OpenCL

Jingke Li

Portland State University

What Is OpenCL?

Usually used for GPU programming but not restricted to it!

OpenCL = Open Computing Language (Doesn't say GPU)

An open specification developed by the (open-membership) Khronos Group. (Quick) - adding new features.

OpenCL provides a framework for writing and running parallel programs across a heterogeneous platform consisting of CPUs, GPUs, and other processors. It includes

- A C99-based language for writing *compute kernels* (functions that execute on OpenCL devices), and
- APIs that are used to manage computing tasks and data objects.

Basically this is language for everything.

The language consits of two parts.
- Kernel (actual task to solve)
- API calls to manage those functions.

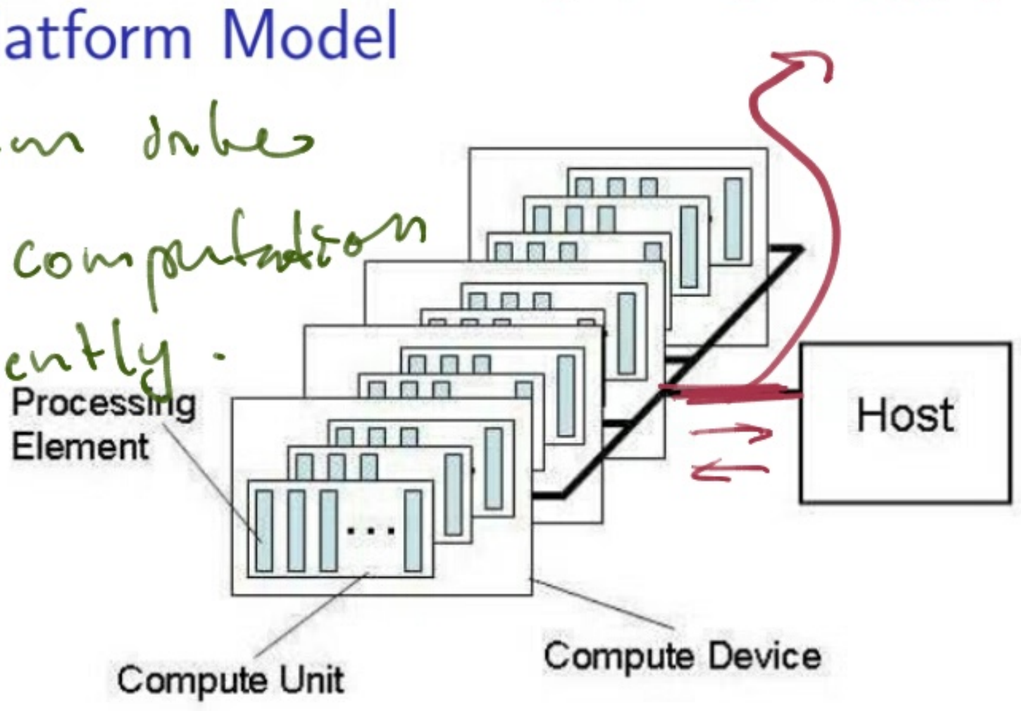
The concept of having meta data for manipulating tasks is not new. (Fibrous herd BUT in high demand)

Model:
- Computing Engines (passive executors, listen for the instructions and perform them)
- host (compiling + coordinating + sending tasks to computing engines)

OpenCL Platform Model

This channel is a bottleneck

Map your problem onto domain and our computation will happen concurrently.



(Figure credit: OpenCL Specification)

- A host connected to one or more *compute devices*.
- A compute device can be a CPU, a GPU, or some other processor.
- Computation is defined over an N-dim global domain (N=1, 2, or 3).
- All elements in the N-D domain execute in data-parallel fashion.

Similar to Chapel But restrictive for 1,2 or 3 dimensional domains

Work-Items and Work-Groups

Can be in form of simple statement or a function.

It is up to user how many work items are in single work group.

- The smallest work unit is called a *work-item*, which corresponds to computation carried out at a single element of the N-D domain.
- To correspond to a typical GPU's organization, a set of work-items are grouped together to form a *work-group*.
- The size of work-groups are up to the programmer to specify. It must evenly divide the N-D domain size. (Different sizes may have different performance implications.) Partition must be even! (issue)
- Work-items can be synchronized at work-group level, but not at the global level.

Sync is a problem. There is no way for a GPU to syncronize globally.

