Need for Speed – Python meets C/C++

Scientific Programming with Python
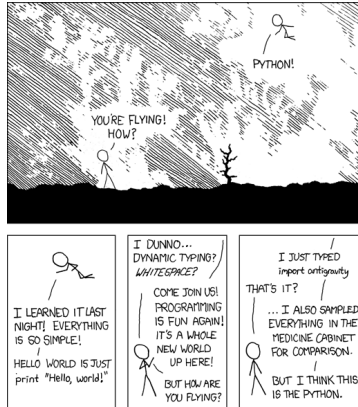
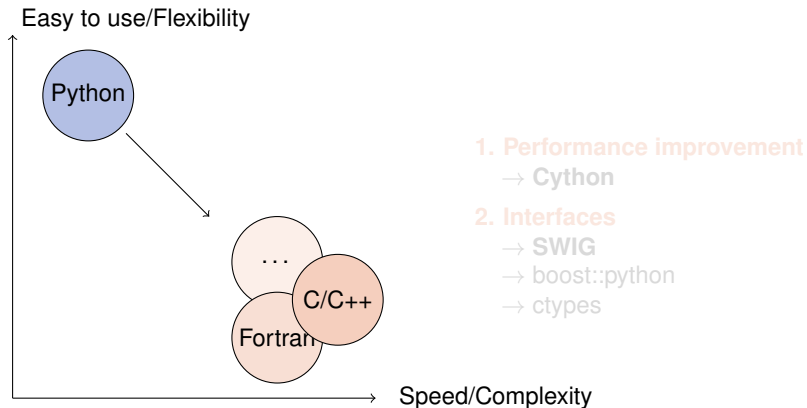Nicola Chiapolini (`Speaker`) & Christian Elsasser (`Author`)

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)

Easy to use/Flexibility

Python

1. **Performance improvement**
   → **Cython**

2. **Interfaces**
   → **SWIG**
   → boost::python
   → ctypes

. . .

C/C++

Fortran

Speed/Complexity

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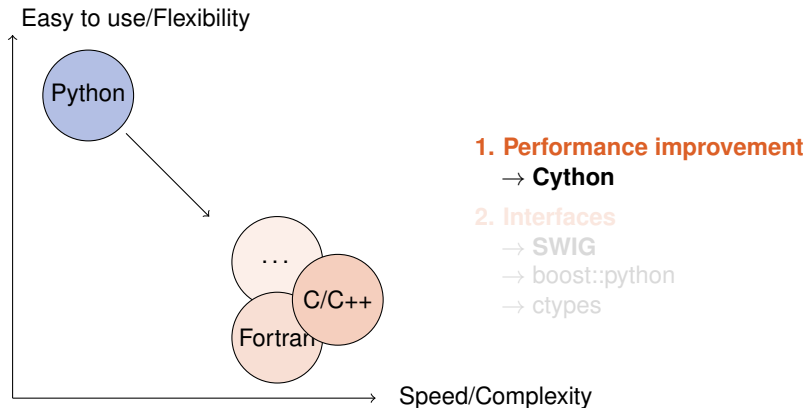
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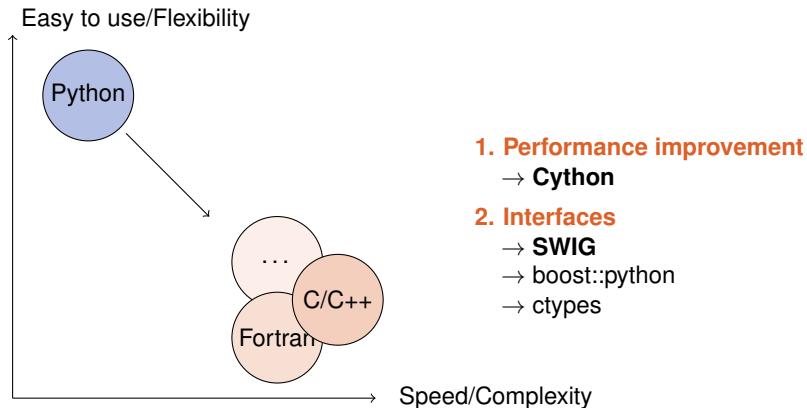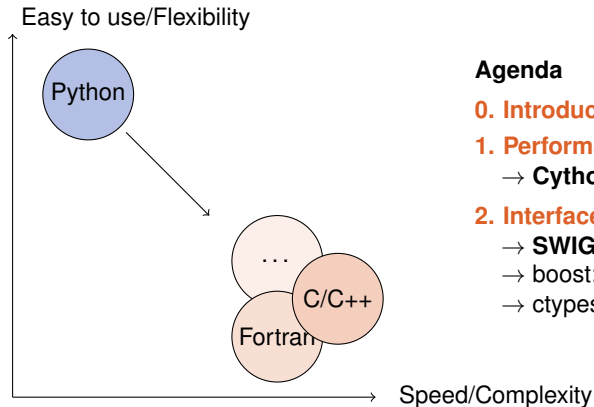
Python

C/C++

Fortran

. . .

