*hi*CUDA: A High-level Directive-based Language for GPU Programming

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Outline

- Motivation of *hi*CUDA
- *hi*CUDA through an example
- Experimental evaluation
- Conclusions
- Future work

Motivation

- CUDA: a C-extended language for programming NVIDIA Graphics Processing Units
- Many “mechanical” steps:
  - Packaging of kernel functions
  - Using thread index variables to partition computation
  - Managing data in GPU memories
- Can become tedious and error prone
  - Particularly when repeated many times for optimizations
- Make programs difficult to understand, debug and maintain

High-level CUDA (*hi*CUDA)

- A directive-based language that maintains the CUDA programming model

```
#pragma hicuda <directive name> [<clauses>]+
```

- Programmers can perform common CUDA tasks directly into the sequential code, with a few directives
  - Keeps the structure of the original code, making it more comprehensible and easier to maintain
  - Eases experimentation with different code configurations

CUDA vs. *hi*CUDA

Typical CUDA programming steps	*hi*CUDA directives
1. Identify and package a kernel	1. **kernel**
2. Partition kernel computation among a grid of GPU threads	2. **loop_partition**
3. Manage data transfer between the host memory and the GPU memory	3. **global, constant**
4. Perform memory optimizations	4. **shared**

An Example: Matrix Multiply

```
float A[32][96], B[96][64], C[32][64];
for (i = 0; i < 32; ++i) {
    for (j = 0; j < 64; ++j) {
        float sum = 0;
        for (k = 0; k < 96; ++k) sum += A[i][k] * B[k][j];
        C[i][j] = sum;
    }
}
```

Standard matrix multiplication algorithm

Kernel identification

```
float A[32][96], B[96][64], C[32][64];
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    for (j = 0; j < 64; ++j) {
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}
```

Kernel identification

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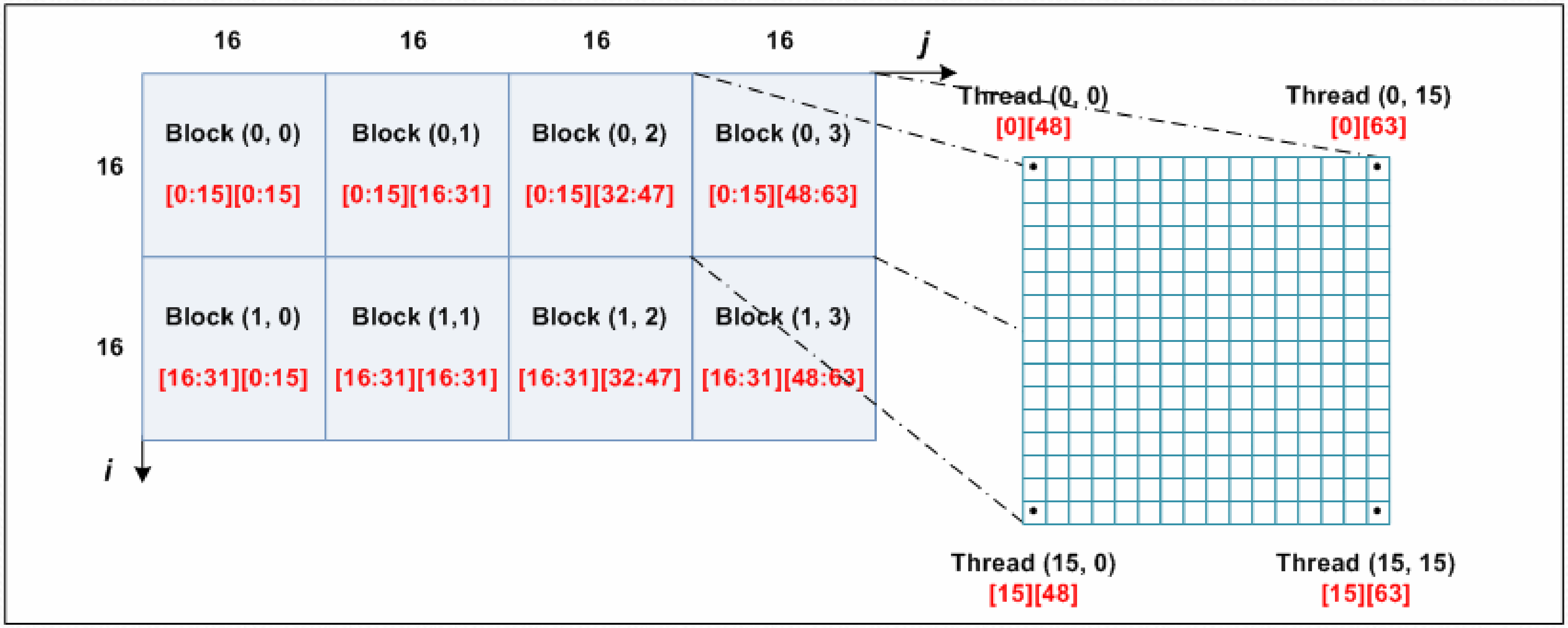
float A[32][96], B[96][64], C[32][64];
#pragma hicuda kernel matrixMul tblock(2,4) thread(16,16)
for (i = 0; i < 32; ++i) {
    for (j = 0; j < 64; ++j) {
        float sum = 0;
        for (k = 0; k < 96; ++k) sum += A[i][k] * B[k][j];
        C[i][j] = sum;
    }
}
#pragma hicuda kernel_end
```

Computation partitioning

```
float A[32][96], B[96][64], C[32][64];
#pragma hicuda kernel matrixMul tblock(2,4) thread(16,16)
#pragma hicuda loop_partition over_tblock over_thread
for (i = 0; i < 32; ++i) {
#pragma hicuda loop_partition over_tblock over_thread
    for (j = 0; j < 64; ++j) {
```



GPU data management

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GPU data management

