HETEROGENEOUS / GPGPU COMPUTING WITH OPENCL

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- Introduces GPGPU basics through 12 example programs
- Examples are written in OpenCL 1.2 or 2.0
- Introduces OpenGL – OpenCL interop
- OpenGL basics not covered.
- OpenCL, CUDA and Apple Metal are conceptually similar, and easier to learn if you know GPGPU basics and any one of them

1. Update Graphics Drivers
2. Install OpenCL SDK
3. Git clone/download the folder
   https://github.com/premsasidharan/GpgpuOpenCL
4. Open GpGpuOpenCL/vs2015/GpGpuOpenCL.sln
5. Try to build VectorAdd

From Wikipedia ---

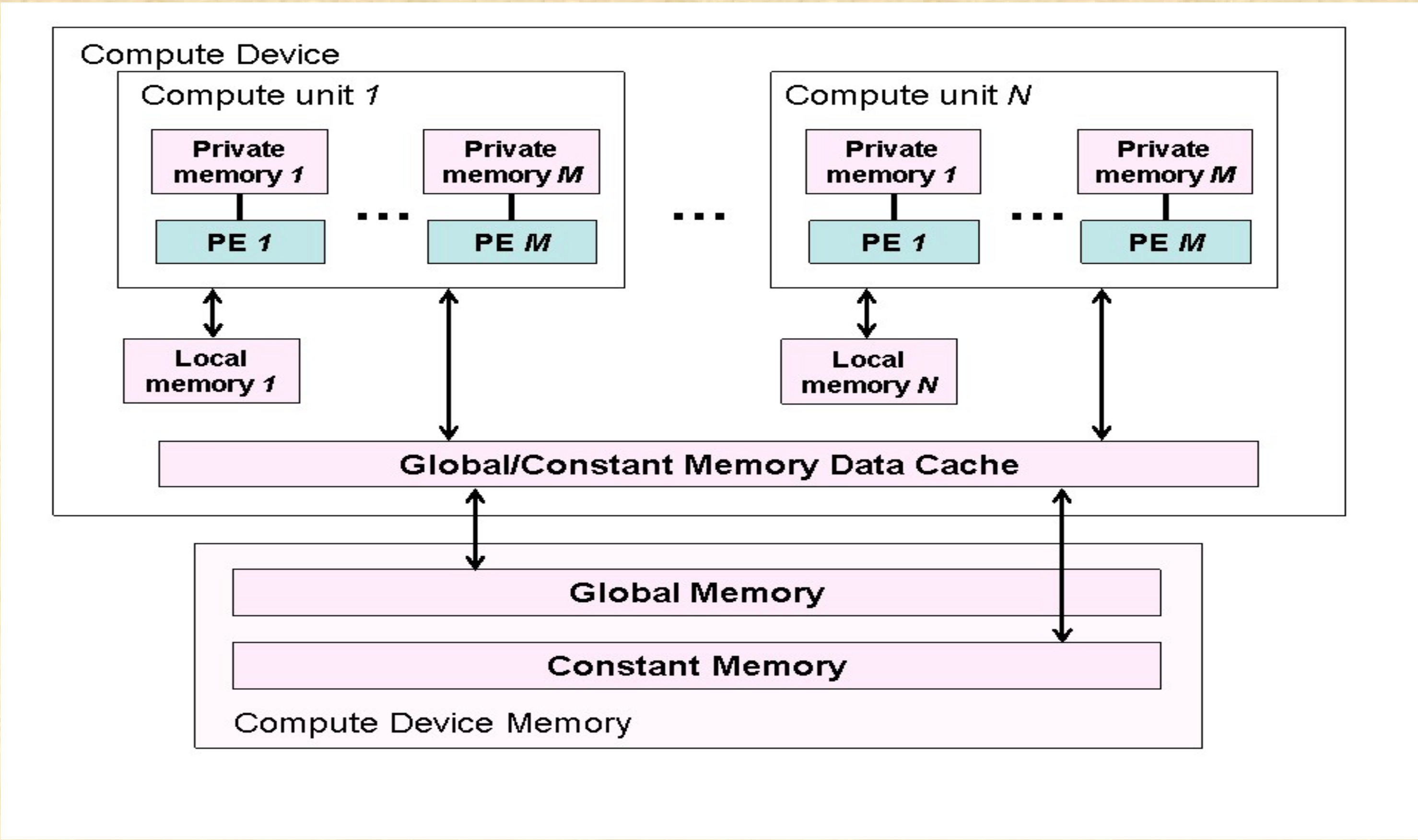
“**Open Computing Language** (**OpenCL**) is a framework for writing programs that execute across heterogeneous platforms consisting of CPUs, GPUs, DSPs, FPGAs and other processors or hardware accelerators”

Platform	Silicon Vendor
x86/x64 SoC’s (Laptop, Desktop)	Intel, AMD
Mobile SoC’s	Qualcomm, Mediatek, Intel Atom, Nvidia Tegra, Samsung Exynos, etc
Discrete GPUs	Nvidia, AMD
FPGA	Xilinix, Altera(Intel)
DSP	TI

Agenda

- Abstract Hardware Architecture
- OpenCL Programming Model
- Coding Example 1: Vector Addition
- Coding Example 2: Color Inversion
- Coding Example 3: Image Gradient
- Coding Example 4: Canny Edge Detection
- Coding Example 5: Image Histogram
- Parallel Processing Patterns
- Coding Example 6: Reduce Sum
- Coding Example 7: Prefix Sum
- Coding Example 8: Harris Corner detection (Stream Compaction)
- OpenCL 2.0
- Coding Example 9: Prefix Sum using OpenCL 2.0
- Coding Example 10: Harris Corner detection using OpenCL 2.0
- Coding Example 11: Radix Sort
- Coding Example 12: Matrix Multiplication
- Reference
- Exercise: RGB Histogram

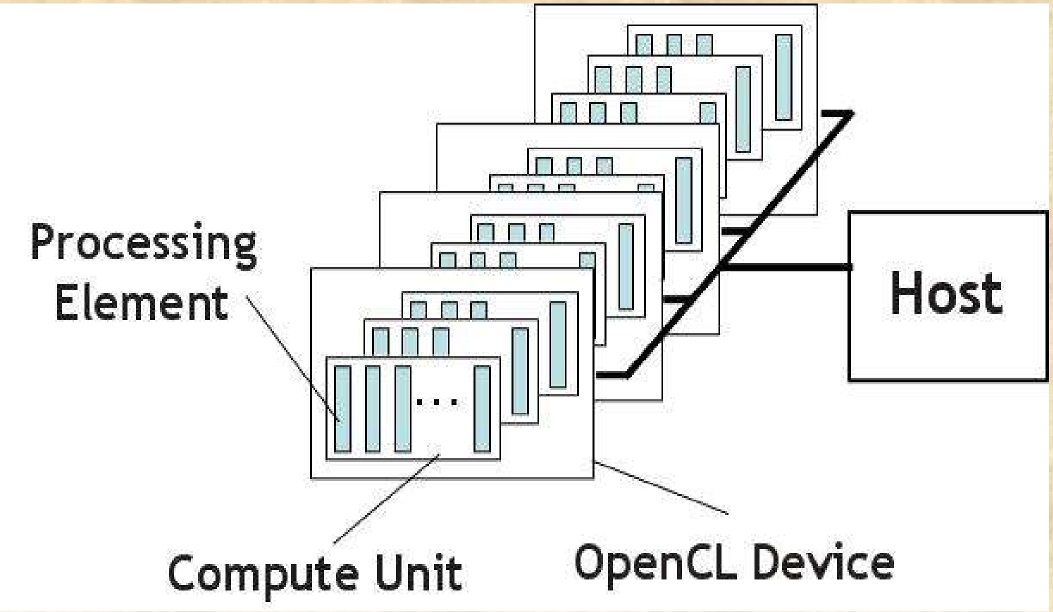
Abstract Hardware Architecture



Processor Architecture

SIMD (Single Instruction Multiple Data)	SIMT (Single Instruction Multiple Threads)	SMT (Simultaneous Multithreading)
• Vector processing instructions • Performance issues with branch divergence Example: Old GPU architectures	• A hybrid between vector processing and hardware threading • Not affected by branch divergence Example: New GPU architectures	• Instructions of several threads run in parallel Example: Modern multicore CPUs

OpenCL Platform Model



- Data Parallelism

  is a form of parallelization across multiple processors in parallel computing environments. It focuses on distributing the data across different nodes, which operate on the data in parallel. It can be applied on regular data structures like arrays and matrices by working on each element in parallel.

- Task Parallelism

  is a form of parallelization of computer code across multiple processors in parallel computing environments. Task parallelism focuses on distributing tasks concurrently performed by processes or threads across different processors.

Courtesy: Wikipedia

OpenCL Memory Model

- Private Memory (registers)
  - Per work-item
- Local Memory
  - Shared within a work-group
- Global Memory
  - OpenCL Buffers
  - OpenCL Images (1D, 2D and 3D)
- Host Memory

OpenCL Application

- Host Code
  - Written in a High level language (C, C++).
  - Runs on the Host machine
  - Host code issues data transfer commands
  - Host code issues commands for OpenCL device execution

- OpenCL Device Code
  - Written in OpenCL C
  - Runs on OpenCL Device
  - Parallel code executes on many PEs

Work Item (thread): The basic unit of work on an OpenCL device

Kernel: The code for a work Item (like a C Function)

Program: Collection of kernels and other functions

Context: The environment within which work items execute

CommandQueue: Queue used by the host application to submit work to an OpenCL device. Work is queued in order. Work can be executed in-order or out-of-order.

OpenCL Execution Model

Tradition C Code (vector addition)

```
void add(const float* a, const float* b, float* c, int N)
{
      for (int i = 0; i < N; i++)
      {
            c[i] = a[i]+b[i];
      }
}
```

OpenCL Kernel (vector addition)

```
kernel void add(global const float* a, global const float* b, global float* c)
{
      int i = get_global_id(0);
      c[i] = a[i]+b[i]
}
```

- Kernels are executed across a global domain of work items (threads)
- Work items (threads) can have 1D, 2D or 3D id
- Work item (thread) ID dimension is configurable from the host side depending on the data
- Work items (threads) are grouped into local work-groups (blocks)

- cl::Platform
- cl::Context
- cl::Device
- cl::CommandQueue
- Cl::Event
- cl::Program
- cl::Kernel
- cl::Buffer, cl::BufferGL
- cl::Image1D, cl::Image2D, cl::Image3D, cl::ImageGL
- cl::Sampler

How to schedule an OpenCL kernel on a GPU (OpenCL Device)?

