Speeding up scientific Python code using Cython

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Lecture Material

https://www.melbournebioinformatics.org.au/as
asia-pacific/cython

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- Motivation
- Motivation (continued)
- Use Cases
- Tutorial Overview

From Python to Cython

Handling NumPy Arrays

Parallelization

Wrapping C and C++ Libraries

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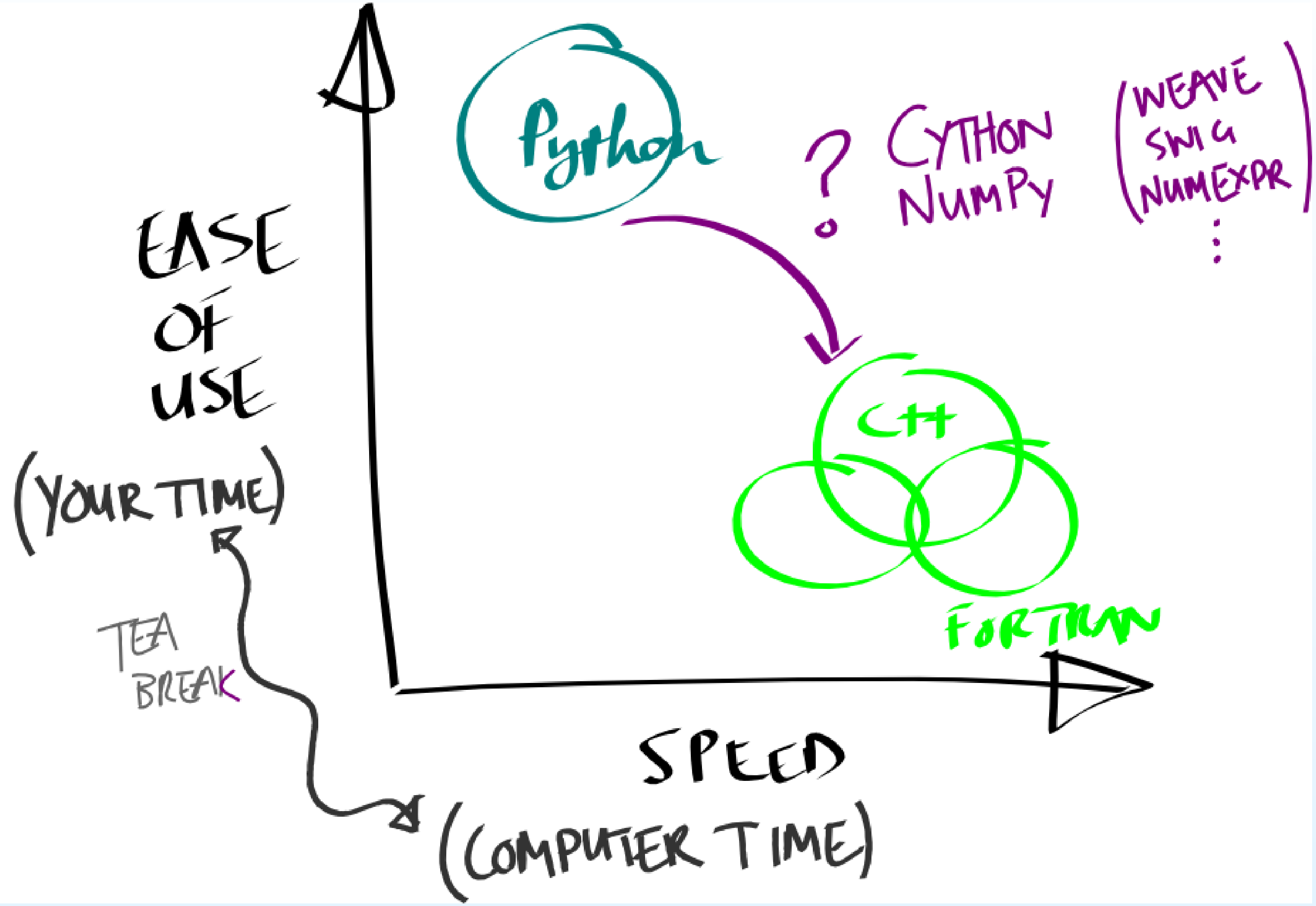
Motivation



