# GPU Compute on Mobile Devices

Tim Hartley

Jon Kirkham

# Agenda

- Introduction
- Mali-T600 Compute Overview
- Optimal OpenCL for Mali-T600
- OpenCL Optimization Case Study

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- Introduction
  - Heterogeneous Computing
  - Compute API's
  - Thinking in Parallel
  - OpenCL
  - RenderScript
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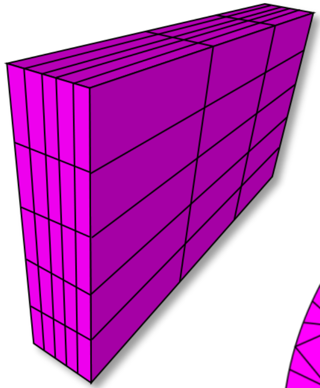
# Heterogeneous Computing

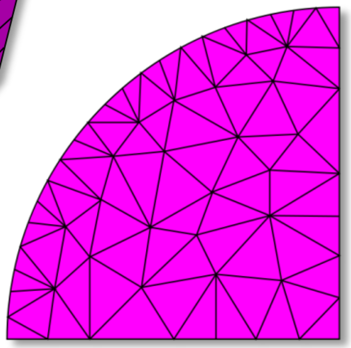
**Using a variety of different types of computational units…**

- **Usually a CPU and one or more units for specialist computation**
- **Most common example combines a CPU with the compute capabilities of a GPU**
  - CPU best for general purpose program flow
  - GPU best for highly-parallel algorithms on large arrays of data
- **Requires different programming models and tools**
  - API's required to pass data and control to specialised processors
  - Parallel programming requires a new way of thinking

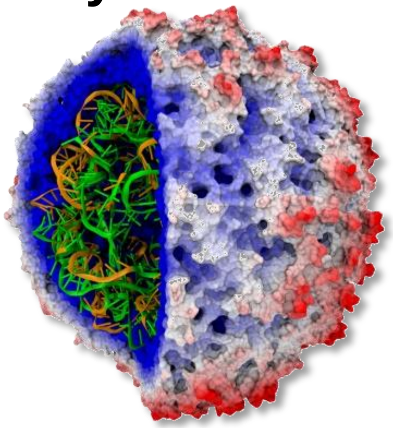
# GPGPU… What is it Good For? (1)

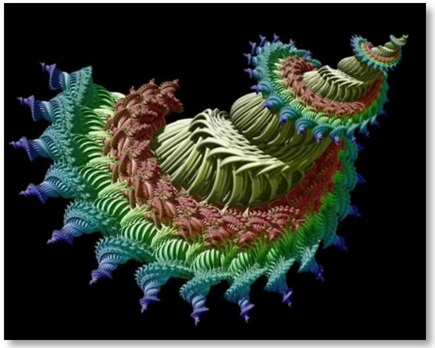
- **Scientific community has pioneered the use of GPU's for general purpose compute**
  - GPU's highly efficient for structured grid, dense linear algebra, particle methods
  - Also promising for unstructured grids, sparse linear algebra, spectral methods





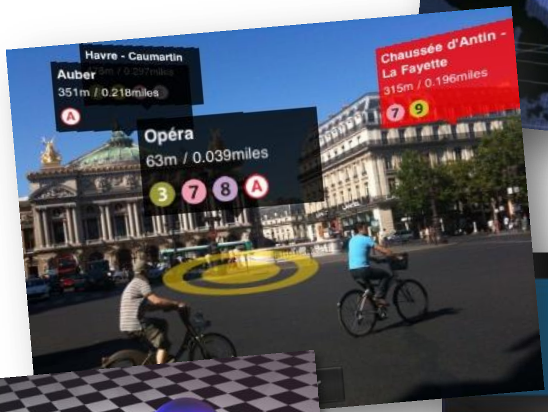
- **As such, mobile computing is likely to benefit from…**
  - Image processing
  - Speech processing
  - Artificial intelligence
  - Games
  - Music

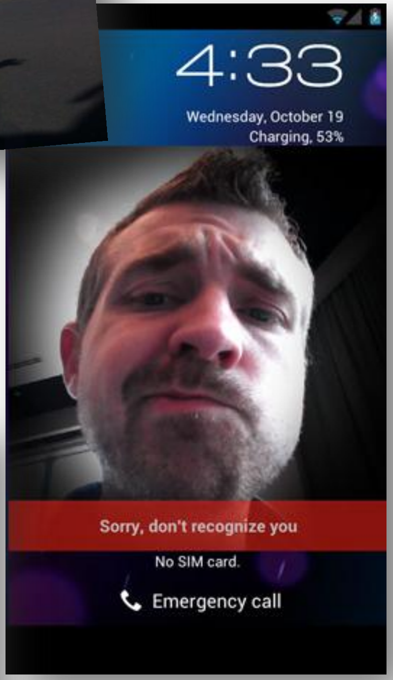


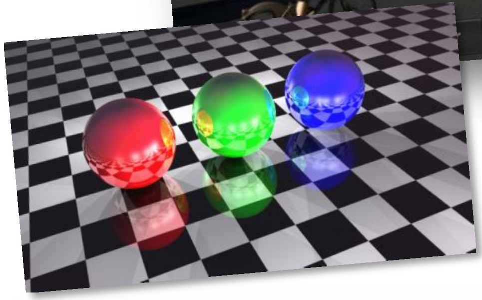


# GPGPU… What is it Good For? (2)

- **Consumer entertainment**
  - HQ graphics (e.g. photorealistic ray tracing, custom render pipelines etc.)
  - Intelligent “artificial intelligence” (at last <u>really</u> smart opponents)
  - Novel UI (e.g. gesture, speech, eye controlled)
  - 3D spatialisation of sound effects
- **Advanced image processing**
  - Computational photography (e.g. region based focussing)
  - High dynamic range (HDR) photography
  - Augmented reality (e.g. head-up navigation)
  - Computer vision
  - Eye tracking



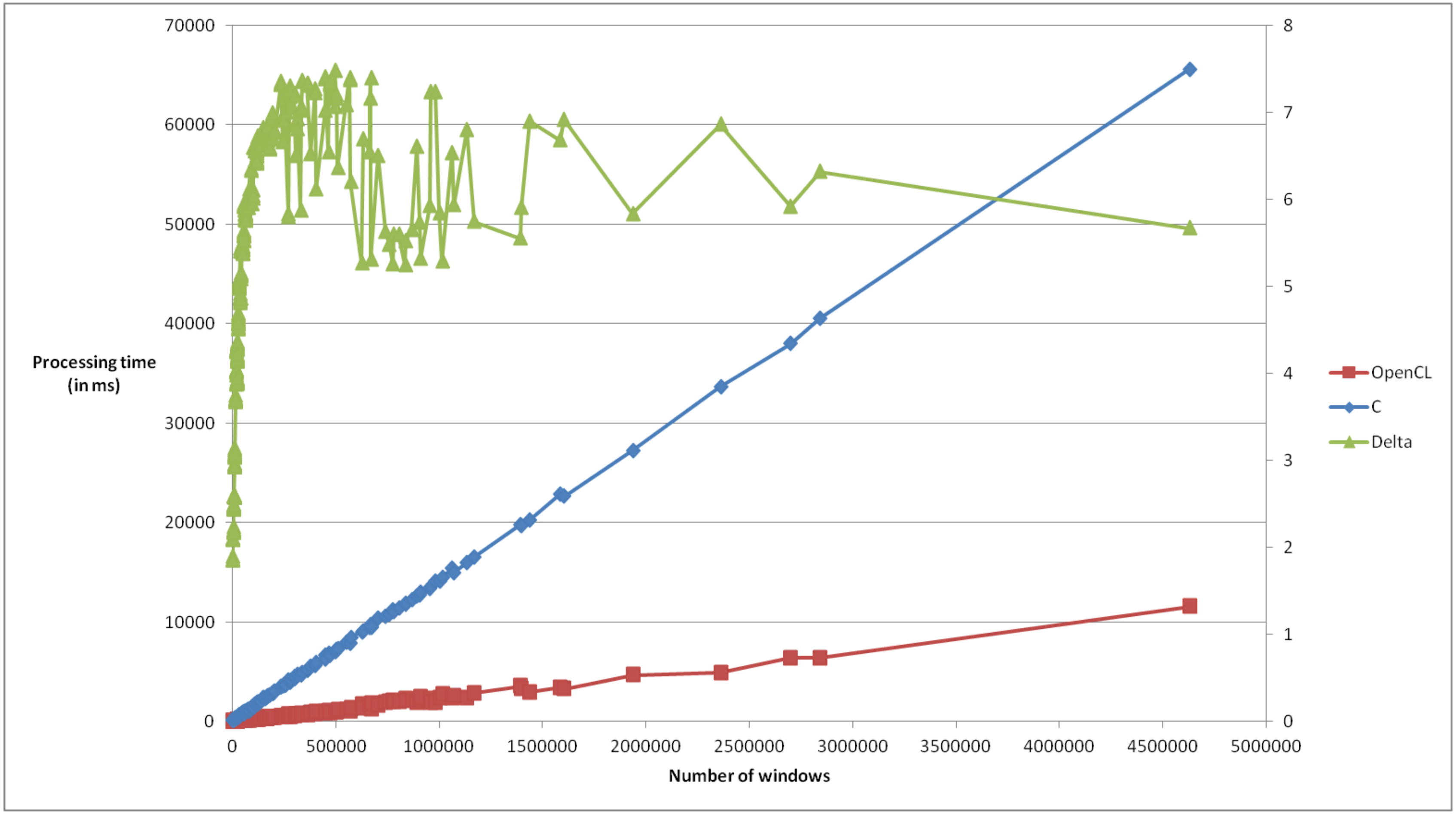
# Physics Demo

- Spring model with 6,000 vertices

- OpenCL version:
  - 8x times faster and twice the number of vertices
  - Single digit CPU load
- Multithreaded C version:
  - 100% CPU load

# Face Detection Case Study

- Initial investigation focused on face detection application accelerated using OpenCL



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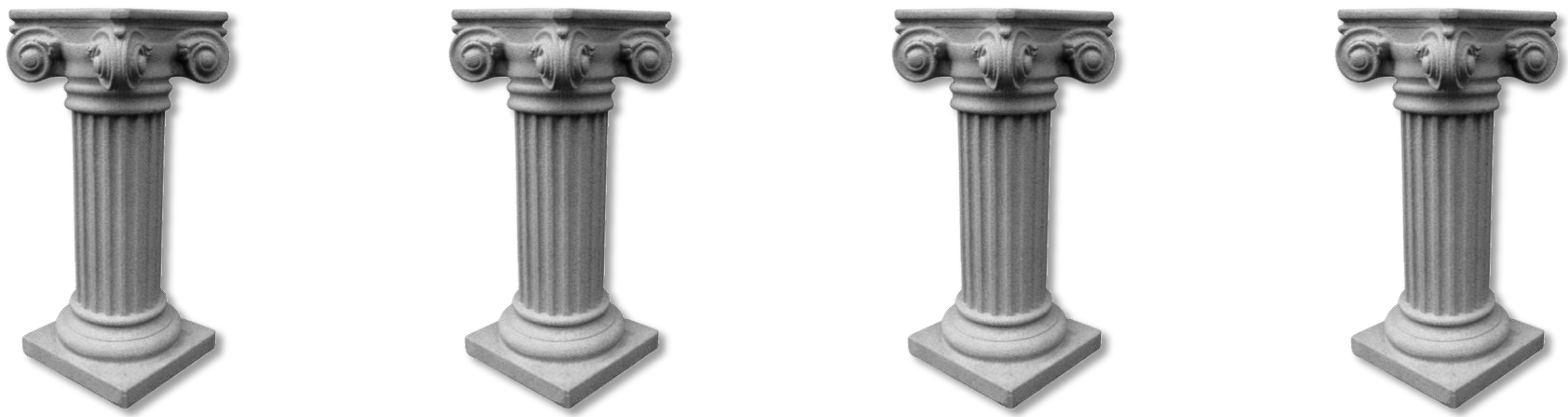
# Compute API's

C++ AMP

OpenCL™ | **DirectCompute** | **CUDA** | **RenderScript**



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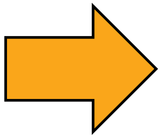
# Thinking in Parallel

- **Writing programs to run in a single thread is well-known / straightforward**
  - Designing algorithms to run in serial is what we are used to doing
  - Making use of parallel processors requires a different approach

- **The skill is to identify which parts of the code can be parallelised**
  - Can be a complex process!
  - Often many different ways to do it
  - Some algorithms can't be parallelised – if possible, find a different algorithm

- **Example: Image Processing…**

# Thinking in Parallel



Sobel filter

Traditional serial method…

```
int x, y;

for (y = 0; y < image_height; y++)
    for (x = 0; x < image_width; x++)
    {
        // process pixel(x, y)
        dest_image[x][y] = sobel(source_image, x, y);
    }
```

# Thinking in Parallel

Thread 0 `sobel(0,0)` `sobel(1,0)` `sobel(2,0)` `sobel(3,0)` . . .

