



# Need for Speed – Python meets C/C++

Scientific Programming with Python

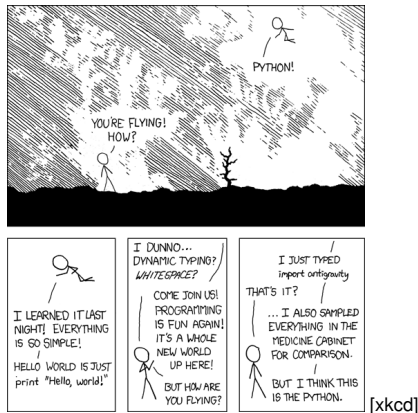
Christian Elsasser

Partially based on a talk by Stéfan van der Walt



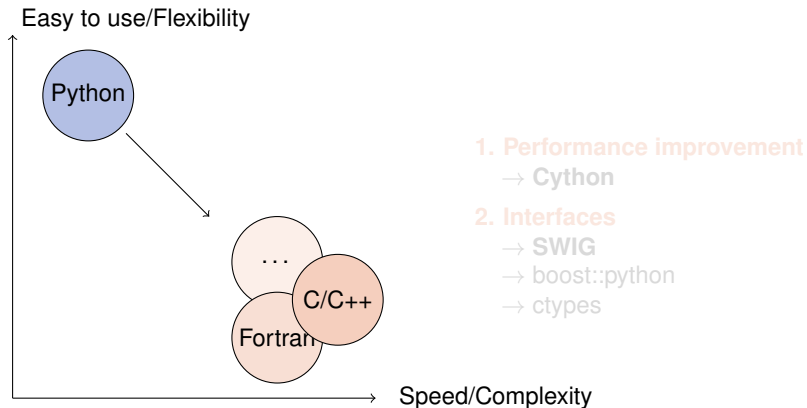
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## Python is nice, but by construction slow ...



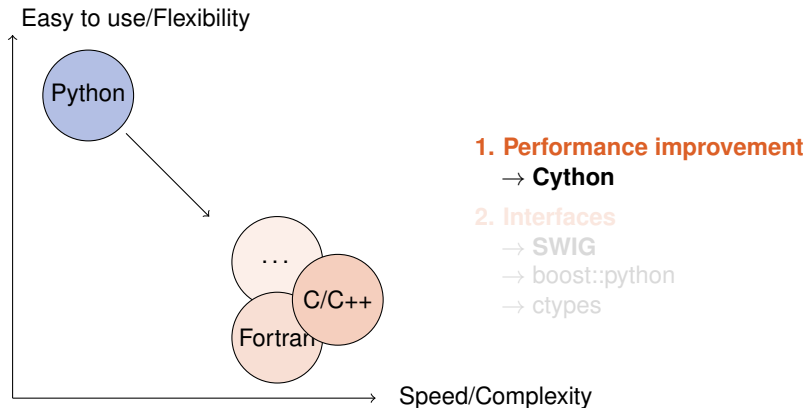
## ... why not therefore interfacing it with C/C++

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



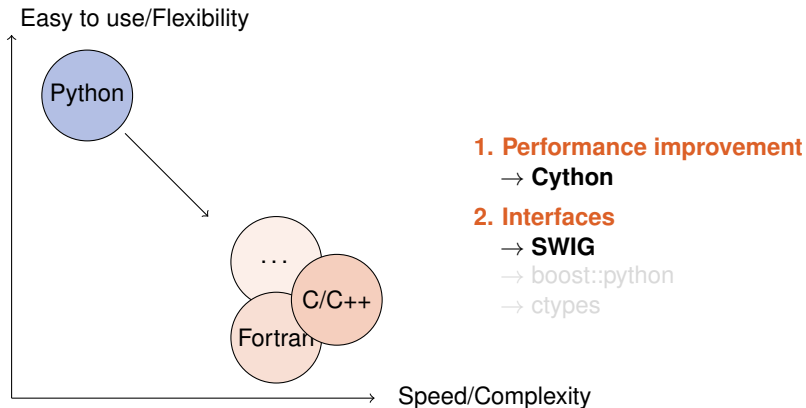
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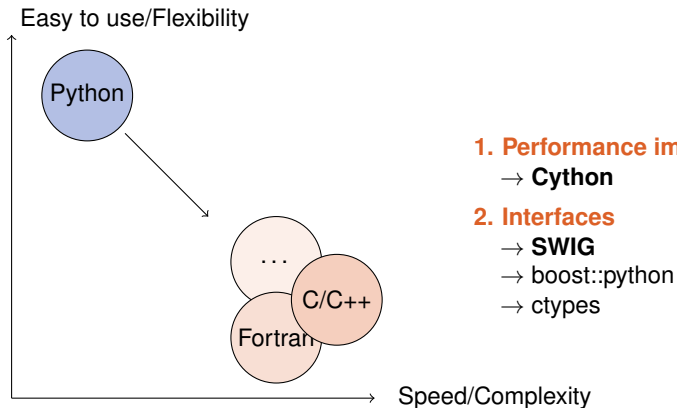
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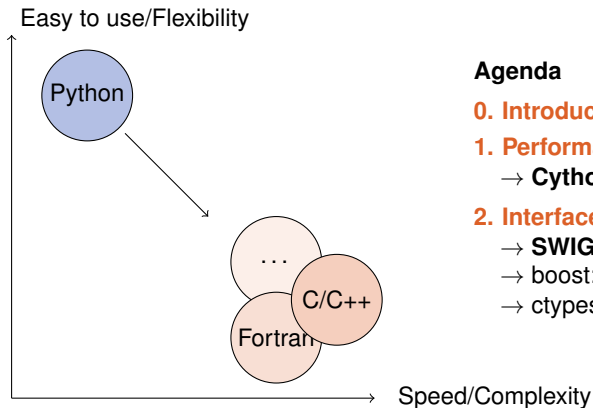
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### Agenda