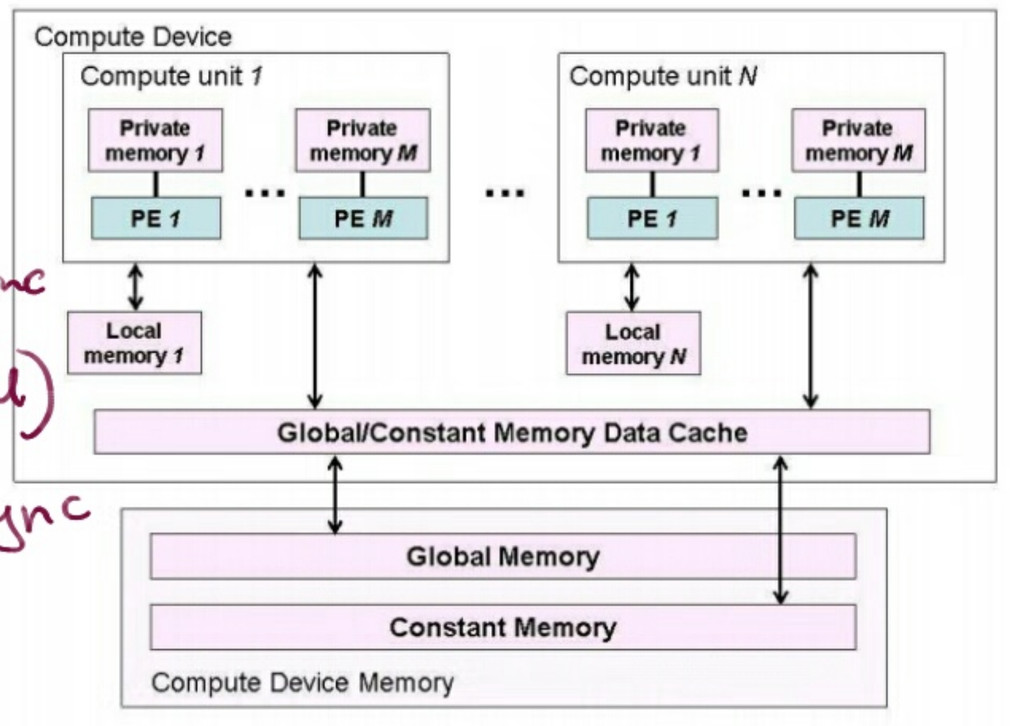
Only the host can do global sync which is very slow.

Memory organization is another issue.

OpenCL Memory Model

1. *Private Memory* (tiny)
   — per work item
2. *Local Memory*
   — shared within a work-group Allows sync
3. *Global Memory* (whole GPU)
   — main memory for a compute device no sync
4. *Constant Memory*
   — special section of the global memory

Read only section of the memory, can be accessed very fast or even cached!



(Figure credit: OpenCL Specification)

Memory Consistency?

Sequential consistency is very strong (disables all possible optimizations!) // usually not used.

- OpenCL uses a relaxed consistency memory model; i.e. the state of memory visible to a work-item is not guaranteed to be consistent across the collection of work-items at all times. (no sync)
- Within a work-item, memory has load/store consistency.
- Local memory is consistent across work-items in a single work-group at a work-group barrier. → allows sync! (within local memory)
- Global memory is consistent across work-items in a single work-group at a work-group barrier, but there are no guarantees of memory consistency between different work-groups executing a kernel.

details are much different than other languages.

Work items from the same work group can be synchronized, but not among different work groups.

OpenCL Programming Model

An OpenCL application consists of two programs: (needs to be written separately)

- *Compute Program*
  - Contains a collection of *kernels* and other functions
  - Similar to a dynamic library
- *Host Program*
  - Handles I/O, memory management, and kernel scheduling

Even for simple appplications, both programs can be very complex when performance optimization is involved.

Typical Data Flow

1. Host produces/captures data
2. Host loads/builds kernels → compile dynamically.
3. Host copy data to device DRAM
4. Kernel loads data from DRAM into local memory once executed - performs additional data movements
   - Work-items execute, in parallel, on data in local memory host is waiting.
   - Once work-items are done, move data back into device DRAM
   - Move results back to host

OpenCL C

- Derived from ISO C99 (simplified version of C)
  - no function pointers, recursion, variable-length arrays, and bit fields

CL = C-

- Additions to the language for parallelism
  - work-items and work-group, vector types, synchronization
- Address space qualifiers
  - `__global`, `__local`, `__constant`, and `__private`
- Built-in functions deals for specific needs (what?)
  - for math, work-item/work-group, vector, and synchronization
- Optimized image access Same (or similar to cuda)

Bunch of transformations for pixels.

