Cython: Blend the best of Python and C/++

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ENTHOUGHT
SCIENTIFIC COMPUTING SOLUTIONS

Cython by example

PYTHON

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

C / C++

```
int fib(int n)
{
    int tmp, i, a, b;
    a = b = 1;
    for(i=0; i<n; i++) {
        tmp = a; a += b; b = tmp;
    }
    return a;
}
```

Cython by example

PYTHON

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

C / C++

```c
int fib(int n)
{
    int tmp, i, a, b;
    a = b = 1;
    for(i=0; i<n; i++) {
        tmp = a; a += b; b = tmp;
    }
    return a;
}
```

CYTHON

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

Cython by example

PYTHON 1x

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

C / C++ 100x faster

```
int fib(int n)
{
    int tmp, i, a, b;
    a = b = 1;
    for(i=0; i<n; i++) {
        tmp = a; a += b; b = tmp;
    }
    return a;
}
```

CYTHON 80x faster

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

For the record...

HAND-WRITTEN EXTENSION MODULE

```
#include "Python.h"

static PyObject* fib(PyObject *self, PyObject *args)
{
    int n, a, b, i, tmp;
    if (!PyArg_ParseTuple(args, "i", &n))
        return NULL;
    a = b = 1;
    for (i=0; i<n; i++) {
        tmp=a; a+=b; b=tmp;
    }
    return Py_BuildValue("i", a);
}

static PyMethodDef ExampleMethods[] = {
    {"fib", fib, METH_VARARGS, ""},
    {NULL, NULL, 0, NULL}        /* Sentinel */
};

PyMODINIT_FUNC
initfib(void)
{
    (void) Py_InitModule(“fib", ExampleMethods);
}
```

For the record...

HAND-WRITTEN EXTENSION MODULE 25x faster

```
#include "Python.h"

static PyObject* fib(PyObject *self, PyObject *args)
{
    int n, a, b, i, tmp;
    if (!PyArg_ParseTuple(args, "i", &n))
        return NULL;
    a = b = 1;
    for (i=0; i<n; i++) {
        tmp=a; a+=b; b=tmp;
    }
    return Py_BuildValue("i", a);
}

static PyMethodDef ExampleMethods[] = {
    {"fib", fib, METH_VARARGS, ""},
    {NULL, NULL, 0, NULL}        /* Sentinel */
};

PyMODINIT_FUNC
initfib(void)
{
    (void) Py_InitModule(“fib", ExampleMethods);
}
```

What is Cython?

Cython is a Python-like language that:

- **Improves Python's performance** – 1000x speedups not uncommon
- **wraps external libraries --** C, C++, Fortran, others...

The `cython` command:

- generates an optimized C/++ source file from a Cython source file,
- which is then compiled into a Python extension module.

Other features:

- built-in support for NumPy,
- integrates with IPython,
- Foundational to Scientific Python ecosystem.

