What

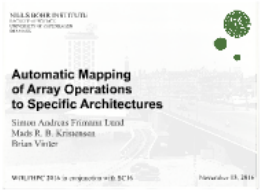
Why

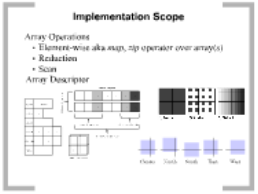
Goal

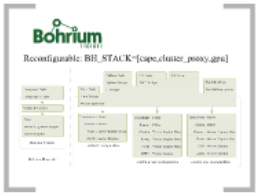
Previous

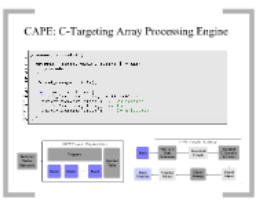
Current

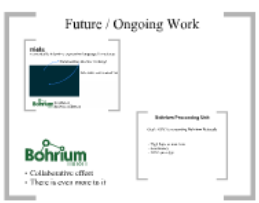
The End

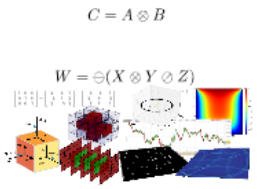


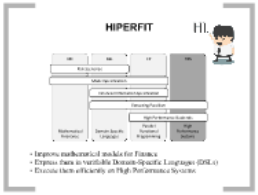


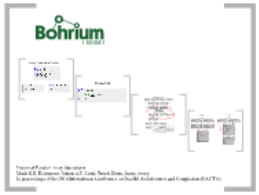


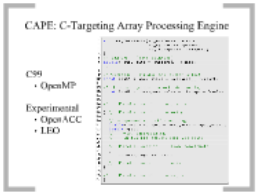




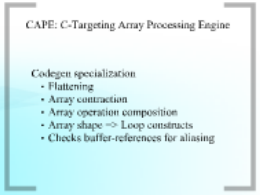


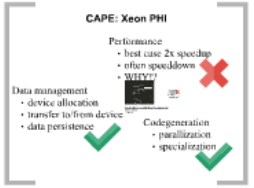


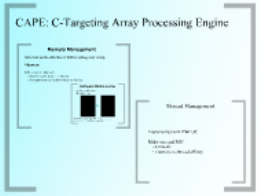


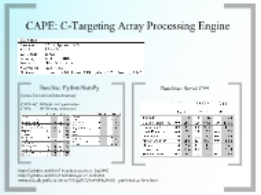


Encore









Thanks

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Automatic Mapping of Array Operations to Specific Architectures

Simon Andreas Frimann Lund
Mads R. B. Kristensen
Brian Vinter

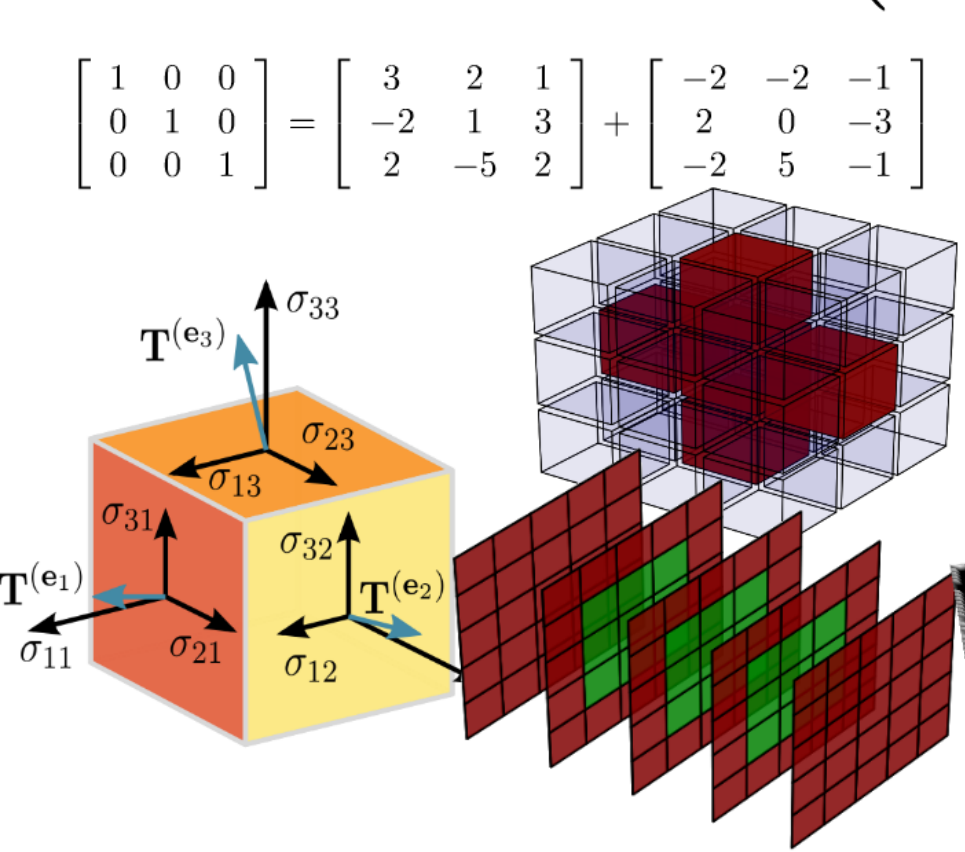
WOLFHPC 2016 in conjunction with SC16

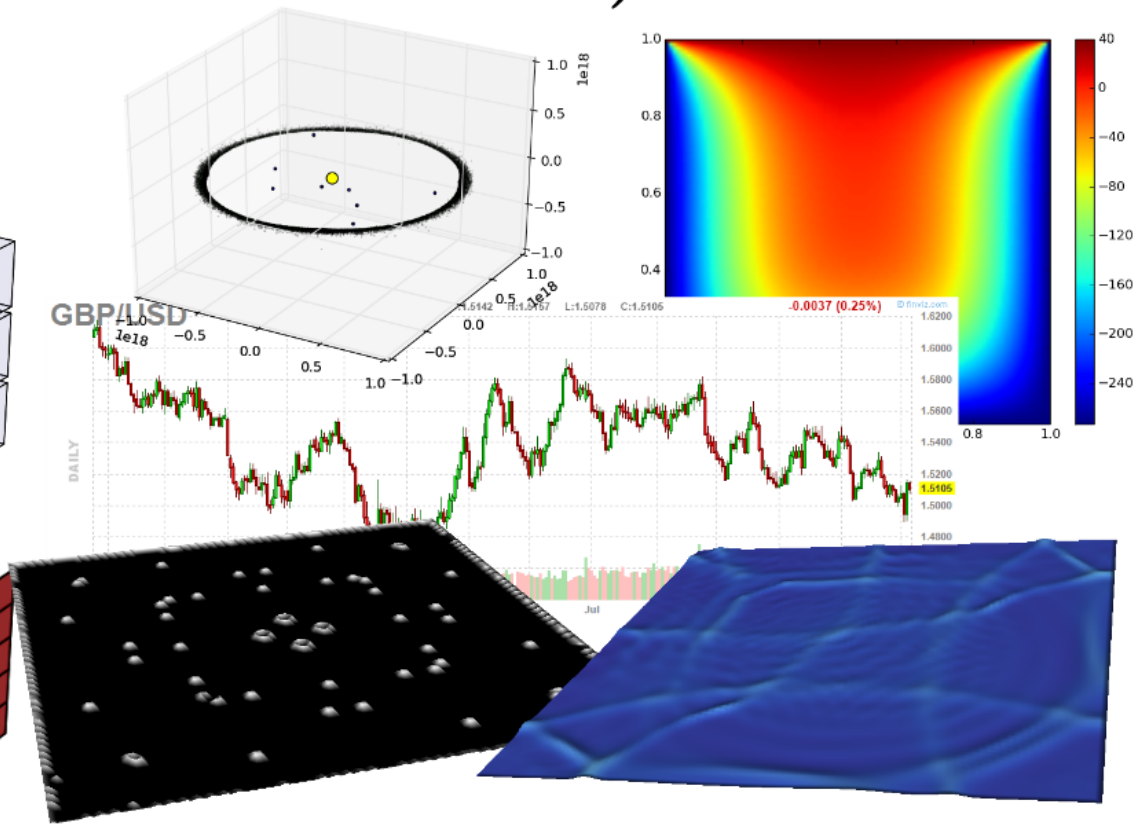
November 13, 2016

$$C = A \otimes B$$

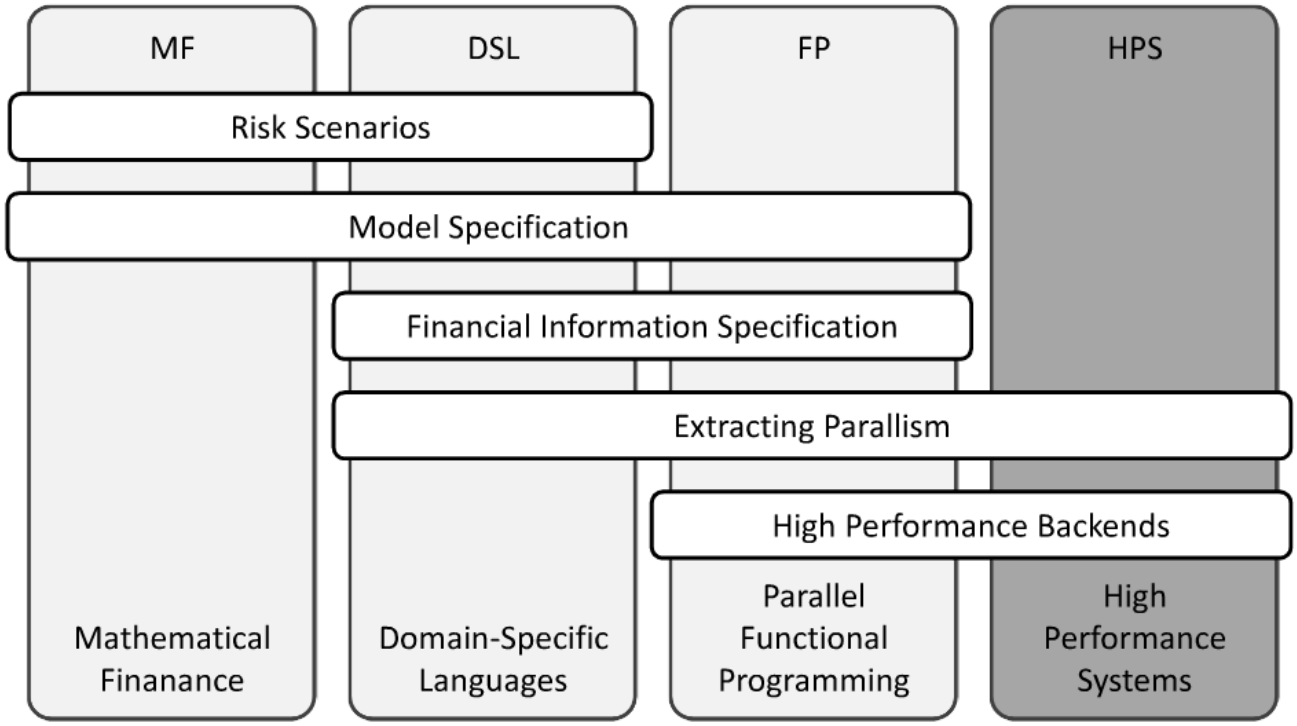
$$W = \ominus(X \otimes Y \oslash Z)$$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 3 & 2 & 1 \\ -2 & 1 & 3 \\ 2 & -5 & 2 \end{bmatrix} + \begin{bmatrix} -2 & -2 & -1 \\ 2 & 0 & -3 \\ -2 & 5 & -1 \end{bmatrix}$$