Speed/Complexity

Agenda

0. Introduction

1. Performance improvement
  → **Cython**

2. Interfaces
  → **SWIG**
  → boost::python
  → ctypes

C++ on one Slide

- ▸ 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.
- ▶ ... 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.

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

⇒ Code needs to be compiled → Time!

- ▶ Translates you "C-enhanced" Python code into C/C++ code using the C API

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

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

Benchmark One: Fibonacci series

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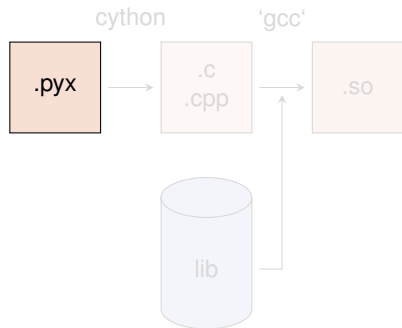
▶ A few (simple) modifications can easily change the CPU time by a factor of $\mathcal{O}(100)$

Compiling Cython Code (The hard way)

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`

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

Compiling Cython Code (The hard way)

cython

'gcc'

.pyx → .c / .cpp → .so

lib

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

1. Compile Cython code to C/C++ code
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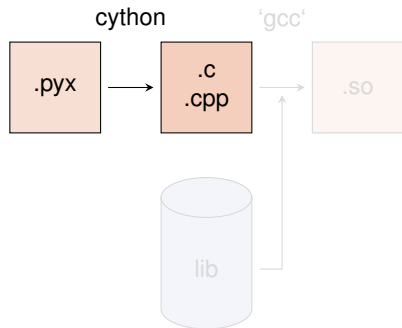2. Compile shared object file (*i.e.* library)
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   School-Laptops:
   `gcc -shared -fPIC -O2 -Wall`
   `-I/usr/include/python3.8/`
   `<name>.c -o <name>.so`

Compiling Cython Code (The hard way)

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.pyx → .c .cpp → .so

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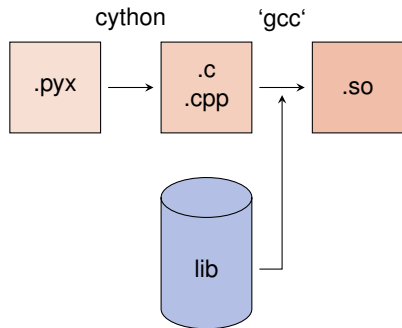   `gcc [options] -fPIC -O2 -Wall`
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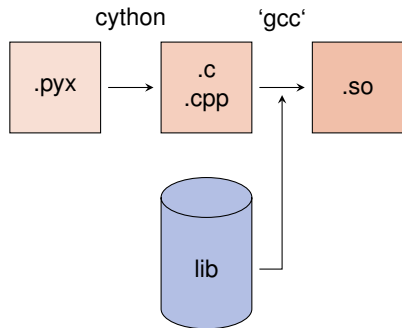   `gcc [options] -fPIC -O2 -Wall`
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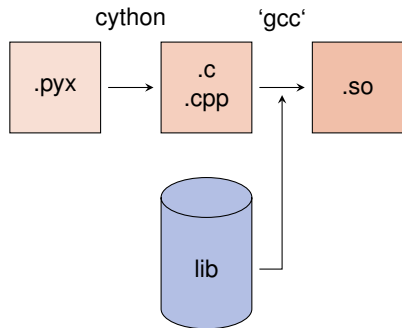
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   School-Laptops:
   `gcc -shared -fPIC -O2 -Wall`
   `-I/usr/include/python3.9/`
   `<name>.c -o <name>.so`

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 .pxy files>],
        language = "c++" #optional
))
```

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

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

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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

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

```
──────── 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

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

```
───── 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

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

```
─── 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

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

```cython
─────── 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

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

- 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/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 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
```

$\Rightarrow$ 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`-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
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

```cython
                          ───── 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)
```

$\Rightarrow$ 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)
```

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
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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()
      ...
```
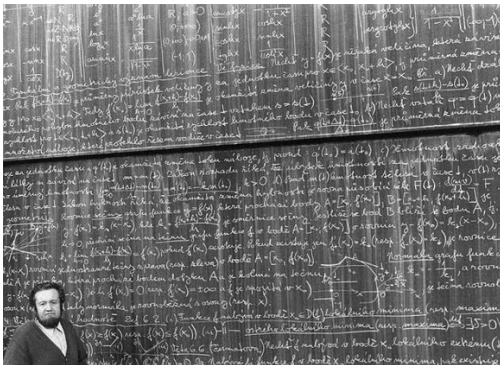
Automatic Wrappers

