and 3.x

>>>  a = np.array([1,2,3], dtype=np.float64)
>>>  a
>>>  a.dtype
```

Slicing

```
>>>  a = np.array([0,10,20,30,40, 50, 60, 70, 80, 90, 100])
>>>  a
>>>  a[2]
>>>  a[-2]
>>>  a[2:8]
>>>  a[2:-1]
>>>  a[2:]
>>>  a[:8]
>>>  a[2:8:2]
>>>  a[2:8:-1]
>>>  a[8:2:-1]
>>>  a[::-1]
>>>  a[[1,3,3,4,5]]
```

2D Arrays

```
>>>   A = np.zeros((4,6))
>>>   A
>>>   A = np.zeros((4,6), dtype=np.int32)
>>>   A
>>>   A = np.ones((3,7))
>>>   A
>>>   A = np.ones((3,8), dtype=np.uint8)
>>>   A
>>>   np.full((4,3), 50.0)
>>>
>>>   A = np.array([[1,2,3,4], [5,6,7,8], [9,10,11,12]])
>>>   A[1,2]
>>>   A[0,-1]
>>>   A[1,2]
>>>   A.shape
>>>   A.shape[0]
>>>   A.shape[1]
>>>   A.shape[::-1]
>>>   A.size
>>>   A.ndim
>>>
>>>   A[0]
>>>   A[1]
>>>   A[0].shape
>>>   A[0,:]
>>>   A[0,:].shape
>>>   A[[0],:]
>>>   A[[0],:].shape
>>>   A[:,2]
>>>   A[:,[2]]
>>>   A[:,2].shape
>>>   A[:,[2]].shape
>>>
>>>   A[1:3]
>>>   A[1:3, :]
>>>   A[:,:3]
>>>   A[:,::2]
>>>   A[:,::-1]
>>>
>>>   r = np.array([0, 1, 0, 2, 2])
>>>   A
>>>   r
>>>   A[r,:]
>>>
>>>
>>>   A
```

```
>>>  A[:,0] = 1
>>>  A
>>>  A[:,0] = [20,30,40]
>>>  A
>>>
>>>  A
>>>  A.T
>>>
>>>  B = np.array([[1,1,1,1], [2,2,2,2], [3,3,3,3]])
>>>  A
>>>  B
>>>  A + B
>>>  A * B
>>>
>>>  np.dot(A,B)
>>>  A.dot(B)
>>>  A @ B
>>>  A.dot(B.T)
>>>
>>>  I = np.eye(3)
>>>  I
>>>
>>>  np.random.random((2,3))
>>>  np.random.random((2,3))
>>>  np.random.random((2,3))
>>>
>>>  np.random.rand(2,3)
>>>  np.random.rand(2,3)
>>>
>>>  np.random.randn(2,3)
>>>  np.random.randn(2,3)
```

Numpy slices are references (not copies)

```
>>> A = np.array([[1,2,3,4], [5,6,7,8], [9,10,11,12]])
>>> b = A[:,1]
>>> b
>>> A
>>> b[1] = 10000
>>> b
>>> A

>>> b = A[:,0].copy()
>>> b
>>> b[1] = -20000
>>> b
>>> A
```

Masks

```
>>>  A = np.array([[1,2,3,4],
                   [5,6,7,8],
                   [9,10,11,12]])
>>>  Mask = np.array([[True,  False,  True,  False],
>>>                   [True,  True,   False, False],
>>>                   [False, False,  False,  True]])
>>>  Mask.dtype
>>>  A
>>>  A[Mask]
>>>  A[~Mask]
>>>  A[Mask] = 222
>>>  A
>>>  A[~Mask] *= 2
>>>  A

>>>  A = np.array([[1,2,3,4], [5,6,7,8], [9,10,11,12]])

>>>  B = np.zeros_like(A)
>>>  B[Mask] = A[Mask]
>>>  B

>>>  A > 2
>>>  Mask = A < 8
>>>  Mask
>>>  A[Mask]
>>>  A[A < 8]
>>>  A[A < 8] += 100
>>>  A
```

Operations on arrays

```
>>>  A = np.array([[1,2,3,4], [5,6,7,8], [9,10,11,12]])
>>>  A.sum()
>>>  A.sum(axis=0)
>>>  A.sum(axis=1)
>>>  A.min()
>>>  A.min(axis=0)
>>>  A.max(axis=0,keepdims=True)
>>>
>>>  A.max(axis=1)
>>>  A.max(axis=1,keepdims=True)
>>>  A.mean(axis=1)
>>>
>>>  A.prod(axis=0)
```

Concatenation

```
>>>  X = np.array([[1,2],[3,4]])
>>>  Y = np.array([[10,20,30],[40,50,60]])
>>>  Z = np.array([[7,7],[8,8],[9,9]])
>>>  X
>>>  Z
>>>  np.concatenate((X,Z))
>>>  np.concatenate((X,Z), axis=0)
>>>  X
>>>  Y
>>>  np.concatenate((X,Y), axis=1)
>>>  np.vstack((X,Z))
>>>  np.r_[X,Z]
>>>  np.hstack(X,Y)     # error
>>>  np.hstack((X,Y))
>>>  np.c_[X,Y]
>>>  Y
>>>  np.tile(Y,(4,3))
```

Reshaping