```
float A[32][96], B[96][64], C[32][64];
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#pragma hicuda global alloc C[*][*]
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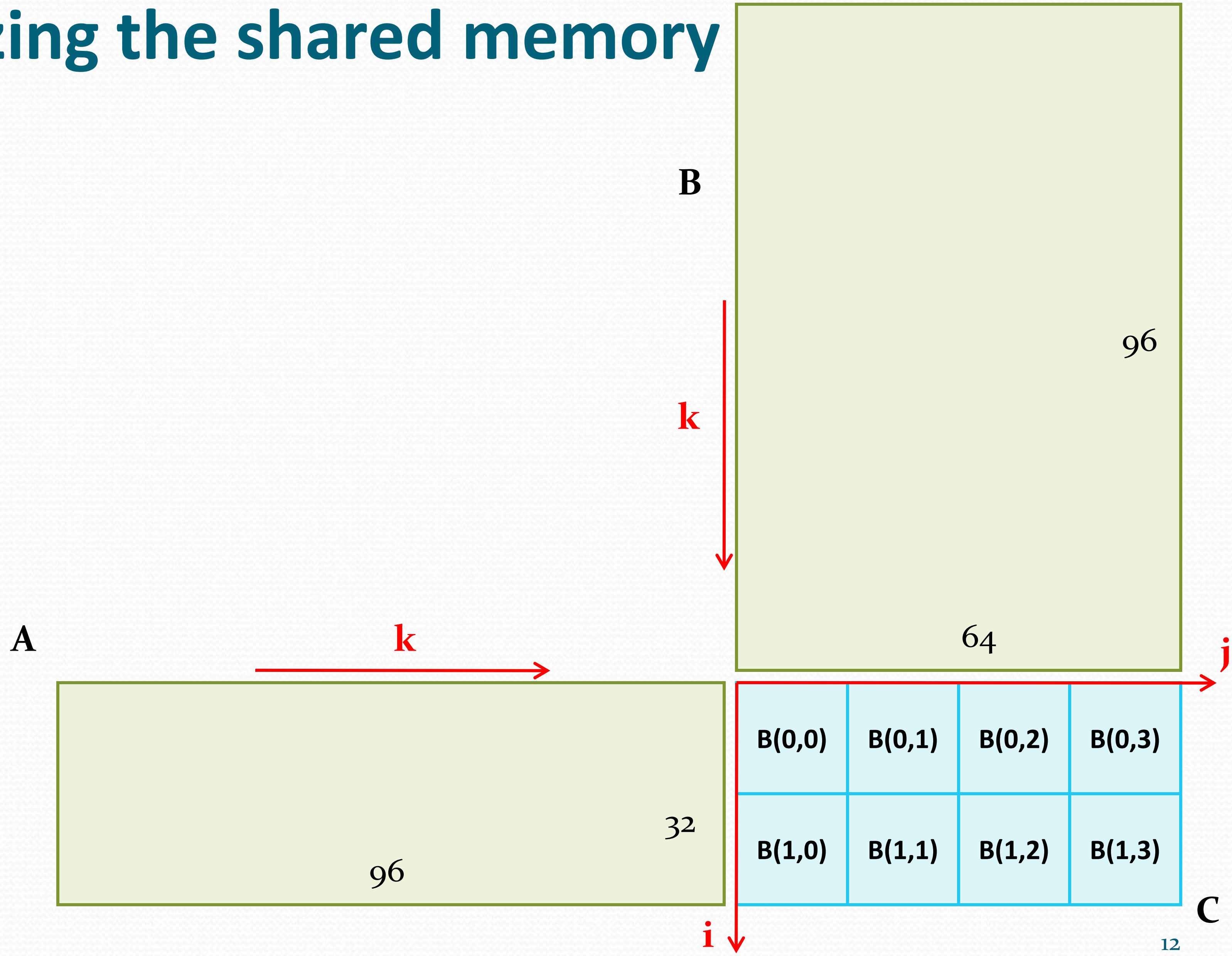
        C[i][j] = sum;
    }
}
#pragma hicuda kernel_end
#pragma hicuda global copyout C[*][*]
#pragma hicuda global free A B C
```

Utilizing the shared memory