Example: Array Operations

Sequential Code:

```
#define n 512
int main(int argc, char** argv) // Sequential version in C
{
  float a[n], b[n], sum[n], prod[n];
  int i;
  ...
  for (i=0; i<n; i++) {
    sum[i] = a[i] + b[i];
    prod[i] = a[i] * b[i];
  }
}
```

OpenCL Compute Program

A compute program consists of a set of kernel definitions. A kernel is a data-parallel function written from *individual element*'s view.

```
// array_ops.cl

__kernel void add(__global const float *a,
    __global const float *b, __global float *sum)
{
    int id = get_global_id(0);
    sum[id] = a[id] + b[id];
}

__kernel void mul(__global const float *a,
    __global const float *b, __global float *prod)
{
    int id = get_global_id(0);
    prod[id] = a[id] * b[id];
}
```


OpenCL Host Program

```
// test_array_ops.c

#define n 512
int main(int argc, char** argv)
{
  float a[n], b[n], sum[n], prod[n];
  int buf_size = sizeof(float) * n;

  // Run OpenCL:
  //   Set up context and command queue
  //   Allocate device memroy
  //   Load and build programs/kernels
  //   Execute kernels
  //   Cleanup
}
```

Set Up Context and Command Queue

Each device requires an individual context

Select a device and create a context and a command queue.

```
cl_context context =
    clCreateContextFromType(0, CL_DEVICE_TYPE_GPU,
                            NULL, NULL, NULL);

cl_command_queue cmd_queue =
    clCreateCommandQueue(context, NULL, 0, NULL);
```


Allocate Device Memory

```
cl_int err;

cl_mem a_buf = clCreateBuffer(context, CL_MEM_READ_ONLY,
                              buf_size, NULL, NULL);
cl_mem b_buf = clCreateBuffer(context, CL_MEM_READ_ONLY,
                              buf_size, NULL, NULL);
cl_mem sum_buf = clCreateBuffer(context, CL_MEM_READ_WRITE,
                                buf_size, NULL, NULL);
cl_mem prod_buf = clCreateBuffer(context, CL_MEM_READ_WRITE,
                                 buf_size, NULL, NULL);

// Copy data from host to device
err = clEnqueueWriteBuffer(cmd_queue, a_buf, CL_TRUE, 0,
                           buf_size, (void*)a, 0, NULL, NULL);
err = clEnqueueWriteBuffer(cmd_queue, b_buf, CL_TRUE, 0,
                           buf_size, (void*)b, 0, NULL, NULL);
```

// buf for arrays a b sum product

create tasks for doing the job

host control can't start a task on the remote system
It hands over the task and let the remote device to decide when to start it.

If device is busy → then task won't start immediately.

Load and Build Programs/Kernels

```
cl_kernel kernel[2];

char *program_source = load_program_source("array_ops.cl");
cl_program program =
    clCreateProgramWithSource(context, 1,
        (const char**)&program_source, NULL, &err);

err = clBuildProgram(program, 0, NULL, NULL, NULL, NULL);

kernel[0] = clCreateKernel(program, "add", &err);
kernel[1] = clCreateKernel(program, "mul", &err);
// Set arguments
err = clSetKernelArg(kernel[0], 0, sizeof(cl_mem), &a_buf);
err = clSetKernelArg(kernel[0], 1, sizeof(cl_mem), &b_buf);
err = clSetKernelArg(kernel[0], 2, sizeof(cl_mem), &sum_buf);
err = clSetKernelArg(kernel[1], 0, sizeof(cl_mem), &a_buf);
err = clSetKernelArg(kernel[1], 1, sizeof(cl_mem), &b_buf);
err = clSetKernelArg(kernel[1], 2, sizeof(cl_mem), &prod_buf);
```


Execute Kernels

Enqueue kernel computation; push them to the device for execution; then read back the results.

Data pumping

```
size_t global_work_size = n;
err = clEnqueueNDRangeKernel(cmd_queue, kernel[0],
          1, NULL, &global_work_size, NULL, 0, NULL, NULL);
err = clEnqueueNDRangeKernel(cmd_queue, kernel[1],
          1, NULL, &global_work_size, NULL, 0, NULL, NULL);

clFinish(cmd_queue); // synchronization
err = clEnqueueReadBuffer(cmd_queue, sum_buf, CL_TRUE, 0,
                          buffer_size, sum, 0, NULL, NULL);
err = clEnqueueReadBuffer(cmd_queue, prod_buf, CL_TRUE, 0,
                          buffer_size, prod, 0, NULL, NULL);
```

send over

wait for the cmd_queue to be empty

get data back.

