Slides from INF3331 lectures

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About this course
Teachers

- Joakim Sundnes
- Glenn Lines
- Guest lecturers TBD
- We use Python to create efficient working (or problem solving) environments
- We also use Python to develop large-scale simulation software (which solves partial differential equations)
- We believe high-level languages such as Python constitute a promising way of making flexible and user-friendly software!
- Some of our research migrates into this course
- There are lots of opportunities for master projects related to this course
Contents

- Scripting in general
- Quick Python introduction (first two weeks)
- Python problem solving
- More advanced Python (class programming++)
- Regular expressions
- Combining Python with C, C++ and Fortran
- The Python C API and the NumPy C API
- Distributing Python modules (incl. extension modules)
- Verifying/testing (Python) software
- Documenting Python software
- Optimizing Python code
- Python coding standards and 'Pythonic' programming
- Basic Bash programming
What you will learn

- Scripting in general, but with most examples taken from scientific computing
- Jump into useful scripts and dissect the code
- Learning by doing
- Find examples, look up man pages, Web docs and textbooks on demand
- Get the overview
- Customize existing code
- Have fun and work with useful things
Teaching material (1)

- Slides from lectures (by Skavhaug, Sundnes, Langtangen et al), download from http://www.uio.no/studier/emner/matnat/ifi/INF3331/h11/inf3331.pdf

- Associated book (for the Python material):

- You must find the rest: manuals, textbooks, google
Teaching material (2)

Good Python literature:
Harms and McDonald: The Quick Python Book (tutorial+advanced)
Beazley: Python Essential Reference
Grayson: Python and Tkinter Programming
Lectures and groups (1)

- Lectures Tuesdays 10.15-12.00
- Groups Thursday 14.15, Monday 10.15, (Friday 10.15)
- Slides will be updated as we go. Printing the entire pdf file in August is not recommended.
- Topics for the lecture, updated slides and page numbers will be made available one week before each lecture.
- Groups and exercises are the core of the course; problem solving is in focus.
Lectures and groups (2)

- Tuesday 23rd:
  - “User survey”
  - Intro/motivation; scripting vs regular programming
- Tuesday 30th:
  - First encounter with Python
What is a script?

- Very high-level, often short, program written in a high-level scripting language
- Scripting languages: Unix shells, Tcl, Perl, Python, Ruby, Scheme, Rexx, JavaScript, VisualBasic, ...
- This course: Python
  + a taste of Bash (Unix shell)
Characteristics of a script

- Glue other programs together
- Extensive text processing
- File and directory manipulation
- Often special-purpose code
- Many small interacting scripts may yield a big system
- Perhaps a special-purpose GUI on top
- Portable across Unix, Windows, Mac
- Interpreted program (no compilation+linking)
Why not stick to Java or C/C++?

Features of scripting languages compared with Java, C/C++ and Fortran:
- shorter, more high-level programs
- much faster software development
- more convenient programming
- you feel more productive

Two main reasons:
- no variable declarations, but lots of consistency checks at run time
- lots of standardized libraries and tools
Scripts yield short code

Consider reading real numbers from a file, where each line can contain an arbitrary number of real numbers:

1.1 9 5.2
1.762543E-02
0 0.01 0.001
9 3 7

Python solution:

```python
F = open(filename, 'r')
n = F.read().split()
```
Using regular expressions (1)

Suppose we want to read complex numbers written as text
(-3, 1.4) or (-1.437625E-9, 7.11) or ( 4, 2 )

Python solution:

```python
m = re.search(r'\((-[^,]+),\s*(-[^,]+)\)', '(-3,1.4)
re, im = [float(x) for x in m.groups()]
```
Using regular expressions (2)

Regular expressions like
\(\{(\s*([^,]+)\s*\),\s*([^,]+)\s*\}\)
constitute a powerful language for specifying text patterns

Doing the same thing, without regular expressions, in Fortran and C requires quite some low-level code at the character array level

Remark: we could read pairs (-3, 1.4) without using regular expressions,

\[s = '(-3, 1.4)'
re, im = s[1:-1].split(',\')\]
Script variables are not declared

Example of a Python function:

```python
def debug(leading_text, variable):
    if os.environ.get('MYDEBUG', '0') == '1':
        print leading_text, variable
```

- Dumps any printable variable
  (number, list, hash, heterogeneous structure)
- Printing can be turned on/off by setting the environment variable
  MYDEBUG
The same function in C++

- Templates can be used to mimic dynamically typed languages
- Not as quick and convenient programming:

```cpp
template <class T>
void debug(std::ostream& o,
           const std::string& leading_text,
           const T& variable)
{
    char* c = getenv("MYDEBUG");
    bool defined = false;
    if (c != NULL) { // if MYDEBUG is defined ...
        if (std::string(c) == "1") { // if MYDEBUG is true ...
            defined = true;
        }
    }
    if (defined) {
        o << leading_text << " " << variable << std::endl;
    }
}
```
The relation to OOP

- Object-oriented programming can also be used to parameterize types
- Introduce base class \( A \) and a range of subclasses, all with a (virtual) print function
- Let \( \texttt{debug} \) work with \( \texttt{var} \) as an \( A \) reference
- Now \( \texttt{debug} \) works for all subclasses of \( A \)

Advantage: complete control of the legal variable types that \( \texttt{debug} \) are allowed to print (may be important in big systems to ensure that a function can allow make transactions with certain objects)

Disadvantage: much more work, much more code, less reuse of \( \texttt{debug} \) in new occasions
Flexible function interfaces

- User-friendly environments (Matlab, Maple, Mathematica, S-Plus, ...) allow flexible function interfaces

- Novice user:
  ```
  # f is some data
  plot(f)
  ```

- More control of the plot:
  ```
  plot(f, label='f', xrange=[0,10])
  ```

- More fine-tuning:
  ```
  plot(f, label='f', xrange=[0,10], title='f demo',
       linetype='dashed', linecolor='red')
  ```
Keyword arguments

Keyword arguments = function arguments with keywords and default values, e.g.,

```python
def plot(data, label='', xrange=None, title='',
       linetype='solid', linecolor='black', ...)
```

The sequence and number of arguments in the call can be chosen by the user
Classification of languages (1)

Many criteria can be used to classify computer languages

Dynamically vs statically typed languages

Python (dynamic):

```python
c = 1 # c is an integer
C = [1,2,3] # C is a list
```

C (static):

```c
double c; c = 5.2; # c can only hold doubles
c = "a string..." # compiler error
```
Classification of languages (2)

Weakly vs strongly typed languages

Perl (weak):

```perl
$b = '1.2'
$c = 5*$b;  # implicit type conversion: '1.2' -> 1.2
```

Python (strong):

```python
b = '1.2'
c = 5*b  # illegal; no implicit type conversion
```
Classification of languages (3)

- Interpreted vs compiled languages
- Dynamically vs statically typed (or type-safe) languages
- High-level vs low-level languages (Python-C)
- Very high-level vs high-level languages (Python-C)
- Scripting vs system languages
Turning files into code (1)

- Code can be constructed and executed at run-time
- Consider an input file with the syntax

```plaintext
a = 1.2
no_of_iterations = 100
solution_strategy = 'implicit'
c1 = 0
c2 = 0.1
A = 4
c3 = StringFunction('A*sin(x)')
```

- How can we read this file and define variables a, no_of_iterations, solution_strategy, c1, c2, A with the specified values?

- And can we make c3 a function c3(x) as specified?

  Yes!
Turning files into code (2)

The answer lies in this short and generic code:

```python
file = open('inputfile.dat', 'r')
for line in file:
    # first replace blanks on the left-hand side of = by _
    variable, value = line.split('=').strip()
    variable = re.sub(' ', '_', variable)
    exec(variable + '=' + value)  # magic...
```

This cannot be done in Fortran, C, C++ or Java!
Scripts can be slow

- Perl and Python scripts are first compiled to byte-code
- The byte-code is then *interpreted*
- Text processing is usually as fast as in C
- Loops over large data structures might be very slow

```python
for i in range(len(A)):
    A[i] = ...
```

- Fortran, C and C++ compilers are good at optimizing such loops at compile time and produce very efficient assembly code (e.g. 100 times faster)
- Fortunately, long loops in scripts can easily be migrated to Fortran or C
Scripts may be fast enough (1)

Read 100 000 \((x,y)\) data from file and write \((x,f(y))\) out again

- Pure Python: 4s
- Pure Perl: 3s
- Pure Tcl: 11s
- Pure C (fscanf/fprintf): 1s
- Pure C++ (iostream): 3.6s
- Pure C++ (buffered streams): 2.5s
- Numerical Python modules: 2.2s (!)

Remark: in practice, 100 000 data points are written and read in binary format, resulting in much smaller differences
Scripts may be fast enough (2)

Read a text in a human language and generate random nonsense text in that language (from "The Practice of Programming" by B. W. Kernighan and R. Pike, 1999):

<table>
<thead>
<tr>
<th>Language</th>
<th>CPU-time</th>
<th>lines of code</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.30</td>
<td>150</td>
</tr>
<tr>
<td>Java</td>
<td>9.2</td>
<td>105</td>
</tr>
<tr>
<td>C++ (STL-deque)</td>
<td>11.2</td>
<td>70</td>
</tr>
<tr>
<td>C++ (STL-list)</td>
<td>1.5</td>
<td>70</td>
</tr>
<tr>
<td>Awk</td>
<td>2.1</td>
<td>20</td>
</tr>
<tr>
<td>Perl</td>
<td>1.0</td>
<td>18</td>
</tr>
</tbody>
</table>

Machine: Pentium II running Windows NT
When scripting is convenient (1)

- The application’s main task is to connect together existing components
- The application includes a graphical user interface
- The application performs extensive string/text manipulation
- The design of the application code is expected to change significantly
- CPU-time intensive parts can be migrated to C/C++ or Fortran
When scripting is convenient (2)

- The application can be made short if it operates heavily on list or hash structures.
- The application is supposed to communicate with Web servers.
- The application should run without modifications on Unix, Windows, and Macintosh computers, also when a GUI is included.
When to use C, C++, Java, Fortran

- Does the application implement complicated algorithms and data structures?
- Does the application manipulate large datasets so that execution speed is critical?
- Are the application’s functions well-defined and changing slowly?
- Will type-safe languages be an advantage, e.g., in large development teams?
Some personal applications of scripting

- Get the power of Unix also in non-Unix environments
- Automate manual interaction with the computer
- Customize your own working environment and become more efficient
- Increase the reliability of your work
  (what you did is documented in the script)
- Have more fun!
Some business applications of scripting

- Python and Perl are very popular in the open source movement and Linux environments
- Python, Perl and PHP are widely used for creating Web services (Django, SOAP, Plone)
- Python and Perl (and Tcl) replace 'home-made' (application-specific) scripting interfaces
- Many companies want candidates with Python experience
What about mission-critical operations?

- Scripting languages are free
- What about companies that do mission-critical operations?
- Can we use Python when sending a man to Mars?
- Who is responsible for the quality of products?
The reliability of scripting tools

- Scripting languages are developed as a world-wide collaboration of volunteers (open source model)
- The open source community as a whole is responsible for the quality
- There is a single repository for the source codes (plus mirror sites)
- This source is read, tested and controlled by a very large number of people (and experts)
- The reliability of large open source projects like Linux, Python, and Perl appears to be very good - at least as good as commercial software
Practical problem solving

Problem: you are not an expert (yet)

Where to find detailed info, and how to understand it?

The efficient programmer navigates quickly in the jungle of textbooks, man pages, README files, source code examples, Web sites, newsgroups, ... and has a gut feeling for what to look for

The aim of the course is to improve your practical problem-solving abilities

You think you know when you learn, are more sure when you can write, even more when you can teach, but certain when you can program (Alan Perlis)
Basic Python Constructs
First encounter with Python

#!/usr/bin/env python

from math import sin
import sys

x = float(sys.argv[1])
print "Hello world, sin(%g) = %g." % (x, sin(x))
Running the Script

Code in file hw.py.
Run with command:

> python hw.py 0.5
Hello world, sin(0.5) = 0.479426.

Linux alternative if file is executable (chmod a+x hw.py):

> ./hw.py 0.5
Hello world, sin(0.5) = 0.479426.
Quick Run Through

On *nix; find out what kind of script language (interpreter) to use:

```
#!/usr/bin/env python
```

Access library functions:

```
from math import sin
import sys
```

Read command line argument and convert it to a floating point:

```
x = float(sys.argv[1])
```

Print out the result using a format string:

```
print "Hello world, sin(%g) = %g." % (x, sin(x))
```
Simple Assignments

a = 10  # a is a variable referencing an
       # integer object of value 10

b = True  # b is a boolean variable

a = b  # a is now a boolean as well
       # (referencing the same object as b)

b = increment(4)  # b is the value returned by a function

is_equal = a == b  # is_equal is True if a == b
Simple control structures

- **Loops:**
  ```python
  while condition:
      <block of statements>
  Here, condition must be a boolean expression (or have a boolean interpretation), for example: i < 10 or !found
  for element in somelist:
      <block of statements>
  Note that element is a copy of the list items, not a reference into the list!
  ```

- **Conditionals:**
  ```python
  if condition:
      <block of statements>
  elif condition:
      <block of statements>
  else:
      <block of statements>
  ```
Ranges and Loops

- `range(start, stop, increment)` constructs a list. Typically, it is used in for loops:
  ```python
  for i in range(10):
      print i
  ```

- `xrange(start, stop, increment)` is better for fat loops since it constructs an iterator:
  ```python
  for i in xrange(10000000):
      sum += sin(i*pi*x)
  ```

- Looping over lists can be done in several ways:
  ```python
  names = ['Ola', 'Per', 'Kari']
surnames = ['Olsen', 'Pettersen', 'Bremnes']
  for name, surname in zip(names, surnames):
      print name, surname # join element by element
  
  for i, name in enumerate(names):
      print i, name # join list index and item
  ```

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Lists and Tuples

mylist = ['a string', 2.5, 6, 'another string']
mytuplet = ('a string', 2.5, 6, 'another string')
mylist[1] = -10
mylist.append('a third string')
mytuplet[1] = -10  # illegal: cannot change a tuple

A tuple is a constant list (immutable)
# List functionality

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>a = []</code></td>
<td>initialize an empty list</td>
</tr>
<tr>
<td><code>a = [1, 4.4, 'run.py']</code></td>
<td>initialize a list</td>
</tr>
<tr>
<td><code>a.append(elem)</code></td>
<td>add <code>elem</code> object to the end</td>
</tr>
<tr>
<td><code>a + [1,3]</code></td>
<td>add two lists</td>
</tr>
<tr>
<td><code>a[3]</code></td>
<td>index a list element</td>
</tr>
<tr>
<td><code>a[-1]</code></td>
<td>get last list element</td>
</tr>
<tr>
<td><code>a[1:3]</code></td>
<td>slice: copy data to sublist (here: index 1, 2)</td>
</tr>
<tr>
<td><code>del a[3]</code></td>
<td>delete an element (index 3)</td>
</tr>
<tr>
<td><code>a.remove(4.4)</code></td>
<td>remove an element (with value 4.4)</td>
</tr>
<tr>
<td><code>a.index('run.py')</code></td>
<td>find index corresponding to an element's value</td>
</tr>
<tr>
<td><code>'run.py' in a</code></td>
<td>test if a value is contained in the list</td>
</tr>
</tbody>
</table>
## More list functionality

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>a.count(v)</code></td>
<td>count how many elements that have the value <code>v</code></td>
</tr>
<tr>
<td><code>len(a)</code></td>
<td>number of elements in list <code>a</code></td>
</tr>
<tr>
<td><code>min(a)</code></td>
<td>the smallest element in <code>a</code></td>
</tr>
<tr>
<td><code>max(a)</code></td>
<td>the largest element in <code>a</code></td>
</tr>
<tr>
<td><code>min([&quot;001&quot;, 100])</code></td>
<td>tricky!</td>
</tr>
<tr>
<td><code>sum(a)</code></td>
<td>add all elements in <code>a</code></td>
</tr>
<tr>
<td><code>a.sort()</code></td>
<td>sort list <code>a</code> (changes <code>a</code>)</td>
</tr>
<tr>
<td><code>as = sorted(a)</code></td>
<td>sort list <code>a</code> (return new list)</td>
</tr>
<tr>
<td><code>a.reverse()</code></td>
<td>reverse list <code>a</code> (changes <code>a</code>)</td>
</tr>
<tr>
<td><code>b[3][0][2]</code></td>
<td>nested list indexing</td>
</tr>
<tr>
<td><code>isinstance(a, list)</code></td>
<td>is True if <code>a</code> is a list</td>
</tr>
</tbody>
</table>
Functions and arguments

User-defined functions:

```python
def split(string, char):
    position = string.find(char)
    if position > 0:
        return string[:position+1], string[position+1:]
    else:
        return string, ""
```

# function call:
message = "Heisann"
print split(message, "i")

prints out (’Hei’, ’sann’).

Positional arguments must appear before keyword arguments:

```python
def split(message, char="i"): [...]
```
How to find more Python information

- The book contains only fragments of the Python language (intended for real beginners!)
- These slides are even briefer
- Therefore you will need to look up more Python information
- Primary reference: The official Python documentation at docs.python.org
- Very useful: The Python Library Reference, especially the index
- Example: what can I find in the math module? Go to the Python Library Reference index, find "math", click on the link and you get to a description of the module
- Alternative: pydoc math in the terminal window (briefer)
- Note: for a newbie it is difficult to read manuals (intended for experts) – you will need a lot of training; just browse, don’t read everything, try to dig out the key info
eval and exec

Evaluating string expressions with `eval`:

```python
>>> x = 20
>>> r = eval('x + 1.1')
>>> r
21.1
>>> type(r)
<type 'float'>
```

Executing strings with Python code, using `exec`:

```python
exec(""
def f(x):
    return %s
""" % sys.argv[1])
```
Exceptions

Handling exceptions:

```
try:
    <statements>
except ExceptionType1:
    <provide a remedy for ExceptionType1 errors>
except ExceptionType2, ExceptionType3, ExceptionType4:
    <provide a remedy for three other types of errors>
except:
    <provide a remedy for any other errors>
...
```

Raising exceptions:

```
if z < 0:
    raise ValueError
        ('z=%s is negative - cannot do log(z)' % z)
a = math.log(z)
```
File reading and writing

Reading a file:

```python
infile = open(filename, 'r')
for line in infile:
    # process line

lines = infile.readlines()
for line in lines:
    # process line

for i in xrange(len(lines)):
    # process lines[i] and perhaps next line lines[i+1]

fstr = infile.read()
# process the while file as a string fstr

infile.close()
```

Writing a file:

```python
outfile = open(filename, 'w')  # new file or overwrite
outfile = open(filename, 'a')  # append to existing file
outfile.write("""Some string
    ....
"""")
```
## Dictionary functionality

```
a = {}
a = {'point':[2,7], 'value':3}
a = dict(point=[2,7], value=3)
a['hide'] = True
a['point']
'value' in a
del a['point']
a.keys()
a.values()
len(a)
for key in a:
for key in sorted(a.keys()):
isinstance(a, dict)
```

- initialize an empty dictionary
- initialize a dictionary
- initialize a dictionary
- add new key-value pair to a dictionary
- get value corresponding to key `point`
- True if `value` is a key in the dictionary
- delete a key-value pair from the dictionary
- list of keys
- list of values
- number of key-value pairs in dictionary `a`
- loop over keys in unknown order
- loop over keys in alphabetic order
- is True if `a` is a dictionary
String operations

s = 'Berlin: 18.4 C at 4 pm'
s[8:17]  # extract substring
s.find(':')  # index where first ':' is found
s.split(':')  # split into substrings
s.split()  # split wrt whitespace
'Berlin' in s  # test if substring is in s
s.replace('18.4', '20')
s.lower()  # lower case letters only
s.upper()  # upper case letters only
s.split()[4].isdigit()
s.strip()  # remove leading/trailing blanks
', ', .join(list_of_words)
Import module as namespace:
import sys
x = float(sys.argv[1])

Import module member `argv` into current namespace:
from sys import argv
x = float(argv[1])

Import everything from `sys` into current namespace (evil)
from sys import *
x = float(argv[1])

Import `argv` into current namespace under an alias
from sys import argv as a
x = float(a[1])
Frequently encountered tasks in Python
Overview

- file globbing, testing file types
- copying and renaming files, creating and moving to directories, creating directory paths, removing files and directories
- directory tree traversal
- parsing command-line arguments
- running an application
- file reading and writing
- list and dictionary operations
- splitting and joining text
- basics of Python classes
- writing functions
Python programming information

Man-page oriented information:
- `pydoc somemodule.somefunc, pydoc somemodule`
- `doc.html! Links to lots of electronic information`
- The Python Library Reference (go to the index)
- Python in a Nutshell
- Beazley’s Python reference book
- Your favorite Python language book
- Google

These slides (and exercises) are closely linked to the “Python scripting for computational science” book, ch. 3 and 8
File globbing

- List all .ps and .gif files (Unix):
  
```
  ls *.ps *.gif
  ```

- Cross-platform way to do it in Python:
  
```
import glob
filelist = glob.glob(‘*.ps’) + glob.glob(‘*.gif’)
```

This is referred to as file globbing
Testing file types

import os.path
print myfile,

if os.path.isfile(myfile):
    print 'is a plain file'
if os.path.isdir(myfile):
    print 'is a directory'
if os.path.islink(myfile):
    print 'is a link'

# the size and age:
size = os.path.getsize(myfile)
time_of_last_access = os.path.getatime(myfile)
time_of_last_modification = os.path.getmtime(myfile)

# times are measured in seconds since 1970.01.01
days_since_last_access = \ (time.time() - os.path.getatime(myfile))/(3600*24)
More detailed file info

```python
import stat

myfile_stat = os.stat(myfile)
filesize = myfile_stat[stat.ST_SIZE]
mode = myfile_stat[stat.ST_MODE]
if stat.S_ISREG(mode):
    print '%(myfile)s is a regular file '
    'with %(filesize)d bytes' % vars()
```

Check out the `stat` module in Python Library Reference
Copy, rename and remove files

- **Copy a file:**
  
  ```python
  import shutil
  shutil.copy(myfile, tmpfile)
  ```

- **Rename a file:**
  
  ```python
  os.rename(myfile, 'tmp.1')
  ```

- **Remove a file:**
  
  ```python
  os.remove('mydata')
  # or os.unlink('mydata')
  ```
Cross-platform construction of file paths:

```python
filename = os.path.join(os.pardir, 'src', 'lib')

# Unix: ../src/lib
# Windows: ..\src\lib

shutil.copy(filename, os.curdir)

# Unix: cp ../src/lib .
# os.pardir : ..
# os.curdir : .
```
Directory management

Creating and moving to directories:

dirname = 'mynewdir'
if not os.path.isdir(dirname):
    os.mkdir(dirname)  # or os.mkdir(dirname,'0755')
os.chdir(dirname)

Make complete directory path with intermediate directories:

path = os.path.join(os.environ['HOME'],'py','src')
os.makedirs(path)

# Unix: mkdirhier $HOME/py/src

Remove a non-empty directory tree:

shutil.rmtree('myroot')
Basename/directory of a path

Given a path, e.g.,

```
fname = '/home/hpl/scripting/python/intro/hw.py'
```

Extract directory and basename:

```
# basename: hw.py
basename = os.path.basename(fname)

# dirname: /home/hpl/scripting/python/intro
dirname = os.path.dirname(fname)

# or
dirname, basename = os.path.split(fname)
```

Extract suffix:

```
root, suffix = os.path.splitext(fname)
# suffix: .py
```
Platform-dependent operations

The operating system interface in Python is the same on Unix, Windows and Mac

Sometimes you need to perform platform-specific operations, but how can you make a portable script?

```python
# os.name : operating system name
# sys.platform : platform identifier

# cmd: string holding command to be run
if os.name == 'posix':  # Unix?
    failure = os.system(cmd + '&')
eelif sys.platform[:3] == 'win':  # Windows?
    failure = os.system('start ' + cmd)
eelse:
    # foreground execution:
    failure, output = commands.getstatusoutput(cmd)
```
Run through all files in your home directory and list files that are larger than 1 Mb

A Unix find command solves the problem:

```
find $HOME -name '*' -type f -size +2000 \  
-exec ls -s {} \;
```

This (and all features of Unix find) can be given a cross-platform implementation in Python
Traversing directory trees (2)

Similar cross-platform Python tool:

```python
root = os.environ['HOME']  # my home directory
os.path.walk(root, myfunc, arg)
```

walks through a directory tree (`root`) and calls, for each directory **dirname**, 

```
myfunc(arg, dirname, files)  # files is list of (local) filenames
```

- **arg** is any user-defined argument, e.g. a nested list of variables
Example on finding large files

def checksize1(arg, dirname, files):
    for file in files:
        # construct the file’s complete path:
        filename = os.path.join(dirname, file)
        if os.path.isfile(filename):
            size = os.path.getsize(filename)
            if size > 1000000:
                print '%.2fMb %s' % (size/1000000.0, filename)

root = os.environ['HOME']
os.path.walk(root, checksize1, None)

# arg is a user-specified (optional) argument,
# here we specify None since arg has no use
# in the present example
Make a list of all large files

- Slight extension of the previous example
- Now we use the `arg` variable to build a list during the walk

```python
def checksize1(arg, dirname, files):
    for file in files:
        filepath = os.path.join(dirname, file)
        if os.path.isfile(filepath):
            size = os.path.getsize(filepath)
            if size > 1000000:
                size_in_Mb = size / 1000000.0
                arg.append((size_in_Mb, filename))

bigfiles = []
root = os.environ['HOME']
os.path.walk(root, checksize1, bigfiles)
for size, name in bigfiles:
    print name, 'is', size, 'Mb'
```
arg must be a list or dictionary

Let's build a tuple of all files instead of a list:

```python
def checksizel(arg, dirname, files):
    for file in files:
        filepath = os.path.join(dirname, file)
        if os.path.isfile(filepath):
            size = os.path.getsize(filepath)
            if size > 1000000:
                msg = '%.2fMb %s' % (size/1000000.0, filepath)
                arg = arg + (msg,)

bigfiles = []
os.path.walk(os.environ['HOME'], checksizel, bigfiles)
for size, name in bigfiles:
    print name, 'is', size, 'Mb'
```

Now `bigfiles` is an empty list! Why? Explain in detail... (Hint: `arg` must be mutable)
Creating Tar archives

Tar is a widespread tool for packing file collections efficiently

Very useful for software distribution or sending (large) collections of files in email

Demo:

```python
>>> import tarfile
>>> files = ['NumPy_basics.py', 'hw.py', 'leastsquares.py']
>>> tar = tarfile.open('tmp.tar.gz', 'w:gz') # gzip compression
>>> for file in files:
...    tar.add(file)
... # check what’s in this archive:
>>> members = tar.getmembers() # list of TarInfo objects
>>> for info in members:
...    print '%s: size=%d, mode=%o, mtime=%s' % 
...    time.strftime('%Y.%m.%d', time.gmtime(info.mtime))
NumPy_basics.py: size=11898, mode=33261, mtime=2004.11.23
hw.py: size=206, mode=33261, mtime=2005.08.12
leastsquares.py: size=1560, mode=33261, mtime=2004.09.14
>>> tar.close()
```

Compressions: uncompressed (w:), gzip (w:gz), bzip2 (w:bz2)
Reading Tar archives

```python
>>> tar = tarfile.open('tmp.tar.gz', 'r')

>>> for file in tar.getmembers():
...     tar.extract(file)  # extract file to current work.dir.
...
>>> # do we have all the files?
>>> allfiles = os.listdir(os.getcwd())
>>> for file in files:
...     if not file in allfiles: print 'missing', file
...
>>> hw = tar.extractfile('hw.py')  # extract as file object
>>> hw.readlines()
```
Measuring CPU time (1)

The time module:

```python
import time
e0 = time.time()  # elapsed time since the epoch
c0 = time.clock()  # total CPU time spent so far
# do tasks...
elapsed_time = time.time() - e0
cpu_time = time.clock() - c0
```

The `os.times` function returns a list:

- `os.times()[0]` : user time, current process
- `os.times()[1]` : system time, current process
- `os.times()[2]` : user time, child processes
- `os.times()[3]` : system time, child processes
- `os.times()[4]` : elapsed time

CPU time = user time + system time
Measuring CPU time (2)

Application:

```python
t0 = os.times()
# do tasks...
os.system(time_consuming_command)  # child process
t1 = os.times()

user_time = t1[0] - t0[0]
system_time = t1[1] - t0[1]
cpu_time = user_time + system_time
```

There is a special Python profiler for finding bottlenecks in scripts (ranks functions according to their CPU-time consumption)
A timer function

Let us make a function \texttt{timer} for measuring the efficiency of an arbitrary function. \texttt{timer} takes 4 arguments:

- a function to call
- a list of arguments to the function
- a dictionary of keyword arguments to the function
- number of calls to make (repetitions)
- name of function (for printout)

\begin{verbatim}
def timer(func, args, kwargs, repetitions, func_name):
    t0 = time.time(); c0 = time.clock()
    for i in xrange(repetitions):
        func(*args, **kwargs)
        print '%s: elapsed=%g, CPU=%g' % (func_name, time.time()-t0, time.clock()-c0)
\end{verbatim}
Parsing command-line arguments

- Running through `sys.argv[1:]` and extracting command-line info 'manually' is easy
- Using standardized modules and interface specifications is better!
- Python’s `getopt` and `optparse` modules parse the command line
  - `getopt` is the simplest to use
  - `optparse` is the most sophisticated
Short and long options

- It is a 'standard' to use either short or long options
  -d dirname # short options -d and -h
  --directory dirname # long options --directory and --help

- Short options have single hyphen, long options have double hyphen

- Options can take a value or not:
  --directory dirname --help --confirm
  -d dirname -h -i

- Short options can be combined
  -iddirname is the same as -i -d dirname
Using the getopt module (1)

- Specify short options by the option letters, followed by colon if the option requires a value
  - Example: ‘id:h’
- Specify long options by a list of option names, where names must end with = if they require a value
  - Example: ['help','directory=', 'confirm']
Using the getopt module (2)

- `getopt` returns a list of (option,value) pairs and a list of the remaining arguments

Example:

```
--directory mydir -i file1 file2
```

makes `getopt` return

```
[('--directory','mydir'), ('-i','')] 
['file1','file2']
```
Using the getopt module (3)

Processing:

```python
import getopt
try:
    options, args = getopt.getopt(sys.argv[1:], 'd:hi',
                                ['directory=', 'help', 'confirm'])
except:
    # wrong syntax on the command line, illegal options,
    # missing values etc.

directory = None; confirm = 0  # default values
for option, value in options:
    if option in ('-h', '--help'):
        # print usage message
    elif option in ('-d', '--directory'):
        directory = value
    elif option in ('-i', '--confirm'):
        confirm = 1
```
Using the interface

- Equivalent command-line arguments:
  
  -d mydir --confirm src1.c src2.c
  --directory mydir -i src1.c src2.c
  --directory=mydir --confirm src1.c src2.c

- Abbreviations of long options are possible, e.g.,
  
  --d mydir --co

- This one also works: --idmydir
Writing Python data structures

Write nested lists:

```python
somelist = ['text1', 'text2']
a = [[1.3, somelist], 'some text']
f = open('tmp.dat', 'w')

# convert data structure to its string repr.:
f.write(str(a))
f.close()
```

Equivalent statements writing to standard output:

```python
print a
sys.stdout.write(str(a) + '
')

# sys.stdin standard input as file object
# sys.stdout standard input as file object
```
Reading Python data structures

- `eval(s)`: treat string $s$ as Python code
- $a = \text{eval} (\text{str}(a))$ is a valid 'equation' for basic Python data structures

Example: read nested lists

```python
f = open('tmp.dat', 'r')  # file written in last slide
# evaluate first line in file as Python code:
newa = eval(f.readline())
```

results in

```python
[[1.3, ['text1', 'text2']], 'some text']
```

# i.e.
```
newa = eval(f.readline())
# is the same as
newa = [[1.3, ['text1', 'text2']], 'some text']
```
Remark about str and eval

- `str(a)` is implemented as an object function `__str__`

- `repr(a)` is implemented as an object function `__repr__`

- `str(a)`: pretty print of an object
- `repr(a)`: print of all info for use with `eval`

\[ a = \text{eval}(\text{repr}(a)) \]

- `str` and `repr` are identical for standard Python objects (lists, dictionaries, numbers)
Persistence

Many programs need to have persistent data structures, i.e., data live after the program is terminated and can be retrieved the next time the program is executed.

*str*, *repr* and *eval* are convenient for making data structures persistent.

pickle, cPickle and shelve are other (more sophisticated) Python modules for storing/loading objects.
Pickling

Write *any* set of data structures to file using the cPickle module:

```python
f = open(filename, 'w')
import cPickle
cPickle.dump(a1, f)
cPickle.dump(a2, f)
cPickle.dump(a3, f)
f.close()
```

Read data structures in again later:

```python
f = open(filename, 'r')
a1 = cPickle.load(f)
a2 = cPickle.load(f)
a3 = cPickle.load(f)
```
Shelving

Think of shelves as dictionaries with file storage

```python
import shelve

database = shelve.open(filename)
database['a1'] = a1  # store a1 under the key 'a1'
database['a2'] = a2
database['a3'] = a3
# or
database['a123'] = (a1, a2, a3)

# retrieve data:
if 'a1' in database:
    a1 = database['a1']
# and so on

# delete an entry:
del database['a2']

database.close()
```
What assignment really means

>>> a = 3  # a refers to int object with value 3
>>> b = a  # b refers to a (int object with value 3)
>>> id(a), id(b)  # print integer identifications of a and b
(135531064, 135531064)
>>> id(a) == id(b)  # same identification?
True  # a and b refer to the same object
>>> a is b  # alternative test
True
>>> a = 4  # a refers to a (new) int object
>>> id(a), id(b)  # let’s check the IDs
(135532056, 135531064)
>>> a is b
False
>>> b  # b still refers to the int object with value 3
3
Assignment vs in-place changes

```python
>>> a = [2, 6]  # a refers to a list [2, 6]
>>> b = a  # b refers to the same list as a
>>> a is b
True
>>> a = [1, 6, 3]  # a refers to a new list
>>> a is b  # a and b refer to the same list object
False
>>> b
[2, 6]

>>> a = [2, 6]
>>> b = a
>>> a[0] = 1  # make in-place changes in a
>>> a.append(3)  # another in-place change
>>> a
[1, 6, 3]
>>> b
[1, 6, 3]
>>> a is b  # a and b refer to the same list object
True
```
Assignment with copy

What if we want \( b \) to be a copy of \( a \)?

Lists: \( a[:] \) extracts a slice, which is a *copy* of all elements:

\[
\begin{align*}
\text{>>> } b &= a[:] \quad \text{# } b \text{ refers to a copy of elements in } a \\
\text{>>> } b \text{ is } a &= False
\end{align*}
\]

In-place changes in \( a \) will not affect \( b \)

Dictionaries: use the \texttt{copy} method:

\[
\begin{align*}
\text{>>> } a &= \{\text{`refine': False}\} \\
\text{>>> } b &= a.copy() \\
\text{>>> } b \text{ is } a &= False
\end{align*}
\]

In-place changes in \( a \) will not affect \( b \)
Running an application

Run a stand-alone program:

```python
cmd = 'myprog -c file.1 -p -f -q > res'
failure = os.system(cmd)
if failure:
    print '%s: running myprog failed' % sys.argv[0]
sys.exit(1)
```

Redirect output from the application to a list of lines:

```python
pipe = os.popen(cmd)
output = pipe.readlines()
pipe.close()

for line in output:
    # process line
```

Better tool: the `commands` module (next slide)
Running applications and grabbing the output

A nice way to execute another program:

```python
import commands
failure, output = commands.getstatusoutput(cmd)

if failure:
    print 'Could not run', cmd; sys.exit(1)

for line in output.splitlines():
    # process line

(output holds the output as a string)

(output holds both standard error and standard output
(os.popen grabs only standard output so you do not see error messages)
Running applications in the background

- `os.system`, `pipes`, or `commands.getstatusoutput` terminates after the command has terminated.

- There are two methods for running the script in parallel with the command:
  - run the command in the background
    - Unix: add an ampersand (&) at the end of the command
    - Windows: run the command with the ‘start’ program
  - run the operating system command in a separate thread

- More info: see “Platform-dependent operations” slide and the `threading` module.
The new standard: subprocess

A module subprocess is the new standard for running stand-alone applications:

```python
from subprocess import call
try:
    returncode = call(cmd, shell=True)
    if returncode:
        print 'Failure with returncode', returncode;
        sys.exit(1)
except OSError, message:
    print 'Execution failed!
', message; sys.exit(1)
```

More advanced use of subprocess applies its `Popen` object

```python
from subprocess import Popen, PIPE
p = Popen(cmd, shell=True, stdout=PIPE)
output, errors = p.communicate()
```
**Output pipe**

- Open (in a script) a dialog with an interactive program:

```python
pipe = Popen('gnuplot -persist', shell=True, stdin=PIPE).stdin
pipe.write('set xrange [0:10]; set yrange [-2:2]
plot sin(x)
quit') # quit Gnuplot
```

- Same as "here documents" in Unix shells:

```bash
gnuplot <<EOF
set xrange [0:10]; set yrange [-2:2]
plot sin(x)
quit
EOF
```
Writing to and reading from applications

- In theory, `Popen` allows us to have two-way communication with an application (read/write), but this technique is not suitable for reliable two-way dialog (easy to get hang-ups).

- The `pexpect` module is the right tool for a two-way dialog with a stand-alone application.