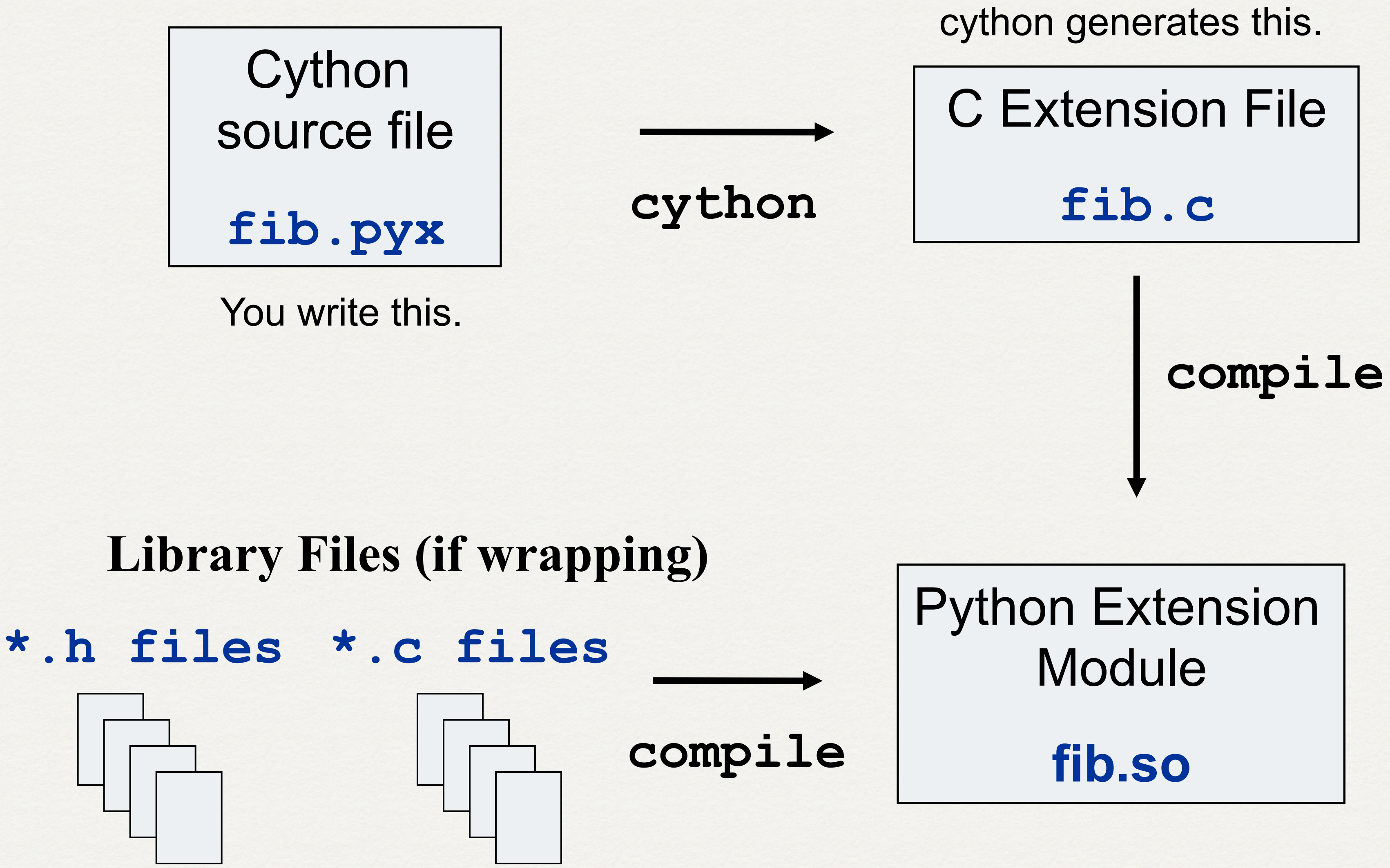
`http://www.cython.org/`

Cython in the wild

Project	Cython files	Cython SLOC
sage	761	477,000
numpy	14	5,000
scipy	28	24,000
pandas	21	27,000
lxml	12	22,000
scikits-learn	35	15,000
scikits-image	48	11,000
mpi4py	48	12,000
yt	45	18,000

Projects master branches as of November 2014

Cython workflow



cython generates this.

Cython source file

`fib.pyx`

You write this.

`cython`

C Extension File

`fib.c`

`compile`

Library Files (if wrapping)

`*.h files` `*.c files`

`compile`

Python Extension Module

fib.so

Speed up Python

PYTHON

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

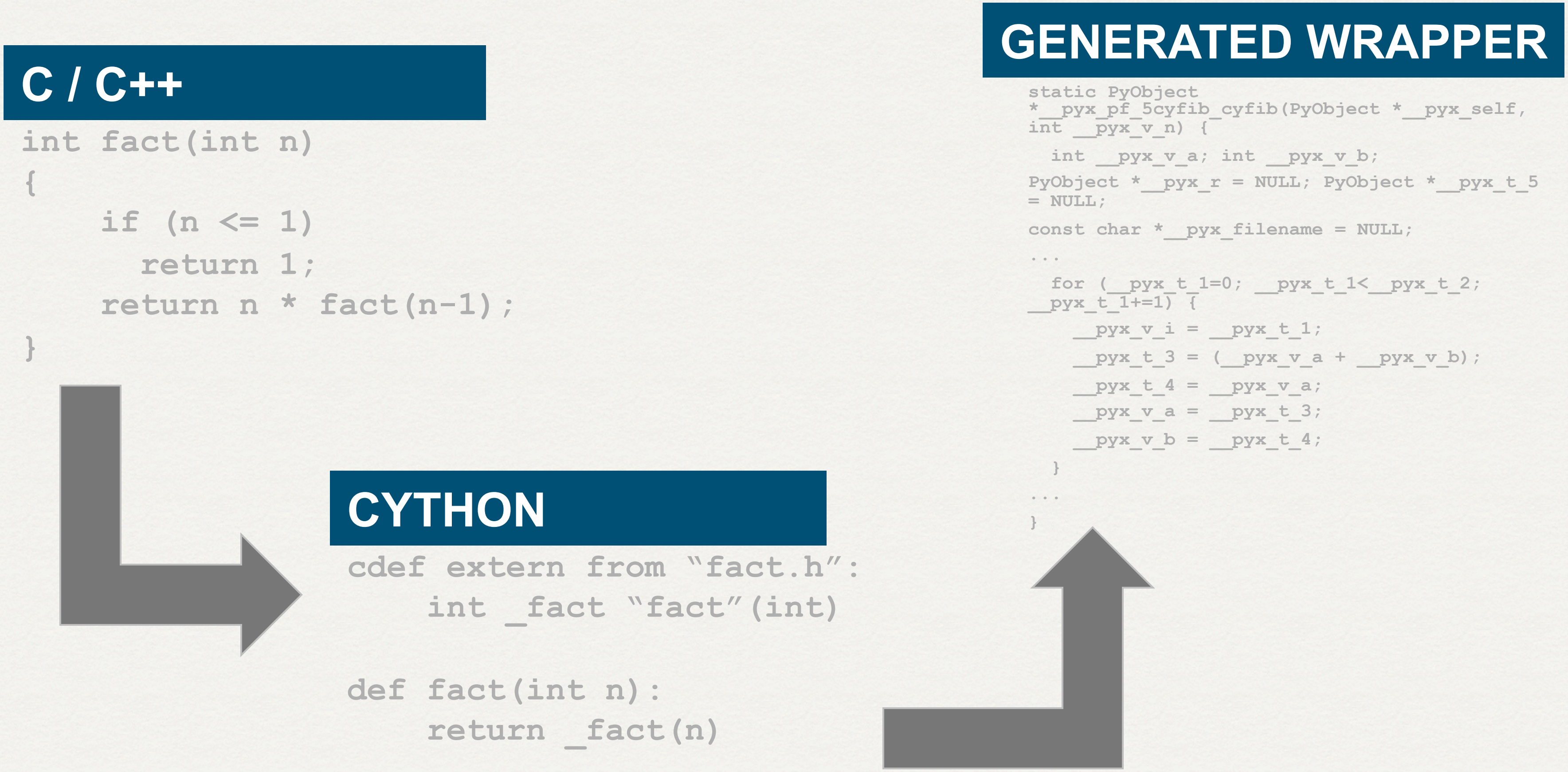
CYTHON

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

GENERATED C

```
static PyObject
*__pyx_pf_5cyfib_cyfib(PyObject *__pyx_self,
int __pyx_v_n) {
  int __pyx_v_a; int __pyx_v_b;
PyObject *__pyx_r = NULL; PyObject *__pyx_t_5
= NULL;
const char *__pyx_filename = NULL;
...
  for (__pyx_t_1=0; __pyx_t_1<__pyx_t_2;
__pyx_t_1+=1) {
    __pyx_v_i = __pyx_t_1;
    __pyx_t_3 = (__pyx_v_a + __pyx_v_b);
    __pyx_t_4 = __pyx_v_a;
    __pyx_v_a = __pyx_t_3;
    __pyx_v_b = __pyx_t_4;
  }
...
}
```