. . . `sobel(w-2,h-1)` `sobel(w-1,h-1)`

SERIAL

| | |
|---|---|
| Thread 0 | `sobel(0,0)` |
| Thread 1 | `sobel(1,0)` |
| Thread 2 | `sobel(2,0)` |
| Thread 3 | `sobel(3,0)` |
| | . . . |
| Thread (w x h) - 2 | `sobel(w-2,h-1)` |
| Thread (w x h) - 1 | `sobel(w-1,h-1)` |

(Embarrassingly) PARALLEL

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# OpenCL: Open Computing Language

- **An open industry standard for programming a heterogeneous collection of CPUs, GPUs and other computing devices**

- **Specifies an API for parallel programming**

- **Designed for GPGPU portability**
  - Via abstracted memory and execution model
  - Still scope for specific hardware optimizations
  - No need to know the GPU instruction set

- **Programs executing on OpenCL devices are called *kernels***
  - **Written in OpenCL C (based on C99)**

- **Fully supported on Mali-T600 GPU's**

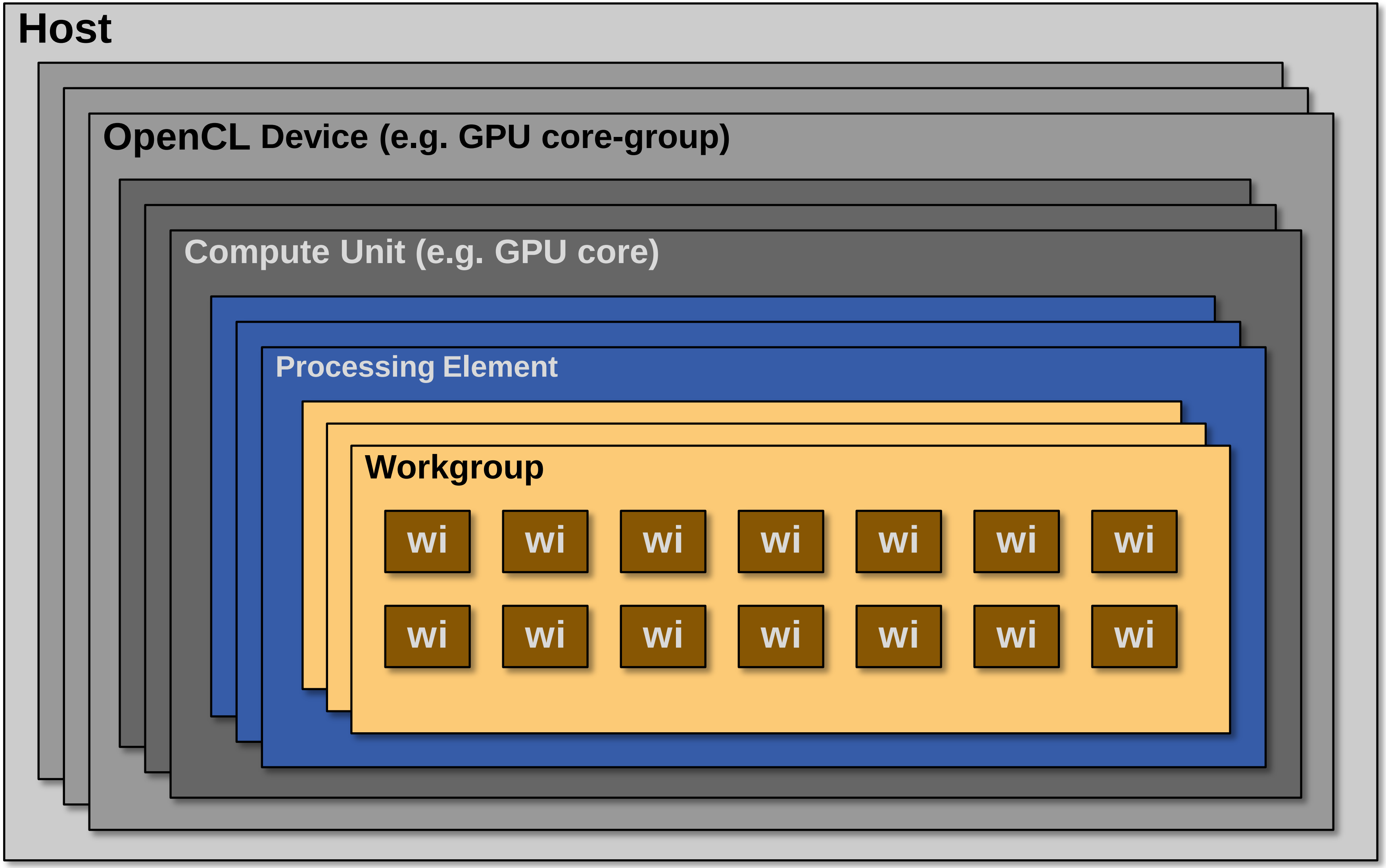
# Writing OpenCL code

- An OpenCL application consists of two parts:
  - The CL **kernel** that does the parallel processing
    - Runs on the compute devices (the GPU cores)
    - Written in OpenCL C language
  - Application (host) side code that calls the OpenCL APIs
    - Compiles the CL kernel
    - Allocates memory buffers to pass data into and out of the kernel
    - Sets up command queues
    - Sets up dependencies between the tasks
    - Sets up the N-Dimensional Range over which the kernel executes
- Both parts need to be written correctly to get the best performance

# OpenCL: Execution Model (1)

- Kernels are programs that run on OpenCL Devices
  - A single execution of a kernel is called a **work-item.**
    - A **work-item** operates on a relatively tiny part of the overall data set e.g. 1 or more pixels of an image
  - Work-items are grouped into **workgroups**
    - Each workgroup executes on a **Processing Element**
  - There are 1 or more Processing Elements in a **Compute Unit**
  - There are 1 or more Compute Units in an **OpenCL Device**
  - There may be more than one OpenCL Device in a system

# OpenCL: Execution Model (2)



# OpenCL: Execution Model (3)

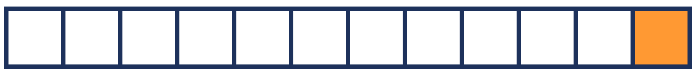
- The Host creates a context that includes the following resources
  - The OpenCL device
  - The OpenCL kernels that run on the OpenCL device
    - Program Objects are built from the kernel sources
  - Memory Objects
    - A set of memory buffers visible to the host and the OpenCL Device

- The Host then issues commands into a command queue
  - Kernel execution commands
    - Execute a kernel on the processing elements of a device
  - Memory commands
    - Transfer data to, from or between memory objects
    - Map & unmap memory objects
  - Synchronization commands

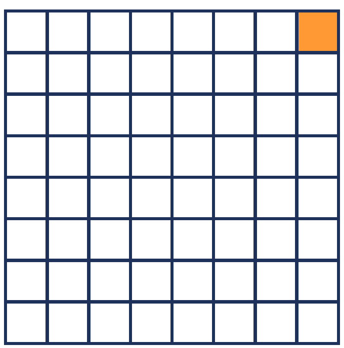
# OpenCL ND-Range

- ND Ranges: defining coordinates for work items
  - OpenCL kernels (work items) are set up to run in 1, 2 or 3 index space…

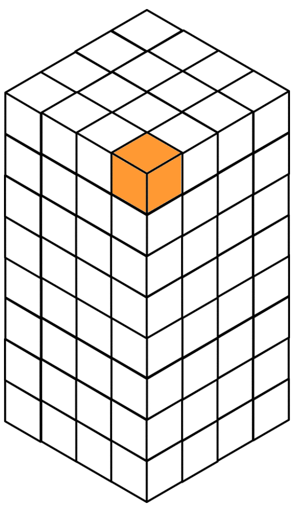
```
size_t global_work_size[work_dim] = { … };

clEnqueueNDRangeKernel( … , work_dim, NULL, global_work_size, … );
```



```
#define work_dim   1
size_t global_work_size[work_dim] = { 12 };
```



```
= 1 work item
```



```
#define work_dim   3
size_t global_work_size[work_dim] = { 4, 4, 8 };
```

```
#define work_dim   2
size_t global_work_size[work_dim] = { 8, 8 };
```

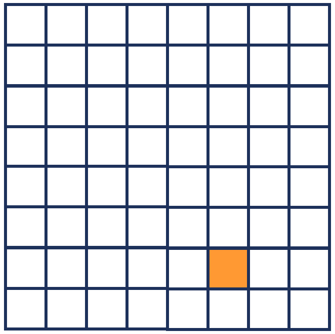
# OpenCL workgroups (1)

- Work items of an NDRange can be divided into equally dimensioned <u>Workgroups…</u>

```
size_t global_work_size[work_dim] = { … };   // Number of work items
size_t local_work_size[work_dim]  = { … };   // Workgroup size

clEnqueueNDRangeKernel( … , work_dim, NULL, global_work_size, local_work_size, … );
```

```
#define work_dim   2
size_t global_work_size[work_dim]  = { 8, 8 };
size_t local_work_size[work_dim]   = { 4, 4 };

Total number of workgroups = ( 8 x 8 ) / ( 4 x 4 ) = 4
```

```
In kernel code…
get_global_id(0)    == 5      get_group_id(0)    == 1
get_global_id(1)    == 6      get_group_id(1)    == 1
get_local_id(0)     == 1      get_work_dim()     == 2
get_local_id(1)     == 2      get_local_size(0) == 4
get_global_size(0) == 8       get_local_size(1) == 4
get_global_size(1) == 8       get_num_groups(0) == 2
                              get_num_groups(1) == 2
```



# OpenCL workgroups (2)

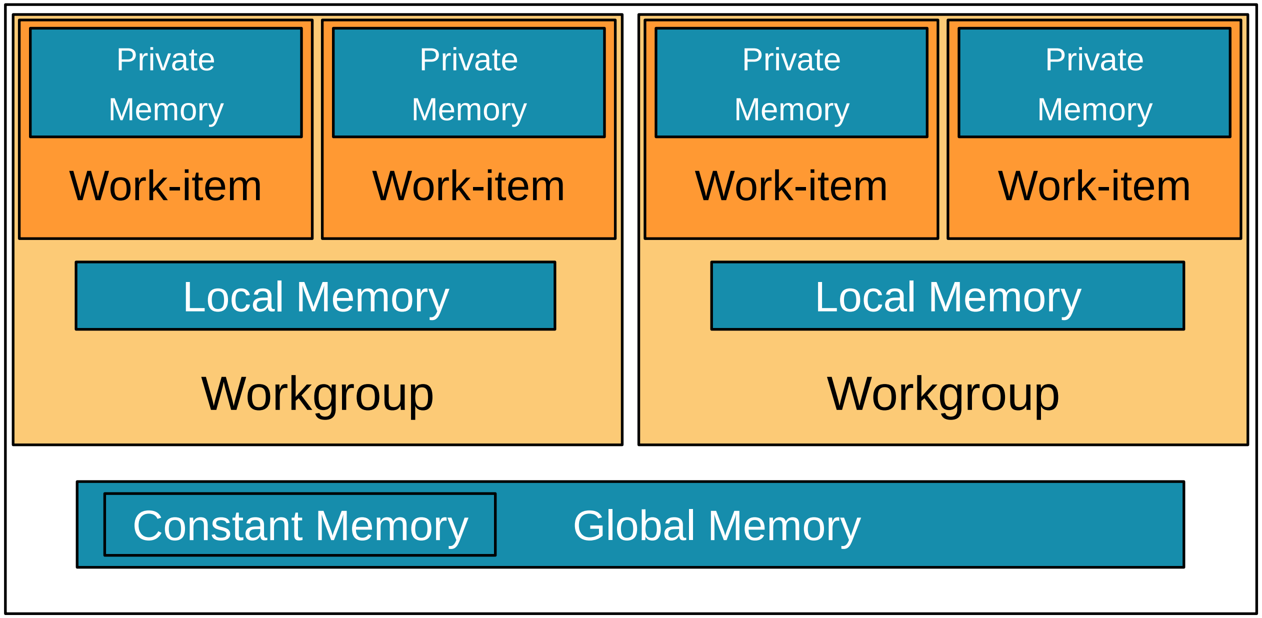
- Work items within a workgroup have a special relationship with each other…
  - They can perform barrier operations to synchronise execution points…

```
...                                  // Some kernel code

barrier(CLK_LOCAL_MEM_FENCE);        // Wait for all kernels in
                                     // this workgroup to catch up

...                                  // Some more kernel code
```

  - Work items in the same workgroup have access to shared memory
  - Local atomic operations are available (and must be fast)
- Workgroups are totally independent from each other
  - No barriers, no dependencies, no ordering, no coherency
  - However global atomics are available (but may be slow)

# OpenCL: Memory Model

- **Private memory**
  - Private to a work-item
- **Local memory**
  - Local to a workgroup
  - Accessible by work-items in that workgroup
- **Constant memory**
  - Accessible as read-only by all work-items
- Global memory
  - Accessible by all work-items



# OpenCL: A Simple Example (1)

## C Version…

```
unsigned char buffer[BUFFER_SIZE];

for (int i = 0; i < BUFFER_SIZE; i++)
    buffer[i] = i % 256;
```

## OpenCL Version…

```
__kernel void fill_buffer( __global unsigned char *buffer )
{
    /* Obtain the ID for this work item - we use this
       to locate the corresponding position in the buffer. */
    size_t id = get_global_id(0);

    /* The kernel might be invoked on data points that are outside
       the buffer to honour global and local work space alignments for a
       particular device. Return in these cases. */
    if ( id < BUFFER_SIZE )
    {
        /* Fill the buffer location corresponding to this work item with
           the global ID (modulo 256) */
        buffer[id] = id % 256;
    }
}
```