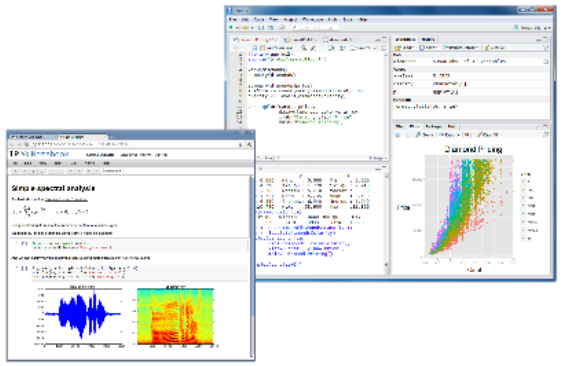


HIPERFIT



- Improve mathematical models for Finance
- Express them in verifiable Domain-Specific Languages (DSLs)
- Execute them efficiently on High Performance Systems

Tools of the trade



Productivity

Performance

MATLAB

python

NumPy

A Programming Language

- Languages used by TOP15 Computational Finance / Financial Engineering / "Quant Programs" https://www.quantnet.com/mfe-programs-rankings/
- As well as the University of Copenhagen
- HIPERFIT industry partners with an affinity for APL

#directives

C / C++ / Fortran

OpenMP / pthreads / Qthread

MPI

OpenACC / LEO

OpenCL / CUDA

PGAs

CPUs,

APUs,
Hybrid,
FPGA,

GPUs,
Accelerators,

and clusters of them configured in
shared and distributed memory systems...

Heat Equation in Python / NumPy

```
 1 def solve(grid, epsilon):
 2   center = grid[1:-1, 1:-1]
 3   north  = grid[0:-2, 1:-1]
 4   south  = grid[2:  , 1:-1]
 5   east   = grid[1:-1, 2:  ]
 6   west   = grid[1:-1, 0:-2]
 7
 8   delta = epsilon + 1
 9   while delta > epsilon:
10     work  = (center+north+east+west+south)*0.2
11     delta = np.sum(np.absolute(work-center))
12     center[:] = work
```

Heat Equation in C

```c
#include <math.h>
solve(int size, double *grid, double epsilon)
{
  int gsize = size+2; //Size + borders.
  double *T = malloc(gsize*gsize*sizeof(double));
  double delta = epsilon+1;
  while(delta > epsilon)
  {
    double *a = grid;
    double *t = T;
    delta = 0;
    for(i=0; i<size; ++i)
    {
      double *up     = a+1;
      double *left   = a+gsize;
      double *right  = a+gsize+2;
      double *down   = a+1+gsize*2;
      double *center = a+gsize+1;
      double *t_center = t+gsize+1;
      for(j=0; j<size; ++j)
      {
        *t_center = (*center + *up++ + *left++ + *right++ + *down++) * 0.2;
        delta += fabs(t_center+center);
      }
      a += gsize;
      t += gsize;
    }
    memcpy(A, T, gsize*gsize*sizeof(double));
  }
}
```

Heat Equation in C and OpenMP

```c
#include <math.h>
solve(int size, double *grid, double epsilon)
{
  int gsize = size+2; //Size + borders.
  double *T = malloc(gsize*gsize*sizeof(double));
  double delta = epsilon+1;
  while(delta > epsilon)
  {
    delta = 0;
    #pragma omp parallel for shared(grid,T) reduction(+:delta)
    for(i=0; i<size; ++i)
    {
      int a = i * gsize;
      double *up     = &grid[a+1];
      double *left   = &grid[a+gsize];
      double *right  = &grid[a+gsize+2];
      double *down   = &grid[a+1+gsize*2];
      double *center = &grid[a+gsize+1];
      double *t_center = &T[a+gsize+1];
      for(j=0; j<size; ++j)
      {
        *t_center = (*center + *up++ + *left++ + *right++ + *down++) * 0.2;
        delta += fabs(t_center+center);
      }
    }
    memcpy(grid, T, gsize*gsize*sizeof(double));
  }
}
```

Heat Equation in C and OpenMP

```c
#include <math.h>
solve(int size, double *grid, double epsilon)
{
  int gsize = size+2; //Size + borders.
  double *T = malloc(gsize*gsize*sizeof(double));
  double delta = epsilon+1;
  while(delta > epsilon)
  {
    delta = 0;
    #pragma omp parallel for shared(grid,T) reduction(+:delta)
    for(i=0; i<size; ++i)
    {
      int a = i * gsize;
      double *up     = &grid[a+1];
      double *left   = &grid[a+gsize];
      double *right  = &grid[a+gsize+2];
      double *down   = &grid[a+1+gsize*2];
      double *center = &grid[a+gsize+1];
      double *t_center = &T[a+gsize+1];
      for(j=0; j<size; ++j)
      {
        *t_center = (*center + *up++ + *left++ + *right++ + *down++) * 0.2;
        delta += fabs(t_center+center);
      }
    }
    memcpy(grid, T, gsize*gsize*sizeof(double));
  }
}
```

Heat Equation in C and OpenMP and MPI

```c
#include <math.h>
#include <mpi.h>
solve(int size, double *grid, double epsilon)
{
  int gsize = SIZE+2; //Size + borders.
  MPI_Comm_rank(MPI_COMM_WORLD, &myrank);
  MPI_Comm_size(MPI_COMM_WORLD, &worldsize);
  MPI_Comm comm;
  int periods[] = {0};
  MPI_Cart_create(MPI_COMM_WORLD, 1, &worldsize,
                  periods, 1, &comm);
  int l_size = SIZE / worldsize;
  if(myrank == worldsize-1)
     l_size += SIZE % worldsize;
  int l_gsize = l_size + 2;//Size + borders.

  double delta = epsilon+1;
  while(delta > epsilon)
  {

    int p_src, p_dest;
    //Send/receive - neighbor above
    MPI_Cart_shift(comm,0,1,&p_src,&p_dest);
    MPI_Sendrecv(grid+gsize,gsize,MPI_DOUBLE,
                 p_dest,1,grid,gsize, MPI_DOUBLE,
                 p_src,1,comm,MPI_STATUS_IGNORE);
    //Send/receive - neighbor below
    MPI_Cart_shift(comm,0,-1,&p_src,&p_dest);
    MPI_Sendrecv(grid+(l_gsize-2)*gsize,
                 gsize,MPI_DOUBLE,
                 p_dest,1,grid+(l_gsize-1)*gsize,
                 gsize,MPI_DOUBLE,
                 p_src,1,comm,MPI_STATUS_IGNORE);
    delta = 0;
    #pragma omp parallel for shared(grid,T) reduction(+:delta)
    for(i=0; i<size; ++i)
    {
      int a = i * gsize;
      double *up     = &grid[a+1];
      double *left   = &grid[a+gsize];
      double *right  = &grid[a+gsize+2];
      double *down   = &grid[a+1+gsize*2];
      double *center = &grid[a+gsize+1];
      double *t_center = &T[a+gsize+1];
      for(j=0; j<size; ++j)
      {
        *t_center = (*center + *up++ + *left++ + *right++ + *down++) * 0.2;
        delta += fabs(t_center+center);
      }
    }
    memcpy(grid, T, gsize*gsize*sizeof(double));
    MPI_Allreduce(delta, delta, 1, MPI_DOUBLE, MPI_SUM, MPI_COMM_WORLD);
  }
}
```

Heat Equation in C and OpenMP and MPI

```c
#include <math.h>
#include <mpi.h>
solve(int size, double *grid, double epsilon)
{
  int gsize = SIZE+2; //Size + borders.
  MPI_Comm_rank(MPI_COMM_WORLD, &myrank);
  MPI_Comm_size(MPI_COMM_WORLD, &worldsize);
  MPI_Comm comm;
  int periods[] = {0};
  MPI_Cart_create(MPI_COMM_WORLD, 1, &worldsize,
                  periods, 1, &comm);
  int l_size = SIZE / worldsize;
  if(myrank == worldsize-1)
     l_size += SIZE % worldsize;
  int l_gsize = l_size + 2;//Size + borders.

  double delta = epsilon+1;
  while(delta > epsilon)
  {

    int p_src, p_dest;
    //Send/receive - neighbor above
    MPI_Cart_shift(comm,0,1,&p_src,&p_dest);
    MPI_Sendrecv(grid+gsize,gsize,MPI_DOUBLE,
                 p_dest,1,grid,gsize, MPI_DOUBLE,
                 p_src,1,comm,MPI_STATUS_IGNORE);
    //Send/receive - neighbor below
    MPI_Cart_shift(comm,0,-1,&p_src,&p_dest);
    MPI_Sendrecv(grid+(l_gsize-2)*gsize,
                 gsize,MPI_DOUBLE,
                 p_dest,1,grid+(l_gsize-1)*gsize,
                 gsize,MPI_DOUBLE,
                 p_src,1,comm,MPI_STATUS_IGNORE);
    delta = 0;
    #pragma omp parallel for shared(grid,T) reduction(+:delta)
    for(i=0; i<size; ++i)
    {
      int a = i * gsize;
      double *up     = &grid[a+1];
      double *left   = &grid[a+gsize];
      double *right  = &grid[a+gsize+2];
      double *down   = &grid[a+1+gsize*2];
      double *center = &grid[a+gsize+1];
      double *t_center = &T[a+gsize+1];
      for(j=0; j<size; ++j)
      {
        *t_center = (*center + *up++ + *left++ + *right++ + *down++) * 0.2;
        delta += fabs(t_center+center);
      }
    }
    memcpy(grid, T, gsize*gsize*sizeof(double));
    MPI_Allreduce(delta, delta, 1, MPI_DOUBLE, MPI_SUM, MPI_COMM_WORLD);
  }
}
```