Wrap C / C++



C / C++

```
int fact(int n)
{
    if (n <= 1)
      return 1;
    return n * fact(n-1);
}
```

CYTHON

```
cdef extern from "fact.h":
    int _fact "fact"(int)

def fact(int n):
    return _fact(n)
```

GENERATED WRAPPER

```
static PyObject
*__pyx_pf_5cyfib_cyfib(PyObject *__pyx_self,
int __pyx_v_n) {
  int __pyx_v_a; int __pyx_v_b;
PyObject *__pyx_r = NULL; PyObject *__pyx_t_5
= NULL;
const char *__pyx_filename = NULL;
...
  for (__pyx_t_1=0; __pyx_t_1<__pyx_t_2;
__pyx_t_1+=1) {
    __pyx_v_i = __pyx_t_1;
    __pyx_t_3 = (__pyx_v_a + __pyx_v_b);
    __pyx_t_4 = __pyx_v_a;
    __pyx_v_a = __pyx_t_3;
    __pyx_v_b = __pyx_t_4;
  }
...
}
```

Compiling with distutils

FIB.PYX

```
def fib(int n):
    ...
```

SETUP_FIB.PY

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

setup(name="fib",
      ext_modules=cythonize("fib.pyx")
)
```

Compiling an extension module

CALLING FIB FROM PYTHON

```
# Mac / Linux
$ python setup_fib.py build_ext --inplace

# Windows
$ python setup_fib.py build_ext --inplace -c mingw32

$ python
>>> import fib
>>> fib.fib()
Traceback (most recent call last):
  File "<stdin>", line 1, in ?
TypeError: function takes exactly 1 argument (0 given)
>>> fib.fib("dsa")
Traceback (most recent call last):
  File "<stdin>", line 1, in ?
TypeError: an integer is required
>>> fib.fib(3)
5
```

pyximport

pyximport: import a Cython source file as if it is a pure Python module.

- Detects changes in Cython file, recompiles if necessary, loads cached module if not.
- Great for simple cases.

RUN_FIB.PY

```
import pyximport
pyximport.install() # hooks into Python's import mechanism.

from fib import fib # finds pi.pyx, automatically compiles.

print fib(10)
```

Cython + IPython

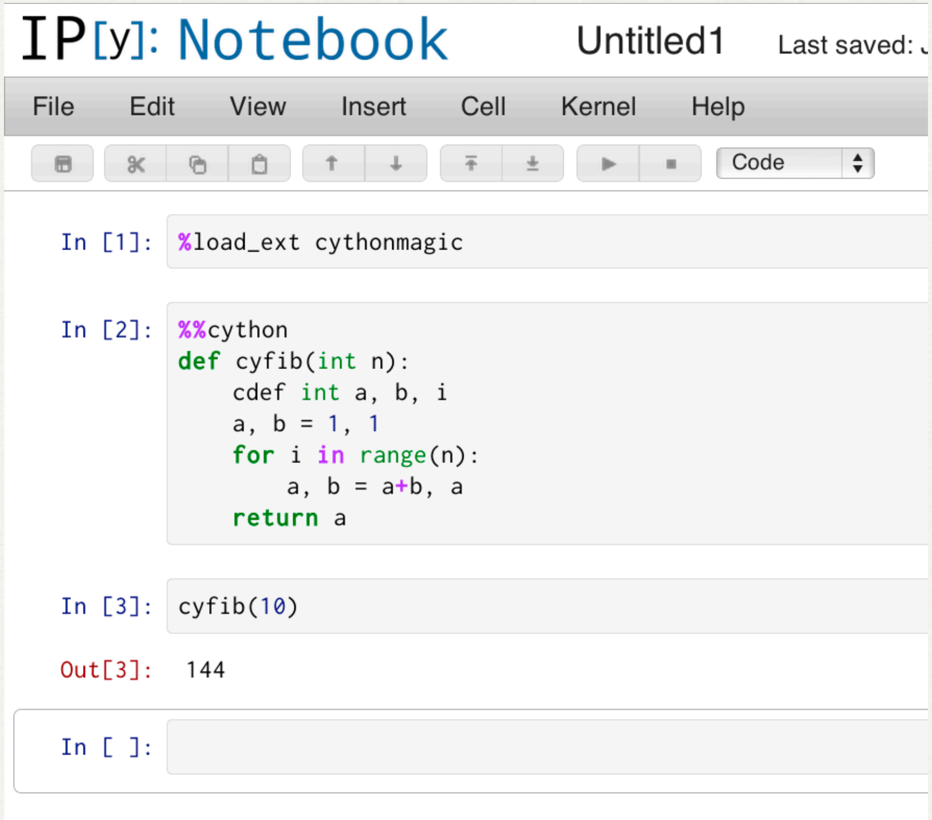
IPython Jupyter provides cython magic commands, the most useful of which is **`%%cython`**.

IPYTHON / IPYTHON NOTEBOOK: CYFIB.IPY / CYFIB.IPYNB

```
In [10]: %load_ext cythonmagic

In [11]: %%cython
    ....: def cyfib(int n):
    ....:     cdef int a, b, i
    ....:     a, b = 1, 1
    ....:     for i in range(n):
    ....:         a, b = a+b, a
    ....:     return a
    ....:

In [12]: cyfib(10)
Out[12]: 144
```



```
In [1]: %load_ext cythonmagic

In [2]: %%cython
        def cyfib(int n):
            cdef int a, b, i
            a, b = 1, 1
            for i in range(n):
                a, b = a+b, a
            return a

In [3]: cyfib(10)

Out[3]: 144

In [ ]:
```

Hello World Exercise

ENTHOUGHT

`cdef`: declare C-level object

LOCAL VARIABLES

```
def fib(int n):
    cdef int a, b, i
    ...
```

C FUNCTIONS

```
cdef float distance(float *x, float *y, int n):
    cdef:
        int i
        float d = 0.0
    for i in range(n):
        d += (x[i] - y[i])**2
    return d
```

EXTENSION TYPES

```
cdef class Particle(object):
    cdef float psn[3], vel[3]
    cdef int id
```

Typed function arguments are declared without `cdef`.

cdef declarations

CDEF DECLARATION	MEANING
`cdef int i, j, k`	declare multiple C integers
`cdef char *s`	declare a C-style string
`cdef float x = 0.0`	declare and init a C float
`cdef double y = 42.0`	C double
`cdef list names`	statically typed Python list
`cdef dict name_to_id = {}`	declare and init a Python dict
`cdef object o`	a reference counted object

def, cdef, cpdef functions

DEF FUNCTIONS: AVAILABLE TO PYTHON + CYTHON

```
def distance(x, y):
    return np.sum((x-y)**2)
```

CDEF FUNCTIONS: FAST, LOCAL TO CURRENT FILE

```
cdef float distance(float *x, float *y, int n):
    cdef:
        int i
        float d = 0.0
    for i in range(n):
        d += (x[i] – y[i])**2
    return d
```

CPDEF FUNCTIONS: LOCALLY C, EXTERNALLY PYTHON

```
cpdef float distance(float[:] x, float[:] y):
    cdef int i
    cdef int n = x.shape[0]
    cdef float d = 0.0
    for i in range(n):
        d += (x[i] – y[i])**2
    return d
```

def & cdef examples

DEF — PYTHON FUNCTIONS

```
# Python callable function.
def inc(int num, int offset):
    return num + offset

# Call inc for values in sequence.
def inc_seq(seq, offset):
    result = []
    for val in seq:
        res = inc(val, offset)
        result.append(res)
    return result
```

INC FROM PYTHON

```
# inc is callable from Python.
>>> inc.inc(1,3)
4
>>> a = range(4)
>>> inc.inc_seq(a, 3)
[3,4,5,6]
```

CDEF — C FUNCTIONS

```
# cdef becomes a C function call.
cdef int fast_inc(int num,
                        int offset):
    return num + offset
# fast_inc for a sequence
def fast_inc_seq(seq, offset):
    result = []
    for val in seq:
        res = fast_inc(val, offset)
        result.append(res)
    return result
```

FAST_INC FROM PYTHON

```
# fast_inc not callable in Python
>>> inc.fast_inc(1,3)
Traceback: ... no 'fast_inc'
# But fast_inc_seq is 2x faster
# for large arrays.
>>> inc.fast_inc_seq(a, 3)
[3,4,5,6]
```

cpdef: combines def + cdef

CPDEF — C AND PYTHON FUNCTIONS

```
# cdef becomes a C function call.
cpdef fast_inc(int num, int offset):
    return num + offset

# Calls compiled version inside Cython file
def inc_seq(seq, offset):
   result = []
   for val in seq:
       res = fast_inc(val, offset)
       result.append(res)
   return result
```

FAST_INC FROM PYTHON

```
# fast_inc is now callable in Python via Python wrapper
>>> inc.fast_inc(1,3)
4
# No speed degradation here
>>> inc.inc_seq(a, 3)
[3,4,5,6]
```

Typing Exercise

Wrapping external C functions

EXTERNAL C FUNCTIONS

```
# len_extern.pyx
# First, "include" the header file you need.
cdef extern from "string.h":
   # Describe the interface for the functions used.
    int strlen(char *c)

def get_len(char *message):
    # strlen can now be used from Cython code (but not Python)…
    return strlen(message)
```

CALL FROM PYTHON

```
>>> import len_extern
>>> len_extern.strlen
Traceback (most recent call last):
AttributeError: 'module' object has no attribute 'strlen'
>>> len_extern.get_len("woohoo!")
7
```

Wrapping external C structures

TIME_EXTERN.PYX

```
cdef extern from "time.h":
    # Declare only what is used from `tm` structure.
    struct tm:
        int tm_mday # Day of the month: 1-31
        int tm_mon  # Months *since* january: 0-11
        int tm_year # Years since 1900

    ctypedef long time_t
    tm* localtime(time_t *timer)
    time_t time(time_t *tloc)