```python
# copy files to remote host via scp and password dialog
cmd = 'scp %s %s@%s:%s' % (filename, user, host, directory)
import pexpect
child = pexpect.spawn(cmd)
child.expect('password:')
child.sendline('%%hQxz?+MbH')
child.expect(pexpect.EOF)  # wait for end of scp session
child.close()
```
File reading

Load a file into list of lines:

```
infilename = '.myprog.cpp'
infile = open(infilename, 'r')  # open file for reading

# load file into a list of lines:
lines = infile.readlines()

# load file into a string:
filestr = infile.read()
```

Line-by-line reading (for large files):

```
while 1:
    line = infile.readline()
    if not line: break
    # process line
```
File writing

- Open a new output file:
  ```python
  outfilename = '.myprog2.cpp'
  outfile = open(outfilename, 'w')
  outfile.write('some string
')
  ```

- Append to existing file:
  ```python
  outfile = open(outfilename, 'a')
  outfile.write('....')
  ```
Python types

- **Numbers**: float, complex, int (+ bool)
- **Sequences**: list, tuple, str, NumPy arrays
- **Mappings**: dict (dictionary/hash)
- **Instances**: user-defined class
- **Callables**: functions, callable instances
**Numerical expressions**

Python distinguishes between strings and numbers:

```python
b = 1.2       # b is a number
b = '1.2'     # b is a string
a = 0.5 * b   # illegal: b is NOT converted to float
a = 0.5 * float(b) # this works
```

- All Python objects are compared with

  ```python
  ==    !=    <    >    <=    >=
  ```
Potential confusion

Consider:

```python
b = '1.2'
if b < 100:    print b, '< 100'
else:           print b, '>= 100'
```

What do we test? string less than number!

What we want is

```python
if float(b) < 100:    # floating-point number comparison
    # or
    if b < str(100):    # string comparison
```
Boolean expressions

- A bool type is True or False
- Can mix bool with int 0 (false) or 1 (true)
- if a: evaluates a in a boolean context, same as if bool(a):

Boolean tests:

```python
>>> a = ''
>>> bool(a)
False
>>> bool('some string')
True
>>> bool([])
False
>>> bool([1,2])
True
```

- Empty strings, lists, tuples, etc. evaluates to False in a boolean context
Setting list elements

- Initializing a list:
  
  \[
  \text{arglist} = [\text{myarg1, 'displacement', "tmp.ps"}]
  \]

- Or with indices (if there are already two list elements):
  
  \[
  \begin{align*}
  \text{arglist}[0] & = \text{myarg1} \\
  \text{arglist}[1] & = \text{'displacement'}
  \end{align*}
  \]

- Create list of specified length:
  
  \[
  \begin{align*}
  \text{n} & = 100 \\
  \text{mylist} & = [0.0]*n
  \end{align*}
  \]

- Adding list elements:
  
  \[
  \begin{align*}
  \text{arglist} & = [] \quad \# \text{ start with empty list} \\
  \text{arglist}.append(\text{myarg1}) \\
  \text{arglist}.append(\text{‘displacement’})
  \end{align*}
  \]
Getting list elements

Extract elements form a list:

```python
filename, plottitle, psfile = arglist
(filename, plottitle, psfile) = arglist
[filename, plottitle, psfile] = arglist
```

Or with indices:

```python
filename = arglist[0]
plottitle = arglist[1]
```
Traversing lists

- For each item in a list:
  ```python
  for entry in arglist:
    print 'entry is', entry
  ```

- For-loop-like traversal:
  ```python
  start = 0; stop = len(arglist); step = 1
  for index in range(start, stop, step):
    print 'arglist[%d]=%s' % (index,arglist[index])
  ```

- Visiting items in reverse order:
  ```python
  mylist.reverse()  # reverse order
  for item in mylist:
    # do something...
  ```
List comprehensions

Compact syntax for manipulating all elements of a list:

\[
y = [ \text{float}(yi) \text{ for } yi \text{ in line.split()} ] \quad \# \text{call function float}
\]
\[
x = [ a+i*h \text{ for } i \text{ in range}(n+1) ] \quad \# \text{execute expression}
\]
(called list comprehension)

Written out:

\[
y = []
\text{for } yi \text{ in line.split():}
\quad y.\text{append}(\text{float}(yi))
\]

etc.
Map function

- map is an alternative to list comprehension:
  
y = map(float, line.split())
y = map(lambda i: a+i*h, range(n+1))

- map is (probably) faster than list comprehension but not as easy to read
Typical list operations

```python
d = []  # declare empty list
d.append(1.2)  # add a number 1.2
d.append('a')  # add a text
d[0] = 1.3  # change an item
del d[1]  # delete an item
len(d)  # length of list
```
Nested lists

- Lists can be nested and heterogeneous
- List of string, number, list and dictionary:

```python
>>> mylist = ['t2.ps', 1.45, ['t2.gif', 't2.png'],
            { 'factor' : 1.0, 'c' : 0.9 } ]
>>> mylist[3]
{ 'c': 0.90000000000000002, 'factor': 1.0 }
>>> mylist[3]['factor']
1.0
>>> print mylist
['t2.ps', 1.45, ['t2.gif', 't2.png'],
 {'c': 0.90000000000000002, 'factor': 1.0}]
```

- Note: print prints all basic Python data structures in a nice format
Sorting a list

In-place sort:

```python
mylist.sort()
```

modifies `mylist`!

```python
>>> print mylist
[1.4, 8.2, 77, 10]
>>> mylist.sort()
>>> print mylist
[1.4, 8.2, 10, 77]
```

Strings and numbers are sorted as expected.
# Defining the comparison criterion

# ignore case when sorting:

def ignorecase_sort(s1, s2):
    s1 = s1.lower()
    s2 = s2.lower()
    if s1 < s2: return -1
    elif s1 == s2: return 0
    else: return 1

# quicker variant, using Python’s built-in
# cmp function:

def ignorecase_sort(s1, s2):
    s1 = s1.lower(); s2 = s2.lower()
    return cmp(s1,s2)

# usage:
mywords.sort(ignorecase_sort)

# Best variant:
mywords.sort(key=lambda s: s.lower())
Tuples (‘constant lists’)

- **Tuple** = constant list; items cannot be modified

```python
>>> s1=[1.2, 1.3, 1.4]  # list
>>> s2=(1.2, 1.3, 1.4)  # tuple
>>> s2=1.2, 1.3, 1.4    # may skip parenthesis
>>> s1[1]=0             # ok
>>> s2[1]=0             # illegal
```

Traceback (innermost last):
  File "<pyshell#17>", line 1, in ?
    s2[1]=0
  TypeError: object doesn’t support item assignment

```python
>>> s2.sort()
```

`AttributeError: ‘tuple’ object has no attribute ‘sort’`

- You cannot append to tuples, but you can add two tuples to form a new tuple
Dictionary operations

- Dictionary = array with text indices (keys)
  (even user-defined objects can be indices!)

- Also called hash or associative array

- Common operations:

  ```
  d['mass']  # extract item corresp. to key 'mass'
  d.keys()   # return copy of list of keys
  d.get('mass',1.0) # return 1.0 if 'mass' is not a key
  d.has_key('mass') # does d have a key 'mass'? 
  d.items()   # return list of (key,value) tuples
  del d['mass']  # delete an item
  len(d)       # the number of items
  ```
Initializing dictionaries

**Multiple items:**

```python
d = { 'key1' : value1, 'key2' : value2 }
# or
```
```python
d = dict(key1=value1, key2=value2)
```

**Item by item (indexing):**

```python
d['key1'] = anothervalue1
d['key2'] = anothervalue2
d['key3'] = value2
```
Dictionary examples

Problem: store MPEG filenames corresponding to a parameter with values 1, 0.1, 0.001, 0.00001

movies[1] = 'heatsim1.mpeg'
movies[0.1] = 'heatsim2.mpeg'
movies[0.001] = 'heatsim5.mpeg'
movies[0.00001] = 'heatsim8.mpeg'

Store compiler data:

g77 = {
    'name': 'g77',
    'description': 'GNU f77 compiler, v2.95.4',
    'compile_flags': '-pg',
    'link_flags': '-pg',
    'libs': '-lf2c',
    'opt': '-O3 -ffast-math -funroll-loops'
}
Another dictionary example (1)

- Idea: hold command-line arguments in a dictionary `cmlargs[option]`, e.g., `cmlargs[‘infile’]`, instead of separate variables

- Initialization: loop through `sys.argv`, assume options in pairs: `-option value`

```python
arg_counter = 1
while arg_counter < len(sys.argv):
    option = sys.argv[arg_counter]
    option = option[2:]  # remove double hyphen
    if option in cmlargs:
        # next command-line argument is the value:
        arg_counter += 1
        value = sys.argv[arg_counter]
        cmlargs[cmlarg] = value
    else:
        # illegal option
        arg_counter += 1
```
Another dictionary example (2)

Working with `cmlargs` in `simviz1.py`:

```python
f = open(cmlargs['case'] + '.', 'w')
f.write(cmlargs['m'] + '\n')
f.write(cmlargs['b'] + '\n')
f.write(cmlargs['c'] + '\n')
f.write(cmlargs['func'] + '\n')
...
# make gnuplot script:
f = open(cmlargs['case'] + '.gnuplot', 'w')
f.write(""
set title '%s: m=%s b=%s c=%s f(y)=%s A=%s w=%s y0=%s dt=%s';" % (cmlargs['case'], cmlargs['m'], cmlargs['b'], cmlargs['c'], cmlargs['func'], cmlargs['A'], cmlargs['w'], cmlargs['y0'], cmlargs['dt']))
if not cmlargs['noscreenplot']:
    f.write("plot 'sim.dat' title 'y(t)' with lines;\n")
```

Note: all `cmlargs[opt]` are (here) strings!
Environment variables

- The dictionary-like `os.environ` holds the environment variables:
  
  ```
  os.environ[‘PATH’]
  os.environ[‘HOME’]
  os.environ[‘scripting’]
  ```

- Write all the environment variables in alphabetic order:
  
  ```
  sorted_env = os.environ.keys()
sorted_env.sort()

  for key in sorted_env:
    print ’%s = %s’ % (key, os.environ[key])
  ```
Find a program

Check if a given program is on the system:

```python
program = 'vtk'
path = os.environ['PATH']
# PATH can be /usr/bin:/usr/local/bin:/usr/X11/bin
# os.pathsep is the separator in PATH
# ( : on Unix, ; on Windows)
paths = path.split(os.pathsep)
for d in paths:
    if os.path.isdir(d):
        if os.path.isfile(os.path.join(d, program)):
            program_path = d; break

try:  # program was found if program_path is defined
    print '%s found in %s' % (program, program_path)
except:
    print '%s not found' % program
```

Cross-platform fix of previous script

- On Windows, programs usually end with `.exe` (binaries) or `.bat` (DOS scripts), while on Unix most programs have no extension.

- We test if we are on Windows:

  ```python
  if sys.platform[:3] == 'win':
      # Windows-specific actions
  ```

- Cross-platform snippet for finding a program:

  ```python
  for d in paths:
      if os.path.isdir(d):
          fullpath = os.path.join(dir, program)
          if sys.platform[:3] == 'win':
              # windows machine?
              for ext in '.exe', '.bat':
                  # add extensions
                  if os.path.isfile(fullpath + ext):
                      program_path = d; break
          else:
              if os.path.isfile(fullpath):
                  program_path = d; break
  ```
Splitting text

Split string into words:

```python
>>> files = 'case1.ps case2.ps case3.ps'
>>> files.split()
['case1.ps', 'case2.ps', 'case3.ps']
```

Can split wrt other characters:

```python
>>> files = 'case1.ps, case2.ps, case3.ps'
>>> files.split(', ')
['case1.ps', 'case2.ps', 'case3.ps']
>>> files.split(', ') # extra erroneous space after comma...
['case1.ps, case2.ps, case3.ps'] # unsuccessful split
```

Very useful when interpreting files
Example on using split (1)

Suppose you have file containing numbers only

The file can be formatted ’arbitrarily’, e.g,

1.432 5E-09
1.0

3.2 5 69 -111
4 7 8

Get a list of all these numbers:

```python
f = open(filename, 'r')
numbers = f.read().split()
```

String objects’s `split` function splits wrt sequences of whitespace (whitespace = blank char, tab or newline)
Example on using split (2)

Convert the list of strings to a list of floating-point numbers, using map:

```python
numbers = [ float(x) for x in f.read().split() ]
```

Think about reading this file in Fortran or C! (quite some low-level code...)

This is a good example of how scripting languages, like Python, yields flexible and compact code.
Joining a list of strings

Join is the opposite of split:

```python
>>> line1 = 'iteration 12: eps= 1.245E-05'
>>> line1.split()
['iteration', '12: ', 'eps=', '1.245E-05']
>>> w = line1.split()
>>> ' '.join(w)  # join w elements with delimiter ''
'iteration 12: eps= 1.245E-05'
```

Any delimiter text can be used:

```python
>>> '@@@'.join(w)
'iteration@@@@12:@@@@eps=@@@@1.245E-05'
```
Common use of join/split

```python
f = open('myfile', 'r')
lines = f.readlines()  # list of lines
filestr = ''.join(lines)  # a single string
# can instead just do
# filestr = file.read()

# do something with filestr, e.g., substitutions...

# convert back to list of lines:
lines = filestr.splitlines()
for line in lines:
    # process line
```
Text processing (1)

Exact word match:

```python
if line == 'double':
    # line equals 'double'

if line.find('double') != -1:
    # line contains 'double'
```

Matching with Unix shell-style wildcard notation:

```python
import fnmatch
if fnmatch.fnmatch(line, 'double'):
    # line contains 'double'
```

Here, double can be any valid wildcard expression, e.g.,

```
double*   [Dd]ouble
```
Text processing (2)

Matching with full regular expressions:

```python
import re
if re.search(r'double', line):
    # line contains 'double'

Here, double can be any valid regular expression, e.g.,

double[A-Za-z0-9_]*  [Dd]ouble   (DOUBLE|double)
```
Substitution

Simple substitution:

```python
newstring = oldstring.replace(substring, newsubstring)
```

Substitute regular expression pattern by replacement in str:

```python
import re
str = re.sub(pattern, replacement, str)
```
Various string types

There are many ways of constructing strings in Python:

```
s1 = 'with forward quotes'
s2 = "with double quotes"
s3 = 'with single quotes and a variable: %(r1)g' \ % vars()
s4 = """as a triple double (or single) quoted string"""
s5 = """triple double (or single) quoted strings allow multi-line text (i.e., newline is preserved) with other quotes like ’ and """

Raw strings are widely used for regular expressions

s6 = r’raw strings start with r and \ remains backslash’
s7 = r"""another raw string with a double backslash: \\
"""
```
String operations

String concatenation:

```python
myfile = filename + '_tmp' + '.dat'
```

Substring extraction:

```python
>>> teststr = '0123456789'
>>> teststr[0:5]; teststr[:5]
'01234'
'01234'
>>> teststr[3:8]
'34567'
>>> teststr[3:]
'3456789'
```
Mutable and immutable objects

- The items/contents of mutable objects can be changed in-place
- Lists and dictionaries are mutable
- The items/contents of immutable objects cannot be changed in-place
- Strings and tuples are immutable

```python
>>> s2 = (1.2, 1.3, 1.4)  # tuple
>>> s2[1] = 0            # illegal
```
## Implementing a subclass

### Class MySub is a subclass of MyBase:

```python
class MySub(MyBase):
    def __init__(self,i,j,k):
        MyBase.__init__(self,i,j)
        self.k = k;
    def write(self):
        print 'MySub: i=',self.i,'j=',self.j,'k=',self.k
```

### Example:

```python
# this function works with any object that has a write func:
def write(v):
    v.write()

# make a MySub instance
i = MySub(7,8,9)
write(i)  # will call MySub’s write
```
Functions

Python functions have the form

```python
def function_name(arg1, arg2, arg3):
    # statements
    return something
```

Example:

```python
def debug(comment, variable):
    if os.environ.get('PYDEBUG', '0') == '1':
        print comment, variable
    ...
    v1 = file.readlines()[3:]
    debug('file %s (exclusive header):' % file.name, v1)

v2 = somefunc()
debug('result of calling somefunc:', v2)
```

This function prints any printable object!
Keyword arguments

Can name arguments, i.e., keyword=default-value

```python
def mkdir(dirname, mode=0777, remove=1, chdir=1):
    if os.path.isdir(dirname):
        if remove: shutil.rmtree(dirname)
        elif : return 0  # did not make a new directory
    os.mkdir(dir, mode)
    if chdir: os.chdir(dirname)
    return 1  # made a new directory
```

Calls look like

- `mkdir('tmp1')`
- `mkdir('tmp1', remove=0, mode=0755)`
- `mkdir('tmp1', 0755, 0, 1)`  # less readable

Keyword arguments make the usage simpler and improve documentation
Variable-size argument list

Variable number of ordinary arguments:

```python
def somefunc(a, b, *rest):
    for arg in rest:
        # treat the rest...

# call:
somefunc(1.2, 9, 'one text', 'another text')
```

Variable number of keyword arguments:

```python
def somefunc(a, b, *rest, **kw):
    for arg in rest:
        # work with arg...
    for key in kw.keys():
        # work kw[key]
```
Example

A function computing the average and the max and min value of a series of numbers:

```python
def statistics(*args):
    avg = 0; n = 0;  # local variables
    for number in args:  # sum up all the numbers
        n = n + 1; avg = avg + number
    avg = avg / float(n)  # float() to ensure non-integer division
    min = args[0]; max = args[0]
    for term in args:
        if term < min: min = term
        if term > max: max = term
    return avg, min, max  # return tuple
```

Usage:

```python
average, vmin, vmax = statistics(v1, v2, v3, b)
```
The Python expert’s version...

The statistics function can be written more compactly using (advanced) Python functionality:

```python
def statistics(*args):
    return (reduce(operator.add, args)/float(len(args)),
            min(args), max(args))
```

- `reduce(op, a)`: apply operation `op` successively on all elements in list `a` (here all elements are added)
- `min(a), max(a)`: find min/max of a list `a`
Call by reference

Python scripts normally avoid call by reference and return all output variables instead.

Try to swap two numbers:

```python
def swap(a, b):
    tmp = b; b = a; a = tmp;

a=1.2; b=1.3; swap(a, b)
print a, b  # has a and b been swapped?
(1.2, 1.3)  # no...
```

The way to do this particular task:

```python
def swap(a, b):
    return (b,a)  # return tuple

# or smarter, just say  (b,a) = (a,b)  or simply  b,a = a,b
```
Arguments are like variables

Consider a function

def swap(a, b):
    b = 2*b
    return b, a

Calling `swap(A, B)` is inside `swap` equivalent to

```python
a = A
b = B
b = 2*b
return b, a
```

Arguments are transferred in the same way as we assign objects to variables (using the assignment operator =)

This may help to explain how arguments in functions get their values
**In-place list assignment**

- Lists can be changed in-place in functions:

  ```python
  >>> def somefunc(mutable, item, item_value):
        mutable[item] = item_value
  >>> a = ['a','b','c']  # a list
  >>> somefunc(a, 1, 'surprise')
  >>> print a
  ['a', 'surprise', 'c']
  ```

- **Note:** `mutable` is a name for the same object as `a`, and we use this name to change the object in-place.

- This works for dictionaries as well (but not tuples) and instances of user-defined classes.
Input and output data in functions

The Python programming style is to have input data as arguments and output data as return values

```python
def myfunc(i1, i2, i3, i4=False, io1=0):
    # io1: input and output variable
    ...
    # pack all output variables in a tuple:
    return io1, o1, o2, o3
```

# usage:
```python
a, b, c, d = myfunc(e, f, g, h, a)
```

Only (a kind of) references to objects are transferred so returning a large data structure implies just returning a reference
Scope of variables

- Variables defined inside the function are local
- To change global variables, these must be declared as global inside the function
  
  ```python
  s = 1
  
  def myfunc(x, y):
      z = 0  # local variable, dies when we leave the func.
      global s
      s = 2  # assignment requires decl. as global
      return y-1, z+1
  ```

- Variables can be global, local (in func.), and class attributes
- The scope of variables in nested functions may confuse newcomers (see ch. 8.7 in the course book)
Regular expressions
Contents

- Motivation for regular expression
- Regular expression syntax
- Lots of examples on problem solving with regular expressions
- Many examples related to scientific computations
More info

- Ch. 8.2 in the course book
- Regular Expression HOWTO for Python (see doc.html)
- perldoc perlrequick (intro), perldoc perlretut (tutorial), perldoc perlre (full reference)
- “Text Processing in Python” by Mertz (Python syntax)
- “Mastering Regular Expressions” by Friedl (Perl syntax)
- Note: the core syntax is the same in Perl, Python, Ruby, Tcl, Egrep, Vi/Vim, Emacs, ..., so books about these tools also provide info on regular expressions
Motivation

Consider a simulation code with this type of output:

\[ t=2.5 \ a: 1.0 \ 6.2 \ -2.2 \ 12 \ iterations \ and \ \text{eps}=1.38756E-05 \]
\[ t=4.25 \ a: 1.0 \ 1.4 \ 6 \ iterations \ and \ \text{eps}=2.22433E-05 \]
>> switching from method AQ4 to AQ1
\[ t=5 \ a: 0.9 \ 2 \ iterations \ and \ \text{eps}=3.78796E-05 \]
\[ t=6.386 \ a: 1.0 \ 1.1525 \ 6 \ iterations \ and \ \text{eps}=2.22433E-06 \]
>> switching from method AQ1 to AQ2
\[ t=8.05 \ a: 1.0 \ 3 \ iterations \ and \ \text{eps}=9.11111E-04 \]
...

You want to make two graphs:

- iterations vs t
- eps vs t

How can you extract the relevant numbers from the text?
Regular expressions

- Some structure in the text, but `line.split()` is too simple (different no of columns/words in each line)
- Regular expressions constitute a powerful language for formulating structure and extract parts of a text
- Regular expressions look cryptic for the novice
- `regex/regexp`: abbreviations for regular expression
t=6.386  a: 1.0 1.1525  6 iterations and eps=2.22433E-06

- Structure: t=, number, 2 blanks, a:, some numbers, 3 blanks, integer, 
  ’ iterations and eps=’, number

- Regular expressions constitute a language for specifying such structures

- Formulation in terms of a regular expression:
  \[ t=(.*)\s{2}a:. * \s+(\d+) \text{ iterations and eps=}(.*) \]
A regex usually contains special characters introducing freedom in the text:

\[t = (.* ) \s{2} a:. * \s+ (\d+) \text{ iterations and eps=} (.* )\]

\[t=6.386 \ a: 1.0 \ 1.1525 \ 6 \text{ iterations and eps=} 2.22433E-06\]

- \(.*\) any character
- \(.*\) zero or more . (i.e. any sequence of characters)
- \((.* )\) can extract the match for .* afterwards
- \(\s\) whitespace (spacebar, newline, tab)
- \(\s\{2\}\) two whitespace characters
- \(a:\) exact text
- \(.*\) arbitrary text
- \(\s+\) one or more whitespace characters
- \(\d+\) one or more digits (i.e. an integer)
- \((\d+)\) can extract the integer later

iterations and eps= exact text
Using the regex in Python code

```python
pattern = r"t=(.*)(\s\d+) iterations and eps=(.*)"

# the output to be processed is stored in the list of lines

for line in lines:
    match = re.search(pattern, line)
    if match:
        t.append(float(match.group(1)))
        iterations.append(int(match.group(2)))
        eps.append(float(match.group(3)))
```
Result

Output text to be interpreted:

\[
\begin{align*}
t &= 2.5 \quad a \text{:} \quad 1 \quad 6 \quad -2 \quad 12 \text{ iterations and eps} &= 1.38756 \times 10^{-5} \\
t &= 4.25 \quad a \text{:} \quad 1.0 \quad 1.4 \quad 6 \text{ iterations and eps} &= 2.22433 \times 10^{-5} \\
&\text{>> switching from method AQ4 to AQ1} \\
t &= 5 \quad a \text{:} \quad 0.9 \quad 2 \text{ iterations and eps} &= 3.78796 \times 10^{-5} \\
t &= 6.386 \quad a \text{:} \quad 1 \quad 1.15 \quad 6 \text{ iterations and eps} &= 2.22433 \times 10^{-5} \\
&\text{>> switching from method AQP1 to AQ2} \\
t &= 8.05 \quad a \text{:} \quad 1.0 \quad 3 \text{ iterations and eps} &= 9.11111 \times 10^{-4}
\end{align*}
\]

Extracted Python lists:

\[
\begin{align*}
t &= [2.5, \ 4.25, \ 5.0, \ 6.386, \ 8.05] \\
\text{iterations} &= [12, \ 6, \ 2, \ 6, \ 3] \\
\text{eps} &= [1.38756e-05, \ 2.22433e-05, \ 3.78796e-05, \ 2.22433e-06, \ 9.11111E-04]
\end{align*}
\]
Another regex that works

Consider the regex
\[ t=(.*)\s+a:.*\s+(\d+)\s+.*=.(.*) \]

compared with the previous regex
\[ t=(.*)\s{2}a:.*\s+(\d+) \] iterations and \( \text{eps}=.(.*) \)

Less structure

How ’exact’ does a regex need to be?

The degree of preciseness depends on the probability of making a wrong match
Failure of a regex

- Suppose we change the regular expression to
  \[t=(.*)\s+a:\s+.*(\d+).*=.(.*)\]

- It works on most lines in our test text but not on
  \[t=2.5\ a: 1\ 6\ \ -2\ \ 12\ \text{iterations and } \text{eps}=1.38756E-05\]

- 2 instead of 12 (iterations) is extracted
  (why? see later)

- Regular expressions constitute a powerful tool, but you need to
devote understanding and experience
List of special regex characters

.  # any single character except a newline
^  # the beginning of the line or string
$  # the end of the line or string
*  # zero or more of the last character
+  # one or more of the last character
?  # zero or one of the last character

[A-Z]  # matches all upper case letters
[abc]  # matches either a or b or c
[^b]   # does not match b
[^a-z] # does not match lower case letters
Context is important

.*  # any sequence of characters (except newline)
[.*] # the characters . and *

^no  # the string 'no' at the beginning of a line
[^no] # neither n nor o

A-Z  # the 3-character string 'A-Z' (A, minus, Z)
[A-Z] # one of the chars A, B, C, ..., X, Y, or Z
More weird syntax...

- **The OR operator:**

  \((eg|le)gs\)  # matches eggs or legs

- **Short forms of common expressions:**

  \n  # a newline
  \t  # a tab
  \w  # any alphanumeric (word) character
      # the same as \[a-zA-Z0-9_\]
  \W  # any non-word character
      # the same as \[^a-zA-Z0-9_\]
  \d  # any digit, same as \[0-9\]
  \D  # any non-digit, same as \[^0-9\]
  \s  # any whitespace character: space,
      # tab, newline, etc
  \S  # any non-whitespace character
  \b  # a word boundary, outside [] only
  \B  # no word boundary
Quoting special characters

\.  # a dot
\|  # vertical bar
\[  # an open square bracket
\)  # a closing parenthesis
\*  # an asterisk
\^  # a hat
\/  # a slash
\\  # a backslash
\{  # a curly brace
\?  # a question mark
GUI for regex testing

src/tools/regexdemo.py:

```
Enter a regex:
\d+\d+

Enter a string:
here is a number 4.32 that matches the regex
```

The part of the string that matches the regex is high-lighted
Regex for a real number

Different ways of writing real numbers:
-3, 42.9873, 1.23E+1, 1.2300E+01, 1.23e+01

Three basic forms:
- integer: -3
- decimal notation: 42.9873, .376, 3.
- scientific notation: 1.23E+1, 1.2300E+01, 1.23e+01, 1e1
A simple regex

Could just collect the legal characters in the three notations:

\[0-9.Ee\-\+]+\]

Downside: this matches text like

12-24
24.-
--E1--
+++++

How can we define precise regular expressions for the three notations?
Decimal notation regex

- Regex for decimal notation:
  - `^-?\d*\.\d+$`
  
  # or equivalently (`\d` is `[0-9]`)
  - `^-?[0-9]*\.[0-9]+$`

- Problem: this regex does not match ’3.’

- The fix
  - `^-?\d*\.\d*`

  is ok but matches text like ’-.’ and (much worse!) ’.’

- Trying it on
  - ’some text. 4. is a number.’

  gives a match for the first period!
Fix of decimal notation regex

- We need a digit before OR after the dot
- The fix:
  
  $-? (\d* . \d+ | \d+ . \d*)$

- A more compact version (just "OR-ing" numbers without digits after the dot):

  $-? (\d* . \d+ | \d+ .)$
Combining regular expressions

- Make a regex for integer or decimal notation:
  (integer OR decimal notation)
  using the OR operator and parenthesis:
  -?\(\d+| (\d+\.\d*| \d*\.\d+)\)

- Problem: 22.432 gives a match for 22
  (i.e., just digits? yes - 22 - match!)
Check the order in combinations!

Remedy: test for the most complicated pattern first

\[(\text{decimal notation OR integer})\]

\[-?((\d+\./\d* | \d*\./\d+) | \d+)\]

Modularize the regex:

\[
\begin{align*}
\text{real}_\text{in} &= \text{r}'\d+' \\
\text{real}_\text{dn} &= \text{r}'(\d+\./\d* | \d*\./\d+)'
\end{align*}
\]

\[
\text{real} = '-?( '+' + \text{real}_\text{dn} + '+' | '+' + \text{real}_\text{in} + '+')'
\]
Scientific notation regex (1)

- Write a regex for numbers in scientific notation
- Typical text: $1.27635E+01$, $-1.27635e+1$
- Regular expression:
  
  ```
  -?\d\.\d+[Ee][+\-]\d\d?
  ```
  
  = optional minus, one digit, dot, at least one digit, E or e, plus or minus, one digit, optional digit
**Scientific notation regex (2)**

- Problem: `1e+00` and `1e1` are not handled
- Remedy: zero or more digits behind the dot, optional e/E, optional sign in exponent, more digits in the exponent (`1e001`):
  
  $$-?[\d.]?\d*[Ee][+-]?\d+$$
Making the regex more compact

- A pattern for integer or decimal notation:
  \[-?((\d+\.\d* | \d* \.\d+) | \d+)]

- Can get rid of an OR by allowing the dot and digits behind the dot be optional:
  \[-? (\d+ (\ .\d*) ? | \d* \ .\d+)]

- Such a number, followed by an optional exponent (a la $\text{e+02}$), makes up a general real number (!)
  \[-? (\d+ (\ .\d*) ? | \d* \ .\d+) ([eE] [+\-] ?\d+)?]
A more readable regex

Scientific OR decimal OR integer notation:

-?\(\d\.?\d* \[Ee\][+-]?\d+ \) \(\d+ \.\d* | \d* \.\d+ \) | \d+

or better (modularized):

real_in = r’\d+’
real_dn = r’(\d+\.\d* | \d*\.\d+)’
real_sn = r’(\d\.?\d* [Ee][+-]?\d+)’
real = ’-?(’ + real_sn + ’|’ + real_dn + ’|’ + real_in + ’)’

Note: first test on the most complicated regex in OR expressions
Groups (in introductory example)

Enclose parts of a regex in () to extract the parts:

```
pattern = r"t=(.* )\s+a:. *\s+(\d+)\s+. * =(. *)"
# groups: ( ) ( ) ( )
```

This defines three groups (t, iterations, eps)

In Python code:

```
match = re.search(pattern, line)
if match:
    time = float(match.group(1))
    iter = int (match.group(2))
    eps = float(match.group(3))
```

The complete match is group 0 (here: the whole line)
Regex for an interval

- **Aim:** extract lower and upper limits of an interval:
  
  \[ -3.14E+00, 29.6524 \]

- **Structure:** bracket, real number, comma, real number, bracket, with embedded whitespace
Easy start: integer limits

Regex for real numbers is a bit complicated

Simpler: integer limits

\[
\text{pattern} = r'\[[\d+,\d+]\]'
\]

but this does must be fixed for embedded white space or negative numbers a la

\[
[\ -3\ ,\ 29\ ]
\]

Remedy:

\[
\text{pattern} = r'\[[\s*-*\d+\s*,\s*-*\d+\s*]\]'
\]

Introduce groups to extract lower and upper limit:

\[
\text{pattern} = r'\[[\s*(-?\d+)\s*,\s*(-?\d+)\s*]\]'
\]
Testing groups

In an interactive Python shell we write

```python
>>> pattern = r'\[\s*(-?\d+)\s*,\s*(-?\d+)\s*\]'
>>> s = "here is an interval: [ -3, 100 ] ...
>>> m = re.search(pattern, s)
>>> m.group(0)
[ -3, 100]
>>> m.group(1)
-3
>>> m.group(2)
100
>>> m.groups()  # tuple of all groups
(''-3', '100')
```
Named groups

- Many groups? inserting a group in the middle changes other group numbers...
- Groups can be given *logical names* instead
- Standard group notation for interval:
  ```
  # apply integer limits for simplicity: [int,int]
  \[\s*(-?\d+)\s*,\s*(-?\d+)\s*\]
  ```

- Using named groups:
  ```
  \[\s*(?P<lower>-?\d+)\s*,\s*(?P<upper>-?\d+)\s*\]
  ```

- Extract groups by their names:
  ```python
  match.group('lower')
  match.group('upper')
  ```
Regex for an interval; real limits

Interval with general real numbers:

```python
real_short = r'\s*(-?(\d+(\.\d*)?|\d*\.\d+)([eE][+-]?\d+)?)\s*'
interval = r'\[' + real_short + ',' + real_short + r'\]'
```

Example:

```python
>>> m = re.search(interval, '[-100,2.0e-1]')
>>> m.groups()
('−100', '100', None, None, '2.0e-1', '2.0', '.0', 'e-1')
```

i.e., lots of (nested) groups; only group 1 and 5 are of interest
Handle nested groups with named groups

Real limits, previous regex resulted in the groups

(‘-100’, ’100’, None, None, ’2.0e-1’, ’2.0’, ’.0’, ’e-1’)

Downside: many groups, difficult to count right

Remedy 1: use named groups for the outer left and outer right groups:

```python
real1 = \r"s* (?P<lower>-?(\d+(\.\d*)?|\d*\.\d+)([eE][+-]?\d+)?)\s*"
real2 = \r"s* (?P<upper>-?(\d+(\.\d*)?|\d*\.\d+)([eE][+-]?\d+)?)\s*"
interval = r"\[" + real1 + "," + real2 + r"]"
...
match = re.search(interval, some_text)
if match:
    lower_limit = float(match.group(’lower’))
    upper_limit = float(match.group(’upper’))
```

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Simplify regex to avoid nested groups

- Remedy 2: reduce the use of groups

- Avoid nested OR expressions (recall our first tries):

  real_sn = r"-?\d\.?\d*[Ee][+\-]\d+"
  real_dn = r"-?\d*=\.d*"
  real = r"\s* (" + real_sn + "|" + real_dn + "|" + real_in + r")\s*"
  interval = r"\s\[" + real + "," + real + r"\]"

- Cost: (slightly) less general and safe regex
Extracting multiple matches (1)

- `re.findall` finds all matches (`re.search` finds the first)

  ```
  >>> r = r"\d+\.\d*"
  >>> s = "3.29 is a number, 4.2 and 0.5 too"
  >>> re.findall(r,s)
  ['3.29', '4.2', '0.5']
  ```

- Application to the interval example:

  ```python
  lower, upper = re.findall(real, '[-3, 9.87E+02]')
  # real: regex for real number with only one group!
  ```
Extracting multiple matches (1)

If the regex contains groups, `re.findall` returns the matches of all groups - this might be confusing!

```python
>>> r = r"(\d+)\..d*"
>>> s = "3.29 is a number, 4.2 and 0.5 too"
>>> re.findall(r,s)
['3', '4', '0']
```

Application to the interval example:

```python
>>> real_short = r"([-+]?\d+(\.\d*)?|\.\d+)([eE][-+]?\d+)?"
>>> # recall: real_short contains many nested groups!
>>> g = re.findall(real_short, '[-3, 9.87E+02]')
>>> g
[('-3', '3', '', ''), ('9.87E+02', '9.87', '.87', 'E+02')]
>>> limits = [ float(g1) for g1, g2, g3, g4 in g ]
>>> limits
[-3.0, 987.0]
```
Making a regex simpler

Regex is often a question of structure \textit{and context}

Simpler regex for extracting interval limits:
\[
\[(\.*), (\.*\)]
\]

It works!

```python
>>> l = re.search(r'\[(. * ), (. * )\]',
                 '[-3.2E+01, 0.11 ]').groups()
```
```python
>>> l
('’-3.2E+01’, ’0.11 ’)
```

# transform to real numbers:
```python
>>> r = [float(x) for x in l]
>>> r
[-32.0, 0.11]
```
Failure of a simple regex (1)

Let us test the simple regex on a more complicated text:

```python
>>> l = re.search(r'\[(.*?),(.*)\]', 
                  '[-3.2E+01,0.11 ] and [-4,8]').groups()
```

```python
>>> l
(''-3.2E+01,0.11 ] and [-4', ',8')
```

Regular expressions can surprise you...!

- Regular expressions are greedy, they attempt to find the longest possible match, here from \[ to the last (!) comma
- We want a shortest possible match, up to the first comma, i.e., a non-greedy match
- Add a ? to get a non-greedy match:

  ```python
  \[(.*?),(.*)\]
  ```

- Now l becomes

  ```python
  (''-3.2E+01', ',0.11 ')
  ```
Failure of a simple regex (2)

Instead of using a non-greedy match, we can use
\( \left[ ([^,]*) , ([^\]]*) \right] \)

Note: only the first group (here first interval) is found by \texttt{re.search}, use \texttt{re.findall} to find all
Failure of a simple regex (3)

The simple regexes

\[ ([^,]*), ([^\]]* ) ]
\[ (.*?), (.*?) ]

are not fool-proof:

```python
>>> l = re.search(r'\[([^,]*),([^\]]* )\]',
                 ' e.g., exception').groups()
>>> l
('e.g.', ' exception')
```

100 percent reliable fix: use the detailed real number regex inside the parenthesis

The simple regex is ok for personal code
Application example

Suppose we, in an input file to a simulator, can specify a grid using this syntax:

\[
\begin{align*}
domain &= [0,1] \times [0,2] \quad \text{indices} = [1:21] \times [0:100] \\
\text{domain} &= [0,15] \quad \text{indices} = [1:61] \\
\text{domain} &= [0,1] \times [0,1] \times [0,1] \quad \text{indices} = [0:10] \times [0:10] \times [0:20]
\end{align*}
\]

Can we easily extract domain and indices limits and store them in variables?
Extracting the limits

- Specify a regex for an interval with real number limits
- Use `re.findall` to extract multiple intervals
- Problems: many nested groups due to complicated real number specifications
- Various remedies: as in the interval examples, see `fdmgrid.py`
- The bottom line: a very simple regex, utilizing the surrounding structure, works well
Utilizing the surrounding structure

We can get away with a simple regex, because of the surrounding structure of the text:

```python
indices = r"\[(\[^:,\]*):(\[^\]\]*)\]"  # works
domain = r"\[(\[^,\]*),(\[^\]\]*)\]"  # works
```

Note: these ones do not work:

```python
indices = r"\[(\[^:\]*):(\[^\]\]*)\]"
indices = r"\[(.*?):(.*?)\]"
```

They match too much:

```python
domain=[0,1]x[0,2]  indices=[1:21]x[1:101]
[......................]
```

we need to exclude commas (i.e. left bracket, anything but comma or colon, colon, anythin but right bracket)
Splitting text

Split a string into words:

```python
line.split(splitstring)
# or
string.split(line, splitstring)
```

Split wrt a regular expression:

```python
>>> files = "case1.ps, case2.ps, case3.ps"
>>> import re
>>> re.split(r","\s*", files)
["case1.ps", "case2.ps", "case3.ps"]

>>> files.split("", ") # a straight string split is undesired
["case1.ps", "case2.ps", " case3.ps"]

>>> re.split(r"\s+", "some words in a text")
["some", "words", "in", "a", "text"]
```

Notice the effect of this:

```python
>>> re.split(r" ", "some words in a text")
["some", ",", ",", ",", "words", ",", ",", ",", "in", "a", "text"]
```
Pattern-matching modifiers (1)

...also called flags in Python regex documentation

Check if a user has written "yes" as answer:

```python
if re.search('yes', answer):
```

Problem: "YES" is not recognized; try a fix

```python
if re.search(r'(yes|YES)', answer):
```

Should allow "Yes" and "YEs" too...

