Parallel Computing with GPUs: CUDA Memory

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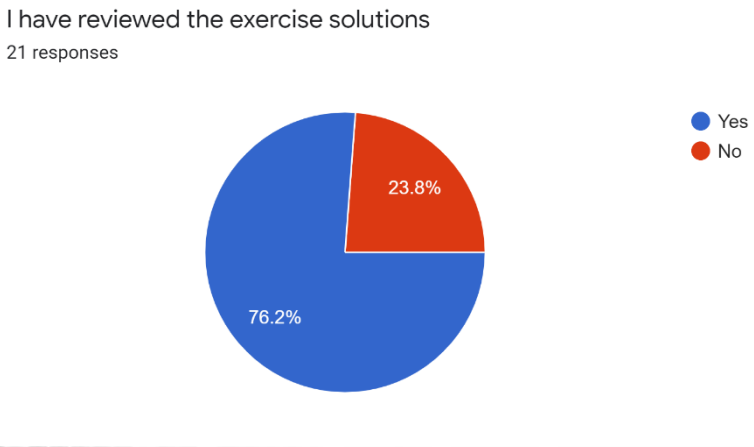
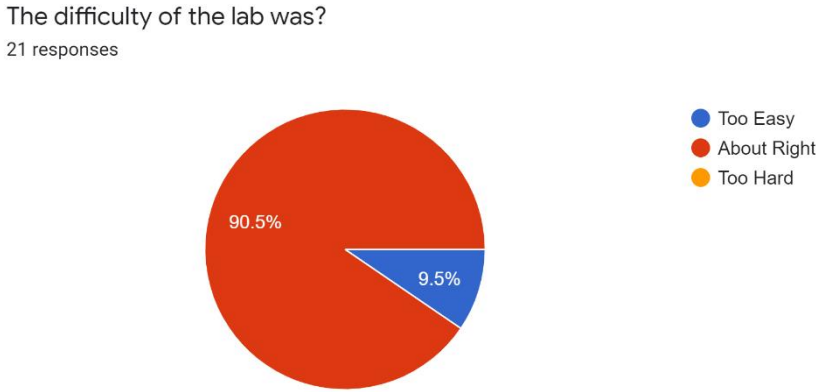
PDC 2020 CUDA 스터디 3주차

<Lecture 9 - CUDA Memory>

Week 3 feedback (only 4 responses for week 5)





Feedback:

“It would be helpful to see the solutions / a "perfect" explanation for 2.3.4 - Which is the best performing technique and why.”

