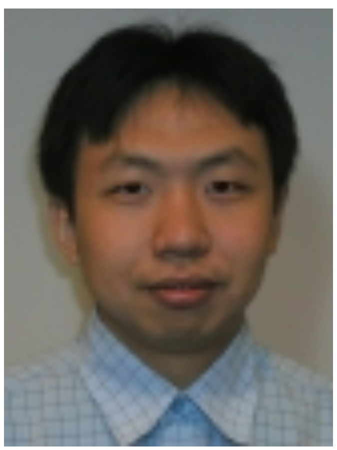
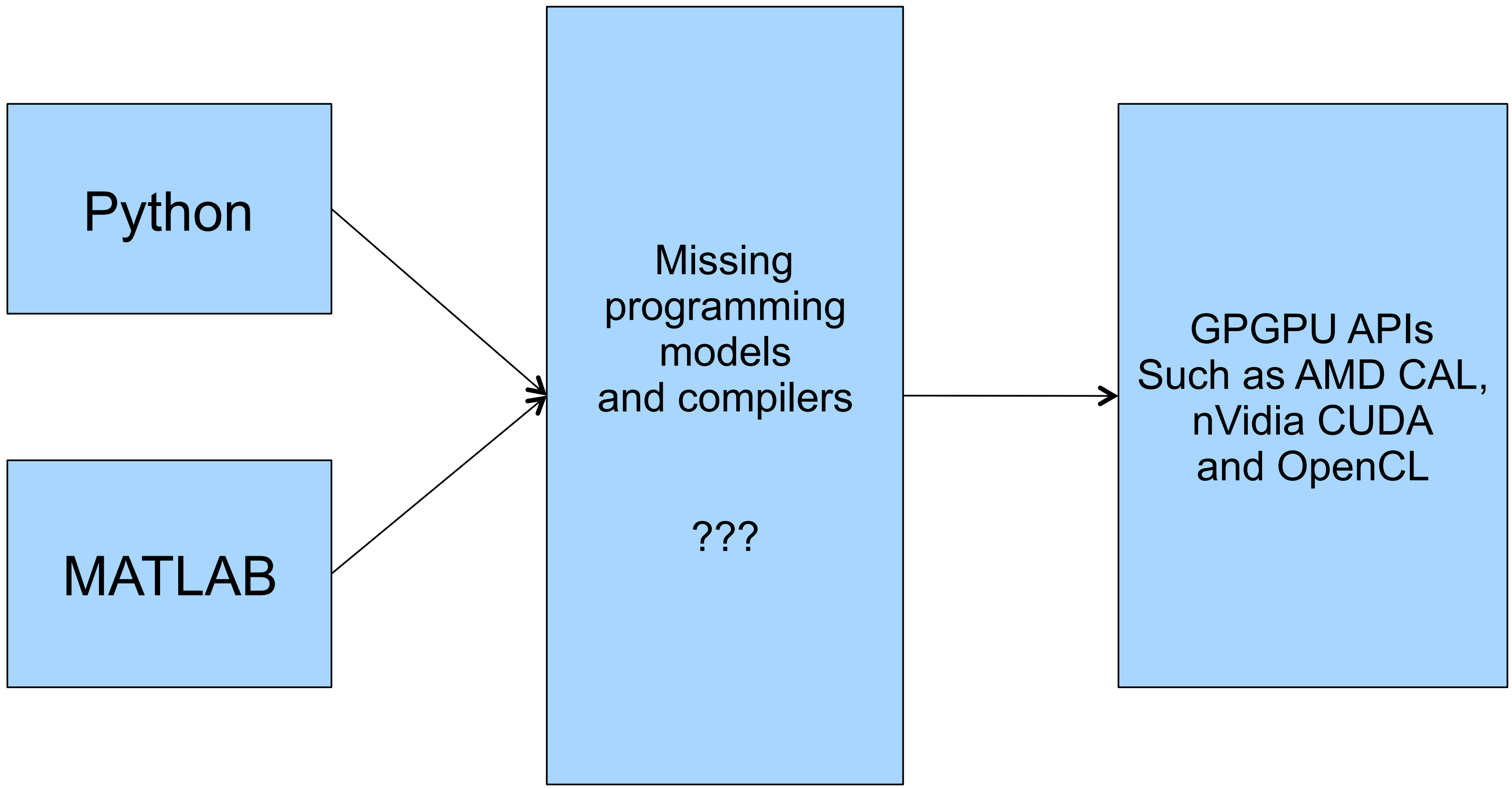
A New Compilation Path: From Python/ NumPy to OpenCL



