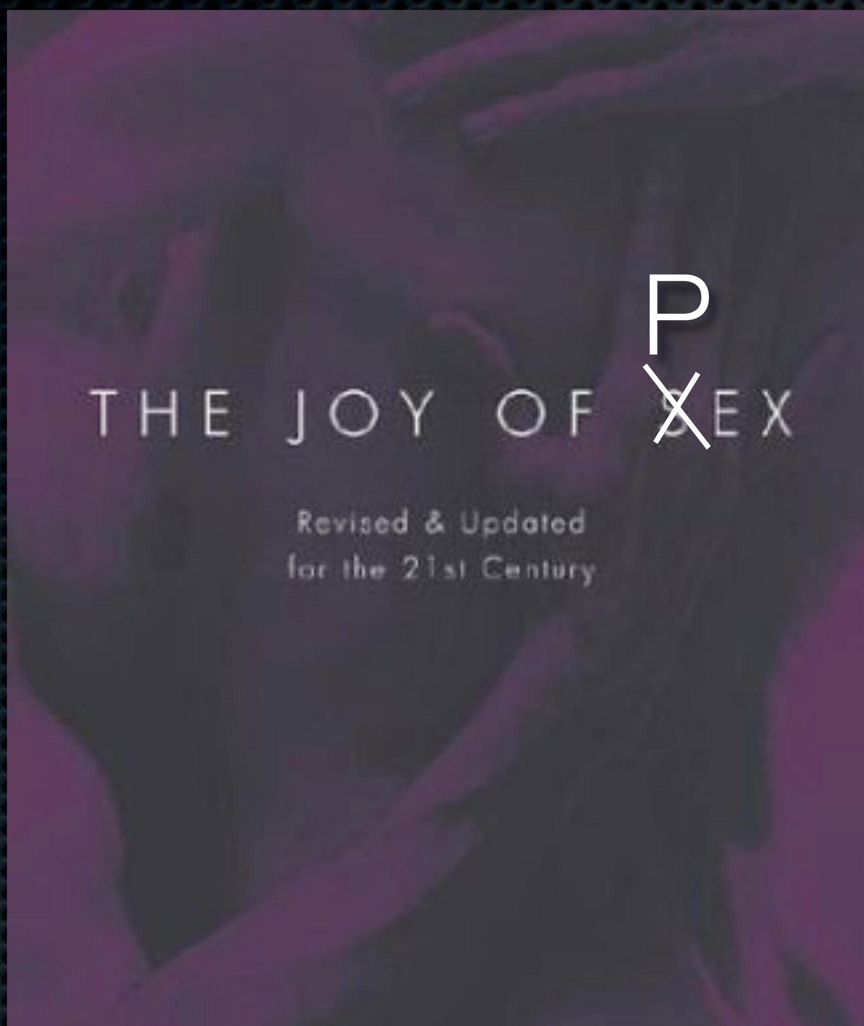

Lazy Man's Cython

Have Your Cake and Eat It Too

Dan Gindikin and Peter Yianilos

6/13/2008

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What Is Pex?

Preprocessor and build system for Cython

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What We Wanted

A language that gets down to the iron, runs at C speeds, and has no surprises in generated assembly, but at the same time guides you along to a clear, succinct and correct expression of complicated systems and algorithms.

What We Wanted More Concretely

What We Wanted More Concretely

1. Ineffable quality

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What We Wanted More Concretely

1. Ineffable quality
    - write complicated algorithm

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    - either it is right the first time

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What We Wanted More Concretely

1. Ineffable quality
    - write complicated algorithm
    - either it is right the first time
    - or it is very close, and easy to diagnose and fix

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2. Look at program assembly execution trace

What We Wanted More Concretely

1. Ineffable quality
   - write complicated algorithm
   - either it is right the first time
   - or it is very close, and easy to diagnose and fix
2. Look at program assembly execution trace
   - most instructions have to do with essence of problem

Real Problem for the World

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- Stay easy, friendly, interpreter-like

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- Stay easy, friendly, interpreter-like
- Yet use all the cycles the computer has to offer to solve the problem, not for overhead

Real Problem for the World

- Stay easy, friendly, interpreter-like
- Yet use all the cycles the computer has to offer to solve the problem, not for overhead
- Feel this has not been addressed, and not for any good technical reason

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Discarded Candidates

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Discarded Candidates

- No C, didn’t feel right in the 21st century

Discarded Candidates

- No C, didn’t feel right in the 21st century
- No C++, didn’t think we were smart enough

Within a Stone’s Throw

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Within a Stone's Throw

- Python, gets you everything except performance

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Within a Stone’s Throw

- Python, gets you everything except performance
  - huge deal, wasn’t clear there could be a language that would corral you in the right direction

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- Pyrex, epsilon away, most of the heavy lifting done

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Within a Stone’s Throw

- Python, gets you everything except performance
  - huge deal, wasn’t clear there could be a language that would corral you in the right direction
- Pyrex, epsilon away, most of the heavy lifting done
  - fast attribute access, exception handling, resource management - all the essentials for large system

Needful Things

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Needful Things

- No gear shifting to C

Needful Things

- No gear shifting to C
- Stay Pythonic, see how far you can push it without sacrificing performance

Needful Things

- No gear shifting to C
- Stay Pythonic, see how far you can push it without sacrificing performance
- Naturally leads to a few desirables

Fast Numerics Essential?