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Motivation (continued)

- Cython allows us to cross the gap
- This is good news because
  - we get to keep coding in Python (or, at least, a superset)
  - but with the speed advantage of C
- You can't have your cake and eat it. *Or can you?*

Use Cases

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- Optimize execution of Python code (profile, like shown by Pietro yesterday)
- Wrap existing C and C++ code
- Breaking out of the Global Interpreter Lock; openmp
- Mixing C and Python, but without the pain of the Python C API

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Tutorial Overview

For this quick introduction, we'll take the following approach:

1. Take a piece of pure Python code and benchmark (we'll find that it is too slow)
2. Run the code through Cython, compile and benchmark (we'll find that it is somewhat faster)
3. Annotate the types and benchmark (we'll find that it is quite a bit faster)

Then we'll look at how Cython allows us to

- Work with NumPy arrays
- Use multiple threads from Python
- Wrap native C libraries

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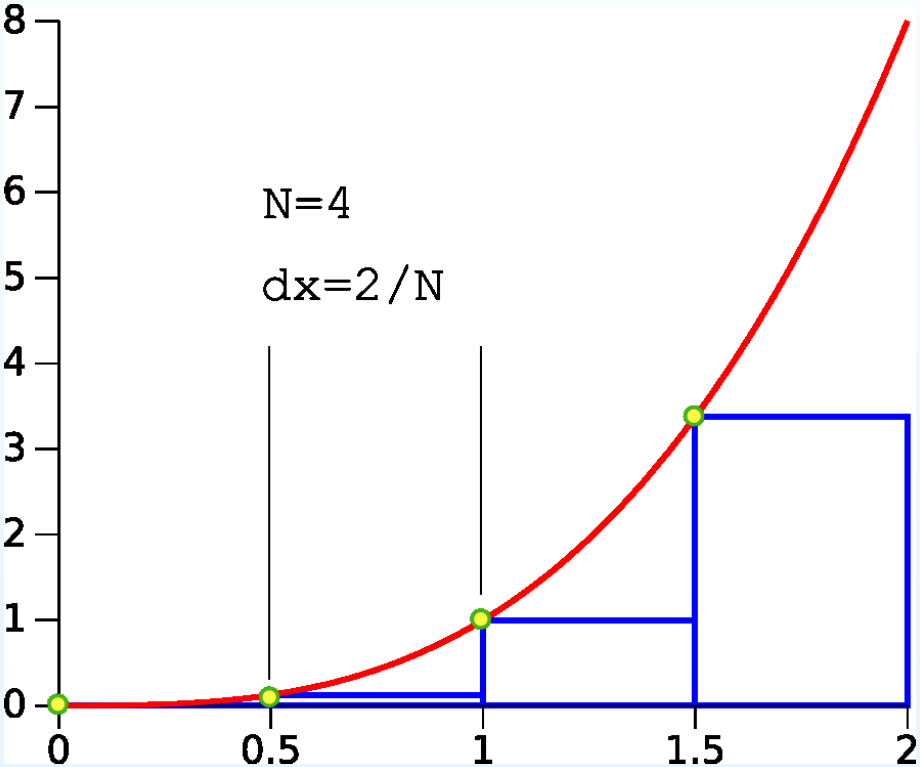
Benchmark Python code