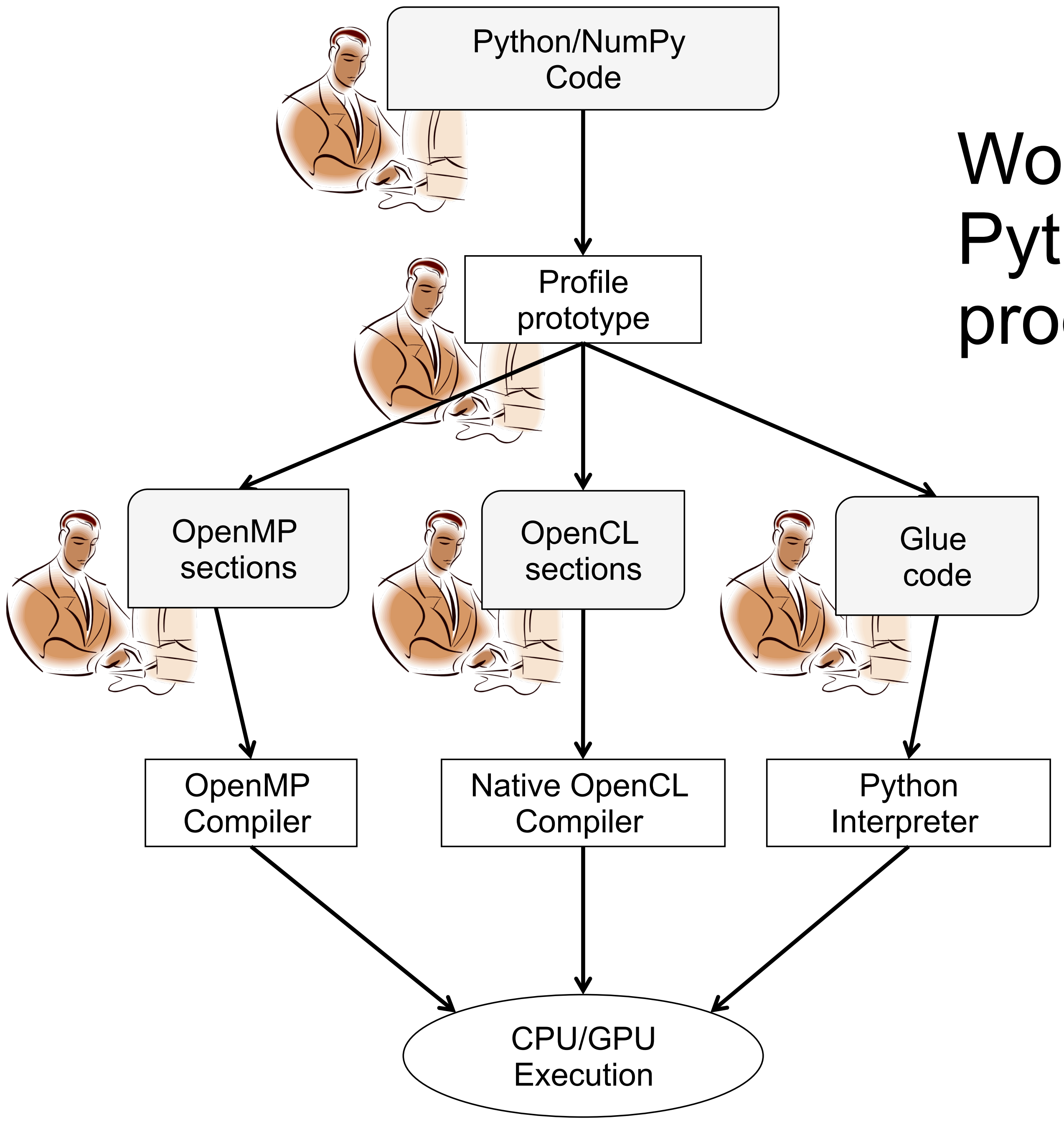
Xunhao Li (IBM Software Lab, Canada)
Rahul Garg (McGill University)
J. Nelson Amaral (University of Alberta)

Special Purpose Computation on Graphics Processing Units

GPGPU from high-level languages?