Heat Equation in C and OpenMP and MPI with Latency Hiding

```c
#include <math.h>
#include <mpi.h>
solve(int size, double *grid, double epsilon)
{
  int gsize = SIZE+2; //Size + borders.
  MPI_Comm_rank(MPI_COMM_WORLD, &myrank);
  MPI_Comm_size(MPI_COMM_WORLD, &worldsize);
  MPI_Comm comm;
  int periods[] = {0};
  MPI_Cart_create(MPI_COMM_WORLD, 1, &worldsize,
                  periods, 1, &comm);
  int l_size = SIZE / worldsize;
  if(myrank == worldsize-1)
     l_size += SIZE % worldsize;
  int l_gsize = l_size + 2;//Size + borders.

  double delta = epsilon+1;
  while(delta > epsilon)
  {

    int p_src, p_dest;
    MPI_Request reqs[4];
    //Initiate send/receive - neighbor above
    MPI_Cart_shift(comm, 0, 1, &p_src, &p_dest);
    MPI_Isend(grid+gsize, gsize, MPI_DOUBLE, p_dest,
              1, comm, &reqs[0]);
    MPI_Irecv(grid, gsize, MPI_DOUBLE, p_src,
              1, comm, &reqs[1]);
    //Initiate send/receive - neighbor below
    MPI_Cart_shift(comm, 0, -1, &p_src, &p_dest);
    MPI_Isend(grid+(l_gsize-2)*gsize, gsize,
              MPI_DOUBLE,
              p_dest, 1, comm, &reqs[2]);
    MPI_Irecv(grid+(l_gsize-1)*gsize, gsize,
              MPI_DOUBLE,
              p_src, 1, comm, &reqs[3]);
    //Handle the non-border elements.
    delta = 0;
    #pragma omp parallel for shared(grid,T) reduction(+:delta)
    for(i=0; i<size-1; ++i)
    {
      int a = i * gsize;
      double *up     = &grid[a+1];
      double *left   = &grid[a+gsize];
      double *right  = &grid[a+gsize+2];
      double *down   = &grid[a+1+gsize*2];
      double *center = &grid[a+gsize+1];
      double *t_center = &T[a+gsize+1];
      for(j=0; j<size-1; ++j)
      {
        *t_center = (*center + *up++ + *left++ + *right++ + *down++) * 0.2;
        delta += fabs(t_center+center);
      }
    }
    //Handle the upper ghost line
    MPI_Waitall(2, reqs, MPI_STATUSES_IGNORE);
    {
      int a = 0 * gsize;
      double *up     = &grid[a+1];
      double *left   = &grid[a+gsize];
      double *right  = &grid[a+gsize+2];
      double *down   = &grid[a+1+gsize*2];
      double *center = &grid[a+gsize+1];
      double *t_center = &T[a+gsize+1];
      for(j=0; j<size-1; ++j)
      {
        *t_center = (*center + *up++ + *left++ + *right++ + *down++) * 0.2;
        delta += fabs(t_center+center);
      }
    }
    //Handle the lower ghost line
    MPI_Waitall(2, reqs+2, MPI_STATUSES_IGNORE);
    {
      int a = (size-1) * gsize;
      double *up     = &grid[a+1];
      double *left   = &grid[a+gsize];
      double *right  = &grid[a+gsize+2];
      double *down   = &grid[a+1+gsize*2];
      double *center = &grid[a+gsize+1];
      double *t_center = &T[a+gsize+1];
      for(j=0; j<size-1; ++j)
      {
        *t_center = (*center + *up++ + *left++ + *right++ + *down++) * 0.2;
        delta += fabs(t_center+center);
      }
    }
    memcpy(grid, T, gsize*gsize*sizeof(double));
    MPI_Allreduce(delta, delta, 1, MPI_DOUBLE, MPI_SUM, MPI_COMM_WORLD);
  }
```

Heat Equation in C and OpenMP and MPI with Latency Hiding

```c
#include <math.h>
#include <mpi.h>
solve(int size, double *grid, double epsilon)
{
  int gsize = SIZE+2; //Size + borders.
  MPI_Comm_rank(MPI_COMM_WORLD, &myrank);
  MPI_Comm_size(MPI_COMM_WORLD, &worldsize);
  MPI_Comm comm;
  int periods[] = {0};
  MPI_Cart_create(MPI_COMM_WORLD, 1, &worldsize,
                  periods, 1, &comm);
  int l_size = SIZE / worldsize;
  if(myrank == worldsize-1)
     l_size += SIZE % worldsize;
  int l_gsize = l_size + 2;//Size + borders.

  double delta = epsilon+1;
  while(delta > epsilon)
  {

    int p_src, p_dest;
    MPI_Request reqs[4];
    //Initiate send/receive - neighbor above
    MPI_Cart_shift(comm, 0, 1, &p_src, &p_dest);
    MPI_Isend(grid+gsize, gsize, MPI_DOUBLE, p_dest,
              1, comm, &reqs[0]);
    MPI_Irecv(grid, gsize, MPI_DOUBLE, p_src,
              1, comm, &reqs[1]);
    //Initiate send/receive - neighbor below
    MPI_Cart_shift(comm, 0, -1, &p_src, &p_dest);
    MPI_Isend(grid+(l_gsize-2)*gsize, gsize,
              MPI_DOUBLE,
              p_dest, 1, comm, &reqs[2]);
    MPI_Irecv(grid+(l_gsize-1)*gsize, gsize,
              MPI_DOUBLE,
              p_src, 1, comm, &reqs[3]);
    //Handle the non-border elements.
    delta = 0;
    #pragma omp parallel for shared(grid,T) reduction(+:delta)
    for(i=0; i<size-1; ++i)
    {
      int a = i * gsize;
      double *up     = &grid[a+1];
      double *left   = &grid[a+gsize];
      double *right  = &grid[a+gsize+2];
      double *down   = &grid[a+1+gsize*2];
      double *center = &grid[a+gsize+1];
      double *t_center = &T[a+gsize+1];
      for(j=0; j<size-1; ++j)
      {
        *t_center = (*center + *up++ + *left++ + *right++ + *down++) * 0.2;
        delta += fabs(t_center+center);
      }
    }
    //Handle the upper ghost line
    MPI_Waitall(2, reqs, MPI_STATUSES_IGNORE);
    {
      int a = 0 * gsize;
      double *up     = &grid[a+1];
      double *left   = &grid[a+gsize];
      double *right  = &grid[a+gsize+2];
      double *down   = &grid[a+1+gsize*2];
      double *center = &grid[a+gsize+1];
      double *t_center = &T[a+gsize+1];
      for(j=0; j<size-1; ++j)
      {
        *t_center = (*center + *up++ + *left++ + *right++ + *down++) * 0.2;
        delta += fabs(t_center+center);
      }
    }
    //Handle the lower ghost line
    MPI_Waitall(2, reqs+2, MPI_STATUSES_IGNORE);
    {
      int a = (size-1) * gsize;
      double *up     = &grid[a+1];
      double *left   = &grid[a+gsize];
      double *right  = &grid[a+gsize+2];
      double *down   = &grid[a+1+gsize*2];
      double *center = &grid[a+gsize+1];
      double *t_center = &T[a+gsize+1];
      for(j=0; j<size-1; ++j)
      {
        *t_center = (*center + *up++ + *left++ + *right++ + *down++) * 0.2;
        delta += fabs(t_center+center);
      }
    }
    memcpy(grid, T, gsize*gsize*sizeof(double));
    MPI_Allreduce(delta, delta, 1, MPI_DOUBLE, MPI_SUM, MPI_COMM_WORLD);
  }
```

Heat Equation in Python / NumPy

```python
def solve(grid, epsilon):
  center = grid[1:-1, 1:-1]
  north  = grid[0:-2, 1:-1]
  south  = grid[2:  , 1:-1]
  east   = grid[1:-1, 2:  ]
  west   = grid[1:-1, 0:-2]

  delta = epsilon + 1
  while delta > epsilon:
    work  = (center+north+east+west+south)*0.2
    delta = np.sum(np.absolute(work-center))
    center[:] = work
```