#### 0. Introduction

#### 1. Performance improvement

→ **Cython**

#### 2. Interfaces

→ **SWIG**

→ **boost::python**

→ **ctypes**



## C++ on one Slide

[www.cplusplus.com](http://www.cplusplus.com) and [www.learncpp.com](http://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  
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    return a
```

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





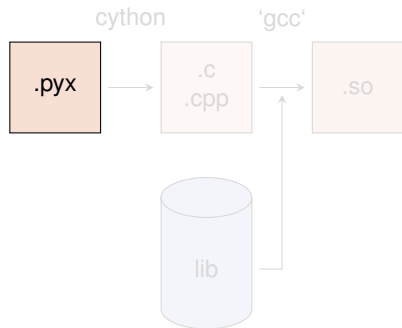
## Benchmark One: Fibonacci series

Fibonacci function - Cython

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def fib(int 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`

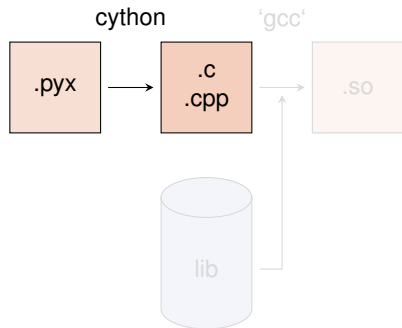
2. Compile shared object file (i.e. library)  
`gcc [options] -fPIC -O2 -Wall  
-I<path_to_python_include>  
-L<path_to_python_library>  
<name>.c -o <name>.so`

- ▶ 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  
-I/usr/include/python3.9/  
<name>.c -o <name>.so
```

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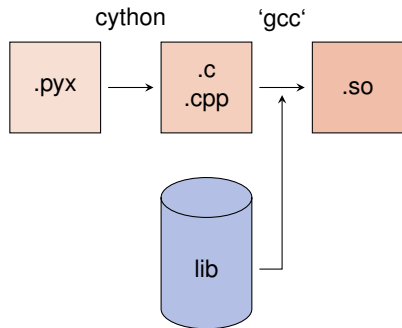
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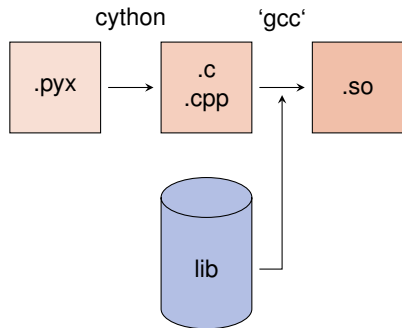
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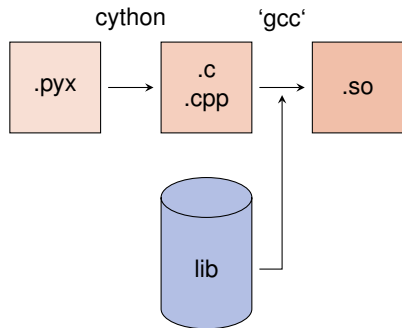
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## Compiling Cython Code (The hard way)



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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  $\Rightarrow$  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.

