Python & NumPy Primer

IC-CVLab

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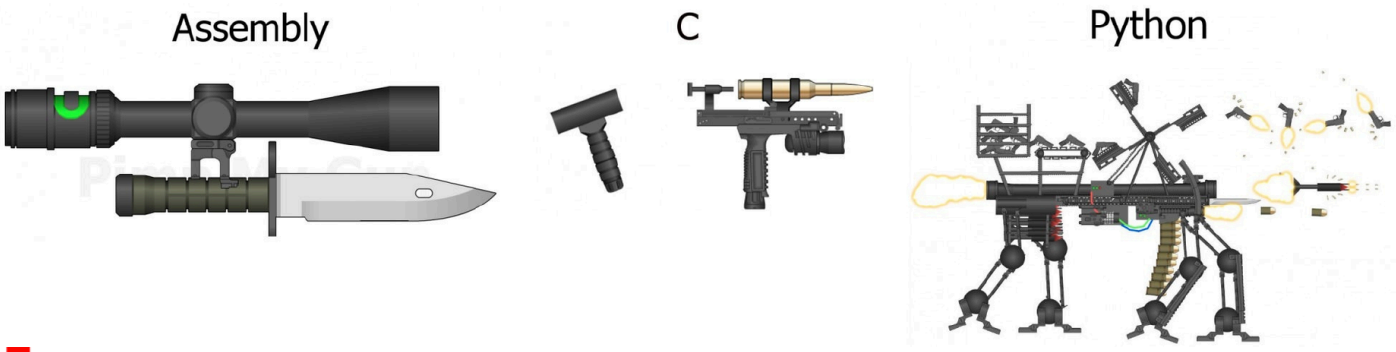
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Python

About Python

- High-level, focus on **readable and concise code** - fast prototyping.
- **Interpreted** language, **dynamic typing** - very flexible.
- **Slow run-time** (dynamic typing, memory management, …)
  - Unless compiled to parallelized machined code (**Numba**) https://public-cvlab.epfl.ch/articles/2020/n-queens-numba/
- Quick-and-dirty scripting, **glue code** - combine components written in other languages (NumPy, SciPy, scikit-learn).
- Vast amount of **libraries** - from backend web development, games to data science.



Working with Python

Installation

- Install the **interpreter** and **packages** manually
  - OSX and some Linux distributions already include Python
  - pip - package installer

- Get a readily available **distribution**
  - Anaconda

Running

- Terminal (interactive or script mode)

```
$ python
>>> print('hello CS322')
'hello CS322'
>>> # Use Ctrl-D, Ctrl-Z or quit() to exit
```

```
$ python my_script.py
'hello 'CS322'
```

- Jupyter Notebook

Data Types

- Python is **dynamically** typed language.
  - Data type inferred at runtime.
  - Can change during runtime.

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

```
>>> a = 'python is fun'
>>> print(type(a))
<class 'str'>
```

- function **type()** returns the type of a value.

```
>>> a = 42          → int
>>> a = 3.142       → float 64 bit
>>> a = 3.          → float 64 bit
>>> a = 2+3j        → Complex
>>> a = True        → bool
>>> a = None        → None
```

Data Types

- **Strings** can be single, double or triple quoted.

```
>>> a = 'stay strong'
>>> a = "it is not that difficult”

>>> a = """This is a string that will span across
multiple lines. Using newline characters
and no spaces for the next lines."""  # docstring
```

- Quotes do not change anything.

```
>>> a = 'this is a string'
>>> b = "this is a string"
>>> print(b == a)
True
```

ADT(Abstract Data Type) - list

- Contains a series of values.

```
>>> a = []                                  # empty
>>> b = [1, 2, 3, 4]                        # 4 elements
>>> c = [1, 'cat', 0.23]                    # mixed types
>>> d = [1, ['cat', 'dog'], 2, 3] # list in list
```

```
>>> a = ['great', 'minds', 'think', 'alike']
>>> print(a[0]) # zero indexed
'great'
```

```
>>> print(a[0:2]) # from start to end-1
['great', 'minds']
```

```
>>> a[2] = 'look' # manipulate vals at given index
>>> print(a)
['great','minds','look','alike']
```

ADT - list

- Length of a list.

```
>>> a = ['great','minds','think','alike']
>>> print(len(a)) #length of list
4
```

- Adding item to a list.

```
>>> a = ['great', 'minds', 'think', 'alike']
>>> a.append('sometimes')
['great', 'minds', 'think', 'alike', 'sometimes']
```

- Extend a list by another list.

```
>>> a = ['great', 'minds']
>>> b = ['think', 'alike']
>>> c = a + b
['great', 'minds', 'think', 'alike']

>>> a.extend(b) # in place
['great', 'minds', 'think', 'alike']
```

ADT - tuple

- Similar as list but fixed in size and **immutable =** change not allowed.
- Declaration with parentheses.

```
>>> username = ('rick', 'morty', 'beth','squanchy')
>>> print(username[1])
'morty'
```

```
>>> username[0] = 'rick2' # from other universe
TypeError: 'tuple' object does not support
assignment
```

