University of Zurich[UZH]

Department of Physics

# Need for Speed – Python meets C/C++

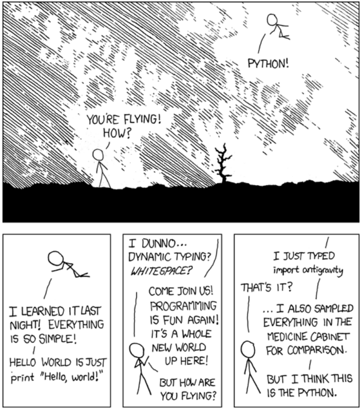
Scientific Programming with Python

Christian Elsasser

Based partially on a talk by Stéfan van der Walt

This work is licensed under the *Creative Commons Attribution-ShareAlike 3.0 License*.

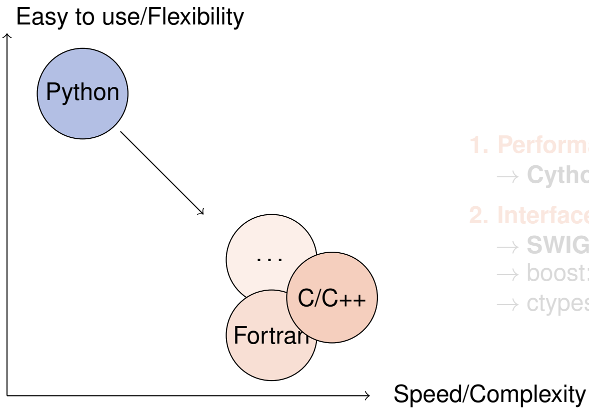
# Python is nice, but by construction slow . . .



[xkcd]

# . . . why not therefore interfacing it with C/C++

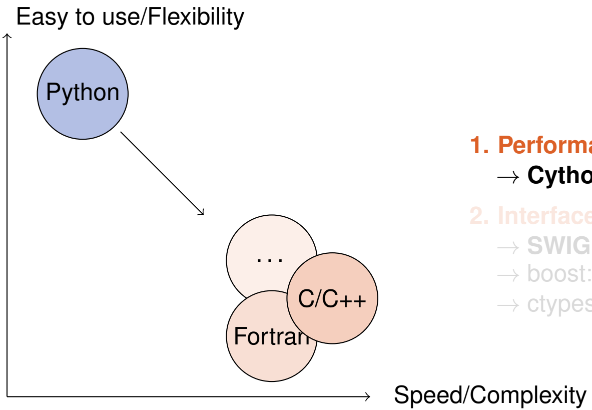
**(or something similar, *e.g.* if you don't feel too young to use Fortran)**




1. **Performance improvement**
   → **Cython**
2. **Interfaces**
   → **SWIG**
   → boost::python
   → ctypes

# . . . why not therefore interfacing it with C/C++

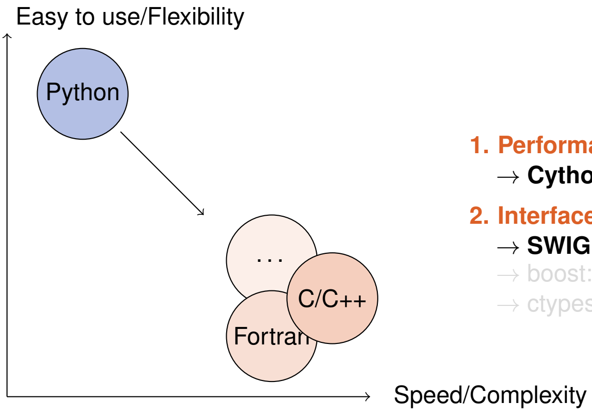
**(or something similar, *e.g.* if you don't feel too young to use Fortran)**




1. **Performance improvement**
   → **Cython**
2. **Interfaces**
   → **SWIG**
   → boost::python
   → ctypes

# . . . why not therefore interfacing it with C/C++

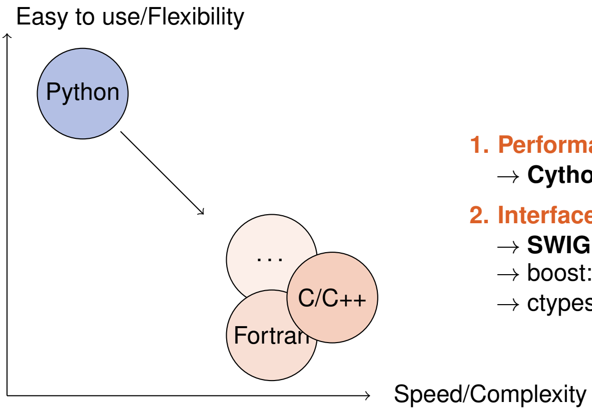
**(or something similar, *e.g.* if you don't feel too young to use Fortran)**




1. **Performance improvement**
   $\rightarrow$ **Cython**
2. **Interfaces**
   $\rightarrow$ **SWIG**
   $\rightarrow$ boost::python
   $\rightarrow$ ctypes

# . . . why not therefore interfacing it with C/C++

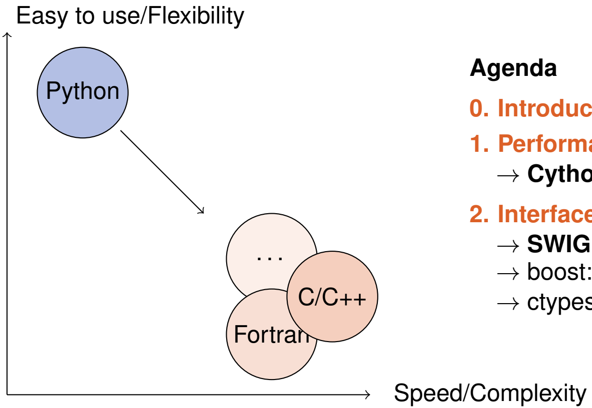
**(or something similar, *e.g.* if you don't feel too young to use Fortran)**




1. **Performance improvement**
   $\rightarrow$ **Cython**
2. **Interfaces**
   $\rightarrow$ **SWIG**
   $\rightarrow$ boost::python
   $\rightarrow$ ctypes

# . . . why not therefore interfacing it with C/C++

**(or something similar, *e.g.* if you don't feel too young to use Fortran)**




**Agenda**

**0. Introduction**

**1. Performance improvement**

→ **Cython**

**2. Interfaces**

→ **SWIG**

→ boost::python

→ ctypes

# C++ on one Slide

www.cplusplus.com and www.learncpp.com

- C++ is an (if not the) object-oriented programming language (like Python)
- including inheritance (like Python does in a slightly different way)
- . . . operator overloading (like Python)
- It has a rich variety of libraries (like Python)
- It can raise exceptions (like Python)
- **It requires declaration of variables (not like Python)**
- **It is (usually) a compiled language! (not like Python)**

$\Rightarrow$ C++ and Python share a lot of similarities!