```python
if re.search(r'[yY][eE][sS]', answer):
```

This is hard to read and case-insensitive matches occur frequently - there must be a better way!
Pattern-matching modifiers (2)

if re.search('yes', answer, re.IGNORECASE):
    # pattern-matching modifier: re.IGNORECASE
    # now we get a match for 'yes', 'YES', 'Yes' ...

    # ignore case:
    re.I or re.IGNORECASE

    # let ^ and $ match at the beginning and
    # end of every line:
    re.M or re.MULTILINE

    # allow comments and white space:
    re.X or re.VERBOSE

    # let . (dot) match newline too:
    re.S or re.DOTALL

    # let e.g. \w match special chars (?, ?, ...):
    re.L or re.LOCALE
Comments in a regex

The `re.X` or `re.VERBOSE` modifier is very useful for inserting comments explaining various parts of a regular expression.

Example:

```python
# real number in scientific notation:
real_sn = r'""
-?     # optional minus
\d\.\d+    # a number like 1.4098
[Ein][+\-]d\d?  # exponent, E-03, e-3, E+12
""'

match = re.search(real_sn, 'text with a=1.92E-04 ',
                  re.VERBOSE)

# or when using compile:
c = re.compile(real_sn, re.VERBOSE)
match = c.search('text with a=1.9672E-04 ')
```
Substitution

Substitute float by double:

```python
# filestr contains a file as a string
filestr = re.sub('float', 'double', filestr)
```

In general:

```python
re.sub(pattern, replacement, str)
```

If there are groups in pattern, these are accessed by

```plain
\1 \2 \3 ...
\g<1> \g<2> \g<3> ...:
\g<lower> \g<upper> ...
```

in replacement
Example: strip away C-style comments

C-style comments could be nice to have in scripts for commenting out large portions of the code:

```c
/*
while 1:
    line = file.readline()
    ...
...
*/
```

Write a script that strips C-style comments away

Idea: match comment, substitute by an empty string
Trying to do something simple

- Suggested regex for C-style comments:

  ```python
  comment = r'\/*.*\*/'
  # read file into string filestr
  filestr = re.sub(comment, '', filestr)

  i.e., match everything between /* and */

  - Bad: . does not match newline
  - Fix: re.S or re.DOTALL modifier makes . match newline:

    ```python
    comment = r'\/*.*\*/'
    c_comment = re.compile(comment, re.DOTALL)
    filestr = c_comment.sub(comment, '', filestr)
    ```

  - OK? No!
Testing the C-comment regex (1)

Test file:

/******************************************** /
/* File myheader.h */
/******************************************** /

#include <stuff.h> // useful stuff

class MyClass
{
  /* int r; */ float q;
  // here goes the rest class declaration
}

/* LOG HISTORY of this file:
 * $ Log: somefile,v $ 
 * Revision 1.2 2000/07/25 09:01:40 hpl
 * update 
 * 
 * Revision 1.1.1.1 2000/03/29 07:46:07 hpl
 * register new files
 */
The regex

`/\*\*\*/ with re.DOTALL (re.S)`

matches the whole file (i.e., the whole file is stripped away!)

Why? a regex is by default greedy, it tries the longest possible match, here the whole file

A question mark makes the regex non-greedy:

`/\*\*\?\*/`
Testing the C-comment regex (3)

- The non-greedy version works
- OK? Yes - the job is done, almost...

```c
const char* str ="/* this is a comment */"
```

gets stripped away to an empty string...
Substitution example

Suppose you have written a C library which has many users.

One day you decide that the function

```c
void superLibFunc(char* method, float x)
```

would be more natural to use if its arguments were swapped:

```c
void superLibFunc(float x, char* method)
```

All users of your library must then update their application codes - can you automate?
Substitution with backreferences

You want locate all strings on the form

\texttt{superLibFunc(arg1, arg2)}

and transform them to

\texttt{superLibFunc(arg2, arg1)}

Let \texttt{arg1} and \texttt{arg2} be groups in the regex for the superLibFunc calls

Write out

\texttt{superLibFunc(\2, \1)}

\# recall: \texttt{\1} is group 1, \texttt{\2} is group 2 in a re.sub command
**Regex for the function calls (1)**

- Basic structure of the regex of calls:
  
  ```
  superLibFunc\s*(\s*arg1\s*,\s*arg2\s*)
  ```
  
  but what should the `arg1` and `arg2` patterns look like?

- **Natural start:** `arg1` and `arg2` are valid C variable names
  
  ```
  arg = r"[A-Za-z_0-9]+"
  ```
  
- Fix; digits are not allowed as the first character:
  
  ```
  arg = "[A-Za-z_] [A-Za-z_0-9]*"
  ```
Regex for the function calls (2)

The regex

\[arg = "[A-Za-z_]\[A-Za-z_0-9\]*/"

works well for calls with variables, but we can call `superLibFunc` with numbers too:

```
superLibFunc ("relaxation", 1.432E-02);
```

Possible fix:

\[arg = r"[A-Za-z0-9_.\-+\"]+"]

but the disadvantage is that `arg` now also matches

```
.+32skj 3.ejks
```
Since arg2 is a float we can make a precise regex: legal C variable name OR legal real variable format

\[
\text{arg2} = r"([A-Za-z_][A-Za-z_0-9]*|" + \text{real} + \ \"|\ \text{float}\s+[A-Za-z_][A-Za-z_0-9]*" + \")"
\]

where \text{real} is our regex for formatted real numbers:

\[
\text{real} = r\\s* ("+ \text{real}\_\text{sn} +"|"+ \text{real}\_\text{dn} +"|"+ \text{real}\_\text{in} +r\")\s*"
\]
Constructing a precise regex (2)

- We can now treat variables and numbers in calls
- Another problem: should swap arguments in a user’s definition of the function:
  ```c
  void superLibFunc(char* method, float x)
  to
  void superLibFunc(float x, char* method)
  Note: the argument names (x and method) can also be omitted!
  ```

- Calls and declarations of superLibFunc can be written on more than one line and with embedded C comments!

- Giving up?
A simple regex may be sufficient

Instead of trying to make a precise regex, let us make a very simple one:

```python
code
arg = '.+'  # any text
```

"Any text" may be precise enough since we have the surrounding structure,

```
code
superLibFunc\s*\(\s*arg\s*,\s*arg\s*\)
```

and assume that a C compiler has checked that `arg` is a valid C code text in this context.
Refining the simple regex

A problem with .+ appears in lines with more than one calls:

```plaintext
superLibFunc(a,x); superLibFunc(ppp,qqq);
```

We get a match for the first argument equal to:

```plaintext
a,x); superLibFunc(ppp
```

Remedy: non-greedy regex (see later) or

```plaintext
arg = r"[^,]+"
```

This one matches multi-line calls/declarations, also with embedded comments (.+ does not match newline unless the `re.S` modifier is used)
Swapping of the arguments

Central code statements:

```python
arg = r"[^,]+"
call = r"superLibFunc\s*(\s*(%s),\s*(%s))" % (arg, arg)

# load file into filestr

# substitute:
filestr = re.sub(call, r"superLibFunc(\2, \1)", filestr)

# write out file again
fileobject.write(filestr)
```

Files: src/py/intro/swap1.py
Testing the code

Test text:

```c
superLibFunc(a, x);  superLibFunc(qqq, ppp);
superLibFunc ( method1, method2 );
superLibFunc(3method /* illegal name! */, method2 );
superLibFunc( _method1,method_2);
superLibFunc (   
    method1 /* the first method we have */ ,
    super_method4 /* a special method that 
    deserves a two-line comment... */ 
) ;
```

The simple regex successfully transforms this into

```c
superLibFunc(x, a);  superLibFunc(ppp, qqq);
superLibFunc(method2 , method1);
superLibFunc(method2 , 3method /* illegal name! */); 
superLibFunc(method_2, _method1) ;
superLibFunc(super_method4 /* a special method that 
    deserves a two-line comment... */ ,
    method1 /* the first method we have */ ) ;
```

Notice how powerful a small regex can be!!

Downside: cannot handle a function call as argument
Shortcomings

- The simple regex

\[[^,]+\]

breaks down for comments with comma(s) and function calls as arguments, e.g.,

```c
superLibFunc(m1, a /* large, random number */);
superLibFunc(m1, generate(c, q2));
```

The regex will match the longest possible string ending with a comma, in the first line

```c
m1, a /* large,
```

but then there are no more commas ...

- A complete solution should *parse* the C code
More easy-to-read regex

The `superLibFunc` call with comments and named groups:

```python
import re

# name of function to match
superLibFunc

# possible whitespace
\s*

# parenthesis before argument list
\(

# possible whitespace
\s*

# first argument plus optional whitespace
(?P<arg1>%s)

# comma between the arguments
,

# second argument plus optional whitespace
(?P<arg2>%s)

# closing parenthesis
\)

# the substitution command:
filestr = call.sub(r"superLibFunc(\g<arg2>, \g<arg1>)", filestr)
```

Files: src/py/intro/swap2.py
**Example**

- Goal: remove C++/Java comments from source codes
- Load a source code file into a string:
  ```python
  filestr = open(somefile, 'r').read()
  # note: newlines are a part of filestr
  ```
- Substitute comments `// some text...` by an empty string:
  ```python
  filestr = re.sub(r'//.*', '', filestr)
  ```
- Note: . (dot) does not match newline; if it did, we would need to say
  ```python
  filestr = re.sub(r'//[^\n]*', '', filestr)
  ```
Failure of a simple regex

How will the substitution

```python
filestr = re.sub(r'//[^\n]*', '', filestr)
```

treat a line like

```c
const char* heading = "-------------/------------";
```

???
The following useful function demonstrates how to extract matches, groups etc. for examination:

def debugregex(pattern, str):
    s = "does \"'" + pattern + '\" match \"'" + str + '\"'?\n"match = re.search(pattern, str)
    if match:
        s += str[:match.start()] + "\[" + \
            str[match.start():match.end()] + \
        "]" + str[match.end():]
        if len(match.groups()) > 0:
            for i in range(len(match.groups())):
                s += "\ngroup %d: [%s]" % \
                    (i+1,match.groups()[i])
    else:
        s += "No match"
    return s
Regex debugging (2)

Example on usage:

```python
>>> print debugregex(r"(\d+\.\d*)","a= 51.243 and b =1.45")

does '(.d+.d*)' match 'a= 51.243 and b =1.45'?
a= [51.243] and b =1.45
group 1: [51.243]
```
Python modules
Contents

- Making a module
- Making Python aware of modules
- Packages
- Distributing and installing modules
More info

- Appendix B.1 in the course book
- Python electronic documentation:
  Distributing Python Modules, Installing Python Modules
Make your own Python modules!

- Reuse scripts by wrapping them in classes or functions
- Collect classes and functions in library modules
- How? just put classes and functions in a file MyMod.py
- Put MyMod.py in one of the directories where Python can find it (see next slide)

Say

```python
import MyMod
# or
import MyMod as M    # M is a short form
# or
from MyMod import *
# or
from MyMod import myspecialfunction, myotherspecialfunction

in any script
```
How Python can find your modules

- Python has some 'official' module directories, typically
  
  `/usr/lib/python2.3`
  `/usr/lib/python2.3/site-packages`
  
  + current working directory

- The environment variable `PYTHONPATH` may contain additional directories with modules

  `unix> echo $PYTHONPATH`
  `/home/me/python/mymodules:/usr/lib/python2.2:/home/you/yourlibs`

- Python's `sys.path` list contains the directories where Python searches for modules

- `sys.path` contains 'official' directories, plus those in `PYTHONPATH`
Setting PYTHONPATH

- In a Unix Bash environment environment variables are normally set in .bashrc:
  ```
  export PYTHONPATH=$HOME/pylib:$scripting/src/tools
  ```

- Check the contents:
  ```
  unix> echo $PYTHONPATH
  ```

- In a Windows environment one can do the same in autoexec.bat:
  ```
  set PYTHONPATH=C:\pylib;%scripting%\src\tools
  ```

- Check the contents:
  ```
  dos> echo %PYTHONPATH%
  ```

- Note: it is easy to make mistakes; PYTHONPATH may be different from what you think, so check sys.path
Summary of finding modules

- Copy your module file(s) to a directory already contained in `sys.path`
  
  unix or dos> python -c 'import sys; print sys.path'

- Can extend `PYTHONPATH`

  # Bash syntax:
  export PYTHONPATH=$PYTHONPATH:/home/me/python/mymodules

- Can extend `sys.path` in the script:

  `sys.path.insert(0, '/home/me/python/mynewmodules')`

  (insert first in the list)
Packages (1)

- A class of modules can be collected in a *package*
- Normally, a package is organized as module files in a directory tree
- Each subdirectory has a file `__init__.py`
  (can be empty)
- Packages allow “dotted modules names” like
  MyMod.numerics.pde.grids

**reflecting a file** MyMod/numerics/pde/grids.py
Packages (2)

Can import modules in the tree like this:

```python
from MyMod.numerics.pde.grids import fdm_grids

grid = fdm_grids()
grid.domain(xmin=0, xmax=1, ymin=0, ymax=1)
...
```

Here, class `fdm_grids` is in module `grids` (file `grids.py`) in the directory `MyMod/numerics/pde`

Or

```python
import MyMod.numerics.pde.grids
grid = MyMod.numerics.pde.grids.fdm_grids()
grid.domain(xmin=0, xmax=1, ymin=0, ymax=1)
# or
import MyMod.numerics.pde.grids as Grid
grid = Grid.fdm_grids()
grid.domain(xmin=0, xmax=1, ymin=0, ymax=1)
```

See ch. 6 of the Python Tutorial (part of the electronic doc)
Test/doc part of a module

Module files can have a test/demo script at the end:

```python
if __name__ == '__main__':
    infile = sys.argv[1]; outfile = sys.argv[2]
    for i in sys.argv[3:]:
        create(infile, outfile, i)
```

- The block is executed if the module file is run as a script
- The tests at the end of a module often serve as good examples on the usage of the module
Public/non-public module variables

Python convention: add a leading underscore to non-public functions and (module) variables

```python
_counter = 0
def _filename():
    """Generate a random filename.""
    ...
```

After a standard import `import MyMod`, we may access

```python
MyMod._counter
n = MyMod._filename()
```

but after a `from MyMod import *` the names with leading underscore are *not* available

Use the underscore to tell users what is public and what is not

Note: non-public parts can be changed in future releases
Installation of modules/packages

- Python has its own build/installation system: Distutils
- Build: compile (Fortran, C, C++) into module (only needed when modules employ compiled code)
- Installation: copy module files to “install” directories
- Publish: make module available for others through PyPi
- Default installation directory:
  ```python
  os.path.join(sys.prefix, 'lib', 'python' + sys.version[0:3], 'site-packages')
  # e.g. /usr/lib/python2.3/site-packages
  ```
- Distutils relies on a `setup.py` script
A simple setup.py script

Say we want to distribute two modules in two files

MyMod.py    mymodcore.py

Typical setup.py script for this case:

```
#!/usr/bin/env python
from distutils.core import setup

setup(name='MyMod',
      version='1.0',
      description='Python module example',
      author='Hans Petter Langtangen',
      author_email='hpl@ifi.uio.no',
      url='http://www.simula.no/pymod/MyMod',
      py_modules=['MyMod', 'mymodcore'],
)
```
setup.py with compiled code

- Modules can also make use of Fortran, C, C++ code
- `setup.py` can also list C and C++ files; these will be compiled with the same options/compiler as used for Python itself
- SciPy has an extension of Distutils for “intelligent” compilation of Fortran files
- **Note:** `setup.py` eliminates the need for makefiles
- Examples of such `setup.py` files are provided in the section on mixing Python with Fortran, C and C++
Installing modules

Standard command:

```
python setup.py install
```

If the module contains files to be compiled, a two-step procedure can be invoked:

```
python setup.py build
# compiled files and modules are made in subdir. build/
python setup.py install
```
Controlling the installation destination

- `setup.py` has many options

- Control the destination directory for installation:
  ```
  python setup.py install --prefix=$HOME/install
  # copies modules to /home/hpl/install/lib/python
  ```

- Make sure that `/home/hpl/install/lib/python` is registered in your `PYTHONPATH`
How to learn more about Distutils

- Go to the official electronic Python documentation
- Look up “Distributing Python Modules” (for packing modules in setup.py scripts)
- Look up “Installing Python Modules” (for running setup.py with various options)
Doc strings
Contents

- How to document *usage* of Python functions, classes, modules
- Automatic testing of code (through doc strings)
More info

- App. B.1/B.2 in the course book
- HappyDoc, Pydoc, Epydoc manuals
- Style guide for doc strings (see doc.html)
Doc strings (1)

Doc strings = first string in functions, classes, files

Put user information in doc strings:

```python
def ignorecase_sort(a, b):
    """Compare strings a and b, ignoring case."""
    ...
```

The doc string is available at run time and explains the purpose and usage of the function:

```python
>>> print ignorecase_sort.__doc__
'Compare strings a and b, ignoring case.'
```
Doc strings (2)

Doc string in a class:

class MyClass:
    """Fake class just for exemplifying doc strings."""
    def __init__(self):
        ...

Doc strings in modules are a (often multi-line) string starting in the top of the file

    """
    This module is a fake module for exemplifying multi-line doc strings.
    """
Doc strings (3)

The doc string serves two purposes:

- documentation in the source code
- on-line documentation through the attribute __doc__
- documentation generated by, e.g., HappyDoc

HappyDoc: Tool that can extract doc strings and automatically produce overview of Python classes, functions etc.

Doc strings can, e.g., be used as balloon help in sophisticated GUIs (cf. IDLE)

Providing doc strings is a good habit!
Doc strings (4)

There is an official style guide for doc strings:

- PEP 257 "Docstring Conventions" from http://www.python.org/dev/peps/
- Use triple double quoted strings as doc strings
- Use complete sentences, ending in a period

```python
def somefunc(a, b):
    """Compare a and b."""
```
The `doctest` module enables automatic testing of interactive Python sessions embedded in doc strings.

```python
class StringFunction:
    """
    Make a string expression behave as a Python function of one variable.
    Examples on usage:
    >>> from StringFunction import StringFunction
    >>> f = StringFunction('sin(3*x) + log(1+x)')
    >>> p = 2.0; v = f(p)  # evaluate function
    >>> p, v
    (2.0, 0.81919679046918392)
    >>> f = StringFunction('1+t', independent_variables='t')
    >>> v = f(1.2)  # evaluate function of t=1.2
    >>> print "%.2f" % v
    2.20
    >>> f = StringFunction('sin(t)')
    >>> v = f(1.2)  # evaluate function of t=1.2
    Traceback (most recent call last):
    v = f(1.2)
    NameError: name 't' is not defined
    """
```
Class StringFunction is contained in the module StringFunction

Let StringFunction.py execute two statements when run as a script:

def _test():
    import doctest
    return doctest.testmod(StringFunction)

if __name__ == '__main__':
    _test()

Run the test:

python StringFunction.py  # no output: all tests passed
python StringFunction.py -v  # verbose output
Numerical Python
Contents

- Efficient array computing in Python
- Creating arrays
- Indexing/slicing arrays
- Random numbers
- Linear algebra
- Plotting
More info

- Ch. 4 in the course book
- www.scipy.org
- The NumPy manual
- The SciPy tutorial
Numerical Python (NumPy)

- NumPy enables efficient numerical computing in Python
- NumPy is a package of modules, which offers efficient arrays (contiguous storage) with associated array operations coded in C or Fortran
- There are three implementations of Numerical Python
  - Numeric from the mid 90s (still widely used)
  - numarray from about 2000
  - numpy from 2006
- We recommend to use numpy (by Travis Oliphant)

  from numpy import *
A taste of NumPy: a least-squares procedure

```python
x = linspace(0.0, 1.0, n)  # coordinates
y_line = -2*x + 3
y = y_line + random.normal(0, 0.25, n)  # line with noise

# goal: fit a line to the data points x, y

# create and solve least squares system:
A = array([x, ones(n)])
A = A.transpose()

result = linalg.lstsq(A, y)
# result is a 4-tuple, the solution (a,b) is the 1st entry:
a, b = result[0]

plot(x, y, 'o',  # data points w/noise
     x, y_line, 'r',  # original line
     x, a*x + b, 'b')  # fitted lines
legend('data points', 'original line', 'fitted line')
hardcopy('myplot.png')
```
$y = -1.86794x + 2.92875$: fit to $y = -2x + 3.0 + \text{normal noise}$
Making arrays

```python
>>> from numpy import *
>>> n = 4
>>> a = zeros(n)  # one-dim. array of length n
>>> print a
[ 0.  0.  0.  0.]
>>> a
array([ 0., 0., 0., 0.])
>>> p = q = 2
>>> a = zeros((p,q,3))  # p*q*3 three-dim. array
>>> print a
[[[ 0.  0.  0.]
  [ 0.  0.  0.]]
 [[ 0.  0.  0.]
  [ 0.  0.  0.]]]
>>> a.shape  # a’s dimension
(2, 2, 3)
```
Making float, int, complex arrays

```python
>>> a = zeros(3)
>>> print a.dtype # a’s data type
float64
>>> a = zeros(3, int)
>>> print a
[0 0 0]
>>> print a.dtype
int32
>>> a = zeros(3, float32) # single precision
>>> print a
[ 0. 0. 0.]
>>> print a.dtype
float32
>>> a = zeros(3, complex)
>>> a
array([ 0.+0.j, 0.+0.j, 0.+0.j])
>>> a.dtype
dtype(‘complex128’)

>>> given an array a, make a new array of same dimension and data type:
>>> x = zeros(a.shape, a.dtype)
```
Array with a sequence of numbers

- **linspace**\((a, b, n)\) generates \(n\) uniformly spaced coordinates, starting with \(a\) and ending with \(b\)

```python
>>> x = linspace(-5, 5, 11)
>>> print x
[-5. -4. -3. -2. -1.  0.  1.  2.  3.  4.  5.]
```

- A special compact syntax is also available:

```python
>>> a = r_[-5:5:11j]  # same as linspace(-5, 5, 11)
>>> print a
[-5. -4. -3. -2. -1.  0.  1.  2.  3.  4.  5.]
```

- **arange** works like **range** (**xrange**)?

```python
>>> x = arange(-5, 5, 1, float)
>>> print x  # upper limit 5 is not included!!
[-5. -4. -3. -2. -1.  0.  1.  2.  3.  4.]
```
Warning: arange is dangerous

- arange’s upper limit may or may not be included (due to round-off errors)

- Better to use a safer method: seq(start, stop, increment)

```python
g>>> from scitools.numpyutils import seq
g>>> x = seq(-5, 5, 1)
g>>> print x  # upper limit always included
[-5. -4. -3. -2. -1. 0. 1. 2. 3. 4. 5.]
```

- The package scitools is available at
  http://code.google.com/p/scitools/
Array construction from a Python list

array(list, [datatype]) generates an array from a list:

```python
>>> pl = [0, 1.2, 4, -9.1, 5, 8]
>>> a = array(pl)
```

The array elements are of the simplest possible type:

```python
>>> z = array([1, 2, 3])
>>> print z                # array of integers
[1 2 3]
>>> z = array([1, 2, 3], float)
>>> print z
[ 1. 2. 3.]
```

A two-dim. array from two one-dim. lists:

```python
>>> x = [0, 0.5, 1]; y = [-6.1, -2, 1.2]  # Python lists
>>> a = array([x, y])  # form array with x and y as rows
```

From array to list: `alist = a.tolist()`
From “anything” to a NumPy array

- Given an object $a$,

  $a = \text{asarray}(a)$

  converts $a$ to a NumPy array (if possible/necessary)

- Arrays can be ordered as in C (default) or Fortran:

  $a = \text{asarray}(a, \text{order}='\text{Fortran}')$
  
  $\text{isfortran}(a)$ # returns True if a’s order is Fortran

- Use \text{asarray} to, e.g., allow flexible arguments in functions:

  \begin{verbatim}
  def myfunc(some_sequence):
    a = \text{asarray}(some_sequence)
    return 3*a - 5
  \end{verbatim}

  myfunc([1,2,3])       # list argument
  myfunc((-1,1))        # tuple argument
  myfunc(zeros(10))     # array argument
  myfunc(-4.5)          # float argument
  myfunc(6)             # int argument
Changing array dimensions

```python
>>> a = array([0, 1.2, 4, -9.1, 5, 8])
>>> a.shape = (2,3)  # turn a into a 2x3 matrix
>>> print a
[[ 0.  1.2  4. ]
 [  9.1  5.  8. ]]
>>> a.size
6
>>> a.shape = (a.size, )  # turn a into a vector of length 6 again
>>> a.shape
(6,)
>>> print a
[ 0.  1.2  4.  -9.1  5.  8. ]
```
Array initialization from a Python function

```python
>>> def myfunc(i, j):
...     return (i+1)*(j+4-i)
...
>>> # make 3x6 array where a[i,j] = myfunc(i,j):
a = fromfunction(myfunc, (3,6))
>>> a
array([[ 4.,  5.,  6.,  7.,  8.,  9.],
       [ 6.,  8., 10., 12., 14., 16.],
       [ 6.,  9., 12., 15., 18., 21.]])
```
Basic array indexing

Note: all integer indices in Python start at 0!

```python
a = linspace(-1, 1, 6)
a[-1] = a[0]  # set last element equal to first one
a[:] = 0  # set all elements of a equal to 0
a.fill(0)  # set all elements of a equal to 0

a.shape = (2,3)  # turn a into a 2x3 matrix
print a[0,1]  # print element (0,1)
a[i,j] = 10  # assignment to element (i,j)
a[i][j] = 10  # equivalent syntax (slower)
print a[:,k]  # print column with index k
print a[1,:]  # print second row
a[:,,:] = 0  # set all elements of a equal to 0
```
More advanced array indexing

```python
>>> a = linspace(0, 29, 30)
>>> a.shape = (5,6)
>>> a
array([[ 0.,  1.,  2.,  3.,  4.,  5.],
       [ 6.,  7.,  8.,  9., 10., 11.],
       [12., 13., 14., 15., 16., 17.],
       [18., 19., 20., 21., 22., 23.],
       [24., 25., 26., 27., 28., 29.]])
>>> a[1:3,::2]  # a[i,j] for i=1,2 and j=0,2,4
array([[ 6.,  8., 10.],
       [12., 14., 16.]])
>>> a[::3,2::2]  # a[i,j] for i=0,3 and j=2,4
array([[ 2.,  4.],
       [20., 22.]])
>>> i = slice(None, None, 3); j = slice(2, None, 2)
>>> a[i,j]
array([[ 2.,  4.],
       [20., 22.]])
```
Slices refer the array data

With \texttt{a} as list, \texttt{a[ : ]} makes a copy of the data

With \texttt{a} as array, \texttt{a[ : ]} is a reference to the data


gg\gg\gg b = a[2, :] \quad \text{# extract 2nd row of } a
\gg\gg print a[2, 0]
12.0
\gg\gg b[0] = 2
\gg\gg print a[2, 0]
2.0 \quad \text{# change in } b \text{ is reflected in } a!

take a copy to avoid referencing via slices:

\gg\gg b = a[2, :].copy()
\gg\gg print a[2, 0]
12.0
\gg\gg b[0] = 2 \quad \text{# } b \text{ and } a \text{ are two different arrays now}
\gg\gg print a[2, 0]
12.0 \quad \text{# } a \text{ is not affected by change in } b

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Loops over arrays (1)

- **Standard loop over each element:**

  ```python
  for i in xrange(a.shape[0]):
      for j in xrange(a.shape[1]):
          a[i, j] = (i+1)*(j+1)*(j+2)
          print 'a[%d,%d]=%g ' % (i,j,a[i,j]),
  print  # newline after each row
  ```

- **A standard for loop iterates over the first index:**

  ```python
  >>> print a
  [[ 2.  6.  12.]
   [ 4. 12. 24.]]
  >>> for e in a:
  ...   print e
  ...   print e
  ...  
  [[ 2.  6.  12.]
   [ 4. 12. 24.]]
  ```
Loops over arrays (2)

- View array as one-dimensional and iterate over all elements:
  ```python
  for e in a.ravel():
      print e
  ```
  Use `ravel()` only when reading elements, for assigning it is better to use `shape` or `reshape` first!

- For loop over all index tuples and values:
  ```python
  >>> for index, value in ndenumerate(a):
      ...     print index, value
      ...  
      (0, 0) 2.0
      (0, 1) 6.0
      (0, 2) 12.0
      (1, 0) 4.0
      (1, 1) 12.0
      (1, 2) 24.0
  ```
Array computations

Arithmetic operations can be used with arrays:

\[ b = 3a - 1 \quad \# \text{a is array, b becomes array} \]

1) compute \( t_1 = 3a \), 2) compute \( t_2 = t_1 - 1 \), 3) set \( b = t_2 \)

Array operations are much faster than element-wise operations:

```python
>>> import time  # module for measuring CPU time
>>> a = linspace(0, 1, 1E+07)  # create some array
>>> t0 = time.clock()
>>> b = 3*a -1
>>> t1 = time.clock()  # t1-t0 is the CPU time of 3*a-1
>>> for i in xrange(a.size): b[i] = 3*a[i] - 1
>>> t2 = time.clock()
>>> print '3*a-1: %g sec, loop: %g sec' % (t1-t0, t2-t1)
3*a-1: 2.09 sec, loop: 31.27 sec
```
Standard math functions can take array arguments

# let b be an array

c = sin(b)
c = arcsin(c)
c = sinh(b)
# same functions for the cos and tan families

c = b**2.5  # power function

c = log(b)
c = exp(b)
c = sqrt(b)
Other useful array operations

# a is an array

a.clip(min=3, max=12)  # clip elements
a.mean(); mean(a)      # mean value
a.var(); var(a)        # variance
a.std(); std(a)        # standard deviation
median(a)
cov(x, y)              # covariance
trapz(a)               # Trapezoidal integration
diff(a)                # finite differences (da/dx)

# more Matlab-like functions:
corrcoeff, cumprod, diag, eig, eye, flip1r, flipud, max, min,
prod, ptp, rot90, squeeze, sum, svd, tri, tril, triu
More useful array methods and attributes

```python
>>> a = zeros(4) + 3
>>> a
array([ 3., 3., 3., 3.])  # float data
>>> a.item(2)  # more efficient than a[2]
3.0
>>> a.itemset(3,-4.5)  # more efficient than a[3]=-4.5
>>> a
array([ 3. , 3. , 3. , -4.5])
>>> a.shape = (2,2)
>>> a
array([[ 3. , 3. ],
       [ 3. , -4.5]])
>>> a.ravel()  # from multi-dim to one-dim
array([ 3. , 3. , 3. , -4.5])
>>> a.ndim  # no of dimensions
2
>>> len(a.shape)  # no of dimensions
2
>>> rank(a)  # no of dimensions
2
>>> a.size  # total no of elements
4
>>> b = a.astype(int)  # change data type
>>> b
array([3, 3, 3, 3])
```
Modules for curve plotting and 2D/3D visualization

- Matplotlib (curve plotting, 2D scalar and vector fields)
- PyX (PostScript/TeX-like drawing)
- Interface to Gnuplot
- Interface to Vtk
- Interface to OpenDX
- Interface to IDL
- Interface to Grace
- Interface to Matlab
- Interface to R
- Interface to Blender
Curve plotting with Easyviz

- Easyviz is a light-weight interface to many plotting packages, using a Matlab-like syntax
- Goal: write your program using Easyviz (“Matlab”) syntax and postpone your choice of plotting package
- Note: some powerful plotting packages (Vtk, R, matplotlib, ...) may be troublesome to install, while Gnuplot is easily installed on all platforms
- Easyviz supports (only) the most common plotting commands
- Easyviz is part of SciTools (Simula development)

```python
from scitools.all import *
(imports all of numpy, all of easyviz, plus scitools)
```
Basic Easyviz example

from scitools.all import *  # import numpy and plotting

\[ t = \text{linspace}(0, 3, 51) \]  # 51 points between 0 and 3

\[ y = t**2 * \text{exp}(-t**2) \]  # vectorized expression

plot(t, y)

hardcopy('tmp1.eps')  # make PostScript image for reports

hardcopy('tmp1.png')  # make PNG image for web pages
Decorating the plot

```python
plot(t, y)
xlabel('t')
ylabel('y')
legend('t^2*exp(-t^2)')
axis([0, 3, -0.05, 0.6])  # [tmin, tmax, ymin, ymax]
title('My First Easyviz Demo')

# or
plot(t, y, xlabel='t', ylabel='y',
     legend='t^2*exp(-t^2)',
     axis=[0, 3, -0.05, 0.6],
     title='My First Easyviz Demo',
     hardcopy='tmp1.eps',
     show=True)  # display on the screen (default)
```
My First Easyviz Demo

t^2 \times \exp(-t^2)

The resulting plot
Plotting several curves in one plot

Compare \( f_1(t) = t^2 e^{-t^2} \) and \( f_2(t) = t^4 e^{-t^2} \) for \( t \in [0, 3] \)

```python
from scitools.all import *  # for curve plotting
def f1(t):
    return t**2*exp(-t**2)
def f2(t):
    return t**2*f1(t)
t = linspace(0, 3, 51)
y1 = f1(t)
y2 = f2(t)

plot(t, y1)
hold('on')  # continue plotting in the same plot
plot(t, y2)

xlabel('t')
ylabel('y')
legend('t^2*exp(-t^2)', 't^4*exp(-t^2)')
title('Plotting two curves in the same plot')
hardcopy('tmp2.eps')
```
The resulting plot

Plotting two curves in the same plot

\[ t^2 \exp(-t^2) \]
\[ t^4 \exp(-t^2) \]
Example: plot a function given on the command line

- Task: plot (e.g.) \( f(x) = e^{-0.2x} \sin(2\pi x) \) for \( x \in [0, 4\pi] \)
- Specify \( f(x) \) and \( x \) interval as text on the command line:

  Unix/DOS> python plotf.py "exp(-0.2*x)*sin(2*pi*x)" 0 4*pi

- Program:

  ```python
  from scitools.all import *
  formula = sys.argv[1]
  xmin = eval(sys.argv[2])
  xmax = eval(sys.argv[3])
  
  x = linspace(xmin, xmax, 101)
  y = eval(formula)
  plot(x, y, title=formula)
  ```

- Thanks to `eval`, input (text) with correct Python syntax can be turned to running code on the fly
from scitools.all import *

x = y = linspace(-5, 5, 21)
xv, yv = ndgrid(x, y)
values = sin(sqrt(xv**2 + yv**2))
surf(xv, yv, values)
Adding plot features

# Matlab style commands:
setp(interactive=False)
surf(xv, yv, values)
shading('flat')
colorbar()
colormap(hot())
axis([-6,6,-6,6,-1.5,1.5])
view(35,45)
show()

# Optional Easyviz (Pythonic) short cut:
surf(xv, yv, values,
    shading='flat',
    colorbar='on',
    colormap=hot(),
    axis=[-6,6,-6,6,-1.5,1.5],
    view=[35,45])
The resulting plot
Other commands for visualizing 2D scalar fields

- `contour` (standard contours), `contourf` (filled contours),
  `contour3` (elevated contours)
- `mesh` (elevated mesh),
  `meshc` (elevated mesh with contours in the xy plane)
- `surf` (colored surface),
  `surfc` (colored surface with contours in the xy plane)
- `pcolor` (colored cells in a 2D mesh)
Commands for visualizing 3D fields

Scalar fields:
- isosurface
- slice_ (colors in slice plane), contourslice (contours in slice plane)

Vector fields:
- quiver3 (arrows), (quiver for 2D vector fields)
- streamline, streamtube, streamribbon (flow sheets)
More info about Easyviz

A plain text version of the Easyviz manual:
pydoc scitools.easyviz

The HTML version:
http://code.google.com/p/scitools/wiki/EasyvizDocumentation

Download SciTools (incl. Easyviz):
http://code.google.com/p/scitools/
Class programming in Python
Contents

- Intro to the class syntax
- Special attributes
- Special methods
- Classic classes, new-style classes
- Static data, static functions
- Properties
- About scope
More info

- Ch. 8.6 in the course book
- Python Tutorial
- Python Reference Manual (special methods in 3.3)
- Python in a Nutshell (OOP chapter - recommended!)
Classes in Python

- Similar class concept as in Java and C++
- All functions are virtual
- No private/protected variables (the effect can be "simulated")
- Single and multiple inheritance
- Everything in Python is an object, even the source code
- Class programming is easier and faster than in C++ and Java (?)
The basics of Python classes

- Declare a base class `MyBase`:
  ```python
class MyBase:
    def __init__(self,i,j): # constructor
        self.i = i; self.j = j
    def write(self): # member function
        print 'MyBase: i=',self.i,'j=',self.j
  
  self is a reference to this object
- Data members are prefixed by `self`:
  `self.i, self.j`
- All functions take `self` as first argument in the declaration, but not in the call
  ```python
  inst1 = MyBase(6,9); inst1.write()
  ```
Implementing a subclass

Class MySub is a subclass of MyBase:

class MySub(MyBase):
    def __init__(self,i,j,k):  # constructor
        MyBase.__init__(self,i,j)
        self.k = k;

    def write(self):
        print 'MySub: i=',self.i,'j=',self.j,'k=',self.k

Example:

# this function works with any object that has a write func:
def write(v): v.write()

# make a MySub instance
i = MySub(7,8,9)

write(i)  # will call MySub’s write
Comment on object-orientation

Consider

def write(v):
    v.write()

write(i)  # i is MySub instance

- In C++/Java we would declare v as a MyBase reference and rely on i.write() as calling the virtual function write in MySub.
- The same works in Python, but we do not need inheritance and virtual functions here: v.write() will work for any object v that has a callable attribute write that takes no arguments.
- Object-orientation in C++/Java for parameterizing types is not needed in Python since variables are not declared with types.
Private/non-public data

There is no technical way of preventing users from manipulating data and methods in an object.

Convention: attributes and methods starting with an underscore are treated as non-public (“protected”)

Names starting with a double underscore are considered strictly private (Python mangles class name with method name in this case: `obj.__some has actually the name _classname__some`)

class MyClass:
    def __init__(self):
        self._a = False # non-public
        self.b = 0 # public
        self.__c = 0 # private
Special attributes

i1 is MyBase, i2 is MySub

Dictionary of user-defined attributes:

```python
>>> i1.__dict__ # dictionary of user-defined attributes
{'i': 5, 'j': 7}
>>> i2.__dict__
{'i': 7, 'k': 9, 'j': 8}
```

Name of class, name of method:

```python
>>> i2.__class__.__name__ # name of class
'MySub'
>>> i2.write.__name__ # name of method
'write'
```

List names of all methods and attributes:

```python
>>> dir(i2)
['__doc__', '__init__', '__module__', 'i', 'j', 'k', 'write']
```
Testing on the class type

Use `isinstance` for testing class type:

```python
if isinstance(i2, MySub):
    # treat i2 as a MySub instance
```

Can test if a class is a subclass of another:

```python
if issubclass(MySub, MyBase):
    ...
```

Can test if two objects are of the same class:

```python
if inst1.__class__ is inst2.__class__
```

(is checks object identity, `==` checks for equal contents)

```python
a.__class__ refers the class object of instance a
```
Creating attributes on the fly

Attributes can be added at run time (!)