Our code aims to compute (an approximation of) $\int_a^b f(x)dx$



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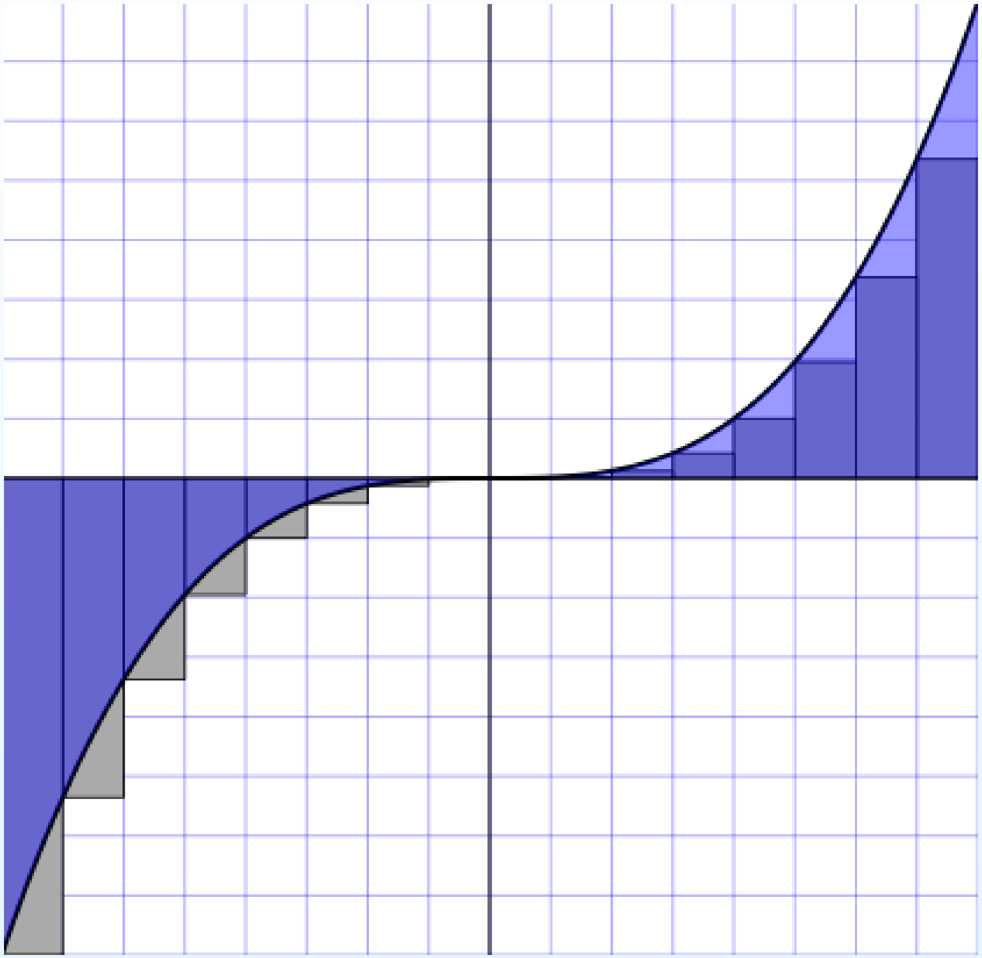
More Segments



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Benchmark Python Code

```python
def f(x):
    return x**4 - 3 * x

def integrate_f(a, b, N):
    """Rectangle integration of a function.

    Parameters
    ----------
    a, b : float
        Interval over which to integrate.
    N : int
        Number of intervals to use in the discretisation.

    """
    s = 0
    dx = (b - a) / N
    for i in range(N):
        s += f(a + i * dx)
    return s * dx
```

Compile the code with Cython

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- `cython filename.`[py|pyx]
- What is happening behind the scenes? `cython -a filename.[py|pyx]`
  - Cython translates Python to C, using the Python C API (let's have a look)
- This code has some serious *bottlenecks.*

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Compile generated code

By hand you would do (but don't do this):

```
$ gcc -O2 -fPIC -I/usr/include/python2.7
  -c integrate.c -o integrate_compiled.so
```

Easier yet, construct a `setup.py`:

```python
from distutils.core import setup
from distutils.extension import Extension
from Cython.Distutils import build_ext

setup(
  cmdclass = {'build_ext': build_ext},
  ext_modules = [
    Extension("integrate", ["integrate.pyx"]),
  ])
```

Run using `python setup.py build_ext -i`. `This means: build the extensions «in-place».`

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Benchmark the new code

- `Use IPython's %timeit` (could do this manually using `from timeit import timeit; timeit(...)`)
- Slight speed increase ($\approx 1.4\times$) probably not worth it.
- Can we help Cython to do even better?
  - Yes—by giving it some clues.
  - Cython has a basic type inferencing engine, but it is very conservative for safety reasons.
  - Why does type information allow such vast speed increases?