- **Tuple unpacking**

```
>>> a, b = (1, 2)
>>> print(b)
2
```

ADT - dictionary

- Collection of `key:value` pairs
  - Access value with keys
  - Key must be **immutable** and **unique**

```
>>> age = {'carl': 23, 'elis': 25}
>>> print(age['carl'])
23
```

```
>>> age['carl'] = 32 # modify
>>> print(age['carl'])
32
```

```
>>> age['peter'] = 18 # add new key
>>> print(age)
{'carl': 32, 'peter': 18, 'elis': 23}
```

```
>>> print(age.keys()) # get keys
dict_keys(['elis', 'carl', 'peter'])
>>> print(age.values()) # get values
dict_values([25, 23, 18])
```

Type Casting

```
>>> a = 42 # int -> float
>>> a = float(a)
>>> print(a, type(a))
42.0 <class 'float'>
```

```
>>> a = 3.14 # float -> int (floor, not round!)
>>> a = int(a)
>>> print(a, type(a))
3 <class 'int'>
```

```
>>> a = '123' # string -> int
>>> a = int(a)
>>> print(a, type(a))
123 <class 'int'>
```

```
>>> a = 123.14 # float -> string
>>> a = str(a)
>>> print(a, type(a))
'123.14' <class 'str'>
```

Type Casting

```
>>> a = [42, 21.2, 'black'] #list -> tuple
>>> a = tuple(a)
>>> print(a)
(42, 21.2, 'black')
```

```
>>> a = (42, 21.2, 'black') # tuple -> list
>>> a = list(a)
>>> print(a)
[42, 21.2, 'black']
```

EPFL

Functions

```
>>> def print_hello():
        print("hello world”)
```

```
>>> def multiply(a, b):
        return a * b
```

- **Default arguments** and multiple return values.

```
>>> def add(a, b, c=0, d=1):
        return a + b + c + d
>>> add(1, 2, d=5)
8
```

- **Multiple return values** - a function returns a tuple, use **tuple unpacking**.

```
>>> def min_max(l):
    return min(l), max(l)
>>> m, x = min_max([1, 2, 3, 4])
>>> print(m, x)
1, 4
```

Builtin Functions

- Python comes with various useful builtin functions.
- range, zip, type, str, int, sorted, len, sum, max, min, abs, any, all, …

```
>>> list(range(9))
[0, 1, 2, 3, 4, 5, 6, 7, 8]
```

```
>>> x = [1, 2, 3]
>>> y = [4, 5, 6]
>>> zipped = zip(x, y)
>>> list(zipped)
[(1, 4), (2, 5), (3, 6)]
```

```
>>> type('hello')
str
>>> sorted((2, 1, 3))
[1, 2, 3]
>>> sorted('eba')
['a', 'b', 'e']
```

Builtin Functions

```
>>>len('abc')
3
>>>sum([1, 2, 3])
6
>>>max([1, 2, 3])
3
>>> min([1, 2, 3])
1
>>> abs(-2)
2
>>> a = [False, False, True]
>>> any(a)
True
>>> b = [False, False, False]
>>> any(b)
False
>>> c = [True, True, True]
>>> all(c)
True
```

List Comprehensions

- List comprehensions provide a concise way to create lists.
- Loosely follows mathematical set-builder notation.

$\{2^x | x \in \{0...10\}\}$

```
>>> powers2 = [2**x for x in range(11)]
>>> print(powers2)
[1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024]
```

$\{2^x | x \in \{0...10\} \wedge x \text{ is even}\}$

```
>>> powers2ev = [2**x for x in range(11) if x % 2 == 0]
>>> print(powers2ev)
[1, 4, 16, 64, 256, 1024]
```

Import

- Gains access to code in another **module** by **importing** it.

```
>>> import numpy
>>> x = numpy.arange(5)
```

- Import module or just specified functions/variables/classes from the module.

```
>>> from numpy import arange
>>> x = arange(5)
```

- Select a name for imported module.

```
>>> import numpy as np
>>> x = np.arange(5)
```

Getting help

- In Jupiter Notebook - function name with “?”.

```
>>> sum?
Signature: sum(iterable, start=0, /)
Docstring:
Return the sum of a 'start' value (default: 0)
plus an iterable of numbers

When the iterable is empty, return the start value.
This function is intended specifically for use with
numeric values and may reject non-numeric types.
Type:      builtin_function_or_method
```

- Read (Python and NumPy) documentation.

NumPy

About NumPy

- Core library for **scientific computing** in Python.
- High-performance multidimensional array - matrix operations.
- Wide ecosystem of libraries that take NumPy arrays as input.