```python
>>> class G: pass

>>> g = G()
>>> dir(g)
['__doc__', '__module__']  # no user-defined attributes

>>> # add instance attributes:
>>> g.xmin=0; g.xmax=4; g.ymin=0; g.ymax=1
>>> dir(g)
['__doc__', '__module__', 'xmax', 'xmin', 'ymax', 'ymin']
>>> g.xmin, g.xmax, g.ymin, g.ymax
(0, 4, 0, 1)

>>> # add static variables:
>>> G.xmin=0; G.xmax=2; G.ymin=-1; G.ymax=1
>>> g2 = G()
>>> g2.xmin, g2.xmax, g2.ymin, g2.ymax  # static variables
(0, 2, -1, 1)
```
Another way of adding new attributes

Can work with \_\_dict\_\_ directly:

```python
g>>> i2.\_\_dict\_\_['q'] = 'some string'
g>>> i2.q
g'some string'
g>>> dir(i2)
g['__doc__', '__init__', '__module__', 'i', 'j', 'k', 'q', 'write']
```
Special methods

Special methods have leading and trailing double underscores (e.g. `__str__`)

Here are some operations defined by special methods:

```python
len(a)  # a.__len__()
c = a*b  # c = a.__mul__(b)
a = a+b  # a = a.__add__(b)
a += c   # a.__iadd__(c)
da = a[3]  # d = a.__getitem__(3)
a[3] = 0  # a.__setitem__(3, 0)
f = a(1.2, True)  # f = a.__call__(1.2, True)
if a:  # if a.__len__() > 0: or if a.__nonzero__():
```

Class programming in Python – p. 287/731
Example: functions with extra parameters

Suppose we need a function of $x$ and $y$ with three additional parameters $a$, $b$, and $c$:

```python
def f(x, y, a, b, c):
    return a + b*x + c*y*y
```

Suppose we need to send this function to another function

```python
def gridvalues(func, xcoor, ycoor, file):
    for i in range(len(xcoor)):
        for j in range(len(ycoor)):
            f = func(xcoor[i], ycoor[j])
            file.write('%g %g %g
' % (xcoor[i], ycoor[j], f)
```

`func` is expected to be a function of $x$ and $y$ only (many libraries need to make such assumptions!)

How can we send our $f$ function to `gridvalues`?
Possible (inferior) solutions

Bad solution 1: global parameters

global a, b, c
...
def f(x, y):
    return a + b*x + c*y*y
...
a = 0.5; b = 1; c = 0.01
gridvalues(f, xcoor, ycoor, somefile)

Global variables are usually considered evil

Bad solution 2: keyword arguments for parameters

def f(x, y, a=0.5, b=1, c=0.01):
    return a + b*x + c*y*y
...
gridvalues(f, xcoor, ycoor, somefile)

useless for other values of a, b, c
Solution: class with call operator

- Make a class with function behavior instead of a pure function
- The parameters are class attributes
- Class instances can be called as ordinary functions, now with $x$ and $y$ as the only formal arguments

```python
class F:
    def __init__(self, a=1, b=1, c=1):
        self.a = a; self.b = b; self.c = c

    def __call__(self, x, y):  # special method!
        return self.a + self.b*x + self.c*y*y

f = F(a=0.5, c=0.01)
# can now call f as
v = f(0.1, 2)
...
gridvalues(f, xcoor, ycoor, somefile)
```
Alternative solution: Closure

Make a function that locks the namespace and constructs and returns a tailor made function

```python
def F(a=1, b=1, c=1):
    def f(x, y):
        return a + b*x + c*y*y
    return f

f = F(a=0.5, c=0.01)
# can now call f as
v = f(0.1, 2)
...
gridvalues(f, xcoor, ycoor, somefile)
```
Some special methods

- `__init__(self [, args])`: constructor
- `__del__(self)`: destructor (seldom needed since Python offers automatic garbage collection)
- `__str__(self)`: string representation for pretty printing of the object (called by `print` or `str`)
- `__repr__(self)`: string representation for initialization (`a==eval(repr(a))` is true)
Comparison, length, call

- **__eq__(self, x):** for equality (\(a==b\)), should return True or False
- **__cmp__(self, x):** for comparison (\(<, \leq, >, \geq, ==, \neq\)); return negative integer, zero or positive integer if \(\text{self}\) is less than, equal or greater than \(x\) (resp.)
- **__len__(self):** length of object (called by \(\text{len}(x)\))
- **__call__(self [, args]):** calls like \(a(x, y)\) implies \(a.__call__(x, y)\)
Indexing and slicing

- `__getitem__(self, i)`: used for subscripting:
  
  ```python
  b = a[i]
  ```

- `__setitem__(self, i, v)`: used for subscripting:
  ```python
  a[i] = v
  ```

- `__delitem__(self, i)`: used for deleting:
  ```python
  del a[i]
  ```

These three functions are also used for slices:

```python
a[p:q:r] implies that i is a slice object with attributes start (p), stop (q) and step (r)
```

```python
b = a[:-1]
# implies
b = a.__getitem__(i)
isinstance(i, slice) is True
i.start is None
i.stop is -1
i.step is None
```
Arithmetic operations

- __add__(self, b): used for self+b, i.e., x+y implies x.__add__(y)
- __sub__(self, b): self-b
- __mul__(self, b): self*b
- __div__(self, b): self/b
- __pow__(self, b): self**b or pow(self,b)
In-place arithmetic operations

- `__iadd__(self, b): self += b`
- `__isub__(self, b): self -= b`
- `__imul__(self, b): self *= b`
- `__idiv__(self, b): self /= b`
Right-operand arithmetics

- `__radd__(self, b)`: This method defines `b+self`, while `__add__(self, b)` defines `self+b`. If `a+b` is encountered and `a` does not have an `__add__` method, `b.__radd__(a)` is called if it exists (otherwise `a+b` is not defined).

- Similar methods: `__rsub__`, `__rmul__`, `__rdiv__`
**Type conversions**

- `__int__(self)`: conversion to integer
  (int(a) makes an a.__int__() call)
- `__float__(self)`: conversion to float
- `__hex__(self)`: conversion to hexadecimal number

Documentation of special methods: see the *Python Reference Manual* (not the Python Library Reference!), follow link from index “overloading - operator”
Boolean evaluations

- if a:
  when is a evaluated as true?
- If a has __len__ or __nonzero__ and the return value is 0 or False, a evaluates to false
- Otherwise: a evaluates to true
- Implication: no implementation of __len__ or __nonzero__ implies that a evaluates to true!!
- while a follows (naturally) the same set-up
Example on call operator: StringFunction

Matlab has a nice feature: mathematical formulas, written as text, can be turned into callable functions.

A similar feature in Python would be like:

```
f = StringFunction_v1('1+sin(2*x)')
print f(1.2)  # evaluates f(x) for x=1.2
```

- \( f(x) \) implies \( f.__call__(x) \)
- Implementation of class StringFunction_v1 is compact! (see next slide)
Implementation of StringFunction classes

Simple implementation:

class StringFunction_v1:
    def __init__(self, expression):
        self._f = expression

    def __call__(self, x):
        return eval(self._f)  # evaluate function expression

Problem: eval(string) is slow; should pre-compile expression

class StringFunction_v2:
    def __init__(self, expression):
        self._f_compiled = compile(expression, '<string>', 'eval')

    def __call__(self, x):
        return eval(self._f_compiled)
New-style classes

- The class concept was redesigned in Python v2.2
- We have *new-style* (v2.2) and *classic* classes
- New-style classes add some convenient functionality to classic classes
- New-style classes must be derived from the *object* base class:

```python
class MyBase(object):
    # the rest of MyBase is as before
```
Static data

Static data (or class variables) are common to all instances

```python
>>> class Point:
    counter = 0  # static variable, counts no of instances
def __init__(self, x, y):
    self.x = x; self.y = y;
    Point.counter += 1

>>> for i in range(1000):
    p = Point(i*0.01, i*0.001)

>>> Point.counter  # access without instance
1000
>>> p.counter      # access through instance
1000
```
Static methods

New-style classes allow static methods (methods that can be called without having an instance)

```python
class Point(object):
    _counter = 0
    def __init__(self, x, y):
        self.x = x; self.y = y; Point._counter += 1
    def ncopies(): return Point._counter
    ncopies = staticmethod(ncopies)
```

Calls:

```python
>>> Point.ncopies()
0
>>> p = Point(0, 0)
>>> p.ncopies()
1
>>> Point.ncopies()
1
```

Cannot access `self` or class attributes in static methods
Properties

- Python 2.3 introduced “intelligent” assignment operators, known as properties
- That is, assignment may imply a function call:
  
  ```
  x.data = mydata; yourdata = x.data
  # can be made equivalent to
  x.set_data(mydata); yourdata = x.get_data()
  ```

- Construction:

  ```
  class MyClass(object):  # new-style class required!
      ...
      def set_data(self, d):
          self._data = d
          # <update other data structures if necessary...>

      def get_data(self):
          # <perform actions if necessary...>
          return self._data

      data = property(fget=get_data, fset=set_data)
  ```
Attribute access; traditional

- Direct access:
  ```python
  my_object.attr1 = True
  a = my_object.attr1
  ```

- get/set functions:
  ```python
class A:
    def set_attr1(attr1):
        self._attr1 = attr # underscore => non-public variable
        self._update(self._attr1) # update internal data too
...

my_object.set_attr1(True)
a = my_object.get_attr1()
```

Tedious to write! Properties are simpler...
Attribute access; recommended style

- Use direct access if user is allowed to read and assign values to the attribute
- Use properties to restrict access, with a corresponding underlying non-public class attribute
- Use properties when assignment or reading requires a set of associated operations
- Never use get/set functions explicitly
- Attributes and functions are somewhat interchanged in this scheme ⇒ that’s why we use the same naming convention

```python
myobj.compute_something()
myobj.my_special_variable = yourobj.find_values(x,y)
```
More about scope

Example: \( a \) is global, local, and class attribute

\[
a = 1 \quad \# \text{ global variable}
\]

\[
def \text{f}(x):
    a = 2 \quad \# \text{ local variable}
\]

\[
\text{class B:}
\]
\[
    \text{def \_\_init\_\_}(self):
        self.a = 3 \quad \# \text{ class attribute}
\]
\[
    \text{def \_scopes\_}(self):
        a = 4 \quad \# \text{ local (method) variable}
\]

Dictionaries with variable names as keys and variables as values:

- \text{locals()} : local variables
- \text{globals()} : global variables
- \text{vars()} : local variables
- \text{vars(self)} : class attributes
Demonstration of scopes (1)

Function scope:

```python
>>> a = 1
>>> def f(x):
    a = 2  # local variable
    print 'locals:', locals(), 'local a:', a
    print 'global a:', globals()['a']

>>> f(10)
locals: {'a': 2, 'x': 10} local a: 2
global a: 1

a refers to local variable
```
Demonstration of scopes (2)

Class:

class B:
    def __init__(self):
        self.a = 3    # class attribute

    def scopes(self):
        a = 4         # local (method) variable
        print 'locals:', locals()
        print 'vars(self):', vars(self)
        print 'self.a:', self.a
        print 'local a:', a, 'global a:', globals()['a']

Interactive test:

>>> b=B()
>>> b.scopes()
locals: {'a': 4, 'self': <scope.B instance at 0x4076fb4c>}
vars(self): {'a': 3}
self.a: 3
local a: 4 global a: 1
Demonstration of scopes (3)

- Variable interpolation with `vars`

```python
class C(B):
    def write(self):
        local_var = -1
        s = '%(local_var)d %(global_var)d %(a)s' % vars()
```

- Problem: `vars()` returns dict with local variables and the string needs global, local, and class variables

- Primary solution: use printf-like formatting:

```python
s = '%d %d %d' % (local_var, global_var, self.a)
```

- More exotic solution:

```python
all = {}
for scope in (locals(), globals(), vars(self)):
    all.update(scope)
    s = '%(local_var)d %(global_var)d %(a)s' % all

(but now we overwrite a...)
```
Namespaces for exec and eval

- `exec` and `eval` may take dictionaries for the global and local namespace:

```python
exec code in globals, locals
eval(expr, globals, locals)
```

- **Example:**

```python
a = 8; b = 9
d = {'a':1, 'b':2}
eval('a + b', d)  # yields 3
```

```
and
from math import *
d['b'] = pi
eval('a+sin(b)', globals(), d)  # yields 1
```

- Creating such dictionaries can be handy
Generalized StringFunction class (1)

Recall the StringFunction-classes for turning string formulas into callable objects

```python
f = StringFunction('1+sin(2*x)')
print f(1.2)
```

We would like:
- an arbitrary name of the independent variable
- parameters in the formula

```python
f = StringFunction_v3('1+A*sin(w*t)',
                      independent_variable='t',
                      set_parameters='A=0.1; w=3.14159')
print f(1.2)
f.set_parameters('A=0.2; w=3.14159')
print f(1.2)
```
First implementation

Idea: hold independent variable and “set parameters” code as strings

Exec these strings (to bring the variables into play) right before the formula is evaluated

class StringFunction_v3:
    def __init__(self, expression, independent_variable='x',
                 set_parameters=''):    
        self._f_compiled = compile(expression,
                                     '<string>', 'eval')
        self._var = independent_variable # 'x', 't' etc.
        self._code = set_parameters

    def set_parameters(self, code):
        self._code = code

    def __call__(self, x):
        exec '%s = %g' % (self._var, x) # assign indep. var.
        if self._code: exec(self._code) # parameters?
        return eval(self._f_compiled)
Efficiency tests

- The exec used in the \_\_call\_\_ method is slow!

- Think of a hardcoded function,

  ```python
def f1(x):
    return \sin(x) + x**3 + 2*x
  ```

  and the corresponding `StringFunction`-like objects

- Efficiency test (time units to the right):

  ```
f1 : 1
StringFunction\_v1: 13
StringFunction\_v2: 2.3
StringFunction\_v3: 22
```

- Why?

- eval w/compile is important; exec is very slow
A more efficient StringFunction (1)

Ideas: hold parameters in a dictionary, set the independent variable into this dictionary, run eval with this dictionary as local namespace

Usage:

```python
f = StringFunction_v4('1+A*sin(w*t)', A=0.1, w=3.14159)
f.set_parameters(A=2)  # can be done later
```
A more efficient StringFunction (2)

Code:

```python
class StringFunction_v4:
    def __init__(self, expression, **kwargs):
        self._f_compiled = compile(expression,
                                     '<string>', 'eval')
        self._var = kwargs.get('independent_variable', 'x')
        self._prms = kwargs
        try:
            del self._prms['independent_variable']
        except:
            pass

    def set_parameters(self, **kwargs):
        self._prms.update(kwargs)

    def __call__(self, x):
        self._prms[self._var] = x
        return eval(self._f_compiled, globals(), self._prms)
```
Extension to many independent variables

We would like arbitrary functions of arbitrary parameters and independent variables:

\[
f = \text{StringFunction\_v5('A*\sin(x)*\exp(-b*t)', A=0.1, b=1, independent\_variables=('x','t'))}
\]

\[
\text{print } f(1.5, 0.01) \ # \ x=1.5, \ t=0.01
\]

Idea: add functionality in subclass

```python
class StringFunction\_v5(StringFunction\_v4):
    def __init__(self, expression, **kwargs):
        StringFunction\_v4.__init__(self, expression, **kwargs)
        self._var = tuple(kwargs.get('independent\_variables', 'x'))

        try: del self._prms['independent\_variables']
        except: pass

    def __call__(self, *args):
        for name, value in zip(self._var, args):
            self._prms[name] = value  # add indep. variable
        return eval(self._f\_compiled,
                    globals(), self._prms)
```
Efficiency tests

Test function: \( \sin(x) + x**3 + 2*x \)

- \( f1 \): 1
- StringFunction_v1: 13 (because of uncompiled eval)
- StringFunction_v2: 2.3
- StringFunction_v3: 22 (because of exec in \_
__call\_
)
- StringFunction_v4: 2.3
- StringFunction_v5: 3.1 (because of loop in \_
__call\_
)
Removing all overhead

Instead of `eval in __call__` we may build a (lambda) function

```python
class StringFunction:
    def _build_lambda(self):
        s = 'lambda ' + ', '.join(self._var)
        # add parameters as keyword arguments:
        if self._prms:
            s += ', ' + ', '.join(['%s=%s' % (k, self._prms[k])
                                    for k in self._prms])
        s += ': ' + self._f
        self.__call__ = eval(s, globals())
```

For a call

```python
f = StringFunction('A*sin(x)*exp(-b*t)', A=0.1, b=1,
                   independent_variables=('x','t'))
```

the s looks like

```python
lambda x, t, A=0.1, b=1: return A*sin(x)*exp(-b*t)
```
**Final efficiency test**

- **StringFunction** objects are as efficient as similar hardcoded objects, i.e.,

```python
class F:
    def __call__(self, x, y):
        return sin(x) * cos(y)
```

but there is some overhead associated with the `__call__` op.

- **Trick**: extract the underlying method and call it directly

```python
f1 = F()
f2 = f1.__call__  # f2(x,y) is faster than f1(x,y)
```

Can typically reduce CPU time from 1.3 to 1.0

- **Conclusion**: now we can grab formulas from command-line, GUI, Web, anywhere, and turn them into callable Python functions *without any overhead*
Adding pretty print and reconstruction

“Pretty print”:

```python
class StringFunction:
    ...
    def __str__(self):
        return self._f  # just the string formula
```

Reconstruction: `a = eval(repr(a))`

```python
# StringFunction('1+x+a*y',
    independent_variables=('x','y'),
    a=1)

def __repr__(self):
    kwargs = ', '.join(['%s=%s' % (key, repr(value)) \n        for key, value in self._prms.items()])
    return "StringFunction1(%s, independent_variable=%s"
        "", %s)" % (repr(self._f), repr(self._var), kwargs)
```
Examples on StringFunction functionality (1)

```python
>>> from scitools.StringFunction import StringFunction
>>> f = StringFunction('1+sin(2*x)')
>>> f(1.2)
1.6754631805511511

>>> f = StringFunction('1+sin(2*t)', independent_variables='t')
>>> f(1.2)
1.6754631805511511

>>> f = StringFunction('1+A*sin(w*t)', independent_variables='t', A=0.1, w=3.14159)
>>> f(1.2)
0.94122173238695939
>>> f.set_parameters(A=1, w=1)
>>> f(1.2)
1.9320390859672263

>>> f(1.2, A=2, w=1) # can also set parameters in the call
2.8640781719344526
```
Examples on StringFunction functionality (2)

```python
>>> # function of two variables:
>>> f = StringFunction('1+sin(2*x)*cos(y)', 
                    independent_variables=('x', 'y'))
>>> f(1.2, -1.1)
1.3063874788637866

>>> f = StringFunction('1+V*sin(w*x)*exp(-b*t)', 
                    independent_variables=('x', 't'))
>>> f.set_parameters(V=0.1, w=1, b=0.1)
>>> f(1.0, 0.1)
1.0833098208613807
>>> str(f)  # print formula with parameters substituted by values
'1+0.1*sin(1*x)*exp(-0.1*t)'
>>> repr(f)
"StringFunction('1+V*sin(w*x)*exp(-b*t)',
               independent_variables=('x', 't'), b=0.10000000000000001,
               w=1, V=0.10000000000000001)"

>>> # vector field of x and y:
>>> f = StringFunction('[a+b*x, y]', 
                    independent_variables=('x', 'y'))
>>> f.set_parameters(a=1, b=2)
>>> f(2, 1)  # [1+2*2, 1]
[5, 1]
```

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Exercise

Implement a class for vectors in 3D

Application example:

```python
>>> from Vec3D import Vec3D
>>> u = Vec3D(1, 0, 0) # (1,0,0) vector
>>> v = Vec3D(0, 1, 0)
>>> print u**v # cross product
(0, 0, 1)
>>> u[1] # subscripting
0
>>> v[2]=2.5 # subscripting w/assignment
>>> u+v # vector addition
(1, 1, 2.5)
>>> u-v # vector subtraction
(1, -1, -2.5)
>>> u*v # inner (scalar, dot) product
0
>>> str(u) # pretty print
'(1, 0, 0)'
>>> repr(u) # u = eval(repr(u))
'Vec3D(1, 0, 0)'
```
Exercise, 2nd part

Make the arithmetic operators +, − and * more intelligent:

```python
u = Vec3D(1, 0, 0)
v = Vec3D(0, -0.2, 8)
a = 1.2
u+v  # vector addition
a+v  # scalar plus vector, yields (1.2, 1, 9.2)
v+a  # vector plus scalar, yields (1.2, 1, 9.2)
a-v  # scalar minus vector
v-a  # scalar minus vector
a*v  # scalar times vector
v*a  # vector times scalar
```
Python optimization
Optimization of C, C++, and Fortran

- Compilers do a good job for C, C++, and Fortran.
- The type system makes aggressive optimization possible.
- Examples: code inlining, loop unrolling, and memory prefetching.
Python optimization

- No compiler.
- No type declaration of variables.
- No inlining and no loop unrolling.
- Probably inefficient in Python:

```python
def f(a, b):
    return a + b
```
Manual timing

- Use `time.time()`.
- Simple statements should be placed in a loop.
- Make sure constant machine load.
- Run the tests several times, choose the fastest.
The `timeit` module (1)

Usage:
```python
import timeit
timer = timeit.Timer(stmt="a+=1", setup="a=0")
time = timer.timeit(number=10000) # or
times = timer.repeat(repeat=5, number=10000)
```
The `timeit` module (2)

- Isolates the global namespace.
- Automatically wraps the code in a for–loop.
- Users can provide their own timer (callback).
- Time a user defined function:
  ```python
  from __main__ import my_func
  ```
Profiling modules

Prior to code optimization, hotspots and bottlenecks must be located.
"First make it work. Then make it right. Then make it fast."
- Kent Beck

Two modules: profile and hotshot.
profile works for all Python versions.
hotshot introduced in Python version 2.2.
The **profile** module (1)

- **As a script:** `profile.py script.py`
- **As a module:**
  ```python
  import profile
  pr = profile.Profile()
  res = pr.run("function()", "filename")
  res.print_stats()
  ```
- Profile data saved to "filename" can be viewed with the **pstats** module.
The `profile` module (2)

- `profile.calibrate(number)` finds the profiling overhead.
- Remove profiling overhead:
  ```
  pr = profile.Profile(bias=overhead)
  ```
- Profile a single function call:
  ```
  pr = profile.Profile()
  pr.runcall(func, *args, **kwargs)
  ```
The **hotshot** module

- **Similar to** `profile`, **but mostly implemented in** C.
- **Smaller performance impact than** `profile`.

**Usage:**

```python
import hotshot
pr = hotshot.Profile("filename")
pr.run(cmd)
pr.close()  # Close log-file and end profiler
```

**Read profile data:**

```python
import hotshot.stats
data = hotshot.stats.load("filename")# profile.Stats instance
data.print_stats()
```
The \texttt{pstats} module

There are many ways to view profiling data.

The module \texttt{pstats} provides the class \texttt{Stats} for creating profiling reports:

```python
import pstats
data = pstats.Stats("filename")
data.print_stats()
```

The method \texttt{sort_stats(key, *keys)} is used to sort future output.

Common used keys: \texttt{‘calls’, ‘cumulative’, ‘time’}. 
Pure Python performance tips

Place references to functions in the local namespace.

```python
from math import *

def f(x):
    for i in xrange(len(x)):
        x[i] = sin(x[i])  # Slow
    return x

def g(x):
    loc_sin = sin  # Local reference
    for i in xrange(len(x)):
        x[i] = loc_sin(x[i])  # Faster
    return x
```

Reason: Local namespace is searched first.
More local references

Local references to instance methods of global objects are even more important, as we need only one dictionary look–up to find the method instead of three (local, global, instance–dictionary).

```python
class Dummy(object):
    def f(self): pass

d = Dummy()

def f():
    loc_f=d.f
    for i in xrange(10000): loc_f()
```

Calling `loc_f()` instead of `d.f()` is 40% faster in this example.
Exceptions should never happen

- Use `if/else` instead of `try/except`

- Example:
  ```python
x = 0
try: 1.0/x
except: 0
if not (x==0): 1.0/x
else: 0
```

- `if/else` is more than 20 times faster.
Function calls

The time of calling a function grows linearly with the number of arguments:
Numerical Python

Vectorized computations are fast:

```python
import numarray # Array functions
x = numarray.arange(-1,1,0.01)
y = numarray.sin(x)

import math # Scalar functions
y = numarray.zeros(len(x), type=numarray.Float)
for i in xrange(len(x)):
    y[i] = math.sin(x[i])
```

The speedup is a factor of 20.
Resizing arrays

- The `resize` method of arrays is very slow.
- Increasing the array size by one in a loop is about 300-350 times slower than appending elements to a Python list.
- Best approach; allocate the memory once, and assign values later.
Numeric vs. numarray

- Numeric is the old array module in Python
- Still very popular, and will probably live for many years
- The difference between pointwise and array evaluation of a vector is about 13 for Numeric (20 for numarray)
- Vectorized functions work on scalars as well, but at a high price
- Using numarray.sin instead of math.sin on a scalar value is slower by a factor of 12. Numeric.sin only slower by a factor of 4
Conclusions

- Python scripts can often be heavily optimized.
- The results given here may vary on different architectures and Python versions
- Be extremely careful about the `from numarray import *`.
Mixed language programming
Contents

- Why Python and C are two different worlds
- Wrapper code
- Wrapper tools
- F2PY: wrapping Fortran (and C) code
- SWIG: wrapping C and C++ code
More info

- Ch. 5 in the course book
- F2PY manual
- SWIG manual
- Examples coming with the SWIG source code
- Ch. 9 and 10 in the course book
Optimizing slow Python code

- Identify bottlenecks (via profiling)
- Migrate slow functions to Fortran, C, or C++
- Tools make it easy to combine Python with Fortran, C, or C++
Getting started: Scientific Hello World

- Python-F77 via F2PY
- Python-C via SWIG
- Python-C++ via SWIG

Later: Python interface to oscillator code for interactive computational steering of simulations (using F2PY)
The nature of Python vs. C

- A Python variable can hold different objects:
  
  ```python
d = 3.2  # d holds a float
d = 'txt'  # d holds a string
d = Button(frame, text='push')  # instance of class Button
  ```

- In C, C++ and Fortran, a variable is declared of a specific type:
  
  ```
  double d; d = 4.2;
d = "some string";  /* illegal, compiler error */
  ```

- This difference makes it quite complicated to call C, C++ or Fortran from Python
Calling C from Python

Suppose we have a C function

```c
extern double hw1(double r1, double r2);
```

We want to call this from Python as

```python
from hw import hw1
r1 = 1.2; r2 = -1.2
s = hw1(r1, r2)
```

The Python variables `r1` and `r2` hold numbers (float), we need to extract these in the C code, convert to double variables, then call `hw1`, and finally convert the double result to a Python float.

All this conversion is done in wrapper code.
Wrapper code

Every object in Python is represented by C struct `PyObject`

Wrapper code converts between `PyObject` variables and plain C variables (from `PyObject r1 and r2` to `double`, and `double result` to `PyObject`):

```c
static PyObject * _wrap_hw1(PyObject * self, PyObject * args) {
    PyObject * resultobj;
    double arg1, arg2, result;

    PyArg_ParseTuple(args,(char * )"dd:hw1",&arg1,&arg2)
    result = hw1(arg1,arg2);
    resultobj = PyFloat_FromDouble(result);
    return resultobj;
}
```
Extension modules

- The wrapper function and `hw1` must be compiled and linked to a shared library file.
- This file can be loaded in Python as module.
- Such modules written in other languages are called *extension modules*.
Writing wrapper code

- A wrapper function is needed for each C function we want to call from Python
- Wrapper codes are tedious to write
- There are tools for automating wrapper code development
- We shall use SWIG (for C/C++) and F2PY (for Fortran)
Integration issues

- Direct calls through wrapper code enables efficient data transfer; large arrays can be sent by pointers
- COM, CORBA, ILU, .NET are different technologies; more complex, less efficient, but safer (data are copied)
- Jython provides a seamless integration of Python and Java
Consider this Scientific Hello World module (\texttt{hw}):

```python
import math
def hw1(r1, r2):
    s = math.sin(r1 + r2)
    return s
def hw2(r1, r2):
    s = math.sin(r1 + r2)
    print 'Hello, World! sin(%g+%g)=%g' % (r1,r2,s)
```

Usage:

```python
from hw import hw1, hw2
print hw1(1.0, 0)
print hw2(1.0, 0)
```

We want to implement the module in Fortran 77, C and C++, and use it as if it were a pure Python module.
Fortran 77 implementation

- We start with Fortran (F77)

- F77 code in a file `hw.f`:

```fortran
real*8 function hw1(r1, r2)
real*8 r1, r2
hw1 = sin(r1 + r2)
return
end

subroutine hw2(r1, r2)
real*8 r1, r2, s
s = sin(r1 + r2)
write(*,1000) 'Hello, World! sin(',r1+r2,')=',s
1000 format(A,F6.3,A,F8.6)
return
end
```
One-slide F77 course

- Fortran is case insensitive (reAL is as good as real)
- One statement per line, must start in column 7 or later
- Comments on separate lines
- All function arguments are input and output (as pointers in C, or references in C++)
- A function returning one value is called function
- A function returning no value is called subroutine
- Types: real, double precision, real*4, real*8, integer, character (array)
- Arrays: just add dimension, as in real*8 a(0:m, 0:n)
- Format control of output requires FORMAT statements
Using F2PY

- F2PY automates integration of Python and Fortran
- Say the F77 code is in the file `hw.f`
- Run F2PY (-m module name, -c for compile+link):
  ```bash
  f2py -m hw -c hw.f
  ```
- Load module into Python and test:
  ```python
  from hw import hw1, hw2
  print hw1(1.0, 0)
  hw2(1.0, 0)
  ```
- In Python, `hw` appears as a module with Python code...
- It cannot be simpler!
Call by reference issues

- In Fortran (and C/C++) functions often modify arguments; here the result \( s \) is an output argument:

  ```fortran
  subroutine hw3(r1, r2, s)
  real*8 r1, r2, s
  s = sin(r1 + r2)
  return
  end
  ```

- Running F2PY results in a module with wrong behavior:

  ```python
  >>> from hw import hw3
  >>> r1 = 1; r2 = -1; s = 10
  >>> hw3(r1, r2, s)
  >>> print s
  10  # should be 0
  ```

- Why? F2PY assumes that all arguments are input arguments
- Output arguments must be explicitly specified!
General adjustment of interfaces to Fortran

- Function with multiple input and output variables
  ```fortran
  subroutine somef(i1, i2, o1, o2, o3, o4, io1)
  end
  ```

- input: `i1`, `i2`
- output: `o1`, ..., `o4`
- input and output: `io1`

- Pythonic interface, as generated by F2PY:
  ```python
  o1, o2, o3, o4, io1 = somef(i1, i2, io1)
  ```
Check F2PY-generated doc strings

What happened to our hw3 subroutine?

F2PY generates doc strings that document the interface:

```python
>>> import hw
>>> print hw.__doc__  # brief module doc string
Functions:
    hw1 = hw1(r1,r2)
    hw2(r1,r2)
    hw3(r1,r2,s)

>>> print hw.hw3.__doc__  # more detailed function doc string
hw3 - Function signature:
    hw3(r1,r2,s)
Required arguments:
    r1 : input float
    r2 : input float
    s : input float
```

We see that hw3 assumes s is \textit{input} argument!

Remedy: adjust the interface
We can tailor the interface by editing an F2PY-generated *interface file*

Run F2PY in two steps: (i) generate interface file, (ii) generate wrapper code, compile and link

Generate interface file `hw.pyf` (*-h option)*:

```
f2py -m hw -h hw.pyf hw.f
```
Outline of the interface file

- The interface applies a Fortran 90 module (class) syntax
- Each function/subroutine, its arguments and its return value is specified:

```python
python module hw ! in
   interface ! in :hw
   ...
   subroutine hw3(r1,r2,s) ! in :hw:hw.f
      real*8 :: r1
      real*8 :: r2
      real*8 :: s
   end subroutine hw3
   end interface
end python module hw
```

(Fortran 90 syntax)
Adjustment of the interface

- We may edit `hw.pyf` and specify `s` in `hw3` as an output argument, using F90’s `intent(out)` keyword:

```python
python module hw
  interface
    ... subroutine hw3(r1,r2,s)
      real*8 :: r1
      real*8 :: r2
      real*8, intent(out) :: s
    end subroutine hw3
  end interface
end python module hw
```

- Next step: run F2PY with the edited interface file:

```
f2py -c hw.pyf hw.f
```
Output arguments are always returned

- Load the module and print its doc string:

  >>> import hw
  >>> print hw.__doc__
  Functions:
    hw1 = hw1(r1,r2)
    hw2(r1,r2)
    s = hw3(r1,r2)

  Oops! \texttt{hw3} takes only two arguments and \textit{returns} \texttt{s}!

- This is the “Pythonic” function style; input data are arguments, output data are returned

- By default, F2PY treats all arguments as input

- F2PY generates Pythonic interfaces, different from the original Fortran interfaces, so check out the module’s doc string!
General adjustment of interfaces

Function with multiple input and output variables

subroutine somef(i1, i2, o1, o2, o3, o4, io1)

input: i1, i2
output: o1, ..., o4
input and output: io1

Pythonic interface (as generated by F2PY):

  o1, o2, o3, o4, io1 = somef(i1, i2, io1)
Specification of input/output arguments; .pyf file

In the interface file:

```python
python module somemodule
    interface ...
        subroutine somef(i1, i2, o1, o2, o3, o4, io1)
            real*8, intent(in) :: i1
            real*8, intent(in) :: i2
            real*8, intent(out) :: o1
            real*8, intent(out) :: o2
            real*8, intent(out) :: o3
            real*8, intent(out) :: o4
            real*8, intent(in,out) :: io1
        end subroutine somef
    end interface ...
end python module somemodule
```

Note: no intent implies intent (in)
Specification of input/output arguments; .f file

Instead of editing the interface file, we can add special F2PY comments in the Fortran source code:

```fortran
subroutine somef(i1, i2, o1, o2, o3, o4, io1)
  real*8  i1, i2, o1, o2, o3, o4, io1
  Cf2py intent(in) i1
  Cf2py intent(in) i2
  Cf2py intent(out) o1
  Cf2py intent(out) o2
  Cf2py intent(out) o3
  Cf2py intent(out) o4
  Cf2py intent(in,out) io1
```

Now a single F2PY command generates correct interface:

```
f2py -m hw -c hw.f
```
Specification of input/output arguments; .f90 file

With Fortran 90:

```fortran
subroutine somef(i1, i2, o1, o2, o3, o4, io1)
  real*8 i1, i2, o1, o2, o3, o4, io1
  !f2py intent(in) i1
  !f2py intent(in) i2
  !f2py intent(out) o1
  !f2py intent(out) o2
  !f2py intent(out) o3
  !f2py intent(out) o4
  !f2py intent(in,out) io1
```

Now a single F2PY command generates correct interface:

```bash
f2py -m hw -c hw.f
```
Let us implement the `hw` module in C:

```c
#include <stdio.h>
#include <math.h>
#include <stdlib.h>

double hw1(double r1, double r2)
{
    double s; s = sin(r1 + r2); return s;
}

void hw2(double r1, double r2)
{
    double s; s = sin(r1 + r2);
    printf("Hello, World! sin(%g+%g)=%g\n", r1, r2, s);
}

/* special version of hw1 where the result is an argument: */
void hw3(double r1, double r2, double * s)
{
    *s = sin(r1 + r2);
}
```
Using F2PY

- F2PY can also wrap C code if we specify the function signatures as Fortran 90 modules.

My procedure:
- write the C functions as empty Fortran 77 functions or subroutines
- run F2PY on the Fortran specification to generate an interface file
- run F2PY with the interface file and the C source code
Step 1: Write Fortran 77 signatures

C file signatures.f

    real*8 function hw1(r1, r2)
    Cf2py intent(c) hw1
    real*8 r1, r2
    Cf2py intent(c) r1, r2
    end

    subroutine hw2(r1, r2)
    Cf2py intent(c) hw2
    real*8 r1, r2
    Cf2py intent(c) r1, r2
    end

    subroutine hw3(r1, r2, s)
    Cf2py intent(c) hw3
    real*8 r1, r2, s
    Cf2py intent(c) r1, r2
    Cf2py intent(out) s
    end
Step 2: Generate interface file

Run

Unix/DOS> f2py -m hw -h hw.pyf signatures.f

Result: hw.pyf

```python
python module hw ! in
  interface ! in :hw
    function hw1(r1,r2) ! in :hw:signatures.f
      intent(c) hw1
      real*8 intent(c) :: r1
      real*8 intent(c) :: r2
      real*8 intent(c) :: hw1
    end function hw1
  ...
  subroutine hw3(r1,r2,s) ! in :hw:signatures.f
    intent(c) hw3
    real*8 intent(c) :: r1
    real*8 intent(c) :: r2
    real*8 intent(out) :: s
  end subroutine hw3
  end interface
  end python module hw
```
Step 3: compile C code into extension module

Run
Unix/DOS> f2py -c hw.pyf hw.c

Test:
import hw
print hw.hw3(1.0,-1.0)
print hw.__doc__

One can either write the interface file by hand or write F77 code to generate, but for every C function the Fortran signature must be specified
Using SWIG

- Wrappers to C and C++ codes can be automatically generated by SWIG
- SWIG is more complicated to use than F2PY
- First make a SWIG interface file
- Then run SWIG to generate wrapper code
- Then compile and link the C code and the wrapper code
The interface file contains C preprocessor directives and special SWIG directives:

```c
/* file: hw.i */
%module hw
{
    /* include C header files necessary to compile the interface */
    #include "hw.h"
}

/* list functions to be interfaced: */
double hw1(double r1, double r2);
void hw2(double r1, double r2);
void hw3(double r1, double r2, double *s);
// or
// %include "hw.h" /* make interface to all funcs in hw.h */
```
Making the module

- Run SWIG (preferably in a subdirectory):
  ```
  swig -python -I.. hw.i
  ```

- SWIG generates wrapper code in
  `hw_wrap.c`

- Compile and link a shared library module:
  ```
  gcc -I.. -fPIC -I/some/path/include/python2.5 -c ../hw.c hw_wrap.c
  gcc -shared -fPIC -o _hw.so hw.o hw_wrap.o
  ```

  Note the underscore prefix in `_hw.so`
A build script

- Can automate the compile+link process
- Can use Python to extract where `Python.h` resides (needed by any wrapper code)

```
swig -python -I.. hw.i

root='python -c 'import sys; print sys.prefix'''
ver='python -c 'import sys; print sys.version[:3]''
gcc -fPIC -I.. -I$root/include/python$ver -c ../hw.c hw_wrap.c
gcc -shared -fPIC -o _hw.so hw.o hw_wrap.o

python -c "import hw" # test
```

This script `make_module_1.sh` is found here:
http://www.ifi.uio.no/~inf3331/scripting/src/py/mixed/hw/C/swig-hw/

- The module consists of two files: `hw.py` (which loads) `_hw.so`
Python has a tool, Distutils, for compiling and linking extension modules

First write a script `setup.py`:

