Why should you learn writing C extensions?

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Background

- AXA IM Chorus Ltd is a quantitative asset management fund.
- Develop in Python
- Research in Python
- Manage the portfolio in Python

Objective

- Understand the performance bottleneck on CPU bound problems
- How to work around it by C extensions
- Modern tools to write C extensions

Problem - Weighted sum on labels

Provided a list of labels, compute the weighted sum for each label.

```
labels  = [   0,   2,   1,   1,   2,   0 ]
weights = [ 0.1, 0.5, 0.2, 0.3, 0.8, 0.6 ]
```

Solution

1. Initialize a list with a size of the number of labels.
2. Iterate for each weight and increment the value on its label.

```
weighted_sum = [ 0.0, 0.0, 0.0 ]

for idx in range(len(weights)):
    weighted_sum[labels[idx]] += weights[idx]

assert weighted_sum == [ 0.7, 0.5, 1.3 ]
```

Runtime Complexity: O(N) where N is the number of elements

List comprehension

```
weighted_sum = [
    sum([weights[idx] for idx in range(len(weights))
         if labels[idx] == label])
    for label in max(labels)
]
```

Runtime Complexity: O(M * N)

where M is the number of labels and N is the number of elements

Numpy

```
weighted_sum = [
    np.where(labels == label, weights, 0.0).sum()
    for label in range(max(labels))
]
```

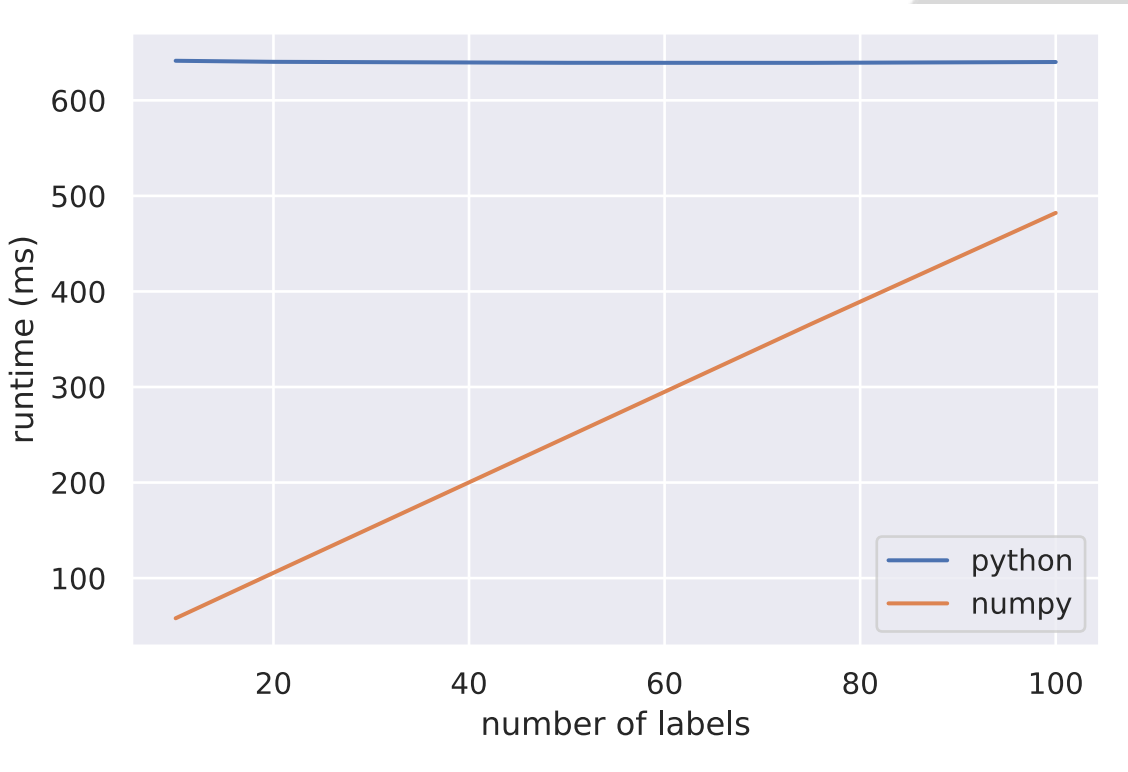
or even, for a better performance,

```
weighted_sum = [
    (labels == label).dot(weights)
    for label in range(max(labels))
]
```