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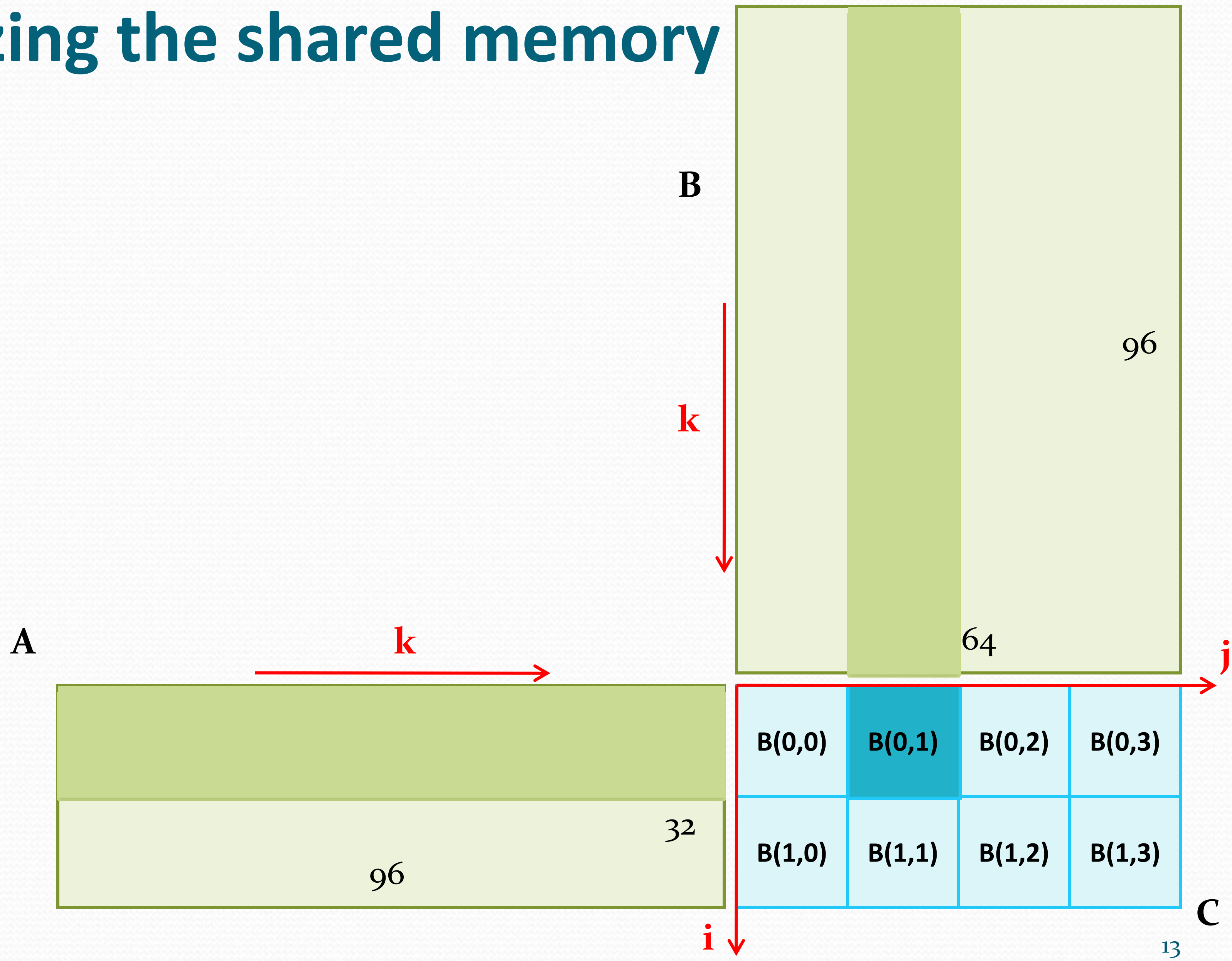

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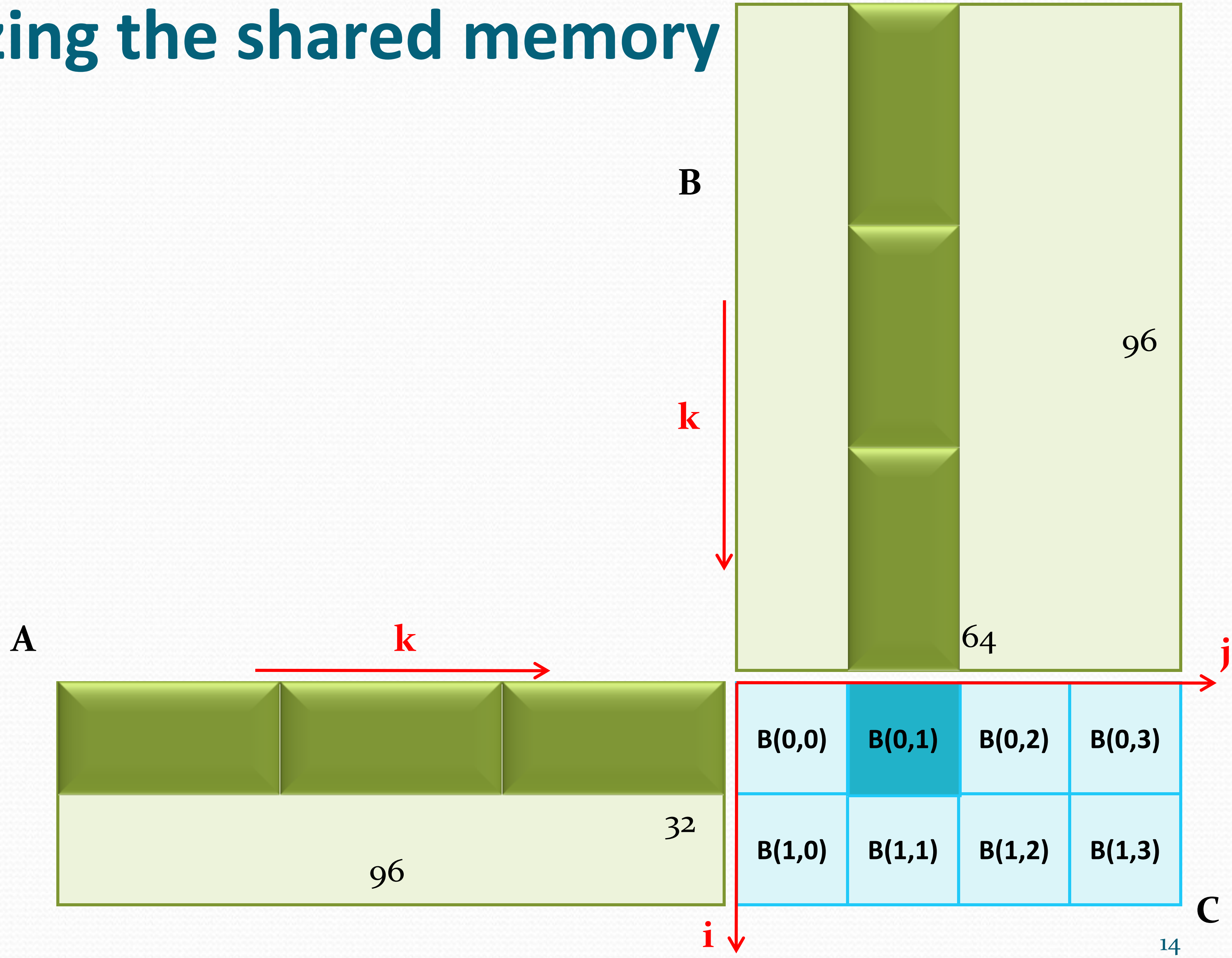

Utilizing the shared memory

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    }
}
#pragma hicuda kernel_end
#pragma hicuda global copyout C[*][*]
#pragma hicuda global free A B C
```