```python
import os
from distutils.core import setup, Extension

name = 'hw'  # name of the module
version = 1.0  # the module’s version number

swig_cmd = 'swig -python -I../ %s.i' % name
print('running SWIG:', swig_cmd)
os.system(swig_cmd)

sources = ['../hw.c', 'hw_wrap.c']

setup(name = name, version = version,
      ext_modules = [Extension('_' + name,  # SWIG requires _
                               sources,
                               include_dirs=[os.pardir])
                     ])
```
Building modules with Distutils (2)

Now run

```python
python setup.py build_ext
python setup.py install --install-platlib=. 
python -c 'import hw'  # test
```

- Can install resulting module files in any directory
- Use Distutils for professional distribution!
Testing the hw3 function

Recall hw3:

```c
void hw3(double r1, double r2, double *s) {
    *s = sin(r1 + r2);
}
```

Test:

```python
>>> from hw import hw3
>>> r1 = 1; r2 = -1; s = 10
>>> hw3(r1, r2, s)
>>> print s
10  # should be 0 (sin(1-1)=0)
```

Major problem - as in the Fortran case
Specifying input/output arguments

- We need to adjust the SWIG interface file:
  
  ```c
  /* typemaps.i allows input and output pointer arguments to be specified using the names INPUT, OUTPUT, or INOUT */
  %include "typemaps.i"
  
  void hw3(double r1, double r2, double *OUTPUT);
  ```

- Now the usage from Python is
  
  ```python
  s = hw3(r1, r2)
  ```

- Unfortunately, SWIG does not document this in doc strings
Other tools

- SIP: tool for wrapping C++ libraries
- Boost.Python: tool for wrapping C++ libraries
- CXX: C++ interface to Python (Boost is a replacement)
- Note: SWIG can generate interfaces to most scripting languages (Perl, Ruby, Tcl, Java, Guile, Mzscheme, ...)

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Integrating Python with C++

- SWIG supports C++

- The only difference is when we run SWIG (-c++ option):

  swig -python -c++ -I.. hw.i  
  # generates wrapper code in hw_wrap.cxx

- Use a C++ compiler to compile and link:

  root=`python -c 'import sys; print sys.prefix'`  
  ver=`python -c 'import sys; print sys.version[:3]'`  
  g++ -fPIC -I.. -I$root/include/python$ver \  
      -c ../hw.cpp hw_wrap.cxx  
  g++ -shared -fPIC -o _hw.so hw.o hw_wrap.o
Interfacing C++ functions (1)

This is like interfacing C functions, except that pointers are usual replaced by references

```c
void hw3(double r1, double r2, double *s) // C style
{ *s = sin(r1 + r2); }

void hw4(double r1, double r2, double& s) // C++ style
{ s = sin(r1 + r2); }
```
Interfacing C++ functions (2)

- Interface file (hw.i):

  ```
  %module hw
  {
  #include "hw.h"
  }
  #include "typemaps.i"
  %apply double *OUTPUT { double* s }
  %apply double *OUTPUT { double& s }
  #include "hw.h"
  ```

- That's it!
Interfacing C++ classes

- C++ classes add more to the SWIG-C story
- Consider a class version of our Hello World module:

```cpp
class HelloWorld
{
    protected:
    double r1, r2, s;
    void compute(); // compute s=sin(r1+r2)

    public:
    HelloWorld();
    ~HelloWorld();

    void set(double r1, double r2);
    double get() const { return s; }
    void message(std::ostream& out) const;
};
```

- Goal: use this class as a Python class
Function bodies and usage

Function bodies:

```cpp
void HelloWorld:: set(double r1_, double r2_)
{
    r1 = r1_;  r2 = r2_;  
    compute();  // compute s
}
void HelloWorld:: compute()
{
    s = sin(r1 + r2);  
}
```

etc.

Usage:

```cpp
HelloWorld hw;
hw.set(r1, r2);
hw.message(std::cout);  // write "Hello, World!" message
```

Files: HelloWorld.h, HelloWorld.cpp
Adding a subclass

To illustrate how to handle class hierarchies, we add a subclass:

```cpp
class HelloWorld2 : public HelloWorld
{
  public:
    void gets(double& s_) const;
};
```

```cpp
void HelloWorld2::gets(double& s_) const { s_ = s; }
```

i.e., we have a function with an output argument

Note: `gets` should return the value when called from Python

Files: `HelloWorld2.h`, `HelloWorld2.cpp`
SWIG interface file

/* file: hw.i */
%module hw
%
/* include C++ header files necessary to compile the interface */
#include "HelloWorld.h"
#include "HelloWorld2.h"
%
#include "HelloWorld.h"

#include "typemaps.i"
%apply double* OUTPUT { double& s }
#include "HelloWorld2.h"
Adding a class method

- SWIG allows us to add class methods
- Calling `message` with standard output (`std::cout`) is tricky from Python so we add a `print` method for printing to std.output
- `print` coincides with Python’s keyword `print` so we follow the convention of adding an underscore:

  ```
  %extend HelloWorld {
    void print_() { self->message(std::cout); }
  }
  ```

- This is basically C++ syntax, but `self` is used instead of `this` and `%extend HelloWorld` is a SWIG directive
- Make extension module:

  ```
  swig -python -c++ -I.. hw.i
  # compile HelloWorld.cpp HelloWorld2.cpp hw_wrap.cxx
  # link HelloWorld.o HelloWorld2.o hw_wrap.o to _hw.so
  ```
from hw import HelloWorld

hw = HelloWorld()  # make class instance
r1 = float(sys.argv[1]);  r2 = float(sys.argv[2])
hw.set(r1, r2)  # call instance method
s = hw.get()
print "Hello, World! sin(%g + %g)=%g" % (r1, r2, s)
hw.print_()

hw2 = HelloWorld2()  # make subclass instance
hw2.set(r1, r2)
s = hw.gets()  # original output arg. is now return value
print "Hello, World2! sin(%g + %g)=%g" % (r1, r2, s)
Remark

- It looks that the C++ class hierarchy is mirrored in Python.

- Actually, SWIG wraps a *function* interface to any class:

```python
import _hw  # use _hw.so directly
hw = _hw.new_HelloWorld()
_hw.HelloWorld_set(hw, r1, r2)
```

- SWIG also makes a proxy class in *hw.py*, mirroring the original C++ class:

```python
import hw  # use hw.py interface to _hw.so
c = hw.HelloWorld()
c.set(r1, r2)  # calls _hw.HelloWorld_set(r1, r2)
```

- The proxy class introduces overhead.
Computational steering

- Consider a simulator written in F77, C or C++
- Aim: write the administering code and run-time visualization in Python
- Use a Python interface to Gnuplot
- Use NumPy arrays in Python
- F77/C and NumPy arrays share the same data
- Result:
  - steer simulations through scripts
  - do low-level numerics efficiently in C/F77
  - send simulation data to plotting a program

The best of all worlds?
Example on computational steering

Consider the oscillator code. The following interactive features would be nice:

- set parameter values
- run the simulator for a number of steps and visualize
- change a parameter
- option: rewind a number of steps
- continue simulation and visualization
Example on what we can do

Here is an interactive session:

```python
>>> from simviz_f77 import *
>>> A=1; w=4*math.pi  # change parameters
>>> setprm()          # send parameters to oscillator code
>>> run(60)           # run 60 steps and plot solution
>>> w=math.pi         # change frequency
>>> setprm()          # update prms in oscillator code
>>> rewind(30)        # rewind 30 steps
>>> run(120)          # run 120 steps and plot
>>> A=10; setprm()
>>> rewind()          # rewind to t=0
>>> run(400)
```
Principles

- The F77 code performs the numerics
- Python is used for the interface
  (setprm, run, rewind, plotting)
- F2PY was used to make an interface to the F77 code (fully automated process)
- Arrays (NumPy) are created in Python and transferred to/from the F77 code
- Python communicates with both the simulator and the plotting program (“sends pointers around”)
About the F77 code

- Physical and numerical parameters are in a common block
- `scan2` sets parameters in this common block:

  ```fortran
  subroutine scan2(m_, b_, c_, A_, w_, y0_, tstop_, dt_, func_ )
  real*8 m_, b_, c_, A_, w_, y0_, tstop_, dt_
  character func_*(*)
  can use `scan2` to send parameters from Python to F77
  ```

- `timeloop2` performs `nsteps` time steps:

  ```fortran
  subroutine timeloop2(y, n, maxsteps, step, time, nsteps)
  integer n, step, nsteps, maxsteps
  real*8 time, y(n,0:maxsteps-1)
  solution available in y
  ```
Creating a Python interface w/F2PY

- **scan2**: trivial (only input arguments)
- **timestep2**: need to be careful with
  - output and input/output arguments
  - multi-dimensional arrays (y)
- Note: multi-dimensional arrays are stored differently in Python (i.e. C) and Fortran!
Using timeloop2 from Python

This is how we would like to write the Python code:

```python
maxsteps = 10000;  n = 2
y = zeros((n,maxsteps), order='Fortran')
step = 0;  time = 0.0

def run(nsteps):
    global step, time, y

    y, step, time = \oscillator.timeloop2(y, step, time, nsteps)

    y1 = y[0,0:step+1]
g.plot(Gnuplot.Data(t, y1, with='lines'))
```
Arguments to timeloop2

Subroutine signature:

subroutine timeloop2(y, n, maxsteps, step, time, nsteps)

integer n, step, nsteps, maxsteps
real*8 time, y(n,0:maxsteps-1)

Arguments:

y : solution (all time steps), input and output
n : no of solution components (2 in our example), input
maxsteps : max no of time steps, input
step : no of current time step, input and output
time : current value of time, input and output
nsteps : no of time steps to advance the solution
Interfacing the timeloop2 routine

Use Cf2py comments to specify argument type:

Cf2py intent(in,out) step
Cf2py intent(in,out) time
Cf2py intent(in,out) y
Cf2py intent(in) nsteps

Run F2PY:

f2py -m oscillator -c --build-dir tmp1 --fcompiler='Gnu' \
../timeloop2.f \n$scripting/src/app/oscillator/F77/oscillator.f \nonly: scan2 timeloop2 :
Testing the extension module

- Import and print documentation:

```python
>>> import oscillator
>>> print oscillator.__doc__
This module 'oscillator' is auto-generated with f2py
Functions:
y, step, time = timeloop2(y, step, time, nsteps,
n=shape(y, 0), maxsteps=shape(y, 1))
    scan2(m_, b_, c_, a_, w_, y0_, tstop_, dt_, func_)
COMMON blocks:
    /data/ m, b, c, a, w, y0, tstop, dt, func(20)
```

- Note: array dimensions (n, maxsteps) are moved to the end of the argument list and given default values!

- Rule: always print and study the doc string since F2PY perturbs the argument list
More info on the current example

Directory with Python interface to the oscillator code:
src/py/mixed/simviz/f2py/

Files:

- simviz_steering.py : complete script running oscillator from Python by calling F77 routines
- simvizGUI_steering.py : as simviz_steering.py, but with a GUI
- make_module.sh : build extension module
Comparison with Matlab

- The demonstrated functionality can be coded in Matlab
- Why Python + F77?
  - We can define our own interface in a much more powerful language (Python) than Matlab
  - We can much more easily transfer data to and from our own F77 or C or C++ libraries
  - We can use any appropriate visualization tool
  - We can call up Matlab if we want
  - Python + F77 gives tailored interfaces and maximum flexibility
Mixed language numerical Python
Contents

- Migrating slow for loops over NumPy arrays to Fortran, C and C++
- F2PY handling of arrays
- Handwritten C and C++ modules
- C++ class for wrapping NumPy arrays
- C++ modules using SCXX
- Pointer communication and SWIG
- Efficiency considerations
More info

- Ch. 5, 9 and 10 in the course book
- F2PY manual
- SWIG manual
- Examples coming with the SWIG source code
- Electronic Python documentation: Extending and Embedding..., Python/C API
- Python in a Nutshell
- Python Essential Reference (Beazley)
Is Python slow for numerical computing?

Fill a NumPy array with function values:

```python
n = 2000
a = zeros((n,n))
xcoor = arange(0,1,1/float(n))
ycoor = arange(0,1,1/float(n))

for i in range(n):
    for j in range(n):
        a[i,j] = f(xcoor[i], ycoor[j])  # f(x,y) = \sin(x\cdot y) + 8\cdot x
```

- Fortran/C/C++ version: (normalized) time 1.0
- NumPy vectorized evaluation of $f$: time 3.0
- Python loop version (version): time 140 ($\text{math.sin}$)
- Python loop version (version): time 350 ($\text{numarray.sin}$)
Comments

- Python loops over arrays are extremely slow
- NumPy vectorization may be sufficient
- However, NumPy vectorization may be inconvenient
  - plain loops in Fortran/C/C++ are much easier
- Write administering code in Python
- Identify bottlenecks (via profiling)
- Migrate slow Python code to Fortran, C, or C++
- Python-Fortran w/NumPy arrays via F2PY: easy
- Python-C/C++ w/NumPy arrays via SWIG: not that easy
Case: filling a grid with point values

Consider a rectangular 2D grid

A NumPy array $a[i, j]$ holds values at the grid points
Python object for grid data

Python class:

class Grid2D:
    def __init__(self,
        xmin=0, xmax=1, dx=0.5,
        ymin=0, ymax=1, dy=0.5):
        self.xcoor = sequence(xmin, xmax, dx)
        self.ycoor = sequence(ymin, ymax, dy)

        # make two-dim. versions of these arrays:
        # (needed for vectorization in __call__)
        self.xcoorv = self.xcoor[:, newaxis]
        self.ycoorv = self.ycoor[newaxis, :]

    def __call__(self, f):
        # vectorized code:
        return f(self.xcoorv, self.ycoorv)
Include a straight Python loop also:

```python
class Grid2D:
    ....
    def gridloop(self, f):
        lx = size(self.xcoor); ly = size(self.ycoor)
        a = zeros((lx,ly))

        for i in xrange(lx):
            x = self.xcoor[i]
            for j in xrange(ly):
                y = self.ycoor[j]
                a[i,j] = f(x, y)

        return a
```

Usage:

```python
g = Grid2D(dx=0.01, dy=0.2)
def myfunc(x, y):
    return sin(x*y) + y
a = g(myfunc)
i=4; j=10;
print 'value at (%g,%g) is %g' % (g.xcoor[i],g.ycoor[j],a[i,j])
```
Migrate gridloop to F77

```python
class Grid2Deff(Grid2D):
    def __init__(self,
        xmin=0, xmax=1, dx=0.5,
        ymin=0, ymax=1, dy=0.5):
        Grid2D.__init__(self, xmin, xmax, dx, ymin, ymax, dy)

    def ext_gridloop1(self, f):
        """compute a[i,j] = f(xi,yj) in an external routine."""
        lx = size(self.xcoor); ly = size(self.ycoor)
        a = zeros((lx,ly))
        ext_gridloop.gridloop1(a, self.xcoor, self.ycoor, f)
        return a
```

We can also migrate to C and C++ (done later)
F77 function

First try (typical attempt by a Fortran/C programmer):

```fortran
subroutine gridloop1(a, xcoor, ycoor, nx, ny, func1)
    integer nx, ny
    real*8 a(0:nx-1,0:ny-1), xcoor(0:nx-1), ycoor(0:ny-1)
    real*8 func1
    external func1

    integer i,j
    real*8 x, y
    do j = 0, ny-1
        y = ycoor(j)
        do i = 0, nx-1
            x = xcoor(i)
            a(i,j) = func1(x, y)
        end do
    end do
end subroutine gridloop1
```

Note: float type in NumPy array must match real*8 or double precision in Fortran! (Otherwise F2PY will take a copy of the array a so the type matches that in the F77 code)
Making the extension module

Run F2PY:
```python
f2py -m ext_gridloop -c gridloop.f
```

Try it from Python:
```python
import ext_gridloop
ext_gridloop.gridloop1(a, self.xcoor, self.ycoor, myfunc, size(self.xcoor), size(self.ycoor))
```

wrong results; `a` is not modified!

Reason: the `gridloop1` function works on a copy of `a` (because higher-dimensional arrays are stored differently in C/Python and Fortran)
Array storage in Fortran and C/C++

- C and C++ has row-major storage
  (two-dimensional arrays are stored row by row)
- Fortran has column-major storage
  (two-dimensional arrays are stored column by column)
- Multi-dimensional arrays: first index has fastest variation in Fortran,
  last index has fastest variation in C and C++
Example: storing a 2x3 array

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

C storage

Fortran storage

\[
\begin{pmatrix}
1 & 2 & 3 \\
4 & 5 & 6
\end{pmatrix}
\]
F2PY and multi-dimensional arrays

- F2PY-generated modules treat storage schemes transparently.
- If input array has C storage, a copy is taken, calculated with, and returned as output.
- F2PY needs to know whether arguments are input, output or both.
- To monitor (hidden) array copying, turn on the flag.
  
  f2py ... -DF2PY_REPORT_ON_ARRAY_COPY=1

- In-place operations on NumPy arrays are possible in Fortran, but the default is to work on a copy, that is why our `gridloop1` function does not work.
Always specify input/output data

- Insert Cf2py comments to tell that \texttt{a} is an output variable:

```fortran
subroutine gridloop2(a, xcoor, ycoor, nx, ny, func1)
  integer nx, ny
  real*8 a(0:nx-1,ny-1), xcoor(0:nx-1), ycoor(0:ny-1), func1
external func1
  Cf2py intent(out) a
  Cf2py intent(in) xcoor
  Cf2py intent(in) ycoor
  Cf2py depend(nx,ny) a
```
gridloop2 seen from Python

F2PY generates this Python interface:

```python
>>> import ext_gridloop
>>> print ext_gridloop.gridloop2.__doc__
gridloop2 - Function signature:
a = gridloop2(xcoor,ycoor,func1,[nx,ny,func1_extra_args])
Required arguments:
xcoor : input rank-1 array(‘d’) with bounds (nx)
ycoor : input rank-1 array(‘d’) with bounds (ny)
func1 : call-back function
Optional arguments:
x := len(xcoor) input int
ny := len(ycoor) input int
func1_extra_args := () input tuple
Return objects:
a : rank-2 array(‘d’) with bounds (nx,ny)
```

nx and ny are optional (!)
Handling of arrays with F2PY

- Output arrays are returned and are not part of the argument list, as seen from Python
- Need `depend(nx, ny) a` to specify that `a` is to be created with size `nx, ny` in the wrapper
- Array dimensions are optional arguments (!)

```python
class Grid2D:
    ...
def ext_gridloop2(self, f):
    a = ext_gridloop.gridloop2(self.xcoor, self.ycoor, f)
    return a
```

- The modified interface is well documented in the doc strings generated by F2PY
Input/output arrays (1)

What if we really want to send `a` as argument and let F77 modify it?

```python
def ext_gridloop1(self, f):
    lx = size(self.xcoor);  ly = size(self.ycoor)
    a = zeros((lx,ly))
    ext_gridloop.gridloop1(a, self.xcoor, self.ycoor, f)
    return a
```

This is not Pythonic code, but it can be realized

1. the array must have Fortran storage
2. the array argument must be `intent(inout)` (in general not recommended)
F2PY generated modules has a function for checking if an array has column major storage (i.e., Fortran storage):

```python
generate >>> a = zeros((n,n), order='Fortran') >>> isfortran(a) True >>> a = asarray(a, order='C') # back to C storage >>> isfortran(a) False```

**Input/output arrays (2)**
Input/output arrays (3)

Fortran function:

```fortran
subroutine gridloop1(a, xcoor, ycoor, nx, ny, func1)
    integer nx, ny
    real*8 a(0:nx-1,ny-1), xcoor(0:nx-1), ycoor(0:ny-1), func1
    C call this function with an array a that has
    C column major storage!
    Cf2py intent(inout) a
    Cf2py intent(in) xcoor
    Cf2py intent(in) ycoor
    Cf2py depend(nx, ny) a
```

Python call:

```python
def ext_gridloop1(self, f):
    lx = size(self.xcoor); ly = size(self.ycoor)
    a = asarray(a, order='Fortran')
    ext_gridloop.gridloop1(a, self.xcoor, self.ycoor, f)
    return a
```
Storage compatibility requirements

- Only when \( a \) has Fortran (column major) storage, the Fortran function works on \( a \) itself.
- If we provide a plain NumPy array, it has C (row major) storage, and the wrapper sends a copy to the Fortran function and transparently transposes the result.
- Hence, F2PY is very user-friendly, at a cost of some extra memory.
- The array returned from F2PY has Fortran (column major) storage.
F2PY and storage issues

- `intent(out) a` is the right specification; `a` should not be an argument in the Python call.
- F2PY wrappers will work on copies, if needed, and hide problems with different storage scheme in Fortran and C/Python.
- Python call:
  
  ```python
  a = ext_gridloop.gridloop2(self.xcoor, self.ycoor, f)
  ```
Find problems with this code (\texttt{comp} is a Fortran function in the extension module \texttt{pde}):\footnote{Mixed language numerical Python – p. 430/731}

\begin{verbatim}
x = arange(0, 1, 0.01)
b = myfunc1(x)  # compute b array of size (n,n)
u = myfunc2(x)  # compute u array of size (n,n)
c = myfunc3(x)  # compute c array of size (n,n)
dt = 0.05
for i in range(n):
    u = pde.comp(u, b, c, i*dt)
\end{verbatim}
About Python callbacks

- It is convenient to specify the `myfunc` in Python.
- However, a callback to Python is costly, especially when done a large number of times (for every grid point).
- Avoid such callbacks; vectorize callbacks.
- The Fortran routine should actually direct a back to Python (i.e., do nothing...) for a vectorized operation.
- Let’s do this for illustration.
class Grid2Deff(Grid2D):
    ...
    def ext_gridloop_vec(self, f):
        """Call extension, then do a vectorized callback to Python."""
        lx = size(self.xcoor); ly = size(self.ycoor)
        a = zeros((lx,ly))
        a = ext_gridloop.gridloop_vec(a, self.xcoor, self.ycoor, f)
        return a

    def myfunc(x, y):
        return sin(x*y) + 8*x

    def vectorize(func):
        def vec77(a, xcoor, ycoor, nx, ny):
            """Vectorized function to be called from extension module."""
            x = xcoor[:,NewAxis]; y = ycoor[NewAxis,:]
            a[:, :] = func(x, y)  # in-place modification of a
            return vec77

    g = Grid2Deff(dx=0.2, dy=0.1)
a = g.ext_gridloop_vec(vectorize(myfunc))
Vectorized callback from Fortran

subroutine gridloop_vec(a, xcoor, ycoor, nx, ny, func1)
integer nx, ny
real*8 a(0:nx-1,ny-1), xcoor(0:nx-1), ycoor(0:ny-1)
Cf2py intent(in,out) a
Cf2py intent(in) xcoor
Cf2py intent(in) ycoor
external func1

C fill array a with values taken from a Python function,
C do that without loop and point-wise callback, do a
C vectorized callback instead:
call func1(a, xcoor, ycoor, nx, ny)

C could work further with array a here...

return
end
Caution

What about this Python callback:

```python
def vectorize(func):
    def vec77(a, xcoor, ycoor, nx, ny):
        """Vectorized function to be called from extension module."""
        x = xcoor[:, NewAxis]; y = ycoor[NewAxis, :]
        a = func(x, y)
        return vec77
```

- a now refers to a new NumPy array; no in-place modification of the input argument
Avoiding callback by string-based if-else wrapper

- Callbacks are expensive
- Even vectorized callback functions degrades performance a bit
- Alternative: implement “callback” in F77
- Flexibility from the Python side: use a string to switch between the “callback” (F77) functions

```python
a = ext_gridloop.gridloop2_str(self.xcoor, self.ycoor, 'myfunc')
```

F77 wrapper:

```fortran
subroutine gridloop2_str(xcoor, ycoor, func_str)
  character(*) func_str
  ...
  if (func_str .eq. 'myfunc') then
    call gridloop2(a, xcoor, ycoor, nx, ny, myfunc)
  else if (func_str .eq. 'f2') then
    call gridloop2(a, xcoor, ycoor, nx, ny, f2)
  ...
```
Compiled callback function

- Idea: if callback formula is a string, we could embed it in a Fortran function and call Fortran instead of Python.

- F2PY has a module for “inline” Fortran code specification and building.

```python
def source = ""
    real*8 function fcb(x, y)
    real*8 x, y
    fcb = %s
    return
end
"" % fstr
import f2py2e
f2py_args = "--fcompiler='Gnu' --build-dir tmp2 etc..."
f2py2e.compile(source, modulename='callback',
               extra_args=f2py_args, verbose=True,
               source_fn='sourcecodefile.f')
import callback
<work with the new extension module>
```
gridloop2 wrapper

To glue F77 gridloop2 and the F77 callback function, we make a gridloop2 wrapper:

```fortran
subroutine gridloop2_fcb(a, xcoor, ycoor, nx, ny)
  integer nx, ny
  real*8 a(0:nx-1,ny-1), xcoor(0:nx-1), ycoor(0:ny-1)
  Cf2py intent(out) a
  Cf2py depend(nx,ny) a
  real*8 fcb
  external fcb

  call gridloop2(a, xcoor, ycoor, nx, ny, fcb)
return
end
```

This wrapper and the callback function fcb constitute the F77 source code, stored in source

The source calls gridloop2 so the module must be linked with the module containing gridloop2 (ext_gridloop.so)
Building the module on the fly

source = ""
    real*8 function fcb(x, y)
    ...
    subroutine gridloop2_fcb(a, xcoor, ycoor, nx, ny)
    ...
"" % fstr

f2py_args = "--fcompiler='Gnu' --build-dir tmp2"
    " -DF2PY_REPORT_ON_ARRAY_COPY=1 "
    "./ext_gridloop.so"

f2py2e.compile(source, modulename='callback',
    extra_args=f2py_args, verbose=True,
    source_fn='_cb.f')

import callback
a = callback.gridloop2_fcb(self.xcoor, self.ycoor)
gridloop2 could be generated on the fly

def ext_gridloop2_compile(self, fstr):
    if not isinstance(fstr, str):
        <error>
    # generate Fortran source for gridloop2:
    import f2py2e
    source = ""
    subroutine gridloop2(a, xcoor, ycoor, nx, ny)
    ...
    do j = 0, ny-1
        y = ycoor(j)
        do i = 0, nx-1
            x = xcoor(i)
            a(i, j) = %s
    ...
    """ # no callback, the expression is hardcoded
    f2py2e.compile(source, modulename='ext_gridloop2', ...)

def ext_gridloop2_v2(self):
    import ext_gridloop2
    return ext_gridloop2.gridloop2(self.xcoor, self.ycoor)
Extracting a pointer to the callback function

- We can implement the callback function in Fortran, grab an F2PY-generated pointer to this function and feed that as the `func1` argument such that Fortran calls Fortran and not Python.

- For a module \( m \), the pointer to a function/subroutine \( f \) is reached as \( m.f._cpointer \):

```python
def ext_gridloop2_fcb_ptr(self):
    from callback import fcb
    a = ext_gridloop.gridloop2(self.xcoor, self.ycoor, fcb._cpointer)
    return a
```

\( fcb \) is a Fortran implementation of the callback in an F2PY-generated extension module `callback`.
C implementation of the loop

Let us write the gridloop1 and gridloop2 functions in C

Typical C code:

```c
void gridloop1(double ** a, double* xcoor, double* ycoor, 
                int nx, int ny, Fxy func1)
{
    int i, j;
    for (i=0; i<nx; i++) {
        for (j=0; j<ny; j++) {
            a[i][j] = func1(xcoor[i], ycoor[j])
        }
    }
}
```

Problem: NumPy arrays use single pointers to data

The above function represents `a` as a double pointer (common in C for two-dimensional arrays)
Manual writing of extension modules

- SWIG needs some non-trivial tweaking to handle NumPy arrays (i.e., the use of SWIG is much more complicated for array arguments than running F2PY)
- We shall write a complete extension module by hand
- We will need documentation of the Python C API (from Python’s electronic doc.) and the NumPy C API (from the NumPy book)
- Source code files in
  src/mixed/py/Grid2D/C/plain
- Warning: manual writing of extension modules is very much more complicated than using F2PY on Fortran code! You need to know C quite well...
NumPy objects as seen from C

NumPy objects are C structs with attributes:

- `int nd`: no of indices (dimensions)
- `int dimensions[nd]`: length of each dimension
- `char *data`: pointer to data
- `int strides[nd]`: no of bytes between two successive data elements for a fixed index

Access element (i,j) by

\[ \text{a->data} + i \times \text{a->strides[0]} + j \times \text{a->strides[1]} \]
Creating new NumPy array in C

Allocate a new array:

```c
PyObject * PyArray_FromDims(int n_dimensions,
                               int dimensions[n_dimensions],
                               int type_num);

PyArrayObject *a; int dims[2];
dims[0] = 10;  dims[1] = 21;
a = (PyArrayObject *) PyArray_FromDims(2, dims, PyArray_DOUBLE);
```
Wrapping data in a NumPy array

Wrap an existing memory segment (with array data) in a NumPy array object:

```c
PyObject * PyArray_FromDimsAndData(int n_dimensions,
int dimensions[n_dimensions],
int item_type,
char *data);
```

/* vec is a double* with 10*21 double entries */
PyArrayObject *a; int dims[2];
dims[0] = 10; dims[1] = 21;
a = (PyArrayObject *) PyArray_FromDimsAndData(2, dims,
PyArray_DOUBLE, (char *) vec);

Note: vec is a stream of numbers, now interpreted as a two-dimensional array, stored row by row
From Python sequence to NumPy array

- Turn any relevant Python sequence type (list, type, array) into a NumPy array:

  ```c
  PyObject * PyArray_ContiguousFromObject(PyObject *object,
                                           int item_type,
                                           int min_dim,
                                           int max_dim);
  ```

  Use `min_dim` and `max_dim` as 0 to preserve the original dimensions of `object`

- Application: ensure that an object is a NumPy array,

  ```c
  /* a_ is a PyObject pointer, representing a sequence
     (NumPy array or list or tuple) */
  PyArrayObject a;
  a = (PyArrayObject *) PyArray_ContiguousFromObject(a_,
                                                   PyArray_DOUBLE, 0, 0);
  ```

  a list, tuple or NumPy array `a` is now a NumPy array
class Grid2DExt(Grid2D):
    def __init__(self,
        xmin=0, xmax=1, dx=0.5,
        ymin=0, ymax=1, dy=0.5):
        Grid2D.__init__(self, xmin, xmax, dx, ymin, ymax, dy)

    def ext_gridloop1(self, f):
        lx = size(self.xcoor);  ly = size(self.ycoor)
        a = zeros((lx,ly))
        ext_gridloop.gridloop1(a, self.xcoor, self.ycoor, f)
        return a

    def ext_gridloop2(self, f):
        a = ext_gridloop.gridloop2(self.xcoor, self.ycoor, f)
        return a
Transform `PyObject` argument tuple to NumPy arrays:

```c
static PyObject *gridloop1(PyObject *self, PyObject *args)
{
    PyArrayObject *a, *xcoor, *ycoor;
    PyObject *func1, *arglist, *result;
    int nx, ny, i, j;
    double *a_ij, *x_i, *y_j;

    /* arguments: a, xcoor, ycoor */
    if (!PyArg_ParseTuple(args, "O!O!O!O:gridloop1",
        &PyArray_Type, &a,
        &PyArray_Type, &xcoor,
        &PyArray_Type, &ycoor,
        &func1)) {
        return NULL; /* PyArg_ParseTuple has raised an exception */
    }
```
gridloop1 in C; safety checks

if (a->nd != 2 || a->descr->type_num != PyArray_DOUBLE) {
    PyErr_Format(PyExc_ValueError,"a array is %d-dimensional or not of type float", a->nd);
    return NULL;
}

nx = a->dimensions[0]; ny = a->dimensions[1];
if (xcoor->nd != 1 || xcoor->descr->type_num != PyArray_DOUBLE ||
    xcoor->dimensions[0] != nx) {
    PyErr_Format(PyExc_ValueError,"xcoor array has wrong dimension (%d), type or length (%d)",
        xcoor->nd,xcoor->dimensions[0]);
    return NULL;
}

if (ycoor->nd != 1 || ycoor->descr->type_num != PyArray_DOUBLE ||
    ycoor->dimensions[0] != ny) {
    PyErr_Format(PyExc_ValueError,"ycoor array has wrong dimension (%d), type or length (%d)",
        ycoor->nd,ycoor->dimensions[0]);
    return NULL;
}

if (!PyCallable_Check(func1)) {
    PyErr_Format(PyExc_TypeError,"func1 is not a callable function");
    return NULL;
}
Callback to Python from C

- Python functions can be called from C

  Step 1: for each argument, convert C data to Python objects and collect these in a tuple

    ```c
    PyObject *arglist; double x, y;
    /* double x,y -> tuple with two Python float objects: */
    arglist = Py_BuildValue("(dd)", x, y);
    ```

  Step 2: call the Python function

    ```c
    PyObject *result; /* return value from Python function */
    PyObject *func1; /* Python function object */
    result = PyEval_CallObject(func1, arglist);
    ```

  Step 3: convert result to C data

    ```c
    double r; /* result is a Python float object */
    r = PyFloat_AS_DOUBLE(result);
    ```
gridloop1 in C; the loop

```c
for (i = 0; i < nx; i++) {
    for (j = 0; j < ny; j++) {
        a_ij = (double *) (a->data + i*a->strides[0] + j*a->strides[1]);
        x_i = (double *) (xcoor->data + i*xcoor->strides[0]);
        y_j = (double *) (ycoor->data + j*ycoor->strides[0]);

        /* call Python function pointed to by func1: */
        arglist = Py_BuildValue("(dd)", *x_i, *y_j);
        result = PyEval_CallObject(func1, arglist);
        *a_ij = PyFloat_AS_DOUBLE(result);
    }
}
return Py_BuildValue(""");  /* return None: */
```
Memory management

There is a major problem with our loop:

\[
\begin{align*}
\text{arglist} &= \text{Py\_BuildValue}("(dd)\), \ *x\_i, \ *y\_j); \\
\text{result} &= \text{PyEval\_CallObject}(\text{func1}, \ \text{arglist}); \\
\*a\_ij &= \text{PyFloat\_AS\_DOUBLE}(\text{result});
\end{align*}
\]

For each pass, arglist and result are dynamically allocated, but not destroyed.

From the Python side, memory management is automatic.

From the C side, we must do it ourselves.

Python applies reference counting.

Each object has a number of references, one for each usage.

The object is destroyed when there are no references.
Reference counting

- Increase the reference count:
  \[ \texttt{Py_INCREF(myobj)}; \]
  (i.e., I need this object, it cannot be deleted elsewhere)

- Decrease the reference count:
  \[ \texttt{Py_DECREF(myobj)}; \]
  (i.e., I don't need this object, it can be deleted)
gridloop1; loop with memory management

for (i = 0; i < nx; i++) {
    for (j = 0; j < ny; j++) {
        a_ij = (double *)(a->data + i*a->strides[0] + j*a->strides[1]);
        x_i = (double *)(xcoor->data + i*xcoor->strides[0]);
        y_j = (double *)(ycoor->data + j*ycoor->strides[0]);

        /* call Python function pointed to by func1: */
        arglist = Py_BuildValue("(dd)", *x_i, *y_j);
        result = PyEval_CallObject(func1, arglist);
        Py_DECREF(arglist);
        if (result == NULL) return NULL; /* exception in func1 */
        *a_ij = PyFloat_AS_DOUBLE(result);
        Py_DECREF(result);
    }
}

gridloop1; more testing in the loop

- We should check that allocations work fine:
  ```c
  arglist = Py_BuildValue("(dd)", *x_i, *y_j);
  if (arglist == NULL) { /* out of memory */
      PyErr_Format(PyExc_MemoryError,
                   "out of memory for 2-tuple");
  }
  ```

- The C code becomes quite comprehensive; much more testing than “active” statements
gridloop2 in C; header

gridloop2: as gridloop1, but array a is returned

static PyObject *gridloop2(PyObject * self, PyObject * args)
{
    PyArrayObject *a, *xcoor, *ycoor;
    int a_dims[2];
    PyObject *func1, *arglist, *result;
    int nx, ny, i, j;
    double *a_ij, *x_i, *y_j;

    /* arguments: xcoor, ycoor, func1 */
    if (!PyArg_ParseTuple(args, "O!O!O:gridloop2",
                           &PyArray_Type, &xcoor, &PyArray_Type, &ycoor,
                           &func1)) {
        return NULL; /* PyArg_ParseTuple has raised an exception */
    }
    nx = xcoor->dimensions[0]; ny = ycoor->dimensions[0];
gridloop2 in C; macros

- NumPy array code in C can be simplified using macros
  
  First, a smart macro wrapping an argument in quotes:
  
```c
#define QUOTE(s) # s /* turn s into string "s" */
```

- Check the type of the array data:

```c
#define TYPECHECK(a, tp) \
    if (a->descr->type_num != tp) { \
        PyErr_Format(PyExc_TypeError, \
        "%s array is not of correct type (%d)", QUOTE(a), tp); \
        return NULL; \
    }
```

- `PyErr_Format` is a flexible way of raising exceptions in C (must return `NULL` afterwards!)
Check the length of a specified dimension:

```c
#define DIMCHECK(a, dim, expected_length) \
if (a->dimensions[dim] != expected_length) { \
    PyErr_Format(PyExc_ValueError, \
             "%s array has wrong %d-dimension=%d (expected %d)\n", \
             QUOTE(a),dim,a->dimensions[dim],expected_length); \
    return NULL; \
}
```
gridloop2 in C; more macros

Check the dimensions of a NumPy array:

```c
#define NDIMCHECK(a, expected_ndim) \
  if (a->nd != expected_ndim) { \
    PyErr_Format(PyExc_ValueError, \
      "%s array is %d-dimensional, expected to be %d-dimensional ", \
      QUOTE(a), a->nd, expected_ndim); \
    return NULL; \
  }
```

Application:

```
NDIMCHECK(xcoor, 1); TYPECHECK(xcoor, PyArray_DOUBLE);
```

If `xcoor` is 2-dimensional, an exceptions is raised by `NDIMCHECK`:

```
exceptions.ValueError
xcoor array is 2-dimensional, but expected to be 1-dimensional
```
Macros can greatly simplify indexing:

```c
#define IND1(a, i) *((double *)(a->data + i*a->strides[0]))
#define IND2(a, i, j) \\
    *((double *)(a->data + i*a->strides[0] + j*a->strides[1]))
```

Application:

```c
for (i = 0; i < nx; i++) {
    for (j = 0; j < ny; j++) {
        arglist = Py_BuildValue("(dd)", IND1(xcoor,i), IND1(ycoor,j));
        result = PyEval_CallObject(func1, arglist);
        Py_XDECREF(arglist);
        if (result == NULL) return NULL; /* exception in func1 */
        IND2(a, i, j) = PyFloat_AsDouble(result);
        Py_XDECREF(result);
    }
}
```
gridloop2 in C; the return array

Create return array:

```c
a_dims[0] = nx; a_dims[1] = ny;
a = (PyArrayObject *) PyArray_FromDims(2, a_dims,
                                  PyArray_DOUBLE);
if (a == NULL) {
    printf("creating a failed, dims=(%d,%d)\n",
            a_dims[0],a_dims[1]);
    return NULL; /* PyArray_FromDims raises an exception */
}
```

After the loop, return `a`:

```c
return PyArray_Return(a);
```
Registering module functions

The method table must always be present - it lists the functions that should be callable from Python:

```c
static PyMethodDef ext_gridloop_methods[] = {
    {"gridloop1", /* name of func when called from Python */
        gridloop1, /* corresponding C function */
        METH_VARARGS, /* ordinary (not keyword) arguments */
        gridloop1_doc}, /* doc string for gridloop1 function */
    {"gridloop2", /* name of func when called from Python */
        gridloop2, /* corresponding C function */
        METH_VARARGS, /* ordinary (not keyword) arguments */
        gridloop2_doc}, /* doc string for gridloop1 function */
    {NULL, NULL}
};
```

- METH_KEYWORDS (instead of METH_VARARGS) implies that the function takes 3 arguments (self, args, kw)
Doc strings

static char gridloop1_doc[] = \n    "gridloop1(a, xcoor, ycoor, pyfunc)";

static char gridloop2_doc[] = \n    "a = gridloop2(xcoor, ycoor, pyfunc)";

static char module_doc[] = \n    "module ext_gridloop:
        gridloop1(a, xcoor, ycoor, pyfunc)\n        a = gridloop2(xcoor, ycoor, pyfunc)";
The required init function

PyMODINIT_FUNC initext_gridloop()
{
    /* Assign the name of the module and the name of the
     method table and (optionally) a module doc string:
     */
    Py_InitModule3("ext_gridloop", ext_gridloop_methods, module_doc);
    /* without module doc string:
    Py_InitModule("ext_gridloop", ext_gridloop_methods);
    */
    import_array();    /* required NumPy initialization */
}
Building the module

```bash
root='python -c 'import sys; print sys.prefix''
ver='python -c 'import sys; print sys.version[:3]''
gcc -O3 -g -I$root/include/python$ver \  
   -I$scripting/src/C  
   -c gridloop.c -o gridloop.o
gcc -shared -o ext_gridloop.so gridloop.o

# test the module:
python -c 'import ext_gridloop; print dir(ext_gridloop)'
```
A setup.py script

The script:

```python
def setup.core import setup, Extension
import os

name = 'ext_gridloop'
setup(name=name,
      include_dirs=[os.path.join(os.environ['scripting'],
                                 'src', 'C')],
      ext_modules=[Extension(name, ['gridloop.c'])])
```

Usage:

```bash
python setup.py build_ext
python setup.py install --install-platlib=.
# test module:
python -c 'import ext_gridloop; print ext_gridloop.__doc__'
```
Using the module

- The usage is the same as in Fortran, when viewed from Python.
- No problems with storage formats and unintended copying of `a` in `gridloop1`, or optional arguments; here we have full control of all details.
- `gridloop2` is the “right” way to do it.
- It is much simpler to use Fortran and F2PY.
Debugging

Things usually go wrong when you program...