Workflow for a Python programmer



unPython:

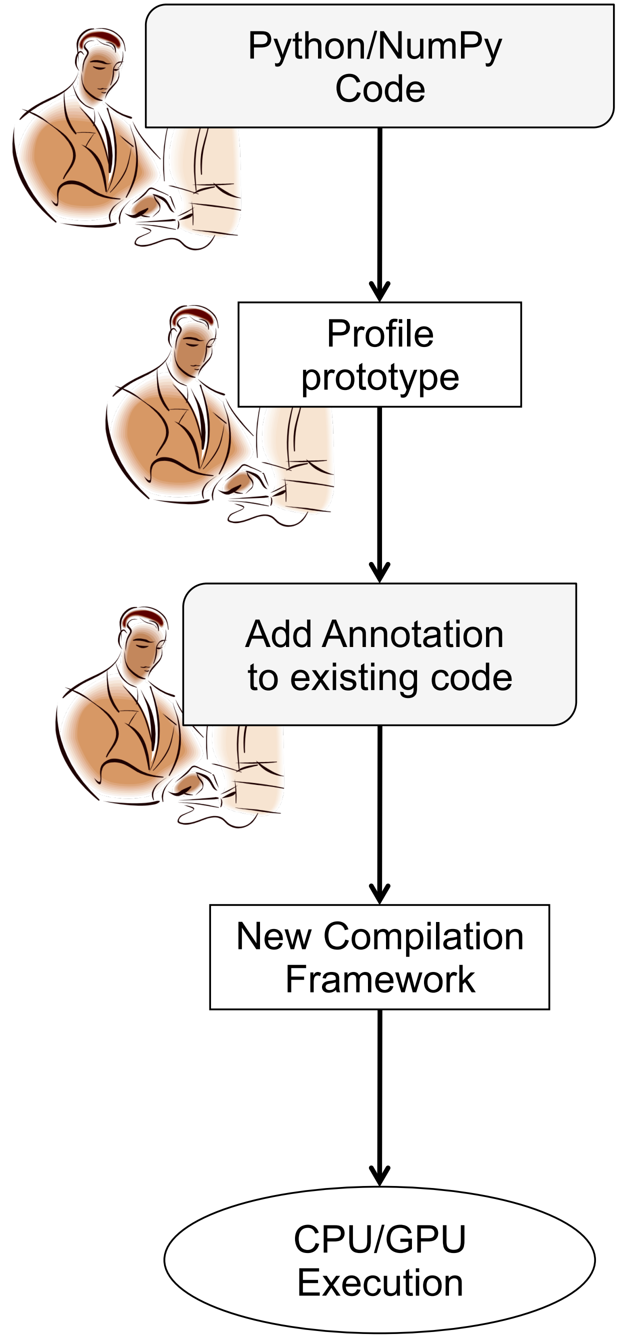
```
for i_1 in prange(u_1):
    for i_2 in prange(u_2):
        ...
        for i_m in prange(u_m):
            for i_(m+1) in range(u_(m+1)):
                .
                .
                for i_d in range(u_d)
                #loop body
```

Figure 5.1: Loop nests considered for array access analysis

Python/NumPy to CPU/GPU

- A special parallel loop annotation to accelerate a particular loop nest using the GPU
- Programming model based on shared memory model similar to OpenMP
- Compiler attempts to identify data accessed inside the loop
- Copies all relevant data to GPU
- Generates GPU code (using CAL API)
- Executes in GPU and copies data back
- If analysis fails, fall back to generated C/C++ code

