



Need for Speed – Python meets C/C++

Scientific Programming with Python

Christian Elsasser

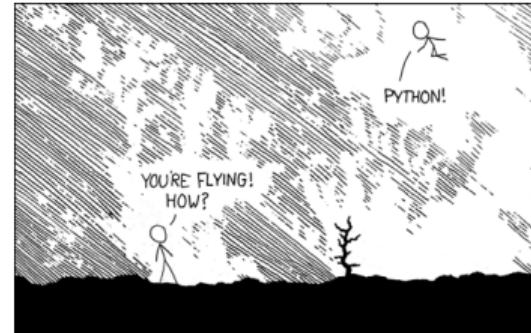
Partially based on a talk by Stéfan van der Walt



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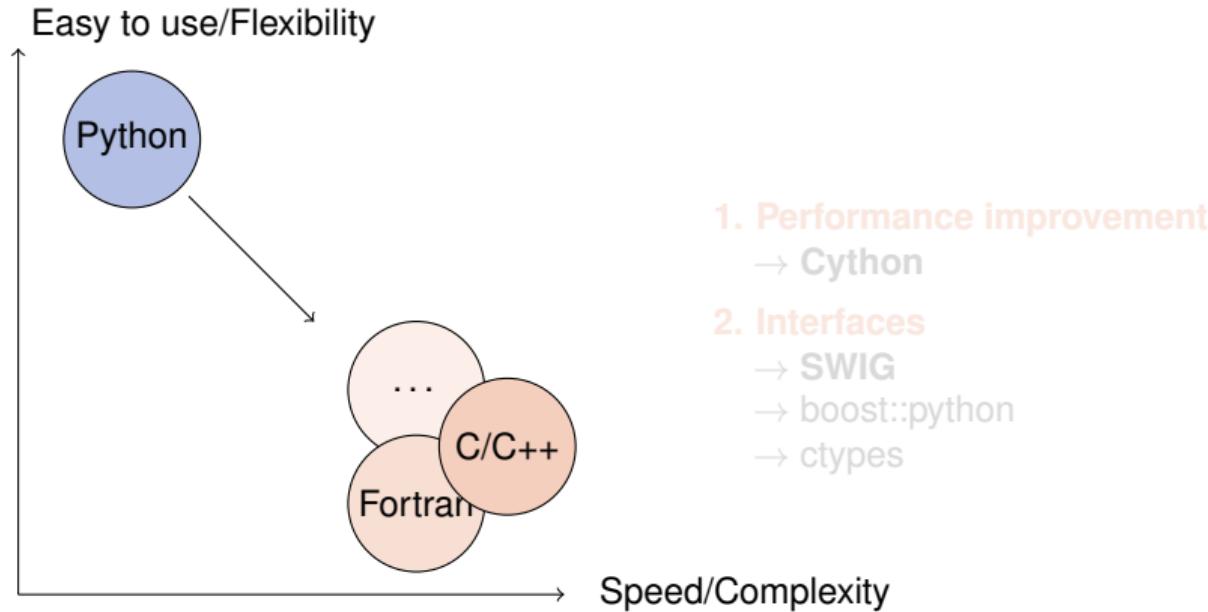
Python is nice, but by construction slow ...





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

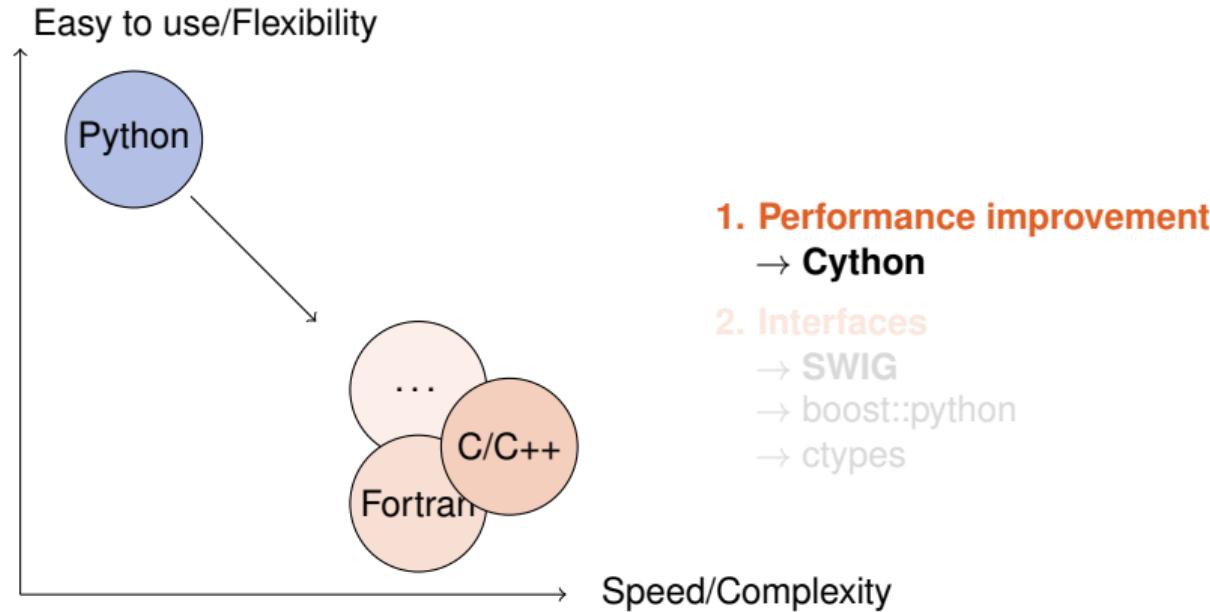
(or something similar, e.g. if you don't feel too young to use Fortran)