Errors in C normally shows up as “segmentation faults” or “bus error” - no nice exception with traceback

Simple trick: run `python` under a debugger

```
unix> gdb `which python`
(gdb) run test.py
```

When the script crashes, issue the `gdb` command `where` for a traceback (if the extension module is compiled with `-g` you can see the line number of the line that triggered the error)

You can only see the traceback, no breakpoints, prints etc., but a tool, PyDebug, allows you to do this
First debugging example

- In src/py/mixed/Grid2D/C/plain/debugdemo there are some C files with errors

- Try

  ./make_module_1.sh gridloop1

This script runs

  ../..../Grid2Deff.py verify1

which leads to a segmentation fault, implying that something is wrong in the C code (errors in the Python script shows up as exceptions with traceback)
1st debugging example (1)

- Check that the extension module was compiled with debug mode on (usually the -g option to the C compiler)
- Run python under a debugger:

```
unix> gdb `which python`
GNU gdb 6.0-debian...
...
(gdb) run ../../../Grid2Deff.py verify1
Starting program: /usr/bin/python ../../../Grid2Deff.py verify1
...
Program received signal SIGSEGV, Segmentation fault.
0x40cdfab3 in gridloop1 (self=0x0, args=0x1) at gridloop1.c:20
20    if (!PyArg_ParseTuple(args, "O!O!O!O:gridloop1",

This is the line where something goes wrong...
```
1st debugging example (2)

(gdb) where
#0 0x40cdfab3 in gridloop1 (self=0x0, args=0x1) at gridloop1.c:20
#1 0x080fde1a in PyCFunction_Call ()
#2 0x080ab824 in PyEval_CallObjectWithKeywords ()
#3 0x080a9bde in Py_MakePendingCalls ()
#4 0x080aa76c in PyEval_EvalCodeEx ()
#5 0x080ab8d9 in PyEval_CallObjectWithKeywords ()
#6 0x080ab71c in PyEval_CallObjectWithKeywords ()
#7 0x080a9bde in Py_MakePendingCalls ()
#8 0x080ab95d in PyEval_CallObjectWithKeywords ()
#9 0x080ab71c in PyEval_CallObjectWithKeywords ()
#10 0x080a9bde in Py_MakePendingCalls ()
#11 0x080aa76c in PyEval_EvalCodeEx ()
#12 0x080acf69 in PyEval_EvalCode ()
#13 0x080d90db in PyRun_FileExFlags ()
#14 0x080d91f in PyRun_String ()
#15 0x08100c20 in _IO_stdin_used ()
#16 0x401ee79c in ?? ()
#17 0x41096bdc in ?? ()
1st debugging example (3)

What is wrong?

The `import_array()` call was removed, but the segmentation fault happened in the first call to a Python C function.
2nd debugging example

Try

./make_module_1.sh gridloop2

and experience that

python -c 'import ext_gridloop; print dir(ext_gridloop); \nprint ext_gridloop.__doc__'

ends with an exception

Traceback (most recent call last):
  File "<string>", line 1, in ?
SystemError: dynamic module not initialized properly

This signifies that the module misses initialization

Reason: no Py_InitModule3 call
3rd debugging example (1)

Try

./make_module_1.sh gridloop3

Most of the program seems to work, but a segmentation fault occurs (according to gdb):

(gdb) where
(gdb) #0 0x40115d1e in mallopt () from /lib/libc.so.6
#1 0x40114d33 in malloc () from /lib/libc.so.6
#2 0x40449fb9 in PyArray_FromDimsAndDataAndDescr ()
    from /usr/lib/python2.3/site-packages/Numeric/_numpy.so...
#42 0x080d90db in PyRun_FileExFlags ()
#43 0x080d9d1f in PyRun_String ()
#44 0x08100c20 in _IO_stdin_used ()
#45 0x401ee79c in ?? ()
#46 0x41096bdc in ?? ()

Hmmm... no sign of where in gridloop3.c the error occurs, except that the Grid2Deff.py script successfully calls both gridloop1 and gridloop2, it fails when printing the returned array
3rd debugging example (2)

- **Next step:** print out information

```c
for (i = 0; i <= nx; i++) {
    for (j = 0; j <= ny; j++) {
        arglist = Py_BuildValue("(dd)", IND1(xcoor,i), IND1(ycoor,j));
        result = PyEval_CallObject(func1, arglist);
        IND2(a,i,j) = PyFloat_AS_DOUBLE(result);

        #ifdef DEBUG
            printf("a[%d,%d]=func1(%g,%g)=%g\n",i,j,
                    IND1(xcoor,i),IND1(ycoor,j),IND2(a,i,j));
        #endif
    }
}
```

- **Run**

  ```bash
  ./make_module_1.sh gridloop3 -DDEBUG
  ```
3rd debugging example (3)

Loop debug output:

a[2,0]=func1(1,0)=1
f1...x-y= 3.0
a[2,1]=func1(1,1)=3
f1...x-y= 1.0
a[2,2]=func1(1,7.15113e-312)=1
f1...x-y= 7.66040480538e-312
a[3,0]=func1(7.6604e-312,0)=7.6604e-312
f1...x-y= 2.0
a[3,1]=func1(7.6604e-312,1)=2
f1...x-y= 2.19626564365e-311
a[3,2]=func1(7.6604e-312,7.15113e-312)=2.19627e-311

Ridiculous values (coordinates) and wrong indices reveal the problem: wrong upper loop limits
4th debugging example

- Try
  
  ```
  ./make_module_1.sh gridloop4
  ```

  and experience

  ```
  python -c import ext_gridloop; print dir(ext_gridloop); \
  print ext_gridloop.__doc__
  ```

  Traceback (most recent call last):
  File "<string>", line 1, in ?
  ImportError: dynamic module does not define init function (initext_gridloop)

- Eventuall we got a precise error message (the initext_gridloop was not implemented)
5th debugging example

- Try
  
  ./make_module_1.sh gridloop5

  and experience

  python -c import ext_gridloop; print dir(ext_gridloop); \ 
  print ext_gridloop.__doc__

  Traceback (most recent call last):
    File "<string>", line 1, in ?
  ImportError: ./ext_gridloop.so: undefined symbol: mydebug

  gridloop2 in gridloop5.c calls a function mydebug, but the
  function is not implemented (or linked)

  Again, a precise ImportError helps detecting the problem
Summary of the debugging examples

- Check that `import_array()` is called if the NumPy C API is in use!
- `ImportError` suggests wrong module initialization or missing required/user functions
- You need experience to track down errors in the C code
- An error in one place often shows up as an error in another place (especially indexing out of bounds or wrong memory handling)
- Use a debugger (gdb) and print statements in the C code and the calling script
- C++ modules are (almost) as error-prone as C modules
Next example

- Implement the computational loop in a traditional C function
- Aim: pretend that we have this loop already in a C library
- Need to write a wrapper between this C function and Python
- Could think of SWIG for generating the wrapper, but SWIG with NumPy arrays is a bit tricky - it is in fact simpler to write the wrapper by hand
Two-dim. C array as double pointer

- C functions taking a two-dimensional array as argument will normally represent the array as a double pointer:

```c
void gridloop1_C(double ** a, double *xcoor, double *ycoor,
                   int nx, int ny, Fxy func1)
{
    int i, j;
    for (i=0; i<nx; i++) {
        for (j=0; j<ny; j++) {
            a[i][j] = func1(xcoor[i], ycoor[j]);
        }
    }
}
```

- `Fxy` is a function pointer:

```c
typedef double (*Fxy)(double x, double y);
```

- An existing C library would typically work with multi-dim. arrays and callback functions this way
Problems

- How can we write wrapper code that sends NumPy array data to a C function as a double pointer?
- How can we make callbacks to Python when the C function expects callbacks to standard C functions, represented as function pointers?
- We need to cope with these problems to interface (numerical) C libraries!

src/mixed/py/Grid2D/C/clibcall
From NumPy array to double pointer

2-dim. C arrays stored as a double pointer:

The wrapper code must allocate extra data:

```c
double **app; double *ap;
ap = (double *) a->data; /* a is a PyArrayObject* pointer */
app = (double **) malloc(nx*sizeof(double*));
for (i = 0; i < nx; i++) {
    app[i] = &(ap[i*ny]); /* point row no. i in a->data */
}
/* clean up when app is no longer needed: */ free(app);
```
Callback via a function pointer (1)

- gridloop1_C calls a function like
  
  ```c
  double somefunc(double x, double y)
  ```

  but our function is a Python object...

- Trick: store the Python function in
  
  ```c
  PyObject* _pyfunc_ptr; /* global variable */
  ```

  and make a “wrapper” for the call:

  ```c
  double _pycall(double x, double y)
  {
      /* perform call to Python function object in _pyfunc_ptr */
  }
  ```
Callback via a function pointer (2)

Complete function wrapper:

```c
double _pycall(double x, double y)
{
    PyObject *arglist, *result;
    arglist = Py_BuildValue("(dd)", x, y);
    result = PyEval_CallObject(_pyfunc_ptr, arglist);
    return PyFloat_AS_DOUBLE(result);
}
```

Initialize `_pyfunc_ptr` with the `func1` argument supplied to the `gridloop1` wrapper function

```c
_pyfunc_ptr = func1; /* func1 is PyObject* pointer */
```
The alternative gridloop1 code (1)

```c
static PyObject * gridloop1(PyObject * self, PyObject * args)
{
    PyArrayObject * a, * xcoor, * ycoor;
    PyObject * func1, * arglist, * result;
    int nx, ny, i;
    double ** app;
    double * ap, * xp, * yp;

    /* arguments: a, xcoor, ycoor, func1 */
    /* parsing without checking the pointer types: */
    if (!PyArg_ParseTuple(args, "OOOO", &a, &xcoor, &ycoor, &func1))
    { return NULL; }
    NDIMCHECK(a, 2); TYPECHECK(a, PyArray_DOUBLE);
    nx = a->dimensions[0]; ny = a->dimensions[1];
    NDIMCHECK(xcoor, 1); DIMCHECK(xcoor, 0, nx);
    TYPECHECK(xcoor, PyArray_DOUBLE);
    NDIMCHECK(ycoor, 1); DIMCHECK(ycoor, 0, ny);
    TYPECHECK(ycoor, PyArray_DOUBLE);
    CALLABLECHECK(func1);
```
The alternative gridloop1 code (2)

_pyfunc_ptr = func1; /* store func1 for use in _pycall */

/* allocate help array for creating a double pointer: */
app = (double **) malloc(nx*sizeof(double*));
ap = (double *) a->data;
for (i = 0; i < nx; i++) { app[i] = &(ap[i*ny]); }
xp = (double *) xcoor->data;
yp = (double *) ycoor->data;
gridloop1_C(app, xp, yp, nx, ny, _pycall);
free(app);
return Py_BuildValue("""); /* return None */
gridloop1 with C++ array object

- Programming with NumPy arrays in C is much less convenient than programming with C++ array objects

```cpp
SomeArrayClass a(10, 21);
a(1,2) = 3; // indexing
```

- Idea: wrap NumPy arrays in a C++ class
- Goal: use this class wrapper to simplify the gridloop1 wrapper

```
src/py/mixed/Grid2D/C++/plain
```
The C++ class wrapper (1)

class NumPyArray_Float
{
    private:
        PyArrayObject* a;

    public:
        NumPyArray_Float () { a=NULL; }
        NumPyArray_Float (int n1, int n2) { create(n1, n2); }
        NumPyArray_Float (double* data, int n1, int n2)
        { wrap(data, n1, n2); }
        NumPyArray_Float (PyArrayObject* array) { a = array; }
The C++ class wrapper (2)

// redimension (reallocate) an array:
int create (int n1, int n2) {
    int dim2[2]; dim2[0] = n1; dim2[1] = n2;
a = (PyArrayObject*) PyArray_FromDims(2, dim2, PyArray DOUBLE);
    if (a == NULL) { return 0; } else { return 1; } }

// wrap existing data in a NumPy array:
void wrap (double* data, int n1, int n2) {
    int dim2[2]; dim2[0] = n1; dim2[1] = n2;
a = (PyArrayObject*) PyArray_FromDimsAndData(
        2, dim2, PyArray_DOUBLE, (char*) data);
}

// for consistency checks:
int checktype () const;
int checkdim (int expected_ndim) const;
int checksize (int expected_size1, int expected_size2=0,
        int expected_size3=0) const;
The C++ class wrapper (3)

// indexing functions (inline!):
double operator()(int i, int j) const
{ return *((double*) (a->data +
   i*a->strides[0] + j*a->strides[1])); }
double& operator()(int i, int j)
{ return *((double*) (a->data +
   i*a->strides[0] + j*a->strides[1])); } // extract dimensions:
int dim() const { return a->nd; } // no of dimensions
int size1() const { return a->dimensions[0]; }
int size2() const { return a->dimensions[1]; }
int size3() const { return a->dimensions[2]; }
PyArrayObject* getPtr () { return a; }
};
Using the wrapper class

```c
static PyObject* gridloop2(PyObject* self, PyObject* args)
{
    PyArrayObject *xcoor_, *ycoor_;  
    PyObject *func1, *arglist, *result;
    /* arguments: xcoor, ycoor, func1 */
    if (!PyArg_ParseTuple(args, "O!O!O:gridloop2",
        &PyArray_Type, &xcoor_,
        &PyArray_Type, &ycoor_,
        &func1)) {
        return NULL; /* PyArg_ParseTuple has raised an exception */
    }  
    NumPyArray_Float xcoor (xcoor_); int nx = xcoor.size1();
    if (!xcoor.checktype()) { return NULL; }
    if (!xcoor.checkdim(1)) { return NULL; }
    NumPyArray_Float ycoor (ycoor_); int ny = ycoor.size1();
    // check ycoor dimensions, check that func1 is callable...
    NumPyArray_Float a(nx, ny); // return array
```
The loop is straightforward

```c
int i,j;
for (i = 0; i < nx; i++) {
    for (j = 0; j < ny; j++) {
        arglist = Py_BuildValue("(dd)", xcoor(i), ycoor(j));
        result = PyEval_CallObject(func1, arglist);
        a(i,j) = PyFloat_AS_DOUBLE(result);
    }
}
return PyArray_Return(a.getPtr());
```
Reference counting

We have omitted a very important topic in Python-C programming: reference counting

Python has a garbage collection system based on reference counting

Each object counts the no of references to itself

When there are no more references, the object is automatically deallocated

Nice when used from Python, but in C we must program the reference counting manually

```c
PyObject *obj;
...
Py_XINCREF(obj); /* new reference created */
...
Py_DECREF(obj); /* a reference is destroyed */
```
SCXX: basic ideas

- Thin C++ layer on top of the Python C API
- Each Python type (number, tuple, list, ...) is represented as a C++ class
- The resulting code is quite close to Python
- SCXX objects performs reference counting automatically
Example

```c
#include <PWONumber.h>    // class for numbers
#include <PWOSSequence.h> // class for tuples
#include <PWOMSequence.h> // class for lists (immutable sequences)

void test_scxx() {
    double a_ = 3.4;
    PWONumber a = a_; PWONumber b = 7;
    PWONumber c; c = a + b;
    PWOList list; list.append(a).append(c).append(b);
    PWOTuple tp(list);
    for (int i=0; i<tp.len(); i++) {
        std::cout << "tp["<<i<<"]="<<double(PWONumber(tp[i]))<<" ";
    }
    std::cout << std::endl;
    PyObject* py_a = (PyObject *) a; // convert to Python C struct
}
```
The similar code with Python C API

```c
void test_PythonAPI()
{
    double a_ = 3.4;
    PyObject* a = PyFloat_FromDouble(a_);
    PyObject* b = PyFloat_FromDouble(7);
    PyObject* c = PyNumber_Add(a, b);
    PyObject* list = PyList_New(0);
    PyList_Append(list, a);
    PyList_Append(list, c);
    PyList_Append(list, b);
    PyObject* tp = PyList_AsTuple(list);
    int tp_len = PySequence_Length(tp);
    for (int i=0; i<tp_len; i++) {
        PyObject* qp = PySequence_GetItem(tp, i);
        double q = PyFloat_AS_DOUBLE(qp);
        std::cout << "tp[" << i << "]=" << q << " ";
    }
    std::cout << std::endl;
}
```

Note: reference counting is omitted
gridloop1 with SCXX

static PyObject* gridloop1(PyObject* self, PyObject* args_)
{
    /* arguments: a, xcoor, ycoor */
    try {
        PWOSequence args (args_);
        NumPyArray_Float a ((PyArrayObject*) ((PyObject*) args[0]));
        NumPyArray_Float xcoor ((PyArrayObject*) ((PyObject*) args[1]));
        NumPyArray_Float ycoor ((PyArrayObject*) ((PyObject*) args[2]));
        PWOCallable func1 (args[3]);

        // work with a, xcoor, ycoor, and func1
        ...

        return PWONone();
    }
    catch (PWException e) { return e; }
}
Error checking

- NumPyArray_Float objects are checked using their member functions (checkdim, etc.)

- SCXX objects also have some checks:

```c
if (!func1.isCallable()) {
    PyErr_Format(PyExc_TypeError,
                 "func1 is not a callable function");
    return NULL;
}
```
The loop over grid points

```c
int i, j;
for (i = 0; i < nx; i++) {
    for (j = 0; j < ny; j++) {
        PWOTuple arglist(Py_BuildValue("(dd)", xcoor(i), ycoor(j)));
        PWONumber result(func1.call(arglist));
        a(i, j) = double(result);
    }
}
```
The Weave tool (1)

- Weave is an easy-to-use tool for inlining C++ snippets in Python codes
- A quick demo shows its potential

```python
class Grid2Deff:
    ...
    def ext_gridloop1_weave(self, fstr):
        """Migrate loop to C++ with aid of Weave.""

        from scipy import weave

        # the callback function is now coded in C++
        # (fstr must be valid C++ code):

        extra_code = r""
        double cppcb(double x, double y) {
            return %s;
        }
        """ % fstr
```

Mixed language numerical Python – p. 501/731
The Weave tool (2)

The loops: inline C++ with Blitz++ array syntax:

code = r""
int i, j;
for (i=0; i<nx; i++) {
    for (j=0; j<ny; j++) {
        a(i, j) = cppcb(xcoor(i), ycoor(j));
    }
}"
""
The Weave tool (3)

Compile and link the extra code `extra_code` and the main code (loop) `code`:

```python
nx = size(self.xcoor); ny = size(self.ycoor)
a = zeros((nx,ny))
xcoor = self.xcoor; ycoor = self.ycoor
err = weave.inline(code, ['a', 'nx', 'ny', 'xcoor', 'ycoor'],
   type_converters=weave.converters.blitz,
   support_code=extra_code, compiler='gcc')
return a
```

Note that we pass the names of the Python objects we want to access in the C++ code.

Weave is smart enough to avoid recompiling the code if it has not changed since last compilation.
Exchanging pointers in Python code

- When interfacing many libraries, data must be grabbed from one code and fed into another
- Example: NumPy array to/from some C++ data class
- Idea: make filters, converting one data to another
- Data objects are represented by pointers
- SWIG can send pointers back and forth without needing to wrap the whole underlying data object
- Let’s illustrate with an example!
Say our favorite C++ array class is **MyArray**

```cpp
template< typename T >
class MyArray
{
    public:
        T* A; // the data
        int ndim; // no of dimensions (axis)
        int size[MAXDIM]; // size/length of each dimension
        int length; // total no of array entries
    ...
};
```

We can work with this class from Python without needing to SWIG the class (!)

We make a filter class converting a NumPy array (pointer) to/from a **MyArray** object (pointer)

```
src/py/mixed/Grid2D/C++/convertptr
```
Filter between NumPy array and C++ class

class Convert_MyArray
{
    public:
        Convert_MyArray();

    // borrow data:
    PyObject*        my2py (MyArray<double>& a);
    MyArray<double>* py2my (PyObject* a);

    // copy data:
    PyObject*        my2py_copy (MyArray<double>& a);
    MyArray<double>* py2my_copy (PyObject* a);

    // print array:
    void             dump(MyArray<double>& a);

    // convert Py function to C/C++ function calling Py:
    Fxy              set_pyfunc (PyObject* f);

    protected:
    static PyObject* _pyfunc_ptr;  // used in _pycall
    static double    _pycall (double x, double y);
};
Typical conversion function

PyObject* Convert_MyArray::my2py(MyArray<double>& a)
{
    PyArrayObject* array = (PyArrayObject*) PyArray_FromDimsAndData(a.ndim, a.size, PyArray_DOUBLE, (char*) a.A);
    if (array == NULL) {
        return NULL; /* PyArray_FromDimsAndData raised exception */
    }
    return PyArray_Return(array);
}
Version with data copying

PyObject* Convert_MyArray::my2py_copy(MyArray<double>& a)
{
    PyArrayObject* array = (PyArrayObject*)
        PyArray_FromDims(a.ndim, a.size, PyArray_DOUBLE);
    if (array == NULL) {
        return NULL; /* PyArray_FromDims raised exception */
    }
    double* ad = (double*) array->data;
    for (int i = 0; i < a.length; i++) {
        ad[i] = a.A[i];
    }
    return PyArray_Return(array);
}
Ideas

- SWIG `Convert_MyArray`
- Do not SWIG `MyArray`
- Write numerical C++ code using `MyArray`
  (or use a library that already makes use of `MyArray`)
- Convert pointers (data) explicitly in the Python code
```cpp
void gridloop1(MyArray<double>& a, 
    const MyArray<double>& xcoor, 
    const MyArray<double>& ycoor, 
    Fxy func1)
{
    int nx = a.shape(1), ny = a.shape(2);
    int i, j;
    for (i = 0; i < nx; i++) {
        for (j = 0; j < ny; j++) {
            a(i,j) = func1(xcoor(i), ycoor(j));
        }
    }
}
```
Instead of just calling

```python
ext_gridloop.gridloop1(a, self.xcoor, self.ycoor, func)
return a
```

as before, we need some explicit conversions:

```python
# a is a NumPy array
# self.c is the conversion module (class Convert_MyArray)
a_p = self.c.py2my(a)
x_p = self.c.py2my(self.xcoor)
y_p = self.c.py2my(self.ycoor)
f_p = self.c.set_pyfunc(func)
ext_gridloop.gridloop1(a_p, x_p, y_p, f_p)
return a  # a_p and a share data!
```
In case we work with copied data, we must copy both ways:

```python
a_p = self.c.py2my_copy(a)
x_p = self.c.py2my_copy(self.xcoor)
y_p = self.c.py2my_copy(self.ycoor)
f_p = self.c.set_pyfunc(func)
ext_gridloop.gridloop1(a_p, x_p, y_p, f_p)
a = self.c.my2py_copy(a_p)
return a
```

Note: final `a` is not the same `a` object as we started with
SWIG’ing the filter class

- **C++ code:** `convert.h/.cpp + gridloop.h/.cpp`
- **SWIG interface file:**

```c
/* file: ext_gridloop.i */
%module ext_gridloop
{
/* include C++ header files needed to compile the interface */
#include "convert.h"
#include "gridloop.h"
%
#include "convert.h"
#include "gridloop.h"
%}

Important: call NumPy’s `import_array` (here in `Convert_MyArray` constructor)

- **Run SWIG:**

```bash
swig -python -c++ -I. ext_gridloop.i
```

- **Compile and link shared library module**
import os
from distutils.core import setup, Extension
name = 'ext_gridloop'

swig_cmd = 'swig -python -c++ -I. %s.i' % name
os.system(swig_cmd)

sources = ['gridloop.cpp', 'convert.cpp', 'ext_gridloop_wrap.cxx']
setup(name=name,
      ext_modules=[Extension('_' + name, # SWIG requires _
                               sources=sources,
                               include_dirs=[os.curdir])])
Manual alternative

swig -python -c++ -I. ext_gridloop.i

root='python -c 'import sys; print sys.prefix''
ver='python -c 'import sys; print sys.version[:3]''
g++ -I. -O3 -g -I$root/include/python$ver \ 
    -c convert.cpp gridloop.cpp ext_gridloop_wrap.cxx

g++ -shared -o _ext_gridloop.so \ 
    convert.o gridloop.o ext_gridloop_wrap.o
Summary

We have implemented several versions of \texttt{gridloop1} and \texttt{gridloop2}:

- Fortran subroutines, working on Fortran arrays, automatically wrapped by F2PY
- Hand-written C extension module, working directly on NumPy array structs in C
- Hand-written C wrapper to a C function, working on standard C arrays (incl. double pointer)
- Hand-written C++ wrapper, working on a C++ class wrapper for NumPy arrays
- As last point, but simplified wrapper utilizing SCXX
- C++ functions based on \texttt{MyArray}, plus C++ filter for pointer conversion, wrapped by SWIG
Comparison

- What is the most convenient approach in this case? Fortran!
- If we cannot use Fortran, which solution is attractive? C++, with classes allowing higher-level programming
- To interface a large existing library, the filter idea and exchanging pointers is attractive (no need to SWIG the whole library)
- When using the Python C API extensively, SCXX simplifies life
Efficiency

Which alternative is computationally most efficient? Fortran, but C/C++ is quite close – no significant difference between all the C/C++ versions.

Too bad: the (point-wise) callback to Python destroys the efficiency of the extension module!

Pure Python script w/NumPy is much more efficient...

Nevertheless: this is a pedagogical case teaching you how to migrate/interface numerical code.
## Efficiency test: 1100x1100 grid

<table>
<thead>
<tr>
<th>Language</th>
<th>Function</th>
<th>Description</th>
<th>CPU time</th>
</tr>
</thead>
<tbody>
<tr>
<td>F77</td>
<td>gridloop1</td>
<td>F77 function with formula</td>
<td>1.0</td>
</tr>
<tr>
<td>C++</td>
<td>gridloop1</td>
<td>C++ function with formula</td>
<td>1.07</td>
</tr>
<tr>
<td>Python</td>
<td>Grid2D.<strong>call</strong></td>
<td>vectorized numpy myfuncfunc</td>
<td>1.5</td>
</tr>
<tr>
<td>Python</td>
<td>Grid2D.gridloop</td>
<td>myfunc w/math.sin</td>
<td>120</td>
</tr>
<tr>
<td>Python</td>
<td>Grid2D.gridloop</td>
<td>myfunc w/numpy.sin</td>
<td>220</td>
</tr>
<tr>
<td>F77</td>
<td>gridloop1</td>
<td>myfunc w/math.sin</td>
<td>40</td>
</tr>
<tr>
<td>F77</td>
<td>gridloop1</td>
<td>myfunc w/numpy.sin</td>
<td>180</td>
</tr>
<tr>
<td>F77</td>
<td>gridloop2</td>
<td>myfunc w/math.sin</td>
<td>40</td>
</tr>
<tr>
<td>F77</td>
<td>gridloop_vec2</td>
<td>vectorized myfunc</td>
<td>2.7</td>
</tr>
<tr>
<td>F77</td>
<td>gridloop2_str</td>
<td>F77 myfunc</td>
<td>1.1</td>
</tr>
<tr>
<td>F77</td>
<td>gridloop_noalloc</td>
<td>(no alloc. as in pure C++)</td>
<td>1.0</td>
</tr>
<tr>
<td>C</td>
<td>gridloop1</td>
<td>myfunc w/math.sin</td>
<td>38</td>
</tr>
<tr>
<td>C</td>
<td>gridloop2</td>
<td>myfunc w/math.sin</td>
<td>38</td>
</tr>
<tr>
<td>C++</td>
<td>(with class NumPyArray)</td>
<td>had the same numbers as C</td>
<td></td>
</tr>
</tbody>
</table>
Conclusions about efficiency

- `math.sin` is much faster than `numpy.sin` for scalar expressions
- Callbacks to Python are extremely expensive
- Python+NumPy is 1.5 times slower than pure Fortran
- C and C++ run equally fast
- C++ w/`MyArray` was only 7% slower than pure F77

Minimize the no of callbacks to Python!
More F2PY features

- **Hide work arrays (i.e., allocate in wrapper):**

  ```fortran
  subroutine myroutine(a, b, m, n, w1, w2)
  integer m, n
  real*8 a(m), b(n), w1(3*n), w2(m)
  Cf2py intent(in,hide) w1
  Cf2py intent(in,hide) w2
  Cf2py intent(in,out) a
  ```

  **Python interface:**

  ```python
  a = myroutine(a, b)
  ```

- **Reuse work arrays in subsequent calls (cache):**

  ```fortran
  subroutine myroutine(a, b, m, n, w1, w2)
  integer m, n
  real*8 a(m), b(n), w1(3*n), w2(m)
  Cf2py intent(in,hide,cache) w1
  Cf2py intent(in,hide,cache) w2
  ```
Other tools

- Pyfort for Python-Fortran integration (does not handle F90/F95, not as simple as F2PY)
- SIP: tool for wrapping C++ libraries
- Boost.Python: tool for wrapping C++ libraries
- CXX: C++ interface to Python (Boost is a replacement)
- Note: SWIG can generate interfaces to most scripting languages (Perl, Ruby, Tcl, Java, Guile, Mzscheme, ...)

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Basic Bash programming
Overview of Unix shells

- The original scripting languages were (extensions of) command interpreters in operating systems
- Primary example: Unix shells
- Bourne shell (sh) was the first major shell
- C and TC shell (csh and tcsh) had improved command interpreters, but were less popular than Bourne shell for programming
- Bourne Again shell (Bash/bash): GNU/FSF improvement of Bourne shell
- Other Bash-like shells: Korn shell (ksh), Z shell (zsh)
- Bash is the dominating Unix shell today
Why learn Bash?

- Learning Bash means learning Unix
- Learning Bash means learning the roots of scripting (Bourne shell is a subset of Bash)
- Shell scripts, especially in Bourne shell and Bash, are frequently encountered on Unix systems
- Bash is widely available (open source) and the dominating command interpreter and scripting language on today’s Unix systems
- Shell scripts are often used to glue more advanced scripts in Perl and Python
More information

- Greg Wilson’s excellent online course: http://www.swc.scipy.org
- man bash
- “Introduction to and overview of Unix” link in doc.html
Let's start with a script writing "Hello, World!"

Scientific computing extension: compute the sine of a number as well

The script (hw.sh) should be run like this:

```bash
./hw.sh 3.4
```

or (less common):

```bash
bash hw.py 3.4
```

Output:

```
Hello, World! sin(3.4)=-0.255541102027
```
Purpose of this script

Demonstrate

- how to read a command-line argument
- how to call a math (sine) function
- how to work with variables
- how to print text and numbers
Remark

- We use plain Bourne shell (/bin/sh) when special features of Bash (/bin/bash) are not needed.
- Most of our examples can in fact be run under Bourne shell (and of course also Bash).
- Note that Bourne shell (/bin/sh) is usually just a link to Bash (/bin/bash) on Linux systems (Bourne shell is proprietary code, whereas Bash is open source).
File hw.sh:

```bash
#!/bin/sh
r=$1 # store first command-line argument in r
s=`echo "s($r)" | bc -l`

# print to the screen:
echo "Hello, World! sin($r)=$s"
```
Comments

- The first line specifies the interpreter of the script (here `/bin/sh`, could also have used `/bin/bash`)

- The command-line variables are available as the script variables $1 $2 $3 $4 and so on

- Variables are initialized as
  
  \[
  \text{r} = \text{r1} \\
  \text{my\_new\_variable} = \text{r} \quad \# \text{copy r to my\_new\_variable}
  \]
Bash and math

Bourne shell and Bash have very little built-in math, we therefore need to use bc, Perl or Awk to do the math

```bash
s=\`echo "s($r)" | bc -l\`
```
s=\`perl -e \$s=sin($ARGV[0]); print $s;\' $r\`
s=\`awk "BEGIN { s=sin($r); print s;}"\`
# or shorter:
s=\`awk "BEGIN {print sin($r)}"\`
```

Back quotes means executing the command inside the quotes and assigning the output to the variable on the left-hand-side

```bash
some_variable=\`some Unix command\`
```
# alternative notation:
some_variable=$(some Unix command)
The bc program

- bc = interactive calculator
- Documentation: man bc
- bc -l means bc with math library
- Note: sin is s, cos is c, exp is e
- echo sends a text to be interpreted by bc and bc responds with output (which we assign to $s$

variable='echo "math expression" | bc -l'
Printing

- The `echo` command is used for writing:
  ```sh
echo "Hello, World! sin($r)=$s"
  
  and variables can be inserted in the text string (variable interpolation)
- Bash also has a `printf` function for format control:
  ```sh
  printf "Hello, World! sin(%g)=%12.5e\n" $r $s
  
  `cat` is usually used for printing multi-line text (see next slide)
Convenient debugging tool: -x

- Each source code line is printed prior to its execution of you -x as option to /bin/sh or /bin/bash

- Either in the header
  
  #!/bin/sh -x

  or on the command line:

  unix> /bin/sh -x hw.sh
  unix> sh -x hw.sh
  unix> bash -x hw.sh

- Very convenient during debugging
File reading and writing

- Bourne shell and Bash are not much used for file reading and manipulation; usually one calls up Sed, Awk, Perl or Python to do file manipulation

- File writing is efficiently done by 'here documents':

  ```
  cat > myfile <<EOF
  multi-line text
  can now be inserted here,
  and variable interpolation
  a la $myvariable is
  supported. The final EOF must
  start in column 1 of the
  script file.
  EOF
  ```
Simulation and visualization script

- Typical application in numerical simulation:
  - run a simulation program
  - run a visualization program and produce graphs
- Programs are supposed to run in batch
- Putting the two commands in a file, with some glue, makes a classical Unix script
# Setting default parameters

```bash
#!/bin/sh

pi=3.14159
m=1.0; b=0.7; c=5.0; func="y"; A=5.0;
w='echo 2*$pi | bc'
y0=0.2; tstop=30.0; dt=0.05; case="tmp1"
screenplot=1
```
# read variables from the command line, one by one:
while [ $# -gt 0 ] # $# = no of command-line args.
do
  option = $1; # load command-line arg into option
  shift;      # eat currently first command-line arg
  case "$option" in
    -m)
      m=$1; shift; ;; # load next command-line arg
    -b)
      b=$1; shift; ;;
    ...*)
      echo "$0: invalid option \"$option\""; exit ;;
  esac
done
Alternative to case: if

case is standard when parsing command-line arguments in Bash, but if-tests can also be used. Consider

```bash
case "\$option" in
  -m)
      m=$1; shift; ;;  # load next command-line arg
  -b)
      b=$1; shift; ;;
  *)
      echo "\$0: invalid option \"\$option\""; exit ;;
esac

versus

if [ "\$option" == "-m" ]; then
    m=$1; shift;  # load next command-line arg
elif [ "\$option" == "-b" ]; then
    b=$1; shift;
else
    echo "$0: invalid option \"\$option\""; exit
fi
```
Creating a subdirectory

dir=$case
# check if $dir is a directory:
if [ -d $dir ]
    # yes, it is; remove this directory tree
    then
        rm -r $dir
    fi
mkdir $dir # create new directory $dir
cd $dir # move to $dir

# the 'then' statement can also appear on the 1st line:
if test -d $dir; then
    rm -r $dir
fi

# another form of if-tests:
if test -d $dir; then
    rm -r $dir
fi

# and a shortcut:
[ -d $dir ] && rm -r $dir
test -d $dir && rm -r $dir
Writing an input file

'Here document' for multi-line output:

```bash
# write to $case.i the lines that appear between
# the EOF symbols:

cat > $case.i <<-EOF
  $m
  $b
  $c
  $func
  $A
  $w
  $y0
  $tstop
  $dt

EOF
```
Running the simulation

- Stand-alone programs can be run by just typing the name of the program

- If the program reads data from standard input, we can put the input in a file and *redirect input*:

  oscillator < $case.i

- Can check for successful execution:

  ```
  # the shell variable $? is 0 if last command # was successful, otherwise $? != 0
  if [ " $?" != "0" ]; then
    echo "running oscillator failed"; exit 1
  fi
  # exit n sets $? to n
  ```
Remark (1)

- Variables can in Bash be integers, strings or arrays.
- For safety, declare the type of a variable if it is not a string:

  ```bash
  declare -i i  # i is an integer
  declare -a A  # A is an array
  ```
Remark (2)

- Comparison of two integers use a syntax different comparison of two strings:

  ```bash
  if [ $i -lt 10 ]; then  # integer comparison
  if [ "$name" == "10" ]; then # string comparison
  ```

- Unless you have declared a variable to be an integer, assume that all variables are strings and use double quotes (strings) when comparing variables in an if test

  ```bash
  if [ "$?" != "0" ]; then # this is safe
  if [ $? != 0 ]; then # might be unsafe
  ```
Making plots

Make Gnuplot script:

```
echo "set title '$case: m=$m ...'" > $case.gnuplot
...
# continue writing with a here document:
cat >> $case.gnuplot <<EOF
set size ratio 0.3 1.5, 1.0;
...
plot 'sim.dat' title 'y(t)' with lines;
...
EOF
```

Run Gnuplot:

```
gnuplot -geometry 800x200 -persist $case.gnuplot
if [ "$?" != "0" ]; then
  echo "running gnuplot failed"; exit 1
fi
```
Some common tasks in Bash

- file writing
- for-loops
- running an application
- pipes
- writing functions
- file globbing, testing file types
- copying and renaming files, creating and moving to directories, creating directory paths, removing files and directories
- directory tree traversal
- packing directory trees
File writing

outfilename="myprog2.cpp"

# append multi-line text (here document):
cat >> $filename <<EOF
/*
   This file, "$outfilename", is a version
   of "$infilename" where each line is numbered.
*/
EOF

# other applications of cat:
cat myfile            # write myfile to the screen
cat myfile >  yourfile # write myfile to yourfile
cat myfile >> yourfile # append myfile to yourfile
cat myfile |  wc       # send myfile as input to wc
For-loops

The for element in list construction:

```bash
files=`/bin/ls *.*tmp`
# we use /bin/ls in case ls is aliased

for file in $files
do
    echo removing $file
    rm -f $file
done
```

Traverse command-line arguments:

```bash
for arg; do
done

# or full syntax; command-line args are stored in @
for arg in $@; do
    # do something with $arg
done
```
Counters

Declare an integer counter:

```bash
declare -i counter
counter=0
# arithmetic expressions must appear inside (( ))
((counter++))
echo $counter  # yields 1
```

For-loop with counter:

```bash
declare -i n; n=1
for arg in $@; do
    echo "command-line argument no. $n is <$arg>"
    ((n++))
done
```
C-style for-loops

declare -i i
for ((i=0; i<$n; i++)); do
  echo $c
done
Example: bundle files

- Pack a series of files into one file
- Executing this single file as a Bash script packs out all the individual files again (!)