1. Create a OpenCL context instance
```
cl::Context context(CL_DEVICE_TYPE_GPU);
std::vector<cl::Device> devices = context.getInfo<CL_CONTEXT_DEVICES>();
```
2. Create a CommandQueue instance using the OpenCL context and on the desired OpenCL device.
```
cl::CommandQueue queue(context, devices[0], CL_QUEUE_PROFILING_ENABLE);
```
3. Create the required OpenCL input, output buffers using OpenCL context
```
cl::Buffer bufferA(context, CL_MEM_READ_WRITE, count*sizeof(cl_int));
```
4. Build the OpenCL program
```
cl::Program program(context, sSource);
program.build();
```
5. Create the OpenCL kernel instance
```
cl::Kernel kernel(program, "add");
```
6. Transfer data from host to OpenCL input buffers(map, or copy) using CommandQueue
```
cl_int* pDataA = (cl_int *)queue.enqueueMapBuffer(bufferC, CL_TRUE, CL_MAP_WRITE, 0, count*sizeof(cl_int));
for (size_t i = 0; i < count; i++) pDataA[i] = rand()/100;
queue.enqueueUnmapMemObject(bufferA, pDataA);
```
7. Set Input, Output arguments to kernel instance
```
kernel.setArg(0, bufferA);
```
8. Enqueue the OpenCL kernel on the Command Queue
```
cl::Event event;
queue.enqueueNDRangeKernel(kernel, cl::NullRange, cl::NDRange(count), cl::NullRange, NULL, &event);
```
9. Wait for the kernel to finish execution
```
event.wait();
```

```
kernel void add(global const int* pA, global const int* pB,
                global int* pC)
{
    const int id = get_global_id(0);
    pC[id] = (pA[id] + pB[id]);"
}
```

Kernel work item ID/Thread ID

- Global ID (Global ID for the work Item)
  - size_t get_global_id(size_t dim)

- Local ID (Work Item ID within the Block)
  - size_t get_local_id(size_t dim)

- Work group ID (Work Group ID for the work Item)
  - size_t get_group_id(size_t dim)

- size_t get_global_size(size_t dim)
- size_t get_local_size(size_t dim)
- size_t get_num_groups(size_t dim)

Kernel Work Item ID (1D data)

Data (0-255) **Block 0**	Data (256-511) **Block 1**	Data (512 – 767) **Block 2**	…	Data (N-255, N) **Block M**

size_t get_global_id(0)

size_t get_local_id(0)

size_t get_group_id(0)

size_t get_num_groups(0)

Kernel Work Item ID (2D Data)

Ex:- Image with 32x24 pixels organized into blocks of size 8x8

Block (0, 0)	**Block (1, 0)**	**Block (2, 0)**	**Block(3, 0)**
Block(0, 1)	**Block(1, 1)**	**Block(2, 1)**	**Block(3, 1)**
Block(0, 2)	**Block(1, 2)**	**Block(2, 2)**	**Block(3, 2)**

8, 8	9, 8	10, 8	11, 8	12, 8	13, 8	14, 8	15, 8
8, 9	9, 9	10, 9	11, 9	12, 9	13, 9	14, 9	15, 9
8, 10	9, 10	10, 10	11, 10	12, 10	13, 10	14, 10	15, 10
8, 11	9, 11	10, 11	11, 11	12, 11	13, 11	14, 11	15, 11
8, 12	9, 12	10, 12	11, 12	12, 12	13, 12	14, 12	15, 12
8, 13	9, 13	10, 13	11, 13	12, 13	13, 13	14, 13	15, 13
8, 14	9, 14	10, 14	11, 14	12, 14	13, 14	14, 14	15, 14
8, 15	9, 15	10, 15	11, 15	12, 15	13, 15	14, 15	15, 15

size_t get_global_id(0)
size_t get_global_id(1)

size_t get_local_id(0)
size_t get_local_id(1)

size_t get_group_id(0)
size_t get_group_id(1)

size_t get_global_size(0)
size_t get_global_size (1)

size_t get_local_size(0)
size_t get_local_size (1)

size_t get_num_groups(0)
size_t get_num_groups(1)

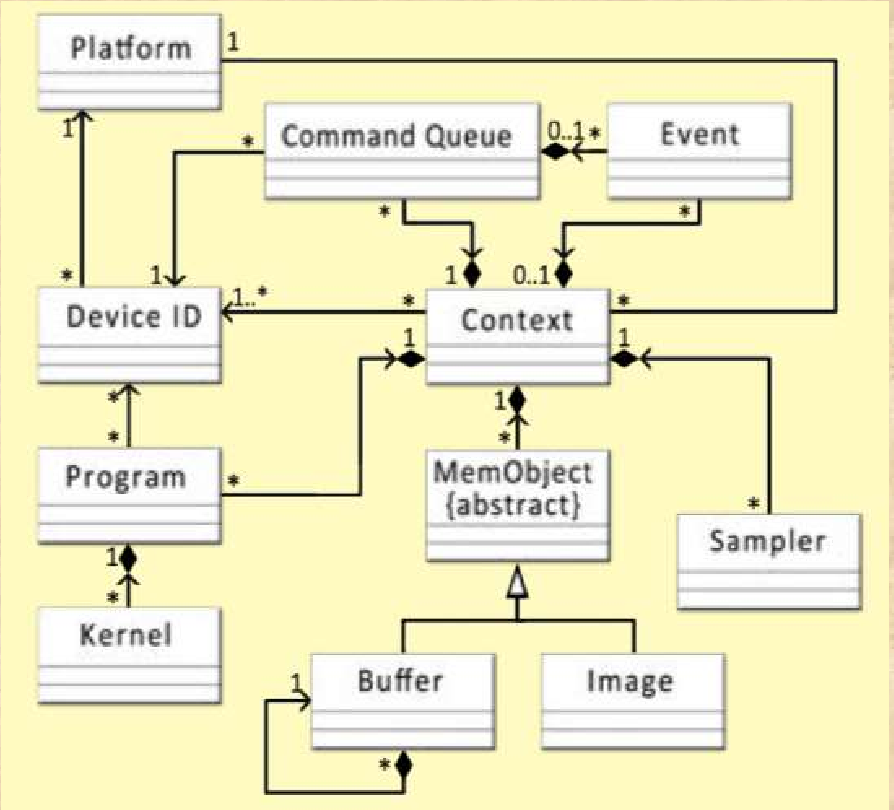
Coding Example 1:

Vector Addition

Summary (Vector Addition)

- Learned to launch a basic kernel on the GPU
- Optimization tips
  - Utilize the available memory band width per processing element
  - Use int4 instead of int and process the 4 elements within the thread

OpenCL Programming Model



<table>
<tr><th>Host</th><th>Kernel</th></tr>
<tr><td>cl::Buffer, cl::BufferGL

size_t count = 1024;
cl::Buffer buffA(context, CL_MEM_READ_WRITE,
count*sizeof(cl_int));
…
kernel.setArg(0, buffA);
kernel.setArg(1, (cl_int)count);
…</td><td>kernel void test(write_only global int* pData, int count)
{
    int id = get_global_id(0);
    ….
    pData[id] = value;
}</td></tr>
<tr><td>cl::Image2D, cl::ImageGL

cl::Image2D inpImg(context, CL_MEM_READ_ONLY,
cl::ImageFormat(CL_RGBA, CL_FLOAT), w, h);

cl::Image2D outImg(context, CL_MEM_READ_WRITE,
cl::ImageFormat(CL_R, CL_FLOAT), w, h);
….

kernel.setArg(0, inpImg);
kernel.setArg(1, outImg);
…</td><td>kernel void avg(read_only image2d_t inp, write_only image2d_t out)
{
  const int x = get_global_id(0);
  const int y = get_global_id(1);

  float4 color = read_imagef(inp, (int2)(x, y));
  float idata = (color.x+color.y+color.z)/3.0;

  write_imagef(out, (int2)(x, y), idata)
}</td></tr>
</table>

Inter-op with OpenGL

- OpenCL Context Creation with OpenGL on Windows

```
cl_context_properties props[] =
        { CL_GL_CONTEXT_KHR, (cl_context_properties)wglGetCurrentContext(),
          CL_WGL_HDC_KHR, (cl_context_properties)wglGetCurrentDC(),
          CL_CONTEXT_PLATFORM, (cl_context_properties)(platforms[i])(), 0 };

mCtxtCL.reset(new cl::Context(CL_DEVICE_TYPE_GPU, props));
```