def get_date():
    """ Return a tuple with the current day, month, and year."""
    cdef time_t t
    cdef tm* ts
    t = time(NULL)
    ts = localtime(&t)
    return ts.tm_mday, ts.tm_mon + 1, ts.tm_year
```

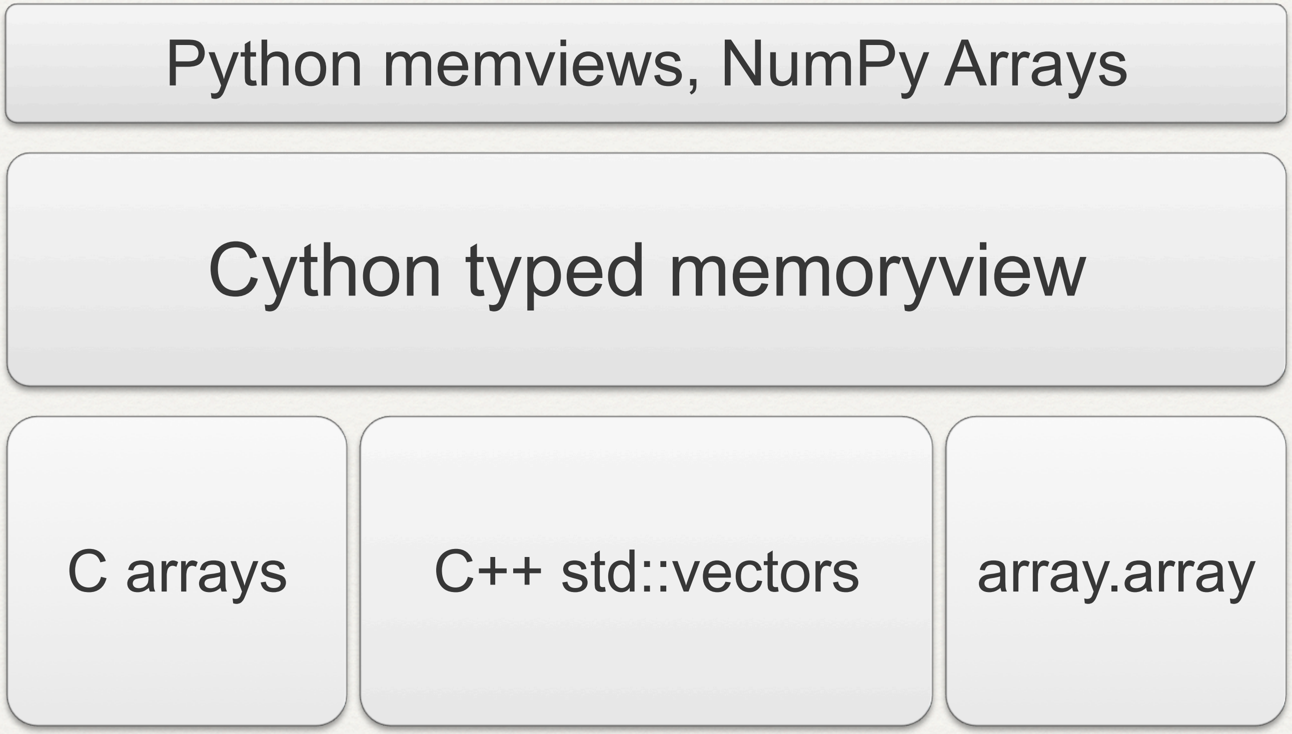
CALLING FROM PYTHON

```
>>> extern_time.get_date()
(7, 6, 2015)
```

Wrapping Exercise

Cython, NumPy, memoryviews

Typed memoryviews allow efficient access to memory buffers (such as NumPy arrays, C arrays, or C++ vectors) without any Python overhead.



Python memviews, NumPy Arrays

Cython typed memoryview

C arrays

C++ std::vectors

array.array

Cython, NumPy, memoryviews

TYPED MEMORYVIEWS

```
def sum(double[::1] a):   # a: contiguous 1D buffer of doubles.
    cdef double s = 0.0
    cdef int i, n = a.shape[0]
    for i in range(n):
        s += a[i]
    return s
```

USE JUST LIKE NUMPY ARRAYS

```
In[1]: from mysum import sum
In[2]: a = arange(1e6)
In[3]: %timeit sum(a)
1000 loops, best of 3: 998 us per loop
In[4]: %timeit a.sum()
1000 loops, best of 3: 991 us per loop
```

Cython, NumPy, memoryviews

ACQUIRING BUFFERS

```
cdef int[:, :, :] mv # a 3D typed memoryview, can be assigned to...

# 1: a C-array:
cdef int a[3][3][3]

# 2: a NumPy-array:
a = np.zeros((10,20,30), dtype=np.int32)

# 3: another memoryview
cdef int[:, :, :] a = b
```

USING MEMORYVIEWS

```
# indexing like NumPy, but faster, at C-level.
mv[1,2,0] # → integer

# Slicing like NumPy, but faster.
mv[10] == mv[10, :, :] == mv[10,...] # → a new memoryview.
```

Cython, NumPy, memoryviews

STRIDED AND CONTIGUOUS MEMORYVIEWS

```
# uses strided lookup when indexing
cdef int[:, :, :] strided_mv

# can acquire buffer from a non-contiguous np array.
strided_mv = arr[::2, 5:, ::-1]

# faster than strided, but only works with C-contiguous buffers.
cdef int[:, :, ::1] c_contig

c_contig = np.zeros((10, 20, 30), dtype=np.int)

c_contig = arr[:, :, :5] # non-contiguous, so ValueError at runtime.