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Fast Numerics Essential?

- Already have linear algebra packages, but...

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- If Python API, Python overhead makes using small matrices infeasible

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  - you jump through hoops to vectorize

Fast Numerics Essential?

- Already have linear algebra packages, but...
- If Python API, Python overhead makes using small matrices infeasible
- May not have what you want
- Limits and contorts your thinking
  - you jump through hoops to vectorize
  - a priori, you only consider things that are vectorizable

Fast Numerics
Basic

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Fast Numerics Basic

In Pyrex

```
cdef int i
arr=numpy.zeros(n)
for i from 0<=i<n:
    arr[i] = i
```

Fast Numerics Basic

In Pyrex

```
cdef int i
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Python speed

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C speed, as if arr is int*

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Python speed

In Pex

```
cdef int i
cdef ndarray<int, n> arr
for i from 0<=i<n:
    arr{i} = i
```

C speed, as if arr is int*

Easily >100x faster

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Matrix Multiply
Pyrex

```
cdef void matmult(ndarray r,
        ndarray A, ndarray B):
    cdef int i,j,k
    for i from 0<=i<A.dimensions[0]:
        for j from 0<=j<B.dimensions[1]:
            for k from 0<=k<A.dimensions[1]:
                r[i,j]=r[i,j]+A[i,k]*B[k,j]
```

Matrix Multiply
Pex