Workflow using unPython

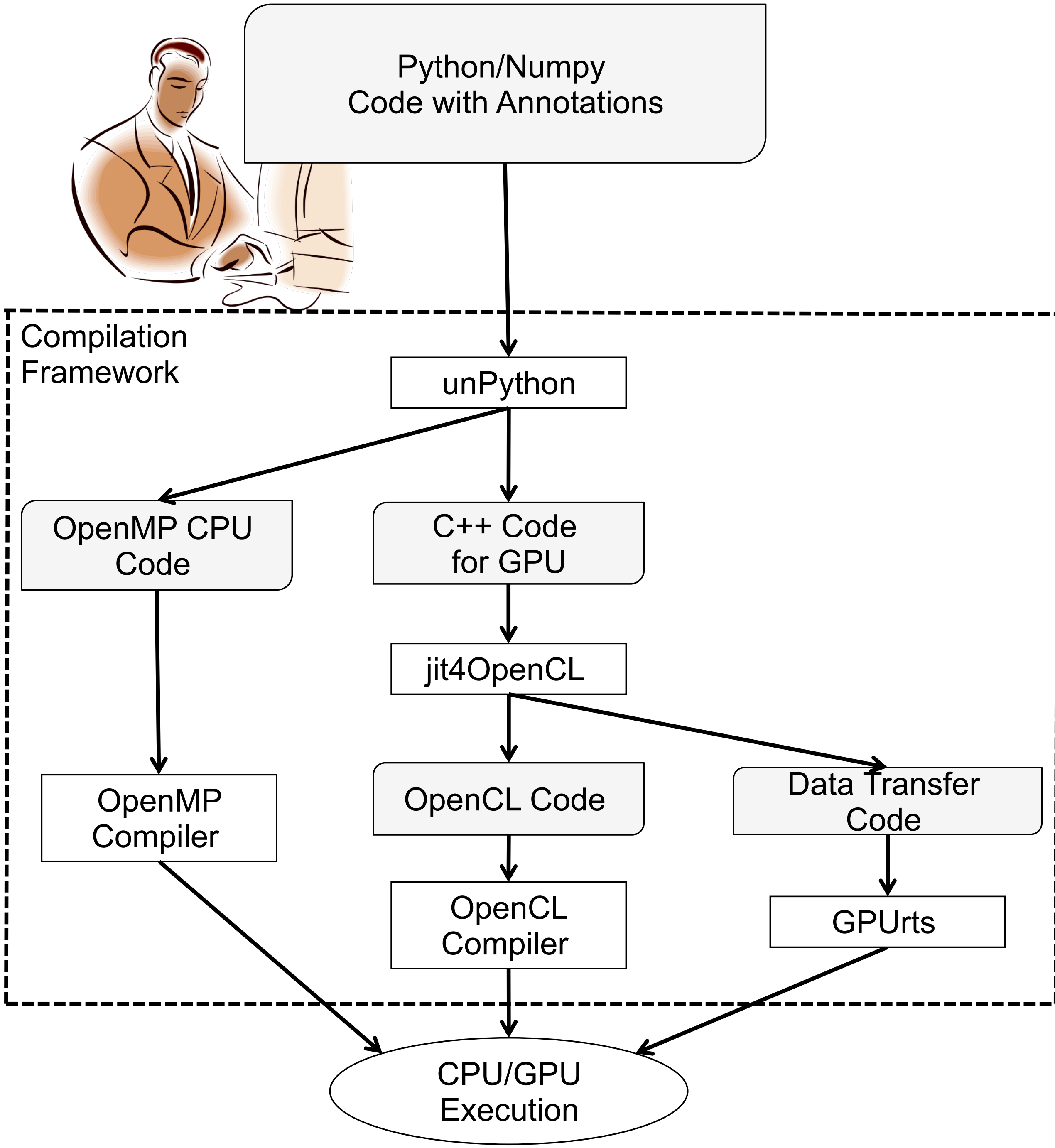


Data Transfer to GPU

- To transfer data to GPU execution:
  - Identify set of memory locations accessed
  - Find the amount of GPU memory required
  - Translate CPU memory addresses to GPU addresses
- Hard to do ahead-of-time, not enough information
- We introduce a new just-in-time compiler named "jit4OpenCL"

jit4OpenCL

- jit4OpenCL is a specialized compiler:
  - Only to handle parallel loop-nests
  - Generated OpenCL code targets GPU execution
- For loops marked parallel, unPython inserts a call to jit4OpenCL to compile the loop
- jit4OpenCL performs data access analysis and attempts to generate OpenCL code
- If jit4OpenCL fails, then execution falls back to OpenMP code generated by unPython
- If jit4OpenCL succeeds, it generates OpenCL code and code for all relevant data transfers


Python/Numpy
Code with Annotations
Compilation
Framework
unPython
OpenMP CPU
Code
C++ Code
for GPU
jit4OpenCL
OpenMP
Compiler
OpenCL Code
Data Transfer
Code
OpenCL
Compiler
GPUrts
CPU/GPU
Execution

Problem:

Given a loop nest:

Which memory locations are accessed?