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Wrapping C and C++ Libraries

Providing type information

```
def f(double x):
    return x**4 - 3 * x

def integrate_f(double a, double b, int N):
    """Rectangle integration of a function.
    ...
    """
    cdef:
        double s = 0
        double dx = (b - a) / N
        Py_ssize_t i

    for i in range(N):
        s += f(a + i * dx)
    return s * dx
```

-

Benchmark...

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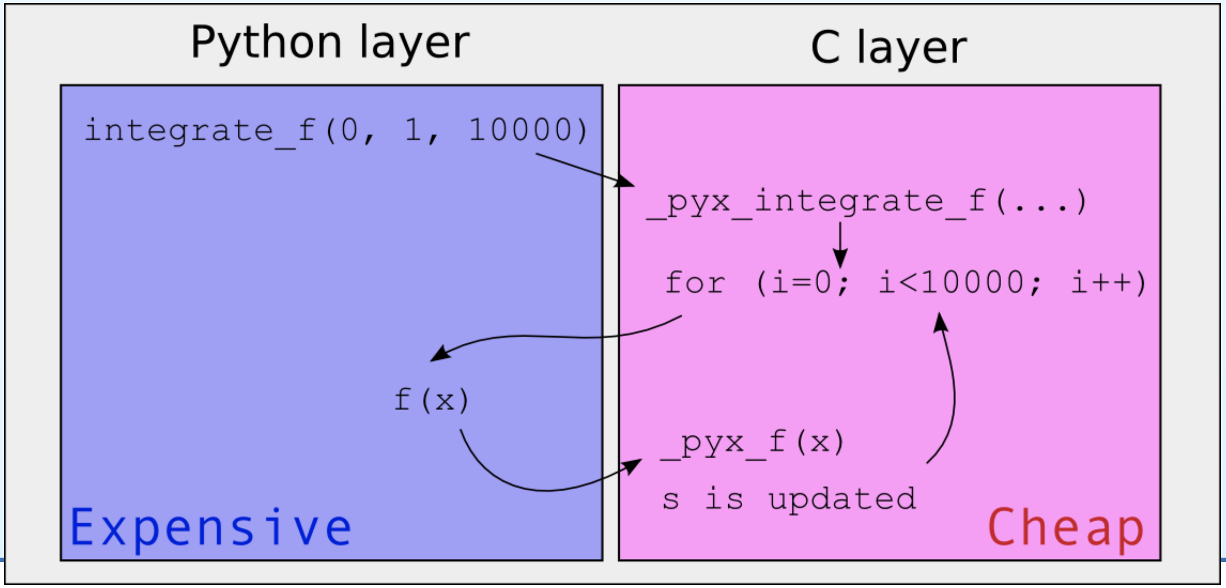
Expense of Python Function Calls

```
def f(double x):
    return x**4 - 3 * x

def integrate_f(double a, double b, int N):
    cdef:
        double s = 0
        double dx = (b - a) / N
        size_t i

    for i in range(N):
        s += f(a + i * dx)
    return s * dx
```



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The Last Bottlenecks

```
# cython: cdivision=True

cdef double f(double x):
    return x*x*x*x - 3 * x

def integrate_f(double a, double b, int N):
    cdef:
        double s = 0
        double dx = (b - a) / N
        Py_ssize_t i

    for i in range(N):
        s += f(a + i * dx)
    return s * dx
```

-

Benchmark!