```
cdef void matmult(ndarray<double 2d> r,
        ndarray<double 2d> A, ndarray<double 2d> B):
    cdef int i,j,k
    for i from 0<=i<A.dimensions[0]:
        for j from 0<=j<B.dimensions[1]:
            for k from 0<=k<A.dimensions[1]:
                r{i,j}=r{i,j}+A{i,k}*B{k,j}
```

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Matrix Multiply Performance

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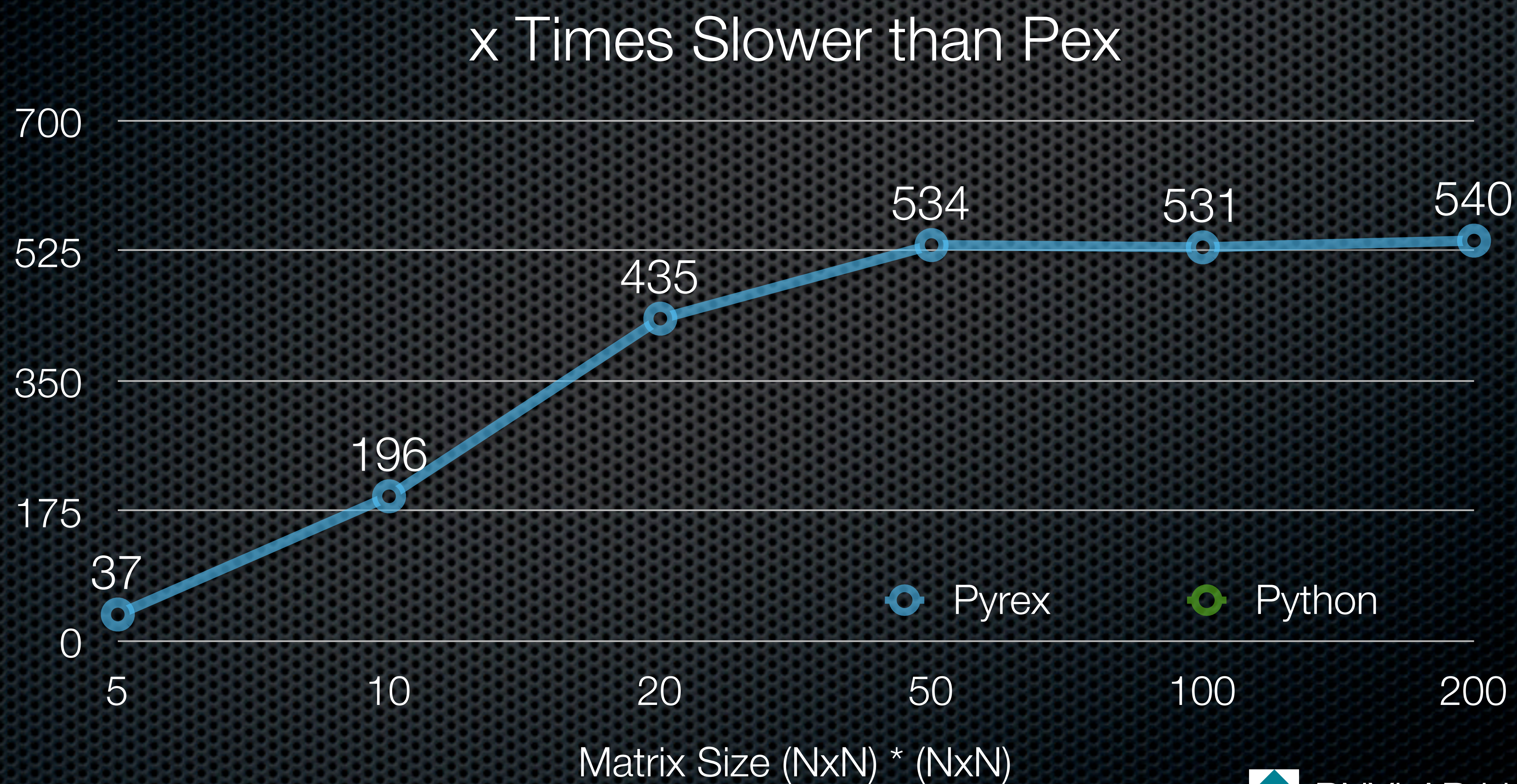
Matrix Multiply Performance



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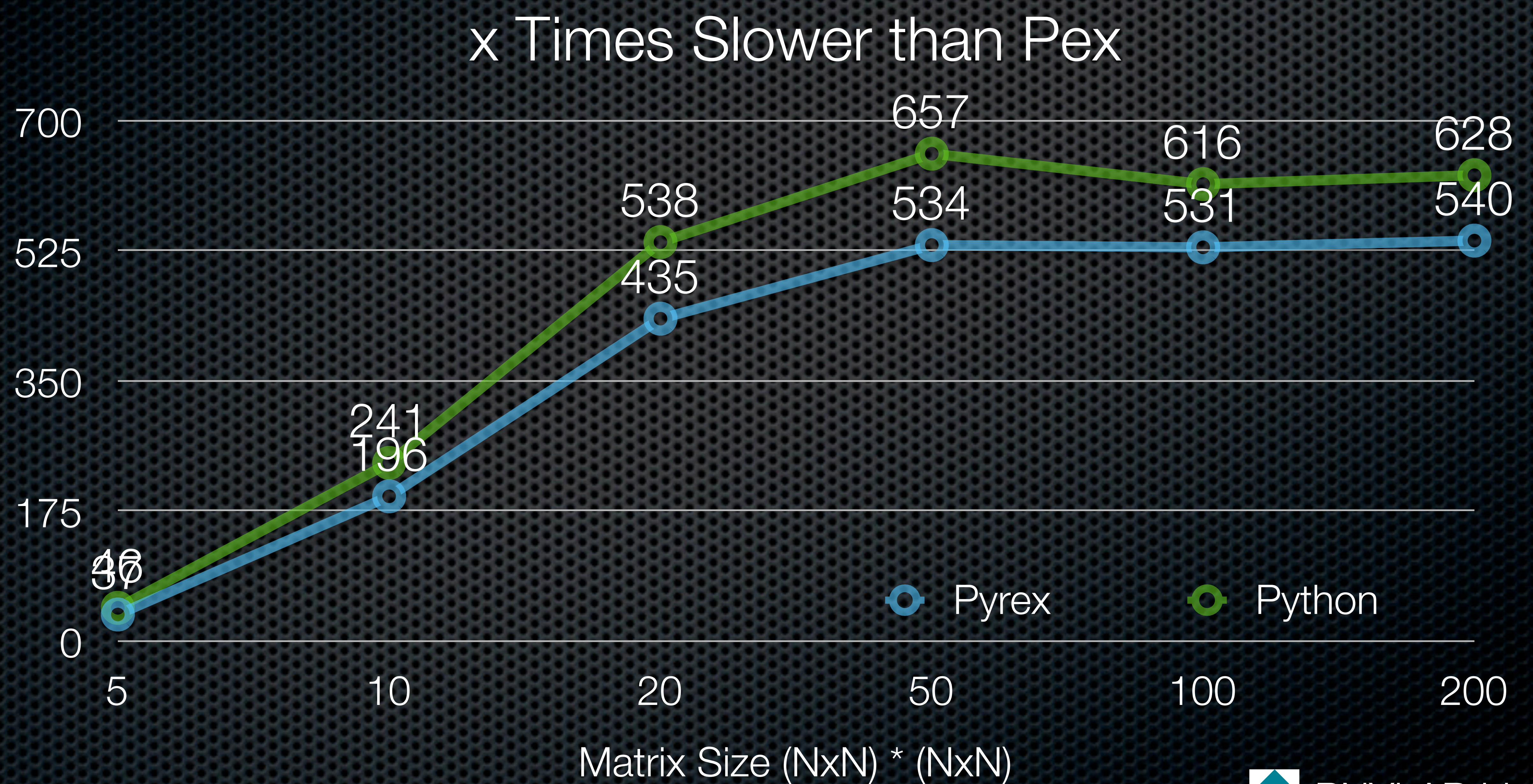
Matrix Multiply Performance



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The Gauss-Jordan Sweep

$$\mathrm{H} = \mathrm{SWP[k]G}$$

$$\mathrm{h}_{kk} = -1/g_{kk}$$
$$h_{jk} = h_{kj} = g_{jk}/g_{kk}, \quad j \neq k$$
$$h_{jl} = h_{lj} = g_{jl} - g_{jk}g_{kl}/g_{kk}, \quad j \neq k \text{ and } l \neq k$$

$$\mathrm{SWP}[1, 2, \ldots, p]G = \left[\begin{array}{cc} -G_{11}^{-1} & G_{11}^{-1}G_{12} \\ G_{21}G_{11}^{-1} & G_{22} - G_{21}G_{11}^{-1}G_{12} \end{array} \right].$$

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```python
import numpy

def sweep(x):

    n = x.shape[0]



    l = 0
    u = n-1

    g_k=numpy.zeros(n,'double')

    pivot_product = 1.0

    for k in range(l,u+1):
        if x[k,k] == 0.0:
            pivot_product = 0.0
            break
        pivot_product *= x[k,k]
        x[k,k] = -1.0 / x[k,k]
        for j in range(n):
            if j == k:
                continue
            g_k[j] = x[j,k]
            x[j,k] = x[k,j] = -x[k,k] * g_k[j]
        for i in range(n):
            if i == k:
                continue
            for j in range(i+1):
                if j == k:
                    continue
                x[j,i] -= g_k[i] * x[k,j]
                x[i,j] = x[j,i]

    return pivot_product
```

```
import numpy

def sweep(ndarray<double 2d> x):

    cdef int    n,l,u,i,j,k
    cdef double pivot_product

    n = x.dimensions[0]
    l = 0
    u = n-1

    cdef ndarray<double,n> g_k

    pivot_product = 1.0

    for k from l <= k <= u:
        if x{k,k} == 0.0:
            pivot_product = 0.0
            break
        pivot_product *= x{k,k}
        x{k,k} = -1.0 / x{k,k}
        for j from 0 <= j < n:
            if j == k:
                continue
            g_k{j} = x{j,k}
            x{j,k} = x{k,j} = -x{k,k} * g_k{j}
        for i from 0 <= i < n:
            if i == k:
                continue
            for j from 0 <= j <= i:
                if j == k:
                    continue
                x{j,i} -= g_k{i} * x{k,j}
                x{i,j} = x{j,i}

    return pivot_product
```