# OpenCL: A Simple Example (2)

```
cl_command_queue        queue;
cl_context              context;
cl_platform_id          platform    =  NULL;
cl_device_id            device_id   =  NULL;
cl_int                  err;
cl_program              program;
cl_kernel               kernel;
cl_mem                  buffer;
unsigned char           *local_buf;
size_t                  global_work_size = BUFFER_SIZE;

err         = clGetPlatformIDs( 1, &platform, NULL );
err         = clGetDeviceIDs( platform, CL_DEVICE_TYPE_GPU, 1, &device_id, NULL );
context     = clCreateContext( NULL, 1, &device_id, NULL, NULL, &err );
program     = clCreateProgramWithSource( context, 1, &kernel_source_code, NULL, &err );
err         = clBuildProgram( program, 1, &device_id, "", NULL, NULL );
kernel      = clCreateKernel( program, "fill_buffer", &err );
queue       = clCreateCommandQueue( context, device_id, 0, &err );
buffer      = clCreateBuffer( context, CL_MEM_READ_WRITE | CL_MEM_ALLOC_HOST_PTR,
                              BUFFER_SIZE, NULL, &err );
err         = clSetKernelArg( kernel, 0, sizeof(cl_mem), &buffer );
err         = clEnqueueNDRangeKernel( queue, kernel, 1, NULL, &global_work_size,
                                      NULL, 0, NULL, NULL );
local_buf   = clEnqueueMapBuffer( queue, buffer, CL_TRUE, CL_MAP_READ, 0, BUFFER_SIZE
                                  0, NULL, NULL, &err );

... access buffer contents here
clEnqueueUnmapMemObject( queue, buffer, local_buf, 0, NULL, NULL );
... clean-up OpenCL objects here (kernel, program, queue etc.)
```

```
__kernel void fill_buffer(__global unsigned char *buffer)
{
    size_t id = get_global_id(0);

    if ( id < BUFFER_SIZE )
            buffer[id] = id % 256;
}
```

# OpenCL Example 2 - Bezier surface evaluation (1)

```
// Evaluate a Bezier patch at a (s, t) determined by the global work item.
    __kernel void evaluateBezier
        (__global __write_only float4 *positions,
         __global __write_only float2 *texCoords,
         float16 matrixX, float16 matrixY, float16 matrixZ,
         int size)
    {
        float s = ((float)(get_global_id(0))) / (size - 1);
        float s2 = s * s;
        float t = ((float)(get_global_id(1))) / (size - 1);
        float t2 = t * t;
        float4 S = (float4)(s2 * s, s2, s, 1);
        float4 T = (float4)(t2 * t, t2, t, 1);

        // Calculate the position of the item at (s, t).
        float4 smx = (float4)(dot(S, matrixX.lo.lo),
                              dot(S, matrixX.lo.hi),
                              dot(S, matrixX.hi.lo),
                              dot(S, matrixX.hi.hi));
        float4 smy = (float4)(dot(S, matrixY.lo.lo),
                              dot(S, matrixY.lo.hi),
                              dot(S, matrixY.hi.lo),
                              dot(S, matrixY.hi.hi));
        float4 smz = (float4)(dot(S, matrixZ.lo.lo),
                              dot(S, matrixZ.lo.hi),
                              dot(S, matrixZ.hi.lo),
                              dot(S, matrixZ.hi.hi));

        // Output the results.
        int offset = get_global_id(0) + get_global_id(1) * size;
        positions[offset] = (float4)(dot(smx, T), dot(smy, T), dot(smz, T), 1);
        texCoords[offset] = (float2)(s, t);
    }
```

# OpenCL Example 2 - Bezier surface evaluation (2)

```
// Evaluate a Bezier patch at a (s, t) determined by the global work item.
    __kernel void evaluateBezier
        (__global __write_only float4 *positions,
         __global __write_only float2 *texCoords,
         float16 matrixX, float16 matrixY, float16 matrixZ,
         int size)
    {
        float s = ((float)(get_global_id(0))) / (size - 1);
        float s2 = s * s;
        float t = ((float)(get_global_id(1))) / (size - 1);
        float t2 = t * t;
        float4 S = (float4)(s2 * s, s2, s, 1);
        float4 T = (float4)(t2 * t, t2, t, 1);

        // Calculate the position of the item at (s, t).
        float4 smx = (float4)(dot(S, matrixX.lo.lo),
                              dot(S, matrixX.lo.hi),
                              dot(S, matrixX.hi.lo),
                              dot(S, matrixX.hi.hi));
        float4 smy = (float4)(dot(S, matrixY.lo.lo),
                              dot(S, matrixY.lo.hi),
                              dot(S, matrixY.hi.lo),
                              dot(S, matrixY.hi.hi));
        float4 smz = (float4)(dot(S, matrixZ.lo.lo),
                              dot(S, matrixZ.lo.hi),
                              dot(S, matrixZ.hi.lo),
                              dot(S, matrixZ.hi.hi));

        // Output the results.
        int offset = get_global_id(0) + get_global_id(1) * size;
        positions[offset] = (float4)(dot(smx, T), dot(smy, T), dot(smz, T), 1);
        texCoords[offset] = (float2)(s, t);
    }
```

2 integer divides

15 vector dot products.
each is:
4 multiplies
3 adds

8 other arithmetic operations

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# RenderScript: Introduction

- An Android-hosted framework
  - Allows Android applications to run specific portions of code on a variety of heterogeneous hardware
  - Provides an API supporting high-performance, vectorised compute operations
  - Cross-platform, device-agnostic and entirely integrated with Android

- Introduced in Android 3.0 (Honeycomb)
  - Originally intended as both a 3D rendering and a compute API
  - 3D rendering API deprecated from Android 4.1 (Jelly Bean)
  - Android 4.2 the first version to support compute on a GPU
  - First RSc GPU-accelerated compute device launched in 2011
    - Nexus 10 (based on Mali-T604)

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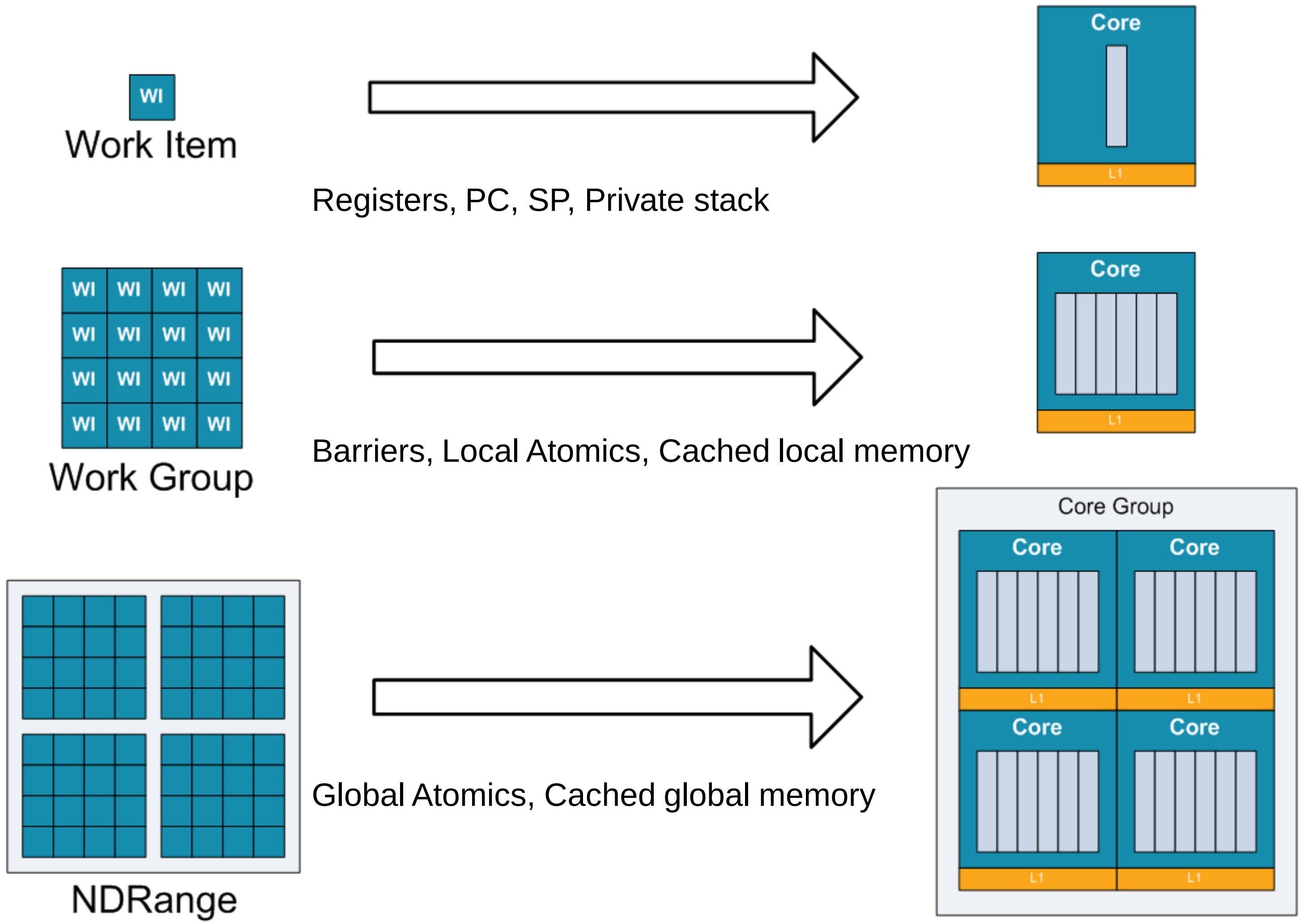
# CL Execution model on Mali-T600 (1)



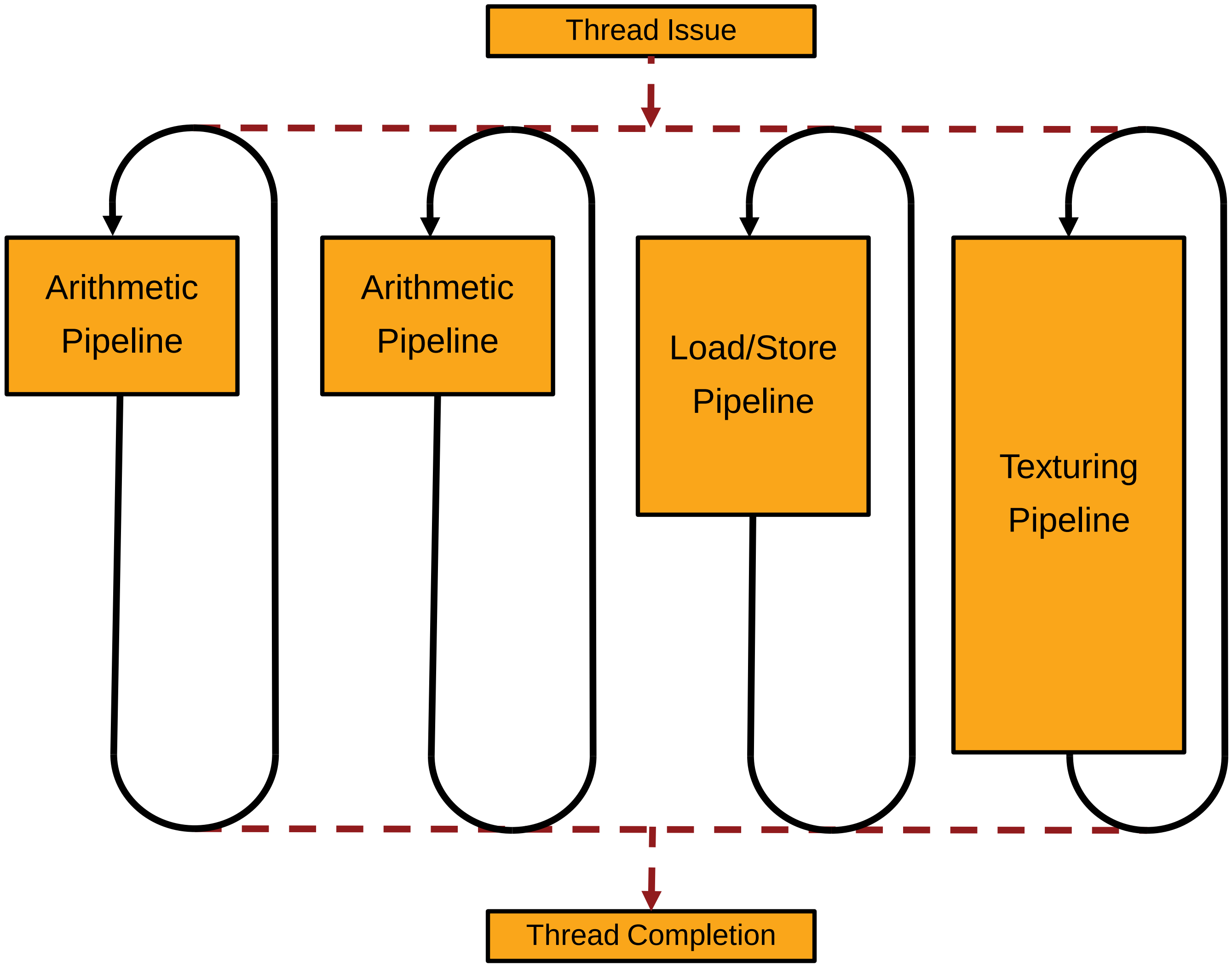
# CL Execution model on Mali-T600 (2)

- Each work-item runs as one of the threads within a core
  - Every Mali-T600 thread has its own independent program counter
    - Which supports divergent threads from the same kernel
      - caused by conditional execution, variable length loops etc.
    - Some other GPGPU's use "WARP" architectures
      - These share a common program counter with a group of work-items
      - This can be highly scalable… but can be slow handling divergent threads
      - T600 effectively has a Warp size of 1
    - Up to 256 threads per core
  - Every thread has its own registers
  - Every thread has its own stack pointer and private stack
  - Shared read-only registers are used for kernel arguments

# CL Execution model on Mali-T600 (3)

- A whole work-group executes on a single core
  - Mali-T600 supports up to 256 work-items per work-group
  - OpenCL barrier operations (which synchronise threads) are handled by the hardware
- For full efficiency you need more work-groups than cores
  - To keep all of the cores fed with work
  - Most GPUs require this, so most CL applications will do this
- Local and global atomic operations are available in hardware
- All memory is cached