NumPy Arrays

- **high-performance multidimensional** arrays.
- A grid of values, all of the **same type**.
- Indexed by a tuple of nonnegative integers.
  - Indexing syntax similar to lists, tuples, and dictionaries
- The **rank** of the array is the **number of dimensions**

Creating Arrays I

```
# import numpy
>>> import numpy as np

# create a rank 1 array
>>> np.array([1, 2, 3])
array([1, 2, 3])

# create a rank 2 array
>>> np.array([[1, 2, 3], [4, 5, 6]])
array([[1, 2, 3],
       [4, 5, 6]])
```

Creating Arrays II

```
>>> np.zeros((2,3))
array([[0., 0., 0.],
       [0., 0., 0.]])

>>> np.ones((2,3))
array([[1., 1., 1.],
       [1., 1., 1.]])

>>> np.eye(3)
array([[1., 0., 0.],
       [0., 1., 0.],
       [0., 0., 1.]])
```

Creating Arrays III

```
>>> np.arange(1, 7, 1).reshape((2, 3))
array([[1, 2, 3],
       [4, 5, 6]])

>>> np.linspace(1, 5, 9)
array([1. , 1.5, 2. , 2.5, 3. , 3.5, 4. ,4.5, 5. ])
```

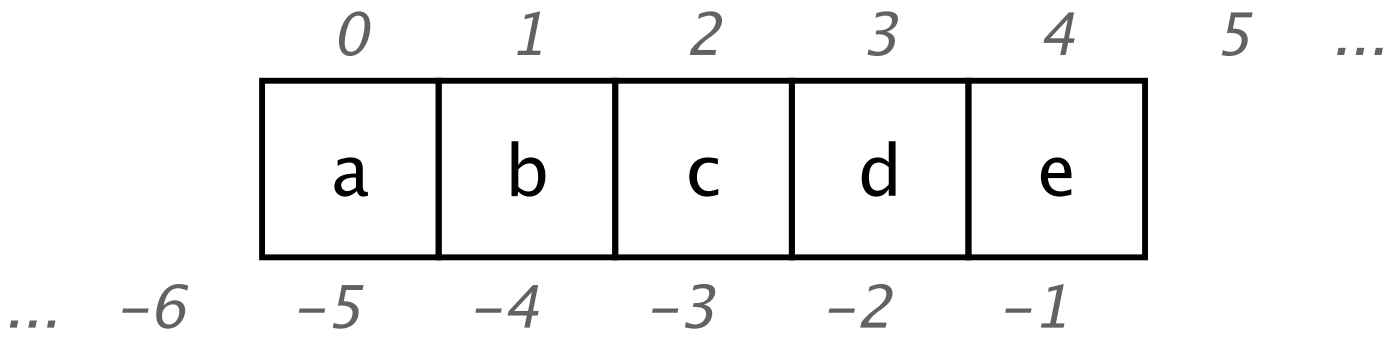
Inspecting Arrays

```
>>> x = np.array([[1, 2, 3], [4, 5, 6]])
array([[1, 2, 3],
       [4, 5, 6]])
```

```
>>> x.shape
(2, 3)

>>> x.ndim
2

>>> x.size
6

>>> x.dtype
dtype('int64')
```

```
>>> y = np.array([1, 2, 3], dtype=np.float32)
>>> y.dtype
dtype('float32')
```

Indexing



- Indexing in python is zero-based.

```
>>> x = ['a', 'b', 'c', 'd', 'e']
>>> x[0]
'a'
```

- The n-th last entry can be indexed by ‘-n’.

```
>>> x[-1]
'e'
```

- For a rank 2 array, the first index refers to the row & the second to the column.

Indexing multidimensional arrays

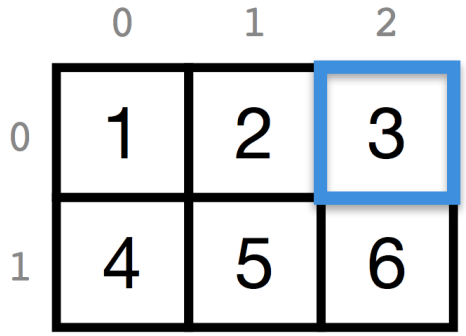
- A `d`-dimensional array - array of `d-1` dimensional arrays
- A 2D numpy array is an array of 1D vectors (rows)

```
>>> m = np.arange(9).reshape((3, 3))
array([[0, 1, 2],
       [3, 4, 5],
       [6, 7, 8]])

>>> m[0]
array([0, 1, 2])

>>> m[1]
array([3, 4, 5])
```

- In the same way, a 3D array is an array of 2D matrices

Indexing multidimensional arrays

- NumPy also allows to index along a specific dimension explicitly



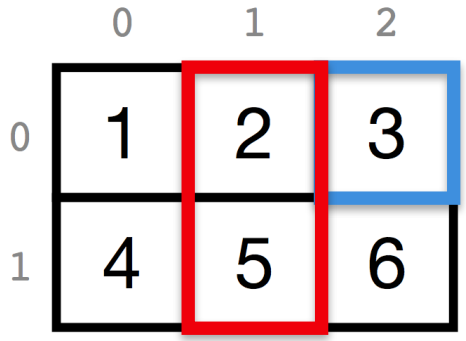
example: **A[0, 2]**

- syntax:
  - **comma** ‘,’ - separate dimensions
  - **colon** ‘**:**’ - get all values in given dimension

```
>>> A = np.array([[1,2,3],[4,5,6]])
>>> print(A)
[[1 2 3]
 [4 5 6]]

>>> print(A[0, 2])
3
```