Sweep Algorithm Performance

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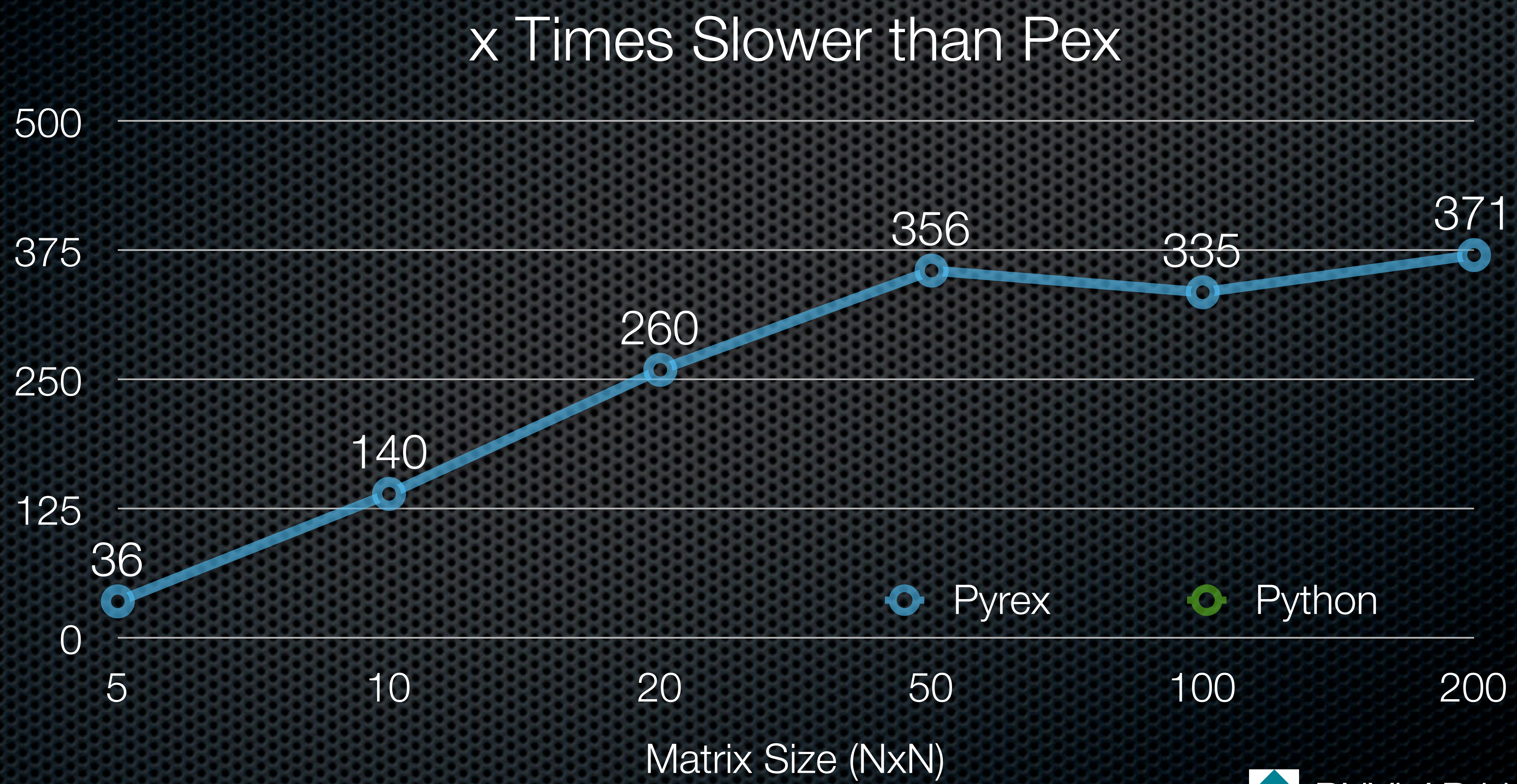
Sweep Algorithm Performance