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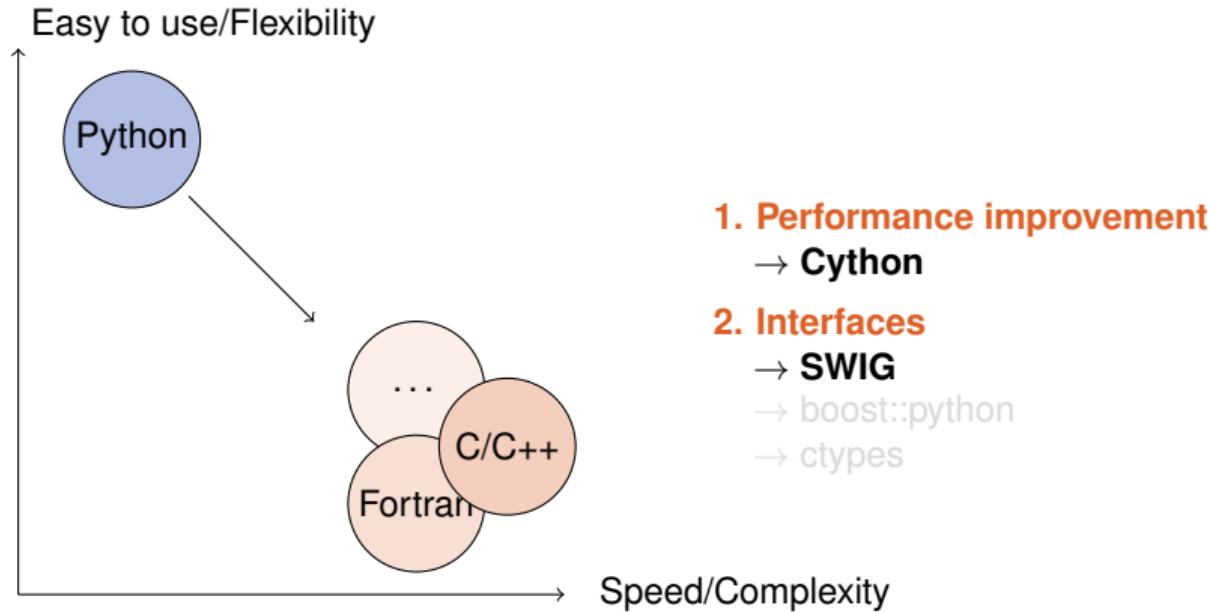
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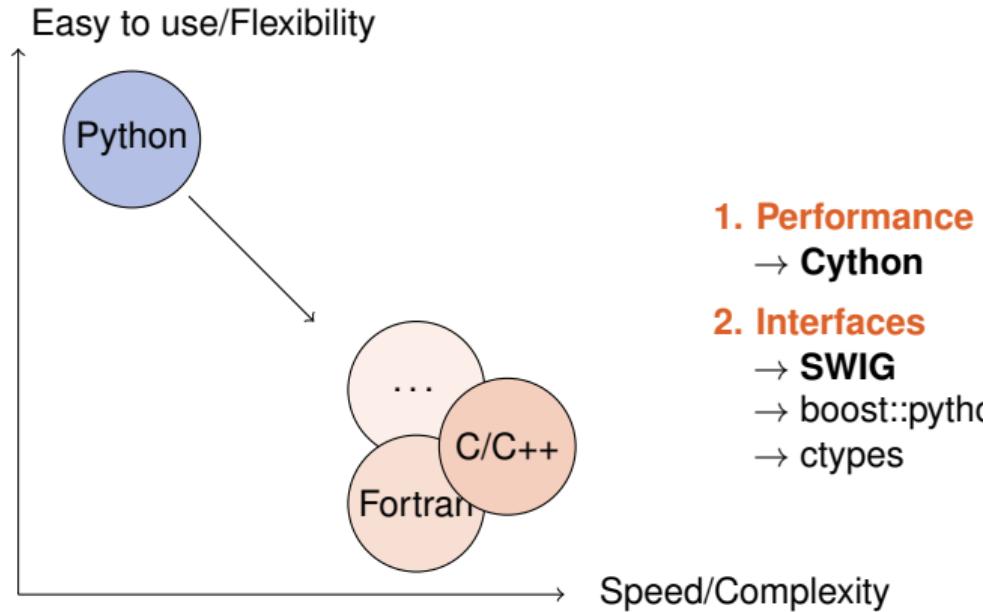
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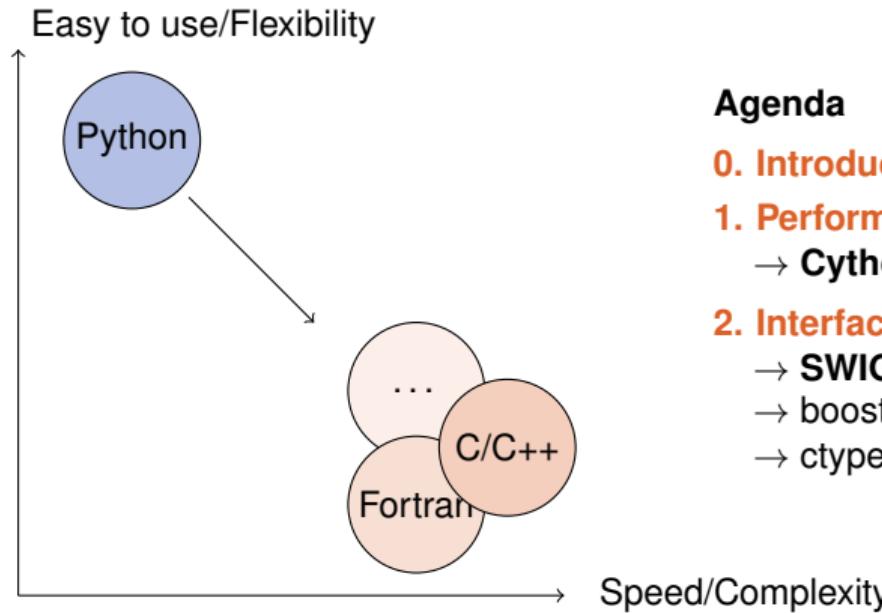