Runtime Complexity: O(M * N)

where M depends on Python runtime and N depends on Numpy runtime

Performance - Python O(N) v.s. Numpy O(M x N)



Median time of 1000 runs on the weighted sum on labels (1000 instruments) (in microseconds)

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How Python works?

- Python is an interpreted language
- Python first compiles the source code into a bytecode

```
from dis import dis

dis(get_python_risk_exposures)
```

```
  2           0 LOAD_GLOBAL              0 (np)
              2 LOAD_ATTR                1 (zeros)
              4 LOAD_FAST                2 (num_of_labels)
              6 LOAD_GLOBAL              0 (np)
              8 LOAD_ATTR                2 (float64)
             10 LOAD_CONST               1 (('dtype',))
             12 CALL_FUNCTION_KW         2
             14 STORE_FAST               3 (risk_exposures)
```

- The bytecode is sent and executed on Python Virtual Machine (PVM)

Extending Python with C / C++

- Extended with CPython API and compiled to a shared library (`.dll` in Windows / `.so` in Unix)
- The shared library is imported as a Python module

and initialize it in your module's initialization function (`PyInit_spam()`) with an exception object:

```c
PyMODINIT_FUNC
PyInit_spam(void)
{
    PyObject *m;

    m = PyModule_Create(&spammodule);
    if (m == NULL)
        return NULL;

    SpamError = PyErr_NewException("spam.error", NULL, NULL);
    Py_XINCREF(SpamError);
    if (PyModule_AddObject(m, "error", SpamError) < 0) {
        Py_XDECREF(SpamError);
        Py_CLEAR(SpamError);
        Py_DECREF(m);
        return NULL;
    }

    return m;
}
```

Note that the Python name for the exception object is `spam.error`. The `PyErr_NewException()` function may

- Caveat: Supported only in CPython but not in PyPy

Well, it looks difficult...

- Compilation and Linkage
  - e.g. test_module.cpython-35m-x86_64-linux-gnu.so
- Reference count
  - Py_INCREF / Py_DECREF
- Ownership rules
- Exception handling
  - PyErr_SetString

Modern tools

- Cython: Syntax alike Python, used by numerous scientific and quant libraries, e.g. scipy, pandas and sklearn
- Pybind11: Binding Python with C++11
- Numba: Just in time compilation by LLVM
- Others
  - SWIG: Interface compiler connecting C / C++ with Python
  - Pythran: Compile on native python module by comments as hints
  - cffi: Dynamic runtime interface to native code in Python