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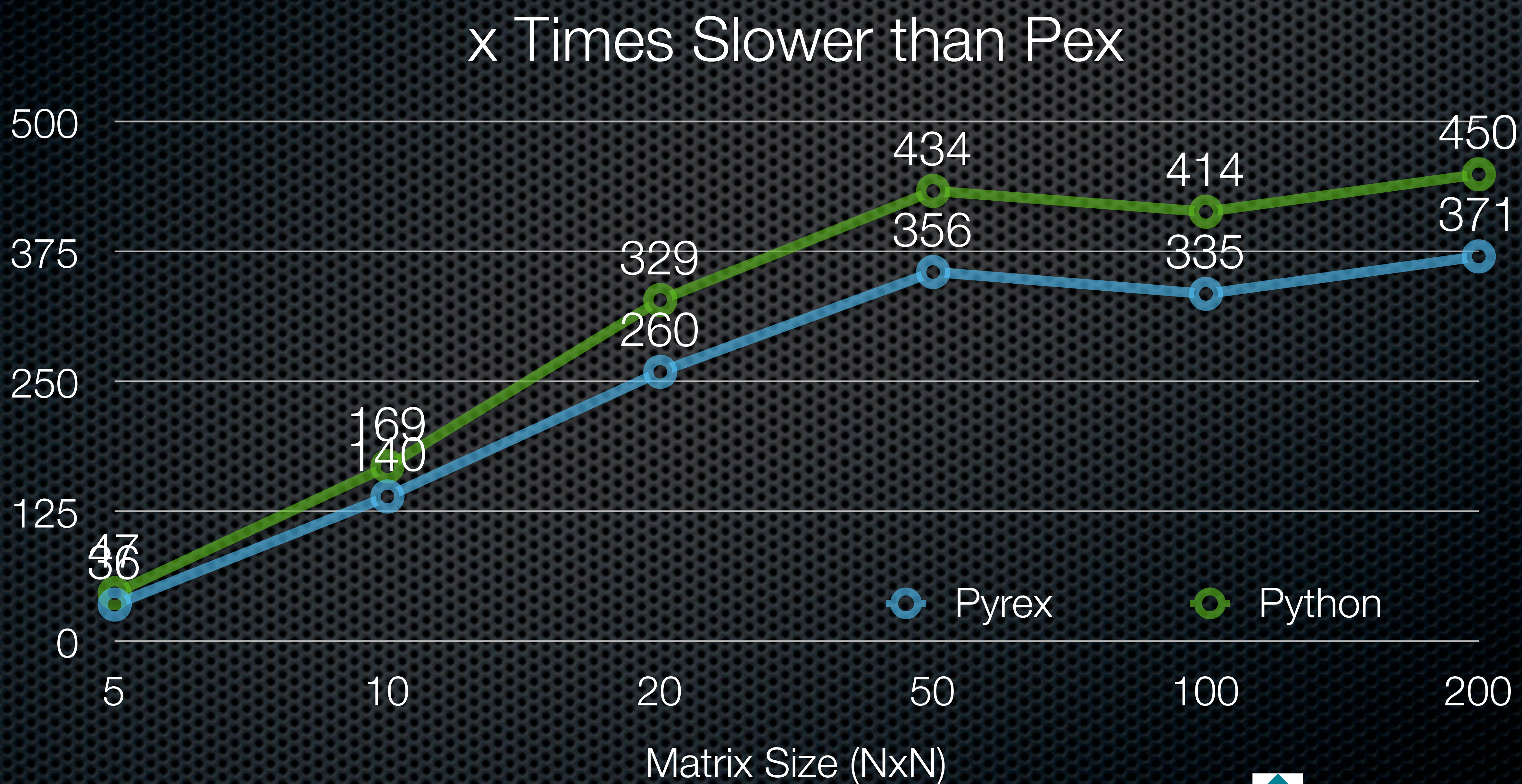
Sweep Algorithm Performance



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No Header Files

No Header Files

You write **file.px**

```
cdef class item:
    cdef double x,y,z
    cdef meth(me): pass
cdef func():pass
```

No Header Files

You write **file.px**

```
cdef class item:
    cdef double x,y,z
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cdef func():pass
```

Pex produces **file.pxd**

```
cdef class item:
    cdef double x,y,z
    cdef meth(me)
cdef func()
```

No Header Files

You write **file.px**

```
cdef class item:
    cdef double x,y,z
    cdef meth(me): pass
cdef func():pass
```

Pex produces **file.pxd**

```
cdef class item:
    cdef double x,y,z
    cdef meth(me)
cdef func()
```