**C is just the non-object-oriented version of C++ (minus some other missing features, *e.g.* exceptions)**

# A Few Words of Warning

**Bad code stays bad code! – Better clean it up than trying to overpaint it!**

**Do not expect miracles! – You have to master two languages!**

# C keeps Python running . . .

- CPython is the standard implementation of the Python interpreter written in C.
- The Python C API (application programming interface) allows to build C libraries that can be imported into Python (`https://docs.python.org/3/c-api/`) . . .
- . . . and looks like this:

Pure Python

```
>>>>>> a = [1,2,3,4,5,6,7,8]
>>>>>> sum(a)
36
```

# . . . but takes a lot of the fun out of Python

C++ implementation of sum of a list

```
sum_list(PyObject *list) {
  int i, n;
  long total = 0;
  PyObject *item;
  n = PyList_Size(list);
  if (n < 0)
    return -1; /* Not a list */
  for (i = 0; i < n; i++) {
    item = PyList_GetItem(list, i); /* Can't fail */
    if (!PyInt_Check(item)) continue; /* Skip non-integers */
    total += PyInt_AsLong(item);
  }
  return total;
}
```

# C/C++ in Python: Not a New Thing

NumPy's C API

```
ndarray typedef struct PyArrayObject {
  PyObject_HEAD;
  char *data;
  int nd;
  npy_intp *dimensions;
  npy_intp *strides;
  PyObject *base;
  PyArray_Descr *descr;
  int flags;
  PyObject *weakreflist;
} PyArrayObject;
```

⇒ Several Python “standard” libraries are using C/C++ to speed things up

# Cython – An easy way to get C-enhanced compiled Python code

(`http://cython.org`)

- Hybrid programming language combining Python and an interface for using C/C++ routines.
- ...or a static compiler for Python allowing to write C/C++ extensions for Python and heavily optimising this code.
- It is a successor of the Pyrex language. (The reason for the `.pyx` file extension)

$\Rightarrow$ Every valid Python statement is also valid when using cython.

$\Rightarrow$ Code needs to be compiled $\rightarrow$ Time!

- Translates your “C-enhanced” Python code into C/C++ code using the C API

**Cython (v0.29.15) understands Python 3, and also most of the features of C++11**

# Requirements: Cython package and a C compiler

- `cython`
  The latest version can be downloaded from http://cython.org.
- C/C++ compiler, *e.g.* `gcc/g++/clang` (or for Windows: `mingw`)

| | |
|---|---|
| Linux: | usually already installed<br>(Ubuntu/Debian: `sudo apt-get install build-essential`) |
| MacOS X: | XCode command line tools |
| Windows: | Download of MinGW from http:// mingw.org and install it |

# Benchmark One: Fibonacci series

Fibonacci function - Python

```
def fib(n):

  a,b = 1,1
  for i in range(n):
    a,b = a+b,a
  return a
```

# Benchmark One: Fibonacci series

Fibonacci function - Cython

```
def fib(int n):
  cdef int i,a,b
  a,b= 1,1
  for i in range(n):
    a,b = a+b,a
  return a
```

- Type declaration (`cdef`) ⇒ Python/Cython knows what to expect

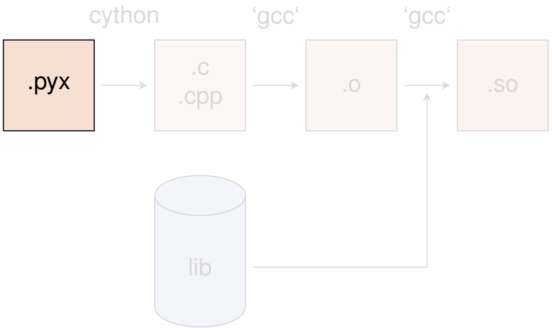
# Benchmark One: Fibonacci series

Fibonacci function - Cython

```
def fib(int n):
  cdef int i,a,b
  a,b= 1,1
  for i in range(n):
    a,b = a+b,a
  return a
```

- Type declaration (`cdef`) $\Rightarrow$ Python/Cython knows what to expect
- A few (simple) modifications can easily change the CPU time by a factor of $\mathcal{O}(100)$

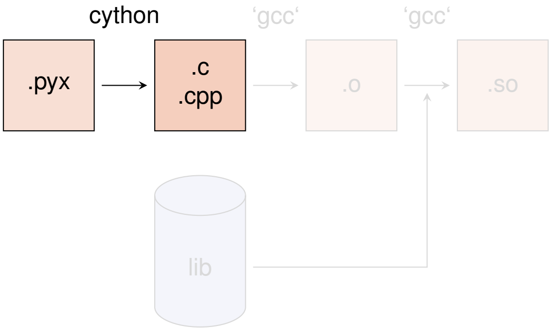
# Compiling Cython Code (The hard way)




Shared object (<name>.so) can be imported into Python with `import name`

1. Compile Cython code to C/C++ code
   `cython/cython3 -3 <name>.pyx`
2. Create object files
   `gcc -O2 -fPIC -I<path_to_python_include> -c <name>.c -o <name>.o`
3. Compile shared object (*i.e.* library)
   `gcc [options] -L<path_to_python_library> <name>.o -o <name>.so`
   - If using C++ code, cython needs the option `-+` and `gcc` → `g++`
   - `options` are for MacOS X `-bundle -undefined dynamic_lookup` and for Debian `-shared`