```
>>>  A = np.array([[1,2,3,4], [5,6,7,8], [9,10,11,12]])
>>>  A.reshape((4,3))
>>>  A.reshape((2,6))
>>>  A.reshape((2,7))
>>>  A.reshape((1,12))
>>>  A.reshape((12,1))
>>>  A.reshape((12,))

>>>  b = A.ravel()
>>>  b
>>>  b.shape
>>>  b.reshape((2,6))

>>>  b
>>>  b.shape = (2,6)
>>>  b

>>>  f = A.flatten()
>>>  r = A.ravel()
>>>  f
>>>  r

>>>  f[0] = 4444
>>>  f
>>>  A
```

```
>>> r[0] = 4444
>>> r
>>> A
```

- What is the difference between **ravel** and **flatten**? Which one do you think is faster?

Numpy arrays vs numpy matrices

```
>>> A = np.array([[1,2,3], [1,1,1], [-1,-2,-1]])
>>> A
>>> A*A        # element-wise multiplication
>>> A.dot(A)   # matrix multiplication
>>> A @ A      # matrix multiplication (same as above)
>>>
>>> M = np.matrix([[1,2,3], [1,1,1], [-1,-2,-1]])
>>> M*M
>>> np.multiply(M,M)

>>> M=np.mat(A)
>>> M
>>> M=np.matrix(A)
>>> M
>>> M.T
>>> M.I
>>> M.I * M
>>> M * M.I
>>> M.A
>>> type(M)
>>> type(M.A)

>>> C = np.matrix("1 2; 3 4; 5 6")
>>> C
>>> M*C
```

N-dimensional arrays

```
>>> A = np.zeros((2,4,3))
>>> A
>>> A.shape

>>> A[:,:,0].shape
>>> A[:,:,0] = [[1,2,3,4],[5,6,7,8]]
>>> A[:,:,1] = [[2,2,2,2],[4,4,4,4]]
>>> A[:,:,2] = [[10,20,30,40],[11,21,31,41]]
>>> A
```

```
>>>
>>> A[0,:,:]
>>> A[0]

>>> A[:,1,:]
>>> A[:,1]
>>> A[:,[1]]

>>> A[:,1].shape
>>> A[:,[1]].shape

>>> A[:,:,0]
>>> A[:,:,2]
>>> A[:,2:,2]
>>> A.ravel()
```

Broadcasting

```
>>> A = np.array([0,1,2,3,4,5,6,7])
>>> A - 10
>>> a = np.array([4])
>>> A * a
>>>
>>> A = np.array([[1,2,3,4], [5,6,7,8], [9,10,11,12]])
>>> b = np.array([1, 0, 2,-2])
>>> A
>>> b
>>> A-b
>>>
>>> c = np.array([1,2,3])
>>> A-c
>>> A-c.reshape((3,1))
>>>
>>>
>>> A = np.arange(24).reshape((2,3,4))
>>> A.shape
>>> A - 2
>>> A - np.array([1,2])
>>> A - np.array([1,2,3,4])
>>> A - np.array([1,2,3])
>>> A - np.array([1,2,3]).reshape((3,1))
>>> A - np.array([1,2])
>>> A - np.array([1,2]).reshape((2,1,1))
>>> A - np.array([[1,2,3,4],[5,6,7,8], [9,10,11,12]])
>>> A - np.array([[1,2,3,4],[5,6,7,8]])
>>> A - np.array([[1,2,3,4],[5,6,7,8]]).reshape((2,1,4))
```

To get a better understanding of broadcasting, read the following (particularly the broadcasting rules) https://numpy.org/doc/stable/user/basics.broadcasting.html

Math functions

```
>>> x = np.arange(0, 2 * np.pi, 0.1)
>>> x
>>> y = np.cos(x)
>>> y
>>> np.sin(x)
>>> np.tan(x)


>>> x = np.linspace(1,8,20)
>>> x
>>> x.shape
>>> np.exp(x)

>>> np.log(x)
>>> np.log10(x)
>>> np.log2(x)
>>> np.floor(x)
>>> np.ceil(x)
>>> np.round(x)

>>> np.sqrt(x)
>>> np.arctan(x)
```

- Here you can find a list of numpy math functions:
    - https://numpy.org/doc/stable/reference/routines.math.html

Plotting with Matplotlib

```
>>> from matplotlib import pyplot as plt
>>>
>>> x = np.arange(0, 2 * np.pi, 0.1)
>>> x
>>> y = np.cos(x)
>>> y
>>> plt.plot(x,y)
>>> plt.show()

>>> plt.plot(x,np.sin(x))
>>> plt.plot(x,np.cos(x))
>>> plt.show()
```

Reading and storing audio files

Read the following code (audio.py in the supplementary files) and run it.

audio.py

```
import numpy as np
import scipy.io.wavfile
import matplotlib.pyplot as plt

sampling_rate, data = scipy.io.wavfile.read('voice1.wav')

print('samping rate:', sampling_rate) # frequency (sample per second)
print('data type:', data.dtype)
print('data shape:', data.shape)