1. **Performance improvement**
→ Cython
2. **Interfaces**
→ SWIG
→ boost::python
→ ctypes



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

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



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)**

⇒ 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

```
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.
- ▶ It allows to write C/C++ extensions for Python **with limited effort writing them**.
- ▶ **C/C++ routines can be integrated** into Python code.

⇒ Every valid Python statement is also valid when using cython.

⇒ Code needs to be compiled → **It takes time!**

Cython (v0.29.23 and 3.0) 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
(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):  
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    return a
```

- ▶ Type declaration (`cdef`) \Rightarrow Python/Cython knows what to expect



Benchmark One: Fibonacci series

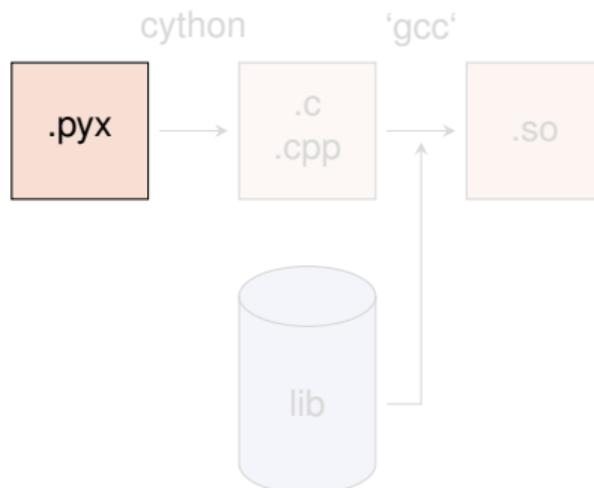
Fibonacci function - Cython

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



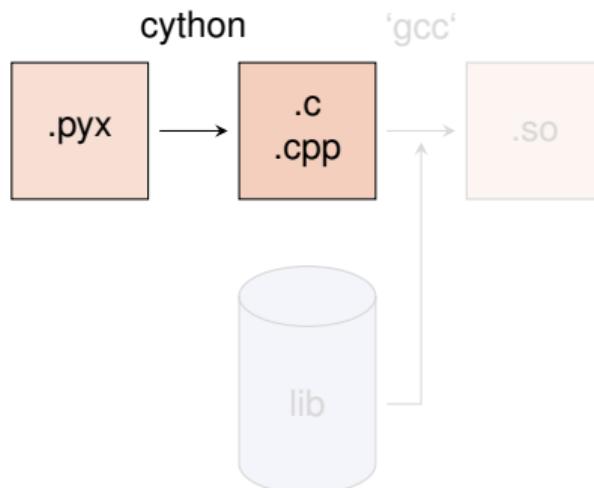
Shared object (<name>.so) can be imported into Python with `import <name>`

1. Compile Cython code to C/C++ code
`cython3 -3 <name>.pyx`
2. Compile shared object file (*i.e.* library)
`gcc [options] -fPIC -O2 -Wall
-I<path_to_python_include>
-L<path_to_python_library>
<name>.c -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`

School-Laptops:
`gcc -shared -fPIC -O2 -Wall
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Compiling Cython Code (The hard way)