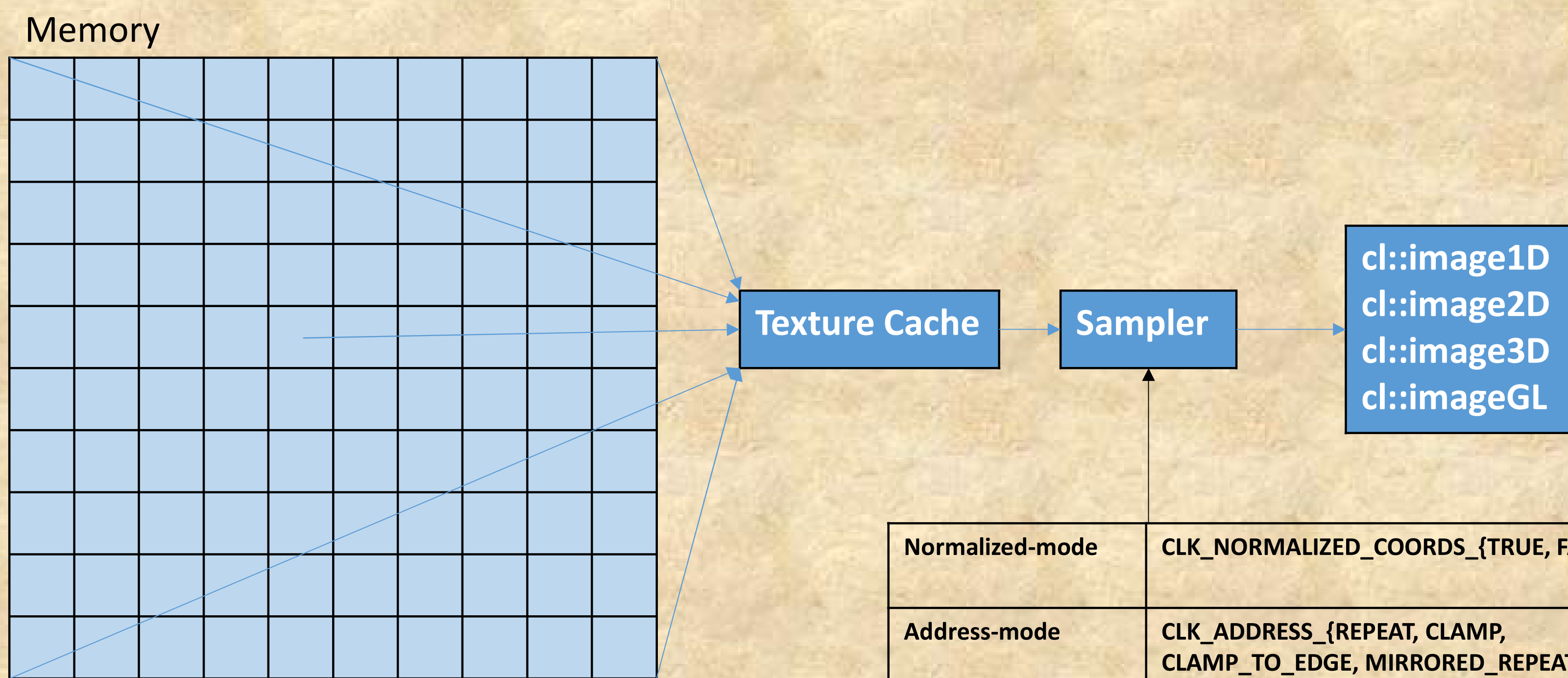
- OpenGL Buffers, Textures can be converted to OpenCL buffers and Images.
  - cl::BufferGL, cl::ImageGL

  - cl::BufferGL buff_gl(ContextCL, CL_MEM_READ_WRITE, glBufferID)
  - cl::ImageGL img_gl(ContextCL, CL_MEM_READ_ONLY, GL_TEXTURE_2D, 0, glTextureID)

  - std::vector<cl::Memory> gl_objs = { buff_gl, img_gl };
  - queueCL.enqueueAcquireGLObjects(&gl_objs)

  …..
  - queueCL.enqueueReleaseGLObjects(&gl_objs);
- For some GPUs (Intel HD graphics) interop works only if OpenGL texture internal format is float32 or float16 (GL_R32F, GL_R16F, GL_RG32F, GL_RGBA32F etc)

  void glTexImage2D(GLenum target, GLint level, GLint internalformat, GLsizei width, GLsizei height, GLint border, GLenum format, GLenum type, const GLvoid * data)



Normalized-mode	CLK_NORMALIZED_COORDS_{TRUE, FALSE}
Address-mode	CLK_ADDRESS_{REPEAT, CLAMP, CLAMP_TO_EDGE, MIRRORED_REPEAT, NONE}
Filter-mode	CLK_FILTER_NEAREST, CLK_FILTER_LINEAR

Coding Example 2:

Color Inversion

DEVICE CODE

```
kernel void invert_color(read_only image2d_t inpImg, write_only image2d_t outImg)
{
    int2 coord = (int2)(get_global_id(0), get_global_id(1));
    float3 idata = read_imagef(inpImg, coord).xyz;
    float4 odata = (float4)(1.0f-idata.x, 1.0f-idata.y, 1.0f-idata.z, 1.0f);
    write_imagef(outImg, coord, odata);
}
```

HOST CODE

```
cl::ImageGL inpImgGL(mCtxtCL, CL_MEM_READ_ONLY, GL_TEXTURE_2D, 0, mBgrImg());
cl::ImageGL outImgGL(mCtxtCL, CL_MEM_WRITE_ONLY, GL_TEXTURE_2D, 0, mInvImg());

std::vector<cl::Memory> gl_objs = { inpImgGL, outImgGL };

cl::Event event;
mKernel.setArg(0, inpImgGL);
mKernel.setArg(1, outImgGL);
mQueueCL.enqueueAcquireGLObjects(&gl_objs);
mQueueCL.enqueueNDRangeKernel(mKernel, cl::NullRange, cl::NDRange(mBgrImg.width(), mBgrImg.height()), cl::NDRange(8, 8), NULL, &event);
event.wait();
mQueueCL.enqueueReleaseGLObjects(&gl_objs);
```

Coding Example 3:

Image Gradient

	MaskX	
-1.0f	+0.0f	+1.0f
-2.0f	+0.0f	+2.0f
-1.0f	+0.0f	+1.0f

	MaskY	
+1.0f	+2.0f	+1.0f
+0.0f	+0.0f	+0.0f
-1.0f	-2.0f	-1.0f

1. Apply MaskX on Every Pixel and Compute Ix
2. Apply MaskY on Every Pixel and Compute Iy
3. I=sqrt((Ix*Ix)+(Iy*Iy))

Summary: Image Gradient

D E V I C E C O D E

```
kernel void gradient(read_only image2d_t inpImg, write_only image2d_t outImg, global const float* pIx, global const float* pIy)
{
   const int x = get_global_id(0);
   const int y = get_global_id(1);
   const sampler_t sampler = CLK_NORMALIZED_COORDS_FALSE|CLK_ADDRESS_CLAMP|CLK_FILTER_LINEAR;

   float ix = 0.0f;
   float iy = 0.0f;
   for (int i = -1; i <= +1; i++)
   {
      for (int j = -1; j <= +1; j++)
      {
         int index = (3*(i+1))+(j+1);
         ix += (pIx[index]*read_imagef(inpImg, sampler, (int2)(x+j, y+i)).x);
         iy += (pIy[index]*read_imagef(inpImg, sampler, (int2)(x+j, y+i)).x);
      }
   }
   float odata = sqrt((ix*ix)+(iy*iy));
   write_imagef(outImg, (int2)(x, y), odata);
}
```

- OpenGL OpenCL interop
- Texture cache (cl::Image)
- Samplers
  - Normalized-mode: CLK_NORMALIZED_COORDS_{TRUE, FALSE}
  - Address-mode: CLK_ADDRESS_{REPEAT, CLAMP, CLAMP_TO_EDGE, MIRRORED_REPEAT, NONE}
  - Filter-mode: CLK_FILTER_NEAREST, CLK_FILTER_LINEAR
- Constant Memory (Accessed through cache)

Coding Example 4:

Canny Edge Detection

1. Apply Gaussian filter to smooth the image in order to remove the noise
2. Find the intensity gradients of the image
3. Apply non-maximum suppression to get rid of spurious response to edge detection
4. Apply double threshold to determine potential edges
5. Finalize the detection of edges by suppressing all the other edges that are weak and not connected to strong edges.

Summary: Canny Edge Detection

- Event wait lists
- Chaining kernel's using Event wait list
- Measuring Kernel Execution time

```
cl::CommandQueue queue(context, devices[0], CL_QUEUE_PROFILING_ENABLE);
…
…

bool kernelExecTime(const cl::CommandQueue& queue, const cl::Event& event, int& time)
{
   cl_command_queue_properties qProp;
   queue.getInfo<cl_command_queue_properties>(CL_QUEUE_PROPERTIES, &qProp);

   if (qProp & CL_QUEUE_PROFILING_ENABLE)
   {
       int start_time = event.getProfilingInfo<CL_PROFILING_COMMAND_START>();
       int end_time = event.getProfilingInfo<CL_PROFILING_COMMAND_END>();
       time = (end_time-start_time);
       return true
   }
   time = 0;
   return false;
}
```

- Barrier
  - All work-items in a work-group executing the kernel on a processor must execute this function before any are allowed to continue execution beyond the barrier. This function must be encountered by all work-items in a work-group executing the kernel.
  - If barrier is inside a conditional statement, then all work-items must enter the conditional if any work-item enters the conditional statement and executes the barrier.
  - If barrier is inside a loop, all work-items must execute the barrier for each iteration of the loop before any are allowed to continue execution beyond the barrier
  - CLK_LOCAL_MEM_FENCE, CLK_GLOBAL_MEM_FENCE.

- Atomic Operations
  - atomic_add, atomic_sub, atomic_xchg, atomic_inc, atomic_dec, atomic_cmpxchg, atomic_min, atomic_max, atomic_and, atomic_or, atomic_xor

Coding Example 5:

Image Histogram computation

```
kernel void init(global int* pHistData)
{
   pHistData[get_global_id(0)] = 0;
}

kernel void histogram(read_only image2d_t inpImg, global int* pHistData)
{
   const int x = get_global_id(0);
   const int y = get_global_id(1);
   int idata = (int)ceil(255.0f*read_imagef(inpImg, (int2)(x, y)).x);
   atomic_inc(&pHistData[idata]);
}
```

How to improve performance?