Indexing multidimensional arrays

- NumPy also allows to index along a specific dimension explicitly



example: **A[0, 2]**

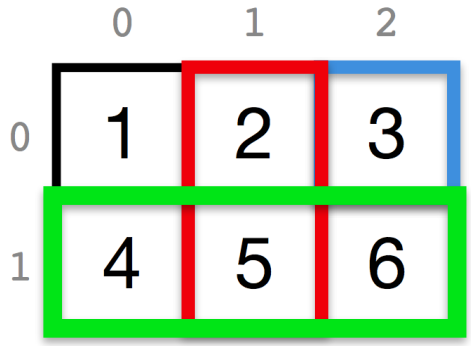
example: **A[:, 1]**

- syntax:
  - **comma** ‘,’ - separate dimensions
  - **colon** ‘:’ - get all values in given dimension

```
>>> A = np.array([[1,2,3],[4,5,6]])
>>> print(A)
[[1 2 3]
 [4 5 6]]

>>> print(A[:, 1])   # all the rows, column 1
array([2, 5])
```

Indexing multidimensional arrays

- NumPy also allows to index along a specific dimension explicitly



example: **A[0, 2]**

example: **A[:, 1]**

example: **A[1, :]**

- syntax:
  - **comma** ‘,’ - separate dimensions
  - **colon** ‘:’ - get all values in given dimension

```
>>> A = np.array([[1,2,3],[4,5,6]])
>>> print(A)
[[1 2 3]
 [4 5 6]]

>>> print(A[1, :])  # all the columns, row 1
array([4, 5, 6])
```

Indexing multidimensional arrays

Structural Indexing

- Syntactic sugar used to add an extra dimension to an existing array.

```
>>> x = np.array([1, 2, 3])
x.shape
(3,)
```

```
>>> x[np.newaxis].shape
(1, 3)

>>> x[:, np.newaxis].shape
(3, 1)
```

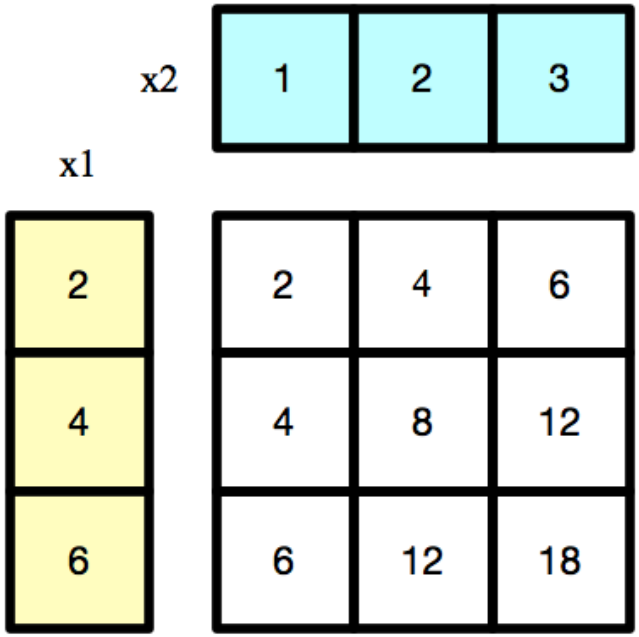
```
>>> y = np.arange(24).reshape((2, 3, 4))
>>> y.shape
(2, 3, 4)

>>> y[:, np.newaxis, :, :].shape
(2, 1, 3, 4)
```