# Compiling Cython Code (The hard way)




Shared object (<name>.so) can be imported into Python with `import name`

1. Compile Cython code to C/C++ code

```
cython/cython3 -3 <name>.pyx
```

2. Create object files

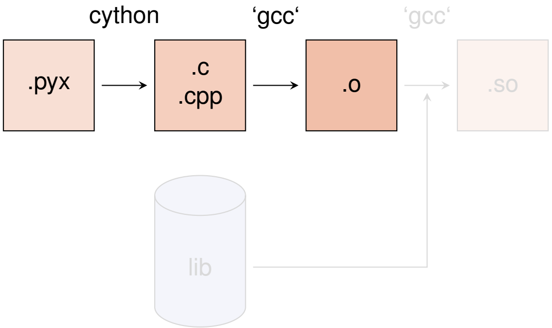
```
gcc -O2 -fPIC
-I<path_to_python_include> -c
<name>.c -o <name>.o
```

3. Compile shared object (*i.e.* library)

```
gcc [options]
-L<path_to_python_library>
<name>.o -o <name>.so
```

- If using C++ code, cython needs the option `-+` and `gcc` → `g++`
- `options` are for MacOS X `-bundle -undefined dynamic_lookup` and for Debian `-shared`

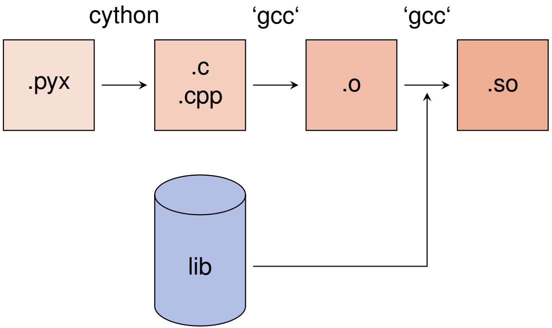
# Compiling Cython Code (The hard way)




1. Compile Cython code to C/C++ code
   cython/cython3 -3 <name>.pyx
2. Create object files
   gcc -O2 -fPIC -I<path_to_python_include> -c <name>.c -o <name>.o
3. Compile shared object (*i.e.* library)
   gcc [options] -L<path_to_python_library> <name>.o -o <name>.so
   - If using C++ code, cython needs the option -+ and gcc → g++
   - options are for MacOS X -bundle -undefined dynamic_lookup and for Debian -shared

Shared object (<name>.so) can be imported into Python with import name

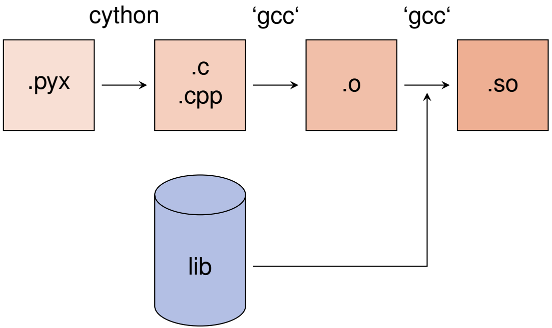
# Compiling Cython Code (The hard way)




Shared object (`<name>.so`) can be imported into Python with `import name`

1. Compile Cython code to C/C++ code
   `cython/cython3 -3 <name>.pyx`
2. Create object files
   `gcc -O2 -fPIC -I<path_to_python_include> -c <name>.c -o <name>.o`
3. Compile shared object (*i.e.* library)
   `gcc [options] -L<path_to_python_library> <name>.o -o <name>.so`
   - If using C++ code, cython needs the option `-+` and `gcc` → `g++`
   - `options` are for MacOS X `-bundle -undefined dynamic_lookup` and for Debian `-shared`

# Compiling Cython Code (The hard way)




Shared object (<name>.so) can be imported into Python with `import name`

1. Compile Cython code to C/C++ code
```
cython/cython3 -3 <name>.pyx
```
2. Create object files
```
gcc -O2 -fPIC
-I<path_to_python_include> -c
<name>.c -o <name>.o
```
3. Compile shared object (*i.e.* library)
```
gcc [options]
-L<path_to_python_library>
<name>.o -o <name>.so
```
   - If using C++ code, cython needs the option `-+` and `gcc` → `g++`
   - `options` are for MacOS X `-bundle -undefined dynamic_lookup` and for Debian `-shared`

# Compiling Cython Code (The easy way)

Support via the distutils (distribution utilities) package in building and installing Python modules
⇒ applicable for cython

Cython setup script

```
from distutils.core import setup
from Cython.Build import cythonize

setup(ext_modules = cythonize([<name of .pxy files>],
        language = "c++" #optional
))
```

Command `python setup.py build_ext --inplace` creates for each `.pyx` file a `.c/.cpp` file, compiles it to an executable (in the build directory of the corresponding OS/architecture/Python version) and compiles a `.so` file (or a `.pxd` if you are using Windows)

Further options for `cythonize` via help explorable

# When to use which way

**1. Cython extension in ipython/Jupyter notebook**

- You want to investigate where are some room for improvement with cython
- Testing of some implementations
- Rather small code snippets
- No complicated dependencies on external C/C++ libraries
- Modules are not available outside (in principle)

**2. Compiling via setup script (or by hand)**

- Creating more complex modules
- (extensive) linkage to external C/C++ libraries
- Usage of additional options (*e.g.* for optimisation)

# How Performant is My Code?

`cython -3 -a/--annotate <name>.pyx` → additional HTML file

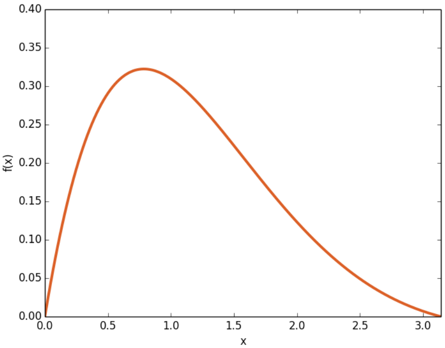
- bad performance → yellow marking
- allows to investigate code and to learn about performance tuning

```
Generated by Cython 0.26

Yellow lines hint at Python interaction.
Click on a line that starts with a "+" to see the C code that Cython generated for it.

Raw output: fib_py.c

 1: # Calculation of n-th fibonacci number
+2: def fib(n):
+3:     a,b = 1,1
+4:     for i in range(n):
+5:         a,b = a+b,a
+6:     return a
   __Pyx_XDECREF(__pyx_r);
   __Pyx_INCREF(__pyx_v_a);
   __pyx_r = __pyx_v_a;
   goto __pyx_L0;
```

- Not every yellow part can be improved!