# faster than strided, only works with Fortran-contiguous.
cdef int[::1, :, :] f_contig

f_contig = np.asfortranarray(arr)
```

Array Exercise

Cython in the age of JIT compilers

How can Cython compete with JIT compilers like PyPy, Numba, Pyston, etc?

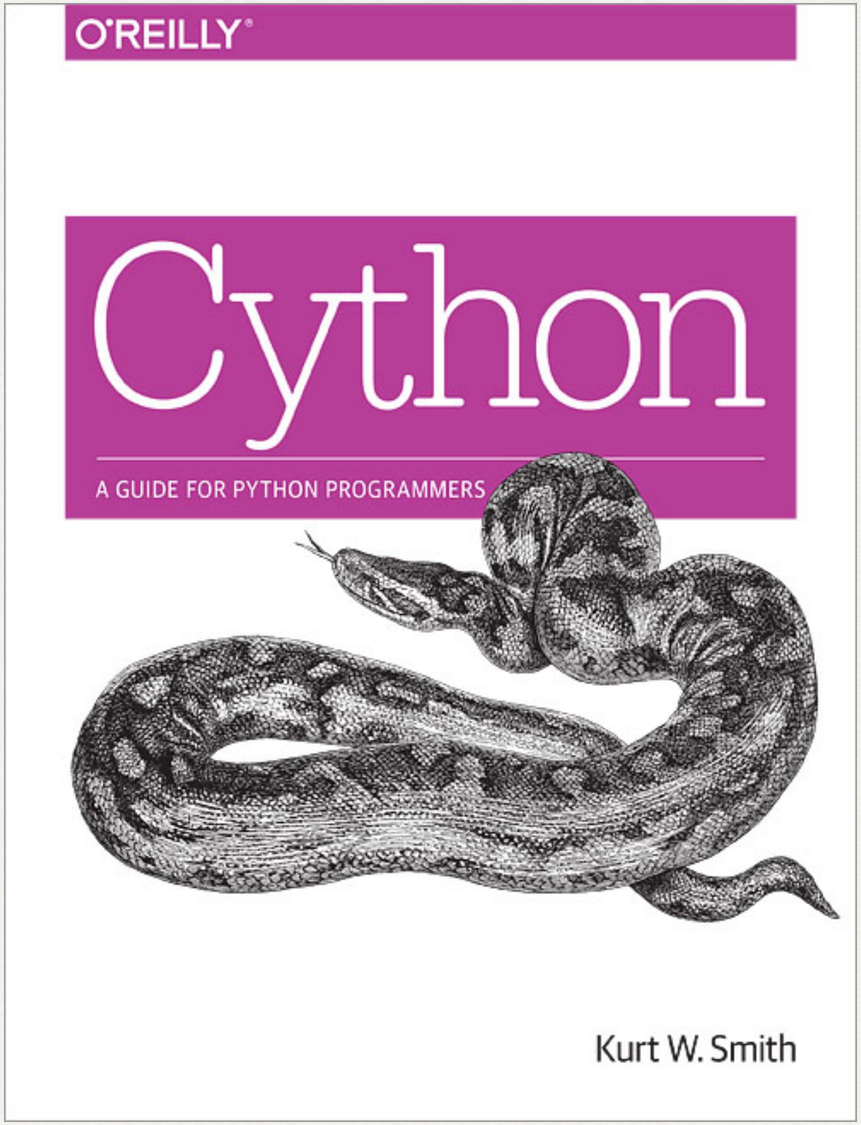
Cython’s strengths:

- **Greater control** over generated code.
- **Greater transparency.**
- **Mature FFI (wrapping) capabilities.**
- **Less end-user complexity**, users do not need to have Cython installed.
- Has **mature diagnosis capabilities** (`cython –a`).
- Useful for both numerical and general purpose Python.

Questions?

Book signing,
Thursday, 3:00.

20 free copies, FCFS!



O'REILLY

Cython

A GUIDE FOR PYTHON PROGRAMMERS

Kurt W. Smith

Profiling with annotations

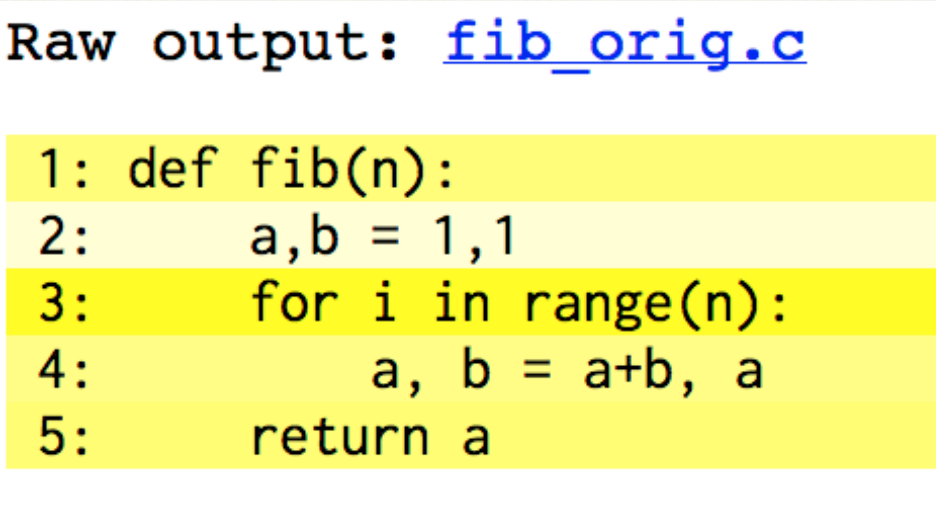
FIB_ORIG.PYX: NO CDEFS

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

CREATE ANNOTATED SOURCE