Usage:

```bash
bundle file1 file2 file3 > onefile  # pack
bash onefile      # unpack
```

Writing bundle is easy:

```bash
#!/bin/sh
for i in $@; do
  echo "echo unpacking file $i"
  echo "cat > $i <<EOF"
  cat $i
  echo "EOF"
done
```

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The bundle output file

Consider 2 fake files; file1

Hello, World!
No sine computations today

and file2

1.0 2.0 4.0
0.1 0.2 0.4

Running `bundle file1 file2` yields the output

```
echo unpacking file file1
cat > file1 <<EOF
Hello, World!
No sine computations today
EOF
echo unpacking file file2
cat > file2 <<EOF
1.0 2.0 4.0
0.1 0.2 0.4
EOF
```
Running an application

Running in the foreground:

```bash
cmd="myprog -c file.1 -p -f -q";
$cmd < my_input_file

# output is directed to the file res
$cmd < my_input_file > res

# process res file by Sed, Awk, Perl or Python
```

Running in the background:

```bash
myprog -c file.1 -p -f -q < my_input_file &
```

or stop a foreground job with Ctrl-Z and then type `bg`
Output from one command can be sent as input to another command via a pipe

```
# send files with size to sort -rn
# (reverse numerical sort) to get a list
# of files sorted after their sizes:

/bin/ls -s | sort -r

cat $case.i | oscillator
# is the same as
oscillator < $case.i
```

Make a new application: sort all files in a directory tree root, with the largest files appearing first, and equip the output with paging functionality:

```
du -a root | sort -rn | less
```
Numerical expressions can be evaluated using `bc`:

```bash
echo "s(1.2)" | bc -l  # the sine of 1.2
# -l loads the math library for bc

echo "e(1.2) + c(0)" | bc -l  # exp(1.2)+cos(0)

# assignment:
s=`echo "s($r)" | bc -l`

# or using Perl:
s=`perl -e "print sin($r)"
```

Numerical expressions
## Functions

# compute $x^5 \exp(-x)$ if $x>0$, else 0 :

```bash
function calc() {
    echo "
    if ( $1 >= 0.0 ) {
        ($1)^5 \times \exp(-(\$1))
    } else {
        0.0
    }
    " | bc -l
}
```

# function arguments: $1$ $2$ $3$ and so on
# return value: last statement

# call:
r=4.2
s=`calc $r`
Another function example

```bash
#!/bin/bash

function statistics {
    avg=0; n=0
    for i in $@; do
        avg=`echo $avg + $i | bc -l`
        n=`echo $n + 1 | bc -l`
    done
    avg=`echo $avg/$n | bc -l`
    max=$1; min=$1; shift;
    for i in $@; do
        if [ `echo "$i < $min" | bc -l` != 0 ]; then
            min=$i;
        fi
        if [ `echo "$i > $max" | bc -l` != 0 ]; then
            max=$i;
        fi
    done
    printf "%.3f %g %g\n" $avg $min $max
}
```
Calling the function

statistics 1.2 6 -998.1 1 0.1

# statistics returns a list of numbers
res='statistics 1.2 6 -998.1 1 0.1'

for r in $res; do echo "result=$r"; done

echo "average, min and max = $res"
File globbing

List all .ps and .gif files using wildcard notation:

```
files=`ls *.ps *.gif`

# or safer, if you have aliased ls:
files=`/bin/ls *.ps *.gif`

# compress and move the files:
gzip $files
for file in $files; do
  mv ${file}.gz $HOME/images
```
Testing file types

```bash
if [ -f $myfile ]; then
    echo "myfile is a plain file"
fi

# or equivalently:
if test -f $myfile; then
    echo "myfile is a plain file"
fi

if [ ! -d $myfile ]; then
    echo "myfile is NOT a directory"
fi

if [ -x $myfile ]; then
    echo "myfile is executable"
fi

[ -z $myfile ] && echo "empty file $myfile"
```
Rename, copy and remove files

# rename $myfile to tmp.1:
mv $myfile tmp.1

# force renaming:
mv -f $myfile tmp.1

# move a directory tree my tree to $root:
mv mytree $root

# copy myfile to $tmpfile:
cp myfile $tmpfile

# copy a directory tree mytree recursively to $root:
cp -r mytree $root

# remove myfile and all files with suffix .ps:
rm myfile *.ps

# remove a non-empty directory tmp/mydir:
rm -r tmp/mydir
Directory management

# make directory:
$dir = "mynewdir";
mkdir $dir
mkdir -m 0755 $dir  # readable for all
mkdir -m 0700 $dir  # readable for owner only
mkdir -m 0777 $dir  # all rights for all

# move to $dir
cd $dir
# move to $HOME
cd

# create intermediate directories (the whole path):
mkdirhier $HOME/bash/prosjects/test1
# or with GNU mkdir:
mkdir -p $HOME/bash/prosjects/test1
The find command

Very useful command!

- `find` visits all files in a directory tree and can execute one or more commands for every file

- **Basic example: find the oscillator codes**
  
  \[
  \text{find } \$\text{scripting/src} \ -\text{name 'oscillator*'} \ -\text{print}
  \]

- Or find all PostScript files
  
  \[
  \text{find } \$\text{HOME} \ \left( \ -\text{name '.*.ps'} \ -o \ -\text{name '.*.eps'} \ \right) \ -\text{print}
  \]

- We can also run a command for each file:
  
  \[
  \text{find } \text{rootdir} \ -\text{name filenamespec} \ -\text{exec command } \{} \ \text{\}; \ \text{\-print}
  \]
  
  # `{}` is the current filename
Applications of find (1)

- Find all files larger than 2000 blocks a 512 bytes (=1Mb):

  ```bash
  find $HOME -name '*' -type f -size +2000 -exec ls -s {} 
  ```

- Remove all these files:

  ```bash
  find $HOME -name '*' -type f -size +2000 
  -exec ls -s {} \; -exec rm -f {} \;
  ```

  or ask the user for permission to remove:

  ```bash
  find $HOME -name '*' -type f -size +2000 
  -exec ls -s {} \; -ok rm -f {} \;
  ```
Applications of find (2)

Find all files not being accessed for the last 90 days:

```
find $HOME -name ' * ' -atime +90 -print
```

and move these to /tmp/trash:

```
find $HOME -name ' * ' -atime +90 -print \n   -exec mv -f {} /tmp/trash \;
```

Note: this one does seemingly nothing...

```
find ~hpl/projects -name ' *.tex'
```

because it lacks the `-print` option for printing the name of all *.tex files (common mistake)
Tar and gzip

- The `tar` command can pack single files or all files in a directory tree into one file, which can be unpacked later.

  ```
  tar -cvf myfiles.tar mytree file1 file2
  
  # options:
  # c: pack, v: list name of files, f: pack into file
  # unpack the mytree tree and the files file1 and file2:
  tar -xvf myfiles.tar
  
  # options:
  # x: extract (unpack)
  
  The tarfile can be compressed:
  
  gzip mytar.tar
  
  # result: mytar.tar.gz
  ```
Two find/tar/gzip examples

- Pack all PostScript figures:
  ```bash
tar -cvf ps.tar 'find $HOME -name '*.ps' -print'
gzip ps.tar
  ```

- Pack a directory but remove CVS directories and redundant files:
  ```bash
# take a copy of the original directory:
cp -r myhacks /tmp/oblig1-hpl
# remove CVS directories
find /tmp/oblig1-hpl -name CVS -print -exec rm -rf {} \;
# remove redundant files:
find /tmp/oblig1-hpl \( -name '.*~' -o -name '*.bak' -o -name '*.log' \) -print -exec rm -f {} \;
# pack files:
tar -cf oblig1-hpl.tar /tmp/tar/oblig1-hpl.tar
gzip oblig1-hpl.tar
# send oblig1-hpl.tar.gz as mail attachment
  ```
Advanced Python
Contents

- Subclassing built-in types
  (Ex: dictionary with default values, list with elements of only one type)
- Assignment vs. copy; deep vs. shallow copy
  (in-place modifications, mutable vs. immutable types)
- Iterators and generators
- Building dynamic class interfaces (at run time)
- Inspecting classes and modules (`dir`)
More info

- Ch. 8.5 in the course book
- copy module (Python Library Reference)
- Python in a Nutshell
Determining a variable’s type (1)

Different ways of testing if an object `a` is a list:

```python
if isinstance(a, list):
    ...
if type(a) == type([]):
    ...
import types
if type(a) == types.ListType:
    ...
```

- `isinstance` is the recommended standard
- `isinstance` works for subclasses:
  ```python
  isinstance(a, MyClass)
  ```
  is true if `a` is an instance of a class that is a subclass of `MyClass`
Determining a variable’s type (2)

Can test for more than one type:

```python
if isinstance(a, (list, tuple)):
    ...
```

or test if `a` belongs to a class of types:

```python
import operator
if operator.isSequenceType(a):
    ...
```

A sequence type allows indexing and for-loop iteration (e.g.: tuple, list, string, NumPy array)
Subclassing built-in types

One can easily modify the behaviour of a built-in type, like list, tuple, dictionary, NumPy array, by subclassing the type.

Old Python: UserList, UserDict, UserArray (in Numeric) are special base-classes.

Now: the types list, tuple, dict, NumArray (in numarray) can be used as base classes.

Examples:
1. dictionary with default values
2. list with items of one type
Dictionaries with default values

Goal: if a key does not exist, return a default value

```python
>>> d = defaultdict(0)
>>> d[4] = 2.2  # assign
>>> d[4]
2.2000000000000002
>>> d[6]  # non-existing key, return default
0
```

Implementation:

```python
class defaultdict(dict):
    def __init__(self, default_value):
        self.default = default_value
        dict.__init__(self)

    def __getitem__(self, key):
        return self.get(key, self.default)

    def __delitem__(self, key):
        if self.has_key(key): dict.__delitem__(self, key)
```

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List with items of one type

Goal: raise exception if a list element is not of the same type as the first element

Implementation:

class typedlist(list):
    def __init__(self, somelist=[]):
        list.__init__(self, somelist)
        for item in self:
            self._check(item)

    def _check(self, self, item):
        if len(self) > 0:
            item0class = self.__getitem__(0).__class__
            if not isinstance(item, item0class):
                raise TypeError, 'items must be %s, not %s' % (item0class.__name__, item.__class__.__name__)
Class typedlist cont.

- Need to call _check in all methods that modify the list
- What are these methods?
  ```python
  >>> dir([])  # get a list of all list object functions
  ['__add__', ..., '__iadd__', ..., '__setitem__',
   '__setslice__', ..., 'append', 'extend', 'insert', ...]
  ```
- Idea: call _check, then call similar function in base class list
Class typedlist; modification methods

def __setitem__(self, i, item):
    self._check(item); list.__setitem__(self, i, item)

def append(self, item):
    self._check(item); list.append(self, item)

def insert(self, index, item):
    self._check(item); list.insert(self, index, item)

def __add__(self, other):
    return typedlist(list.__add__(self, other))

def __iadd__(self, other):
    return typedlist(list.__iadd__(self, other))

def __setslice__(self, slice, somelist):
    for item in somelist: self._check(item)
    list.__setslice__(self, slice, somelist)

def extend(self, somelist):
    for item in somelist: self._check(item)
    list.extend(self, somelist)
Using typedlist objects

```python
>>> from typedlist import typedlist
>>> q = typedlist((1, 4, 3, 2))  # integer items
>>> q = q + [9, 2, 3]  # add more integer items
>>> q
[1, 4, 3, 2, 9, 2, 3]
>>> q += [9.9, 2, 3]  # oops, a float...
Traceback (most recent call last):
...  
TypeError: items must be int, not float

>>> class A:
    pass
>>> class B:
    pass
>>> q = typedlist()
>>> q.append(A())
>>> q.append(B())
Traceback (most recent call last):
...  
TypeError: items must be A, not B
```
Copy and assignment

- What actually happens in an assignment \( b = a \)?
- Python objects act as references, so \( b = a \) makes a reference \( b \) pointing to the same object as \( a \) refers to.
- *In-place* changes in \( a \) will be reflected in \( b \).
- What if we want \( b \) to become a copy of \( a \)?
Examples of assignment; numbers

```python
>>> a = 3  # a refers to int object with value 3
>>> b = a  # b refers to a (int object with value 3)
>>> id(a), id(b)  # print integer identifications of a and b
(135531064, 135531064)
>>> id(a) == id(b)  # same identification?
True  # a and b refer to the same object
>>> a is b  # alternative test
True
>>> a = 4  # a refers to a (new) int object
>>> id(a), id(b)  # let's check the IDs
(135532056, 135531064)
>>> a is b  # a is b
False
>>> b  # b still refers to the int object with value 3
3
```
Examples of assignment; lists

```python
>>> a = [2, 6]  # a refers to a list [2, 6]
>>> b = a  # b refers to the same list as a
True
>>> a = [1, 6, 3]  # a refers to a new list
>>> a is b  # a and b refer to the same list object
False
>>> b  # b still refers to the old list
[2, 6]

>>> a = [2, 6]
>>> b = a
>>> a[0] = 1  # make in-place changes in a
>>> a.append(3)  # another in-place change
>>> a
[1, 6, 3]
>>> b
[1, 6, 3]
>>> a is b  # a and b refer to the same list object
True
```
Examples of assignment; dicts

```python
>>> a = {'q': 6, 'error': None}
>>> b = a
>>> a['r'] = 2.5
>>> a
{'q': 6, 'r': 2.5, 'error': None}
>>> a is b
True
>>> a = 'a string'  # make a refer to a new (string) object
>>> b  # new contents in a do not affect b
{'q': 6, 'r': 2.5, 'error': None}
```
Copying objects

- What if we want \( b \) to be a copy of \( a \)?
- Lists: \( a[\ :\] \) extracts a slice, which is a *copy* of all elements:
  ```python
  >>> b = a[:]
  # b refers to a copy of elements in a
  >>> b is a
  False
  
  In-place changes in \( a \) will not affect \( b \)

- Dictionaries: use the `copy` method:
  ```python
  >>> a = {'refine': False}
  >>> b = a.copy()
  >>> b is a
  False
  
  In-place changes in \( a \) will not affect \( b \)
The copy module

The copy module allows a deep or shallow copy of an object

Deep copy: copy everything to the new object

Shallow copy: let the new (copy) object have references to attributes in the copied object

Usage:

```python
b_assign = a  # assignment (make reference)
b_shallow = copy.copy(a)  # shallow copy
b_deep = copy.deepcopy(a)  # deep copy
```
Examples on copy (1)

- Test class:
  
  ```python
class A:
    def __init__(self, value=None):
        self.x = x
    def __repr__(self):
        return 'x=%s' % self.x
  ```

- Session:
  
  ```
>>> a = A(-99) # make instance a
>>> b_assign = a # assignment
>>> b_shallow = copy.copy(a) # shallow copy
>>> b_deep = copy.deepcopy(a) # deep copy
>>> a.x = 9 # let’s change a!
>>> print 'a.x=%s, b_assign.x=%s, b_shallow.x=%s, b_deep.x=%s' %
    (a.x, b_assign.x, b_shallow.x, b_deep.x)
a.x=9, b_assign.x=9, b_shallow.x=-99, b_deep.x=-99
  ```

shallow refers the original `a.x`, deep holds a copy of `a.x`
Examples on copy (2)

Let `a` have a mutable object (list here), allowing in-place modifications

```python
>>> a = A([-2,3])
>>> b_assign = a
>>> b_shallow = copy.copy(a)
>>> b_deep = copy.deepcopy(a)
>>> a.x[0] = 8 # in-place modification
>>> print 'a.x=%s, b_assign.x=%s, b_shallow.x=%s, b_deep.x=%s' % (a.x, b_assign.x, b_shallow.x, b_deep.x)
a.x=[8,3], b_assign.x=[8,3], b_shallow.x=[8,3], b_deep.x=[-2,3]
```

shallow refers the original object and reflects in-place changes, deep holds a copy
Examples on copy (3)

Increase complexity: a holds a heterogeneous list

```python
>>> a = [4, 3, 5, ['some string', 2], A(-9)]
>>> b_assign = a
>>> b_shallow = copy.copy(a)
>>> b_deep = copy.deepcopy(a)
>>> b_slice = a[0:5]
>>> print 'b_assign=%s
b_shallow=%s
b_deep=%s
b_slice=%s' % (b_assign, b_shallow, b_deep, b_slice)
b_assign=[4, 3, 5, 999, x=-6]
b_shallow=[4, 3, 5, ['some string', 2], x=-6]
b_deep=[4, 3, 5, ['some string', 2], x=-9]
b_slice=[4, 3, 5, ['some string', 2], x=-6]
```
Generating code at run time

With `exec` and `eval` we can generate code at run time

`eval` evaluates expressions given as text:

```python
x = 3.2
e = 'x**2 + sin(x)'
v = eval(e)  # evaluate an expression
v = x**2 + sin(x)  # equivalent to the previous line
```

`exec` executes arbitrary text as Python code:

```python
s = 'v = x**2 + sin(x)'  # complete statement stored in a string
exec s  # run code in s
```

`eval` and `exec` are recommended to be run in user-controlled namespaces
Fancy application

Consider an input file with this format:

```plaintext
set heat conduction = 5.0
set dt = 0.1
set rootfinder = bisection
set source = V*exp(-q*t) is function of (t) with V=0.1, q=1
set bc = sin(x)*sin(y)*exp(-0.1*t) is function of (x,y,t)
```
(last two lines specifies a StringFunction object)

Goal: convert this text to Python data for further processing

```python
heat_conduction, dt : float variables
rootfinder : string
source, bc : StringFunction instances
```

Means: regular expressions, string operations, StringFunction, exec, eval
# target line:
# set some name of variable = some value
from scitools import misc
def parse_file(somefile):
    namespace = {}  # holds all new created variables
    line_re = re.compile(r"set (. *)=(.*)$")
    for line in somefile:
        m = line_re.search(line)
        if m:
            variable = m.group(1).strip()
            value = m.group(2).strip()
            # test if value is a StringFunction specification:
            if value.find('is function of') >= 0:
                # interpret function specification:
                value = eval(string_function_parser(value))
            else:
                value = misc.str2obj(value)  # string -> object
                # space in variables names is illegal
                variable = variable.replace(' ', '_')
            code = 'namespace["%s"] = value' % variable
            exec code
    return namespace
Implementation (2)

# target line (with parameters A and q):
# expression is a function of (x,y) with A=1, q=2
# or (no parameters)
# expression is a function of (t)

def string_function_parser(text):
    m = re.search(r'(. * ) is function of \((. * )\)( with .+)?', text)
    if m:
        expr = m.group(1).strip();
        args = m.group(2).strip()
        # the 3rd group is optional:
        prms = m.group(3)
        if prms is None: # the 3rd group is optional
            prms = '' # works fine below
        else:
            prms = ' '.join(prms.split()[1:]) # strip off 'with'
        # quote arguments:
        args = ', '.join(['%s' % v for v in args.split(',')])
        if args.find(',') < 0: # single argument?
            args = args + ', '
        args = '(%s)' % args # tuple needs parenthesis
        s = "StringFunction('%s', independent_variables=%s, %s)" % 
        (expr, args, prms)
        return s
Testing the general solution

```python
>>> import somemod
>>> newvars = somemod.parse_file(testfile)
>>> globals().update(newvars)  # let new variables become global
>>> heat_conduction, type(heat_conduction)
(5.0, <type 'float'>)
>>> dt, type(dt)
(0.10000000000000001, <type 'float'>)
>>> rootfinder, type(rootfinder)
('bisection', <type 'str'>)
>>> source, type(source)
(StringFunction('V*exp(-q*t)', independent_variables=('t',),
  q=1, V=0.10000000000000001), <type 'instance'>)
>>> bc, type(bc)
(StringFunction('sin(x)*sin(y)*exp(-0.1*t)',
  independent_variables=('x', 'y', 't'), ), <type 'instance'>)
>>> source(1.22)
0.029523016692401424
>>> bc(3.14159, 0.1, 0.001)
2.64890450854893e-07
```
Iterators

- Typical Python for loop,
  
  ```python
  for item in some_sequence:
    # process item
  ```

  allows *iterating* over any object `some_sequence` that supports such iterations

- Most built-in types offer iterators

- User-defined classes can also implement iterators
Iterating with built-in types

for element in some_list:
for element in some_tuple:
for s in some_NumPy_array:  # iterates over first index
for key in some_dictionary:
for line in file_object:
for character in some_string:
Iterating with user-defined types

- Implement `__iter__`, returning an iterator object (can be `self`) containing a `next` function.
- Implement `next` for returning the next element in the iteration sequence, or raise `StopIteration` if beyond the last element.
Example using iterator object

class MySeq:
    def __init__(self, *data):
        self.data = data

    def __iter__(self):
        return MySeqIterator(self.data)

    # iterator object:
class MySeqIterator:
    def __init__(self, data):
        self.index = 0
        self.data = data

    def next(self):
        if self.index < len(self.data):
            item = self.data[self.index]
            self.index += 1  # ready for next call
            return item
        else:  # out of bounds
            raise StopIteration
Example without separate iterator object

class MySeq2:  
    def __init__(self, *data):
        self.data = data

    def __iter__(self):
        self.index = 0
        return self

    def next(self):
        if self.index < len(self.data):
            item = self.data[self.index]
            self.index += 1  # ready for next call
            return item
        else:  # out of bounds
            raise StopIteration
Example on application

Use iterator:

```python
>>> obj = MySeq(1, 9, 3, 4)
>>> for item in obj:
    print item,
1 9 3 4
```

Write out as complete code:

```python
obj = MySeq(1, 9, 3, 4)
iterator = iter(obj)  # iter(obj) means obj.__iter__()
while True:
    try:
        item = iterator.next()
    except StopIteration:
        break
    # process item:
    print item
```
Remark

Could omit the iterator in this sample class and just write

```python
for item in obj.data:
    print item
```

since the `self.data` list already has an iterator...
A more comprehensive example

Consider class `Grid2D` for uniform, rectangular 2D grids:

```python
class Grid2D:
    def __init__(self, 
        xmin=0, xmax=1, dx=0.5, 
        ymin=0, ymax=1, dy=0.5):
        self.xcoor = sequence(xmin, xmax, dx, Float)
        self.ycoor = sequence(ymin, ymax, dy, Float)

        # make two-dim. versions of these arrays:
        # (needed for vectorization in __call__)
        self.xcoorv = self.xcoor[:,NewAxis]
        self.ycoorv = self.ycoor[NewAxis,:]
```

Make iterators for internal points, boundary points, and corner points (useful for finite difference methods on such grids)
A uniform rectangular 2D grid
# this is what we would like to do:

for i, j in grid.interior():
    <process interior point with index (i,j)>

for i, j in grid.boundary():
    <process boundary point with index (i,j)>

for i, j in grid.corners():
    <process corner point with index (i,j)>

for i, j in grid.all():  # visit all points
    <process grid point with index (i,j)>
Implementation overview

- Derive a subclass `Grid2Dit` equipped with iterators
- Let `Grid2Dit` be its own iterator (for convenience)
- `interior`, `boundary`, `corners` must set an indicator for the type of desired iteration
- `__iter__` initializes the two iteration indices `(i,j)` and returns `self`
- `next` must check the iteration type (interior, boundary, corners) and call an appropriate method
- `_next_interior`, `_next_boundary`, `_next_corners`, `find` next `(i,j)` index pairs or raise `StopIteration`
- We also add a possibility to iterate over all points (easy)
Implementation; interior points

# iterator domains:
INTERIOR=0; BOUNDARY=1; CORNERS=2; ALL=3

class Grid2DIter(Grid2D):
    def interior(self):
        self._iterator_domain = INTERIOR
        return self

    def __iter__(self):
        if self._iterator_domain == INTERIOR:
            self._i = 1; self._j = 1
        return self

    def _next_interior(self):
        if self._i >= len(self.xcoor)-1:
            self._i = 1; self._j += 1 # start on a new row
        if self._j >= len(self.ycoor)-1:
            raise StopIteration # end of last row
        item = (self._i, self._j)
        self._i += 1 # walk along rows...
        return item

    def next(self):
        if self._iterator_domain == INTERIOR:
            return self._next_interior()
Application; interior points

>>> # make a grid with 3x3 points:
>>> g = Grid2D(dx=1.0, dy=1.0, xmin=0, xmax=2.0, ymin=0, ymax=2.0)
>>> for i, j in g.interior():
...     print g.xcoor[i], g.ycoor[j]
1.0 1.0

Correct (only one interior point!)
Implementation; boundary points (1)

# boundary parts:
RIGHT=0; UPPER=1; LEFT=2; LOWER=3

class Grid2Dit(Grid2D):
    def boundary(self):
        self._iterator_domain = BOUNDARY
        return self

    def __iter__(self):
        if self._iterator_domain == BOUNDARY:
            self._i = len(self.xcoor)-1; self._j = 1
            self._boundary_part = RIGHT
            return self

    def next(self):
        if self._iterator_domain == BOUNDARY:
            return self._next_boundary()
```python
def _next_boundary(self):
    """Return the next boundary point."""
    if self._boundary_part == RIGHT:
        if self._j < len(self.ycoor)-1:
            item = (self._i, self._j)
            self._j += 1  # move upwards
        else:  # switch to next boundary part:
            self._boundary_part = UPPER
            self._i = 1;  self._j = len(self.ycoor)-1
    if self._boundary_part == UPPER:
        ...
    if self._boundary_part == LEFT:
        ...
    if self._boundary_part == LOWER:
        if self._i < len(self.xcoor)-1:
            item = (self._i, self._j)
            self._i += 1  # move to the right
        else:  # end of (interior) boundary points:
            raise StopIteration
    if self._boundary_part == LOWER:
        ...
    return item
```

Application; boundary points

```python
>>> g = Grid2Dit(dx=1.0, dy=1.0, xmax=2.0, ymax=2.0)
>>> for i, j in g.boundary():
    print g.xcoor[i], g.ycoor[j]
2.0 1.0
1.0 2.0
0.0 1.0
1.0 0.0
```

(i.e., one boundary point at the middle of each side)
A vectorized grid iterator

- The one-point-at-a-time iterator shown is slow for large grids
- A faster alternative is to generate index slices (ready for use in arrays)

```python
grid = Grid2Ditv(dx=1.0, dy=1.0, xmax=2.0, ymax=2.0)
grid = Grid2Ditv(dx=1.0, dy=1.0, xmax=2.0, ymax=2.0)
for imin, imax, jmin, jmax in grid.interior():
    # yields slice (1:2,1:2)
for imin, imax, jmin, jmax in grid.boundary():
    # yields slices (2:3,1:2) (1:2,2:3) (0:1,1:2) (1:2,0:1)
for imin, imax, jmin, jmax in grid.corners():
    # yields slices (0:1,0:1) (2:3,0:1) (2:3,2:3) (0:1,2:3)
```
2D diffusion equation (finite difference method):

for imin,imax, jmin, jmax in grid.interior():
    u[imin:imax, jmin:jmax] = \
        u[imin:imax, jmin:jmax] + h* ( \
            u[imin+1:imax+1, jmin+1:jmax+1] - 2*u[imin+1:imax+1, jmin+1:jmax+1] + \
            u[imin-1:imax-1, jmin-1:jmax-1] - 2*u[imin-1:imax-1, jmin-1:jmax-1] + \
            u[imin+1:imax+1, jmin+1:jmax+1] - 2*u[imin+1:imax+1, jmin+1:jmax+1] + \
            u[imin+1:imax+1, jmin:jmax])

for imin,imax, jmin, jmax in grid.boundary():
    u[imin:imax, jmin:jmax] = \
        u[imin:imax, jmin:jmax] + h* ( \
            u[imin+1:imax+1, jmin:jmax])
class Grid2DItv(Grid2DIt):
    """Vectorized version of Grid2DIt."""
    def __iter__(self):
        nx = len(self.xcoor) - 1; ny = len(self.ycoor) - 1
        if self._iterator_domain == INTERIOR:
            self._indices = [(1, nx, 1, ny)]
        elif self._iterator_domain == BOUNDARY:
            self._indices = [(nx, nx+1, 1, ny),
                             (1, nx, ny, ny+1),
                             (0, 1, 1, ny),
                             (1, nx, 0, 1)]
        elif self._iterator_domain == CORNERS:
            self._indices = [(0, 1, 0, 1),
                             (nx, nx+1, 0, 1),
                             (nx, nx+1, ny, ny+1),
                             (0, 1, ny, ny+1)]
        elif self._iterator_domain == ALL:
            self._indices = [(0, nx+1, 0, ny+1)]
        self._indices_index = 0
        return self
class Grid2Ditv(Grid2DIt):
    ...
    def next(self):
        if self._indices_index <= len(self._indices)-1:
            item = self._indices[self._indices_index]
            self._indices_index += 1
            return item
        else:
            raise StopIteration
Generators

Generators enable writing iterators in terms of a single function (no \_\_iter\_\_ and next methods)

for item in some_func(some_arg1, some_arg2):
    # process item

The generator implements a loop and jumps for each element back to the calling code with a return-like yield statement

class MySeq3:
    def \_\_init\_\_(self, *data):
        self.data = data

    def items(obj):
        # generator
        for item in obj.data:
            yield item

    for item in items(obj):
        print item

# use generator
Generator-list relation

- A generator can also be implemented as a standard function returning a list

  Generator:
  ```python
def mygenerator(...):
    ...
    for i in some_object:
      yield i
  ```

- Implemented as standard function returning a list:

  ```python
def mygenerator(...):
    ...
    return [i for i in some_object]
  ```

- The usage is the same:

  ```python
  for i in mygenerator(...):
    # process i
  ```
Generators as short cut for iterators

- Consider our `MySeq` and `MySeq2` classes with iterators
- With a generator we can implement exactly the same functionality very compactly:

```python
class MySeq4:
    def __init__(self, *data):
        self.data = data

    def __iter__(self):
        for item in self.data:
            yield item

obj = MySeq4(1,2,3,4,6,1)
for item in obj:
    print item
```

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Exercise

Implement a sparse vector (most elements are zeros and not stored; use a dictionary for storage with integer keys (element no.))

Functionality:

```python
>>> a = SparseVec(4)
>>> a[2] = 9.2
>>> a[0] = -1
>>> print a
>>> print a.nonzeros()
{0: -1, 2: 9.2}
```
Exercise cont.

```python
>>> b = SparseVec(5)
>>> b[1] = 1
>>> print b
>>> print b.nonzeros()
{1: 1}
>>> c = a + b
>>> print c
>>> print c.nonzeros()
{0: -1, 1: 1, 2: 9.2}
>>> for ai, i in a: # SparseVec iterator
    print 'a[%d]=%g' % (i, ai),
```
Inspecting class interfaces

What type of attributes and methods are available in this object $s$?

Use `dir(s)`!

```python
>>> dir(()), # what's in a tuple?
['__add__', '__class__', '__contains__', ...
 '__repr__', '__rmul__', '__setattr__', '__str__']
>>> # try some user-defined object:
>>> class A:
...     def __init__(self):
...         self.a = 1
...         self.b = 'some string'
...     def method1(self, c):
...         self.c = c

>>> a = A()
>>> dir(a)
['__doc__', '__init__', '__module__', 'a', 'b', 'method1']
```
Dynamic class interfaces

- Dynamic languages (like Python) allows adding attributes to instances at run time
- Advantage: can tailor interfaces according to input data
- Simplest use: mimic C structs by classes

```python
>>> class G: pass  # completely empty class
>>> g = G()  # instance with no data (almost)
>>> dir(g)
['__doc__', '__module__']  # no user-defined attributes

>>> # add instance attributes:
>>> g.xmin=0; g.xmax=4; g.ymin=0; g.ymax=1
>>> g.xmax
4
```
Generating properties

Adding a property to some class A:

```
A.x = property(fget=lambda self: self._x)  # grab A’s _x attribute
```

(“self” is supplied as first parameter)

Example: a 1D/2D/3D point class, implemented as a NumPy array (with all built-in stuff), but with attributes (properties) x, y, z for convenient extraction of coordinates

```
>>> p1 = Point((0,1)); p2 = Point((1,2))
>>> p3 = p1 + p2
>>> p3
[ 1.  3.]
>>> p3.x, p3.y
(1.0, 3.0)
>>> p3.z  # should raise an exception
Traceback (most recent call last):
  ... AttributeError: 'NumArray' object has no attribute 'z'
```
Implementation

Must use numarray or numpy version of NumPy (where the array is an instance of a class such that we can add new class attributes):

class Point(object):
    """Extend NumPy array objects with properties."
    def __new__(self, point):
        # __new__ is a constructor in new-style classes,
        # but can return an object of any type (!)
        a = array(point, Float)

        # define read-only attributes x, y, and z:
        if len(point) >= 1:
            NumArray.x = property(fget=lambda o: o[0])
            # or a.__class__.x = property(fget=lambda o: o[0])
        if len(point) >= 2:
            NumArray.y = property(fget=lambda o: o[1])
        if len(point) == 3:
            NumArray.z = property(fget=lambda o: o[2])
        return a
Note

Making a Point instance actually makes a NumArray instance with extra data.

In addition it has read-only attributes x, y and z, depending on the no of dimensions in the initialization.

```python
>>> p = Point((1.1,))  # 1D point
>>> p.x
1.1
>>> p.y
Traceback (most recent call last):
... AttributeError: 'NumArray' object has no attribute 'y'
```

Can be done in C++ with advanced template meta programming.
Automatic generation of properties

Suppose we have a set of non-public attributes for which we would like to generate read-only properties.

Three lines of code are enough:

```python
for v in variables:
    exec('%s.%s = property(fget=lambda self: self._%s' % 
        (self.__class__.__name__, v, v))
```

Application: list the variable names as strings and collect in list/tuple:

```python
variables = ('counter', 'nx', 'x', 'help', 'coor')
```

This gives read-only property `self.counter` returning the value of non-public attribute `self._counter` (initialized elsewhere), etc.
Adding a new method on the fly: setattr

That a class should have a method `hw`!

Add it on the fly, if you need it:

```python
>>> class A:
    pass

>>> def hw(self, r, file=sys.stdout):
    file.write('Hi! sin(%g)=%g')

>>> def func_to_method(func, class_, method_name=None):
    setattr(class_, method_name or func.__name__, func)

>>> func_to_method(hw, A)  # add hw as method in class A
>>> a = A()
>>> dir(a)
['__doc__', '__module__', 'hw']
>>> a.hw(1.2)
'Hi! sin(1.2)=0.932039'
```
Adding a new method: subclassing

- We can also subclass to add a new method:
  ```python
class B(A):
    def hw(self, r, file=sys.stdout):
        file.write('Hi! sin(%g)=%g' % (r, math.sin(r)))
  ```

- Sometimes you want to extend a class with methods without changing the class name:
  ```python
  from A import A as A_old  # import class A from module file A.py
  class A(A_old):
    def hw(self, r, file=sys.stdout):
        file.write('Hi! sin(%g)=%g' % (r, math.sin(r)))
  ```

- The new `A` class is now a subclass of the old `A` class, but for users it looks like the original class was extended.