Heat Equation in Python / NumPy

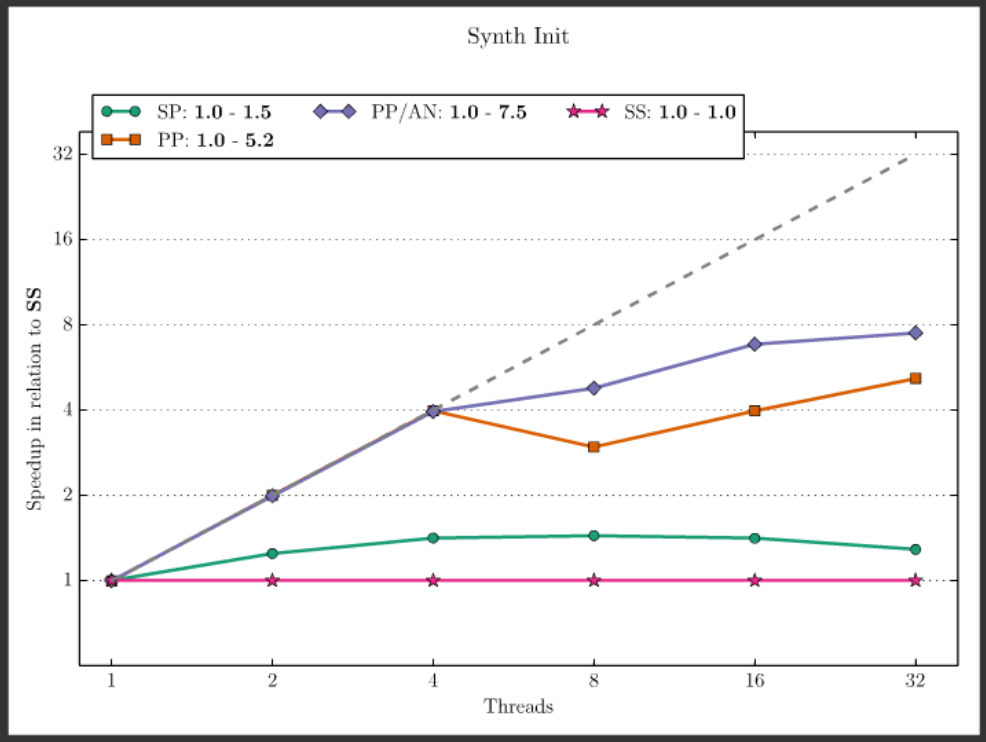
```
 1 def solve(grid, epsilon):
 2   center = grid[1:-1, 1:-1]
 3   north  = grid[0:-2, 1:-1]
 4   south  = grid[2:  , 1:-1]
 5   east   = grid[1:-1, 2:  ]
 6   west   = grid[1:-1, 0:-2]
 7
 8   delta = epsilon + 1
 9   while delta > epsilon:
10     work  = (center+north+east+west+south)*0.2
11     delta = np.sum(np.absolute(work-center))
12     center[:] = work
```

Programming Pitfalls

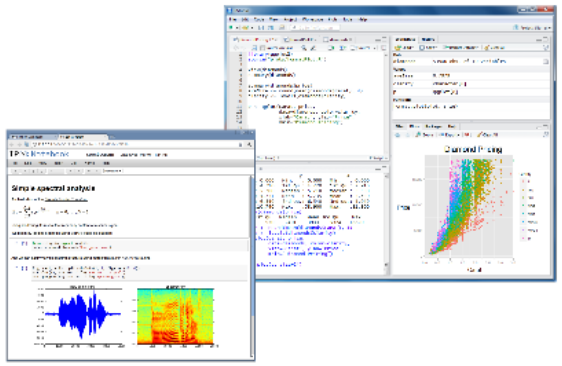
Performance

Correctness

- Deadlocks
- Race-conditions



Tools of the trade



Productivity

Performance

MATLAB

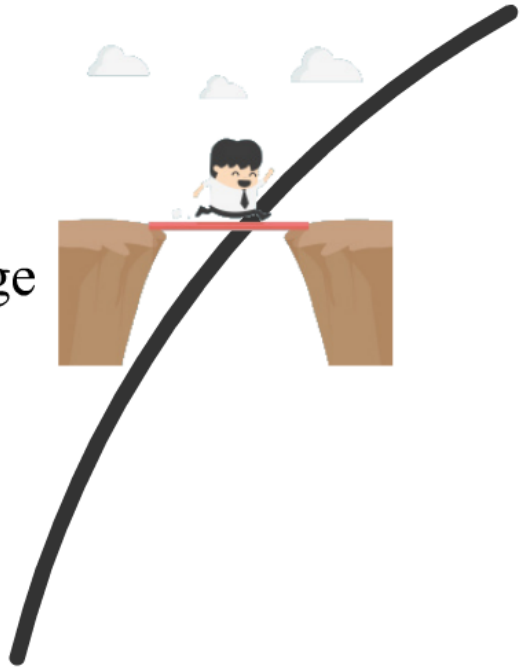
python

NumPy

A Programming Language

- Languages used by TOP15 Computational Finance / Financial Engineering / "Quant Programs" https://www.quantnet.com/mfe-programs-rankings/
- As well as the University of Copenhagen
- HIPERFIT industry partners with an affinity for APL

Backend Design Criteria



Language agnostic
Support a programming model not a specific language

Programming Model

- High-level
- Declarative
- **Array-oriented**

Language integration via intermediate representation

Efficient

Target a performance comparable to straight forward hand-coded C/C++ for the same application

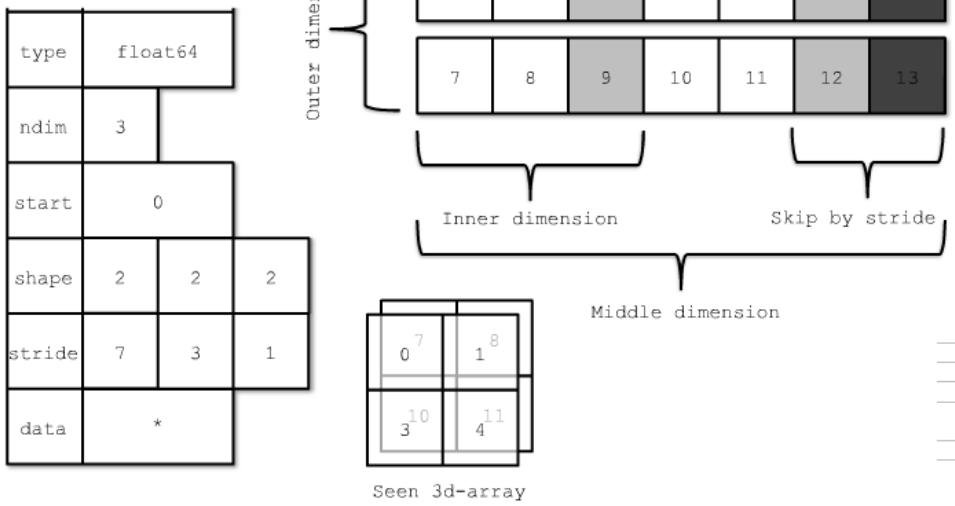
Question: *Is it possible to construct a language agnostic back for high-level languages without sacrificing performance?*

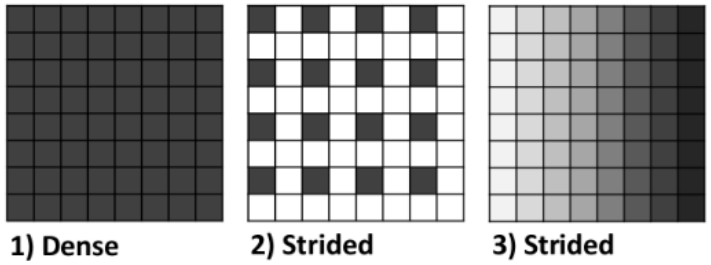
Implementation Scope

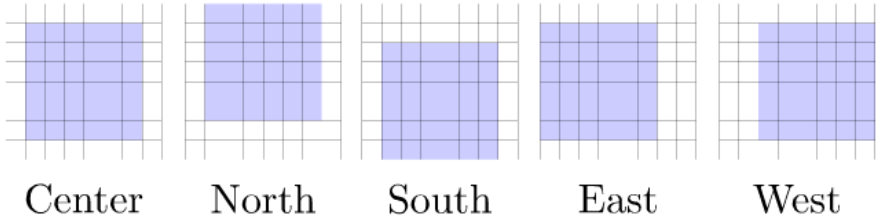
Array Operations

- Element-wise aka *map*, *zip* operator over array(s)
- Reduction
- Scan

Array Descriptor







Language Integration

- Map abstractions
- *vector bytecode* - intermediate representation

Internal Representation BhIr

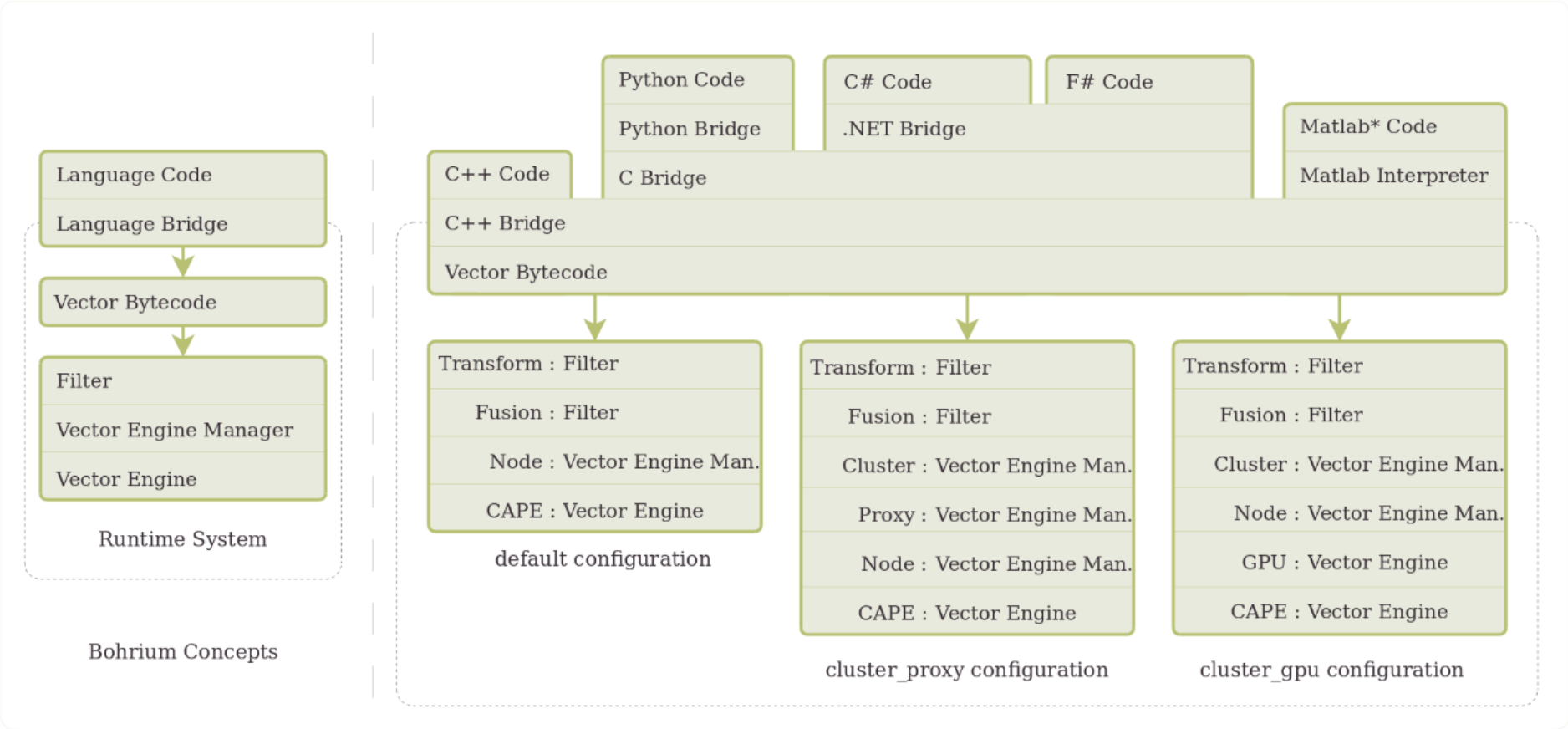
- Annotated *vector bytecode*

Transformations

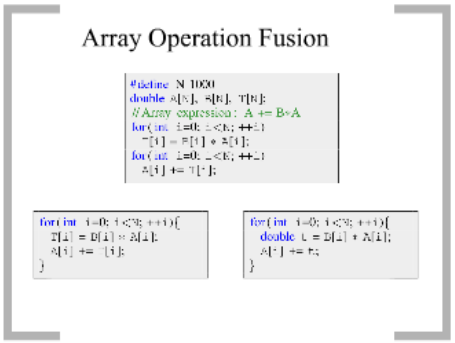
- Optimization
- Normalization
- Fusion, grouping bytecode sequences