```
$ cython -a fib_orig.pyx
$ open fib_orig.html
```

FIB_ORIG.HTML

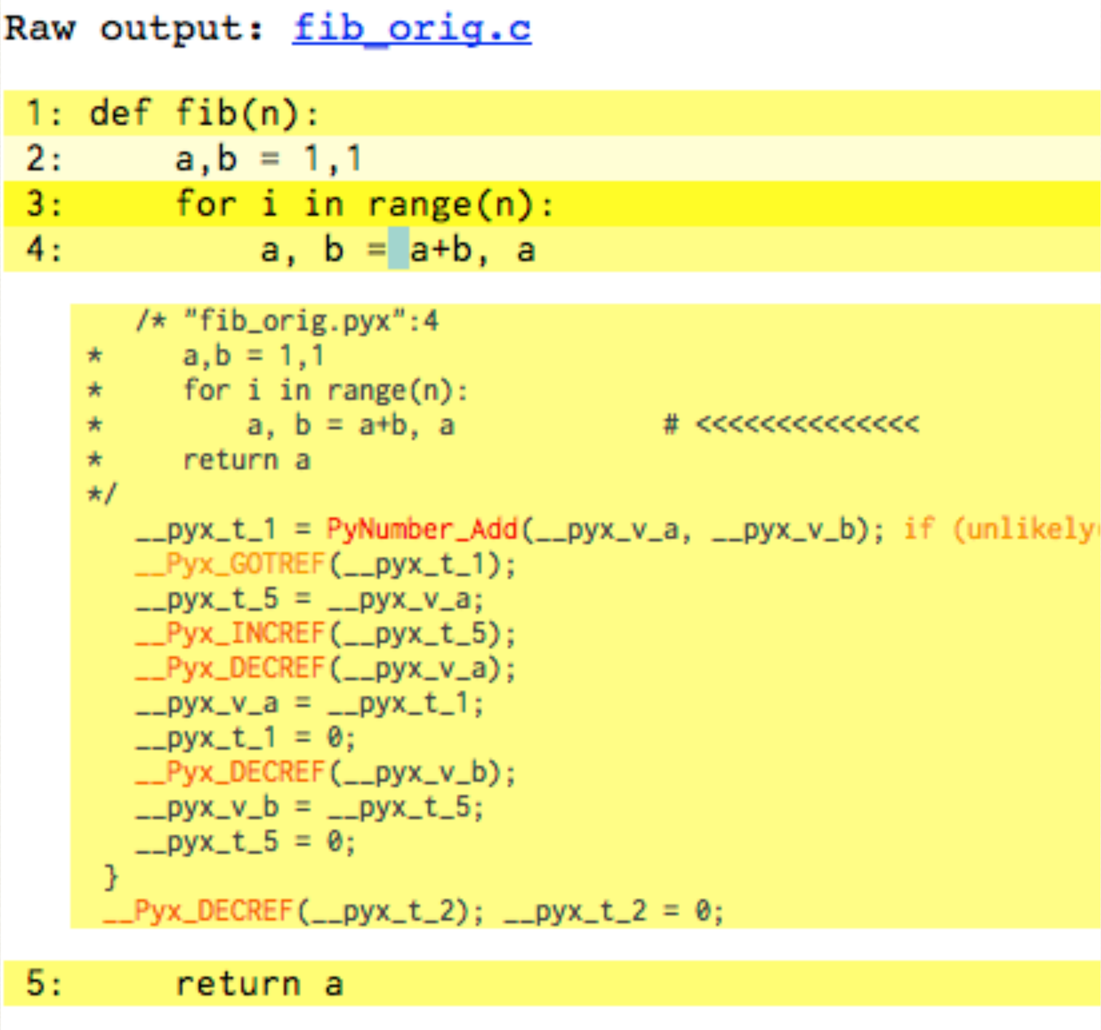


Raw output: fib_orig.c

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

The darker the highlighting, the more lines of C code are required for the given line of Cython code.

Profiling with annotations



Raw output: fib_orig.c

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

   /* "fib_orig.pyx":4
 *     a,b = 1,1
 *     for i in range(n):
 *         a, b = a+b, a             # <<<<<<<<<<<<<<
 *     return a
 */
   __pyx_t_1 = PyNumber_Add(__pyx_v_a, __pyx_v_b); if (unlikely
   __Pyx_GOTREF(__pyx_t_1);
   __pyx_t_5 = __pyx_v_a;
   __Pyx_INCREF(__pyx_t_5);
   __Pyx_DECREF(__pyx_v_a);
   __pyx_v_a = __pyx_t_1;
   __pyx_t_1 = 0;
   __Pyx_DECREF(__pyx_v_b);
   __pyx_v_b = __pyx_t_5;
   __pyx_t_5 = 0;
 }
 __Pyx_DECREF(__pyx_t_2); __pyx_t_2 = 0;

    return a
```

Profiling with annotations

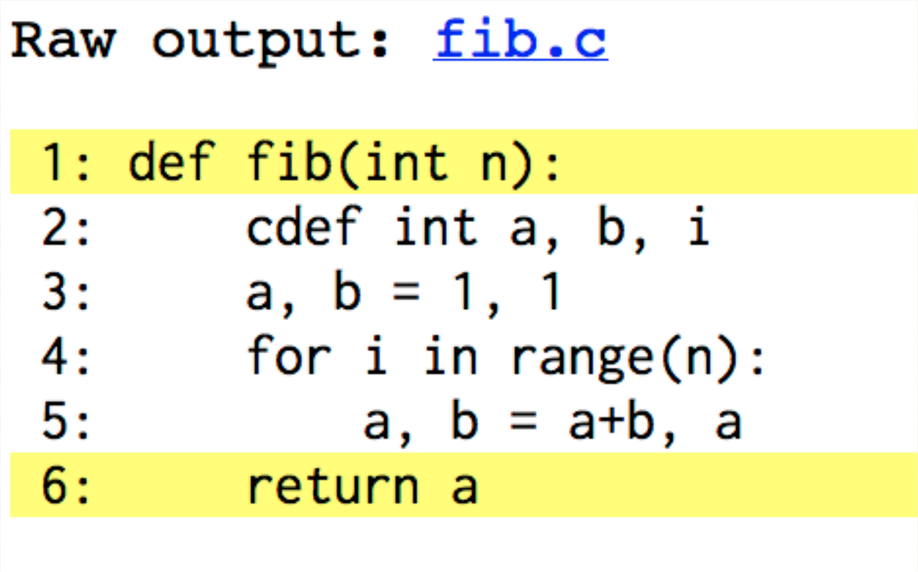
FIB.PYX: WITH CDEFS

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

CREATE ANNOTATED SOURCE

```
$ cython -a fib.pyx
$ open fib.html
```

FIB.HTML



Raw output: fib.c

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

Python classes, extension types

PYTHON CLASS

```
class Particle(object):  # Inherits from object; can use multiple inh.

  def __init__(self, m, p, v): # attributes stored in instance __dict__
    self.m = float(m)   # creating / updating attribute allowed anywhere.
    self.vel = np.asarray(v) # All attributes are Python objects.
    self.pos = np.asarray(p)

  def apply_impulse(self, f, t): # can be defined in or out of class.
    newv = self.vel + t / self.m * f
    self.pos = (newv + self.vel) * t / 2.
    self.vel = newv

  def speed(self):
    ...
```