# Benchmark Two: Numerical Integration

Integral of $f(x) = \sin x \cdot e^{-x}$ between 0 and $\pi$
$\Rightarrow$ Exact result: $(e^{-\pi} + 1)/2 = 0.521607$



# Benchmark Two: Numerical Integration

Integral of $f(x) = \sin x \cdot e^{-x}$ between 0 and $\pi$
$\Rightarrow$ Exact result: $(e^{-\pi} + 1)/2 = 0.521607$

Integration - version 1

```
from math import sin,exp

def f(double x):
        return sin(x)*exp(-x)

def integrate(double a,double b,int N):
        cdef double dx,s
        cdef int i
        dx = (b-a)/N
        s = 0.0
        for i in range(N):
                s += f(a+(i+0.5)*dx)
        return s*dx
```

# Benchmark Two: Numerical Integration

Integral of $f(x) = \sin x \cdot e^{-x}$ between 0 and $\pi$
$\Rightarrow$ Exact result: $(e^{-\pi} + 1)/2 = 0.521607$

Python layer (expensive)

```
integrate(a,b,N)
.
.
f(x)
.
.
```

C layer (cheap)

```
.
_pyx_integrate(a,b,N)
for (i=0; i<N; i++)
.
_pyx_f(x)
sum updated
```

# Benchmark Two: Numerical Integration

Integral of $f(x) = \sin x \cdot e^{-x}$ between 0 and $\pi$
$\Rightarrow$ Exact result: $(e^{-\pi} + 1)/2 = 0.521607$

Integration - version 2

```
from math import sin,exp

cdef double f(double x):
        return sin(x)*exp(-x)

def integrate(double a,double b,int N):
        cdef double dx,s
        cdef int i
        dx = (b-a)/N
        s = 0.0
        for i in range(N):
                s += f(a+(i+0.5)*dx)
        return s*dx
```

# Benchmark Two: Numerical Integration

Integral of $f(x) = \sin x \cdot e^{-x}$ between 0 and $\pi$

$\Rightarrow$ Exact result: $(e^{-\pi} + 1)/2 = 0.521607$

Integration - version 3

```
from math import sin,exp

cpdef double f(double x):
        return sin(x)*exp(-x)

def integrate(double a,double b,int N):
        cdef double dx,s
        cdef int i
        dx = (b-a)/N
        s = 0.0
        for i in range(N):
                s += f(a+(i+0.5)*dx)
        return s*dx
```

# Benchmark Two: Numerical Integration

Integral of $f(x) = \sin x \cdot e^{-x}$ between 0 and $\pi$
$\Rightarrow$ Exact result: $(e^{-\pi} + 1)/2 = 0.521607$

Integration - version 4

```
from libc.math cimport sin,exp

cpdef double f(double x):
        return sin(x)*exp(-x)

def integrate(double a,double b,int N):
        cdef double dx,s
        cdef int i
        dx = (b-a)/N
        s = 0.0
        for i in range(N):
                s += f(a+(i+0.5)*dx)
        return s*dx
```

# Benchmark Two: Numerical Integration

Integral of $f(x) = \sin x \cdot e^{-x}$ between 0 and $\pi$
$\Rightarrow$ Exact result: $(e^{-\pi} + 1)/2 = 0.521607$

- Return values of function can be specified via the key word `cdef`
- `cpdef` $\Rightarrow$ function also transparent to Python itself (no performance penalty)

- C/C++ library can be imported via `from libc/libcpp.<module> cimport <name>` (see later)
- Using C++ functions can lead to a huge speed-up
- Try to do as much as you can in the C-layer

- Already huge speed-up when leveraging numpy and its vectorisation

# You are here!

# STL Containers

An often used feature of C++ are the Standard Template Library containers (*e.g.* std::vector, std::map, etc.)

Object holders with specific memory access structure, *e.g.*

- `std::vector` allows to access any element
- `std::list` only allows to access elements via iteration
- `std::map` represents an associative container with a key and a mapped values

# STL Containers

An often used feature of C++ are the Standard Template Library containers (*e.g.* std::vector, std::map, etc.)

. . . and Cython knows how to treat them!

| Python | → | C++ | → | Python |
|---|---|---|---|---|
| iterable | → | std::vector | → | list |
| iterable | → | std::list | → | list |
| iterable | → | std::set | → | set |
| iterable (len 2) | → | std::pair | → | tuple (len 2) |
| dict | → | std::map | → | dict |
| bytes | → | std::string | → | bytes |

# STL Containers

An often used feature of C++ are the Standard Template Library containers (*e.g.* std::vector, std::map, etc.)

### A few remarks!

- iterators (*e.g.* `it`) can be used ⇒ dereferencing with `dereference(it)` and incrementing/decrementing with `preincrement` (*i.e.* `++it`), `postincrement` (*i.e.* `it++`), `predecrement` (*i.e.* `--it`) and `postdecrement` (*i.e.* `it--`) from `cython.operator`
- Be careful with performance! ⇒ performance lost due to shuffling of data
- More indepth information can be found directly in the corresponding sections of the cython code https://github.com/cython/cython/tree/master/Cython/Includes/libcpp
- C++11 containters (like `std::unordered_map`) are partially implemented

# Exceptions/Errors

In terms of exception and error handling three different cases need to be considered:

- Raising of a **Python error** in cython code $\Rightarrow$ return values make it impossible to raise properly Python errors (Warning message, but continuing)
- Handling of **error codes from pure C functions**
- Raising of a **C++ exception** in C++ code used in cython $\Rightarrow$ C++ exception terminates – if not caught – program

# Errors in Python

Python Error in Cython - untreated

```
cpdef int raiseError():
        raise RuntimeError("A problem")
        return 1
```

⇒ Just prints a warning (and worse gives an ambigious return value)

# Errors in Python

Python Error in Cython - untreated

```
cpdef int raiseError():
        raise RuntimeError("A problem")
        return 1
```

⇒ Just prints a warning (and worse gives an ambigious return value)

Python Error in Cython - treated

```
cpdef int raiseError()  except *:
        raise RuntimeError("A problem")
        return 1
```

⇒ Propagates the `RuntimeError`

# Errors in C

C does not know exceptions like Python or C++. If errors should be caught, it is usually done via dedicated return values of functions which cannot appear in a regular function call.