N, no_channels = data.shape # signal length and no. of channels

print('signal length:', N)

channel0 = data[:,0]
channel1 = data[:,1]

scale = 2**np.linspace(-2,4, N)

plt.plot(np.arange(N), scale)
plt.show()

print('shape_old:', scale.shape)
scale.shape = (N,1)
print('shape_new:', scale.shape)

data_new = np.int16(scale * data)

scipy.io.wavfile.write('output1.wav', sampling_rate, data_new)
```

- Play the audio file **voice1.wav**.
- Run the code to create **output1.wav**. Play the output audio file **output1.wav**.
- What is the above doing?
- What data type has been used for storing audio signals in a **.wav** file? Is it signed or unsigned?
- What are the variables **`N`** and **`sampling_rate`**. The audio signal has N samples played at **`sampling_rate`** samples per second. Calculate the length of the signal in seconds. Verify your answer by opening **`voice1.wav`** in an audio player.
- Why does the array **`data`** have two columns? What are the columns of **`data`**? Is this a mono or stereo audio?
- What is the array **`scale`**? How is it used here?

- Why did we change the shape of the **`scale`** array from **`N`** to **`(N,1)`**?
- What does the line **`data_new = np.int16(scale * data)`** do?
- Why did we cast the output data to **`int16`** (16-bit signed integer)?

Reading and displaying images

```
>>> from matplotlib import pyplot as plt

>>> I = plt.imread('masoleh_gray.jpg')
>>> I.shape
>>> I.dtype
>>> plt.imshow(I)
>>> plt.show()
>>> plt.imshow(I,cmap='gray')
>>> plt.show()
>>>
>>> plt.imshow(I[100:200,50:250],cmap='gray')
>>> plt.show()
```

Task 1 - Practice Vectorization

Consider an arbitrary **A** matrix like

```
A = np.random.rand(200,10)
```

We perform the following operation on **A** to create the matrix **B**.

```
mu = np.zeros(A.shape[1])
for i in range(A.shape[0]):
    mu += A[i]
mu /= A.shape[0]

B = np.zeros_like(A)
for i in range(A.shape[0]):
    B[i] = A[i] - mu
```

- What does the above piece of code do?
- Write an equivalent program ***without loops***. Do it in just **a single line of code**. (Hint: look at the **Broadcasting** section).

```
B = ...
```

Task 2

Plot the two channels of the input audio file (columns of the array `data`).

- Plot the two channels together in the same axes (like in the **sin** and **cos** example above)
- Analyse the audio signal. How does it correspond to what is said in the audio file?
- Use the zoom tool to zoom in the plot. How does an audio signal look like?
- Plot both channels using a single `plt.plot` function. This can be done by directly giving the array `data` as the second argument of `plt.plot`.
- Plot the channels of the output data (`data_new`). How has the shape changed compared to the input signal? Why?

Task 3

- Save the output audio using a different sampling rate. Try different choices such as `sampling_rate*2` and `sampling_rate//2`. What happens?

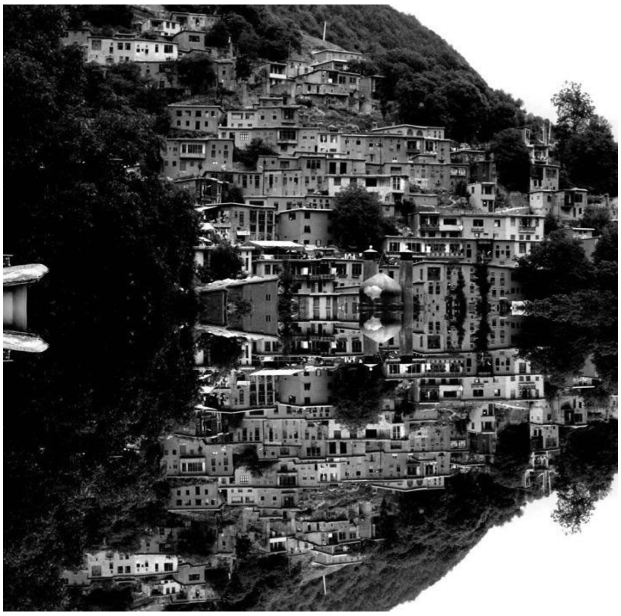
Task 4

Change the file `audio.py` to, instead of scaling the signal, reverse it. Play the output to see how the audio sounds when played backwards.

- (Optional) Try using it on different audio files. Combine it with task 2. Have fun!

Task 5

Read the image 'masoleh_gray.jpg' and create a new image by vertically concatenating it with its vertically inverted image (like below). Display the new image.



References

1. Numpy Quickstart https://numpy.org/doc/stable/user/quickstart.html
2. https://docs.scipy.org/doc/numpy-dev/user/numpy-for-matlab-users.html
3. https://docs.scipy.org/doc/numpy-dev/user/quickstart.html
4. http://cs231n.github.io/python-numpy-tutorial
5. Broadcasting https://numpy.org/doc/stable/user/basics.broadcasting.html