# The Mali-T600 Architecture



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# ARM's OpenCL Driver

- Full profile OpenCL v1.1 in hardware and Mali-T600 driver
  - Backward compatibility support for OpenCL v1.0
  - Embedded profile is a subset of full profile
  - Image types supported in HW and driver
  - Atomic extensions (32 and 64-bit)
  - Hardware is OpenCL v1.2 ready (driver to follow)

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# CL Built-in function library (BIFL)

- CL language provides a built-in function library
- Functional groups include
  - Maths, integer, common, geometric, work-item, vector, atomic, relational, image
- Fast operation of the BIFLs is essential for CL performance
  - Every kernel calls at least one work-item function:
    - e.g. `get_global_id(0)`
- Functions like dot products are also very commonly used
- There are about 200 functions
  - But many BIFLs are overloaded with data types
    - e.g. `sin(float x)`, `sin(double x)`, `sin(half x)`
  - Also many BIFLs can handle all 6 vector sizes (1,2,3,4,8,16)
  - So there are actually thousands of variants

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  - Tools and Support
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# Porting OpenCL code from other GPUs

- Desktop GPUs require data to be copied to local or private memory buffers
  - Otherwise their performance suffers
  - These copy operations are expensive
  - These are sometimes done in the first part of a kernel, followed by a synchronisation barrier instruction, before the actual processing begins in the second half
  - The barrier instruction is also expensive

- When running on Mali just use global memory instead
  - Thus the copy operations can be removed
  - And also any barrier instructions that wait for the copy to finish
  - Query the device flag `CL_DEVICE_HOST_UNIFIED_MEMORY` if you want to write performance portable code for Mali and desktop PC's
    - The application can then switch whether or not it performs copying to local memory

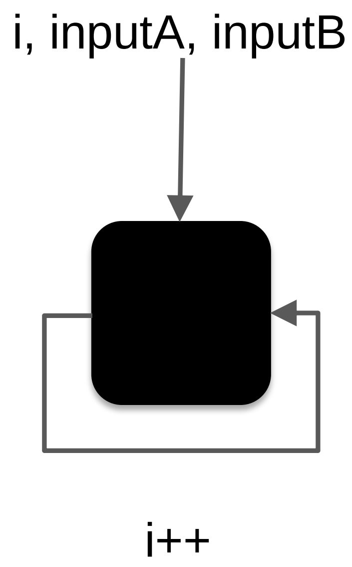
# Use Vectors

- Mali-T600 series GPUs have a vector capable GPU
- OpenCL supports explicit vector functions

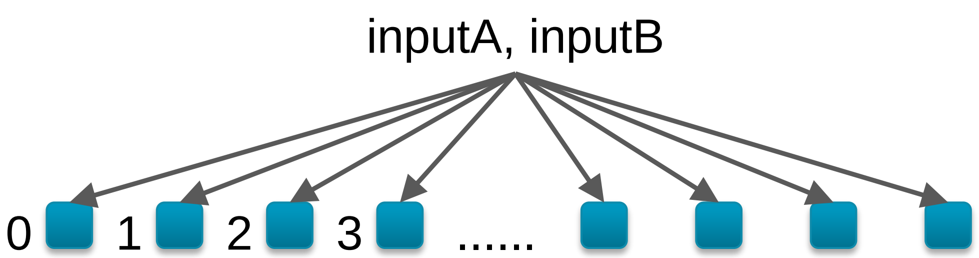
- **clGetDeviceInfo**
  - CL_DEVICE_NATIVE_VECTOR_WIDTH_CHAR
  - CL_DEVICE_NATIVE_VECTOR_WIDTH_SHORT
  - CL_DEVICE_NATIVE_VECTOR_WIDTH_INT
  - CL_DEVICE_NATIVE_VECTOR_WIDTH_LONG
  - CL_DEVICE_NATIVE_VECTOR_WIDTH_FLOAT
  - CL_DEVICE_NATIVE_VECTOR_WIDTH_DOUBLE
  - CL_DEVICE_NATIVE_VECTOR_WIDTH_HALF

# Hello OpenCL

```
for (int i = 0; i < arraySize; i++)
{
    output[i] =
              inputA[i] + inputB[i];
}
```

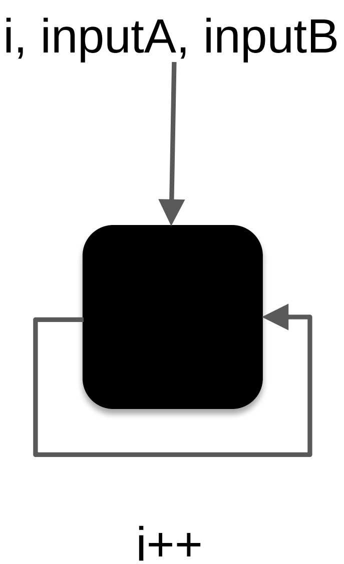



```
__kernel void kernel_name(__global int* inputA,
                          __global int* inputB,
                          __global int* output)
{
    int i = get_global_id(0);
    output[i] = inputA[i] + inputB[i];
}

clEnqueueNDRangeKernel(..., kernel, ...,
                            arraySize, ...)
```

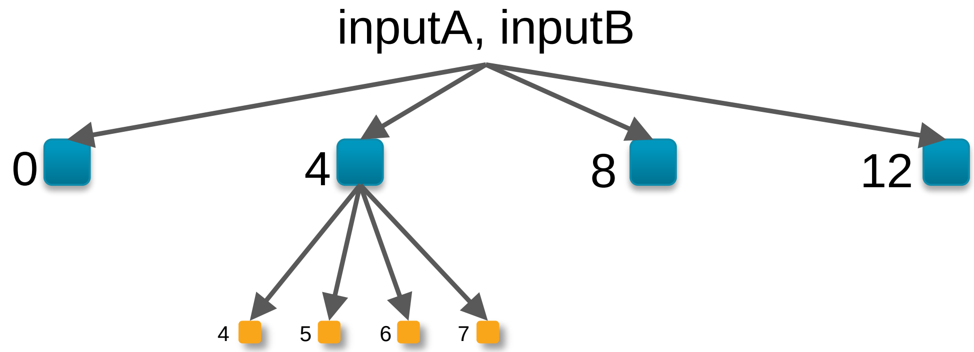


# Hello OpenCL Vectors

```
for (int i = 0; i < arraySize; i++)
{
    output[i] =
              inputA[i] + inputB[i];
}
```



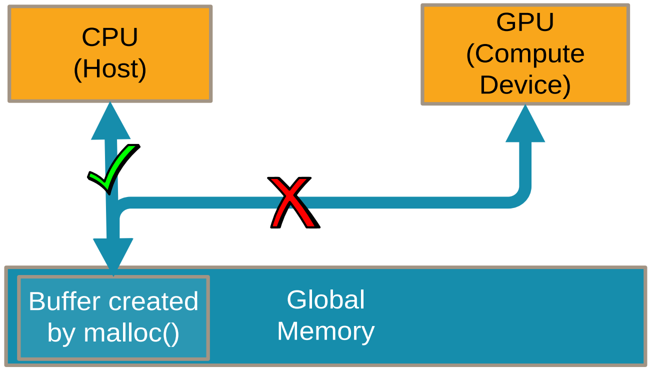

```
__kernel void kernel_name(__global int* inputA,
                          __global int* inputB,
                          __global int* output)
{
    int i = get_global_id(0);
    int4 a = vload4(i, inputA);
    int4 b = vload4(i, inputB);
    vstore4(a + b, i, output);
}

clEnqueueNDRangeKernel(..., kernel, ...,
                       arraySize / 4, ...)
```



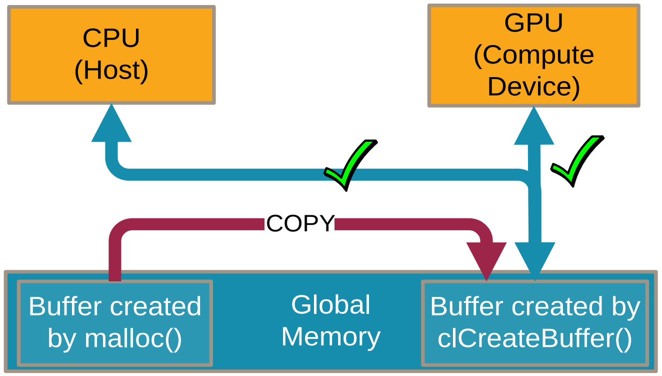
# Creating buffers

- The application creates buffer objects that pass data to and from the kernels by calling the OpenCL API **`clCreateBuffer()`**
- All CL memory buffers are allocated in global memory that is physically accessible by both CPU and GPU cores
  - However, only memory that is allocated by **`clCreateBuffer`** is mapped into both the CPU and GPU virtual memory spaces
  - Memory allocated using **`malloc()`**, etc, is only mapped onto the CPU
- So calling **`clCreateBuffer()`** with **`CL_MEM_USE_HOST_PTR`** and passing in a user created buffer requires the driver to create a new buffer and copy the data (identical to **`CL_MEM_COPY_HOST_PTR`**)
  - This copy reduces performance
- So where possible always use **`CL_MEM_ALLOC_HOST_PTR`**
  - This allocates memory that both CPU and GPU can use without a copy

# Host data pointers

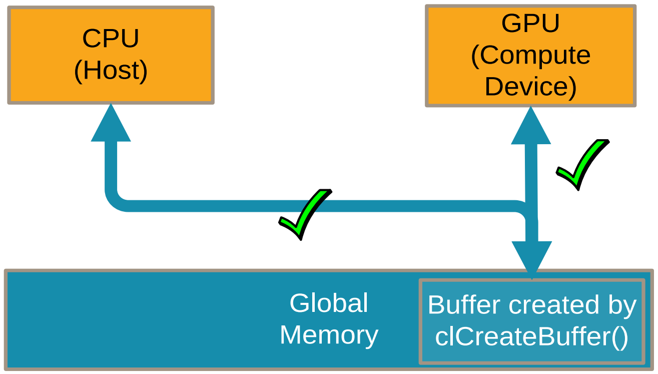



Buffers created by user (**`malloc`**) are not mapped into the GPU memory space




**`clCreateBuffer(CL_MEM_USE_HOST_PTR)`** creates a new buffer and copies the data over (but the copy operations are expensive)

# Host data pointers




**`clCreateBuffer(CL_MEM_ALLOC_HOST_PTR)`** creates a buffer visible by both GPU and CPU

- Where possible don't use `CL_MEM_USE_HOST_PTR`
  - Create buffers at the start of your application
  - Use **`CL_MEM_ALLOC_HOST_PTR`** instead of **`malloc()`**
  - Then you can use the buffer on both CPU host and GPU

# Run Time

- Where your kernel has no preference for work-group size, for maximum performance...
  - either use the compiler recommended work-group size...

    ```
    clGetKernelWorkgroupInfo(kernel, dev, CL_KERNEL_WORK_GROUP_SIZE, sizeof(size_t)... );
    ```

  - or use a power of 2
  - You can pass NULL, but performance might not be optimal
- If you want your kernel to access host memory
  - use mapping operations in place of read and write operations
  - mapping operations do not require copies so are faster and use less memory

# Compiler

- Run-time compilation isn't free!

- Compile each kernel only once if possible
  - If your kernel source is fixed, then compile the kernel during your application's initialisation
  - If your application has an installation phase then cache the binary on a storage device for the application's next invocation
  - Keep the resultant binary ready for when you want to run the kernel

- `clBuildProgram` only partially builds the source code
  - If the kernels in use are known at initialization time, then also call **`clCreateKernel`** for each kernel to initiate the finalizing compile
  - Creating the same kernels in the future will then be faster because the finalized binary is used

# BIFLs

- Where possible use the built-in functions as the commonly occurring ones compile to fast hardware instructions
  - Many will target vector versions of the instructions where available

- Using "`half`" or "`native`" versions of built-in functions
  - e.g. **`half_sin(x)`**
    - Specification mandates a minimum of 10-bits of accuracy
  - e.g. **`native_sin(x)`**
    - Accuracy and input range implementation defined
  - Often not an advantage on Mali-T600… for some functions the precise versions are just as fast

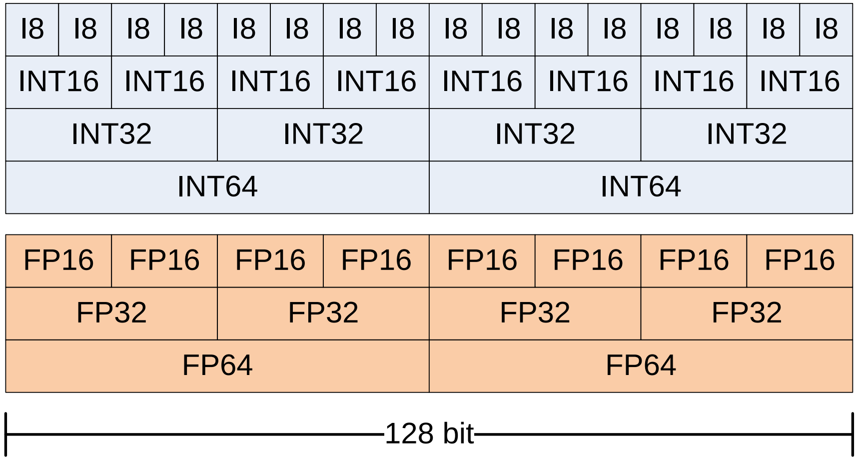
# Arithmetic

- Mali-T604 has a register and ALU width of 128-bits
  - Avoid writing kernels that operate on single bytes or scalar values
  - Write kernels that work on vectors of at least 128-bits.
  - Smaller data types are quicker
    - you can fit eight shorts into 128-bits compared to four integers