Use the `except` statement to tell cython about this value

Handling a C Error

```
cpdef int raiseException()  except -1:
        return -1
```

# Exceptions in C++


[xkcd]

In cython this is also true for C++ exceptions!

Cython is not able to deal with C++ exceptions in a `try`'n'`except` clause!

⇒ But caption in cython and translation to Python exceptions/errors is possible!

# Exceptions in C++

## …and how to tackle them!

- `cdef <C++ function>() except +`
  $\Rightarrow$ translates a C++ exception into a Python error according to the right-hand scheme
- `cdef <C++ function>() except +<Python Error>` *e.g.* `MemoryError` $\Rightarrow$ translates every thrown C++ exception into a MemoryError
- `cdef <C++ function>() except +<function raising Python error>` $\Rightarrow$ runs the indicated function if the C++ function throws any exception. If `<function raising Python error>` does not raise an error, a RuntimeError will be raised.

| C++ | → | Python |
|---:|---|---|
| bad_alloc | → | MemoryError |
| bad_cast | → | TypeError |
| domain_error | → | ValueError |
| invalid_argument | → | ValueError |
| ios_base::failure | → | IOError |
| out_of_range | → | IndexError |
| overflow_error | → | OverflowError |
| range_error | → | ArithmeticError |
| underflow_error | → | ArithmeticError |
| (all others) | → | RuntimeError |

# Classes

Classes are a common feature of Python and C++

There are two aspects when dealing with cython:

- **Defining classes containing C++ code in cython**
- C++ classes integrated into Python

# Defining Classes in Cython

Let's go back to the integration examples

Defining classes in Cython

```
cdef class Integrand:
        cpdef double evaluate(self,double x) except *:
                raise NotImplementedError()

cdef class SinExpFunction(Integrand):
        cpdef double evaluate(self,double x):
                return sin(x)*exp(-x)

def integrate(Integrand f,double a,double b,int N):
        ...
        s += f.evaluate(a+(i+0.5)*dx)
```

Cython does not know `@abstractmethod` from the module `abc`!

# Defining Classes in Cython

Let's go back to the integration examples

Adding classes in Python

```
class Poly(Integrand):
        def evaluate(self,double x):
                return x*x-3*x
integrate(Poly(),0.0,2.0,1000)
```

⇒ Speed lost with respect to definition in cython, but still faster than a pure Python implementation

# Integration of C++ Classes in Cython – Possible but cumbersome

**Starting point:** `.cpp/.h` file for class `Rectangle` defined in a namespace `shapes`

1. Expose it to Cython by delaring the class structure and method signatures
2. Integrating it into Cython either via direct usage or by defining a wrapper class

Exposing C++ classes in Cython

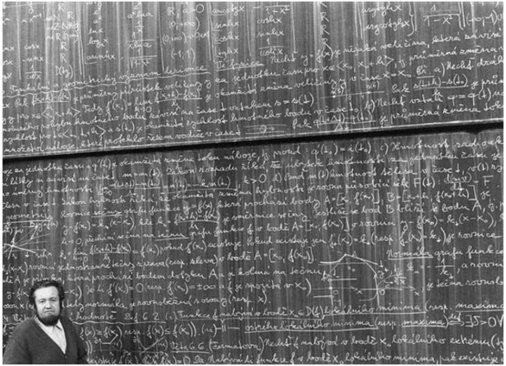
```
# distutils: language = c++
# distutils: sources = Rectangle.cpp
cdef extern from "Rectangle.h" namespace "shapes":
        cdef cppclass Rectangle:
                Rectangle(int, int, int, int) except +
                int x0, y0, x1, y1
                int getLength()
                int getHeight()
                int getArea()
                void move(int, int)
```

# Automatic Wrappers

. . . since not everybody likes to write lines of error-prone code

- SWIG
- boost::python
- ctypes
- . . .

Goal: creating compilable C/C++ code based on the Python C API

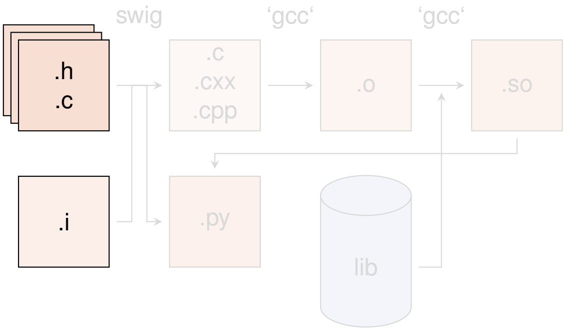


# SWIG

## SWIG: Simplified Wrapper and Interface Generator

- Generic Wrapper for C/C++ to script-like languages
  - R
  - Perl
  - Ruby
  - Tcl
  - PHP5
  - Java
  - ... and **Python**
- Pretty old – created in 1995 by Dave Beazley
- Current version is 4.0.2

# SWIG – in a Nutshell

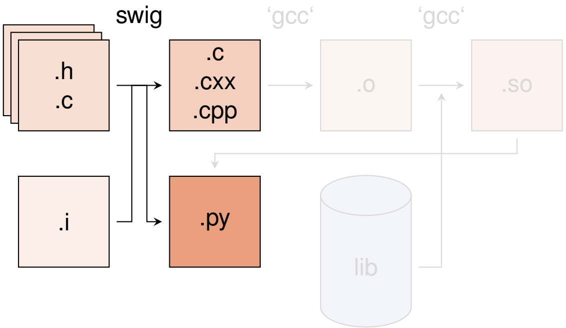



1. Create python wrapper and necessary C files
   `swig -c++ -python <name>.i`
2. Create object files based on output from the wrapper plus native C/C++ code
3. Compile shared object (*i.e.* library)

   Normally step 2 and 3 can be combined with via Distutils `setup.py`
   `python setup.py build_ext --inplace`

Moduel (`<name>.py`) can be imported into Python with `import name` ⇒ Shared object needs different name