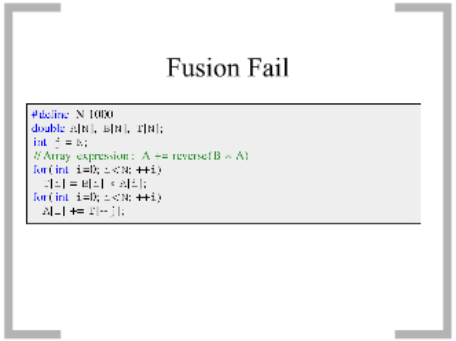
Bohrium: a virtual machine approach to portable parallelism
Mads R.B. Kristensen, Simon A.F. Lund, Troels Blum, Kenneth Skovhede, Brian Vinter.
In proceedings of the Parallel & Distributed Processing Symposium Workshops (IPDPSW14)

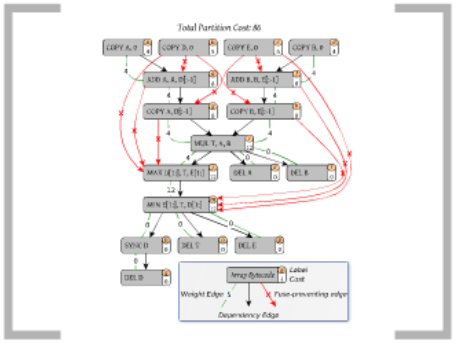
Reconfigurable: BH_STACK=[cape,cluster_proxy,gpu]

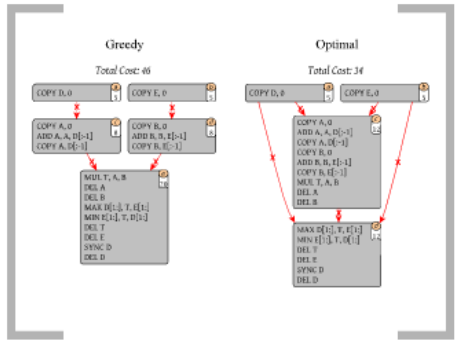


Bohrium









Fusion of Parallel Array Operations
Mads R.B. Kristensen, Simon A.F. Lund, Troels Blum, James Avery.
In proceedings of the 2016 International Conference on Parallel Architectures and Compilation (PACT16).

Array Operation Fusion

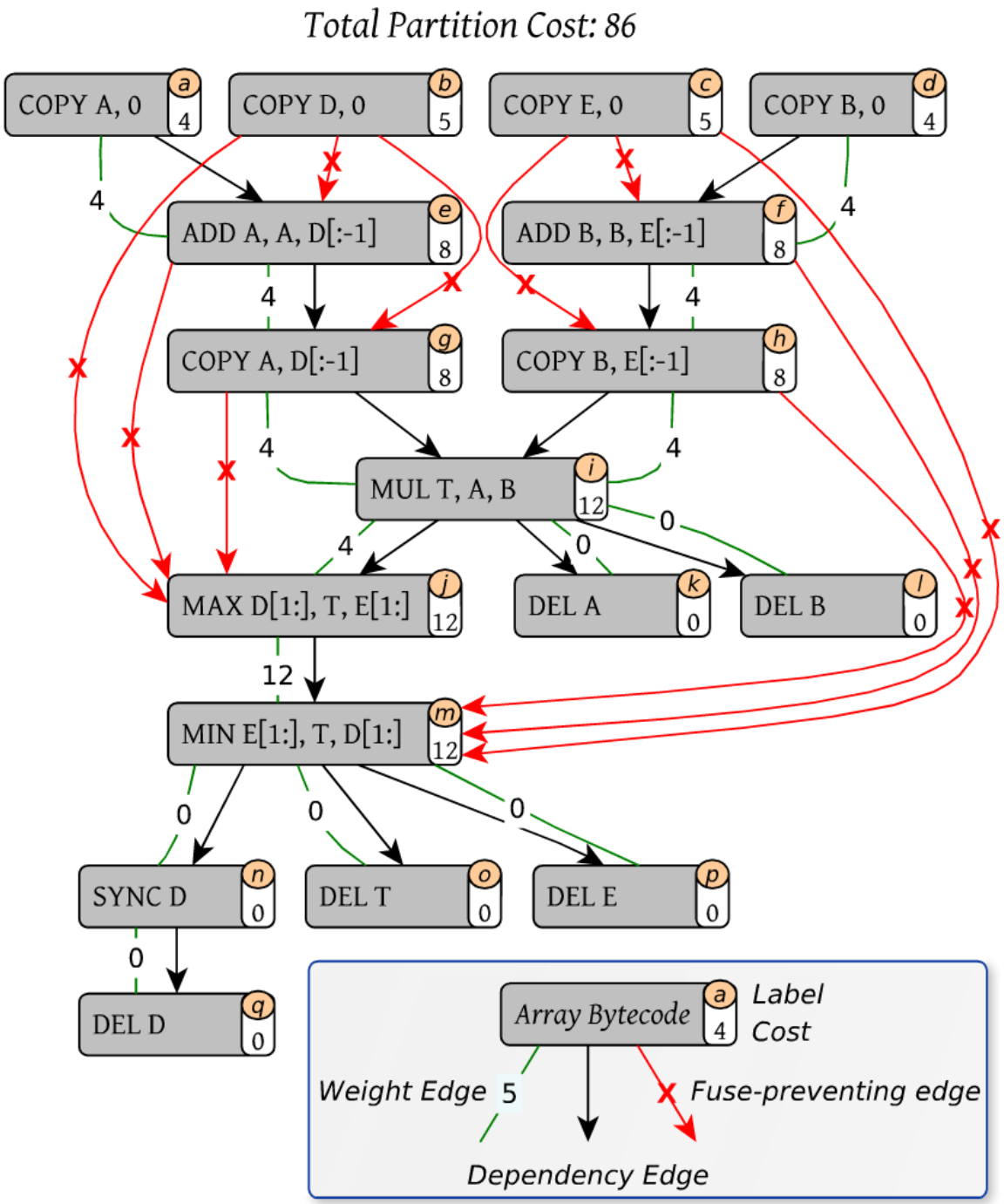
```
#define N 1000
double A[N], B[N], T[N];
// Array expression : A += B*A
for(int i=0; i<N; ++i)
  T[i] = B[i] * A[i];
for(int i=0; i<N; ++i)
  A[i] += T[i];
```

```
for(int i=0; i<N; ++i){
  T[i] = B[i] * A[i];
  A[i] += T[i];
}
```

```
for(int i=0; i<N; ++i){
  double t = B[i] * A[i];
  A[i] += t;
}
```

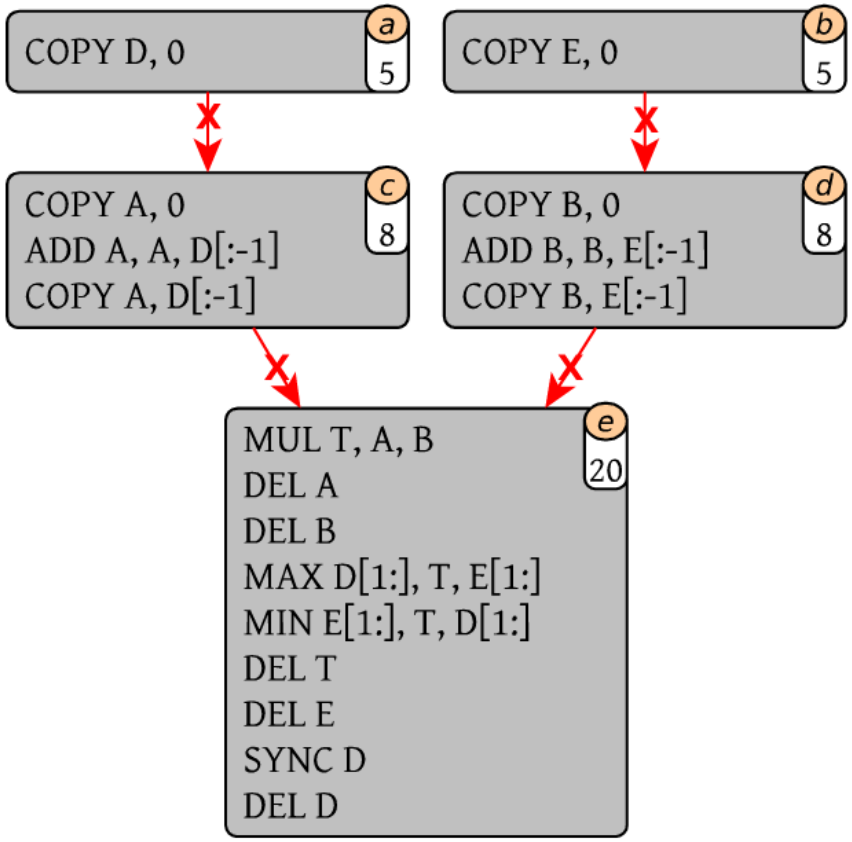
Fusion Fail

```
#define N 1000
double A[N], B[N], T[N];
int j = N;
// Array expression: A += reverse(B * A)
for(int i=0; i<N; ++i)
  T[i] = B[i] * A[i];
for(int i=0; i<N; ++i)
  A[i] += T[--j];
```