float sum = 0;
for (k = 0; k < 96; ++k) sum += A[i][k] * B[k][j];
C[i][j] = sum;

Utilizing the shared memory

```
float sum = 0;
for (kk = 0; kk < 96; kk += 32) {
    for (k = 0; k < 32; ++k) {
        sum += A[i][kk+k] * B[kk+k][j];
    }
}
C[i][j] = sum;
```

Strip-mine loop *k*

Utilizing the shared memory

```
float sum = 0;
for (kk = 0; kk < 96; kk += 32) {
#pragma hicuda shared alloc A[i][kk:kk+31] copyin
#pragma hicuda shared alloc B[kk:kk+31][j] copyin
#pragma hicuda barrier
    for (k = 0; k < 32; ++k) {
        sum += A[i][kk+k] * B[kk+k][j];
    }
#pragma hicuda barrier
#pragma hicuda shared remove A B
}
C[i][j] = sum;
```

Add the shared directives

Evaluation of *hi*CUDA

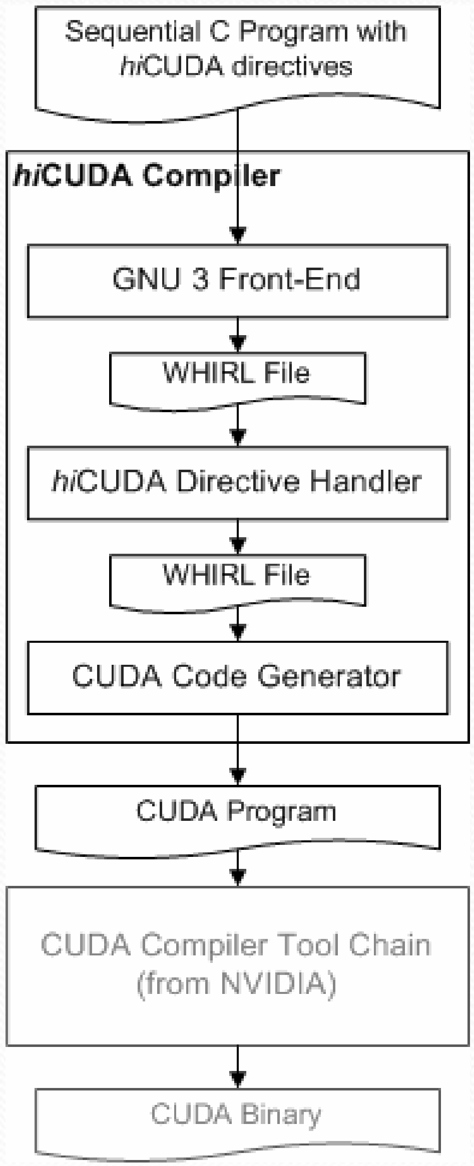
- We have developed a prototype *hi*CUDA compiler for translation into CUDA programs
- We evaluated the performance of *hi*CUDA programs against manually written CUDA programs
  - Four benchmarks from the *Parboil* suite (UIUC Impact Research Group)
- User assessment on *hi*CUDA
  - Monte Carlo simulation for Multi-Layer media (MCML)