- With this technique you can extend libraries without touching the original source code and without introducing new subclass names.
Adding another class’ method as new method (1)

Suppose we have a module file `A.py` with

```python
class A:
    def __init__(self):
        self.v = 'a'
    def func1(self, x):
        print '%s.%s, self.v=%s' % (self.__class__.__name__, self.func1.__name__, self.v)
```

Can we “steal” `A.func1` and attach it as method in another class? Yes, but this new method will not accept instances of the new class as `self` (see next example)
Adding another class’ method as new method (2)

```python
>>> class B:
...     def __init__(self):
...         self.v = 'b'
...     def func2(self, x):
...         print '%s.%s, self.v=%s' % (self.__class__.__name__, self.func2.__name__, self.v)
...>>> import A>>> a = A.A()>>> b = B()>>> print dir(b)['__doc__', '__init__', '__module__', 'func2', 'v']>>> b.func2(3) # does the created b get a new func1?
B.func2, self.v=b
>>> setattr(B, 'func1', a.func1)
>>> print dir(b) # does the created b get a new func1?
['__doc__', '__init__', '__module__', 'func1', 'func2', 'v']
>>> b.func1(3)
A.func1, self.v=a # note: self is a!
```
Adding another class’ method as new method (3)

```python
>>> def func3(self, x):  # stand-alone function
...     print '%s.%s, self.v=%s' % (self.__class__.__name__,
...                               self.func3.__name__, self.v)
...     print dir(B)

>>> setattr(B, 'func3', func3)
>>> b.func3(3)  # function -> method
B.func3, self.v=b
>>> setattr(B, 'func1', A.A.func1)  # unbound method
>>> print dir(B)
['__doc__', '__init__', '__module__', 'func1', 'func2', 'func3']

>>> b.func1(3)
Traceback (most recent call last):
  File "<input>", line 1, in ?
    TypeError: unbound method func1() must be called with A instance as first argument (got int instance instead)

>>> B.func1(a,3)
A.func1, self.v=a
>>> B.func1(b,3)
Traceback (most recent call last):
  File "<input>", line 1, in ?
    TypeError: unbound method func1() must be called with A instance as first argument (got B instance instead)
```
Python review
Python info

- `doc.html` is the resource portal for the course; load it into a web browser from
  
  http://www.ifi.uio.no/~inf3330/scripting/doc.html

  and make a bookmark

- `doc.html` has links to the electronic Python documentation, F2PY, SWIG, Numeric/numarray, and lots of things used in the course

- The course book “Python scripting for computational science” (the PDF version is fine for searching)

- Python in a Nutshell (by Martelli)

- Programming Python 2nd ed. (by Lutz)

- Python Essential Reference (Beazley)

- Quick Python Book
Electronic Python documentation

- Python Tutorial
- Python Library Reference (start with the index!)
- Python Reference Manual (less used)
- Extending and Embedding the Python Interpreter
- Quick references from `doc.html`
- `pydoc anymodule`, `pydoc anymodule.anyfunc`
Python variables

- Variables are not declared
- Variables hold references to objects of any type

```python
a = 3      # reference to an int object containing 3
a = 3.0    # reference to a float object containing 3.0
a = '3.'   # reference to a string object containing '3.'
a = ['1', 2]  # reference to a list object containing
              # a string '1' and an integer 2
```

- Test for a variable’s type:

```python
if isinstance(a, int):   # int?
if isinstance(a, (list, tuple)): # list or tuple?
```
Common types

- **Numbers**: `int`, `float`, `complex`
- **Sequences**: `str` (string), `list`, `tuple`, `NumPy array`
- **Mappings**: `dict` (dictionary/hash)
- **User-defined type in terms of a class**
Numbers

- Integer, floating-point number, complex number

```python
a = 3  # int
a = 3.0  # float
a = 3 + 0.1j  # complex (3, 0.1)
```
List and tuple

- **List:**
  
  ```python
  a = [1, 3, 5, [9.0, 0]]  # list of 3 ints and a list
  a[2] = 'some string'
  a[3][0] = 0              # a is now [1,3,5,[0,0]]
  b = a[0]                 # b refers first element in a
  ```

- **Tuple ("constant list"):**
  
  ```python
  a = (1, 3, 5, [9.0, 0])  # tuple of 3 ints and a list
  a[3] = 5               # illegal! (tuples are const/final)
  ```

- **Traversing list/tuple:**
  
  ```python
  for item in a:          # traverse list/tuple a
    # item becomes, 1, 3, 5, and [9.0,0]
  ```
Dictionary

Making a dictionary:

```python
a = {'key1': 'some value', 'key2': 4.1}
a['key1'] = 'another string value'
a['key2'] = [0, 1]  # change value from float to string
a['another key'] = 1.1E+7  # add a new (key,value) pair
```

Important: no natural sequence of (key,value) pairs!

Traversing dictionaries:

```python
for key in some_dict:
    # process key and corresponding value in some_dict[key]
```
Strings

Strings apply different types of quotes

s = 'single quotes'
s = "double quotes"
s = """triple quotes are used for multi-line strings"""
s = r'raw strings start with r and backslash \ is preserved'
s = '\t\n' # tab + newline
s = r'\t\n' # a string with four characters: \t\n
Some useful operations:

if sys.platform.startswith('win'): # Windows machine?
    ...
    file = infile[:-3] + '.gif' # string slice of infile
    answer = answer.lower() # lower case
    answer = answer.replace(' ', '_')
    words = line.split()
NumPy arrays

Efficient arrays for numerical computing

from Numeric import *  # classical, widely used module
from numarray import *  # alternative version

a = array([[1, 4], [2, 1]], Float)  # 2x2 array from list
a = zeros((n,n), Float)  # nxn array with 0

Indexing and slicing:

for i in xrange(a.shape[0]):
    for j in xrange(a.shape[1]):
        a[i,j] = ...

b = a[0,:]  # reference to 1st row
b = a[:,1]  # reference to 2nd column

Avoid loops and indexing, use operations that compute with whole
arrays at once (in efficient C code)
Mutable and immutable types

Mutable types allow in-place modifications

```python
>>> a = [1, 9, 3.2, 0]
>>> a[2] = 0
>>> a
[1, 9, 0, 0]
```

Types: list, dictionary, NumPy arrays, class instances

Immutable types do not allow in-place modifications

```python
>>> s = 'some string containing x'
>>> s[-1] = 'y'  # try to change last character - illegal!
TypeError: object doesn't support item assignment
>>> a = 5
>>> b = a  # b is a reference to a (integer 5)
>>> a = 9  # a becomes a new reference
>>> b  # b still refers to the integer 5
5
```

Types: numbers, strings
Operating system interface

- Run arbitrary operating system command:
  
  ```python
  cmd = 'myprog -f -g 1.0 < input'
  failure, output = commands.getstatusoutput(cmd)
  ```

- Use `commands.getstatusoutput` for running applications

- Use Python (cross platform) functions for listing files, creating directories, traversing file trees, etc.

  ```python
  psfiles = glob.glob('*.ps') + glob.glob('*.eps')
  allfiles = os.listdir(os.curdir)
  os.mkdir('tmpl'); os.chdir('tmpl')
  print os.getcwd()  # current working dir.

  def size(arg, dir, files):
      for file in files:
          fullpath = os.path.join(dir, file)
          s = os.path.getsize(fullpath)
          arg.append((fullpath, s))  # save name and size

  name_and_size = []
  os.path.walk(os.curdir, size, name_and_size)
  ```
Files

Open and read:

```python
f = open(filename, 'r')
filestr = f.read()  # reads the whole file into a string
lines = f.readlines() # reads the whole file into a list of lines

for line in f:       # read line by line
    <process line>

while True:          # old style, more flexible reading
    line = f.readline()
    if not line: break
    <process line>

f.close()
```

Open and write:

```python
f = open(filename, 'w')
f.write(somestring)
f.writelines(list_of_lines)
print >> f, somestring
```
**Functions**

- Two types of arguments: positional and keyword
  
  ```python
def myfync(pos1, pos2, pos3, kw1=v1, kw2=v2):
    ...
  ```

  3 positional arguments, 2 keyword arguments
  (keyword=default-value)

- Input data are arguments, output variables are returned as a tuple
  
  ```python
def somefunc(i1, i2, i3, io1):
    """i1,i2,i3: input, io1: input and output""
    ...
    o1 = ...; o2 = ...; o3 = ...; io1 = ...
    ...
    return o1, o2, o3, io1
  ```
Example: a grep script (1)

Find a string in a series of files:

grep.py 'Python' *.txt *.tmp

Python code:

```python
def grep_file(string, filename):
    res = {}  # result: dict with key=line no. and value=line
    f = open(filename, 'r')
    line_no = 1
    for line in f:
        #if line.find(string) != -1:
        if re.search(string, line):
            res[line_no] = line
            line_no += 1
```

Example: a grep script (2)

- Let us put the previous function in a file `grep.py`
- This file defines a module `grep` that we can import
- Main program:

```python
import sys, re, glob, grep

grep_res = {}
string = sys.argv[1]
for filespec in sys.argv[2:]:
    for filename in glob.glob(filespec):
        grep_res[filename] = grep.grep(string, filename)

# report:
for filename in grep_res:
    for line_no in grep_res[filename]:
        print '%-20s.%5d: %s' % (filename, line_no, grep_res[filename][line_no])
```

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Interactive Python

- **Just write python in a terminal window to get an interactive Python shell:**

  >>> 1269*1.24
  1573.5599999999999
  >>> import os; os.getcwd()
  '/home/hpl/work/scripting/trunk/lectures'
  >>> len(os.listdir('modules'))
  60

- **We recommend to use IPython as interactive shell**

  Unix/DOS> ipython
  In [1]: 1+1
  Out[1]: 2
IPython and the Python debugger

Scripts can be run from IPython:

In [1]: run scriptfile arg1 arg2 ...

  e.g.,
  In [1]: run datatrans2.py .datatrans_infile tmp1

IPython is integrated with Python’s `pdb` debugger

`pdb` can be automatically invoked when an exception occurs:

  In [29]: %pdb on  # invoke pdb automatically
  In [30]: run datatrans2.py infile tmp2
More on debugging

This happens when the infile name is wrong:

```
/home/work/scripting/src/py/intro/datatrans2.py
  7     print "Usage:" , sys.argv[0] , "infile outfile" ; sys.exit (1)
  8
----> 9     ifile = open(infilename, 'r')    # open file for reading
 10     lines = ifile.readlines()            # read file into list of lines
 11     ifile.close()

IOError: [Errno 2] No such file or directory: 'infile'
> /home/work/scripting/src/py/intro/datatrans2.py(9)?()
-> ifile = open(infilename, 'r')    # open file for reading
(Pdb) print infilename
infile
```
Software engineering
Version control systems

Why?

- Can retrieve old versions of files
- Can print history of incremental changes
- Very useful for programming or writing teams
- Contains an official repository
- Programmers work on copies of repository files
- Conflicting modifications by different team members are detected
- Can serve as a backup tool as well
- So simple to use that there are no arguments against using version control systems!
Some svn commands

- svn: a modern version control system, with commands much like the older widespread CVS tool
- Or the course book for a quick introduction
- `svn import/checkout`: start with CVS
- `svn add`: register a new file
- `svn commit`: check files into the repository
- `svn remove`: remove a file
- `svn move`: move/rename a file
- `svn update`: update file tree from repository
- See also `svn help`
Contents

- How to verify that scripts work as expected
- Regression tests
- Regression tests with numerical data
- doctest module for doc strings with tests/examples
- Unit tests
More info

- Appendix B.4 in the course book
- `doctest`, `unittest` module documentation
Verifying scripts

How can you know that a script works?

- Create some tests, save (what you think are) the correct results
- Run the tests frequently, compare new results with the old ones
- Evaluate discrepancies
- If new and old results are equal, one believes that the script still works
- This approach is called regression testing
The limitation of tests

Program testing can be a very effective way to show the presence of bugs, but is hopelessly inadequate for showing their absence. -Dijkstra, 1972
Three different types of tests

- Regression testing:
  test a complete application ("problem solving")

- Tests embedded in source code (doc string tests):
  test user functionality of a function, class or module
  (Python grabs out interactive tests from doc strings)

- Unit testing:
  test a single method/function or small pieces of code
  (emphasized in Java and extreme programming (XP))

Info: App. B.4 in the course book
doctest and unittest module documentation (Py Lib.Ref.)
Regression testing

- Create a number of tests
- Each test is run as a script
- Each such script writes some key results to a file
- This file must be compared with a previously generated ‘exact’ version of the file
A suggested set-up

- Say the name of a script is `myscript`
- Say the name of a test for `myscript` is `test1`
- `test1.verify`: script for testing
- `test1.verify` runs `myscript` and directs/copies important results to `test1.v`
- Reference (‘exact’) output is in `test1.r`
- Compare `test1.v` with `test1.r`
- The first time `test1.verify` is run, copy `test1.v` to `test1.r` (if the results seem to be correct)
Recursive run of all tests

- Regression test scripts \(*.verify\) are distributed around in a directory tree
- Go through all files in the directory tree
- If a file has suffix \(.*verify\), say \(test.verify\), execute \(test.verify\)
- Compare \(test.v\) with \(test.r\) and report differences
File comparison

How can we determine if two (text) files are equal?

\texttt{some\_diff\_program test1.v test1.r > test1.diff}

Unix \texttt{diff}:
output is not very easy to read/interpret,
tied to Unix

Perl script \texttt{diff.pl}:
easy readable output, but very slow for large files

Tcl/Tk script \texttt{tkdiff.tcl}:
very readable graphical output

gvimdiff (part of the Vim editor):
highlights differences in parts of long lines

Other tools: emacs \texttt{ediff}, \texttt{diff.py}, \texttt{windiff} (Windows only)
tkdiff.tcl hw-GUI2.py hw-GUI3.py
**Example**

- We want to write a regression test for src/ex/circle.py (solves equations for circular movement of a body)

\[
\text{python circle.py 5 0.1}
\]

# 5: no of circular rotations  
# 0.1: time step used in numerical method

- Output from circle.py:

\[
\begin{align*}
\text{xmin} & \quad \text{xmax} & \quad \text{ymin} & \quad \text{ymax} \\
x1 & \quad y1 \\
x2 & \quad y2 \\
\ldots \\
\text{end}
\end{align*}
\]

\[
\text{xmin, xmax, ymin, ymax: bounding box for all the } x1, y1, x2, y2 \text{ etc. coordinates}
\]
Establishing correct results

- When is the output correct? (for later use as reference)
- Exact result from `circle.py, x1, y1, x2, y2` etc., are points on a circle
- Numerical approximation errors imply that the points deviate from a circle
- One can get a visual impression of the accuracy of the results from

  ```
  python circle.py 3 0.21 | plotpairs.py
  ```

Try different time step values!
Plot of approximate circle
Regression test set-up

- Test script: circle.verify
- Simplest version of circle.verify (Bourne shell):

```
#!/bin/sh
./circle.py 3 0.21 > circle.v
```

- Could of course write it in Python as well:

```
#!/usr/bin/env python
import os
os.system("./circle.py 3 0.21 > circle.v")
# or completely cross platform:
os.system(os.path.join(os.curdir,"circle.py") + \
    " 3 0.21 > circle.v")
```
The .v file with key results

How does `circle.v` look like?

```
-1.8  1.8  -1.8  1.8
 1.0  1.31946891451
-0.278015372225  1.64760748997
-0.913674369652  0.491348066081
 0.048177073882  -0.411890560708
 1.16224152523  0.295116238827
end
```

If we believe `circle.py` is working correctly, `circle.v` is copied to `circle.r`

`circle.r` now contains the reference (‘exact’) results
Executing the test

- Manual execution of the regression test:
  
  ```bash
  ./circle.verify
diff.py circle.v circle.r > circle.log
  ```

- View `circle.log`; if it is empty, the test is ok; if it is non-empty, one must judge the quality of the new results in `circle.v` versus the old ('exact') results in `circle.r`
Automating regression tests

- We have made a Python module Regression for automating regression testing.
- `scitools regression` is a script, using the Regression module, for executing all `*.verify` test scripts in a directory tree, run a diff on `*.v` and `*.r` files and report differences in HTML files.
- Example:
  
  `scitools regression verify .`

  runs all regression tests in the current working directory and all subdirectories.
Presentation of results of tests

- Output from the scitools regression command are two files:
  - verify_log.htm: overview of tests and no of differing lines between .r and .v files
  - verify_log_details.htm: detailed diff

- If all results (verify_log.htm) are ok, update latest results (*.v) to reference status (*.r) in a directory tree:
  scitools regression update .

- The update is important if just changes in the output format have been performed (this may cause large, insignificant differences!)
Running a single test

One can also run `scitools regression` on a single test (instead of traversing a directory tree):

```
scitools regression verify circle.verify
scitools regression update circle.verify
```
Tools for writing test files

Our Regression module also has a class TestRun for simplifying the writing of robust *.verify scripts

Example: mytest.verify

```python
import Regression
test = Regression.TestRun("mytest.v")
# mytest.v is the output file

# run script to be tested (myscript.py):
test.run("myscript.py", options="-g -p 1.0")
# runs myscript.py -g -p 1.0

# append file data.res to mytest.v
test.append("data.res")
```

Many different options are implemented, see the book
Numerical round-off errors

Consider `circle.py`, what about numerical round-off errors when the regression test is run on different hardware?

-0.16275412    # Linux PC
-0.16275414    # Sun machine

The difference is not significant wrt testing whether `circle.py` works correctly.

Can easily get a difference between each output line in `circle.v` and `circle.r`.

How can we judge if `circle.py` is really working?

Answer: try to ignore round-off errors when comparing `circle.v` and `circle.r`.
Tools for numeric data

- **Class** `TestRunNumerics` in the Regression module extends class `TestRun` with functionality for ignoring round-off errors
- **Idea:** write real numbers with (say) five significant digits only
- `TestRunNumerics` modifies all real numbers in `*.v`, after the file is generated
- **Problem:** small bugs can arise and remain undetected
- **Remedy:** create another file `*.vd` (and `*.rd`) with a few selected data (floating-point numbers) written with all significant digits
Example on a .vd file

The *.vd file has a compact format:

```
## field 1
number of floats
float1
float2
float3
...
## field 2
number of floats
float1
float2
float3
...
## field 3
...
```
A test with numeric data

- Example file: src/ex/circle2.verify (and circle2.r, circle2.rd)

- We have made a tool that can visually compare *.vd and *.rd in the form of two curves
  
  scitools regression verify circle2.verify
  scitools floatdiff circle2.vd circle2.rd

  # usually no diff in the above test, but we can fake
  # a diff for illustrating scitools floatdiff:
  perl -pi.old~ -e 's/\d$/0;/' circle2.vd
  scitools floatdiff circle2.vd circle2.rd

- Random curve deviation imply round-off errors only

- Trends in curve deviation may be caused by bugs
The floatdiff GUI

scitools floatdiff circle2.vd circle2.rd

<table>
<thead>
<tr>
<th>List of fields</th>
<th>Intelligent float diff between circle2.vd and circle2.rd</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>## exact data</strong></td>
<td><strong>line: circle2.vd</strong></td>
</tr>
<tr>
<td>1</td>
<td>1.31946091450</td>
</tr>
<tr>
<td>2</td>
<td>-0.278015372222</td>
</tr>
<tr>
<td>3</td>
<td>1.64760748997</td>
</tr>
<tr>
<td>4</td>
<td>-0.913674369650</td>
</tr>
<tr>
<td>5</td>
<td>0.491348066080</td>
</tr>
<tr>
<td>6</td>
<td>0.048177073882</td>
</tr>
<tr>
<td>7</td>
<td>-0.411809560700</td>
</tr>
<tr>
<td>8</td>
<td>1.16224152520</td>
</tr>
<tr>
<td>9</td>
<td>0.295116238820</td>
</tr>
</tbody>
</table>
Automatic doc string testing

- The doctest module can grab out interactive sessions from doc strings, run the sessions, and compare new output with the output from the session text.

- Advantage: doc strings shows example on usage and these examples can be automatically verified at any time.
Example

class StringFunction:
    """
    Make a string expression behave as a Python function
    of one variable.
    Examples on usage:

    >>> from StringFunction import StringFunction
    >>> f = StringFunction('sin(3*x) + log(1+x)')
    >>> p = 2.0; v = f(p)  # evaluate function
    >>> p, v
    (2.0, 0.81919679046918392)
    >>> f = StringFunction('1+t', independent_variables='t')
    >>> v = f(1.2)  # evaluate function of t=1.2
    >>> print "%.2f" % v
    2.20
    >>> f = StringFunction('sin(t)')
    >>> v = f(1.2)  # evaluate function of t=1.2
    Traceback (most recent call last):
      v = f(1.2)
NameError: name 't' is not defined
    """
def _test():
    import doctest, StringFunction
    return doctest.testmod(StringFunction)

if __name__ == '__main__':
    _test()
Example on output (1)

Running `StringFunction.StringFunction.__doc__`

Trying: from StringFunction import StringFunction
Expecting: nothing
ok
Trying: f = StringFunction('sin(3*x) + log(1+x)')
Expecting: nothing
ok
Trying: p = 2.0; v = f(p)  # evaluate function
Expecting: nothing
ok
Trying: p, v
Expecting: (2.0, 0.81919679046918392)
ok
Trying: f = StringFunction('1+t', independent_variables='t')
Expecting: nothing
ok
Trying: v = f(1.2)  # evaluate function of t=1.2
Expecting: nothing
ok
Example on output (1)

Trying: \( v = f(1.2) \)  # evaluate function of \( t=1.2 \)
Expecting:
Traceback (most recent call last):
  \( v = f(1.2) \)
NameError: name 't' is not defined
ok
0 of 9 examples failed in StringFunction.StringFunction.__doc__
...
Test passed.
Unit testing

- Aim: test all (small) pieces of code (each class method, for instance)
- Cornerstone in extreme programming (XP)
- The Unit test framework was first developed for Smalltalk and then ported to Java (JUnit)
- The Python module unittest implements a version of JUnit
- While regression tests and doc string tests verify the overall functionality of the software, unit tests verify all the small pieces
- Unit tests are particularly useful when the code is restructured or newcomers perform modifications
- Write tests first, then code (!)
Using the unit test framework

- Unit tests are implemented in classes derived from class `TestCase` in the `unittest` module.
- Each test is a method, whose name is prefixed by `test`.
- Generated and correct results are compared using methods `assert*` or `failUnless*` inherited from class `TestCase`.
- Example:

```python
from scitools.StringFunction import StringFunction
import unittest

class TestStringFunction(unittest.TestCase):
    def test_plain1(self):
        f = StringFunction('1+2*x')
        v = f(2)
        self.failUnlessEqual(v, 5, 'wrong value')
```
Tests with round-off errors

Compare \( v \) with correct answer to 6 decimal places:

```python
def test_plain2(self):
    f = StringFunction('sin(3*x) + log(1+x)')
    v = f(2.0)
    self.failUnlessAlmostEqual(v, 0.81919679046918392, 6, 'wrong value')
```
More examples

def test_independent_variable_t(self):
    f = StringFunction('1+t', independent_variables='t')
    v = '%.2f' % f(1.2)
    self.failUnlessEqual(v, '2.20', 'wrong value')

# check that a particular exception is raised:
def test_independent_variable_z(self):
    f = StringFunction('1+z')
    self.failUnlessRaises(NameError, f, 1.2)

def test_set_parameters(self):
    f = StringFunction('a+b*x')
    f.set_parameters('a=1; b=4')
    v = f(2)
    self.failUnlessEqual(v, 9, 'wrong value')
Initialization of unit tests

Sometimes a common initialization is needed before running unit tests

This is done in a method `setUp`:

```python
class SomeTestClass(unittest.TestCase):
    ...
    def setUp(self):
        <initializations for each test go here...>
```
Run the test

- Unit tests are normally placed in a separate file
- Enable the test:
  
  ```python
  if __name__ == '__main__':
      unittest.main()
  
  Example on output:
  
  ......
  Ran 5 tests in 0.002s
  OK
If some tests fail...

This is how it looks like when unit tests fail:

FAIL: test_plain1 (__main__.TestStringFunction)
Traceback (most recent call last):
  File "./test_StringFunction.py", line 16, in test_plain1
    self.failUnlessEqual(v, 5, 'wrong value')
  File "/some/where/unittest.py", line 292, in failUnlessEqual
    raise self.failureException, \
AssertionError: wrong value
More about unittest

- The unittest module can do much more than shown here
- Multiple tests can be collected in test suites
- Look up the description of the unittest module in the Python Library Reference!
- There is an interesting scientific extension of unittest in the SciPy package
Contents

- How to make man pages out of the source code
- Doc strings
- Tools for automatic documentation
- Pydoc
- HappyDoc
- Epydoc

Write code and doc strings, autogenerate documentation!
More info

- App. B.2.2 in the course book
- Manuals for HappyDoc and Epydoc (see doc.html)
- `pydoc --h`
Man page documentation (1)

- Man pages = list of implemented functionality
  (preferably with examples)
- Advantage: man page as part of the source code
  - helps to document the code
  - increased reliability: doc details close to the code
  - easy to update doc when updating the code
Python tools for man page doc

- Pydoc: comes with Python
- HappyDoc: third-party tool
- HappyDoc support StructuredText, an “invisible”/natural markup of the text
Suppose you have a module `doc` in `doc.py`

View a structured documentation of classes, methods, functions, with arguments and doc strings:

```
pydoc doc.py
```

*(try it out on `src/misc/doc.py`)*

Or generate HTML:

```
pydoc -w doc.py
firefox\emp\{doc.html\}  # view generated file
```

You can view any module this way (including built-ins)

```
pydoc math
```
Advantages of Pydoc

- Pydoc gives complete info on classes, methods, functions
- Note: the Python Library Reference does not have complete info on interfaces
- Search for modules whose doc string contains “keyword”:
  
  pydoc -k keyword

  e.g. find modules that do something with dictionaries:
  
  pydoc -k dictionary

  (searches all reachable modules (sys.path))
HappyDoc gives more comprehensive and sophisticated output than Pydoc

Try it:

```
cp $scripting/src/misc/doc.py .
happydoc doc.py
cd doc  # generated subdirectory
firefox index.html  # generated root of documentation
```

HappyDoc supports StructuredText, which enables easy markup of plain ASCII text
Example on StructuredText

See `src/misc/doc.py` for more examples and references

Simple formatting rules

Paragraphs are separated by blank lines. Words in running text can be *emphasized*. Furthermore, text in single forward quotes, like `'s = sin(r)'`, is typeset as code. Examples of lists are given in the `func1` function in class `MyClass` in the present module. Hyperlinks are also available, see the `README.txt` file that comes with HappyDoc.

Headings

To make a heading, just write the heading and indent the proceeding paragraph.

Code snippets

To include parts of a code, end the preceding paragraph with `example::`, `examples::`, or a double colon::

```python
if a == b:
    return 2+2
```
Browser result

interpreted by the HappyDoc tool. The doc strings can make use of the the
StructuredText format, which is documented in the StructuredText.py file
that comes with HappyDoc. We refer to that file for a complete description of
the very simple format. The README.txt file that comes with HappyDoc is a very
good example of writing plain ASCII files in the StructuredText format. The
present example should get you quickly started.

Simple formatting rules

Paragraphs are separated by blank lines. Words in running text can be
emphasized. Furthermore, text in single forward quotes, like s = sin(r), is
typeset as code. Examples of lists are given in the func1 function in class
MyClass in the present module.

Headings

To make a heading, just write the heading and indent the proceeding
paragraph.

Code snippets

To include parts of a code, end the preceding paragraph with
example:, examples:, or a double colon:

```python
if a == b:
    return 2+2
```

Running HappyDoc

To make a documentation of the doc.py module, run:
Epydoc

- Epydoc is like Pydoc; it generates HTML, LaTeX and PDF
- Generate HTML document of a module:
  ```
  epydoc --html -o tmp -n 'My First Epydoc Test' docex_epydoc.py
  firefox tmp/index.html
  ```
- Can document large packages (nice toc/navigation)
Docutils

- Docutils is a coming tool for extracting documentation from source code
- Docutils supports an extended version of StructuredText
- See link in doc.html for more info
POD = Plain Old Documentation

Perl's documentation system

POD applies tags and blank lines for indicating the formatting style

=head1 SYNOPSIS

use File::Basename;

($name,$path,$suffix) = fileparse($fullname,@suff)
fileparse_set_fstype($os_string);
$basename = basename($fullname,@suffixlist);
$dirname =dirname($fullname);

=head1 DESCRIPTION

=over 4

=item fileparse_set_fstype

=cut
POD (2)

- Perl ignores POD directives and text
- Filters transform the POD text to nroff, HTML, LaTeX, ASCII, ...
- Disadvantage: only Perl scripts can apply POD
- Example: src/sdf/simviz1-poddoc.pl
Unix systems have an enormous amount of useful software
Each package has its own huge set of command-line options
The overwhelming software makes it hard to discover useful packages
Here we will try to present some of the "most useful" commands
These slides are therefore organized as a set of commands
gcc fundamentals

gcc - GNU project C and C++ compiler

Commonly used flags

- `-I<directory-for-hearders>`
- `-L<directory-for-libraries>`
- `-l<libname>` e.g. `-lpython` means libpython.so or libpython.a
- `-Dmacro`
- `-E` stop after the preprocessing stage
- `-o file` (place output in file)
gcc fundamentals

- `-O1 .. -O3` optimize
- `-pg` generate extra code to write profile information (used by `gprof`)
- `-g` produce debugging information
- `-shared` produce a shared object
- `-fpic` generate position-independent code suitable for use in a shared library
gcc fundamentals

A compilation command:
g++  -pg  -Dgpp_Cplusplus  -Wall  -O (flags)
    -DPOINTER_ARITHMETIC  -DNUMT=double (preprocessor flags)
    -I.  -I/usr/X11/include  -I/dp/include (include directories)
    -o Poisson1.o  -c Poisson1.cpp

A linking command:
g++  -pg  -L.  -L/dp/lib/linux/opt (flags and lib dirs)
    -o app  ./Poisson1.o  -ldpU  -larr3  -larr2 (libs++)

Notice that the order of -I, -l and -L matters

Use -fpic and -shared to compile shared libraries
Look at the file
$scripting/src/py/mixed/Grid2D/C++/plain/NumPyArray.h

class NumPyArray_Float
{

...  

double operator() (int i) const {
    #ifdef INDEX_CHECK
        assert(a->nd == 1 && i >= 0 && i < a->dimensions[0]);
    #endif
    return *((double*) (a->data + i*a->strides[0]));
}
};
Typically index checking reduce performance significantly, but is very useful during debugging. Therefore index checking can be turned on/off at compile time with the `-DINDEX_CHECK` macro:

```bash
~/src/py/mixed/Grid2D/C++/plain >gcc -E NumPyArray.h \ 2>/dev/null | grep assert
```

i.e. no calls to assert

On the other hand, when using the `-DINDEX_CHECK` macro:

```bash
~/src/py/mixed/Grid2D/C++/plain >gcc -E -DINDEX_CHECK NumPyArray.h \ 2>/dev/null | grep assert \ assert(a->nd == 1 && i >= 0 && i < a->dimensions[0]);
```
gdb - The GNU Debugger

Gdb is powerful!

However, you get far by knowing just one gdb command

```
where
```

The command `where` gives you the line number where the crash occurred

Remember to compile with the command line option `-g`

There are several graphical front-ends to gdb, but `ddd` is recommended
gdb example

gdb python
(gdb) run
>>> import Heat1D
>>> simulator = Heat1D.Heat1D()
>>> simulator.scan()
>>> simulator.n = 120
>>> simulator.solveProblem()

Program received signal SIGSEGV, Segmentation fault.
[Switching to Thread 16384 (LWP 17287)]
0x406b1431 in TimePrm::initTimeLoop() at gen/TimePrm.cpp:51
      if (stationary_simulation)
Current language: auto; currently c++
(gdb) where
#0 0x406b1431 in TimePrm::initTimeLoop() (this=0x0) at gen/TimePrm.cpp:51
#1 0x4061571c in Heat1D::timeLoop() (this=0x81ed920) at Heat1D.cpp:205
...
WAD

WAD - Wrapped Application Debugger

WAD is a Python module that turns segmentation faults etc. to Python exceptions

```
try:
    solveProblem()
except SegFault, s:
    print s
```

(It has been a while since the last release)
gprof

gprof - display call graph profile data

compile and link with -pg

gcc -pg -c test.c -o test.o
gcc -pg -shared -o app -o test.o -lm
app <command-line arguments>
gprof app | head -10

Each sample counts as 0.01 seconds.

<table>
<thead>
<tr>
<th>% cumulative</th>
<th>time</th>
<th>self</th>
<th>seconds</th>
<th>name</th>
</tr>
</thead>
<tbody>
<tr>
<td>87.72</td>
<td>6.43</td>
<td>6.43</td>
<td>MatBand::factLU()</td>
<td></td>
</tr>
<tr>
<td>1.64</td>
<td>6.55</td>
<td>0.12</td>
<td>BasisFuncAtPt::calcJacobiEtc(Mat&amp;)</td>
<td></td>
</tr>
<tr>
<td>1.36</td>
<td>6.65</td>
<td>0.10</td>
<td>MatBand::forwBackLU(Vec&amp;, Vec&amp;)</td>
<td></td>
</tr>
<tr>
<td>1.36</td>
<td>6.75</td>
<td>0.10</td>
<td>MatSimple::fill(double)</td>
<td></td>
</tr>
<tr>
<td>0.82</td>
<td>6.81</td>
<td>0.06</td>
<td>sv_single2multiple(int, int, int)</td>
<td></td>
</tr>
</tbody>
</table>
make

make - utility to maintain groups of programs

A typical make command is

```
file :  dependency-file1 dependency-file2
      <tab>  rule to make file from dependency-file1
      <tab>  and dependency-file2
```

Notice that whitespace, tab and newline are important (This is the standard newbie problem)

make checks whether the time stamp on the dependencies are newer than the time stamp on file

If these are newer then make applies the rule to make a newer file
make

- All variables are on the form $(VARIABLE)$
- General rules can be made, e.g. for compiling .c files to .o files
  
  `.c.o:
     gcc $(INCLUDES) $(FLAGS) -c $<

- $< holds the name of the dependency
- `.c.o` means that the file.o is made from file.c
- If the variable $(VAR)$ is not defined then the corresponding environment variable is used
Sample Makefile

INCLUDES = -I$(SOFTWARE)/include/python2.2/ -I.
SWIG_INCLUDES = -I$(SOFTWARE)/src/SWIG-1.3.19/Lib
Lib/python
FLAGS = -fpic -DHAVE_CONFIG_H -g
LIB_PATH = -L$(SOFTWARE)/lib/.

.c.o:
gcc $(INCLUDES) $(FLAGS) -c $<

default: _simple.so

simple_wrap.c: simple.h simple.c
    swig -python $(SWIG_INCLUDES) simple.i

_simple.so: simple_wrap.o simple.o
    gcc -shared simple_wrap.o simple.o -o _simple.so \
    -lswigpy -lnumpy $(LIB_PATH)
make command line options

- `make -f file` forces `make` to use `file` as the makefile
- `make -n` tells `make` to print out the commands instead of executing them
- `make -j n` tells `make` to run `n` processes in parallel if possible
- `make -w` forces `make` to print out the working directory before and after execution
autoconf - generate configuration scripts

**autoconf** is a tool for producing (stand-alone) shell scripts that adapt Makefiles to a Unix system

**autoconf** typically makes a Bourne shell script called **configure**. **configure** generates a **Makefile** based on **Makefile.in**. **configure** is based on **configure.in**.

The goal when using **autoconf** is to make the following installation procedure possible:

```
./configure
make
make install
```
configure generates Makefile by replacing @ enclosed words such as @prefix@ and @CFLAGS@

Example (lines) from the Makefile.pre.in in the Python distribution

```plaintext
CC= @CC@  
CXX= @CXX@  
AR= @AR@  
RANLIB= @RANLIB@  
srcdir= @srcdir@  
...

Modules/getbuildinfo.o: $(srcdir)/Modules/getbuildinfo.c  
$(CC) -c $(PY_CFLAGS) -DBUILD=‘cat buildno’ \  
-o $@ $(srcdir)/Modules/getbuildinfo.c
```
configure.in

autoscan generates a preliminary configure.in file

autoscan examine a directory tree (either SRCDIR or the current directory) and creates configure.scan

configure.scan is modified and copied to configure.in
Libraries

Libraries can be

- **static** - code included in the executable during linking, all symbols are defined in the executable
- **dynamic** - code is loaded during execution
- **shared** - the same library is shared by all its users

In practice we usually only distinguish between shared (.so) and static (.a) libraries

The standard format for both libraries (and executables) are now ELF.
Libraries

- `.a`: static library in containing raw object files stored in an archive made by `ar`
  > file /usr/lib/libz.a /usr/lib/libz.a: current ar archive

- `.so`: shared and dynamic library
  > file /usr/lib/libz.so.1.2.1
  /usr/lib/libz.so.1.2.1: ELF 32-bit LSB shared object, Intel 80386, version 1 (SYSV), stripped

The command `file` is useful to determine the type of a file
Common Problem

A common problem when using shared libraries!

```
python
>>> import some_module
ImportError: _some_module.so:
>>>     undefined symbol: vertCases
```

Typically `vertCases` is defined in a library somewhere.

We need to locate it.

In the following we will describe shortly various tools.

See also: The inside story on shared libraries and dynamic loading
http://ieeexplore.ieee.org/xpl/abs_free.jsp?arNumber=947112
nm - list symbols from object files

```
~ > nm -o /home/kent-and/stable/lib/* .a \n    | grep daxpy | grep " T "
/home/kent-and/stable/lib/blas.a:daxpy.o:
  00000000 T daxpy_
/home/kent-and/stable/lib/libblas.a:daxpy.o:
  00000000 T daxpy_

nm gridloop.o | grep NumPy
000003b0 T _ZN16NumPyArray_Floa"phantom agency"
000001e0 T _ZN16NumPyArray_Floa"phantom agency"
 createEi...
```

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c++filt

c++filt - Demangle C++ and Java symbols

What is this?

000003b0 T _Z4dumpRSoRK16NumPyArray_Float

>c++filt _Z4dumpRSoRK16NumPyArray_Float
dump(std::ostream&, NumPyArray_Float const&)
ranlib - generate index to archive

- static libraries (suffix .a) are a collection of object files
- it usually have a index table that can be printed out with \texttt{nm}
- if not, this index table can be generate with \texttt{ranlib}
- \texttt{ranlib libpython.a}
objdump

objdump - display information from object files

~/stable/src/Python-2.2 >objdump -a libpython2.2.a \      
| egrep -2 readline

readline.o: file format elf32-i386
rw-r--r-- 5889/15889 67224 Sep 8 10:38 2003 readline.o
ar

ar - create, modify, and extract from archives
remove readline.o from libpython2.2.a

    ar d  libpython2.2.a readline.o

insert it again

    ar cr  libpython2.2.a readline.o
readelf - Displays information about ELF files
Useful for finding symbols that are undefined

    readelf -s _simple.so | grep -v UND
**ldd**

**ldd - print shared library dependencies**

```
~ > ldd libvtkRenderingPython.so
   libvtkGraphics.so => libvtkGraphics.so (0x40175000)
   libvtkImaging.so => libvtkImaging.so (0x4034c000)
   libvtkFiltering.so => libvtkFiltering.so (0x40439000)
   libvtkCommonPython.so => not found
   libpthread.so.0 => not found
   libdl.so.2 => /lib/libdl.so.2 (0x4073d000)
   libGL.so.1 => /usr/X11R6/lib/libGL.so.1 (0x40741000)
   libvtkCommon.so => libvtkCommon.so (0x407b4000)
```

**libraries that are not found must be found for proper execution**
indent

indent - changes the appearance of a C program by inserting or deleting whitespace

- indent indent the C code according to a certain standard
- indent -gnu file.c indent according to the GNU standard
- indent is highly configurable
- Many similar programs
Further reading

- info, e.g. info binutils
- man pages
- tutorial shared and static libraries
  http://users.actcom.co.il/~choo/lupg/tutorials/libraries/unix-c-libraries.html
- The inside story on shared libraries and dynamic loading
  http://ieeexplore.ieee.org/xpl/abs_free.jsp?arNumber=947112
- Lots of documentation: www.gnu.org