Indexing multidimensional arrays

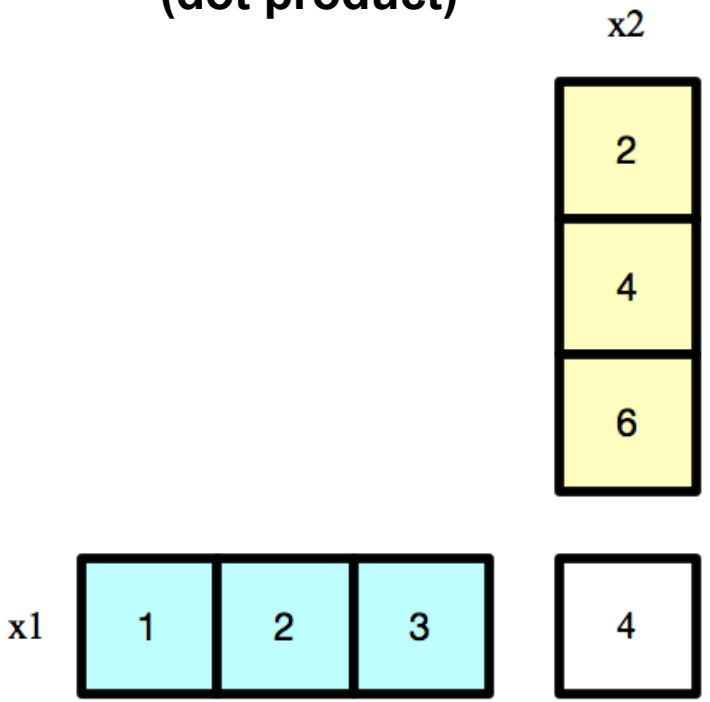
Structural Indexing

- Useful for **broadcasting.**
- Explicit shape, e.g. row/column vectors.

outer product



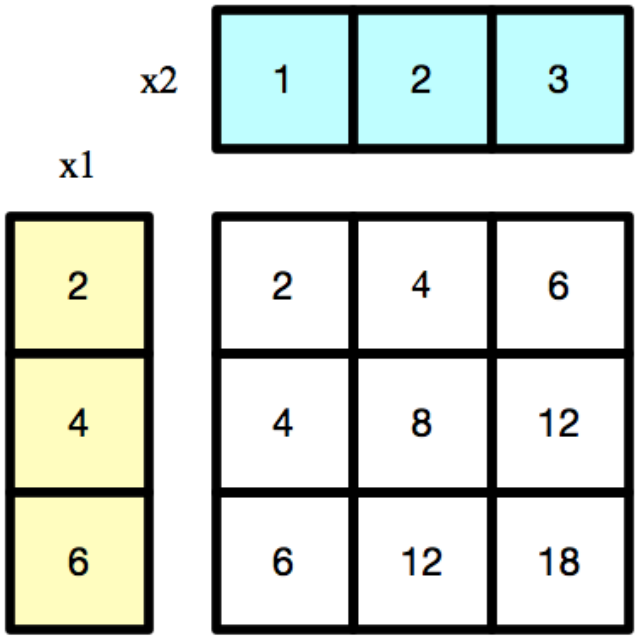
inner product (dot product)



Indexing multidimensional arrays

Structural Indexing

outer product

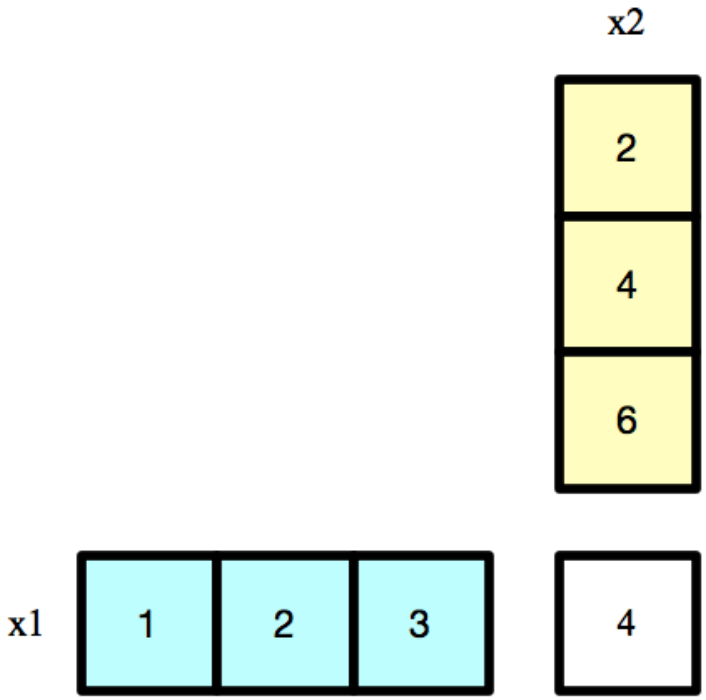



```
>>> x1 = np.array([1, 2, 3])
>>> x2 = np.array([2, 4, 6])

>>> x1 = x1[:, np.newaxis]
>>> x1.shape
(3, 1)

>>> x2 = x2[np.newaxis]
>>> x2.shape
(1, 3)

>>> x1 @ x2
array([[ 2,  4,  6],
       [ 4,  8, 12],
       [ 6, 12, 18]])
```

Indexing multidimensional arrays

Structural Indexing

inner product (dot product)




```
>>> x1 = np.array([1, 2, 3])
>>> x2 = np.array([2, 4, 6])

>>> x1 = x1[np.newaxis]
>>> x1.shape
(1, 3)

>>> x2 = x2[:, np.newaxis]
>>> x2.shape
(3, 1)

>>> x1 @ x2
array([[28]])
```

Slicing: Basics

- Slicing is indexing of the form [**start : stop : step**]
  - start including
  - stop excluding