- Atomic operation on global memory is very slow
- Intermediate Image Histogram using local (shared) memory and atomic ops
- Accumulate the intermediate histograms using atomic addition to global memory

```
kernel void init(global int* pHistData)
{
   pHistData[get_global_id(0)] = 0;
}

kernel void histogram(read_only image2d_t inpImg, global int* pHistData)
{
   local int shHistData[256];
   const int x = get_global_id(0);
   const int y = get_global_id(1);

   int index = (get_local_size(0)*get_local_id(1)) + get_local_id(0);
   if (index < 256) shHistData[index] = 0;
   barrier(CLK_LOCAL_MEM_FENCE);

   int idata = (int)ceil(255.0f*read_imagef(inpImg, (int2)(x, y)).x);
   atomic_inc(&shHistData[idata]);
   barrier(CLK_LOCAL_MEM_FENCE);

   if (index < 256) atomic_add(&pHistData[index], shHistData[index]);
}
```

More performance improvement

- Write the intermediate histogram’s into global memory
- Accumulate the intermediate histogram data using a second kernel
  - Accumulation using Simple addition
  - Accumulation using reduce sum

INTERMEDIATE HISTOGRAM

	Bin: 0	Bin: 1	Bin: 2	…	…	…	…	Bin:254	Bin:255
Block 0:									
	+	+	+	+	+	+	+	+	+
Block 1:									
	+	+	+	+	+	+	+	+	+
	+	+	+	+	+	+	+	+	+
Block N:									
Final Histogram									

- How about Histogram without atomics ??? [Exercise]

Parallel Processing Patterns (Building Blocks)

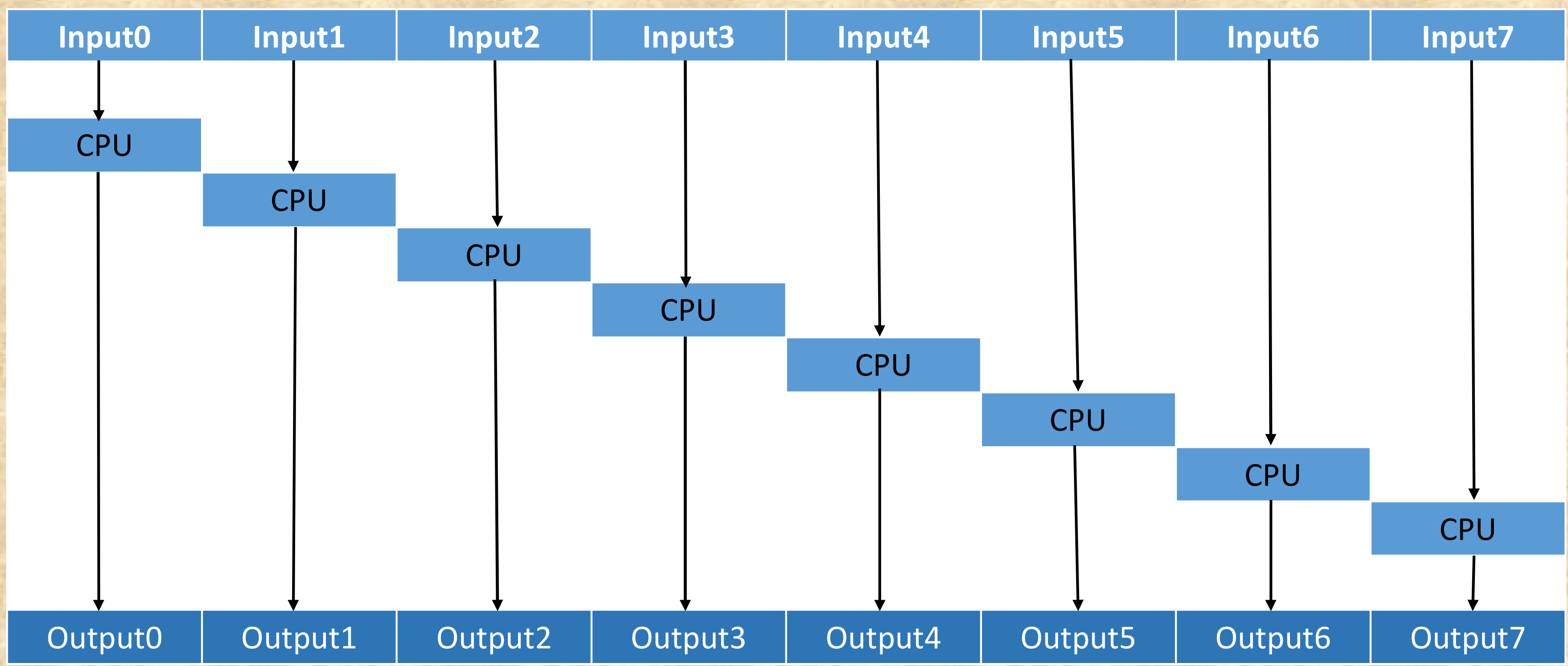
- Map
- Stencil
- Gather
- Scatter
- Reduction (Eg:- sum, min, max etc)
- Scan
  - Inclusive Sum (Prefix Sum)
  - Exclusive Sum
- Stream Compaction
- Histogram

Map

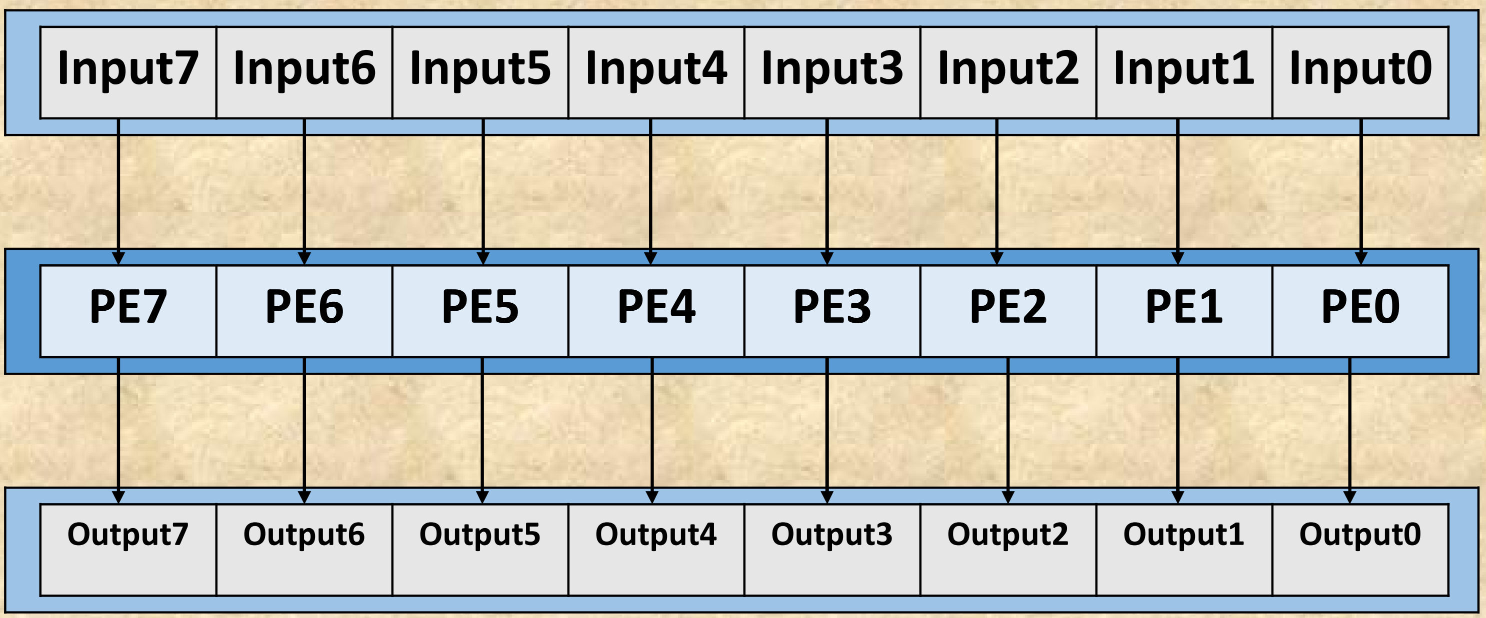
- In the map pattern a function, which we call an elemental function, is applied to different data.

Ex:- vector addition, color inversion, image gradient

Map (Serial)


Input0
Input1
Input2
Input3
Input4
Input5
Input6
Input7
CPU
CPU
CPU
CPU
CPU
CPU
CPU
CPU
Output0
Output1
Output2
Output3
Output4
Output5
Output6
Output7

Map (Parallel)



- Gather
  - Given a collection of locations (addresses or array indices) and a source array, gather collects all the data from the source array at the given locations and places them into an output collection.

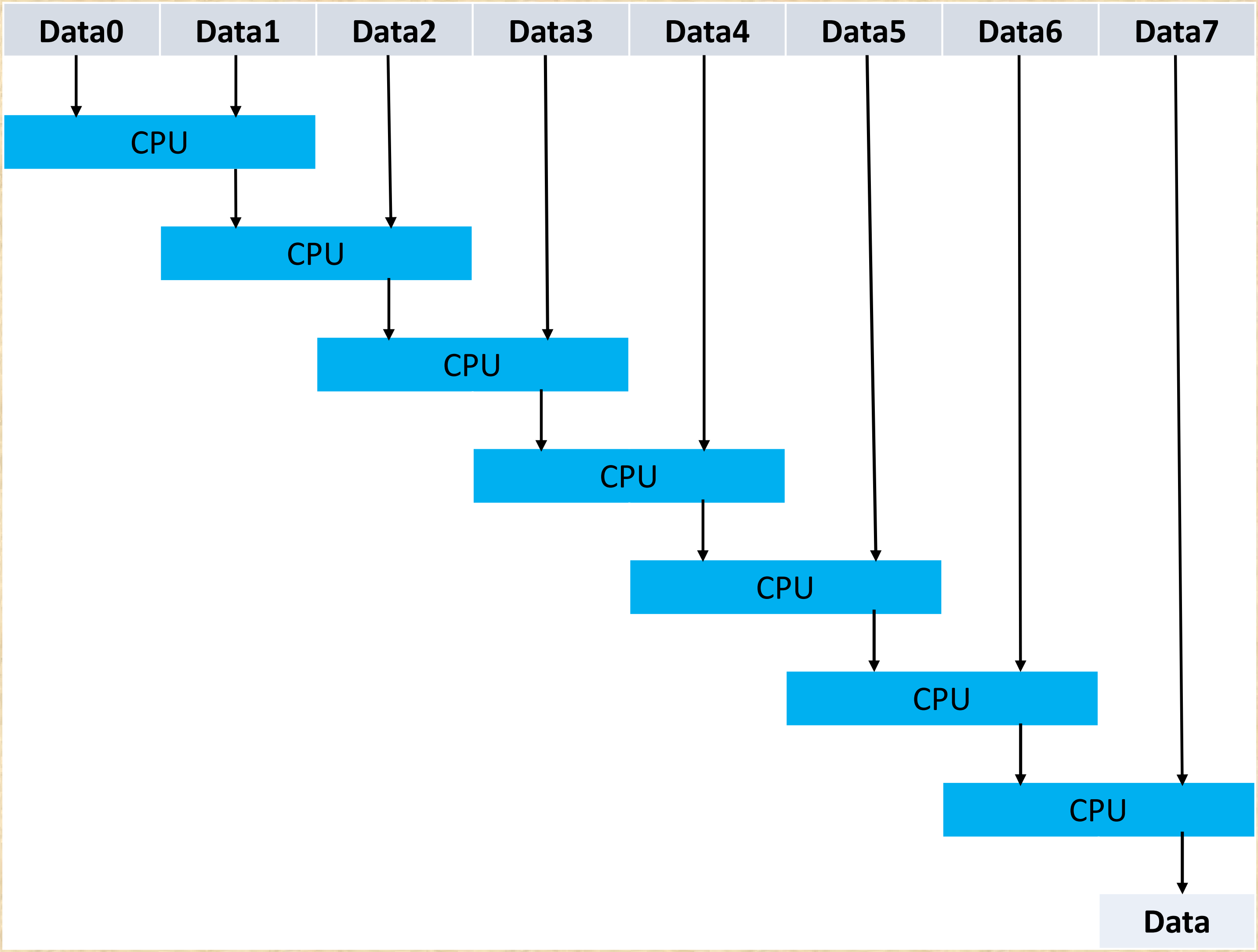
- Scatter
  - Scatter is similar to gather, but write locations rather than read locations are provided as input.