*hi*CUDA Compiler

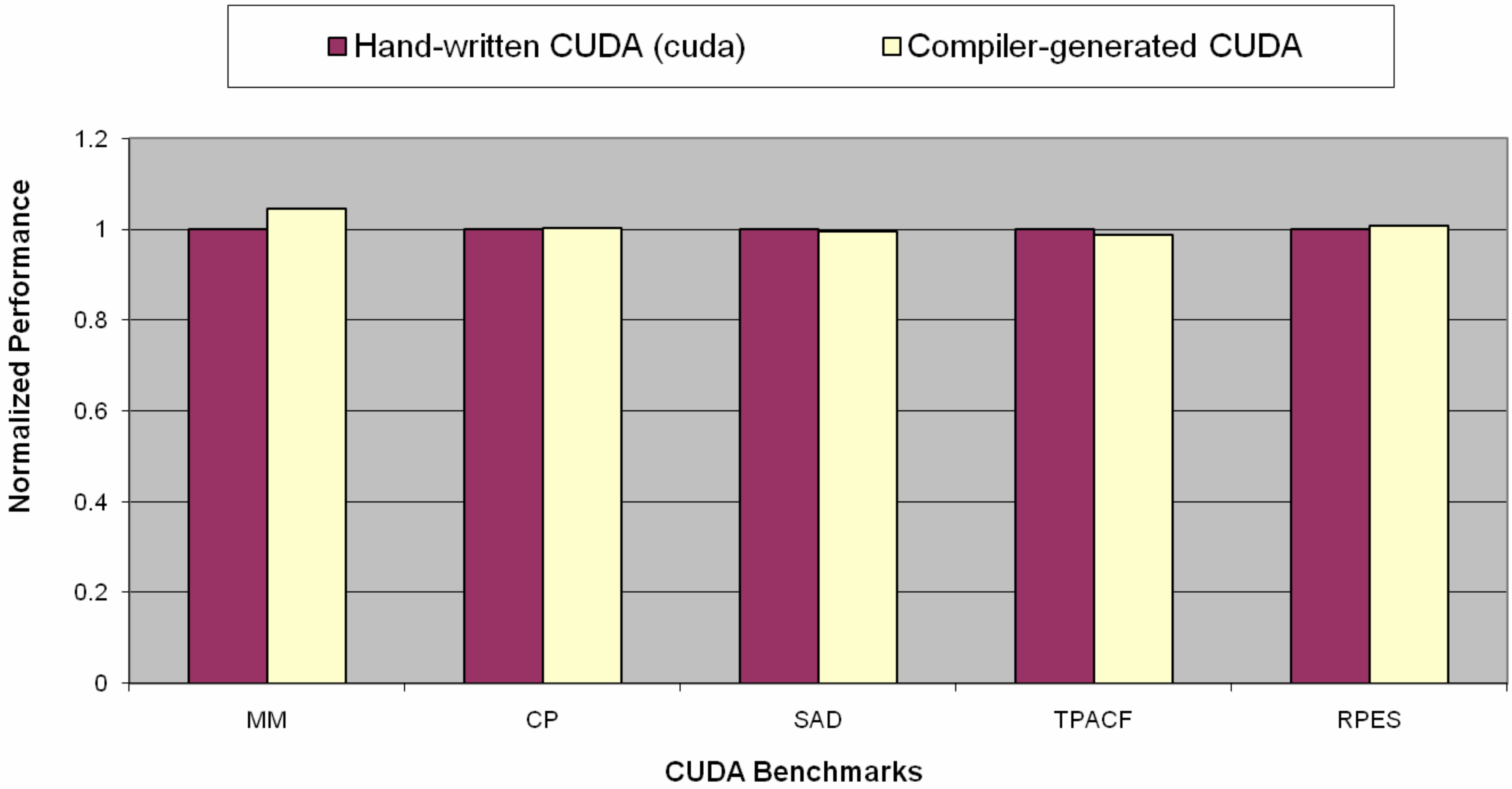
- Source-to-source
- Based on Open64 (v4.1)

- Kernel outlining
  - Array section analysis (inter-procedural)
  - Data flow analysis
- Distribution of kernel loops
  - Data dependence analysis

- Access redirection inside kernels
  - Array section analysis
- Generation of optimized data transfer code
  - Auto-pad shared memory variables for bank-conflict-free transfers



Performance Evaluation



Ease of Use

- Used by a medical research group at University of Toronto, in accelerating Monte Carlo simulation for Multi-Layer media (MCML)
- CUDA version was developed in 3 months, while *hi*CUDA version was developed in 4 weeks
  - Both include the learning phase
- Disclaimer

Conclusions

- *hi*CUDA provides a high-level abstraction of CUDA, through compiler directives
  - No explicit creation of kernel functions
  - No use of thread index variables
  - Simplified management of GPU data
- We believe *hi*CUDA results in:
  - More comprehensible and maintainable code
  - Easier experimentation with multiple code configurations
- Promising evaluation using our prototype compiler

Future Work

- Finalize and release the *hi*CUDA compiler, to be available at:

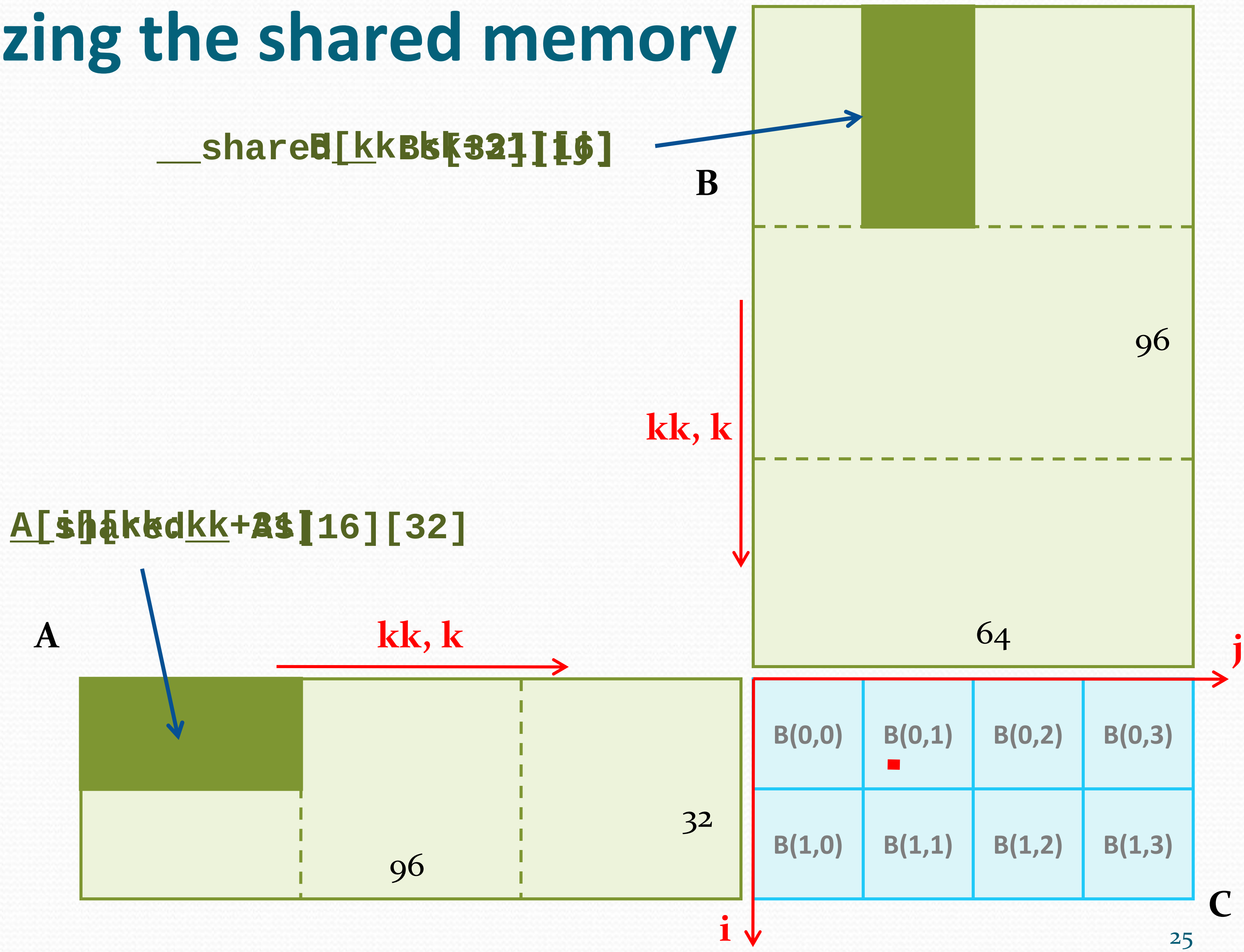
  www.hicuda.org

- Assess and evolve the language design based on feedback
  - High-level programming patterns/idioms, such as reduction, histogram, etc.

- Explore compiler analyses and optimizations for automatic generation of *hi*CUDA directives

Backup slides

Utilizing the shared memory



Matrix Multiply Kernel in *hi*CUDA

```
#pragma hicuda kernel matrixMul tblock(2,4) thread(16,16)

#pragma hicuda loop_partition over_tblock over_thread
for (i = 0; i < 32; ++i) {
#pragma hicuda loop_partition over_tblock over_thread
    for (j = 0; j < 64; ++j) {
        float sum = 0;
        for (kk = 0; kk < 96; kk += 32) {
#pragma hicuda shared alloc A[i][kk:kk+31] copyin
#pragma hicuda shared alloc B[kk:kk+31][j] copyin
#pragma hicuda barrier
            sum += A[i][k] * B[k][j];
        }
#pragma hicuda barrier
#pragma hicuda shared remove A B
        C[i][j] = sum;
    }
}

#pragma hicuda kernel_end
```

Matrix Multiply Kernel in CUDA

```
__global__ void matrixMul(float *A, float *B, float *C, int wA, int wB)
{
    int bx = blockIdx.x, by = blockIdx.y;
    int tx = threadIdx.x, ty = threadIdx.y;

    int aBegin = wA * 16 * by + wA * ty + tx, aEnd = aBegin + wA, aStep = 32;
    int bBegin = 16 * bx + wB * ty + tx, bStep = 32 * wB;

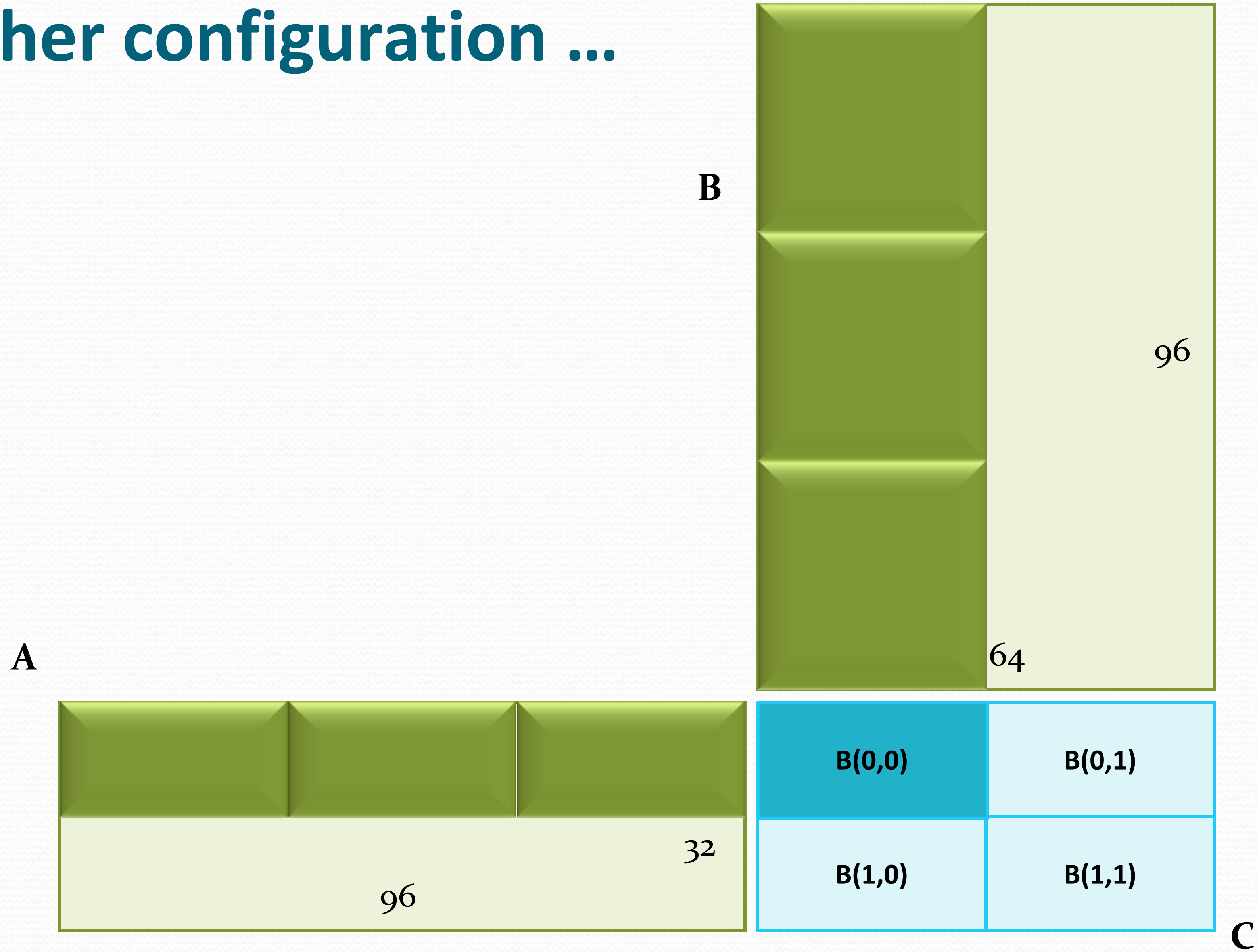
    __shared__ float As[16][32]; __shared__ float Bs[32][16];

    float Csub = 0;

    for (int a = aBegin, b = bBegin; a < aEnd; a += aStep, b += bStep)
    {
        As[ty][tx] = A[a]; As[ty][tx+16] = A[a + 16];
        Bs[ty][tx] = B[b]; Bs[ty+16][tx] = B[b + 16*wB];
        __syncthreads();
        for (int k = 0; k < 32; ++k) Csub += As[ty][k] * Bs[k][tx];
        __syncthreads();
    }

    C[wB*16*by + 16*bx + wB*ty + tx] = Csub;
}
```