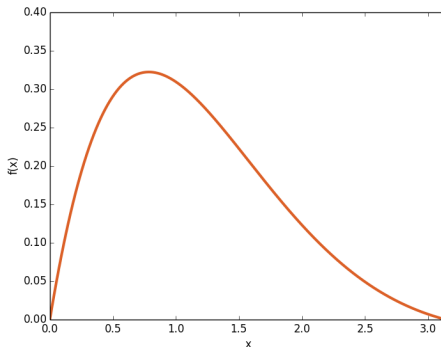
Raw output: [fib\\_py.c](#)

```
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

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





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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

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 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`  $\Rightarrow$  function also transparent to Python itself (no performance penalty)
- ▶ C/C++ library can be imported via `from libc/libc++.<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>	→	list
iterable	→	<code>std::list</code>	→	list
iterable	→	<code>std::set</code>	→	set
iterable (len 2)	→	<code>std::pair</code>	→	tuple (len 2)
dict	→	<code>std::map</code>	→	dict
bytes	→	<code>std::string</code>	→	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  $\Rightarrow$  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!  $\Rightarrow$  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  $\Rightarrow$  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 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>ArithmeticError</code>
<code>underflow_error</code>	→	<code>ArithmeticError</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.
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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)
```





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Wrapping the class for Python

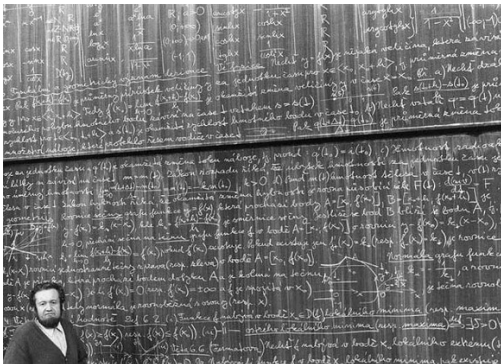
```
cdef class PyRectangle:
    cdef Rectangle *thisptr
    def __cinit__(self, int x0, int y0, int x1, int y1):
        self.thisptr = new Rectangle(x0, y0, x1, y1)
    def __dealloc__(self):
        del self.thisptr
    def getLength(self):
        return self.thisptr.getLength()
    def getHeight(self):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



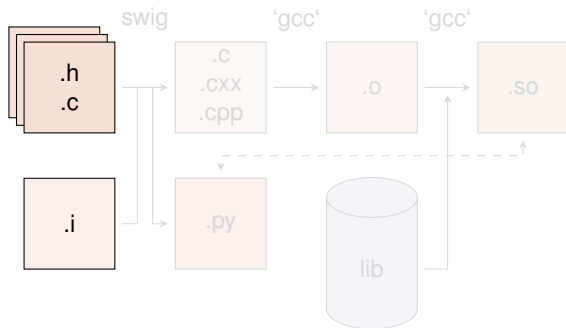


## SWIG

### 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

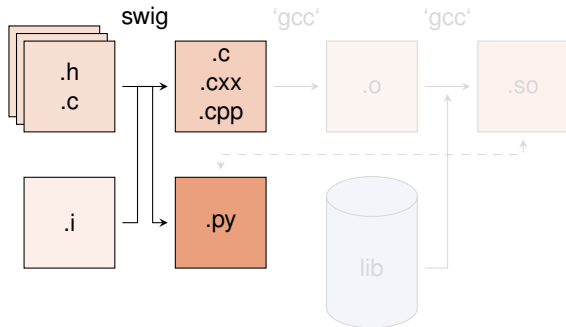


1. Create python wrapper and necessary C files  
`swig -c++ -python <name>.i`
2. Compile shared object (*i.e.* library)

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



1. Create python wrapper and necessary C files