# SWIG – in a Nutshell

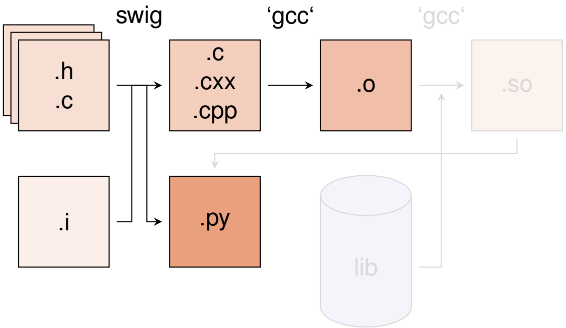



1. Create python wrapper and necessary C files
   `swig -c++ -python <name>.i`
2. Create object files based on output from the wrapper plus native C/C++ code
3. Compile shared object (*i.e.* library)

   Normally step 2 and 3 can be combined with via Distutils `setup.py`
   `python setup.py build_ext --inplace`

Moduel (`<name>.py`) can be imported into Python with `import name` ⇒ Shared object needs different name

# SWIG – in a Nutshell




1. Create python wrapper and necessary C files
   `swig -c++ -python <name>.i`
2. Create object files based on output from the wrapper plus native C/C++ code
3. Compile shared object (*i.e.* library)

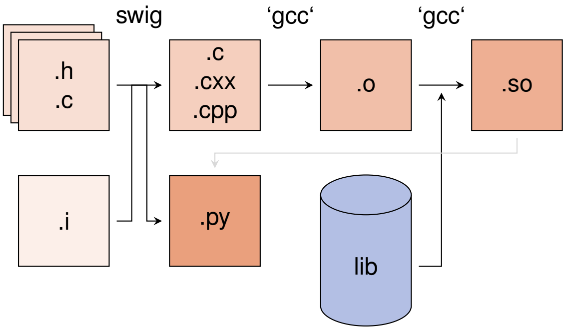
   Normally step 2 and 3 can be combined with via Distutils `setup.py`
   `python setup.py build_ext --inplace`

Moduel (`<name>.py`) can be imported into Python with `import name` ⇒ Shared object needs different name

University of Zurich[UZH]

Department of Physics

# SWIG – in a Nutshell

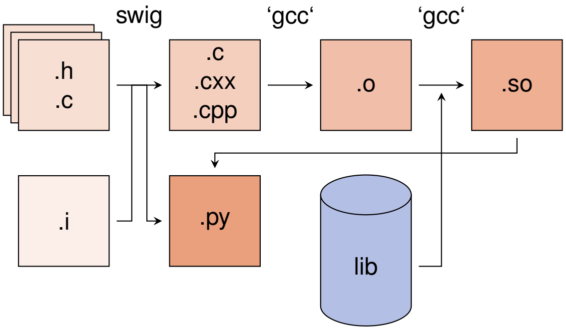



1. Create python wrapper and necessary C files
   `swig -c++ -python <name>.i`
2. Create object files based on output from the wrapper plus native C/C++ code
3. Compile shared object (*i.e.* library)

   Normally step 2 and 3 can be combined with via Distutils `setup.py`
   `python setup.py build_ext --inplace`

Moduel (`<name>.py`) can be imported into Python with `import name` ⇒ Shared object needs different name

# SWIG – in a Nutshell




1. Create python wrapper and necessary C files
   `swig -c++ -python <name>.i`
2. Create object files based on output from the wrapper plus native C/C++ code
3. Compile shared object (*i.e.* library)

   Normally step 2 and 3 can be combined with via Distutils `setup.py`
   `python setup.py build_ext --inplace`

Moduel (`<name>.py`) can be imported into Python with `import name` ⇒ Shared object needs different name

# SWIG – The interface file

Main configuration with interface (`.i`) files

- tells which (header) file(s) contains the C/C++ code to wrap
- defines some special data types (*e.g.* `std::vector<...>`)
- handles some additional configuration (*e.g.* exception/error translation)

Interface file

```
%module geom // name of the module
...
// things swig should know about
%include "Shape.h"
%include "Rectangle.h"

// things that should be put into the
// header of the wrapper file (.c/.cxx)
%{
#include "Shape.h"
#include "Rectangle.h"
%}
```

# SWIG – The Distutils file

Distutils setup script (setup.py)

```
from distutils.core import setup, Extension
extension_mod = Extension("_<name>" , # Use _ to distinguish to final module name
                         ["<name_wrap>.cxx",
                          "<source1>.cpp",
                          "<source2>.cpp","..."],
                         language='c++')
setup(name = "_<name>", ext_modules=[extension_mod])
```

- To be build extension needs a different name than the module set up by switch ⇒ Avoid name conflicts
- Language option only for C++
- `python setup.py build_ext --inplace`

# A Few Remarks about SWIG

- SWIG $\approx$ performance loss with respect to cython
- If SWIG works: ☺
- If it does not: ☹
- . . . and therefore you can lose a lot of time with special problems
- It is not always optimal to expose the whole class to Python

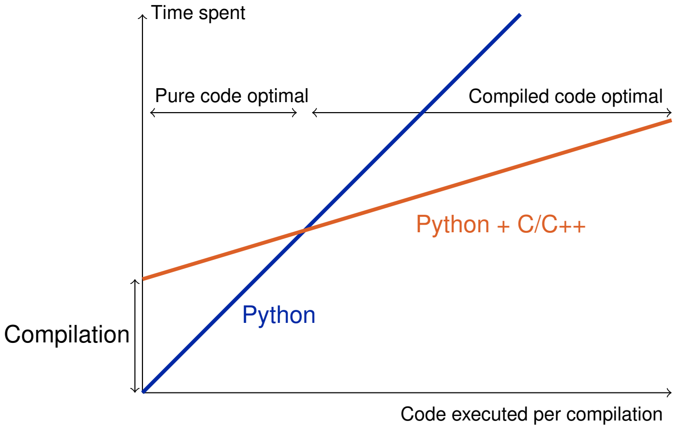
# Conclusion

- Interfacing Python with C/C++ is – or better – can be a way to create powerful code
- cython and SWIG are two nice tools to do so
- . . . but always make the interfacing maintainable/useful/etc. *i.e.* not a British train door
- And it's all about finding the sweet spot!