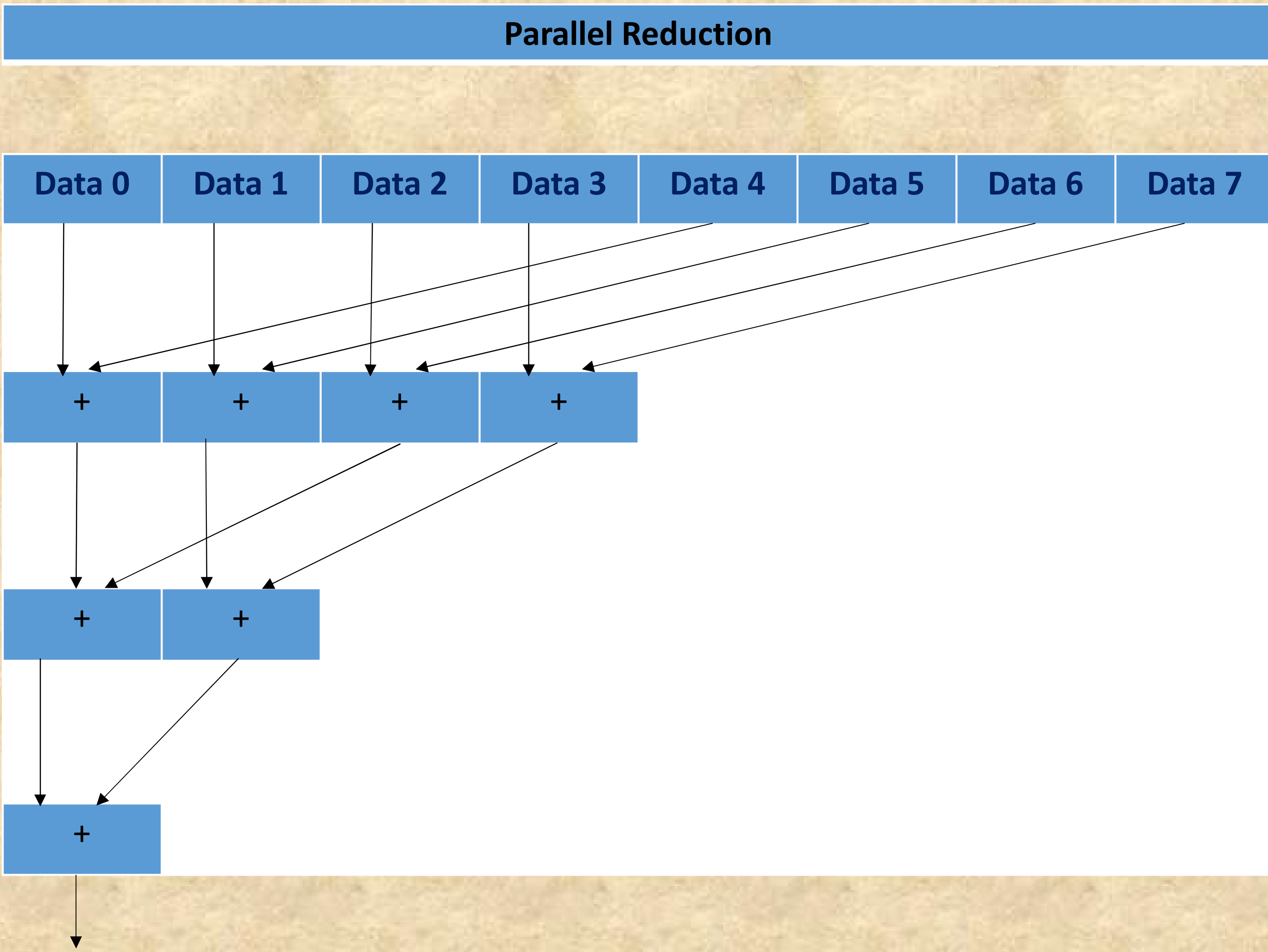
Reduce

The reduce pattern allows data to be summarized; it combines all the elements in a collection into a single element using some associative combiner operator.

Ex:- min, max, sum, etc

Serial Reduction




Parallel Reduction
Data 0
Data 1
Data 2
Data 3
Data 4
Data 5
Data 6
Data 7
+
+
+
+
+
+
+

Parallel Reduction (Sum)

Index	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
Data	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	**Initial Data in shared Memory**
Step 1									10	12	14	16	18	20	22	24	If (id < 8) data[id] += data[id+8]
Step 2													28	32	36	40	If (id < 4) data[id] += data[id+4]
Step 3															64	72	If (id < 2) data[id] += data[id+2]
Step 4																136	If (id < 1) data[id] += data[id+1]

Block(workgroup) Reduction

Load the Elements into shared memory. For example if the Block contains 256 work items, Bring 512 data items into shared memory and do the reduction as described in the next block.

```
int bSize = get_local_size(0);
int i = get_local_id(0);
While (bSize > 0)
{
    if (i < bSize) data[i] += data[bSize+i];
    barrier(CLK_LOCAL_MEM_FENCE);
    bSize /= 2;
}
```

Coding Example 6:

Reduce Sum

DEVICE CODE

```
kernel void reduceSum(global const int* pInput, global int* pOutput, const int count)
{
   local int shData[SH_MEM_SIZE];
   int i = get_local_id(0);
   int id = (SH_MEM_SIZE*get_group_id(0))+i;
   shData[i] = (id < count)?pInput[id]:0;
   i += get_local_size(0);
   id += get_local_size(0);
   shData[i] = (id < count)?pInput[id]:0;
   barrier(CLK_LOCAL_MEM_FENCE);
   breduce_sum(shData);
   if (get_local_id(0) == 0) pOutput[get_group_id(0)] = shData[0];
}
```

```
inline void breduce_sum(local volatile int* shData)
{
   int bSize = get_local_size(0);
   while (bSize > 0)
   {
      int i = get_local_id(0);
      if (i < bSize) shData[i] += shData[bSize+i];
      barrier(CLK_LOCAL_MEM_FENCE);
      bSize /= 2;
   }
}
```

HOST CODE

```
size_t count = 1000000;
size_t gSize = count/256;
if ((count % 256)) ++gSize;

cl::Buffer buffInp(context, CL_MEM_READ_ONLY, count*sizeof(cl_int));
cl::Buffer buffOut(context, CL_MEM_READ_WRITE, gSize*sizeof(cl_int));
....
reduce.setArg(0, buffInp);
reduce.setArg(1, buffOut);
reduce.setArg(2, (int)count);
queue.enqueueNDRangeKernel(reduce, cl::NullRange, cl::NDRange(256*gSize), cl::NDRange(128), NULL, &events[evtCount]);

while (gSize > 1)
{
      reduce.setArg(0, buffOut);
      reduce.setArg(1, buffOut);
      reduce.setArg(2, (int)gSize);
      wEvents[wEvtCount].push_back(events[evtCount++]);
      size_t ngSize = (gSize/256)+(((gSize%256)!=0)?1:0);
      queue.enqueueNDRangeKernel(reduce, cl::NullRange, cl::NDRange(ngSize*256), cl::NDRange(128), &wEvents[wEvtCount++], &events[evtCount]);
      gSize = ngSize;
}
events[evtCount].wait();
```

Optimized Reduce Sum

```
inline void breduce_sum(local volatile int* sh_data)
{
   if (get_local_id(0) < 256) sh_data[get_local_id(0)] += sh_data[256+get_local_id(0)];
   barrier(CLK_LOCAL_MEM_FENCE);

   if (get_local_id(0) < 128) sh_data[get_local_id(0)] += sh_data[128+get_local_id(0)];
   barrier(CLK_LOCAL_MEM_FENCE);

   if (get_local_id(0) < 64) sh_data[get_local_id(0)] += sh_data[64+get_local_id(0)];
   barrier(CLK_LOCAL_MEM_FENCE);

   if (get_local_id(0) < 32) sh_data[get_local_id(0)] += sh_data[32 + get_local_id(0)];
   if (get_local_id(0) < 16) sh_data[get_local_id(0)] += sh_data[16 + get_local_id(0)];
   if (get_local_id(0) < 8) sh_data[get_local_id(0)] += sh_data[8 + get_local_id(0)];
   if (get_local_id(0) < 4) sh_data[get_local_id(0)] += sh_data[4 + get_local_id(0)];
   if (get_local_id(0) < 2) sh_data[get_local_id(0)] += sh_data[2 + get_local_id(0)];
   if (get_local_id(0) < 1) sh_data[get_local_id(0)] += sh_data[1 + get_local_id(0)];
   barrier(CLK_LOCAL_MEM_FENCE);
}
```

No need to place barrier instruction within WARP

Scan

- The scan collective operation produces all partial reductions of an input sequence, resulting in a new output sequence. There are two variants: inclusive scan and exclusive scan. For inclusive scan, the nth output value is a reduction over the first n input values. For exclusive scan, the nth output value is a reduction over the first n-1 input values.

Prefix Sum

- The prefix sum, scan, or cumulative sum of a sequence of numbers x_0, x_1, x_2, ... is a second sequence of numbers y_0, y_1, y_2, ..., the sums of prefixes of the input sequence: $y_0 = x_0$ $y_1 = x_0 + x_1$ $y_2 = x_0 + x_1 + x_2$ ...