```
swig -c++ -python <name>.i
```

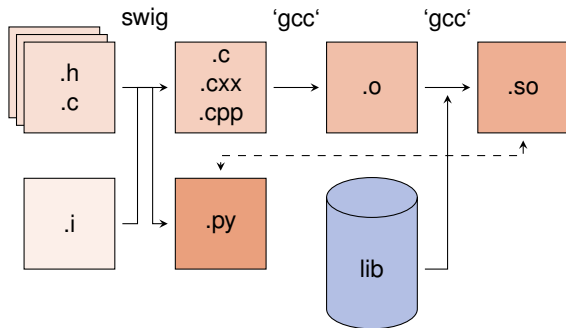
2. Compile shared object (*i.e.* library)

Step 2 best handed to setuptools  
(setup.py)

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

Module (<name>.py) can be imported into Python  
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## SWIG – in a Nutshell



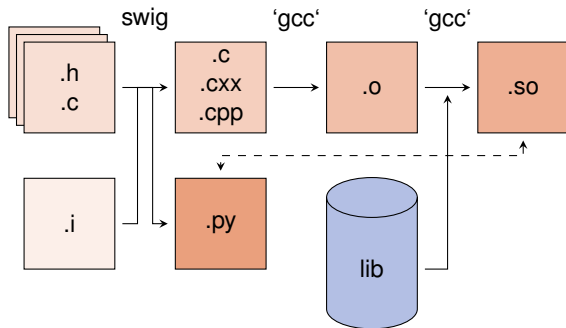
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## SWIG – in a Nutshell



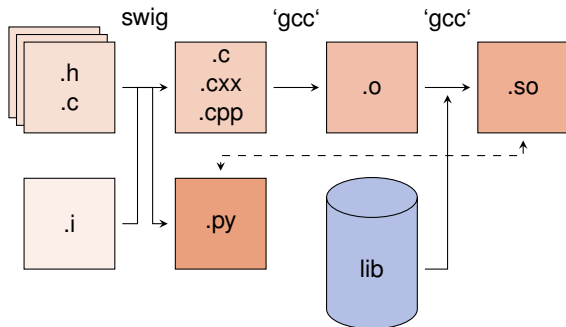
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## SWIG – in a Nutshell



1. Create python wrapper and necessary C files  
`swig -c++ -python <name>.i`
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(`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 – 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_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 SWIG (default: `_name`)
- ▶ Language option only needed for C++
- ▶ `python setup.py build_ext --inplace`



## A Few Remarks about SWIG

- ▶  $\text{SWIG} \approx$  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



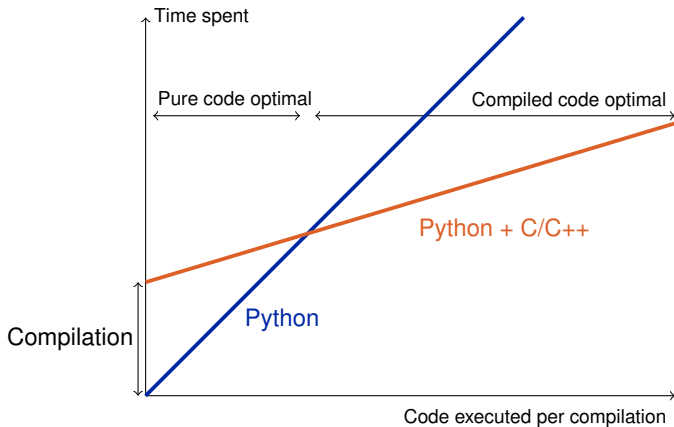
## Conclusion

- ▶ 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!

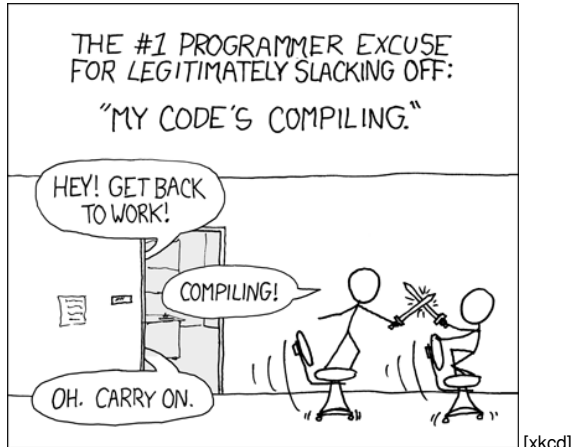




## The Sweet Spot!



## 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 8<sup>th</sup> 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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**Department of Physics**



# 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

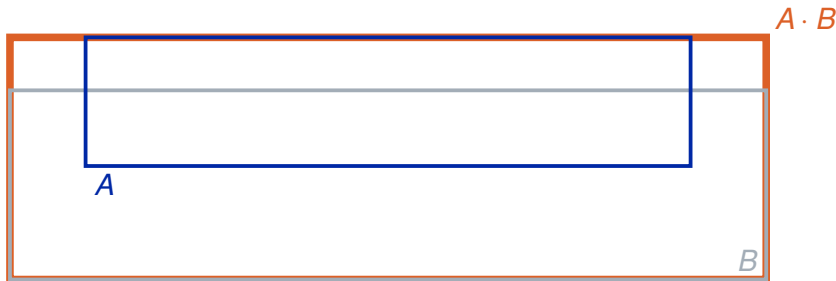
C++ classes - inheritance exposed

```
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, :]` 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!**