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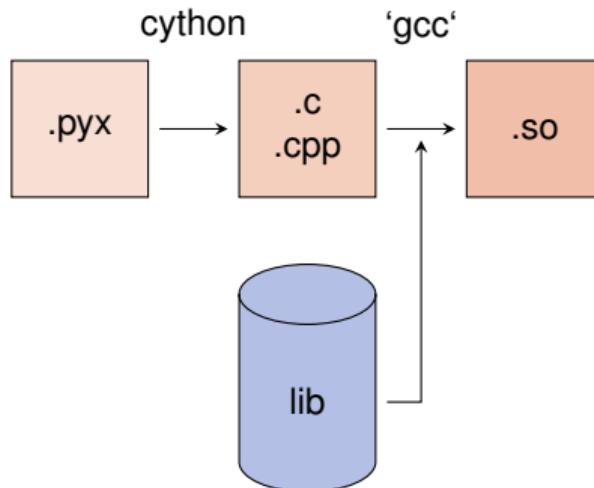
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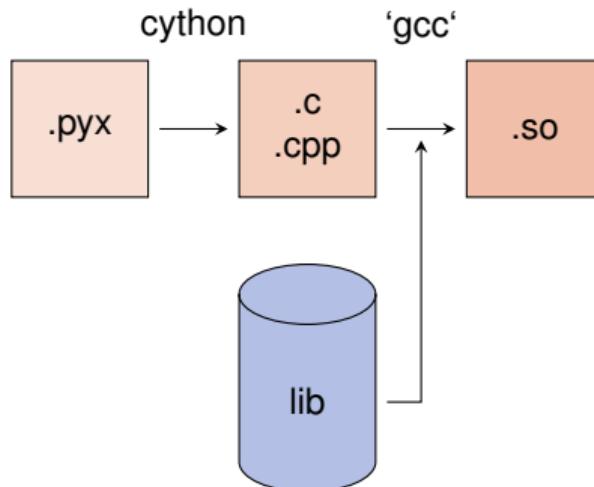
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Compiling Cython Code (The hard way)



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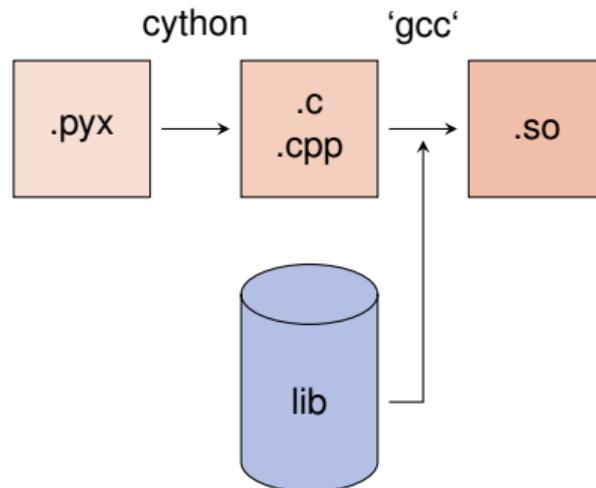
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Compiling Cython Code (The hard way)



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School-Laptops:

```
gcc -shared -fPIC -O2 -Wall  
-I/usr/include/python3.9/  
<name>.c -o <name>.so
```



Compiling Cython Code (The easy way)

Support via `setuptools` for building and installing Python modules ⇒ applicable for cython

Cython setup script

```
from setuptools import setup
from Cython.Build import cythonize

setup(ext_modules = cythonize([<name of .pyx files>],
                           language_level=3
))
```

Execute: `python setup.py build_ext --inplace`

Creates a .c/.cpp file for each .pyx file, then compiles it to an executable (in `build` sub-directory) 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

- ▶ Investigate room for improvements with cython
- ▶ Testing of different 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) linking to external C/C++ libraries
- ▶ Configuring 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 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_pyx.c