Do these locations fit in the GPU memory?

If not, how to make them fit?

Key Insights:

Use Linear Memory Access Descriptors to represent referenced locations

Restrict to loops with constant-stride accesses

Further restrict to loops in which each reference is to a unique memory location.

Tile loop nest to make it fit in the GPU memory.

Array access analysis in jit4OpenCL

- identifies the set of memory locations accessed by array references in a loop nest
- uses a new array access analysis algorithm based on Linear Memory Access Descriptors (LMADs) [PaekHoeflingPaduaTOPLAS02]
- LMADs:
    - represent memory-address expressions directly
    - require subscripts to be affine expressions of loop counters

Constant-Stride LMADs (CSLMADs)

- Given a loop nest with *d* nested loops:
  - The lower bound of all loops is 0
  - Upper bounds are affine functions of the loop indices of the outer loops
  - The indices and the strides of the loops are:

$$\vec{i} = (i_1, i_2, \cdots, i_d)$$

$$\vec{s} = (s_1, s_2, \cdots, s_d)$$

CSLMADs (cont.)

- The set of memory locations accessed by a CSLMAD are given by:

$$M = f(\vec{i}) = b + \sum_{k=1}^{d} s_k \times i_k$$

Base (b) Strides (s_k) Indices (i_k)

CSLMADs (example)

```
char A[P][80]

for(u=0; u<100; u++)
    for(v=0; v< v+5; v++)
        … = A[u+v+1][2*u+2];
```

$$f(i,j) = \&A[0][0] + 80 \times (u+v+1)+(2 \times u +2)$$

$$= \&A[0][0] + 82 \times u + 80 \times v + 82$$

$$= \underbrace{(\&A[0][0] + 82)}_{b} + \underbrace{82}_{s_1} \times u + \underbrace{80}_{s_2} \times v$$

$$M = f(\vec{i}) = b + \sum_{k=1}^{d} s_k \times i_k$$

Restricted CSLMADs

CSLMAD:

$$M = f(\vec{i}) = b + \sum_{k=1}^{d} s_k \times i_k$$

Additional constraint for RCSLMAD:

$$s_{r_k} \geq s_{r_d} - 1 + \sum_{j=k+1}^{d} u_{r_j} \times s_{r_j}$$

r_k : position of stride s_{r_k} in a stride list sorted in decreasing order.

s_{r_d} : smallest stride

s_{r_1} : largest stride

In an RSCLMAD each reference is to a unique memory location.

CSLMAD × RCSLMAD (examples)

CSLMAD:

$M = 3u+v$, $u<10$, $v<4$

$(u, v) = (0,3) \rightarrow M = 3$
$(u, v) = (1,0) \rightarrow M = 3$

RCSLMAD:

$M = 4u+v$, $u<10$, $v<4$

$(u, v) = (0,3) \rightarrow M = 3$
$(u, v) = (1,0) \rightarrow M = 4$

There are no two pairs (u,v) that map to the same location.

jit4OpenCL Code Generation

- For OpenCL compiler has to perform on-chip memory allocations.
- jit4OpenCL introduces new memory compactation techniques.
- Transform reference addresses to new space
- Match # of accesses with # of thread blocks (currently uses 16×16 blocks)

Data Transfers

- OpenCL API requires initialization of device memory objects with specific sizes
- Jit4OpenCL:
  - Configures the OpenCL grid
  - Sorts RCSLMAD elements
    - Use memory-address mapping for memory transfers
  - Matches RCSLMAD elements to threads
    - Decides which elements will be in local memory for each thread.
  - Redirects Array Access References

Evaluation - Benchmarks

CP: Columbic Potential (planar grid)