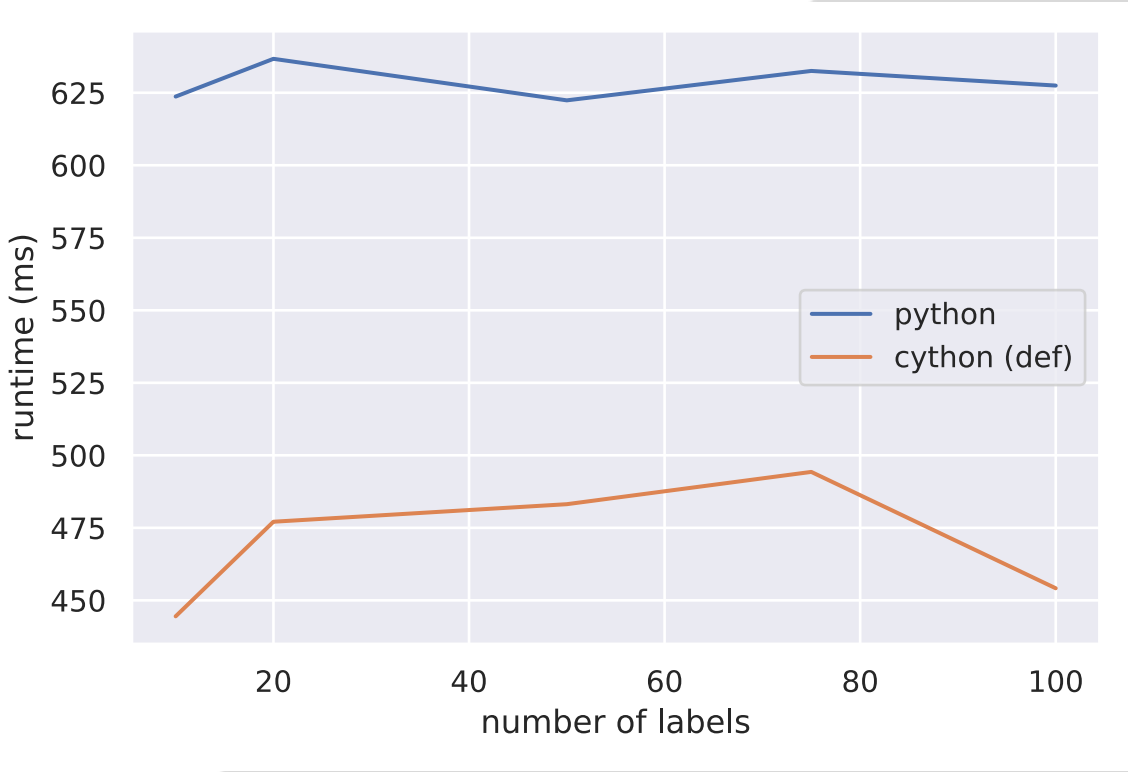
Cython - Classical approach

- First rename the python extension (.py) to cython extension (.pyx)

```
import numpy as np

def get_cython_def_risk_exposures(labels, weights, num_of_labels):
  risk_exposures = np.zeros(num_of_labels, dtype=np.float64)
  weight_len = len(weights)

  for idx in range(weight_len):
      risk_exposures[labels[idx]] += weights[idx]

  return risk_exposures
```

Cython - Classical approach

- Even compiling the native python code in cython can get 20% - 30% performance gain.



Median time of 1000 runs on the weighted sum on labels (1000 instruments) (in microseconds)

Cython - Classical approach

- To achieve C runtime, you may need to declare the function as `cpdef` and `cdef`
- `cpdef` is a hybrid function, accessible in Python but using the faster C calling conventions
- `cdef` is a pure C function which is not accessible in Python level

Cython - Classical approach

```
import numpy as np


cpdef get_cython_cpdef_risk_exposures(
        long[:] labels,
        double[:] weights,
        int num_of_labels):
    """Compute exposures by iterating the weights.
    """
    cdef:
        np.ndarray[np.float64_t, ndim=1] exposures = (
            np.zeros(num_of_labels, dtype=np.float64)
        )
        Py_ssize_t idx, label
        Py_ssize_t weight_len = len(weights)
        np.float64_t label_exposure
        double[:] exposures_view = exposures

    for idx in range(weight_len):
        exposures_view[labels[idx]] += weights[idx]

    return exposures
```

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Cython - Classical approach

- Performance improves greatly working in the array memory view

labels	python	cython (def)	cython (cpdef)
10	612.48	452.210	4.901
20	656.188	485.757	4.952
50	663.531	494.514	4.870
75	645.385	477.440	4.857
100	643.298	474.337	4.917

Median time of 1000 runs on the weighted sum on labels (1000 instruments) (in microseconds)