- Integers and floating point are supported equally quickly
  - Don’t be afraid to use the data type best suited to your algorithm

- Mali-T600 can natively support all CL data types

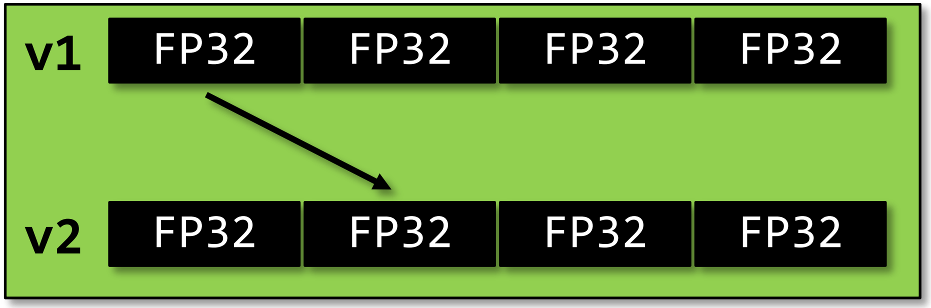
```
16 x 8-bit chars (char16)
2 x 64-bit integers (long2)
4 x 32-bit floats (float4)
2 x 64-bit floats (double2)
```



# Register operations

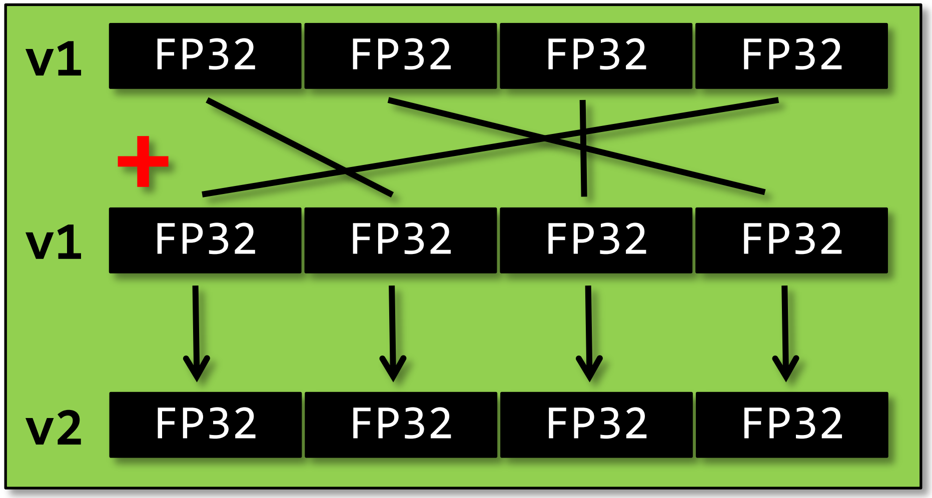
- **All operations can read or write any element or elements within a register**

```
float4 v1, v2;
...
v2.y = v1.x
```




- **All operations can swizzle the elements in their input registers**

```
float4 v1, v2;
...
v2 = v1 + v1.wxzy
```




- **These operations are mostly free, as are various data type expansion and shrinking operations**
  - e.g. `char -> short`

# Images

- Image data types are supported in hardware so use them!
  - Supports coordinate clipping, border colours, format conversion, etc
  - Bi-linear pixel read only takes a cycle
  - Happens in the texture pipeline
    - Can do things in parallel in the ALU and L/S pipes

- However buffers of integer arrays can be even faster still:
  - If you don't read off the edge of the image, and you use integer coordinates, and you don't need format conversion then…
    - You can read and operate on 16 x 8-bit greyscale pixels at once
    - Or **`4 x RGBA8888`** pixels at once

# Load/Store Pipeline

- The L1 and L2 caches are not as large as on desktop systems…
  - and there are a great many threads
  - If you do a load in one instruction, by the next instruction (in the same thread) the data could possibly have been evicted
  - So pull as much data into registers in a single instruction as you can
  - One instruction is always better than using several instructions!
  - And a 16-byte load or store will typically take a single cycle

# Miscellaneous

- Process large data sets!
  - OpenCL setup overhead can limit the GPU over CPU benefit with smaller data sets
- Feed the beast!
  - The ALU’s work at their most efficient when running lots of compute
    - Don’t be afraid to use a high density of vector calculations in your kernels
- Avoid writing kernels that use a large numbers of variables
  - Reduces the available registers
    - and therefore the maximum  workgroup size reduces
  - Sometimes better to re-compute a value than store in a variable
- Avoid prime number work size dimensions
  - Cannot select an efficient workgroup size with a prime number of work items
  - Ideally workgroup size should be a power of 2

# Agenda

- Introduction
- Mali-T600 Compute Overview
- Optimal OpenCL for Mali-T600
  - Programming Suggestions
  - Tools and Support
- OpenCL Optimization Case Study

# OpenCL Tools and Support

- Mali OpenCL SDK
  - Available for download at **`malideveloper.com`**
  - Several OpenCL samples and guides

- Debugging
  - Notoriously difficult to do with parallel programming
    - Serial programming paradigms don't apply
  - DS-5 Streamline compatible with OpenCL
    - Raw instrumentation output also available
  - Mali Graphics Debugger
    - Logs OpenGL ES and OpenCL API calls
    - Download from **`malideveloper.com`**

# Agenda

- Introduction
- Mali-T600 Compute Overview
- Optimal OpenCL for Mali-T600
- OpenCL Optimization Case Study

# OpenCL Laplace Case Study

- **Laplace filters are typically used in image processing**
  - … often used for edge detection or image sharpening
- **This case study will go through a number of stages…**
  - Demonstrating a variety of optimisation techniques
  - and showing the change in performance at each stage
- **Our example will process and output 24-bit images**
  - and we'll measure performance across a range of image sizes
- **But first, a couple of image samples showing the effect of the filter we are using…**

# OpenCL Laplace Case Study

**Original**

# OpenCL Laplace Case Study


**Filtered**

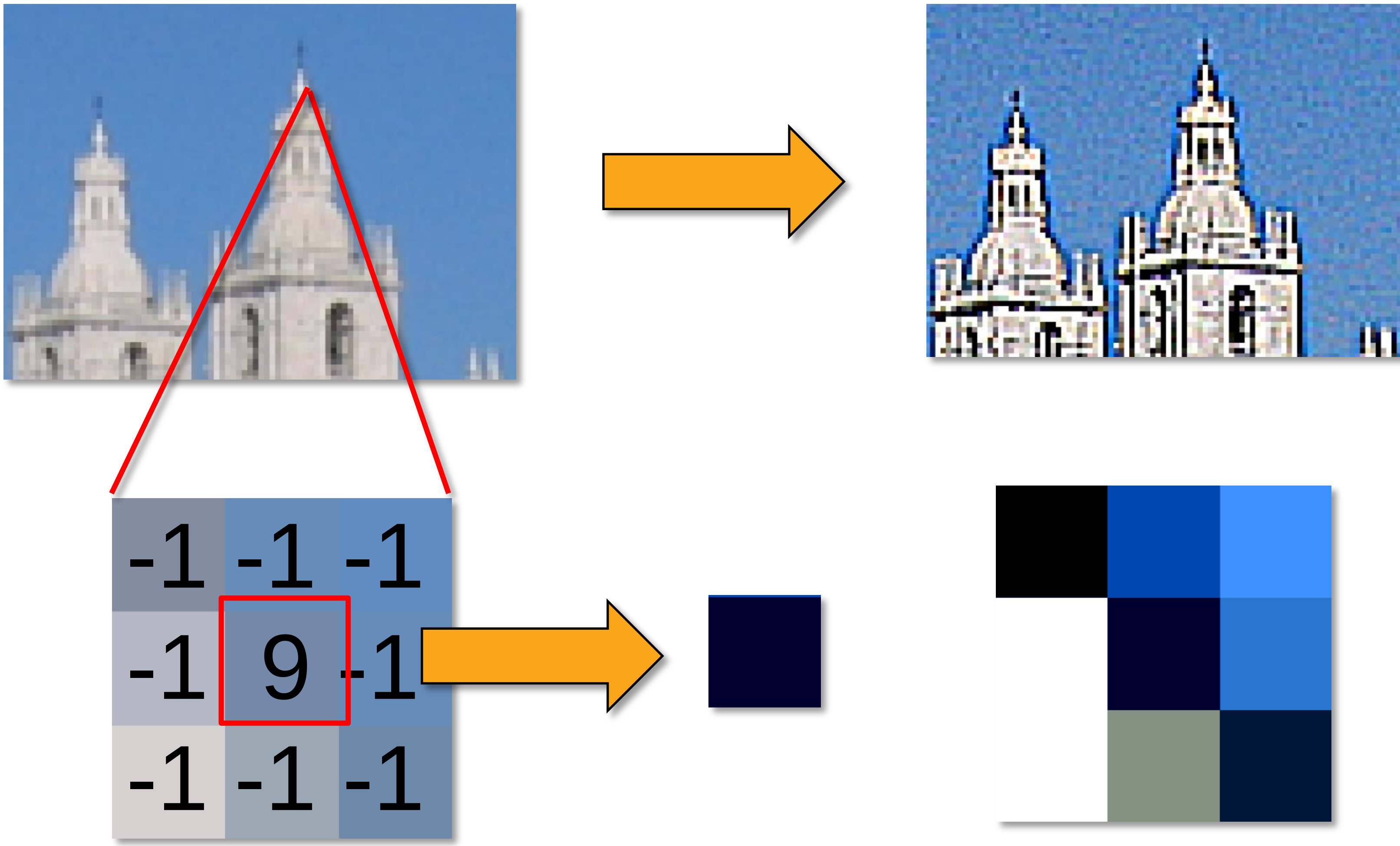
# OpenCL Laplace Case Study


**Original**

# OpenCL Laplace Case Study


**Filtered**

# OpenCL Laplace Case Study



# OpenCL Laplace Case Study

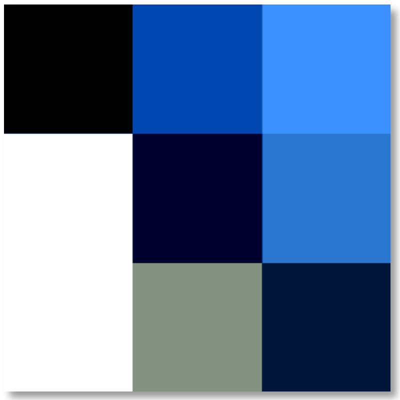
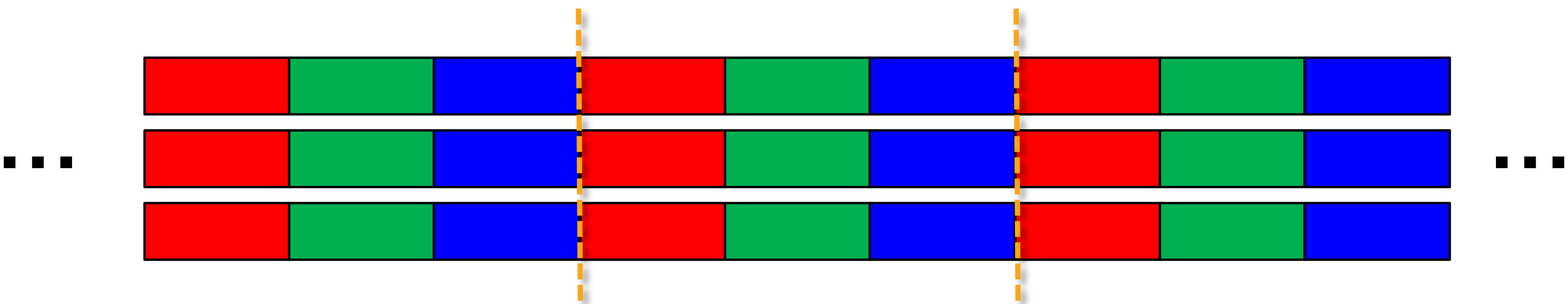



image “stride” = width x 3



# OpenCL Laplace Case Study

```
#define MAX(a,b) ((a)>(b)?(a):(b))
#define MIN(a,b) ((a)<(b)?(a):(b))

__kernel void math(__global unsigned char *pdst, __global unsigned char *psrc, int width, int height)
{
    int y          = get_global_id(0);
    int x          = get_global_id(1);
    int w          = width;
    int h          = height;
    int ind        = 0;
    int xBoundary = w - 2;
    int yBoundary = h - 2;

    if (x >= xBoundary || y >= yBoundary)
    {
        ind            = 3 * (x + w * y);
        pdst[ind]      = psrc[ind];
        pdst[ind + 1] = psrc[ind + 1];
        pdst[ind + 2] = psrc[ind + 2];
        return;
    }

    int bColor = 0, gColor = 0, rColor = 0;
    ind        = 3 * (x + w * y);

    bColor = bColor - psrc[ind] - psrc[ind+3] - psrc[ind+6] - psrc[ind+3*w] + psrc[ind+3*(1+w)] * 9 –
             psrc[ind+3*(2+w)]- psrc[ind+3*2*w]- psrc[ind+3*(1+2*w)]- psrc[ind+3*(2+2*w)];
    gColor = gColor - psrc[ind+1] - psrc[ind+4] - psrc[ind+7] - psrc[ind+3*w+1] + psrc[ind+3*(1+w)+1] * 9 –
             psrc[ind+3*(2+w)+1]- psrc[ind+3*2*w+1]- psrc[ind+3*(1+2*w)+1]- psrc[ind+3*(2+2*w)+1];
    rColor = rColor - psrc[ind+2] - psrc[ind+5] - psrc[ind+8] - psrc[ind+3*w+2] + psrc[ind+3*(1+w)+2] * 9 –
             psrc[ind+3*(2+w)+2]- psrc[ind+3*2*w+2]- psrc[ind+3*(1+2*w)+2]- psrc[ind+3*(2+2*w)+2];

    unsigned char blue  = (unsigned char)MAX(MIN(bColor, 255), 0);
    unsigned char green = (unsigned char)MAX(MIN(gColor, 255), 0);
    unsigned char red   = (unsigned char)MAX(MIN(rColor, 255), 0);
    ind            = 3 * (x + 1 + w * (y + 1));
    pdst[ind]      = blue;
    pdst[ind + 1] = green;
    pdst[ind + 2] = red;
}
```