Total Partition Cost: 86
COPY A, 0
a
4
COPY D, 0
b
5
COPY E, 0
c
5
COPY B, 0
d
4
ADD A, A, D[:-1]
e
8
ADD B, B, E[:-1]
f
8
COPY A, D[:-1]
g
8
COPY B, E[:-1]
h
8
MUL T, A, B
i
12
MAX D[1:], T, E[1:]
j
12
DEL A
k
0
DEL B
l
0
MIN E[1:], T, D[1:]
m
12
SYNC D
n
0
DEL T
o
0
DEL E
p
0
DEL D
q
0
Array Bytecode
a
4
Label
Cost
Weight Edge
5
Fuse-preventing edge
Dependency Edge

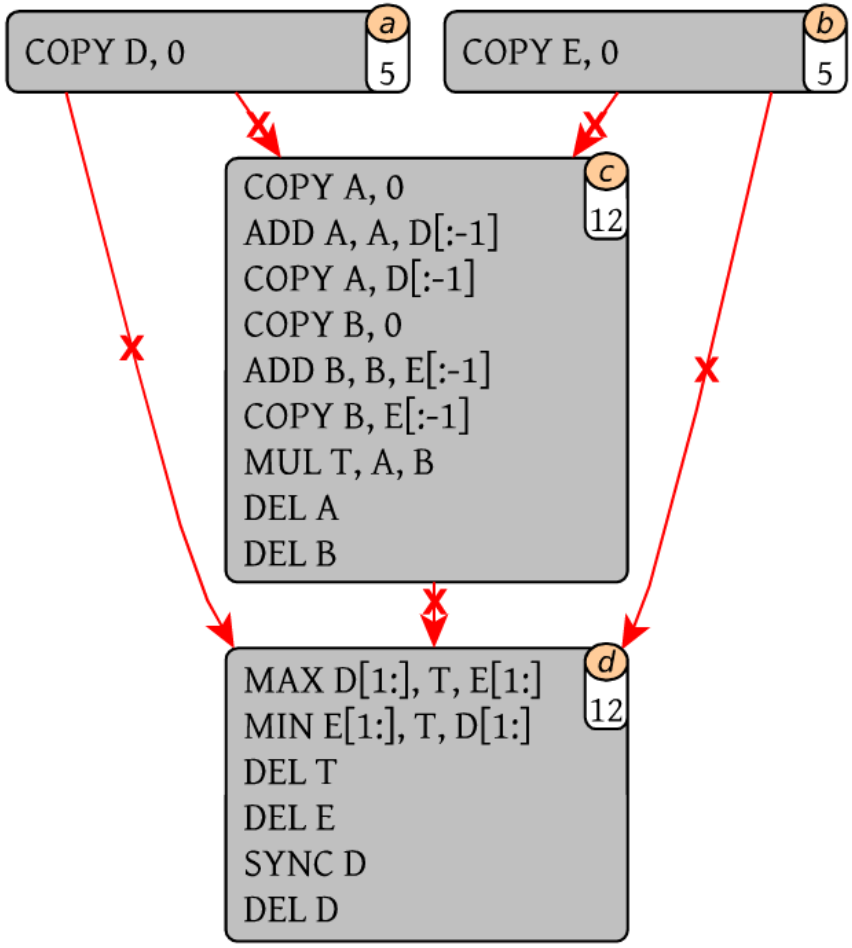
Greedy

Total Cost: 46

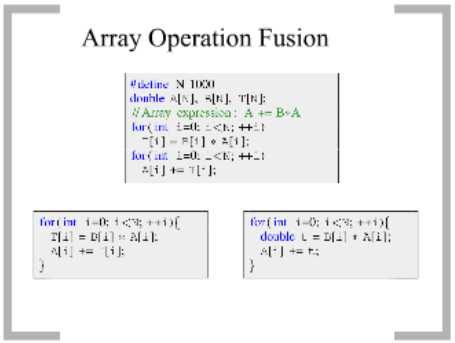


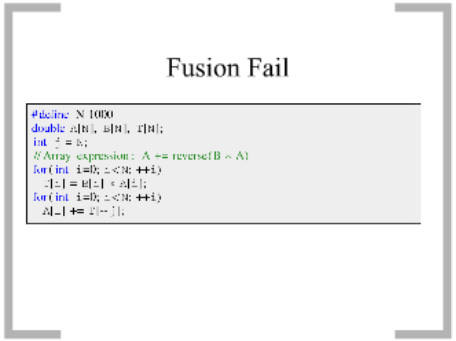
Optimal

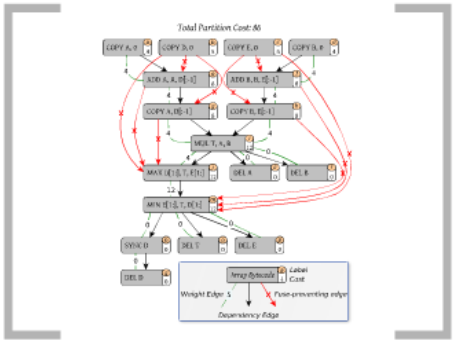
Total Cost: 34

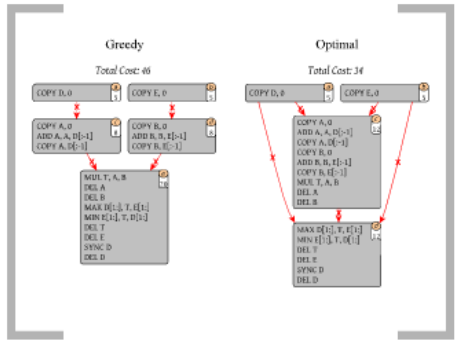


Bohrium









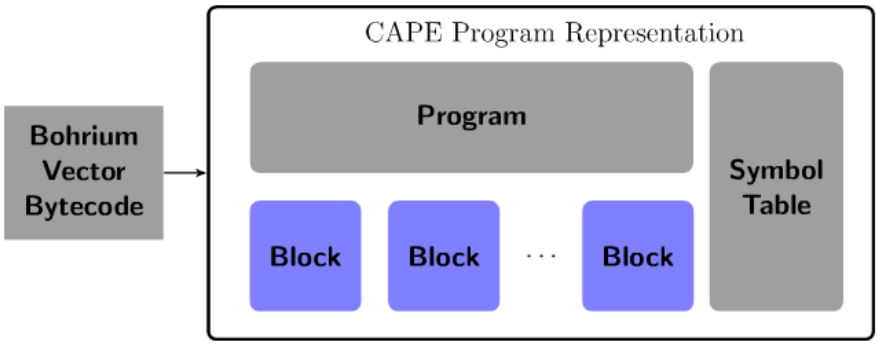
Fusion of Parallel Array Operations
Mads R.B. Kristensen, Simon A.F. Lund, Troels Blum, James Avery.
In proceedings of the 2016 International Conference on Parallel Architectures and Compilation (PACT16).

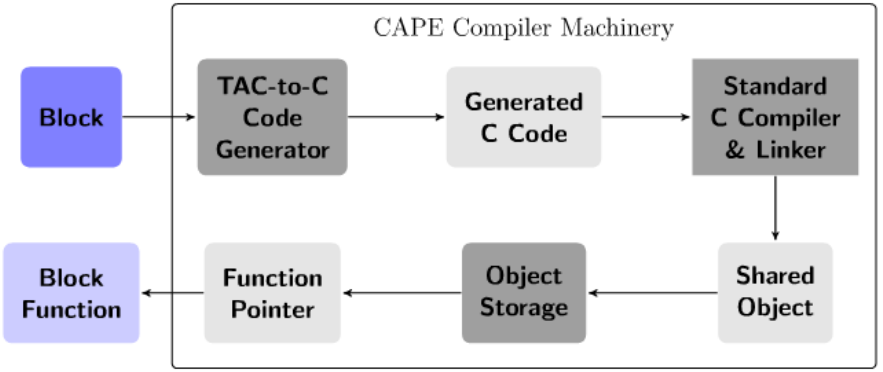
CAPE: C-Targeting Array Processing Engine

- Code generator for array operations with parallelization and composition of multiple array operations
- Caching JIT-Compiler and object storage for array operation kernels
- Runtime instrumenting compilation, buffer management, array operation scheduling and execution

CAPE: C-Targeting Array Processing Engine

```
1  process(bytecode) {
2
3    program, symbol_table, blocks[] = map(
4      bytecode
5    );
6
7    thread_manager.bind();
8
9    for block in blocks {
10     block_function = jit_compiler(block);
11     memory_manager(block);   // Allocation
12     block_function(block);   // Execution
13     memory_manager(block);   // De-allocation
14   }
15 }
```





CAPE: C-Targeting Array Processing Engine

C99
- OpenMP

Experimental
- OpenACC
- LEO

```
1  void KP_IDENTHASH(kp_buffer** buffers,
2                    kp_operand** operands,
3                    kp_iterspace* iterspace)
4  {
5  // Buffers   (data pointers)
6  double* buf0_data = buffers[0]->data;
7  ...
8
9  // Operands  (strides and buffer offset)
10 const int64_t opd0_start = operands[0]->start;
11
12 // Iterspace (shape, layout, #elements)
13 const int64_t iterspace_nelem = iterspace->nelem;
14 ...
15
16 //    Parallel section   - prequel
17
18 { //  Parallel section   - entry
19
20   //  - operand to buffer mapping
21   double* restrict opd0 = buf0_data + opd0_start;
22   double opd1;
23   //  - work distribution
24   //  - initialize accumulator variables
25
26   //  Parallel section   - loop constructs
27   {
28       ...array operations...
29   }
30   //  Parallel section   - exit
31 }
32
33 //    Parallel section   - sequel
34 }
```

CAPE: C-Targeting Array Processing Engine

Codegen specialization

- Flattening
- Array contraction
- Array operation composition
- Array shape => Loop constructs
- Checks buffer-references for aliasing

CAPE: C-Targeting Array Processing Engine

Memory Management

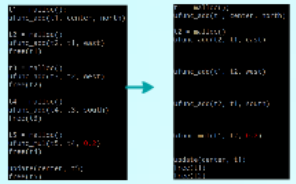
Allocation and de-allocation of buffers backing array storage

Alignment

GPUs and Accelerators
- data transfer: host <-> device
- data persistence: buffer-reuse on device

Software Victim cache

- Delay de-allocation
- Reuse buffers



Doubling the Performance of Python/NumPy With Less Than 100 SLOC
Simon A.F. Lund, Kenneth Skovhede, Mads R.B. Kristensen, Brian Vinter. In proceedings of the 3rd Python for High Performance and Scientific Computing (PyHPC13@SC13).