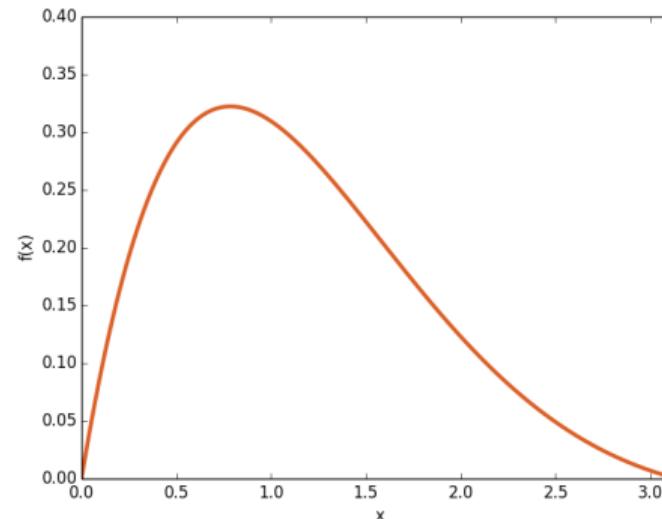
1: # Calculation of n-th fibonacci number
+2: def fib(n):
+3:     a,b = 1,1
+4:     for i in range(n):
+5:         a,b = a+b,a
+6:     return a
    __Pyx_XDECREF(__pyx_r);
    __Pyx_INCREF(__pyx_v_a);
    __pyx_r = __pyx_v_a;
    goto __pyx_L0;
```

- ▶ Not every yellow part can be improved!



Benchmark Two: Numerical Integration

$$\int_0^{\pi} f(x) = \sin x \cdot e^{-x} \quad \text{Exact result: } \frac{e^{-\pi} + 1}{2} = 0.521607$$





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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

$$\int_0^{\pi} f(x) = \sin x \cdot e^{-x} \quad \text{Exact result: } \frac{e^{-\pi} + 1}{2} = 0.521607$$

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

$$\int_0^{\pi} f(x) = \sin x \cdot e^{-x} \quad \text{Exact result: } \frac{e^{-\pi} + 1}{2} = 0.521607$$

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

$$\int_0^{\pi} f(x) = \sin x \cdot e^{-x} \quad \text{Exact result: } \frac{e^{-\pi} + 1}{2} = 0.521607$$

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

$$\int_0^{\pi} f(x) = \sin x \cdot e^{-x} \quad \text{Exact result: } \frac{e^{-\pi} + 1}{2} = 0.521607$$

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

$$\int_0^{\pi} f(x) = \sin x \cdot e^{-x} \quad \text{Exact result: } \frac{e^{-\pi} + 1}{2} = 0.521607$$

- ▶ Return values of function can be specified via the key word `cdef`
- ▶ `cpdef` ⇒ 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	→	<code>std::vector</code>	→	<code>list</code>
iterable	→	<code>std::list</code>	→	<code>list</code>
iterable	→	<code>std::set</code>	→	<code>set</code>
iterable (len 2)	→	<code>std::pair</code>	→	<code>tuple (len 2)</code>
dict	→	<code>std::map</code>	→	<code>dict</code>
bytes	→	<code>std::string</code>	→	<code>bytes</code>





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 containers (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 ⇒ 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 ⇒ 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 ambiguous 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 ambiguous 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++



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

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

⇒ But capturing in cython and translating to Python exceptions/errors is possible!



Exceptions in C++

... and how to tackle them!

- ▶ `cdef <C++ function>() except +`
⇒ translates a C++ exception into a Python error according to the right-hand scheme
- ▶ `cdef <C++ function>() except +<Python Error>` e.g. `MemoryError` ⇒ translates every thrown C++ exception into a `MemoryError`
- ▶ `cdef <C++ function>() except +<function raising Python error>` ⇒ 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
<code>bad_alloc</code>	→	<code>MemoryError</code>
<code>bad_cast</code>	→	<code>TypeError</code>
<code>domain_error</code>	→	<code>ValueError</code>
<code>invalid_argument</code>	→	<code>ValueError</code>
<code>ios_base::failure</code>	→	<code>IOError</code>
<code>out_of_range</code>	→	<code>IndexError</code>
<code>overflow_error</code>	→	<code>OverflowError</code>
<code>range_error</code>	→	<code>ArithmeError</code>
<code>underflow_error</code>	→	<code>ArithmeError</code>
(all others)	→	<code>RuntimeError</code>



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)
```



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 Functions in Cython

Starting point: .c/.h file for function definition *e.g.* `fast_inv_sqrt`

1. Expose it to **Cython** by **declaring the function signature**.
2. Integrating it into Cython either via direct usage or by defining a wrapper function.

C function definition in `c_func.c`

```
#include <stdio.h>

double fast_inv_sqrt( double number )
{
    ...
}
```



Integration of C Functions in Cython

Starting point: .c/.h file for function definition *e.g.* `fast_inv_sqrt`

1. Expose it to **Cython** by declaring the function signature.
2. Integrating it into Cython either via direct usage or by **defining a wrapper function**.

Wrapping the function

```
cdef extern from "c_func.c":  
    double fast_inv_sqrt(double number)  
  
def py_fis(number:double) -> double:  
    return fast_inv_sqrt(number)  
  
def norm_vector(values:list) -> list:  
    length_squared = sum([x**2 for x in values])  
    return [x*fast_inv_sqrt(length_squared) for x in values]
```



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 **declaring 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)
```



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

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1. Expose it to **Cython** by declaring the class structure and method signatures
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Wrapping the class for Python

```
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()
    ...
    