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Integrating Arbitrary Functions (callbacks)

```
# cython: cdivision=True

cdef class Integrand:
    cdef double f(self, double x):
        raise NotImplementedError()

cdef class MyFunc(Integrand):
    cdef double f(self, double x):
        return x*x*x*x - 3 * x

def integrate_f(Integrand integrand,
                double a, double b, int N):
    cdef double s = 0
    cdef double dx = (b - a) / N
    cdef Py_ssize_t i
    for i in range(N):
        s += integrand.f(a + i * dx)
    return s * dx
```

Exploring Cython Further

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From Python to Cython

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- Declaring the Numpy Array type
- Matrix Multiplication
- Our Own MatMul

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Declaring the MemoryView type

```
import numpy as np

def foo(double[:, ::1] arr):
    cdef double[:, ::1] out = np.zeros_like(arr)
    cdef Py_ssize_t i, j
    for i in range(arr.shape[0]):
        for j in range(arr.shape[1]):
            out[i, j] = arr[i, j] * i + j

    return np.asarray(out)
```

Declaring the Numpy Array type

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Wrapping C and C++ Libraries

An alternative to the MemoryView syntax that corresponds more closely with ndarray dtypes:

```
cimport numpy as cnp
import numpy as np

def foo(cnp.ndarray[cnp.float64_t, ndim=2] arr):
    cdef cnp.ndarray[cnp.float64\_t, ndim=2] out = \
        np.zeros_like(arr)
    cdef Py_ssize_t i, j
    for i in range(arr.shape[0]):
        for j in range(arr.shape[1]):
            arr[i, j] = i + j

    return out
```

Different types are defined in `Cython/Includes/numpy.pxd`.

Matrix Multiplication

```
rows_A, cols_A = A.shape[0], A.shape[1]
rows_B, cols_B = B.shape[0], B.shape[1]

out = np.zeros(rows_A, cols_B)

# Take each row in A
for i in range(rows_A):

    # And multiply by each column in B
    for j in range(cols_B):
        s = 0
        for k in \
            range(cols_A):
            s = s + A[i, k] *
                    B[k, j]

        out[i, j] = s
```

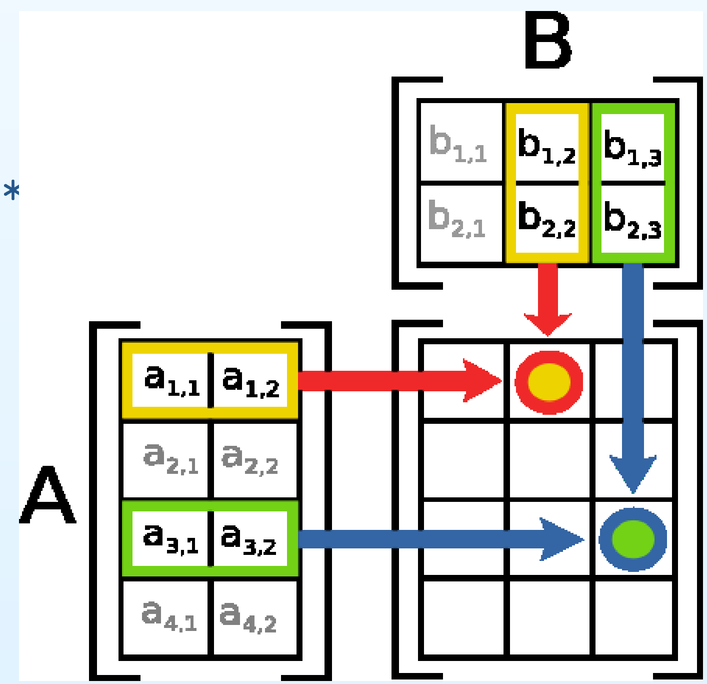

Image credits: http://en.wikipedia.org/wiki/File:Matrix_multiplication_diagram_2.svg