Thread Management

Implemented with HWLOC

Multi-core and MIC
- # threads
- Control core/thread affinity

Memory Management

Allocation and de-allocation of buffers backing array storage

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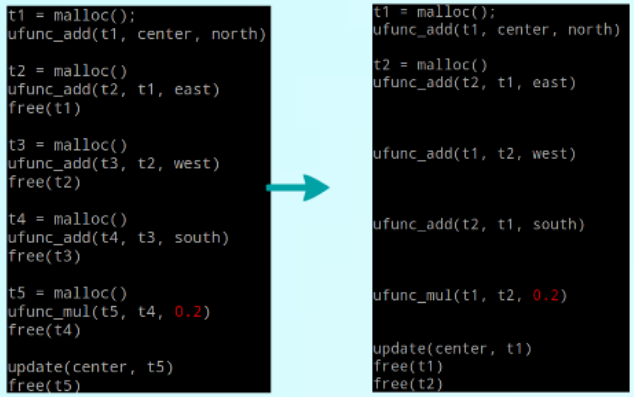

```
t1 = malloc();
ufunc_add(t1, center, north)

t2 = malloc()
ufunc_add(t2, t1, east)
free(t1)

t3 = malloc()
ufunc_add(t3, t2, west)
free(t2)

t4 = malloc()
ufunc_add(t4, t3, south)
free(t3)

t5 = malloc()
ufunc_mul(t5, t4, 0.2)
free(t4)

update(center, t5)
free(t5)
```

```
t1 = malloc();
ufunc_add(t1, center, north)

t2 = malloc()
ufunc_add(t2, t1, east)


ufunc_add(t1, t2, west)


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Thread Management

Implemented with HWLOC

Multi-core and MIC

- # threads
- Control core/thread affinity

CAPE: C-Targeting Array Processing Engine

Machine:	
Processor:	AMD Opteron 6272
Clock:	2.1 GHz
L3 Cache:	16MB
Memory:	128GB DDR3
Network:	Gigabit Ethernet
Compiler:	GCC 4.8.4
Software:	Ubuntu 14.04, Linux 3.13, Python 2.7.6, NumPy 1.8.2

Baseline: Python/NumPy

python [-m bohrium] benchmark.py

CAPE-AC: Without array contraction
CAPE: WITH array contraction

	CAPE-AC		CAPE	
Threads	1	32	1	32
Synthetic Inplace Update	1.4	8.6	14.1	236.9
Synthetic Stream Ones	1.5	9.7	10.0	137.3
Synthetic Stream Range	0.9	8.0	1.8	45.5
Synthetic Stream Random	1.0	18.0	1.0	29.8
1D Stencil	0.7	8.5	1.1	21.8
2D Stencil	0.6	8.8	3.6	53.9
3D Stencil	0.8	11.0	1.8	48.6
27 Point Stencil	1.0	5.5	1.2	13.6
Jacobi	1.4	10.3	3.9	76.2
Gauss Elimination	0.7	1.6	2.1	3.8
LU Factorization	0.7	1.6	1.9	3.4
Leibnitz PI	1.0	6.1	2.2	48.3
Monte Carlo PI	1.0	17.7	1.0	30.1
Matrix Multiplication	0.9	10.1	2.1	47.3
Rosenbrock	1.5	9.9	12.5	169.4

	CAPE-AC		CAPE	
Threads	1	32	1	32
Black Scholes	3.4	27.4	6.0	84.9
Game of Life v1	1.2	8.6	1.5	32.2
Game of Life v2	1.2	8.0	2.2	39.6
Heat Equation	1.3	9.1	4.4	41.0
Lattice Boltzmann 3D	0.8	4.0	0.8	5.3
NBody	4.7	17.2	5.1	23.6
NBody Nice	1.2	7.3	0.4	8.1
SOR	1.4	8.3	1.9	20.1
Shallow Water	1.5	9.2	6.9	62.2
Water-Ice Simulation	0.8	5.7	1.6	10.9
kNN Naive 1	0.7	10.2	1.0	26.1

Baseline: Serial C99

	C++ / OpenMP		NumPy / CAPE		C++ / CAPE	
Threads	1	32	1	32	1	32
Black Scholes +O	0.9	29.1	4.8	67.3	4.9	118.9
Black Scholes –O	0.9	29.1	1.1	26.1	1.1	31.7
Heat Equation	0.6	7.1	0.7	7.0	0.8	7.6
Leibnitz PI	1.0	22.6	0.6	14.6	0.6	15.2
Monte Carlo PI	1.0	29.8	1.0	27.8	0.9	28.2
Mxmul	1.0	9.5	1.0	14.9	1.1	15.1
Rosenbrock	1.0	21.0	1.2	15.8	1.2	21.4
Shallow Water	0.5	9.1	0.7	6.6	0.7	10.9

https://github.com/bh107/benchpress.git rev. 0aa2942
https://github.com/bh107/bohrium.git rev. b4d3586
www.erda.dk/public/archives/YXJjaGl2ZS0xSWhQSmU=/published-archive.html

Baseline: Python/NumPy

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Jacobi	1.4	10.3	3.9	76.2
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LU Factorization	0.7	1.6	1.9	3.4
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Lattice Boltzmann 3D	0.8	4.0	0.8	5.3
NBody	4.7	17.2	5.1	23.6
NBody Nice	1.2	7.3	0.4	8.1
SOR	1.4	8.3	1.9	20.1
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Mxmul	1.0	9.5	1.0	14.9	1.1	15.1
Rosenbrock	1.0	21.0	1.2	15.8	1.2	21.4
Shallow Water	0.5	9.1	0.7	6.6	0.7	10.9

Conclusion

Question: *Is it possible to construct a language agnostic backend for high-level languages without sacrificing performance?*

User knows his high-level array-oriented programming

Bohrium

Knows the configuration of the computing system

Combined: the high-level array-oriented programming model and its declarative nature provides implicit data-parallel operations and freedom for the backend to decide how to efficiently compute them.

Future / Ongoing Work

niels
numerically intensive expression language for science

Command-line interface via docopt

```
/*
    PI-approximation using the Leibnitz formular.

    -d --domain     Number of samples
    -t --timesteps  Number of times to run

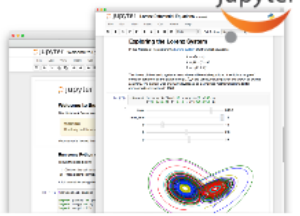
Options:
    -h --help   Show this screen.
*/

n      <- args.domain
smpls <- [0..n]
tstep <- args.timesteps

res <- 0.0
while(tstep>0) {
    tstep <- tstep-1
    pi    <- 4 * +reduce 1.0/(4.0*smpl+1.0) - 1.0/(4.0*smpl+3.0)
}

? res
```

Interactive environment via jupyter



Bohrium for efficient hardware utilization

Bohrium

- Collaborative effort
- There is even more to it

Bohrium Processing Unit

Goal: ASIC for executing Bohrium Bytecode

- High flops-to-watt ratio
- Low latency
- FPGA prototype

niels

numerically intensive expression language for science

Command-line interface via docopt

```
/*
    PI-approximation using the Leibnitz formular.

    -d --domain     Number of samples
    -t --timesteps  Number of times to run

Options:
    -h --help   Show this screen.
*/

n     <- args.domain
smpls <- [0..n]
tstep <- args.timesteps

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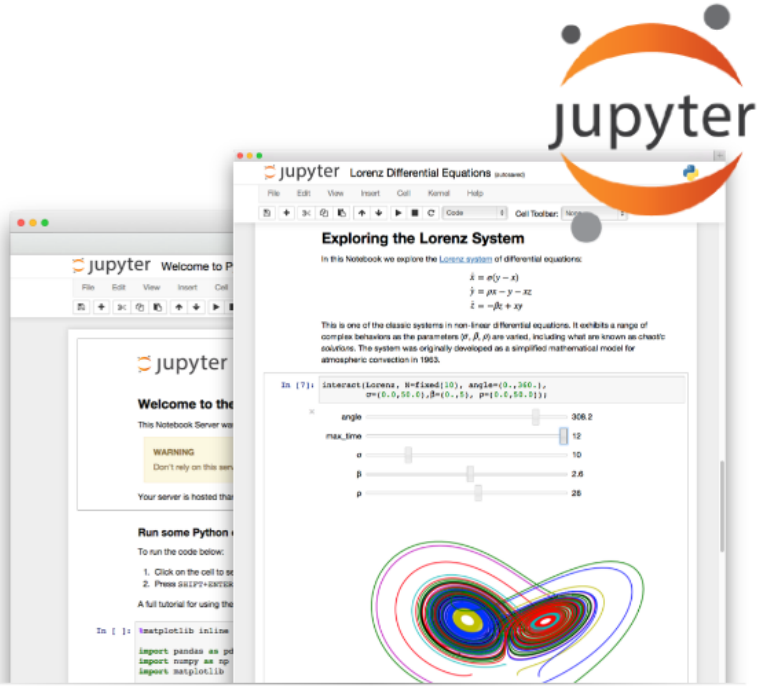
Interactive environment via



Bohrium

for efficient hardware utilization

Bohrium Processing Unit

Goal: ASIC for executing Bohrium Bytecode

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Future / Ongoing Work

niels
numerically intensive expression language for science

Command-line interface via docopt

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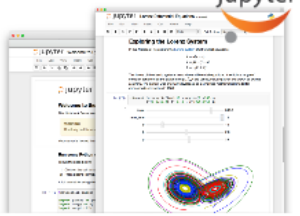
Interactive environment via jupyter