```

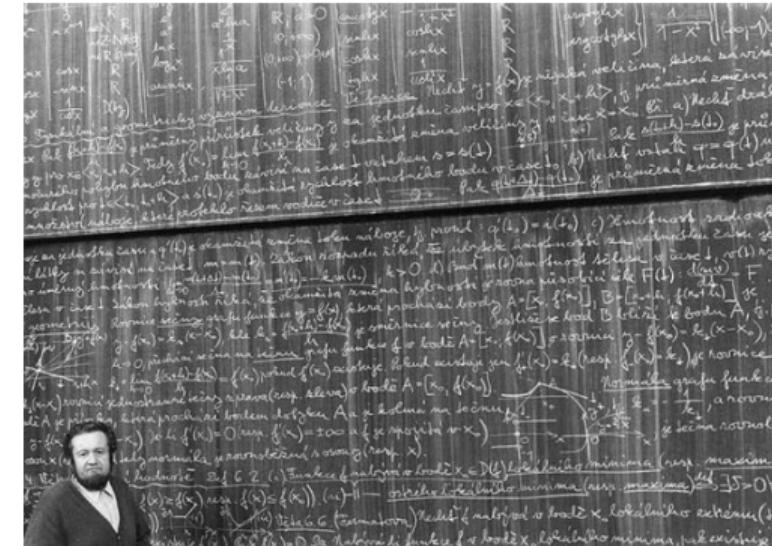


Automatic Wrappers

...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





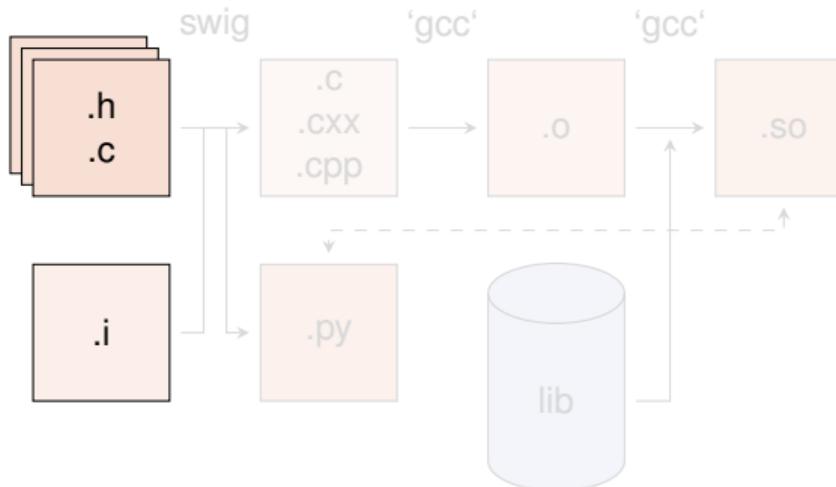
SWIG

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



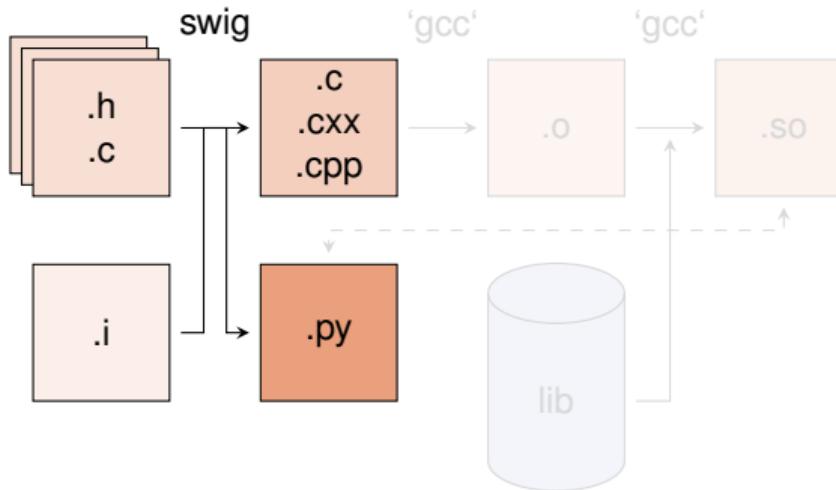
1. Create python wrapper and necessary C files
`swig -c++ -python <name>.i`
2. Compile shared object (*i.e.* library)

Step 2 best handed to setuptools
(`setup.py`)
`python setup.py build_ext
--inplace`

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



SWIG – in a Nutshell



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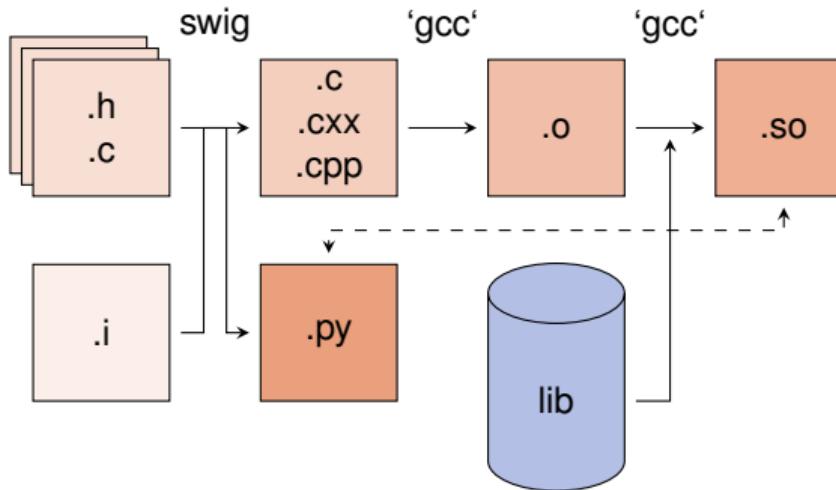
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SWIG – in a Nutshell



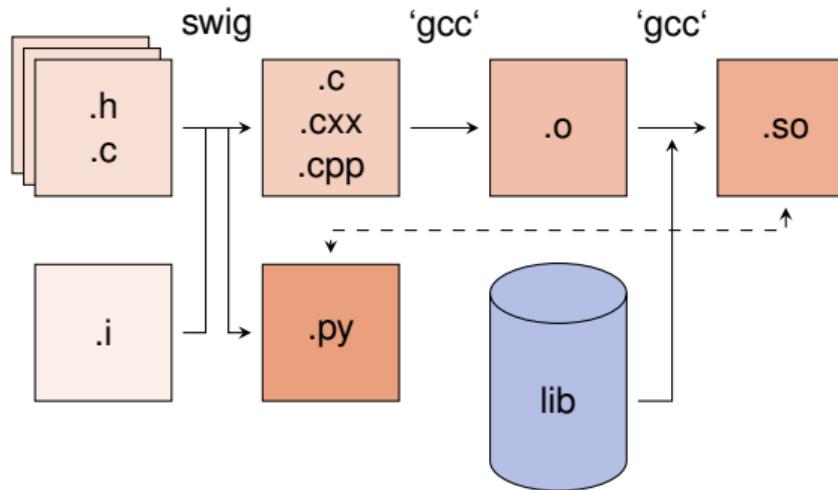
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SWIG – in a Nutshell



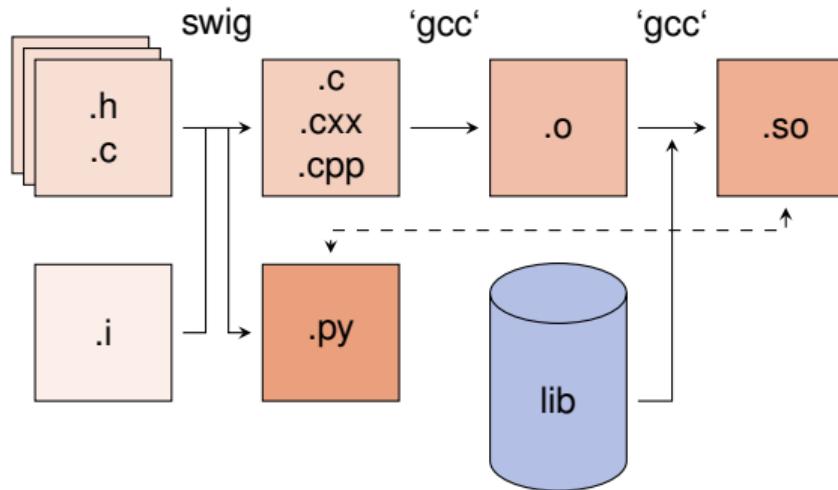
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SWIG – in a Nutshell