Python classes, extension types

EXTENSION TYPE

```
cdef class Particle:        # Creates a new type, like list, int, dict
  cdef float *vel, *pos     # attributes stored in instance's struct
  cdef public float m       # expose variable to Python.

  def __cinit__(self, float m, p, v): # allocate C-level data,
    self.m = m                        # called before __init__()
    self.vel = malloc(3*sizeof(float))
    self.pos = malloc(3*sizeof(float))
    # check if vel or pos are NULL...
    for i in range(3):
        self.vel[i] = v[i]; self.pos[i] = p[i]

  cpdef apply_impulse(self, f, t): # methods can be def, cdef, or cpdef.
    ...
  def __dealloc__(self): # deallocate C arrays, called when gc'd.
    if self.vel: free(self.vel)
    if self.pos: free(self.pos)
```

Python classes, extension types

PYTHON CLASS

```
>>> vec = arange(3.)
>>> p = Particle(1.0, vec, vec)
>>> print p.vel  # can access attributes (and modify them)
array([0., 1., 2.]
>>> p.apply_impulse(vec, 1.0)
>>> p.vel
array([0., 2., 4.])
>>> p.charge = 4.0 # set new attribute outside of class.
```

EXTENSION TYPE

```
>>> vec = arange(3.)
>>> p = Particle(1.0, vec, vec)
>>> print p.vel  # attributes are private by default
AttributeError: ...
>>> print p.m    # ...but can access readonly and public attributes.
1.0
>>> p.apply_impulse(vec, 1.0) # can call def or cpdef methods.
>>> p.charge = 4.0  # AttributeError: attributes fixed at compile time.
```

Wrap C++ class

PARTICLE_EXTERN.H

```
 class Particle {
    public:
        float mass, charge;
        float vel[3], pos[3];
        Particle(float m, float c, float *p, float *v);
        ~Particle();
        float getMass();
        void setMass(float m);
        float getCharge();
        const float *getVel();
        const float *getPos();
        void applyImpulse(float *f, float t);
};
```

Wrap C++ class

PARTICLE.PYX

```
cdef extern from ”particle_extern.h":
    cppclass _Particle “Particle”:
        float mass, charge, vel[3], pos[3]
        _Particle(float m, float c, float *p, float *v)
        float getMass()
        void setMass()
        float getCharge()
        const float *getVel()
        const float *getPos()
        void applyImpulse(float *f, float t)

# continued on next slide...
```

Wrap C++ class

PARTICLE.PYX

```
cdef class Particle:
    cdef _Particle *thisptr # ptr to C++ instance

    def __cinit__(self, m, c, float[::1] p, float[::1] v):
        if p.shape[0] != 3 or v.shape[0] != 3:
            raise ValueError(“...”)
        self.thisptr = new _Particle(m, c, &p[0], &v[0])

    def __dealloc__(self):
        del self.thisptr

    def applyImpulse(self, float[::1] v, float t):
        self.thisptr.applyImpulse(&v[0], t)
```

Wrap C++ class

PARTICLE.PYX

```
# ...continued

    property mass:  # Cython-style properties.

      def __get__(self):
        return self.thisptr.getMass()

      def __set__(self, m):
        self.thisptr.setMass(m)
```

Classes from C++ libraries

SETUP.PY

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

sources = [‘particle.pyx’, particle_extern.cpp’]

setup(
  ext_modules=[Extension(”particle",
                   sources=sources, language="c++")],
  cmdclass = {'build_ext': build_ext}
)
```

Classes from C++ libraries

CALLING FROM PYTHON

```
>>> p = Particle(1.0, 2.0, arange(3.), arange(1., 4.))
>>> print p.mass  # can access a __get__-able property.
1.0
>>> p.mass = 5.0  # can assign to a __set__-able property.
>>> p.apply_impulse(arange(3.), 1.0)
>>> del p # calls __dealloc__(), which calls C++ delete.
```

cimport and pxd files

To use Cython code in multiple files, create a **pyd** file of declarations for a corresponding **pyx** file and **cimport** it elsewhere.

PARTICLE.PXD

```
cdef extern from “particle.h”:
  cppclass _Particle “Particle”:
    ...

cdef class Particle:
  cdef _Particle *thisptr
```

COLLISIONS.PYX

```
from particle cimport Particle

def detect_collision(Particle p0,
                     Particle p1):
    ...
```

PYD FILES PROVIDED WITH CYTHON

```
from libc.stdlib cimport malloc, free # C std library
cimport numpy as cnp # numpy C-API
from libcpp.vector cimport vector # C++ std::vector
```

cimport: access C stdlib functions

```
# uses Python’s sin implementation
# Incurs Python overhead when calling
from math import sin as pysin

# NumPy’s sin ufunc: fast for arrays, slower for scalars
from numpy import sin as npsin

# uses C stdlib’s sin from math.h: no Python overhead
from libc.math cimport sin

# other headers are supported
from libc.stdlib cimport malloc, free

# ... more on cimport later ...
```

Pure Python mode

FIB.PYX

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

FIB.PY

```
import cython

# Can put all type dels here
@cython.locals(n=cython.int)
def fib(n):
  cython.declare(a=cython.int,
                 b=cython.int,
                 i=cython.int)
  a,b = 1,1
  for i in range(n):
    a, b = a+b,
  return a
```