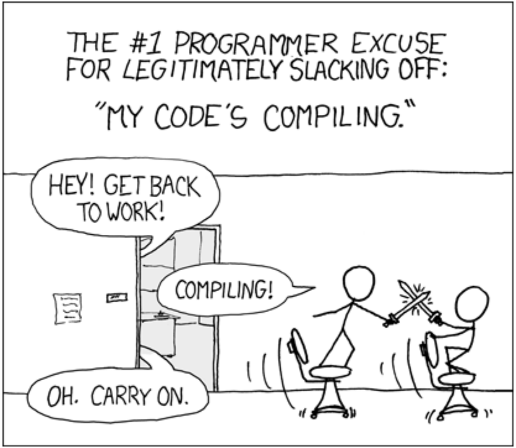
University of Zurich[UZH]

Department of Physics

# The Sweet Spot!



# The End!


THE #1 PROGRAMMER EXCUSE FOR LEGITIMATELY SLACKING OFF:
"MY CODE'S COMPILING."
HEY! GET BACK TO WORK!
COMPILING!
OH. CARRY ON.

[xkcd]

# References


1. Stéfan van der Walt, *Speeding up scientific Python code using Cython*, Advanced Scientific Programming in Python, 2013 (Zurich) & 2014 (Split)
2. Stefan Behnel et al., *Cython tutorial*, Proceedings of the 8th Python in Science Conference (SciPy 2009) ⇒ based on older cython version, but the main reference of cython
3. Dave Beazley, *Swig Master Class*, PyCon'2008
4. http://docs.cython.org/src/tutorial/
5. http://www.swig.org

# Backup

# Fortran meets Python

The `f2py` compiler (`http://docs.scipy.org/doc/numpy-dev/f2py/`) offers – in a similar way as cython – the possibility to generate extension modules for Python from Fortran code.

`f2py -c -m <module name> <fortran file>.f/.f90 -I<path to python header file>` builds from the code in `<fortran file>.f/.f90` a importable module (*i.e.* shared object) `<module name>.so`

Fortran modules and subroutines are exposed to Python on time of the import of the built module.

The compilation can also be split into a first step generating a signature file, which is in a second step compiled into the extension module

# Exceptions in C++

## Examples

Two C++ functions `void raiseException()` and `void raiseBadAlloc()` defined in `except_cy.h`

Exception Example 1

```
cdef extern from 'except_cy.h'
        cdef void raiseException() except +
def tryIt():
        try:
                raiseException()
        except RuntimeError as e:
                print(e)
```

$\Rightarrow$ OK as `raiseException()` throws a `std::exception` $\rightarrow$ `RuntimeError`

# Exceptions in C++

## Examples

Two C++ functions `void raiseException()` and `void raiseBadAlloc()` defined in `except_cy.h`

Exception Example 2

```
cdef extern from 'except_cy.h'
        cdef void raiseException() except +MemoryError
def tryIt():
        try:
                raiseException()
        except RuntimeError as e:
                print(e)
```

⇒ Not OK as `raiseException()` throws a `std::exception` which is explicitly transformed into a `MemoryError`

# Exceptions in C++

## Examples

Two C++ functions `void raiseException()` and `void raiseBadAlloc()` defined in `except_cy.h`

Exception Example 3

```
cdef extern from 'except_cy.h'
        cdef void raiseBadAlloc() except +
def tryIt():
        try:
                raiseBadAlloc()
        except RuntimeError as e:
                print(e)
```

⇒ Not OK as `raiseBadAlloc()` throws a `std::bad_alloc` which is transformed into a `MemoryError`

# Exceptions in C++

## Examples

Two C++ functions `void raiseException()` and `void raiseBadAlloc()` defined in `except_cy.h`

Exception Example 4

```
cdef extern from 'except_cy.h'
        cdef void raiseBadAlloc() except +
def tryIt():
        try:
                raiseBadAlloc()
        except MemoryError as e:
                print(e)
```

⇒ OK as `raiseBadAlloc()` throws a `std::bad_alloc` which is transformed into a `MemoryError`

# Exceptions in C++

## Examples

Two C++ functions `void raiseException()` and `void raiseBadAlloc()` defined in `except_cy.h`

Exception Example 5

```
cdef void raise_py_error() except *:
        raise MemoryError("Problem")
cdef extern from 'except_cy.h':
        cdef void raiseBadAlloc() except +raise_py_error
def tryIt():
        try:
                raiseBadAlloc()
        except MemoryError as e:
                print(e)
```

⇒ OK as `raise_py_error()` throws an error

# Exceptions in C++

## Examples

Two C++ functions `void raiseException()` and `void raiseBadAlloc()` defined in `except_cy.h`

Exception Example 6

```
cdef void raise_py_error() except *:
        pass
cdef extern from 'except_cy.h':
        cdef void raiseBadAlloc() except +raise_py_error
def tryIt():
        try:
                raiseBadAlloc()
        except MemoryError as e:
                print(e)
```

⇒ Not OK as no error is thrown by `raise_py_error()`

# Integration of C++ Classes

Assuming a C++ class `Rectangle`

Rectangle.h – C++ header file

```
namespace shapes {
        class Rectangle {
        public:
                int x0, y0, x1, y1;
                Rectangle(int x0, int y0, int x1, int y1);
                ~Rectangle(); // destructor
                int getLength();
                int getHeight();
                int getArea();
                void move(int dx, int dy);
        };
}
```

# Integration of C++ Classes

Assuming a C++ class `Rectangle`

Rectangle.cpp - C++ implementation file

```cpp
#include "Rectangle.h"
#include <iostream>
using namespace shapes;
Rectangle::Rectangle(int X0, int Y0, int X1, int Y1) {
        x0 = X0;
        y0 = Y0;
        x1 = X1;
        y1 = Y1;
        std::cout << "Here I am" << std::endl;}
Rectangle::~Rectangle() {
        std::cout << "Byebye" << std::endl;}
...
```

# Integration of C++ Classes

Now exposing it to Cython . . .

rect.pyx - expose interface in Cython

```
# distutils: language = c++
# distutils: sources = Rectangle.cpp
cdef extern from "Rectangle.h" namespace "shapes":
        cdef cppclass Rectangle:
                Rectangle(int, int, int, int) except +
                int x0, y0, x1, y1
                int getLength()
                int getHeight()
                int getArea()
                void move(int, int)
```