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SWIG – The interface file

Main configuration with interface (.i) files

- ▶ specify which (header) file(s) contain(s) the C/C++ code to wrap
- ▶ define special data types (e.g. `std::vector<...>`)
- ▶ handle 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 setup.py file

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

- ▶ To build extension needs a different name than the module set up by SWIG (default: `_name`)
- ▶ Language option only needed 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



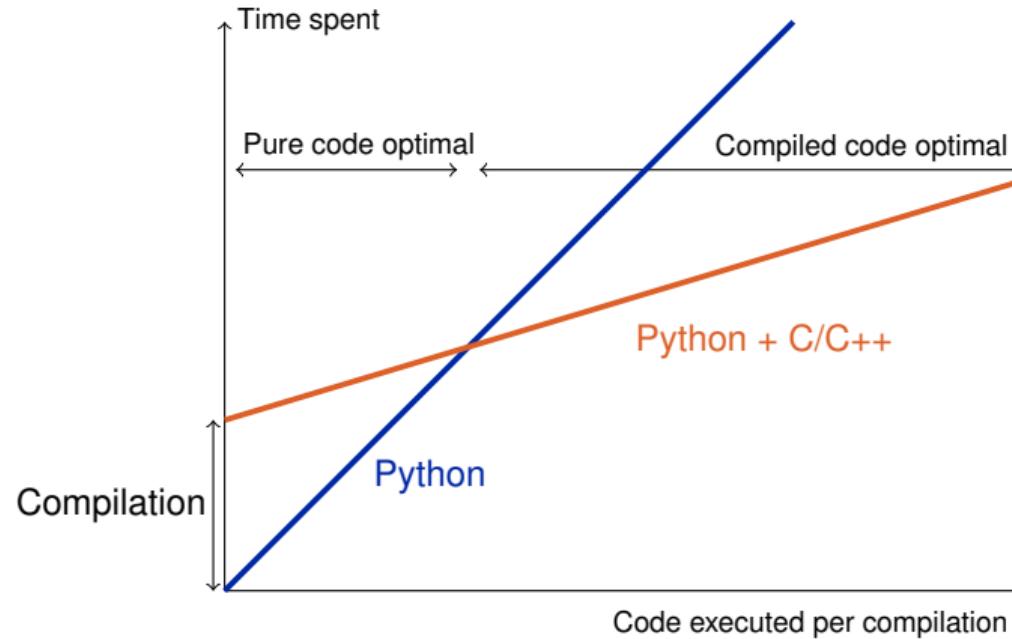
Conclusion

- ▶ 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!



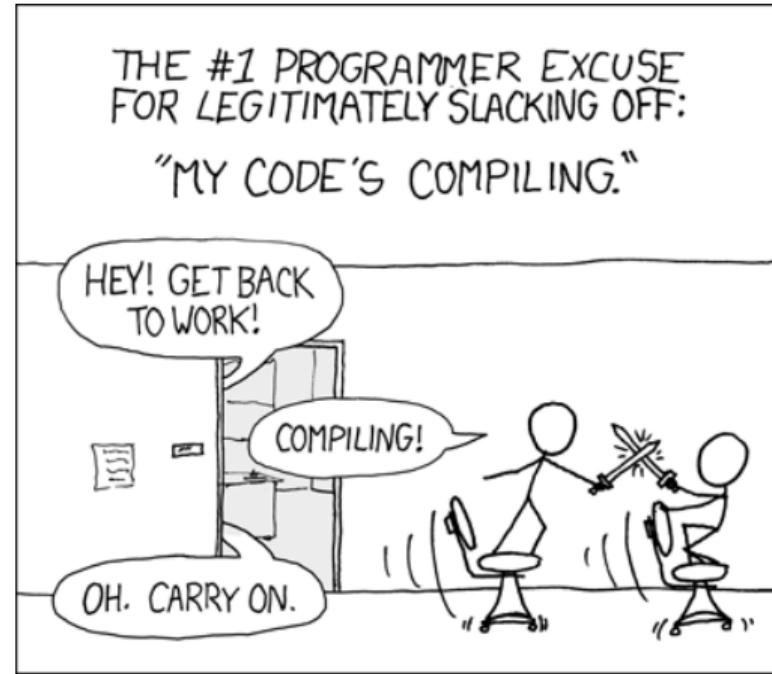


The Sweet Spot!





The End!





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>



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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)
```