Input	1	2	3	4	5	6	7	8
Prefix Sum(Inclusive Sum)	1	3	6	10	15	21	28	36

Input	1	2	3	4	5	6	7	8
Exclusive Sum	0	1	3	6	10	15	21	28

Prefix Sum

ID	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
Data	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Step 1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2		if (id >= 1) data[id] += data[id-1]
Step 2	4	4	4	4	4	4	4	4	4	4	4	4	4	3	2		if (id >= 2) data[id] += data[id-2]
Step 3	8	8	8	8	8	8	8	8	8	7	6	5					if (id >= 4) data[id] += data[id-4]
Step 4	16	15	14	13	12	11	10	9									if (id >= 8) data[id] += data[id-8]

```
inline void bscan(local volatile int* shData)
{
    int level = 1;
    const int id = get_local_id(0);
    while (level < SH_MEM_SIZE)
    {
        if (id >= level) shData[id] += shData[id-level];
        barrier(CLK_LOCAL_MEM_FENCE);
        level *= 2;
    }
}
```

Not very GPU friendly. Suffers from bank conflict issues

Efficient Prefix Sum on a GPU workgroup

SIMD7	SIMD6	SIMD5	SIMD4	SIMD3	SIMD2	SIMD1	SIMD0
PE (255-224)	PE (223-192)	PE (191-160)	PE (159-128)	PE (127-96)	PE (95-64)	PE (63-32)	PE (31-0)

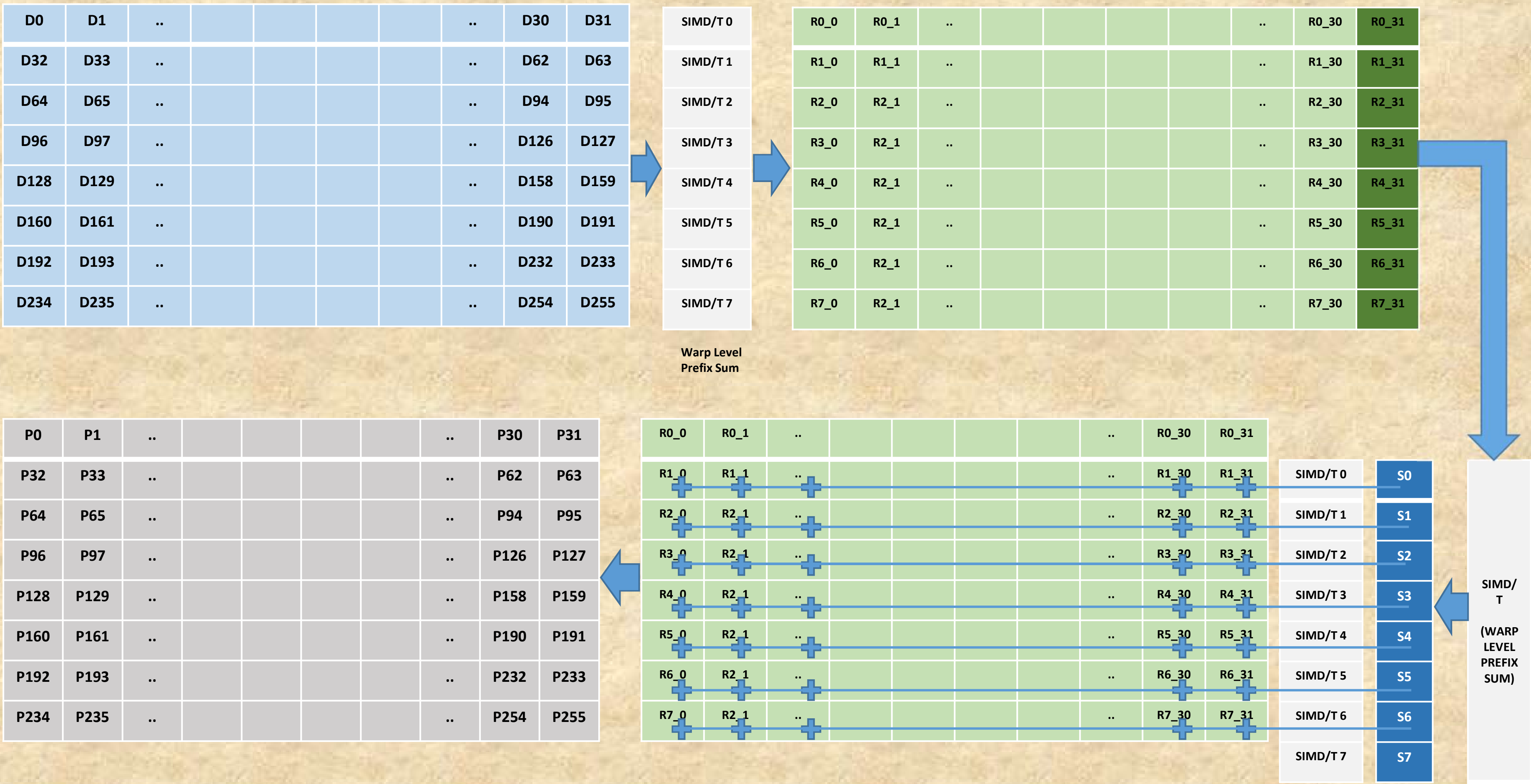
For most of the GPUs the workgroup contains eight 32-wide SIMD processors. (Nvidia uses the term WARP to denote these SIMD processors, AMD calls them WAVEFRONT).

Follow the below steps for doing a block scan (Data is available in shared memory)

1. **Perform Eight WARP/WAVEFRONT/32 wide prefix sum on the shared Memory (WARP wide sum). Eight 32-wide prefix sums are available in memory.**
2. **Grab the 31st, 63rd, 95th, 127th, 159th, 191th, 223rd and 255th elements and place them in shared memory variable**

255th(7th)	223rd(6th)	191th(5th)	159th(4th)	127th(3rd)	95th(2nd)	63rd(1st)	31st (0)

3. **Do a warp prefix sum on the above shared memory variable**
4. **Add the above elements WARP wide on the WARP wide sum (add 0th element to elements 63-32, add 1st elements 95-64, add 2nd element to elements 127-96, add 3rd element to elements 159-128, add 4th element to elements 191-160, add 5th element to elements 223-192 and 6th element to elements 255-224)**



D0 D1 .. .. D30 D31
D32 D33 .. .. D62 D63
D64 D65 .. .. D94 D95
D96 D97 .. .. D126 D127
D128 D129 .. .. D158 D159
D160 D161 .. .. D190 D191
D192 D193 .. .. D232 D233
D234 D235 .. .. D254 D255
SIMD/T 0
SIMD/T 1
SIMD/T 2
SIMD/T 3
SIMD/T 4
SIMD/T 5
SIMD/T 6
SIMD/T 7
Warp Level
Prefix Sum
R0_0 R0_1 .. .. R0_30 R0_31
R1_0 R1_1 .. .. R1_30 R1_31
R2_0 R2_1 .. .. R2_30 R2_31
R3_0 R2_1 .. .. R3_30 R3_31
R4_0 R2_1 .. .. R4_30 R4_31
R5_0 R2_1 .. .. R5_30 R5_31
R6_0 R2_1 .. .. R6_30 R6_31
R7_0 R2_1 .. .. R7_30 R7_31
SIMD/
T
(WARP
LEVEL
PREFIX
SUM)
S0 S1 S2 S3 S4 S5 S6 S7
SIMD/T 0
SIMD/T 1
SIMD/T 2
SIMD/T 3
SIMD/T 4
SIMD/T 5
SIMD/T 6
SIMD/T 7
R0_0 R0_1 .. .. R0_30 R0_31
R1_0 R1_1 .. .. R1_30 R1_31
R2_0 R2_1 .. .. R2_30 R2_31
R3_0 R2_1 .. .. R3_30 R3_31
R4_0 R2_1 .. .. R4_30 R4_31
R5_0 R2_1 .. .. R5_30 R5_31
R6_0 R2_1 .. .. R6_30 R6_31
R7_0 R2_1 .. .. R7_30 R7_31
P0 P1 .. .. P30 P31
P32 P33 .. .. P62 P63
P64 P65 .. .. P94 P95
P96 P97 .. .. P126 P127
P128 P129 .. .. P158 P159
P160 P161 .. .. P190 P191
P192 P193 .. .. P232 P233
P234 P235 .. .. P254 P255

Coding Example 7:
Prefix Sum

```
inline void wscan(int i, local volatile int* sh_data)
{
   const int wid = i&(WARP_SIZE-1);
   if (wid >= 1) sh_data[i] += sh_data[i-1];
   if (wid >= 2) sh_data[i] += sh_data[i-2];
   if (wid >= 4) sh_data[i] += sh_data[i-4];
   if (wid >= 8) sh_data[i] += sh_data[i-8];
   if (WARP_SIZE == 32)
   {
      if (wid >= 16) sh_data[i] += sh_data[i-16];
   }
}

inline void bscan(int i, local volatile int* shData, local volatile int* shDataT)
{
   wscan(i, shData);
   barrier(CLK_LOCAL_MEM_FENCE);

   if (i < (SH_MEM_SIZE/WARP_SIZE)) shDataT[i] = shData[(WARP_SIZE*i)+(WARP_SIZE-1)];
   barrier(CLK_LOCAL_MEM_FENCE);

   if (i < WARP_SIZE) wscan(i, shDataT);
   barrier(CLK_LOCAL_MEM_FENCE);

   if (i >= WARP_SIZE) shData[i] += shDataT[(i/WARP_SIZE)-1];
   barrier(CLK_LOCAL_MEM_FENCE);
}

kernel void scan(global const int* pInput, global int* pOutput, const int count)
{
   local int shData[SH_MEM_SIZE+WARP_SIZE];
   int i = get_local_id(0);
   int id = get_global_id(0);
   shData[i] = (id < count)?pInput[id]:0;
   bscan(i, shData, &shData[SH_MEM_SIZE]);
   if (id < count) pOutput[id] = shData[i];
}
```

```
kernel void gather(global const int* pInput, global int* pOutput, const int start, const int count)
{
   local int shData[SH_MEM_SIZE+WARP_SIZE];
   int i = get_local_id(0);
   int id = start+(get_local_size(0)*get_local_id(0));
   shData[i] = (id < count)?pInput[id]:0;
   bscan(i, shData, &shData[SH_MEM_SIZE]);
   pOutput[i] = shData[i];
}

kernel void add(global const int* pInput, global int* pOutput, const int start, const int count)
{
   local int shData;
   if (get_local_id(0) == 0) shData = pInput[get_group_id(0)];
   barrier(CLK_LOCAL_MEM_FENCE);
   const int id = start+get_global_id(0);
   if (id < count) pOutput[id] += shData;
}
```