Another configuration …



Changes in *hi*CUDA code

```
#pragma hicuda kernel matrixMul tblock(2,4) thread(16,16)
   ...
#pragma hicuda kernel_end
```

```
#pragma hicuda kernel matrixMul tblock(2,2) thread(16,32)
   ...
#pragma hicuda kernel_end
```

Changes in CUDA kernel code

```
__global__ void matrixMul(float *A, float *B, float *C, int wA, int wB)
{
    int bx = blockIdx.x, by = blockIdx.y;
    int tx = threadIdx.x, ty = threadIdx.y;

    int aBegin = wA * 16 * by + wA * ty + tx, aEnd = aBegin + wA, aStep = 32;
    int bBegin = 32 * bx + wB * ty + tx, bStep = 32 * wB;

    __shared__ float As[16][32]; __shared__ float Bs[32][32];

    float Csub = 0;

    for (int a = aBegin, b = bBegin; a < aEnd; a += aStep, b += bStep)
    {
        As[ty][tx] = A[a]; As[ty][tx+16] = A[a + 16];
        Bs[ty][tx] = B[b]; Bs[ty+16][tx] = B[b + 16*wB];
        __syncthreads();
        for (int k = 0; k < 32; ++k) Csub += As[ty][k] * Bs[k][tx];
        __syncthreads();
    }

    C[wB*16*by + 16*bx + wB*ty + tx] = Csub;
}
```

Related Work

- OpenMP to GPGPU (S. Lee, S-J. Min, and R. Eigenmann)
  - Weak support in CUDA-specific features, like thread blocks and the shared memory
  - Many OpenMP directives are not necessary in data-parallel programming
- OpenCL
  - Involve similar "mundane" tasks as in CUDA
- CUDA-lite (S. Ueng, M. Lathara, S. Baghsorkhi, W-M. Hwu)
  - Still requires the programmer to write CUDA code
  - Automation on an optimization pattern: utilizing the shard memory for coalescing global memory accesses

More Features of *hi*CUDA

- Support asynchronous kernel execution
  - `nowait` clause in the `kernel` directive

- Allow arbitrary dimensionality of the thread space

- Support `BLOCK`/`CYCLIC` distribution of loop iterations

- Support code execution by a single thread in each thread block
  - `singular` directive

More Features of *hi*CUDA

- Support the use of dynamic arrays in all data directives
  - `shape` directive
- Support allocation and transfer of array sections
  - `A[1:99][1:99]`
- Support data transfer across arrays with different names
  - `copyout A[1:99][1:99] to B[*][*]`
- Support the use of constant memory
  - `constant` directive