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

>>> x[1:10:2]
array([ 2,  4,  6,  8, 10])
```

- If not specified, **start = 0**, **stop = last elem.**, **step = 1**

```
>>> x[::2]
array([ 1,  3,  5,  7, 9])

>>> x[9:0:-1]
array([10,  9,  8,  7,  6,  5,  4,  3,  2])

>>> x[::-1]
array([10,  9,  8,  7,  6,  5,  4,  3,  2,  1])
```

Slicing: Basics

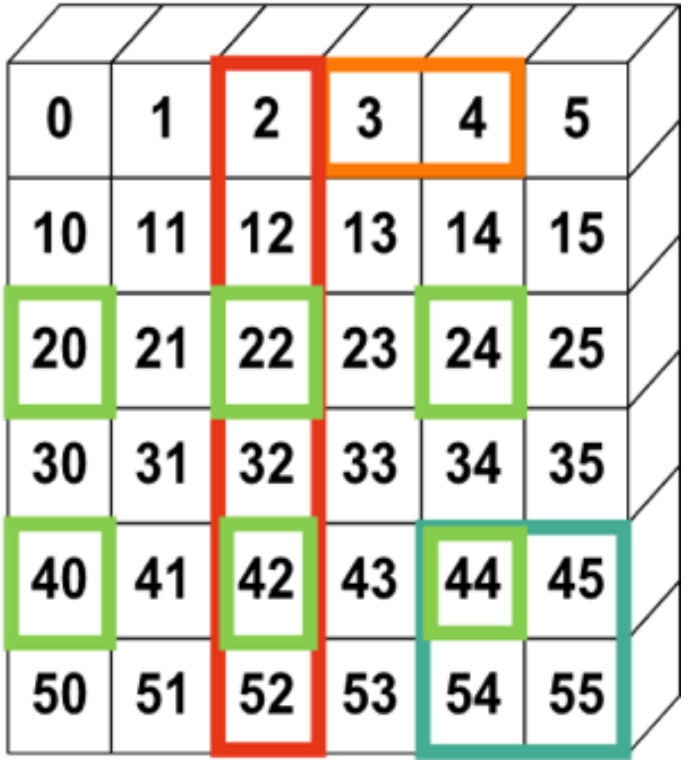
- Slicing provides a ***view*** of the original array.

```
>>> y = x[0:2]
>>> y[:] = 42
>>> x
array([42, 42,  3,  4,  5,  6,  7,  8,  9, 10])
```

Slicing: Example

syntax: **[start : stop : step]**

```
>>> a[0,3:5]
array([3,4])


>>> a[4:,4:]
array([[44, 45],
       [54, 55]])

>>> a[:,2]
array([2,12,22,32,42,52])

>>> a[2::2,::2]
array([[20,22,24]
       [40,42,44]])
```



Masking: Basics

- Masking is indexing an array with an identically shaped **Boolean array**.
- Elements indexed with **True / False** are **taken / discarded**, respectively.

```
>>> x = np.arange(1, 6)
>>> x
array([1, 2, 3, 4, 5])

>>> mask = np.array([True, False, False, True, False])
>>> x[mask]
array([1, 4])
```

Masking: Example

- Get all even numbers in [1, 6] which are multiplies of 3.

```
>>> m = np.arange(1, 7)
array([1, 2, 3, 4, 5, 6])

>>> div2 = (m % 2 == 0)
array([False,  True, False,  True, False,  True])

>>> div3 = (m % 3 == 0)
array([False, False,  True, False, False,  True])

>>> mask = div2 & div3
array([False, False, False, False, False,  True])