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

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

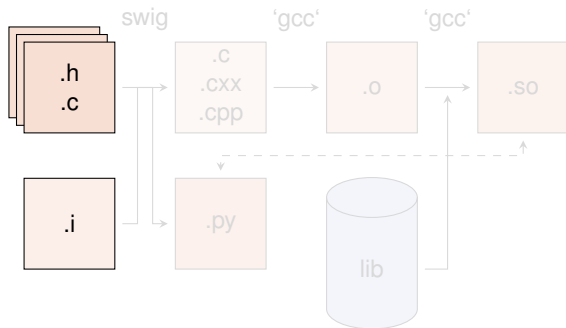Goal: creating compilable C/C++ code based on the Python C API

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 setuptool (`setup.py`)
   `python setup.py build_ext --inplace`

Moduel (`<name>.py`) can be imported into Python with `import name` ⇒ Shared object needs different name
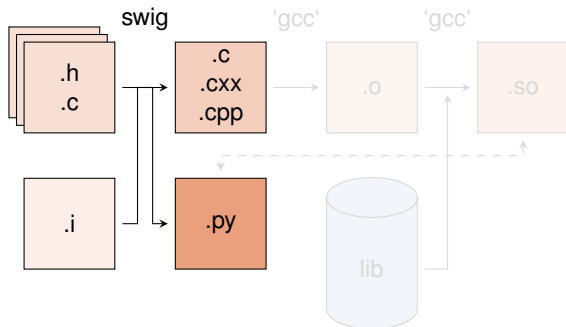
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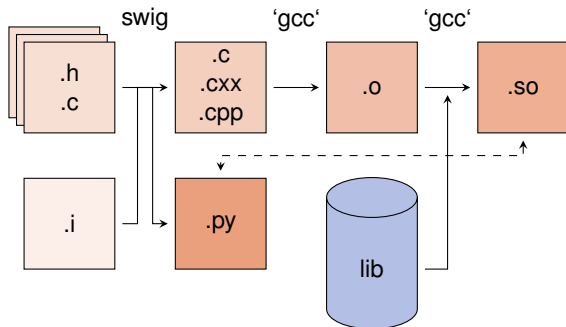2. Compile shared object (*i.e.* library)

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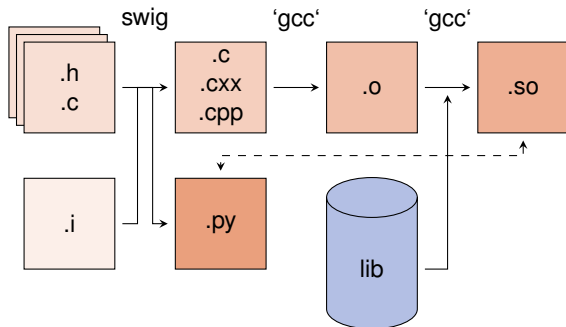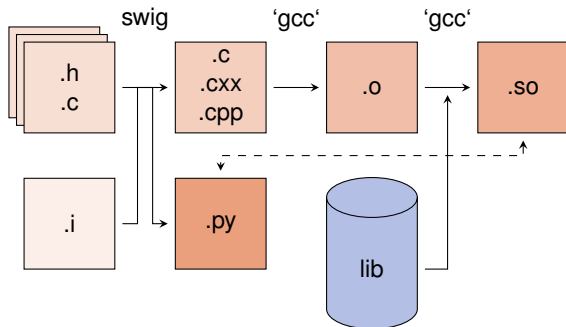## SWIG – in a Nutshell

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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_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

- ▶ 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

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 raiseException() except +MemoryError
def tryIt():
        try:
                raiseException()
        except RuntimeError as e:
                print(e)
```

$\Rightarrow$ 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)
```

$\Rightarrow$ 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)
```

$\Rightarrow$ 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`

```cpp
                        ┌─ 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!

```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)
```

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

```cpp
                        ═══ 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
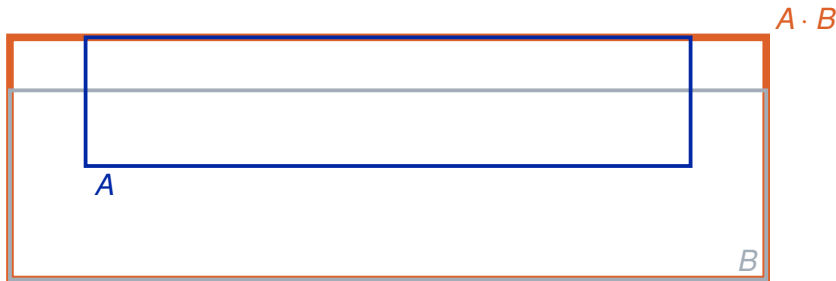
```
————————— C++ classes - inheritance exposed —————————
cdef extern from "Rectangle.h" namespace "shapes":
        cdef cppclass Shape:
                Shape() except +
                void printInfo()
        cdef cppclass Rectangle(Shape):
                Rectangle(int, int, int, int) except +
                ...
                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!