Bohrium for efficient hardware utilization

Bohrium

- Collaborative effort
- There is even more to it

Bohrium Processing Unit

Goal: ASIC for executing Bohrium Bytecode

- High flops-to-watt ratio
- Low latency
- FPGA prototype

What

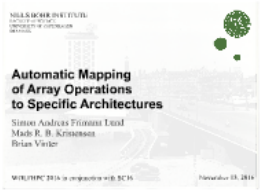
Why

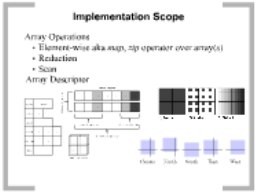
Goal

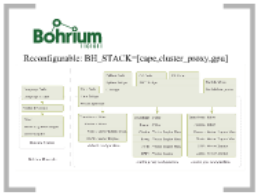
Previous

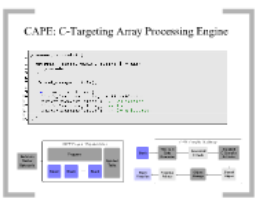
Current

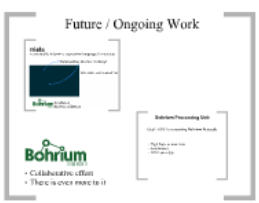
The End

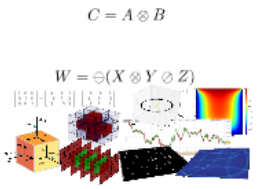


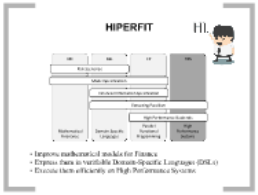


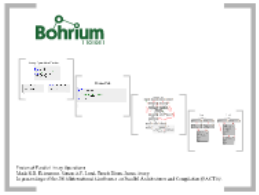


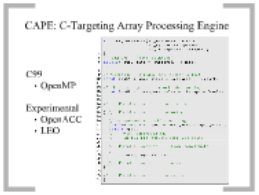




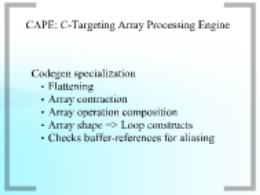


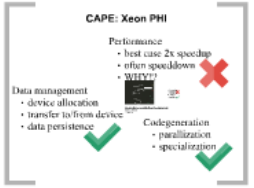


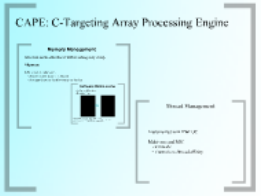


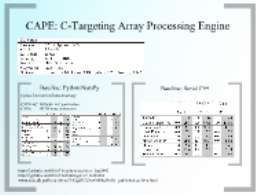


Encore







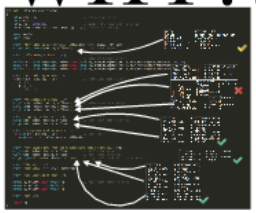


Thanks

CAPE: Xeon PHI

Performance

- best case 2x speedup
- often speeddown
- WHY!?



Allocation
~250MB/s
Transfer
~5.5GB/s

https://github.com/safl/offload/tree/master/mic
make broken
./broken

Data management

- device allocation
- transfer to/from device
- data persistence

Codegeneration

- parallization
- specialization

WHY!?


int main (int argc, char **argv)
{
int device = 0; // The mic device id
int iter = 3;
int nelem = 50000000; // Number of elements in the arrays
int offload = argc > 1 ? atoi(argv[1]) : 1; // Control offloading
void* handle;
char* error;
printf("Initializing device(%d)... offload(%d)?\n", device, offload);
mic_get_max_threads(device, offload); // Initialize device
printf("Allocating on host...\n");
// Allocate memory on host
double* a = (double*)mmap(0, nelem*sizeof(double), PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0);
double* b = (double*)mmap(0, nelem*sizeof(double), PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS
double* c = (double*)mmap(0, nelem*sizeof(double), PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS
printf("Initializing on host...\n");
for(int i=0; i<nelem; ++i) { // Initialize data on host
a[i] = i;
b[i] = i;
//c[i] = i;
}
printf("Allocating on device...\n");
mic_alloc(a, nelem, device, offload); // Allocate data on device
mic_alloc(b, nelem, device, offload);
mic_alloc(c, nelem, device, offload);
printf("Copying to device...\n");
mic_push(a, nelem, device, offload); // Copy input-data to device
mic_push(a, nelem, device, offload);
printf("Doing some work on device...\n");
for (int i=0; i<iter; ++i) { // Call the
voodoo(a, b, c, nelem, device, offload);
}
printf("Retrieving data from and deallocating data on device...\n");
mic_free(a, nelem, device, offload); // Deallocate on device
mic_free(b, nelem, device, offload); // Deallocate on device
mic_pull_free(c, nelem, device, offload); // Copy result back and free on device
printf("Bla bla...\n");
printf("c[nelem/2] = %f\n", c[nelem/2]);
printf("Deallocating on host...");
munmap(a, nelem*sizeof(double)); // Deallocate memory on host
munmap(b, nelem*sizeof(double));
munmap(c, nelem*sizeof(double));
printf("Bye!\n");
return 0;
}
[Var] mthreads OUT
[State] Target->host copyout data 4
[CPU Time] 0.498360(seconds)
[CPU->MIC Data] 0 (bytes)
[MIC Time] 0.032039(seconds)
[MIC->CPU Data] 4 (bytes)
[CPU Time] 1.283028(seconds)
[CPU->MIC Data] 0 (bytes)
[MIC Time] 0.000108(seconds)
[MIC->CPU Data] 0 (bytes)
[Var] data 1064 vs15 NOCOPY
[State] Target->host copyout data 0
[CPU Time] 1.273670(seconds)
[CPU->MIC Data] 0 (bytes)
[MIC Time] 0.000227(seconds)
[MIC->CPU Data] 0 (bytes)
[CPU Time] 1.385024(seconds)
[CPU->MIC Data] 0 (bytes)
[MIC Time] 0.000108(seconds)
[MIC->CPU Data] 0 (bytes)
[CPU Time] 0.072744(seconds)
[CPU->MIC Data] 400000000 (bytes)
[MIC Time] 0.000000(seconds)
[MIC->CPU Data] 0 (bytes)
[CPU Time] 0.071028(seconds)
[CPU->MIC Data] 400000000 (bytes)
[MIC Time] 0.000000(seconds)
[MIC->CPU Data] 0 (bytes)
[CPU Time] 1.823075(seconds)
[CPU->MIC Data] 48 (bytes)
[MIC Time] 1.814970(seconds)
[MIC->CPU Data] 8 (bytes)
[CPU Time] 0.000791(seconds)
[CPU->MIC Data] 8 (bytes)
[MIC Time] 0.000180(seconds)
[MIC->CPU Data] 0 (bytes)
[CPU Time] 0.000791(seconds)
[CPU->MIC Data] 8 (bytes)
[MIC Time] 0.000180(seconds)
[MIC->CPU Data] 0 (bytes)
[CPU Time] 0.064531(seconds)
[CPU->MIC Data] 8 (bytes)
[MIC Time] 0.000183(seconds)
[MIC->CPU Data] 400000000 (bytes)

WHY!?

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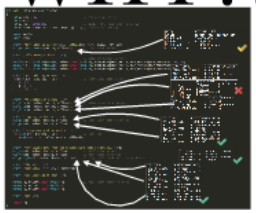

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Codegeneration

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SIMD utilization

CAPE codegen takes SIMD into consideration, however, current implementation relies on auto-vectorization by the backend C-compiler

Brittle, example:
gcc often fails where commercial compilers prevail.

Simplistic approach by using #pragma omp simd [...]
did not yield expected results

Investigate further and possibly expand codegen with intrinsics or explicit means of ensuring the compiler that vectorization makes sense.

What

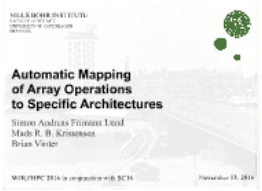
Why

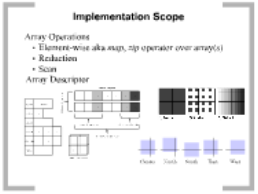
Goal

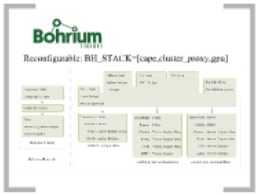
Previous

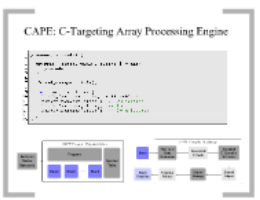
Current

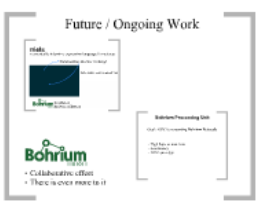
The End

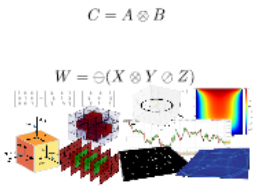


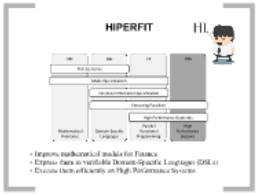


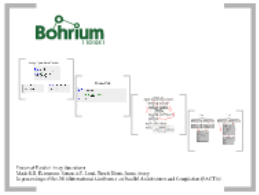


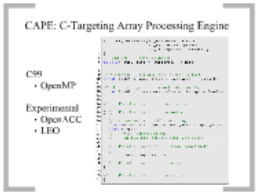












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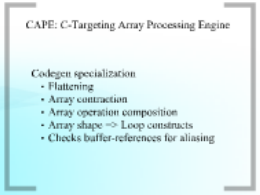

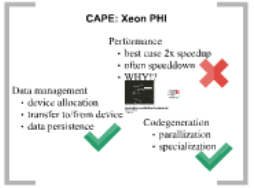

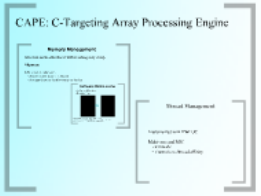

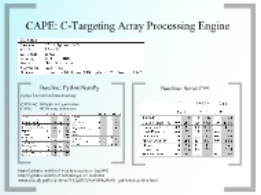

Thanks