This is not

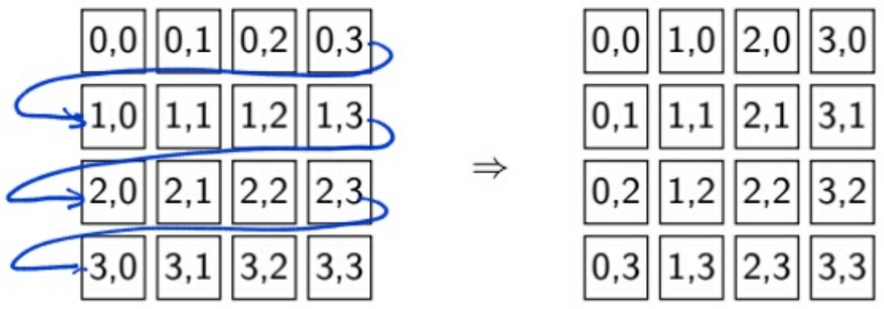
Cleanup

```
clReleaseKernel(kernel[0]);
clReleaseKernel(kernel[1]);
clReleaseProgram(program);
clReleaseCommandQueue(cmd_queue);
clReleaseContext(context);
```


Example: Matrix Transpose

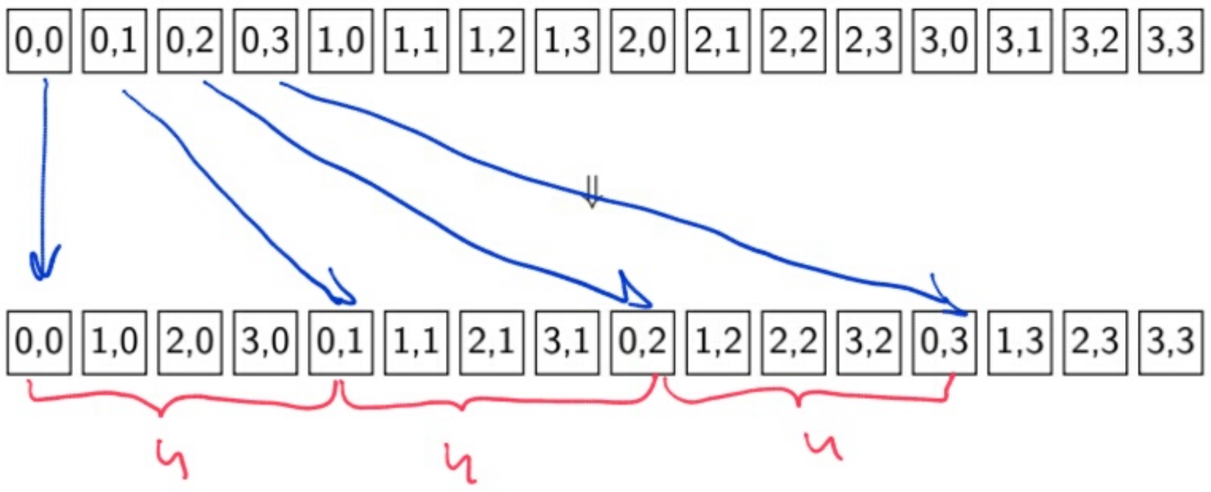
How to utilize all available resources? → Big issue

row major →



Will be very short sequential program

From memory's view: // In GPU:



Stest with sequential implementation.

GPU all computation defined over a domain, which can be 1D 2D and 3D

Naive Kernel

Work directly with global memory:

```
__kernel void naive_transpose(
    __global float *idata, __global float* odata, int nx, int ny)
{
    unsigned int id_x, id_y, idx_in, idx_out;

    id_x = get_global_id(0); // get thread id in dimension 0
    id_y = get_global_id(1); // get thread id in dimension 1
    idx_in  = id_y * nx + id_x;
    idx_out = id_x * ny + id_y;
    odata[idx_out] = idata[idx_in];
}
```

unique thread ID.

transforming 2D view to 1D memory layout index.