And **file.pyx**

```
<... implementation ...>
```

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No Makefiles

No Makefiles

main.px

%pimport mod

No Makefiles

main.px

%pimport mod

mod.px

%pimport submod

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No Makefiles

main.px

```
%pimport mod
```

mod.px

```
%pimport submod
```

submod.px

```
pass
```

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No Makefiles

main.px

```
%pimport mod
```

mod.px

```
%pimport submod
```

submod.px

```
pass
```

- In the shell

```
$ pex main.px
```

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No Makefiles

main.px

```
%pimport mod
```

mod.px

```
%pimport submod
```

submod.px

```
pass
```

- In the shell

```
$ pex main.px
```

- Or in Python

```
main=pex.pimport('main')
```

No Makefiles

main.px

```
%pimport mod
```

mod.px

```
%pimport submod
```

submod.px

```
pass
```

- In the shell

  $ pex main.px

- Or in Python

  main=pex.pimport('main')

- **submod** gets compiled, then **mod**, then **main**

No Makefiles

main.px

```
%pimport mod
```

mod.px

```
%pimport submod
```

submod.px

```
pass
```

- In the shell

```
$ pex main.px
```

- Or in Python

```
main=pex.pimport('main')
```

- **submod** gets compiled, then **mod**, then **main**
- Feels interpreted

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Automatically pickleable cdef classes

Automatically pickleable cdef classes

- They are!
- Pex generates the magic __reduce__ and __setstate__ methods
- Caveat: can not have C pointer or struct attributes

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Discovered We Wanted More

Fast Slices

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Fast Slices

```
cdef ndarray<double,(n,m,k)> arr

arr{:,1:7,:-4}
```

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Fast Slices

```
cdef ndarray<double,(n,m,k)> arr
arr{:,1:7,:-4}
```

same as

```
arr[:,1:7,:-4]
```

but does not plumb through python runtime, just quick creation of an ndarray header (in C code)

Faster Serialization

Faster Serialization

- Pickling

Faster Serialization

- Pickling
  - write
    - cdef class item: pass
    - pickle.dump(item(),open('file','w'))

Faster Serialization

- Pickling
  - write
    - `cdef class item: pass`
    - `pickle.dump(item(),open(‘file’,’w’))`
  - read
    - `x = pickle.load(open(‘file’))`

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Faster Serialization

- Pickling
  - write
    - cdef class item: pass
    - pickle.dump(item(),open('file','w'))
  - read
    - x = pickle.load(open('file'))
- Goes through Python, slow

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Faster Serialization - FastIO

Faster Serialization - FastIO

- write

    - cdef item x = item()
    - x._fastdump_(open('file','w'))

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Faster Serialization - FastIO

write

```
cdef item x = item()
x._fastdump_(open('file','w'))
```

read

```
x = pex_create_uninitialized(item)
x._fastload_(open('file'))
```

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Faster Serialization - FastIO

write

```
cdef item x = item()
x._fastdump_(open('file','w'))
```

read

```
x = pex_create_uninitialized(item)
x._fastload_(open('file'))
```

>12x faster than pickling, as fast as writing a C struct

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FastIO Limitations

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FastIO Limitations

- Can’t dump a Python list

FastIO Limitations

- Can't dump a Python list
- Can't dump an ndarray of Python object

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- Can’t dump a Python list
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- All attributes must be either primitive C types (int, double, etc), or decorated ndarrays

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- This is just for the leafs of your object hierarchy

FastIO Limitations

- Can’t dump a Python list
- Can’t dump an ndarray of Python object
- All attributes must be either primitive C types (int, double, etc), or decorated ndarrays
- This is just for the leafs of your object hierarchy
- Still, can read/write mammoth data at C speed

Less Vigorous Coredump (1)

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Less Vigorous Coredump (1)

Have **main.px**

```
cdef poof():
    cdef int *p=NULL
    p[0]
def func(): poof()
def main(): func()
```

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Less Vigorous Coredump (1)

Have **main.px**

```
cdef poof():
    cdef int *p=NULL
    p[0]
def func(): poof()
def main(): func()
```

Guess what happens

```
$ pex main.px
```

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Less Vigorous Coredump (2)

$ pex main.px

```
---- BEG BACKTRACE -----------
    Containing Executable File        Instruction Addr              Closest Symbol
    ./main.so                         0x3ACA                       __pyx_pf_201_func

    /usr/lib/libpython2.3.so.1.0      0x43991                      PyCFunction_Call
    /usr/lib/libpython2.3.so.1.0      0x20637                        PyObject_Call
    /usr/lib/libpython2.3.so.1.0      0x721B0           PyEval_CallObjectWithKeywords
    /usr/lib/libpython2.3.so.1.0      0x205FE                  PyObject_CallObject

    ./main.so                         0x37C3                       __pyx_pf_201_main

    /usr/lib/libpython2.3.so.1.0      0x780A6                       PyEval_EvalCodeEx
    /usr/lib/libpython2.3.so.1.0      0x7836D                         PyEval_EvalCode
    /usr/lib/libpython2.3.so.1.0      0x92952               PyRun_SimpleFileExFlags
    /usr/lib/libpython2.3.so.1.0      0x939A4                  PyRun_AnyFileExFlags
    /usr/lib/libpython2.3.so.1.0      0x9869E                                 Py_Main

    python                            0x5B2                                      main

    /lib/tls/libc.so.6                0x14DE3                       __libc_start_main

    python                            0x501                                    (null)
                                                                              [START]
---- END BACKTRACE -----------
```