⇒ OK as `raiseException()` throws a `std::exception` → `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 raiseException() except +MemoryError
def tryIt():
    try:
        raiseException()
    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 raiseException() except +MemoryError
def tryIt():
    try:
        raiseException()
    except RuntimeError 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 extern from 'except_cy.h'
    cdef void raiseException() except +MemoryError
def tryIt():
    try:
        raiseException()
    except RuntimeError 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 extern from 'except_cy.h'
    cdef void raiseException() except +MemoryError
def tryIt():
    try:
        raiseException()
    except RuntimeError 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 - Class 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 - Class implementation

```
#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_wrap.pyx - exposing the class to 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()
    ...
```



Integration of C++ Classes

... and using it!

Either in further cython code!

Using it in Cython code

```
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 for creating a Python (wrapper) class!

Wrapping the Class

```
# 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)
```



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

Interface file with advanced type def

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



Special features: Exceptions with SWIG

Interface file with exception definition -

```
...
%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 in the interface - it works

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

but it cannot happen in a Python wrapper class:

Overloading in the wrapper - it 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

C++ classes - inheritance

```
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)

----- C++ classes - inheritance wrapper -----

```
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: Inheritance

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

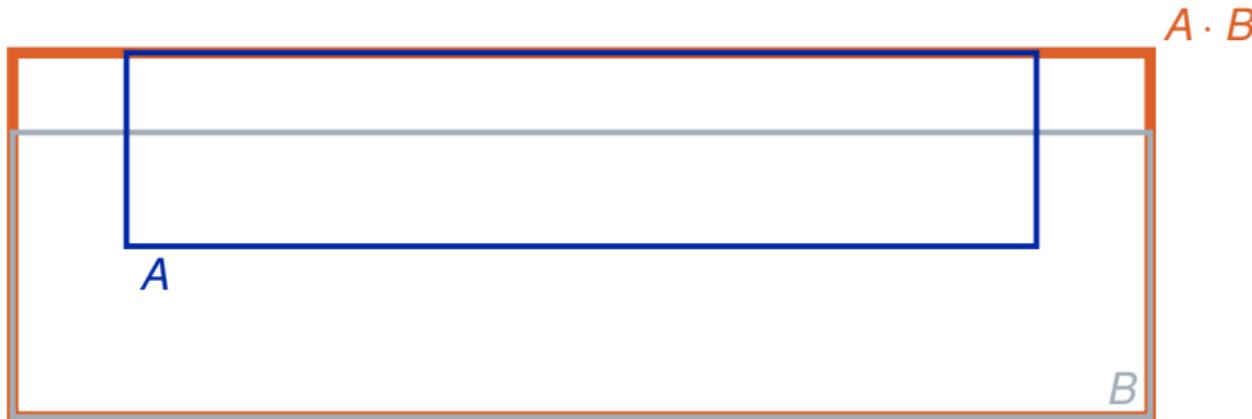
———— C++ classes - inheritance exposed ————

```
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: Operator Overloading

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

Example with Rectangles:



Multiplication of rectangles: Create the rectangle that is the bounding box of the two



Special features: Operator Overloading

C++ code - operator overloading

```
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);  
};
```

Cython wrapper - operator overloading

```
# 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, :, :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!