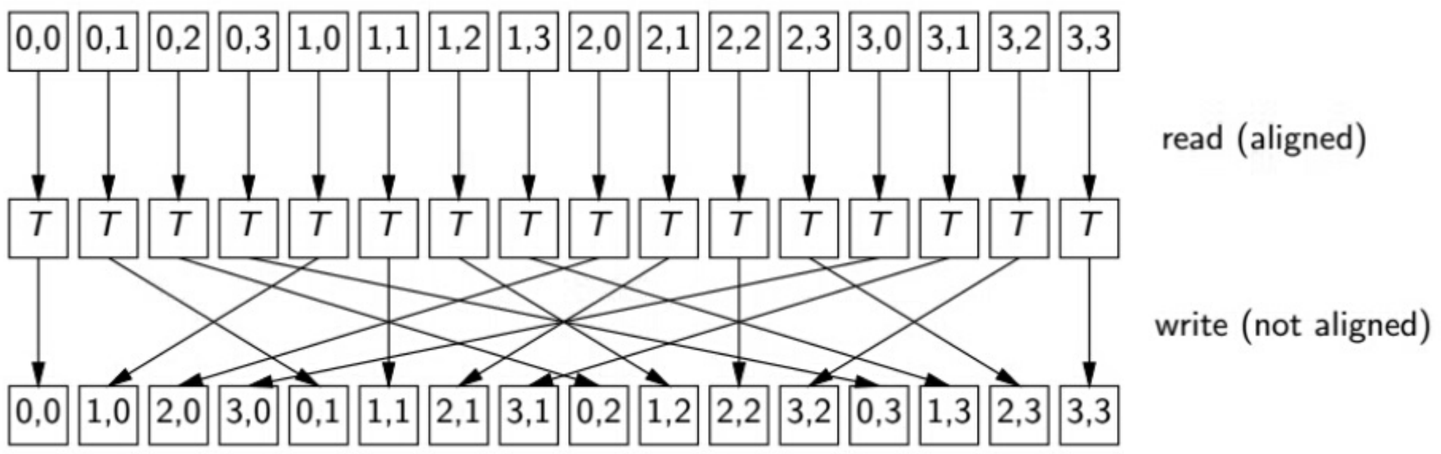
copy data to new destination

Main issue

Performance is the Problem.

Problem with Naive Kernel

Global memory access pattern:



If global memory accesses are aligned, they can be coalesced (into 64-byte chuncks on current GPUs). Peformance difference: 16x.

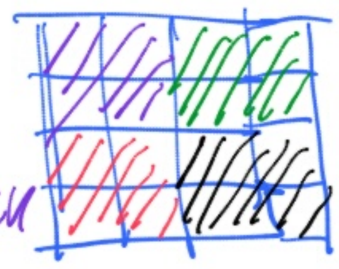
No issue running since GPU can access the entire global space

Issue: All threads execute in locked steps no variance 16 thread execute simultaneous read/write. — all from different memory resulting in 16 memory faults.

Can we get 16 factor back and work around hardware limitations?

Break matrix in smaller matrices

Utilize local memory → copy each block to local memory.