# OpenCL Laplace Case Study

```
#define MAX(a,b) ((a)>(b)?(a):(b))
#define MIN(a,b) ((a)<(b)?(a):(b))

__kernel void math(__global unsigned char *pdst, __global unsigned char *psrc, int width, int height)
{
    int y         = get_global_id(0);
    int x         = get_global_id(1);
    int w         = width;
    int h         = height;
    int ind       = 0;
    int xBoundary = w - 2;
    int yBoundary = h - 2;

    if (x >= xBoundary || y >= yBoundary)
    {
        ind         = 3 * (x + w * y);
        pdst[ind]     = psrc[ind];
        pdst[ind + 1] = psrc[ind + 1];
        pdst[ind + 2] = psrc[ind + 2];
        return;
    }

    int bColor = 0, gColor = 0, rColor = 0;
    ind        = 3 * (x + w * y);

    bColor = bColor - psrc[ind] - psrc[ind+3] - psrc[ind+6] - psrc[ind+3*w] + psrc[ind+3*(1+w)] * 9 –
             psrc[ind+3*(2+w)]- psrc[ind+3*2*w]- psrc[ind+3*(1+2*w)]- psrc[ind+3*(2+2*w)];
    gColor = gColor - psrc[ind+1] - psrc[ind+4] - psrc[ind+7] - psrc[ind+3*w+1] + psrc[ind+3*(1+w)+1] * 9 –
             psrc[ind+3*(2+w)+1]- psrc[ind+3*2*w+1]- psrc[ind+3*(1+2*w)+1]- psrc[ind+3*(2+2*w)+1];
    rColor = rColor - psrc[ind+2] - psrc[ind+5] - psrc[ind+8] - psrc[ind+3*w+2] + psrc[ind+3*(1+w)+2] * 9 –
             psrc[ind+3*(2+w)+2]- psrc[ind+3*2*w+2]- psrc[ind+3*(1+2*w)+2]- psrc[ind+3*(2+2*w)+2];

    unsigned char blue  = (unsigned char)MAX(MIN(bColor, 255), 0);
    unsigned char green = (unsigned char)MAX(MIN(gColor, 255), 0);
    unsigned char red   = (unsigned char)MAX(MIN(rColor, 255), 0);
    ind           = 3 * (x + 1 + w * (y + 1));
    pdst[ind]     = blue;
    pdst[ind + 1] = green;
    pdst[ind + 2] = red;
}
```

Destination buffer | Source buffer | Image width | Image height

# OpenCL Laplace Case Study

```
#define MAX(a,b) ((a)>(b)?(a):(b))
#define MIN(a,b) ((a)<(b)?(a):(b))

__kernel void math(__global unsigned char *pdst, __global unsigned char *psrc, int width, int height)
{
    int y         = get_global_id(0);
    int x         = get_global_id(1);
    int w         = width;
    int h         = height;
    int ind       = 0;
    int xBoundary = w - 2;
    int yBoundary = h - 2;

    if (x >= xBoundary || y >= yBoundary)
    {
        ind            = 3 * (x + w * y);
        pdst[ind]      = psrc[ind];
        pdst[ind + 1] = psrc[ind + 1];
        pdst[ind + 2] = psrc[ind + 2];
        return;
    }

    int bColor = 0, gColor = 0, rColor = 0;
    ind        = 3 * (x + w * y);

    bColor = bColor - psrc[ind] - psrc[ind+3] - psrc[ind+6] - psrc[ind+3*w] + psrc[ind+3*(1+w)] * 9 –
             psrc[ind+3*(2+w)]- psrc[ind+3*2*w]- psrc[ind+3*(1+2*w)]- psrc[ind+3*(2+2*w)];
    gColor = gColor - psrc[ind+1] - psrc[ind+4] - psrc[ind+7] - psrc[ind+3*w+1] + psrc[ind+3*(1+w)+1] * 9 –
             psrc[ind+3*(2+w)+1]- psrc[ind+3*2*w+1]- psrc[ind+3*(1+2*w)+1]- psrc[ind+3*(2+2*w)+1];
    rColor = rColor - psrc[ind+2] - psrc[ind+5] - psrc[ind+8] - psrc[ind+3*w+2] + psrc[ind+3*(1+w)+2] * 9 –
             psrc[ind+3*(2+w)+2]- psrc[ind+3*2*w+2]- psrc[ind+3*(1+2*w)+2]- psrc[ind+3*(2+2*w)+2];

    unsigned char blue  = (unsigned char)MAX(MIN(bColor, 255), 0);
    unsigned char green = (unsigned char)MAX(MIN(gColor, 255), 0);
    unsigned char red   = (unsigned char)MAX(MIN(rColor, 255), 0);
    ind           = 3 * (x + 1 + w * (y + 1));
    pdst[ind]     = blue;
    pdst[ind + 1] = green;
    pdst[ind + 2] = red;
}
```

Boundary checking… ideally we don't want to calculate for values at the right and bottom edges.
(But this might not be the best place to handle this.)

# OpenCL Laplace Case Study

```
#define MAX(a,b) ((a)>(b)?(a):(b))
#define MIN(a,b) ((a)<(b)?(a):(b))

__kernel void math(__global unsigned char *pdst, __global unsigned char *psrc, int width, int height)
{
    int y         = get_global_id(0);
    int x         = get_global_id(1);
    int w         = width;
    int h         = height;
    int ind       = 0;
    int xBoundary = w - 2;
    int yBoundary = h - 2;

    if (x >= xBoundary || y >= yBoundary)
    {
        ind            = 3 * (x + w * y);
        pdst[ind]      = psrc[ind];
        pdst[ind + 1] = psrc[ind + 1];
        pdst[ind + 2] = psrc[ind + 2];
        return;
    }

    int bColor = 0, gColor = 0, rColor = 0;
    ind        = 3 * (x + w * y);

    bColor = bColor - psrc[ind] - psrc[ind+3] - psrc[ind+6] - psrc[ind+3*w] + psrc[ind+3*(1+w)] * 9 –
             psrc[ind+3*(2+w)]- psrc[ind+3*2*w]- psrc[ind+3*(1+2*w)]- psrc[ind+3*(2+2*w)];
    gColor = gColor - psrc[ind+1] - psrc[ind+4] - psrc[ind+7] - psrc[ind+3*w+1] + psrc[ind+3*(1+w)+1] * 9 –
             psrc[ind+3*(2+w)+1]- psrc[ind+3*2*w+1]- psrc[ind+3*(1+2*w)+1]- psrc[ind+3*(2+2*w)+1];
    rColor = rColor - psrc[ind+2] - psrc[ind+5] - psrc[ind+8] - psrc[ind+3*w+2] + psrc[ind+3*(1+w)+2] * 9 –
             psrc[ind+3*(2+w)+2]- psrc[ind+3*2*w+2]- psrc[ind+3*(1+2*w)+2]- psrc[ind+3*(2+2*w)+2];

    unsigned char blue  = (unsigned char)MAX(MIN(bColor, 255), 0);
    unsigned char green = (unsigned char)MAX(MIN(gColor, 255), 0);
    unsigned char red   = (unsigned char)MAX(MIN(rColor, 255), 0);
    ind           = 3 * (x + 1 + w * (y + 1));
    pdst[ind]     = blue;
    pdst[ind + 1] = green;
    pdst[ind + 2] = red;
}
```

The main calculation… we need to perform this for the red, green and blue color components…

# OpenCL Laplace Case Study

```
#define MAX(a,b) ((a)>(b)?(a):(b))
#define MIN(a,b) ((a)<(b)?(a):(b))

__kernel void math(__global unsigned char *pdst, __global unsigned char *psrc, int width, int height)
{
    int y         = get_global_id(0);
    int x         = get_global_id(1);
    int w         = width;
    int h         = height;
    int ind       = 0;
    int xBoundary = w - 2;
    int yBoundary = h - 2;

    if (x >= xBoundary || y >= yBoundary)
    {
        ind           = 3 * (x + w * y);
        pdst[ind]     = psrc[ind];
        pdst[ind + 1] = psrc[ind + 1];
        pdst[ind + 2] = psrc[ind + 2];
        return;
    }

    int bColor = 0, gColor = 0, rColor = 0;
    ind        = 3 * (x + w * y);

    bColor = bColor - psrc[ind] - psrc[ind+3] - psrc[ind+6] - psrc[ind+3*w] + psrc[ind+3*(1+w)] * 9 -
             psrc[ind+3*(2+w)]- psrc[ind+3*2*w]- psrc[ind+3*(1+2*w)]- psrc[ind+3*(2+2*w)];
    gColor = gColor - psrc[ind+1] - psrc[ind+4] - psrc[ind+7] - psrc[ind+3*w+1] + psrc[ind+3*(1+w)+1] * 9 -
             psrc[ind+3*(2+w)+1]- psrc[ind+3*2*w+1]- psrc[ind+3*(1+2*w)+1]- psrc[ind+3*(2+2*w)+1];
    rColor = rColor - psrc[ind+2] - psrc[ind+5] - psrc[ind+8] - psrc[ind+3*w+2] + psrc[ind+3*(1+w)+2] * 9 -
             psrc[ind+3*(2+w)+2]- psrc[ind+3*2*w+2]- psrc[ind+3*(1+2*w)+2]- psrc[ind+3*(2+2*w)+2];

    unsigned char blue  = (unsigned char)MAX(MIN(bColor, 255), 0);
    unsigned char green = (unsigned char)MAX(MIN(gColor, 255), 0);
    unsigned char red   = (unsigned char)MAX(MIN(rColor, 255), 0);
    ind           = 3 * (x + 1 + w * (y + 1));
    pdst[ind]     = blue;
    pdst[ind + 1] = green;
    pdst[ind + 2] = red;
}
```

Finally we clamp the results to make sure they lie between 0 and 255… and then write out to the destination…

# OpenCL Laplace Case Study

## Results vs. CPU

| Image | Pixels | vs. CPU |
|---|---|---|
| 768 x 432 | 331,776 | x0.5 |
| 2560 x 1600 | 4,096,000 | x0.7 |
| 2048 x 2048 | 4,194,304 | x1.2 |
| 5760 x 3240 | 18,662,400 | x0.7 |
| 7680 x 4320 | 33,177,600 | x0.7 |

**GPU:** Mali T604 @ 533MHz

**CPU:** Single A15 @ 1.7GHz

# OpenCL Laplace Case Study

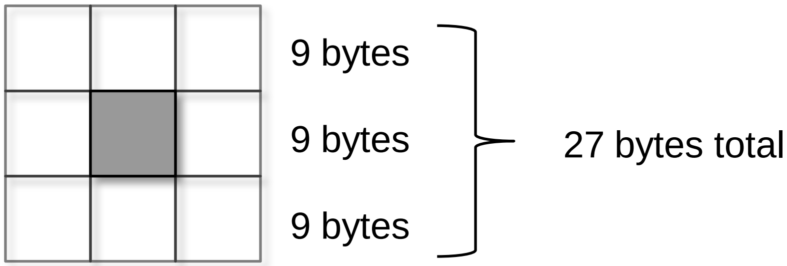
**Optimisation 1**

- Replace the data fetch `(= psrc[index])` with `vloadN`
  - Each `vload16` can load 5 pixels at a time (at 3 bytes-per-pixel)
  - This load should complete in a single cycle
- Perform the Laplace calculation as a vector calculation
  - Then Mali works on all 5 pixels at once
- Replace the data store (`pdst[index] =` ) with `vstoreN`
  - Allows us to write out multiple values at a time
  - Need to be careful to only output 15 bytes (3 pixels)
- As we'll be running 5 times fewer work items, we'll need to update the `globalWorkSize` values…

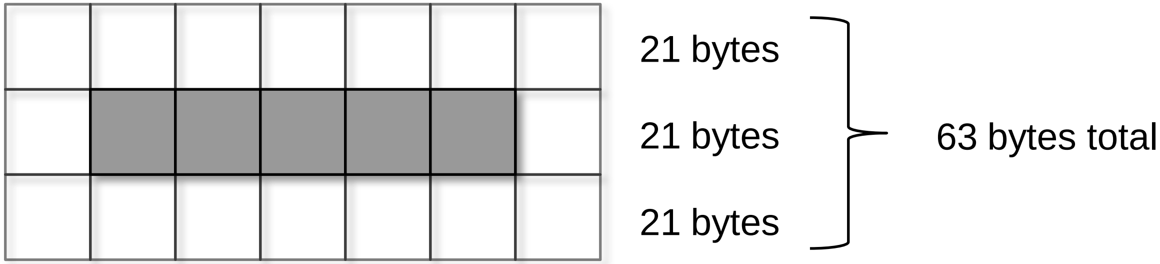
```
globalWorkSize[0] = image_height;
globalWorkSize[1] = (image_width / 5);
```

# OpenCL Laplace Case Study

From processing 1 pixel…



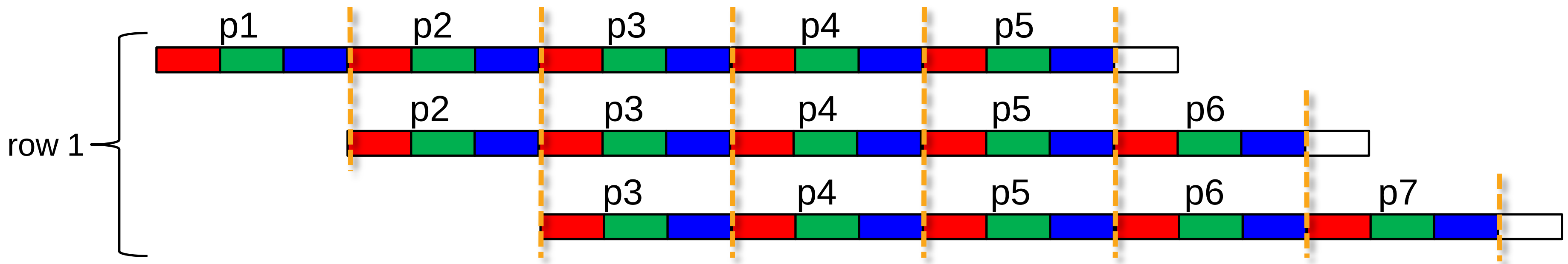

…to processing 5 pixels...