>>> m[mask]
array([6])
```

Type casting

- Use `.astype` to convert numpy arrays between types.
- Use `dtype` to check the type.

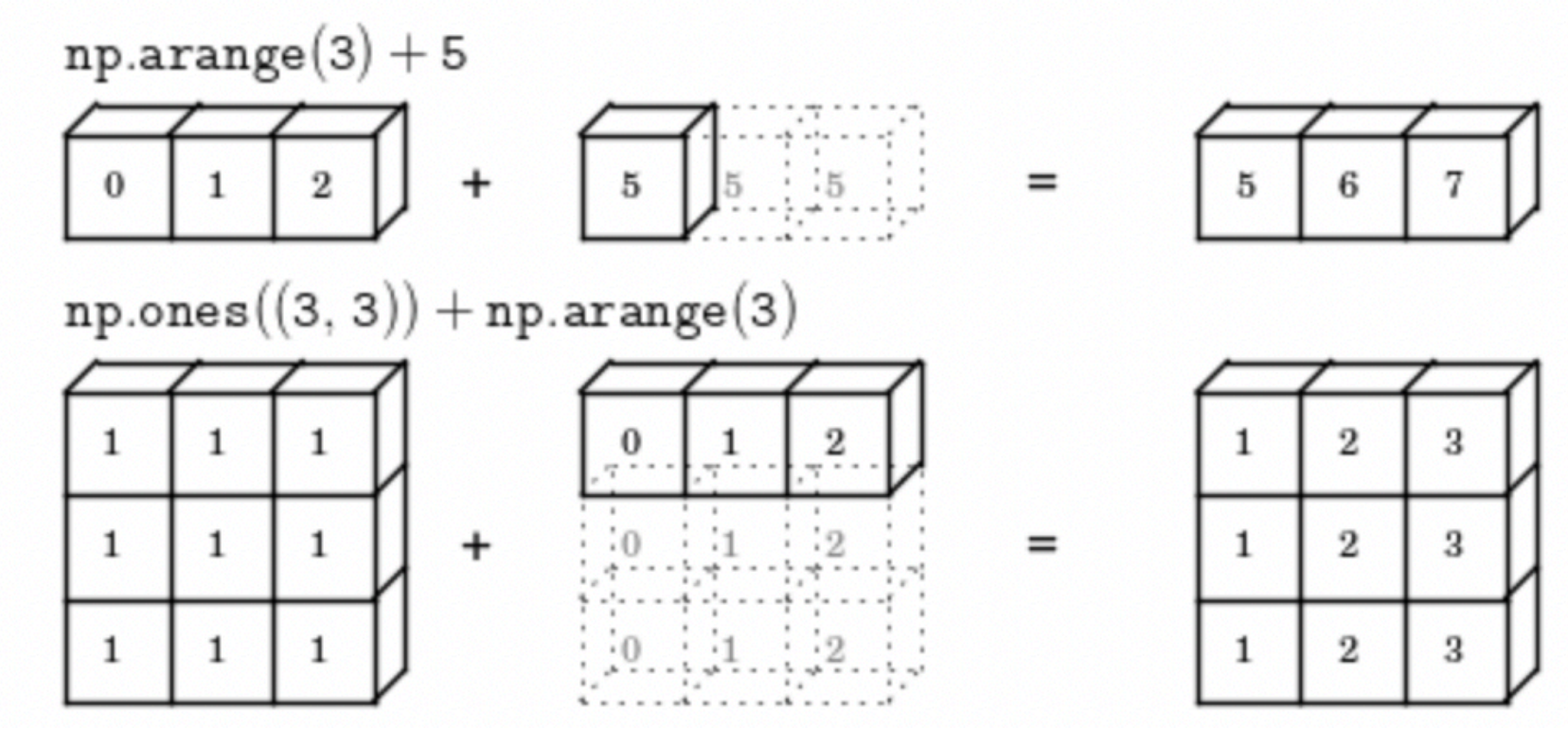
```
>>> m = np.arange(0, 5)
array([ 0, 1, 2, 3, 4])

>>> m.astype(np.float32)
array([ 0., 1., 2., 3., 4.])

>>> m.astype(np.bool)
array([False, True, True, True])

>>> m.dtype
dtype('bool')
```

Broadcasting

- Describes how `numpy` treats arrays with **different shapes** during arithmetic operations.
- **Fast** - operation is **vectorised**, heavily **parallelized**.
- Performed **without making needless copies** of data.

How broadcast works

- Smaller array is “broadcast” across the larger array so that they have compatible shapes



Broadcasting: Basic Example

- Add scalar to every element of a vector.

```
>>> my_vector = np.array([1, 3, 5, 7, 9])
>>> my_scalar = -5
>>> print(my_vector)
[1 3 5 7 9]

>>> new_vector = my_vector + my_scalar
>>> print(new_vector)
[-4 -2 0 2 4]
```

Broadcasting: Advanced Example

- Convert binary numbers (in rows) to decimal

```
>>> bnums = np.random.randint(0, 2, (3, 6))
array([[0, 1, 1, 1, 1, 0],
       [1, 0, 1, 0, 1, 1],
       [0, 0, 1, 1, 1, 1]])

>>> ords = (2 ** np.arange(6))
array([ 1,  2,  4,  8, 16,  32])


>>> dnums = bnums * ords[np.newaxis]
array([[ 0,  2,  4,  8, 16,  0],
       [ 1,  0,  4,  0, 16, 32],
       [ 1,  0,  4,  8, 16, 32]])

>>> np.sum(dnums, axis=1)
array([31, 53, 61])
```

Broadcasting Rules

- The corresponding dimensions of 2 arrays must satisfy one of the following:
  - Same dimension
  - One of the dimensions is 1
- Non-existent dimensions are treated as 1

```
A      (2d array):  5 x 4
B      (1d array):      1
Result (2d array):  5 x 4
```

```
A      (3d array):  15 x 3 x 5
B      (3d array):  15 x 1 x 5
Result (3d array):  15 x 3 x 5
```

```
A      (2d array):  5 x 4
B      (1d array):      4
Result (2d array):  5 x 4
```

```
A      (3d array):  15 x 3 x 5
B      (2d array):       3 x 1
Result (3d array):  15 x 3 x 5
```