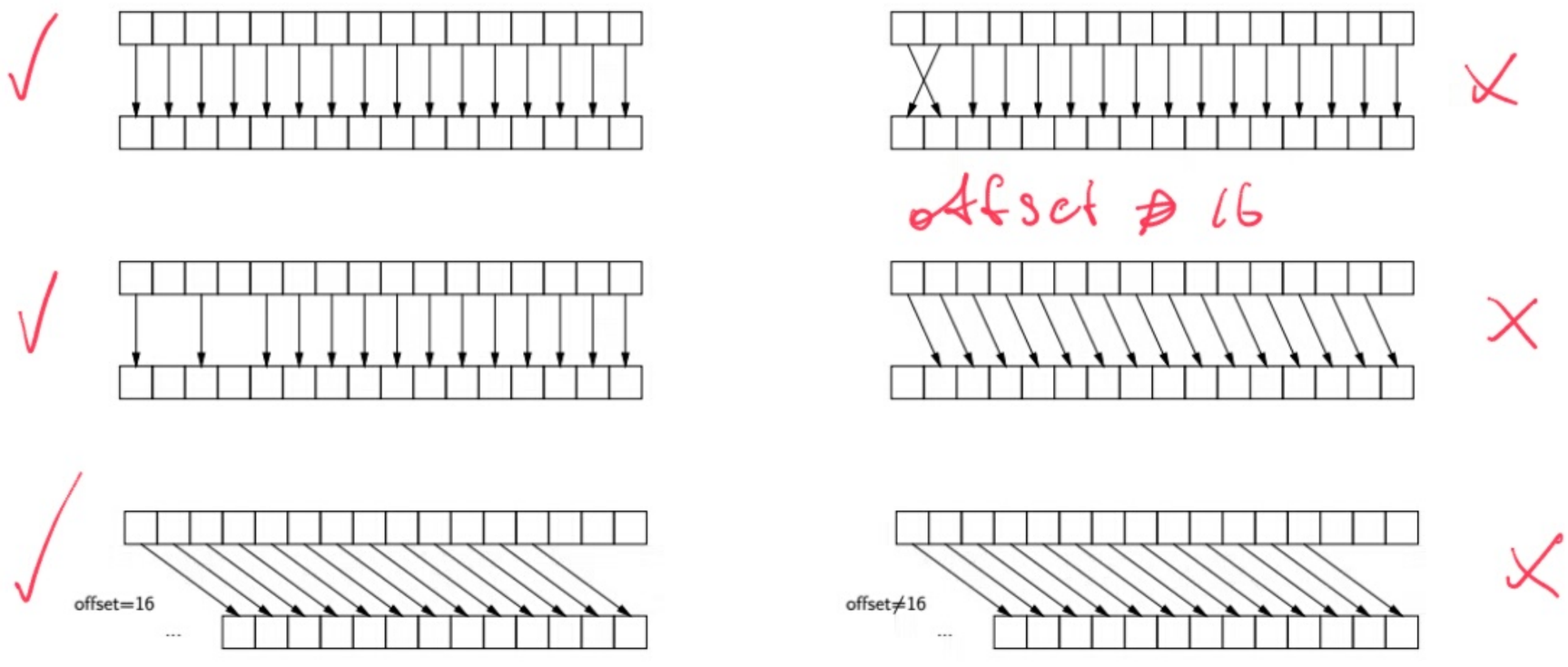
Global Memory Access Patterns

Good locality

Bad locality

Aligned:

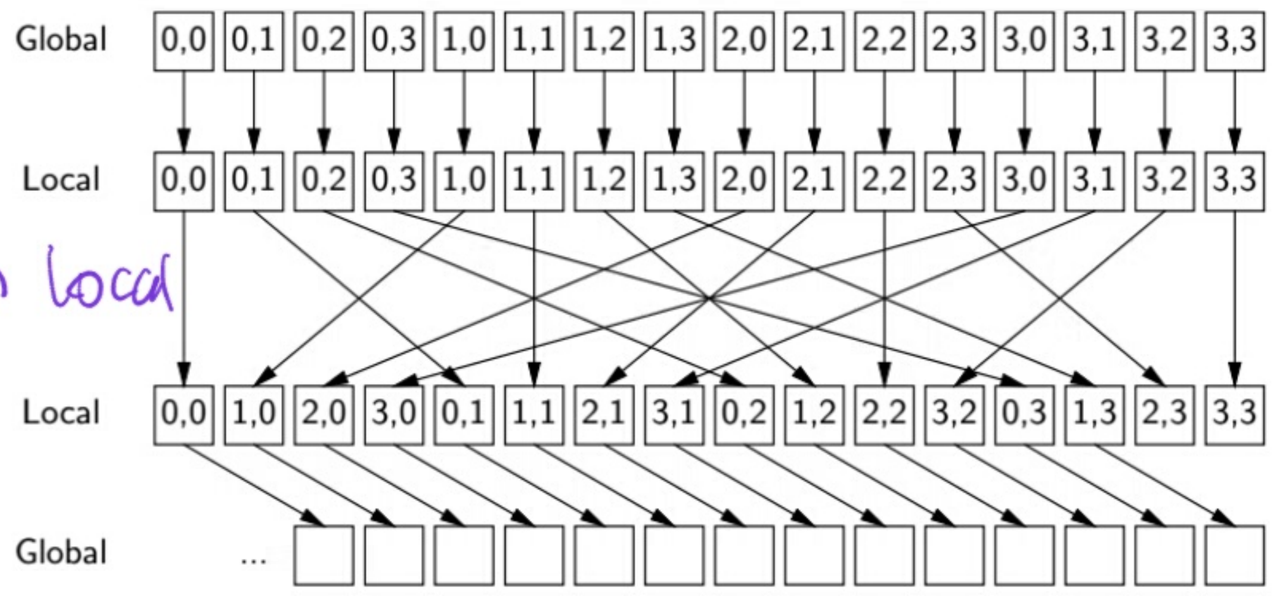
Not-aligned:



Offset ≠ 16

Better Kernel Using Local Memory

- Load data from global memory to local memory in aligned form.
- Perform block transpose in local memory.
- Write data back to global memory in aligned form.



→ happens in local memory

That solves global memory alignment problem.