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Pybind11 - Approach from C++11 world

```cpp
#include <pybind11/pybind11.h>
#include <pybind11/stl.h>
#include <pybind11/numpy.h>

using namespace std;
namespace py = pybind11;

/* Return the portfolio exposures as numpy array */
py::array_t<double> iterate_weight(    /* Return numpy array */
    py::array_t<int64_t>* labels,       /* Accept numpy array */
    py::array_t<double>* weights,       /* Accept numpy array */
    uint32_t num_of_labels)
{
    auto exposures = py::array_t<double>( num_of_labels );

    /* Read and write the buffer without boundary check */
    auto unchked_exposures = exposures.mutable_unchecked<1>();
    auto unchked_labels = labels->unchecked<1>();
    auto unchked_weight = weights->unchecked<1>();

    /* Add the exposure */
    for (size_t idx = 0; idx < weights->size(); idx++)
        unchked_exposures[unchked_labels[idx]] += unchked_weight[idx];

    return exposures;
}
```

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Pybind11 - Approach from C++11 world

- Bind the C / C++ functions into Python
- Specify the ownership policy - Return Value Policy
- Specify the docstring and the argument names in the binding function
- You can specify function overloading in binding the function as well

```
PYBIND11_PLUGIN(example) {
    py::module m("example");
    m.def("get_pybind11_risk_exposures",
          &iterate_weight,
          py::return_value_policy::move,
          "Iterate weight on list.",
          py::arg("labels").noconvert(),
          py::arg("weights").noconvert(),
          py::arg("num_of_labels").noconvert());
    return m.ptr();
}
```

Numba - A rising new star

- Numba first convert the source to bytecode and then compile bytecode to machine code on the fly (object mode)
- Meanwhile, Numba can compile in the path without any calls into Python C API (nopython mode)
- Support ahead-of-time (AOT) compilation
- Support CUDA GPU programming

Numba - A rising new star

```
from numba import jit

@jit(nopython=True)
def get_numba_risk_exposures(labels, weights, num_of_labels):
  risk_exposures = np.zeros(num_of_labels, dtype=np.float64)
  weight_len = len(weights)

  for idx in range(weight_len):
      risk_exposures[labels[idx]] += weights[idx]

  return risk_exposures
```

```
import numba as nb
from numba import njit

@njit(nb.float64[:](nb.int64[:], nb.float64[:], nb.int64))
def get_numba_risk_exposures(labels, weights, num_of_labels):
  risk_exposures = np.zeros(num_of_labels, dtype=np.float64)
  weight_len = len(weights)

  for idx in range(weight_len):
      risk_exposures[labels[idx]] += weights[idx]

  return risk_exposures
```

Performance - Cython v.s. pybind11 v.s. Numba

labels	cython	pybind11	numba
10	4.98033	3.89457	2.06971
20	4.87757	3.85737	1.99318
50	4.80866	3.83329	1.95670
75	4.63414	3.88455	1.91998
100	4.64511	3.87454	1.90687

Median time of 1000 runs on the weighted sum on labels (1000 instruments) (in microseconds)

Why do we still learn writing C extension?

```
from numba import jit

@jit
def get_numba_risk_exposures(labels, weights, num_of_labels):
  risk_exposures = np.zeros(num_of_labels, dtype=np.float64)
  weight_len = len(weights)

  for idx in range(weight_len):
    assert labels[idx] < num_of_labels, (
        'Label at index %s does not align the specified number of labels' % idx
    )
    risk_exposures[labels[idx]] += weights[idx]

  return risk_exposures
```

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Why do we still learn writing C extension?

- Numba fails over to object mode if any line in the function fails to compile into the nopython mode
- Scalability
  - Exception handling: Only constant string can be thrown out in nopython mode
  - Limited support on object oriented design and ahead of time compilation
- Distribution
  - Numba requires llvmlite, which requires Python 3.6+ and LLVM 7.0.x
  - Exception handling is only available until Python 3.7

Parting words

"If you’re not at all interested in performance, shouldn’t you be in the Python room down the hall?"

Effective Modern C++, Scott Meyers

Colab example: https://bit.ly/2YFSm3F

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Linkedin: Gavin, Ying In Chan

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Reference

Extending Python with C or C++

Understanding Python Bytecode

Interfecing with C, Scipy lecture notes

Replace SWIG with pybind11