```
>>> a = np.ones((15, 3, 5))
>>> b = np.arange(3).reshape((3, 1))
>>> c = a * b
>>> c.shape
(15, 3, 5)
```

Common Functions in Numpy

$$a = \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix}$$

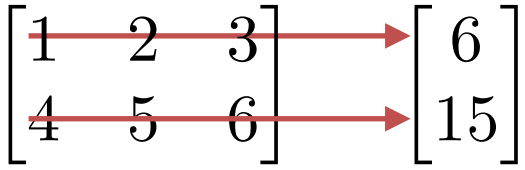
- When we do not specify the **axis** parameter:

```
>>> sum_all_vals = np.sum(a)
>>> print(sum_all_vals)
21
```

Common Functions in Numpy

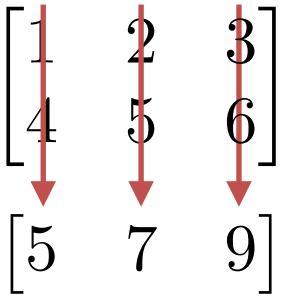
- Sum along the columns:

```
>>> sum_along_cols = np.sum(a, axis=1)
>>> print(sum_along_cols)
[ 6 15 ]
```



- Sum along the rows:

```
>>> sum_along_rows = np.sum(a, axis=0)
>>> print(sum_along_rows)
[ 5 7 9 ]
```



Common Functions in Numpy

$$a = \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix}$$

- Find minimum value in an array:

```
>>> all_min = np.min(a)
>>> print(all_min)
[ 1 ]
```

- Along cols:

```
>>> col_min = np.min(a, axis=1)
>>> print(col_min)
[ 1 4 ]
```

- Along rows:

```
>>> row_min = np.min(a, axis=0)
>>> print(row_min)
[ 1 2 3 ]
```

For finding the maximum value, you can use `np.max`

Common Functions in Numpy

- Find **index** of minimum value in an array:

$$b = \begin{bmatrix} 5 & 3 & 10 \end{bmatrix}$$

```
>>> b = np.array([5, 3, 10])
>>> min_ind_b = np.argmin(b)
>>> print(min_ind_b)
1
```

- Be careful with multi-dimensional arrays!

$$c = \begin{bmatrix} 1 & 2 & 3 \\ 4 & \mathbf{0} & 6 \end{bmatrix}$$

```
>>> c = np.array([[1,2,3],[4,0,6]])
>>> min_ind_c = np.argmin(c)
>>> print(min_ind_c)
4
```

- To get 2D index, use `np.unravel_index()`

Common Functions in Numpy

$$a = \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix}$$

- Find mean value of an array:

```
>>> overall_mean = np.mean(a)
>>> print(overall_mean)
3.5
```

- Along columns:

```
>>> col_mean = np.mean(a, axis=1)
>>> print(col_mean)
[2. 5.]
```

- Along rows (this is useful for whitening your data!):

```
>>> row_mean = np.mean(a, axis=0)
>>> print(row_mean)
[2.5 3.5 4.5]
```

You can use `np.std` similarly to find the standard deviation and `np.var` to find the variance

Random

- The module `np.random` implements pseudo-random number generators for various distributions.

- Almost all module functions depend on the basic function `random()`, which generates a random float uniformly in the semi-open range `[0.0, 1.0)`.

```
>>> x = np.random.random()
>>> print(x)
0.22402776143655379
```

Random

- How to fix the pseudo-random generator?

```
>>> np.random.random()
0.4353
>>> np.random.random()
0.4204
```

- Use **seed**.

```
>>> np.random.seed(2)
>>> np.random.random()
0.4360
>>> np.random.seed(2)
>>> np.random.random()
0.4360
```

Random: Useful Functions

- Getting random integer `n` such that `a <= n <= b`:

```
>>> n = random.randint(3, 10)
>>> print(n)
7
```

- Getting random float `x` such that `min <= x <= max`:

```
>>> minim = 3
>>> maxim = 10
>>> x = (maxim - minim) * random.random() + minim
print(x)
3.1815
```

Random: Useful Stuff

- How to shuffle (in-place) randomly list of indices?

```
>>> x = np.arange(10)
>>> print(x)
[0 1 2 3 4 5 6 7 8 9]

>>> np.random.shuffle(x)
>>> print(x)
[9 5 4 7 1 8 0 3 2 6]
```

- Some useful distributions (uniform, normal):

```
>>> x = random.uniform(low=0, high=1, size=(2, 3))
>>> x = random.randn(2, 3)
```

References

- Python Documentation:
  https://docs.python.org/3/
- Official python3 tutorial:
  https://docs.python.org/3/tutorial/index.html
- All built-in functions:
  https://docs.python.org/3/library/functions.html
- Jupyter Notebook documentation:
  https://jupyter.readthedocs.io/en/latest/
- NumPy Basics:
  https://docs.scipy.org/doc/numpy/user/basics.html
- Official NumPy tutorial:
  https://docs.scipy.org/doc/numpy/user/quickstart.html