Better Kernel (cont.)

```
__kernel void better_transpose(
    __global float *idata, __global flo at* odata,
    __local float *block, int nx, int ny, blockSize)
{
    unsigned int gid_x, gid_y, g_src, g_dst, grp_x, grp_y;
    unsigned int lid_x, lid_y, l_src, l_dst;

    gid_x = get_global_id(0);
    gid_y = get_global_id(1);
    g_src = gid_y * nx + gid_x;
    lid_x = get_local_id(0);
    lid_y = get_local_id(1);
    l_src = lid_x * blockSize + lid_y;
    block[l_src] = idata[g_src];

    barrier(CLK_LOCAL_MEM_FENCE);
    gid_x = get_group_id(1) * blockSize + lid_y;
    gid_y = get_group_id(0) * blockSize + lid_x;
    g_dst = gid_y * ny + gid_x;
    l_dst = lid_y * blockSize + lid_x;
    odata[g_dst] = block[l_dst];
}
```

global id (memory)

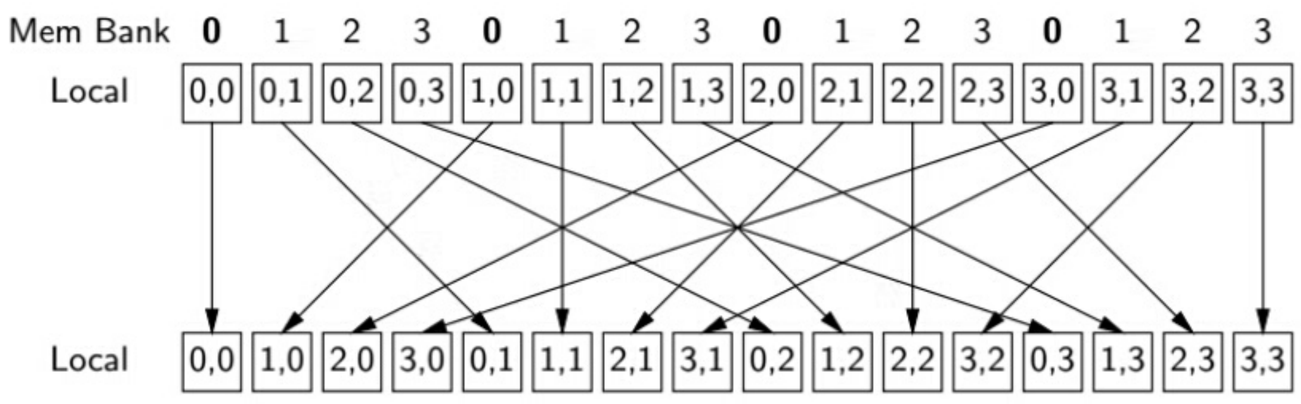
local id (memory)

Still a Problem ...

Local memory access conflicts:

- Local memory is organized into memory banks (on current GPUs, there are typically 16 banks)
- Simultaneous multiple accesses from different threads to the same memory bank will be serialized.

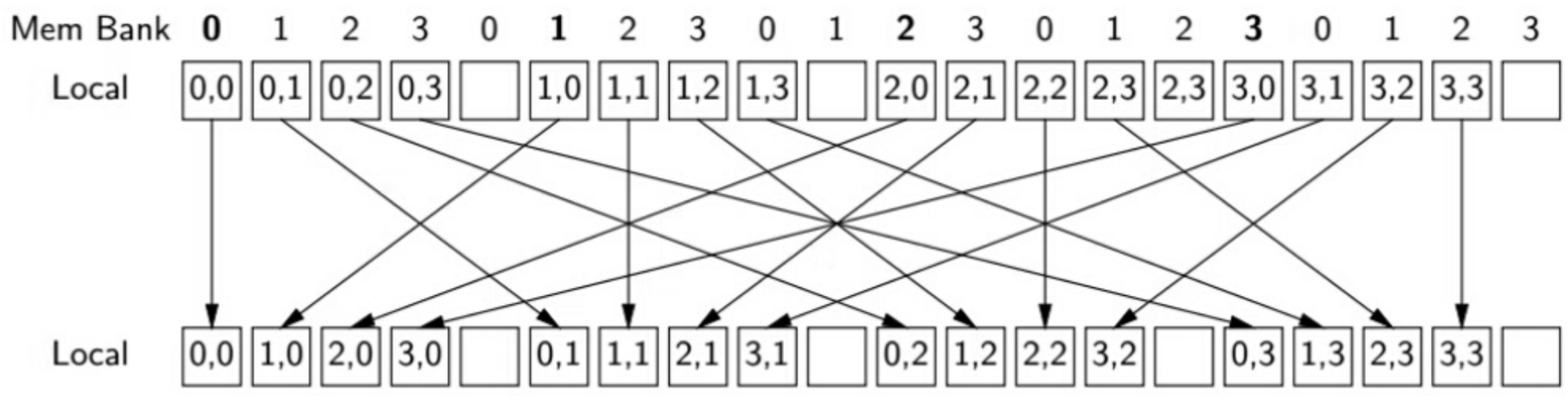
(For illustration, assume 4 memory banks.)