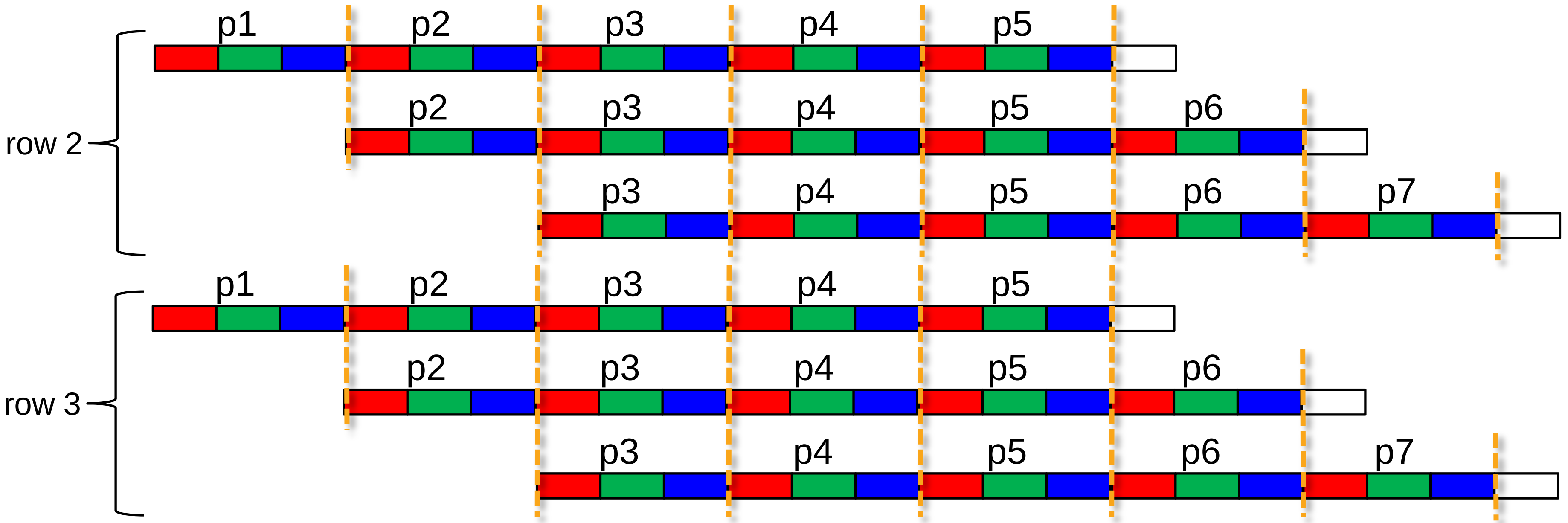

But we would like to load this data in a way that allows us to efficiently calculate the results in a single vector calculation…

# OpenCL Laplace Case Study

3 x overlapping, 16-byte reads from row1 (`vload16`)…

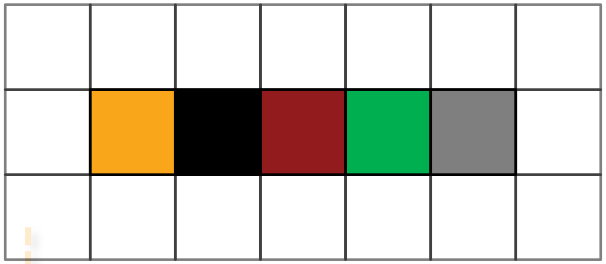


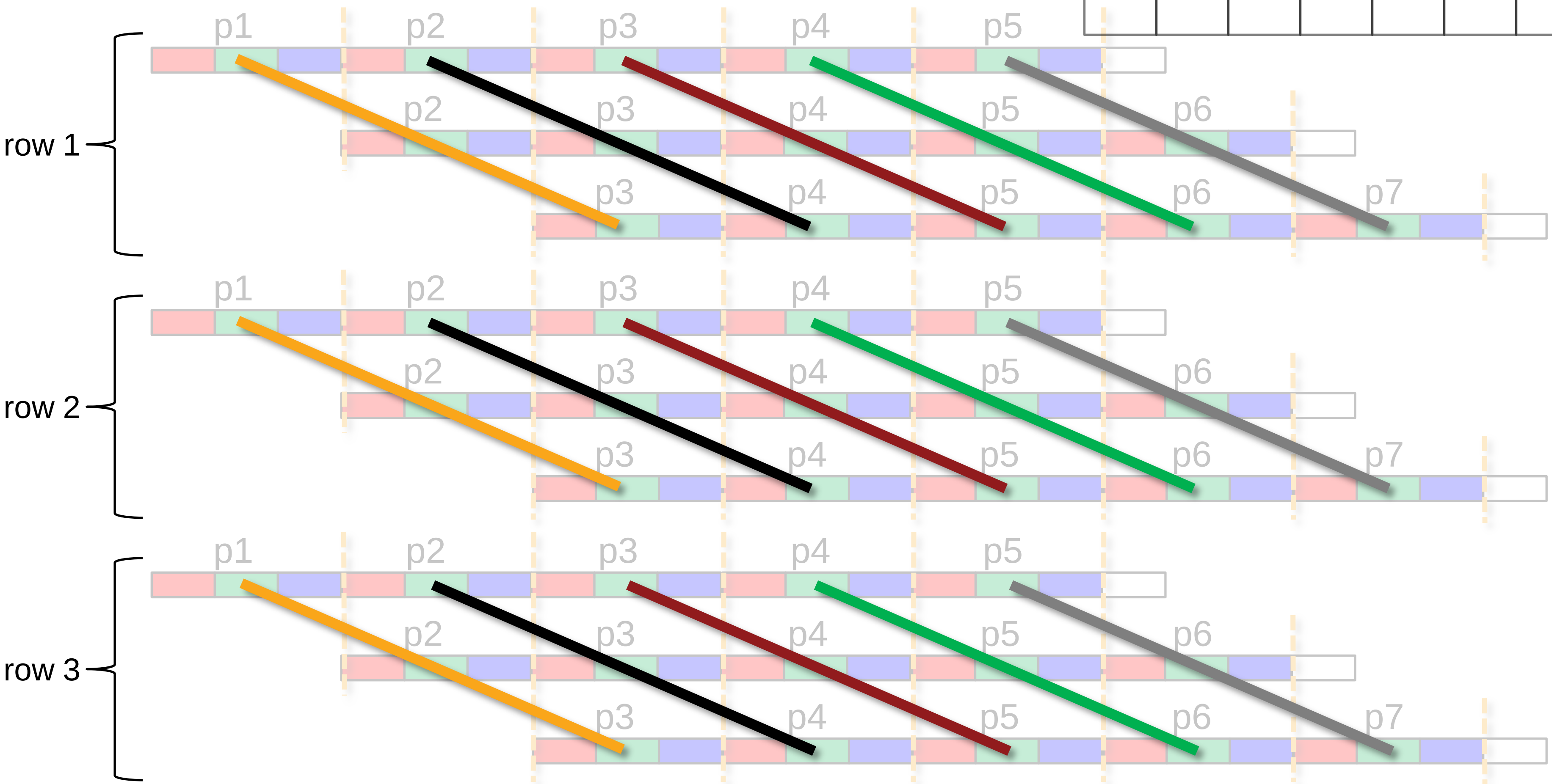

And the same for rows 2 and 3…



# OpenCL Laplace Case Study

The five pixels can then be computed as follows…





# OpenCL Laplace Case Study

```
__kernel void math(__global unsigned char *pdst, __global unsigned char *psrc, int width, int height)
{
    int y          = get_global_id(0);
    int x          = get_global_id(1);
    int w          = width;
    int h          = height;
    int ind        = x * 5 * 3 + w * y * 3;

    uchar16 row1a_    = vload16(0, psrc + ind);
    uchar16 row1b_    = vload16(0, psrc + ind + 3);
    uchar16 row1c_    = vload16(0, psrc + ind + 6);
    uchar16 row2a_    = vload16(0, psrc + ind + (w * 3));
    uchar16 row2b_    = vload16(0, psrc + ind + (w * 3) + 3);
    uchar16 row2c_    = vload16(0, psrc + ind + (w * 3) + 6);
    uchar16 row3a_    = vload16(0, psrc + ind + (w * 6));
    uchar16 row3b_    = vload16(0, psrc + ind + (w * 6) + 3);
    uchar16 row3c_    = vload16(0, psrc + ind + (w * 6) + 6);

    int16 row1a       = convert_int16(row1a_);
    int16 row1b       = convert_int16(row1b_);
    int16 row1c       = convert_int16(row1c_);
    int16 row2a       = convert_int16(row2a_);
    int16 row2b       = convert_int16(row2b_);
    int16 row2c       = convert_int16(row2c_);
    int16 row3a       = convert_int16(row3a_);
    int16 row3b       = convert_int16(row3b_);
    int16 row3c       = convert_int16(row3c_);

    int16 res         = (int)0 - row1a - row1b - row1c - row2a - row2b * (int)9 - row2c - row3a - row3b - row3c;
    res               = clamp(res, (int16)0, (int16)255);
    uchar16 res_row   = convert_uchar16(res);

    vstore8(res_row.s01234567, 0, pdst + ind);
    vstore4(res_row.s89ab,     0, pdst + ind + 8);
    vstore2(res_row.scd,       0, pdst + ind + 12);
    pdst[ind + 14]    = res_row.se;
}
```

Parameter 3 now refers to the width of the image / 5.

3 overlapping 16-byte reads for each of the 3 rows
(5 pixels-worth in each read)

Convert each 16-byte uchar vector to int16 vectors
(This happens for free!)

# OpenCL Laplace Case Study

```
__kernel void math(__global unsigned char *pdst, __global unsigned char *psrc, int width, int height)
{
    int y          = get_global_id(0);
    int x          = get_global_id(1);
    int w          = width;
    int h          = height;
    int ind        = x * 5 * 3 + w * y * 3;

    uchar16 row1a_    = vload16(0, psrc + ind);
    uchar16 row1b_    = vload16(0, psrc + ind + 3);
    uchar16 row1c_    = vload16(0, psrc + ind + 6);
    uchar16 row2a_    = vload16(0, psrc + ind + (w * 3));
    uchar16 row2b_    = vload16(0, psrc + ind + (w * 3) + 3);
    uchar16 row2c_    = vload16(0, psrc + ind + (w * 3) + 6);
    uchar16 row3a_    = vload16(0, psrc + ind + (w * 6));
    uchar16 row3b_    = vload16(0, psrc + ind + (w * 6) + 3);
    uchar16 row3c_    = vload16(0, psrc + ind + (w * 6) + 6);

    int16 row1a       = convert_int16(row1a_);
    int16 row1b       = convert_int16(row1b_);
    int16 row1c       = convert_int16(row1c_);
    int16 row2a       = convert_int16(row2a_);
    int16 row2b       = convert_int16(row2b_);
    int16 row2c       = convert_int16(row2c_);
    int16 row3a       = convert_int16(row3a_);
    int16 row3b       = convert_int16(row3b_);
    int16 row3c       = convert_int16(row3c_);

    int16 res         = (int)0 – row1a – row1b – row1c – row2a – row2b * (int)9 – row2c – row3a – row3b – row3c;
    res               = clamp(res, (int16)0, (int16)255);
    uchar16 res_row   = convert_uchar16(res);

    vstore8(res_row.s01234567, 0, pdst + ind);
    vstore4(res_row.s89ab,     0, pdst + ind + 8);
    vstore2(res_row.scd,       0, pdst + ind + 12);
    pdst[ind + 14]    = res_row.se;
}
```

Perform the Laplace calculation on all five pixels at once
Then clamp the values between 0 and 255 (using the BIFL!)