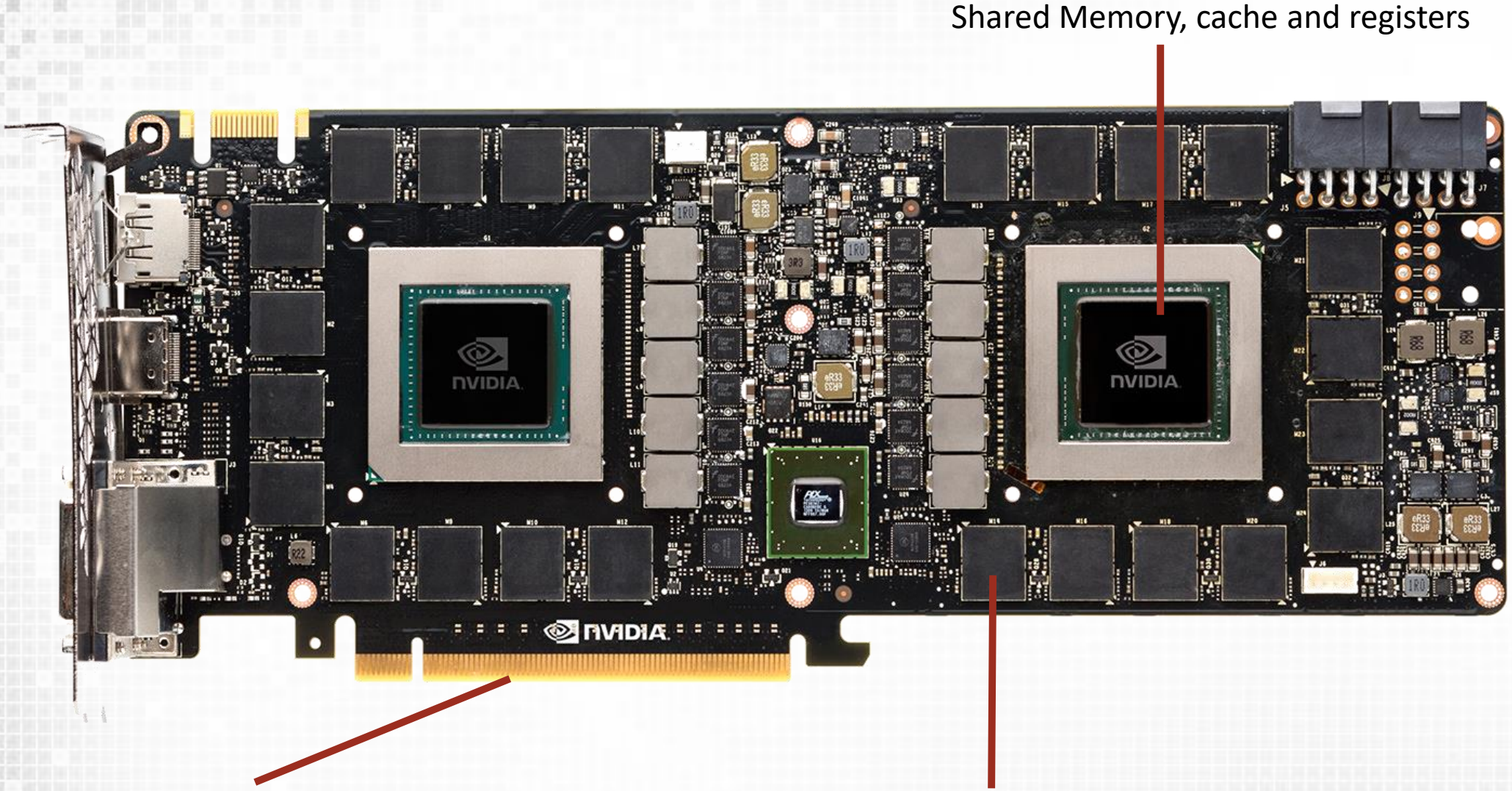
“Very good example with the Mandelbrot set but the lab could have been used to reinforce previous concepts. For example by creating a program from scratch and then optimising with open mp.”

Previous Lecture and Lab

- We started developing some CUDA programs
- We had to move data from the host to the device memory
- We learnt about mapping problems to grids of thread blocks and how to index data

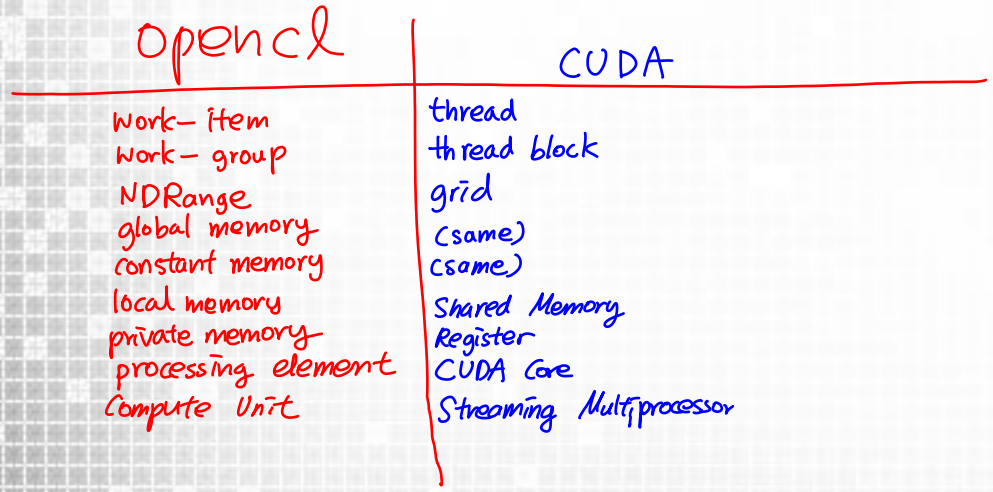
- ❑Memory Hierarchy Overview
- ❑Global Memory
- ❑Constant Memory
- ❑Texture and Read-only Memory
- ❑Roundup & Performance Timing