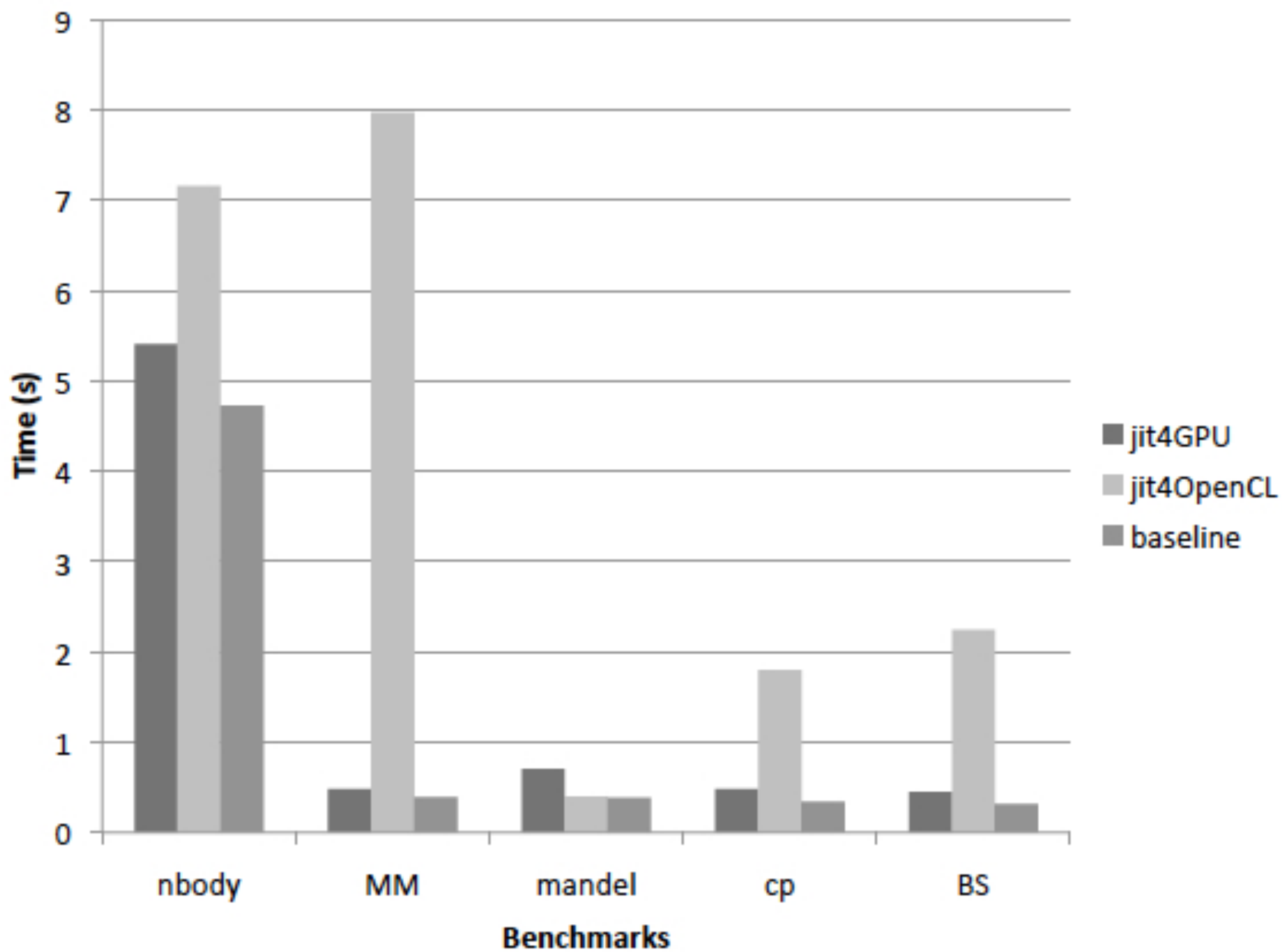
NB: N-Body simulation (a kernel only)