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Bounds Checking

Bounds Checking

file **main.px**

```
cdef ndarray<int,n> arr
arr{n+1}
```

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cdef ndarray<int,n> arr

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run with bounds checking (about 20 times slower)

Bounds Checking

file **main.px**

```
cdef ndarray<int,n> arr
arr{n+1}
```

run with bounds checking (about 20 times slower)

```
$ pex -b main.px
```

Bounds Checking

file **main.px**

```
cdef ndarray<int,n> arr
arr{n+1}
```

run with bounds checking (about 20 times slower)

```
$ pex -b main.px
```

```
Traceback (most recent call last):
  File "main.pyx", line 298, in main.main
    __px__ndarray_int_get1(arr,"arr",n+1,'n+1')   ##  arr{n+1} | main.px,4
IndexError: Out of bounds index access "n+1"==11 for dimension 1 of "arr" which has length 10
```

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Compilation Configuration

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Compilation Configuration

Setup link with external C libraries inside your **file.px**

```
%whencompiling:
    env.cc.append('-I../../vector/include')
    env.link.append('../../vector/vector.so')
```

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Compilation Configuration

Setup link with external C libraries inside your **file.px**

```
%whencompiling:
    env.cc.append('-I../../vector/include')
    env.link.append('../../vector/vector.so')
```

Then bring in prototypes as usual

```
cdef extern from "vector.h": ...
```

General Pragma Mechanism

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General Pragma Mechanism

```
def func(ndarray<int 2d> arr):
```

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General Pragma Mechanism

```
def func(ndarray<int 2d> arr):
    %whencompiling:
        scope.pragma_ndarray_bounds_checks = True
```

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General Pragma Mechanism

```
def func(ndarray<int 2d> arr):
    %whencompiling:
        scope.pragma_ndarray_bounds_checks = True
    arr{1,n+1}    # THROWS EXCEPTION
```

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General Pragma Mechanism

```
def func(ndarray<int 2d> arr):
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Turns on bounds checks

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General Pragma Mechanism

```
def func(ndarray<int 2d> arr):
    %whencompiling:
        scope.pragma_ndarray_bounds_checks = True
    arr{1,n+1}    # THROWS EXCEPTION
```

Turns on bounds checks

Works by scope, so here pragma applies only to `func()`

Conversion to and from Dictionaries

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Conversion to and from Dictionaries

- cdef classes opaque to Python

Conversion to and from Dictionaries

- cdef classes opaque to Python
- Pex generates _todict_ and _fromdict_ methods

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Conversion to and from Dictionaries

- cdef classes opaque to Python
- Pex generates _todict_ and _fromdict_ methods
- Define in Pex, **mod.px**

```
cdef class item:
    cdef int x,y
```

Conversion to and from Dictionaries

- cdef classes opaque to Python
- Pex generates _todict_ and _fromdict_ methods
- Define in Pex, **mod.px**

```
cdef class item:
    cdef int x,y
```

- From Python

```
mod=pex.pimport('mod')
x = mod.item()
```

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Conversion to and from Dictionaries

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- Pex generates _todict_ and _fromdict_ methods
- Define in Pex, **mod.px**

```
cdef class item:
    cdef int x,y
```

- From Python

```
mod=pex.pimport('mod')
x = mod.item()
x._fromdict_({'x':7,'y':12})
```

Conversion to and from Dictionaries

- cdef classes opaque to Python
- Pex generates _todict_ and _fromdict_ methods
- Define in Pex, **mod.px**

```
cdef class item:
    cdef int x,y
```

- From Python

```
mod=pex.pimport('mod')
x = mod.item()
x._fromdict_({'x':7,'y':12})
print x._todict_()
```

out: {'y': 12, 'x': 7}

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Gotchas

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Gotchas

- Pex has no parser, regular expression based

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Gotchas

- Pex has no parser, regular expression based
- Leads to annoying quirks, eg

```
def func(a, # comment
         b):
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- Leads to annoying quirks, eg

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def func(a, # comment
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- Joined to `def func(a, # comment b):`, so syntax error

Gotchas

- Pex has no parser, regular expression based
- Leads to annoying quirks, eg

```
def func(a, # comment
         b):
```

- Joined to `def func(a, # comment b):`, so syntax error
- Also, no real type system

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Off the Reservation

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Off the Reservation

- pointers (tool of the devil)
  - don’t use them
  - don’t think you need to
  - would like to prohibit them
- structs (use cdef classes instead)

Best of Both Worlds

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Best of Both Worlds

- Luxuriate in Python decadence

Best of Both Worlds

- Luxuriate in Python decadence
    - lists, tuples, dicts, itertools, anything goes

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  - most of the time

Best of Both Worlds

- Luxuriate in Python decadence
    - lists, tuples, dicts, itertools, anything goes
    - most of the time
- Get down to the iron where it matters

Best of Both Worlds

- Luxuriate in Python decadence
  - lists, tuples, dicts, itertools, anything goes
  - most of the time
- Get down to the iron where it matters
  - not much additional pain, lots of performance