Every write creates memory conflict.
we don't want blocks of 16 inside local memory
total opposite of global

Fixing the Problem

To create a production-quality matrix-transpose kernel, the data arrays have to be *padded*:



This will result in an even-more complex kernel code.

Avoid local memory write conflicts!

Things get very messy from here!

Matrix Transpose Kernel (from Apple Inc.)

```
#define PADDING         (32)
#define GROUP_DIMX      (32)
#define LOG_GROUP_DIMX  (5)
#define GROUP_DIMY      (2)
#define WIDTH           (256)
#define HEIGHT          (4096)

__kernel void transpose(
    __global float *output,
    __global float *input,
    __local float *tile)
{
  int block_x = get_group_id(0);
  int block_y = get_group_id(1);
  int local_x = get_local_id(0) & (GROUP_DIMX - 1);
  int local_y = get_local_id(0) >> LOG_GROUP_DIMX;

  int local_input  = mad24(local_y, GROUP_DIMX + 1, local_x);
  int local_output = mad24(local_x, GROUP_DIMX + 1, local_y);
  int in_x = mad24(block_x, GROUP_DIMX, local_x);
  int in_y = mad24(block_y, GROUP_DIMX, local_y);
  int input_index = mad24(in_y, WIDTH, in_x);

  int out_x = mad24(block_y, GROUP_DIMX, local_x);
  int out_y = mad24(block_x, GROUP_DIMX, local_y);
  int output_index = mad24(out_y, HEIGHT + PADDING, out_x);

  int global_input_stride  = WIDTH * GROUP_DIMY;
  int global_output_stride = (HEIGHT + PADDING) * GROUP_DIMY;
  int local_input_stride  = GROUP_DIMY * (GROUP_DIMX + 1);
  int local_output_stride = GROUP_DIMY;
```

original code from Apple

Matrix Transpose Kernel (cont.)

```
    tile[local_input] = input[input_index];       local_input += local_input_stride; input_index += global
    tile[local_input] = input[input_index];       local_input += local_input_stride; input_index += global
    tile[local_input] = input[input_index];       local_input += local_input_stride; input_index += global
    tile[local_input] = input[input_index];       local_input += local_input_stride; input_index += global
    tile[local_input] = input[input_index];       local_input += local_input_stride; input_index += global
    tile[local_input] = input[input_index];       local_input += local_input_stride; input_index += global
    tile[local_input] = input[input_index];       local_input += local_input_stride; input_index += global
    tile[local_input] = input[input_index];       local_input += local_input_stride; input_index += global
    tile[local_input] = input[input_index];       local_input += local_input_stride; input_index += global
    tile[local_input] = input[input_index];       local_input += local_input_stride; input_index += global
    ... // total 16 groups of statements

    barrier(CLK_LOCAL_MEM_FENCE);

    output[output_index] = tile[local_output]; local_output += local_output_stride; output_index += global_
    output[output_index] = tile[local_output]; local_output += local_output_stride; output_index += global_
    output[output_index] = tile[local_output]; local_output += local_output_stride; output_index += global_
    output[output_index] = tile[local_output]; local_output += local_output_stride; output_index += global_
    output[output_index] = tile[local_output]; local_output += local_output_stride; output_index += global_
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    output[output_index] = tile[local_output]; local_output += local_output_stride; output_index += global_
    ... // total 16 groups of statements
}
```

Total # lines in the program: 148 (many contain multiple statements!)

$3 \times 148 > 5$?

Performance Tuning

Overhead come from many places:

- Compiling programs
- Moving data to/from devices
- Starting kernels
- Synchronization
- Divergent execution at work-item level
- Non-coalesced global memory accesses
- Local memory access conflicts

To get the best performance, one needs to

- know the details of the target device
- refine kernels to optimize memory operation performance
- take tuning runs

Data transfer to/from GPU is slow.