OLD SLIDES

Kernel identification

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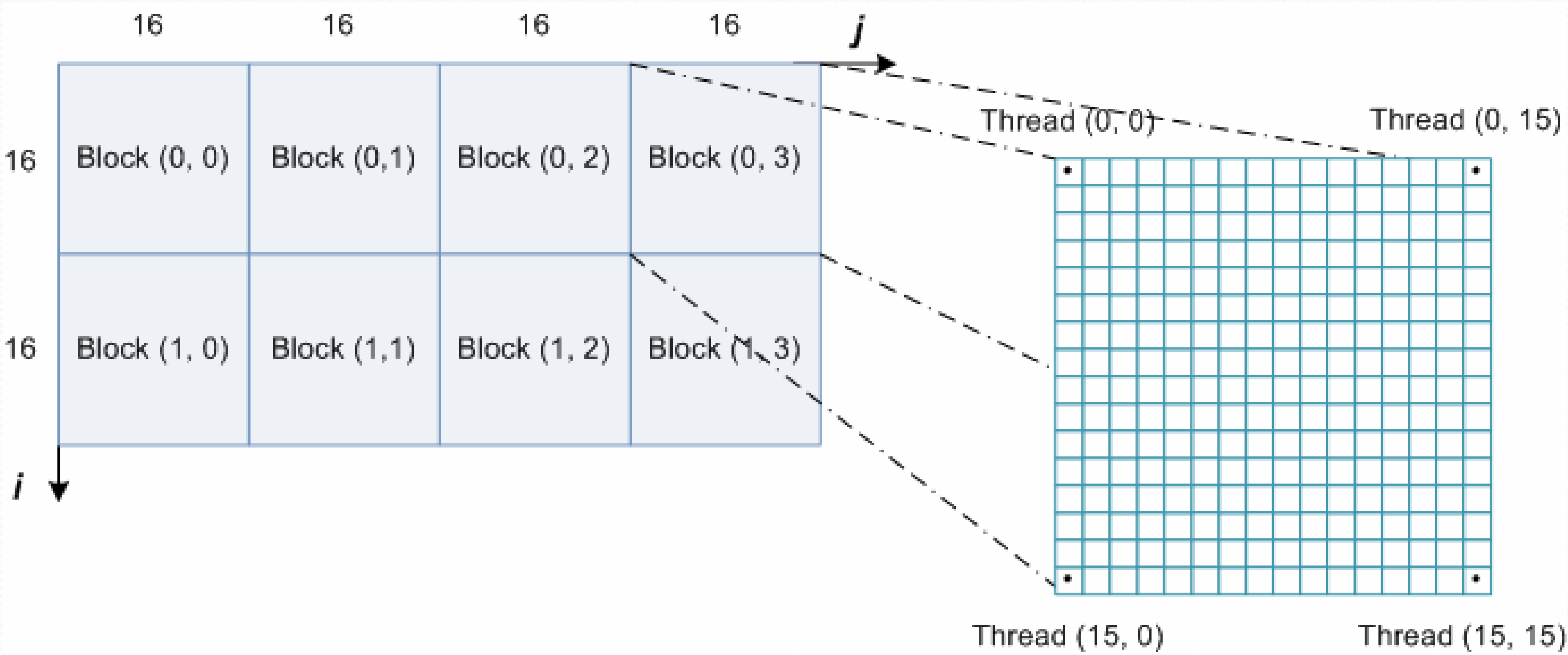
Computation partitioning



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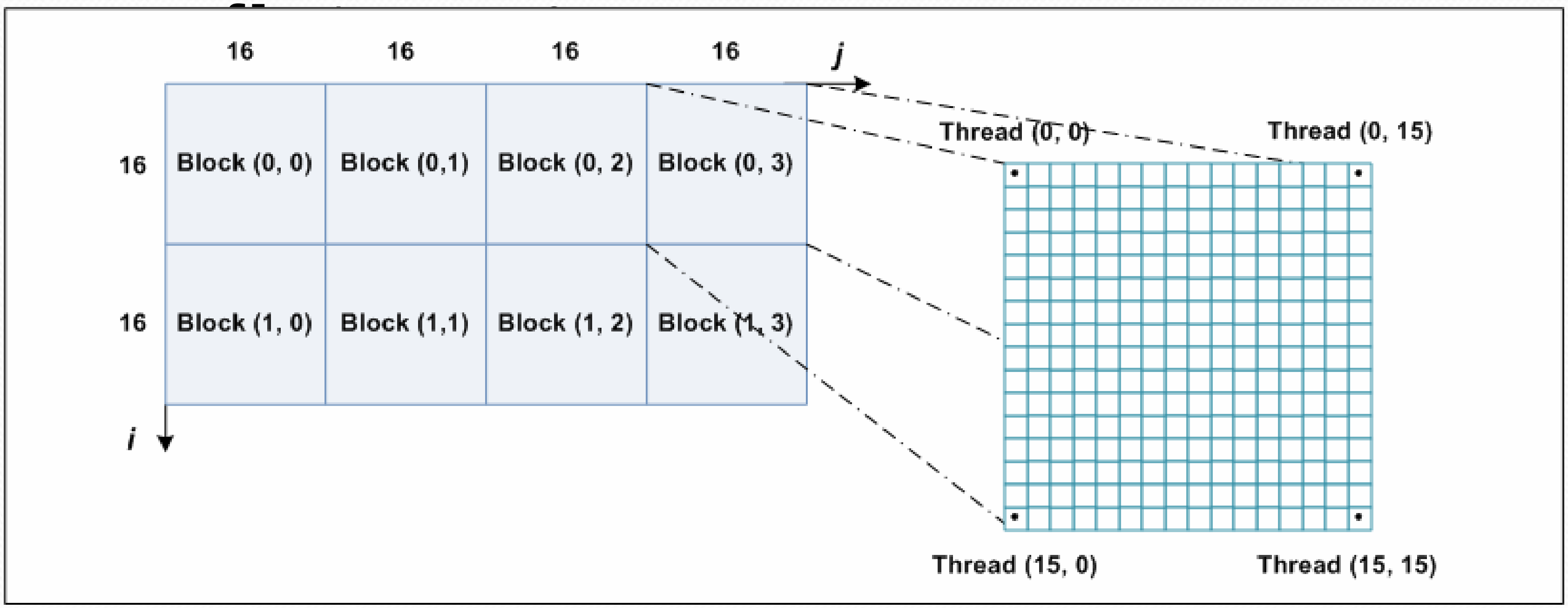

GPU data management

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Utilizing the shared memory

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#pragma hicuda barrier
    for (k = 0; k < 32; ++k) {
        sum += A[i][kk+k] * B[kk+k][j];
    }
#pragma hicuda barrier
#pragma hicuda shared remove A B
}
C[i][j] = sum;
```

Add the shared directives