# Integration of C++ Classes

. . . and using it! Directly in Cython . . .

rect.pyx - inclusion in Cython

```
def tryIt():
        cdef Rectangle* r
        try:
                r = new Rectangle(1,2,3,4)
                print("My length is {0:f}".format(r.getLength()))
                print("My first x-coordinate is {0:f}".format(r.x0))
        finally:
                del r
```

# Integration of C++ Classes

. . . and using it! . . . or to create class in Cython accessible in Python

rect.pyx - create wrapping class in Cython

```
cdef class PyRectangle:
        cdef Rectangle *thisptr
        def __cinit__(self, int x0, int y0, int x1, int y1):
                self.thisptr = new Rectangle(x0, y0, x1, y1)
        def __dealloc__(self):
                del self.thisptr
        def getLength(self):
                return self.thisptr.getLength()
        def getHeight(self):
                return self.thisptr.getHeight()
        ...
```

# Special features: STL Stuff with SWIG

- Dedicated interface files need to be integrated when running SWIG
- . . . and templates for **each** containers + **each** content need to be defined

SWIG interface file with vectors and strings

```
...
%include "std_vector.i"
%include "std_string.i"
...
%template(dVector) std::vector<double>;
%template(rectVector) std::vector<Rectangle*>;
...
```

# Special features: Exceptions with SWIG

SWIG interface file with exceptions

```
...
%include "exception.i"
...
%exceptionclass ShapeError;
%exception *::whine {
    try {
        $action
    } catch(ShapeError & e) {
        ShapeError *ecopy = new ShapeError(e);
        PyObject *err = SWIG_NewPointerObj(ecopy, SWIGTYPE_p_ShapeError, 1);
        PyErr_SetObject(SWIG_Python_ExceptionType(SWIGTYPE_p_ShapeError), err);
        SWIG_fail;
    }
}
```

# Special features: Overloading

Cython deals the usual way with overloaded methods in C++:

Overloading that works (since not creating a Python class) - does work

```
cdef extern from "Rectangle.h" namespace "shapes":
        ...
        void move(int, int)
        void move(int)
```

...but it cannot happen in a Python wrapper class:

Need to avoid overloading (since creating a Python class) - does not work

```
cdef class PyRectangle:
        ...
        def move(self,dx,dy):
                return self.thisptr.move(dx,dy)
        def move(self,d):
                return self.thisptr.move(d)
```

# Special features: Inheritance

As in Python C++ classes can inherit from parent classes including overriding of methods

Inheritiance in C++ header file

```
class Shape {
public:
        ...
        void virtual printInfo(); // Prints "Shape"
};
class Rectangle : public Shape {
public:
        ...
        void printInfo(); // Prints "Rectangle"
};
```

# Special features: Inheritance

Cython can also deal with this feature, but there are two points to keep in mind:
1. If parent class is also exposed to cython, no redefinition of overridden methods is required (and also allow → mis-interpreted as overloading)

Exposing inheritance in Cython

```
cdef extern from "Rectangle.h" namespace "shapes":
        cdef cppclass Shape:
                Shape() except +
                void printInfo()
        cdef cppclass Rectangle(Shape):
                Rectangle(int, int, int, int) except +
                ...
                void printInfo() # causes problems
                ...
```

# Special features: Inheritance

2. The inheritance can only be transported into wrapper classes if child classes have the same set of methods as the mother class

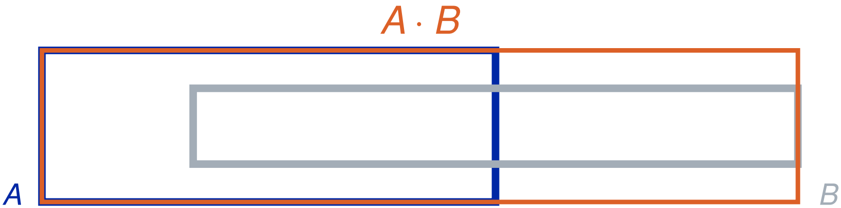
Wrapping inheritance in Cython

```
cdef class PyObject:
        cdef Object* thisptr
        def __cinit__(self):
                self.thisptr = new Object()
        def __dealloc__(self):
                del self.thisptr
        def printInfo(self):
                self.thisptr.printInfo()
cdef class PyRectangle(PyObject):
        def __cinit__(self,int x0,int y0,int x1,int y1):
                self.thisptr = new Rectangle(x0,y0,x1,y1)
```

# Special features: Operator Overloading

C++ as well as Python offers the potential to define operators for objects.

**Example with Rectangles:**




Multiplication of rectangles: Create a new rectangle acting as a bounding boox

# Special features: Operator Overloading

Wrapping operator overloading in C++

```
Rectangle operator*(Rectangle& rhs){
        double x0_n = min(min(x0,x1),min(rhs.x0,rhs.x1)),x1_n = max(max(x0,x1),max(rhs.x0,rhs.x1));
        double y0_n = min(min(y0,y1),min(rhs.y0,rhs.y1)),y1_n = max(max(y0,y1),max(rhs.y0,rhs.y1));
        return Rectangle(x0_n,y0_n,x1_n,y1_n);
};
```

Wrapping operator overloading in Cython

```
# to expose it to Cython
Rectangle operator*(Rectangle)

# in the wrapper class
def __mul__(PyRectangle lhs,PyRectangle rhs):
        res = PyRectangle(0,0,0,0)
        res.thisptr[0] = lhs.thisptr[0]*rhs.thisptr[0] # ptr deref
        return res
```

# Arrays

Arrays in cython are usually treated via typed memoryviews (*e.g.* `double[:,:]` means a two-dimensional array of doubles, *i.e.* compatible with *e.g.* `np.ones((3,4))`)

Further you can specify which is the fastest changing index by `:1`, *e.g.*

- `double[::1,:,:]` is a F-contiguous three-dimensional array
- `double[:,:,::1]` is a C-contiguous three-dimensional array
- `double[:,::1,:]` is neither F- nor C-contiguous

For example a variable `double[:,::1] a` has as NumPy arrays variables like `shape` and `size` and the elements can be accessed by `a[i,j]`

**But be aware: NumPy is already heavily optimised, so do not to reinvent the wheel!**