BS: Black-Sholes formulas

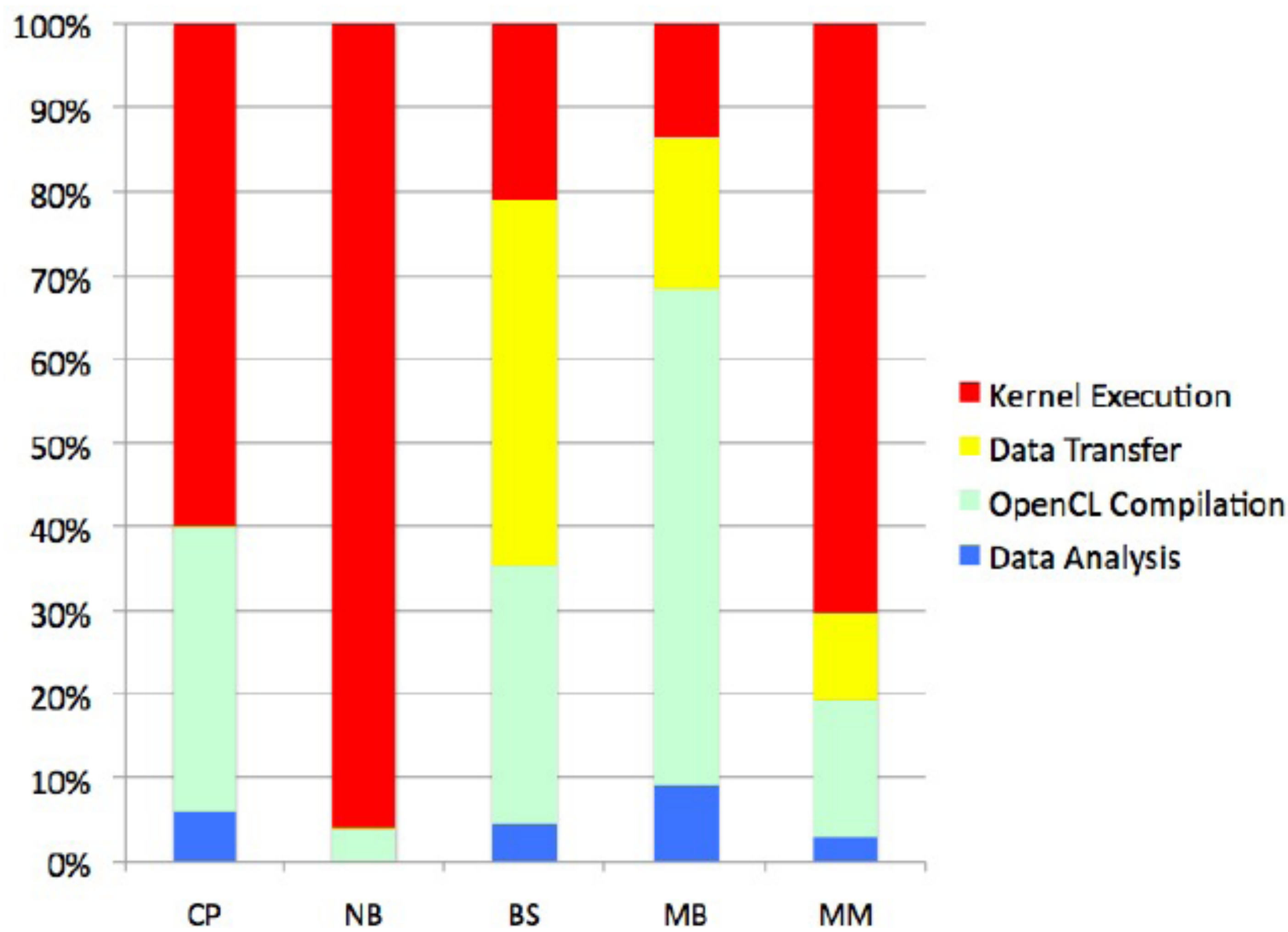
MB: approximation of Madelbrot set

MM: Matrix multiplication

Comparison with jit4GPU and Hand-written OpenCL code
(on AMD Radeon 5850)



Where is time spent? (jit4OpenCL on NVidia GTX260)



Take-Away Points

- OpenCL portability comes with a performance cost
- Data transfers in OpenCL are more constrained and might be limiting speed.
- Jit4OpenCL is a quick way to test a Python/NumPy application in many platforms.
- Increased memory bandwidth in GPUs and improvement of native OpenCL compilers is likely to help with performance.