Big Picture
Lessons Learned

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Big Picture Lessons Learned

- Have enough performance

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Big Picture
Lessons Learned

- Have enough performance
  - INCREFd memory management - fast, good

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Big Picture
Lessons Learned

- Have enough performance
    - INCREFd memory management - fast, good
- Compiler working hard not only OK, but what you want

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Big Picture
Lessons Learned

- Have enough performance
  - INCREFd memory management - fast, good
- Compiler working hard not only OK, but what you want
- With this setup, someone who only knows Python, can write C efficient code

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Big Picture Lessons Learned

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Big Picture Lessons Learned

- **Coredumps change feel of language**

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Big Picture
Lessons Learned

- **Coredumps change feel of language**
  - completely

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Big Picture
Lessons Learned

- **Coredumps change feel of language**
    - completely
    - sleep worse

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Big Picture
Lessons Learned

- **Coredumps change feel of language**
  - completely
  - sleep worse
  - waste life chasing down horrific memory bugs

Big Picture
Lessons Learned

- **Coredumps change feel of language**
  - completely
  - sleep worse
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  - die younger

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Big Picture Lessons Learned

- **Coredumps change feel of language**
  - completely
  - sleep worse
  - waste life chasing down horrific memory bugs
  - die younger
  - taken away from essence of problem

Big Picture
Going Forward

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- Control coredumps

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- Give up pointers, naked memory access (Hello Fortran!)

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Big Picture
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- Control coredumps
- Give up pointers, naked memory access (Hello Fortran!)
  - not as horrible as it sounds
  - have fast arrays, add in fast multiple value return
  - the only thing you give up: blitting
  - allows safe mode guaranteed to catch corruption

Going Forward
Safe Mode

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- Runs within 3-4x times slower

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Going Forward
Safe Mode

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- Guaranteed to catch any memory corruption
- Set a mask at compile time
  - bounds checking
  - uninitialized variable access
  - keeps track of object creation, detects leaked cycles

Wishlist - Performance

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- Pragma C_code_only

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Wishlist - Performance

- Pragma `C_code_only`
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- Fast multiple return
- Fast comprehensions: `arr={i*i for i from 0<=i<n if i%2}`

Wishlist - Performance

- Pragma C_code_only
- Fast operator overloading
- Fast multiple return
- Fast comprehensions: arr={i*i for i from 0<=i<n if i%2}
- Tool color codes source based on whether it’s C or Py

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Wishlist - Comfort

Now	Want

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Now	Want
cdef ndarray<int,(3,4)> arr	cdef int arr{3,4}

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Wishlist - Comfort

Now	Want
cdef ndarray<int,(3,4)> arr	cdef int arr{3,4}
cdef item x=item(arg1,arg2)	cdef item x(arg1, arg2)

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Wishlist - Comfort

Now	Want
`cdef ndarray<int,(3,4)> arr`	`cdef int arr{3,4}`
`cdef item x=item(arg1,arg2)`	`cdef item x(arg1, arg2)`

And also want, efficient append to 1d ndarray

Status

Our Shop

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- 30 KLOC of Pex code (1.4 MLOC generated C)

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- 30 KLOC of Pex code (1.4 MLOC generated C)
- 5 people actively using Pex, more soon
- Business unforgiving, speed and quality essential

Status
Availability

- Python Software Foundation License (PSF)
- Works on Unix, Mac (all but coredump backtraces), Windows - probably close, but who knows
- Get
    - tarball
    - manual TODO (72 pages)

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Status
Immediate Future

- Want to stop heavy development for a year or so
- Happy to help move any features into Cython proper
- Happy to accept any patches

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Conclusion

- Initial goal

  A language that gets down to the iron, runs at C speeds, and has no surprises in generated assembly, but at the same time guides you along to a clear, succinct and correct expression of complicated systems and algorithms.

- We feel we are there, and are prepared to live with rough edges for awhile

Implementation Details
Fast Numerics

```
cdef ndarray<int 2d> A
```

```
int *data = A.data
int st0,st1
st0 = A.strides[0]/sizeof(int)
st1 = A.strides[1]/sizeof(int)
```

```
arr{i,j}
```

```
data[st0 * i + st1 * j]
```

Implementation Details
Build

Implementation Details
Build

```
        Root.px
        /     \
    A.px      B.px
    /   \        \
AA.px   AB.px     |
          |      /
        ABA.px
```

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In Python could say

Root.A.AB.ABA.func

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In Python could say

Root.A.AB.ABA.func

In Pyrex, same thing!

func could be cdef

Root must know all prototypes of **ABA** at compile time

Implementation Details
Build

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   /    \        \
AA.px   AB.px    |
          |     /
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Build

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```

If **ABA** changes

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Implementation Details
Build

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   /    \       \
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          |     /
         ABA.px*
```

If **ABA** changes

need **Root** recompile

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Implementation Details
Build

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If **ABA** changes

- need **Root** recompile
- must detect this before **Root** is imported, else it is too late

Implementation Details
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         |      /
         ABA.px*
```

If **ABA** changes

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- must detect this before **Root** is imported, else it is too late

Must walk import tree in preorder