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Our Own MatMul

We won't even try this in pure Python (way too slow).

```
def dot(double[:, ::1] A,
        double[:, ::1] B,
        double[:, ::1] out):

    cdef:
        Py_ssize_t rows_A, cols_A, rows_B, cols_B
        Py_ssize_t i, j, k
        double s

    rows_A, cols_A = A.shape[0], A.shape[1]
    rows_B, cols_B = B.shape[0], B.shape[1]

    # Take each row in A
    for i in range(rows_A):
        # And multiply by every column in B
        for j in range(cols_B):
            s = 0
            for k in range(cols_A):
                s = s + A[i, k] * B[k, j]

            out[i, j] = s
```

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- Parallel Loops with «prange»
-

Wrapping C and C++ Libraries

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Parallel Loops with «prange»

```
@cython.boundscheck(False)
@cython.wraparound(False)
def pdot(double[:, ::1] A,
         double[:, ::1] B,
         double[:, ::1] out):
    cdef:
        Py_ssize_t rows_A, cols_A, rows_B, cols_B
        Py_ssize_t i, j, k
        double s
    rows_A, cols_A = A.shape[0], A.shape[1]
    rows_B, cols_B = B.shape[0], B.shape[1]

    with nogil:
        # Take each row in A
        for i in prange(rows_A):
            # And multiply by every column in B
            for j in range(cols_B):
                s = 0
                for k in range(cols_A):
                    s = s + A[i, k] * B[k, j]
```


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```
                out[i, j] = s
```

-

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Fortran

We won't be talking about that here, but Ondrej Certik has some excellent notes:

http://fortran90.org/src/best-practices.html#interfacing-with-python

External Definitions

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Create a file, `trig.pyx`, with the following content:

```
cdef extern from "math.h":
    double cos(double x)
    double sin(double x)
    double tan(double x)

    double M_PI

def test_trig():
    print('Some trig functions from C:',
          cos(0), cos(M_PI))
```

Build: Link Math Library

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```python
from distutils.core import setup
from distutils.extension import Extension
from Cython.Distutils import build_ext

setup(
    cmdclass = {'build_ext': build_ext},
    ext_modules = [
        Extension("trig" ,
                  ["trig.pyx"],
                  libraries=["m"] ,
        ),
])
```

C++ Class Wrapper

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```cpp
namespace geom {
    class Circle {
    public:
        Circle(double x, double y, double r);
        ~Circle();
        double getX();
        double getY();
        double getRadius();
        double getArea();
        void setCenter(double x, double y);
        void setRadius(double r);
    private:
        double x;
        double y;
        double r;
    };
}
```

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C++ Class Wrapper

```
cdef extern from "Circle.h" namespace "geom":
    cdef cppclass Circle:
        Circle(double, double, double)
        double getX()
        double getY()
        double getRadius()
        double getArea()
        void setCenter(double, double)
        void setRadius(double)
```

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C++ Class Wrapper

```
cdef class PyCircle:
    cdef Circle *thisptr

    def __cinit__(self, double x, double y, double r):
        self.thisptr = new Circle(x, y, r)

    def __dealloc__(self):
        del self.thisptr

    @property
    def area(self):
        return self.thisptr.getArea()

    @property
    def radius(self):
        return self.thisptr.getRadius()

    def set_radius(self, r):
        self.thisptr.setRadius(r)

    @property
    def center(self):
        return (self.thisptr.getX(), self.thisptr.getY
```

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```
from distutils.core import setup
from distutils.extension import Extension
from Cython.Distutils import build_ext

setup(
    cmdclass = {'build_ext': build_ext},
    ext_modules = [
        Extension("circ", ["circ.pyx", "Circle.cpp"],
                  language="c++"),
        Extension("trig", ["trig.pyx"],
                  libraries=["m"]),
])
```

In conclusion...

- Build functional and tested code
- Profile
- Re-implement bottlenecks (behavior verified by tests)
- Et voilà—high-level code, low-level performance. [It's no silver bullet, but it's still pretty good.]