Prefix Sum on a binary (0 or 1) sequence

ID	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Input	0	0	0	0	1	0	1	0	0	0	0	1	0	0	0	1	0	0	1	0
Inc. Sum	0	0	0	0	1	1	2	2	2	2	2	3	3	3	3	4	4	4	5	5
Ex. Sum	0	0	0	0	0	0	1	1	1	1	1	2	2	2	2	3	3	3	4	4

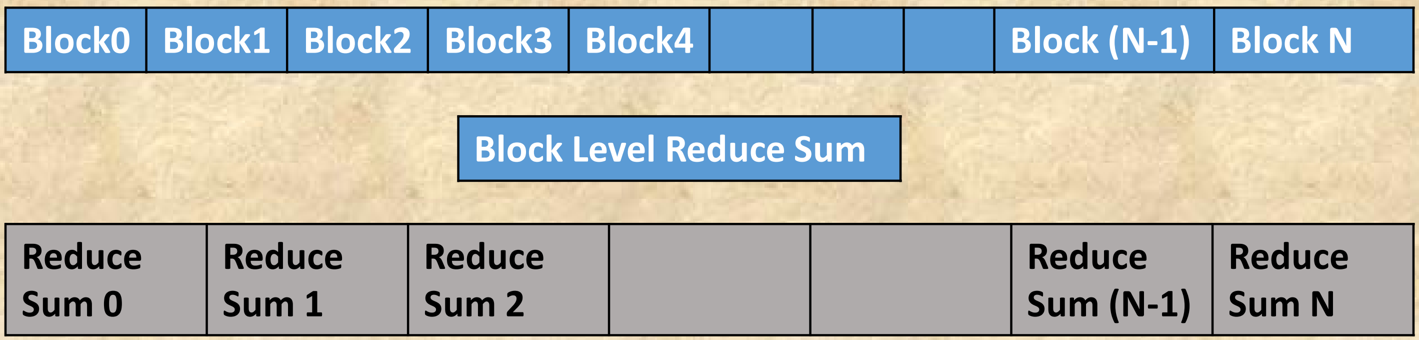
Exclusive Sum	Inclusive Sum	Index's with 1's
0	1	4
1	2	6
2	3	11
3	4	15
4	5	18

Prefix Sum Applications

- Stream Compaction
- Radix-sort
- Parallel Quick-sort
- Integral Image
- Polynomial Evaluation
- Histogram
- Lexical Analysis
- Solving recurrences

Faster Stream Compaction

1. Do block level reduce sum's on the input and store the outputs on global memory.



1. Do an Exclusive Prefix Sum on the block level reduce sum's
2. Add the results in Step2 block wise to all elements in the block. (add the value at index 0 to all elements in block 0, add the value at index 1 to all elements in block1, add the value at index N to all elements in blockN)

Coding Example 8:

Harris Corner Detection

1. Compute Ix (gradient x) and Iy (gradient y) at every pixel
2. Compute the product of derivative at every pixel
    1. **Ix2 = Ix*Ix**
    2. **Iy2 = Iy*Iy**
    3. **Ixy =Ix*Iy**
3. Apply Gaussian smoothing on Ix2, Iy2, Ixy and compute G_Ix2, G_Iy2, and G_Ixy
4. Define at each pixel Matrix H

G_Ix2	**G_Ixy**
G_Ixy	**G_Iy2**

5. Calculate R = det(H)-k*trace(H)*trace(H)
6. Threshold on value of R and due non max suppression
7. Do stream compaction

OpenCL 2.0

- Dynamic parallelism (Nested parallelism)
  - Device side kernels capable of launching other kernels
- Built-in work group functions
  - Scan (Inclusive, Exclusive)
  - Reduce (Min, Max, Sum etc)
- Shared virtual memory
  - Map Free access
  - Fine Grained Coherent access
  - Fine Grained Synchronization
  - Complex Data structures with Pointers (eg:- BTree, Graphs etc)

```
cl::Context context(CL_DEVICE_TYPE_GPU);
std::vector<cl::Device> devices = context.getInfo<CL_CONTEXT_DEVICES>();
cl::CommandQueue queue(context, devices[0], CL_QUEUE_PROFILING_ENABLE);

cl_queue_properties qprop[] = { CL_QUEUE_PROPERTIES,
(cl_command_queue_properties)(CL_QUEUE_OUT_OF_ORDER_EXEC_MODE_ENABLE|CL_QUEUE_ON_DEVICE|
CL_QUEUE_ON_DEVICE_DEFAULT|CL_QUEUE_PROFILING_ENABLE), 0 };

int err = 0;
cl_command_queue dev_q = clCreateCommandQueueWithProperties(context(), devices[0](), qprop, &err);


    …..
    …..

std::ostringstream options;
options << "-cl-std=CL2.0";

cl::Program program(context, sSource);
program.build(options.str().c_str());
```

Coding Example 9:

Prefix Sum using OpenCL 2.0

```
kernel void scan(global int* pdata, global int* tempData, int count)
{
   clk_event_t event1;
   clk_event_t event2;
   int ncount = count/4;
   int ncount4 = ncount*4;
   int gcount = ((ncount/BLK_SIZE)+(((ncount%
   const int BLK_SIZE = 256;
   const int BLK_SIZE2 = (BLK_SIZE*BLK_SIZE); BLK_SIZE) == 0)?0:1))*BLK_SIZE;

   enqueue_kernel(get_default_queue(), CLK_ENQUEUE_FLAGS_NO_WAIT,
          ndrange_1D(gcount, BLK_SIZE), 0, 0, &event1, ^{ child_scan(pdata, ncount); });

   for (int i = (4*BLK_SIZE); i < ncount4; i += (16*BLK_SIZE2))
   {
      enqueue_kernel(get_default_queue(), CLK_ENQUEUE_FLAGS_NO_WAIT, ndrange_1D(BLK_SIZE, BLK_SIZE), 1,
            &event1, &event2, ^{ gather_scan(pdata, tempData, i, ncount4); });
      enqueue_kernel(get_default_queue(), CLK_ENQUEUE_FLAGS_NO_WAIT, ndrange_1D((4*BLK_SIZE2), BLK_SIZE), 1,
            &event2, &event1, ^{ add_data(pdata, tempData, i, ncount); });
   }
   enqueue_kernel(get_default_queue(), CLK_ENQUEUE_FLAGS_NO_WAIT, ndrange_1D(1, 1), 1,
          &event1, &event2, ^{ add_remainders(&pdata[ncount4], count%4); });
   release_event(event2);
}
```

Coding Example 10:

Harris Corner Detection using OpenCL 2.0

Radix Sort

Input Data

Data	Binary
6	0110
13	1101
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001

Re-ordering based on bit position 0 (Stream compaction with the mask b'0001)

Data	Binary
6	0110
2	0010
4	0100
6	0110
8	1000
13	1101
3	0011
5	0101
7	0111
9	1001

Re-ordering based on bit position 1 (Stream compaction with the mask b'0010)

Data	Binary
4	0100
8	1000
13	1101
5	0101
9	1001
6	0110
2	0010
6	0110
3	0011
7	0111

Re-ordering based on bit position 2 (Stream compaction with the mask b'0100)

Data	Binary
8	1000
9	1001
2	0010
3	0011
4	0100
13	1101
5	0101
6	0110
6	0110
7	0111

Re-ordering based on bit position 3 (Stream compaction with the mask b'1000)

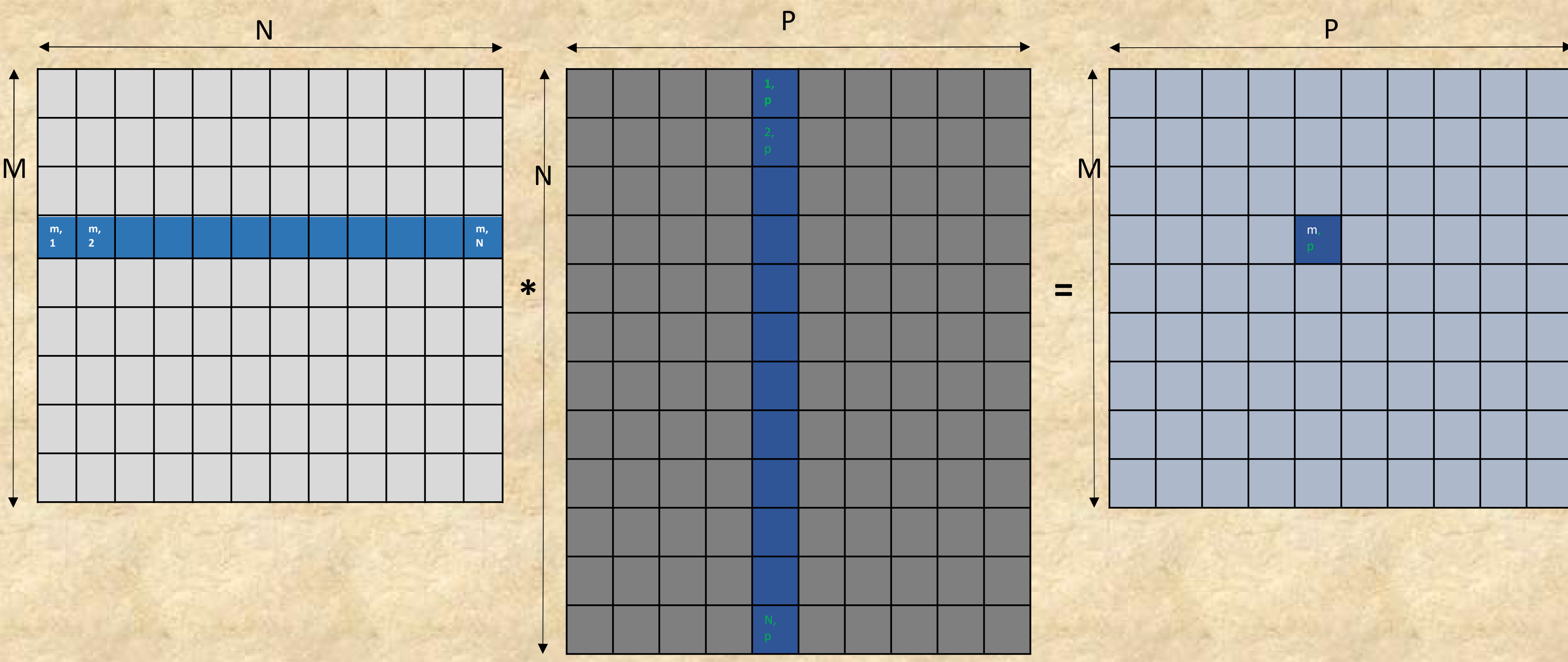
Data	Binary
2	0010
3	0011
4	0100
5	0101
6	0110
6	0110
7	0111
8	1000
9	1001
13	1101