Convert back to uchar16… and then write 5 pixels to destination buffer

# OpenCL Laplace Case Study

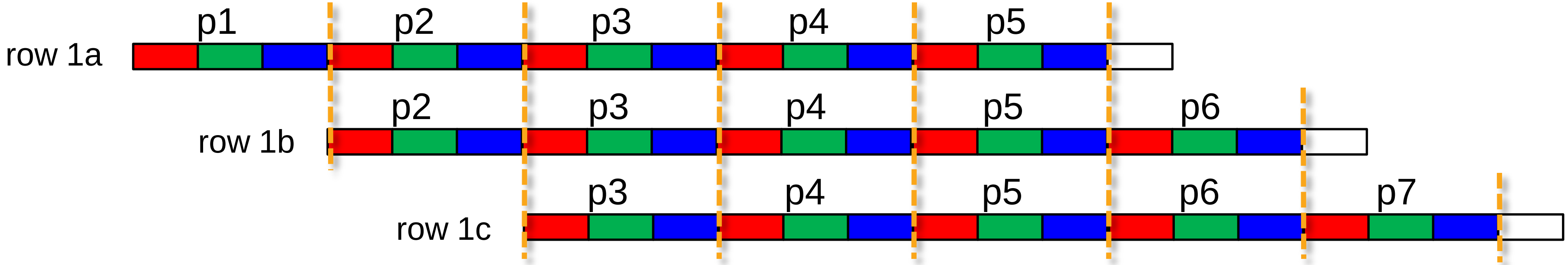
## Optimisation 1 Results

| Image | Pixels | Opt 1 |
|---|---|---|
| 768 x 432 | 331,776 | x1.5 |
| 2560 x 1600 | 4,096,000 | x1.3 |
| 2048 x 2048 | 4,194,304 | x1.8 |
| 5760 x 3240 | 18,662,400 | x3.5 |
| 7680 x 4320 | 33,177,600 | x3.7 |

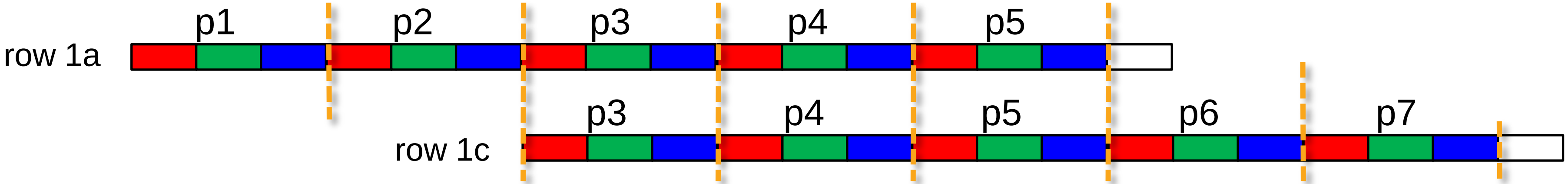
# OpenCL Laplace Case Study

## Optimisation 2

- We can reduce the number of loads
  - by synthesizing the middle vector row from the left and right rows…




**becomes…**




row 1b ⟵ row1(p2, p3, p4, p5) + row2(p6)

# OpenCL Laplace Case Study

## Optimisation 2

- We can reduce the number of loads
  - by synthesizing the middle vector row from the left and right rows…

```
uchar16 row1a_    = vload16(0, psrc + ind);
uchar16 row1b_    = vload16(0, psrc + ind + 3);
uchar16 row1c_    = vload16(0, psrc + ind + 6);
uchar16 row2a_    = vload16(0, psrc + ind + (w * 3));
uchar16 row2b_    = vload16(0, psrc + ind + (w * 3) + 3);
uchar16 row2c_    = vload16(0, psrc + ind + (w * 3) + 6);
uchar16 row3a_    = vload16(0, psrc + ind + (w * 6));
uchar16 row3b_    = vload16(0, psrc + ind + (w * 6) + 3);
uchar16 row3c_    = vload16(0, psrc + ind + (w * 6) + 6);
```

becomes…

```
uchar16 row1a_    = vload16(0, psrc + ind);
uchar16 row1c_    = vload16(0, psrc + ind + 6);
uchar16 row1b_    = (uchar16)(row1a_.s3456789a, row1c_.s56789abc);
uchar16 row2a_    = vload16(0, psrc + ind + (w * 3));
uchar16 row2c_    = vload16(0, psrc + ind + (w * 3) + 6);
uchar16 row2b_    = (uchar16)(row2a_.s3456789a, row2c_.s56789abc);
uchar16 row3a_    = vload16(0, psrc + ind + (w * 6));
uchar16 row3c_    = vload16(0, psrc + ind + (w * 6) + 6);
uchar16 row3b_    = (uchar16)(row3a_.s3456789a, row3c_.s56789abc);
```

# OpenCL Laplace Case Study

## Optimisation 2 Results

| Image | Pixels | Opt 1 |
|---|---|---|
| 768 x 432 | 331,776 | x1.5 |
| 2560 x 1600 | 4,096,000 | x1.3 |
| 2048 x 2048 | 4,194,304 | x1.8 |
| 5760 x 3240 | 18,662,400 | x3.5 |
| 7680 x 4320 | 33,177,600 | x3.7 |

| Opt 2 |
|---|
| x1.5 |
| x4.2 |
| x3.3 |
| x5.3 |
| x5.5 |

# OpenCL Laplace Case Study

## Optimisation 3

- Use **`short16`** instead of **`int16`**
  - smaller register use allows for a larger **`CL_KERNEL_WORK_GROUP_SIZE`** available for kernel execution

```
int16 row1a       = convert_int16(row1a_);
int16 row1b       = convert_int16(row1b_);
int16 row1c       = convert_int16(row1c_);
int16 row2a       = convert_int16(row2a_);
int16 row2b       = convert_int16(row2b_);
int16 row2c       = convert_int16(row2c_);
int16 row3a       = convert_int16(row3a_);
int16 row3b       = convert_int16(row3b_);
int16 row3c       = convert_int16(row3c_);

int16 res         = (int)0 – row1a – row1b – row1c – row2a – row2b * (int)9 – row2c – row3a – row3b – row3c;
res               = clamp(res, (int16)0, (int16)255);
uchar16 res_row   = convert_uchar16(res);
```

becomes…

```
short16 row1a     = convert_short16(row1a_);
short16 row1b     = convert_short16(row1b_);
short16 row1c     = convert_short16(row1c_);
short16 row2a     = convert_short16(row2a_);
short16 row2b     = convert_short16(row2b_);
short16 row2c     = convert_short16(row2c_);
short16 row3a     = convert_short16(row3a_);
short16 row3b     = convert_short16(row3b_);
short16 row3c     = convert_short16(row3c_);

short16 res       = (short)0 – row1a – row1b – row1c – row2a – row2b * (short)9 – row2c – row3a – row3b – row3c;
res               = clamp(res, (short16)0, (short16)255);
uchar16 res_row   = convert_uchar16(res);
```

# OpenCL Laplace Case Study

## Optimisation 3 Results

| Image | Pixels | Opt 1 | Opt 2 | Opt 3 |
|---|---|---|---|---|
| 768 x 432 | 331,776 | x1.5 | x1.5 | x1.5 |
| 2560 x 1600 | 4,096,000 | x1.3 | x4.2 | x5.8 |
| 2048 x 2048 | 4,194,304 | x1.8 | x3.3 | x3.4 |
| 5760 x 3240 | 18,662,400 | x3.5 | x5.3 | x7.8 |
| 7680 x 4320 | 33,177,600 | x3.7 | x5.5 | x8.1 |

# OpenCL Laplace Case Study

- **Optimisation 4**
  - Try 4-pixels per work-item rather than 5
    - With some image sizes perhaps the driver can optimize more efficiently
      when 4 pixels are being calculated

```
__kernel void math(__global unsigned char *pdst, __global unsigned char *psrc, int width, int height)
{
    int y           = get_global_id(0);
    int x           = get_global_id(1);
    int w           = width;
    int h           = height;
    int ind         = x * 5 * 3 + w * y * 3;

    ...
```

becomes…

```
__kernel void math(__global unsigned char *pdst, __global unsigned char *psrc, int width, int height)
{
    int y           = get_global_id(0);
    int x           = get_global_id(1);
    int w           = width;
    int h           = height;
    int ind         = x * 4 * 3 + w * y * 3;

    ...
```

# OpenCL Laplace Case Study

- **Optimisation 4**
  - And our date write out becomes simpler…

```
...

    vstore8(res_row.s01234567, 0, pdst + ind);
    vstore4(res_row.s89ab,     0, pdst + ind + 8);
    vstore2(res_row.scd,       0, pdst + ind + 12);
    pdst[ind + 14]     = res_row.se;
```

becomes…

```
...

    vstore8(res_row.s01234567, 0, pdst + ind);
    vstore4(res_row.s89ab,     0, pdst + ind + 8);
```

…and we need to adjust the setup code to adjust the work-item count.

# OpenCL Laplace Case Study

## Optimisation 4 Results

| Image | Pixels | Opt 1 | Opt 2 | Opt 3 |
|---|---|---|---|---|
| 768 x 432 | 331,776 | x1.5 | x1.5 | x1.5 |
| 2560 x 1600 | 4,096,000 | x1.3 | x4.2 | x5.8 |
| 2048 x 2048 | 4,194,304 | x1.8 | x3.3 | x3.4 |
| 5760 x 3240 | 18,662,400 | x3.5 | x5.3 | x7.8 |
| 7680 x 4320 | 33,177,600 | x3.7 | x5.5 | x8.1 |

| Opt 4 |
|---|
| x1.7 |
| x5.4 |
| x8.8 |
| x7.0 |
| x7.2 |

# OpenCL Laplace Case Study

## Optimisation 5

- How about 8 pixels per work-item?

# OpenCL Laplace Case Study

```
__kernel void math(__global unsigned char *pdst, __global unsigned char *psrc, int w, int h)
{
    const int y       = get_global_id(0);
    const int x       = get_global_id(1) * 8;
    int       ind     = (x + w * y) * 3;
    short16   acc_xy;
    short8    acc_z;

    uchar16 l_0    = vload16(0, psrc + ind);
    uchar16 r_0    = vload16(0, psrc + ind + 14);
    short16 a_xy_0 = convert_short16((uchar16)(l_0.s0123456789abcdef));
    short8  a_z_0  = convert_short8((uchar8)(r_0.s23456789));
    short16 b_xy_0 = convert_short16((uchar16)(l_0.s3456789a, l_0.sbcde, r_0.s1234));
    short8  b_z_0  = convert_short8((uchar8)(r_0.s56789abc));
    short16 c_xy_0 = convert_short16((uchar16)(l_0.s6789abcd, r_0.s01234567));
    short8  c_z_0  = convert_short8((uchar8)(r_0.s89abcdef));
    acc_xy         = -a_xy_0 - b_xy_0 - c_xy_0;
    acc_z          = -a_z_0  - b_z_0  - c_z_0;

    uchar16 l_1    = vload16(0, psrc + ind + (w * 3));
    uchar16 r_1    = vload16(0, psrc + ind + (w * 3) + 14);
    short16 a_xy_1 = convert_short16((uchar16)(l_1.s0123456789abcdef));
    short8  a_z_1  = convert_short8((uchar8)(r_1.s23456789));
    short16 b_xy_1 = convert_short16((uchar16)(l_1.s3456789a, l_0.sbcde, r_0.s1234));
    short8  b_z_1  = convert_short8((uchar8)(r_1.s56789abc));
    short16 c_xy_1 = convert_short16((uchar16)(l_1.s6789abcd, r_0.s01234567));
    short8  c_z_1  = convert_short8((uchar8)(r_1.s89abcdef));
    acc_xy         = -a_xy_1 + b_xy_1 * (short)9 - c_xy_1;
    acc_z         += -a_z_1  + b_z_1  * (short)9 - c_z_1;

    uchar16 l_2    = vload16(0, psrc + ind + (w * 6));
    uchar16 r_2    = vload16(0, psrc + ind + (w * 6) + 14);
    short16 a_xy_2 = convert_short16((uchar16)(l_2.s0123456789abcdef));
    short8  a_z_2  = convert_short8((uchar8)(r_2.s23456789));
    short16 b_xy_2 = convert_short16((uchar16)(l_2.s3456789a, l_0.sbcde, r_0.s1234));
    short8  b_z_2  = convert_short8((uchar8)(r_2.s56789abc));
    short16 c_xy_2 = convert_short16((uchar16)(l_2.s6789abcd, r_0.s01234567));
    short8  c_z_2  = convert_short8((uchar8)(r_2.s89abcdef));
    acc_xy         += -a_xy_2 - b_xy_2 - c_xy_2;
    acc_z          += -a_z_2  - b_z_2  - c_z_2;

    short16 res_xy = clamp(acc_xy, (short16)0, (short16)255);
    short8 res_z   = clamp(acc_z,  (short8)0,  (short8)255);

    vstore16(convert_uchar16(res_xy), 0, pdst + ind);
    vstore8(convert_uchar8(res_z), 0, pdst + ind + 16);
}
```

# OpenCL Laplace Case Study

## Results

| Image | Pixels | Opt 1 | Opt 2 | Opt 3 | Opt 4 | Opt 5 |
|---|---|---|---|---|---|---|
| 768 x 432 | 331,776 | x1.5 | x1.5 | x1.5 | x1.7 | x1.5 |
| 2560 x 1600 | 4,096,000 | x1.3 | x4.2 | x5.8 | x5.4 | x4.4 |
| 2048 x 2048 | 4,194,304 | x1.8 | x3.3 | x3.4 | x8.8 | x7.2 |
| 5760 x 3240 | 18,662,400 | x3.5 | x5.3 | x7.8 | x7.0 | x5.4 |
| 7680 x 4320 | 33,177,600 | x3.7 | x5.5 | x8.1 | x7.2 | x5.5 |

# OpenCL Laplace Case Study

## Summary

- **Original version: Scalar code**
- **Optimisation 1: Vectorize**
  - Process 5 pixels per work-item
  - Vector loads (`vloadn`) and vector stores (`vstoren`)
  - Much better use of the GPU ALU: Up to **x3.7** performance increase
- **Optimisation 2: Synthesised loads**
  - Reduce the number of loads by synthesising values
  - Performance increase: up to **x5.5** over original
- **Optimisation 3: Replace `int16` with `short16`**
  - Reduces the kernel register count
  - Performance increase: up to **x8.1** over original
- **Optimisation 4: Try 4 pixels per work-item rather than 5**
  - Performance increase: up to **x8.8** over original
    - but it depends on the image size
- **Optimisation 5: Try 8 pixels per work-item**
  - A step too far!

# GPU Compute on Mobile Devices

Tim Hartley

Jon Kirkham