Coding Example 11:

Radix Sort

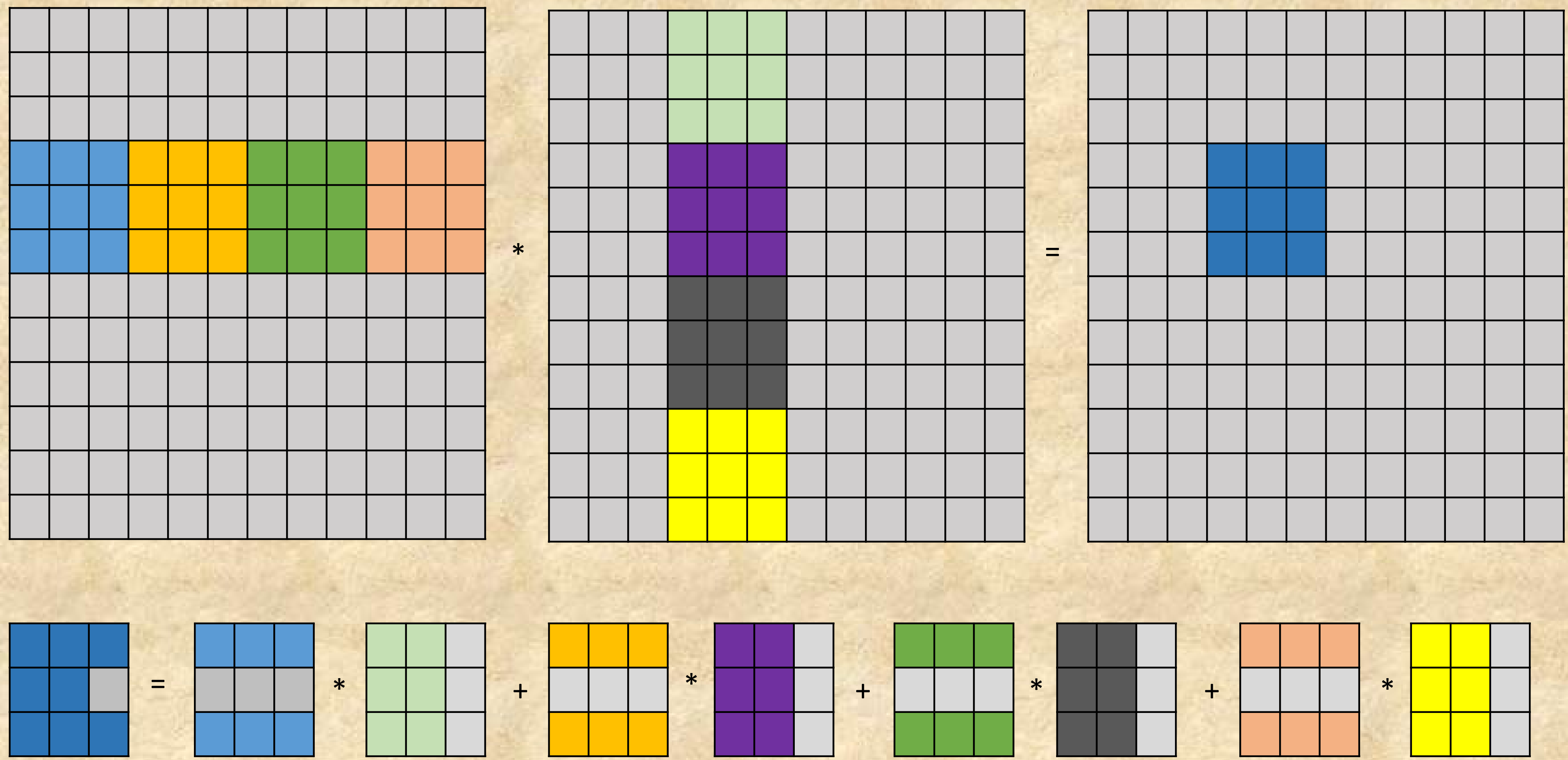
```
kernel void radix_sort(global int* p_in_data, global int* p_temp_data, int count)
{
   clk_event_t event[4];
   const int BLK_SIZE = 256;
   int size = 4+(count/256);
   int temp_buff_size = 1024*((size/1024)+((size%1024)==0?0:1));

   global int* p_odd_blk_count = p_temp_data + temp_buff_size;
   global int* p_even_blk_count = p_odd_blk_count + size;
   global int* p_out_data = p_even_blk_count + size;

   unsigned int mask = 0x0001;
   for (int i = 0; mask != 0; i++)
   {
      global int* p_input_data = ((i%2) == 0)?p_in_data:p_out_data;
      global int* p_output_data = ((i%2) == 0)?p_out_data:p_in_data;

      enqueue_kernel(get_default_queue(), CLK_ENQUEUE_FLAGS_NO_WAIT, ndrange_1D(count, BLK_SIZE), (i==0)?0:1,
                                 (i==0)?0:&event[3], &event[0], ^{ block_even_odd_count(p_input_data, mask, p_even_blk_count, p_odd_blk_count); });
      enqueue_kernel(get_default_queue(), CLK_ENQUEUE_FLAGS_NO_WAIT, ndrange_1D(1, 1), 1,
                                 &event[0], &event[1], ^{ scan(p_even_blk_count, p_temp_data, size); });
      enqueue_kernel(get_default_queue(), CLK_ENQUEUE_FLAGS_NO_WAIT, ndrange_1D(1, 1), 1,
                                 &event[0], &event[2], ^{ scan(p_odd_blk_count, p_temp_data, size); });
      enqueue_kernel(get_default_queue(), CLK_ENQUEUE_FLAGS_NO_WAIT, ndrange_1D(count, BLK_SIZE), 2,
                                 &event[1], &event[3], ^{ compact(p_input_data, mask, p_even_blk_count, p_odd_blk_count, p_output_data); });
      mask = mask << 1;
   }
   release_event(event[3]);
}
```

Matrix Multiplication



```
kernel void multiply(global float* pMatC, global const float* pMatA, global const float* pMatB, int M, int N, int P)
{
   int m = get_global_id(0);
   int p = get_global_id(1);
   float result = 0.0;
   for (int n = 0; n < N; n++)
   {
       result += (pMatA[(m*N)+n]*pMatB[(n*P)+p]);
   }
   pMatC[(P*m)+p] = result;
}
```

- Too much global memory access
- Is it possible to reduce the global memory acces?



Coding Example 12:

Matrix Multiplication

```
kernel void multiply(global float* pMatC, global const float* pMatA, global const float* pMatB, int M, int N, int P)
{
   local float shA[16][16];
   local float shB[16][16];

   int m = get_global_id(0);
   int p = get_global_id(1);
   int pc = (get_group_id(1)<<4)+get_local_id(0);

   float result = 0.0;
   for (int n = get_local_id(1); n < N; n += 16)
   {
      shA[get_local_id(0)][get_local_id(1)] = pMatA[(N*m)+n];
      shB[get_local_id(0)][get_local_id(1)] = pMatB[(P*n)+pc];
      barrier(CLK_LOCAL_MEM_FENCE);

      for (int i = 0; i < 16; i++)
      {
         result += (shA[get_local_id(0)][i]*shB[get_local_id(1)][i]);
      }
      barrier(CLK_LOCAL_MEM_FENCE);
   }

   pMatC[(P*m)+p] = result;
}
```

Optimization tips

- Algorithm (Parallelization ?)
- Memory
    - Cached access
    - Use of local memory
    - Bandwidth
- Parallel patterns
- Inline assembly ???
    - Many different GPU architectures (Nvidia, AMD, Intel, ARM, Qualcomm, Imagination)
    - Instruction set open for Nvidia and AMD

Debugging

- Intel OpenCL SDK
  - Breakpoints (Remote)
  - Single stepping (Remote)
  - Profiling
- Nvidia Nsight
  - Profiling support for OpenCL
  - Breakpoints (Only for CUDA apps)
  - Single stepping (Only for CUDA apps)
- Visual Studio supports OpenCL CPU device debugging

CUDA, OpenCL, Metal

Nvidia Cuda	OpenCL	Apple Metal
- Proprietary Framework (Only Nvidia GPUs)	+ Open (Available on most of the Platforms) OpenCL 1.2 is supported by Intel, AMD, Nvidia GPUs	- Proprietary Framework (Only on Apple Platforms)
+ Supports C++ (Templates are very useful)	- Supports only C (C++ support available in OpenCL 2.1)	+ Supports C++
+ CUDA preprocessor (Allows mixing of device and host code)	- No preprocessor	
+ CUDA compiler optimizations much better	- Not as good as CUDA	
+ Lots of optimized 3rd party libraries available	- Not as good as CUDA	
+ Excellent tools for debugging, profiling etc.	- Not good	

Reference

- Books
  - OpenCL Programming Guide [Aftab Munshi, Benedict R. Gaster etc]
  - Structured Parallel Programming Patterns for Efficient Computation [Michael McCool, Arch D.Robinson, James Reinders]
  - The CUDA Handbook [Nicholas Wilt]
  - GPGPU Gems [Nvidia]

- Useful Libraries
  - Boost compute
  - clBLAS
  - Intel clDNN (Neural Network inference)

Exercise

1. Compute and display RGB histogram for a real time camera feed?
    a) with atomics
    b) without atomics
    c) Analyze the impact of bin size on a and b

   Compare the performance of both options.

THANK YOU