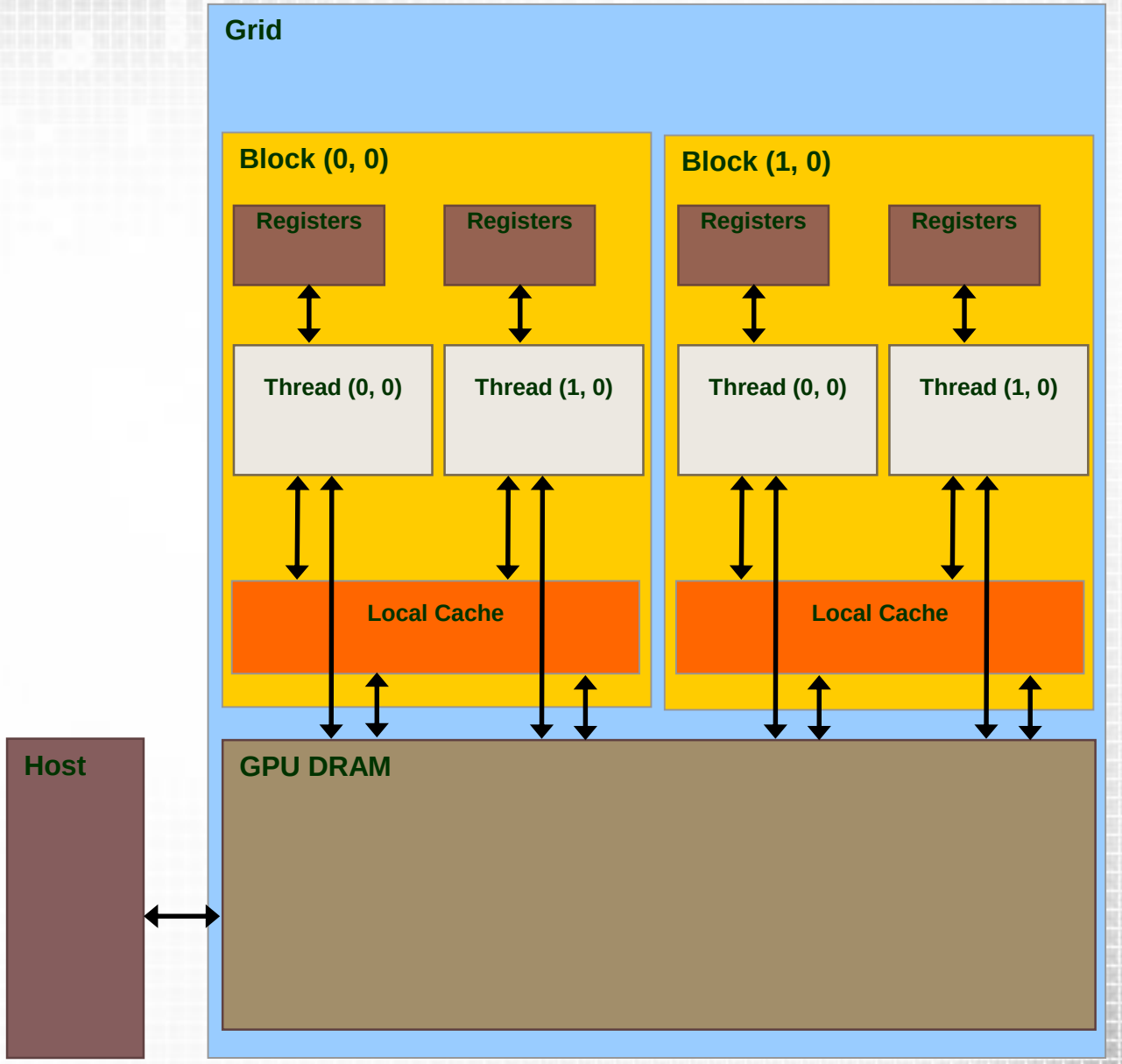
GPU Memory (GTX Titan Z)



Simple Memory View

- Threads have access to;
  - **Registers**
    - Read/Write **per thread**
  - **Local memory**
    - Read/Write **per thread**
  - **Local Cache**
    - Read/Write **per block**
  - **Main DRAM Memory**
    - Read/Write **per grid**





Local Memory

- **Local memory (Thread-Local Global Memory)**
  - Read/Write per thread
  - Local cache does not physically exist
    - Mapped to reserved area in global memory
    - Usually uses some form of more local cache (e.g. L1)
  - Used for variables if you exceed the number of registers available
    - Very bad for perf!
  - Arrays go in local memory if they are indexed with non constants

```
__global__ void localMemoryExample
(int * input)
{

    int a;
    int b;
    int index;

    int myArray1[4];
    int myArray2[4];
    int myArray3[100];

    index = input[threadIdx.x];
    a = myArray1[0];
    b = myArray2[index];

}
```

non constant index

https://stackoverflow.com/questions/10297067/in-a-cuda-kernel-how-do-i-store-an-array-in-local-thread-memory

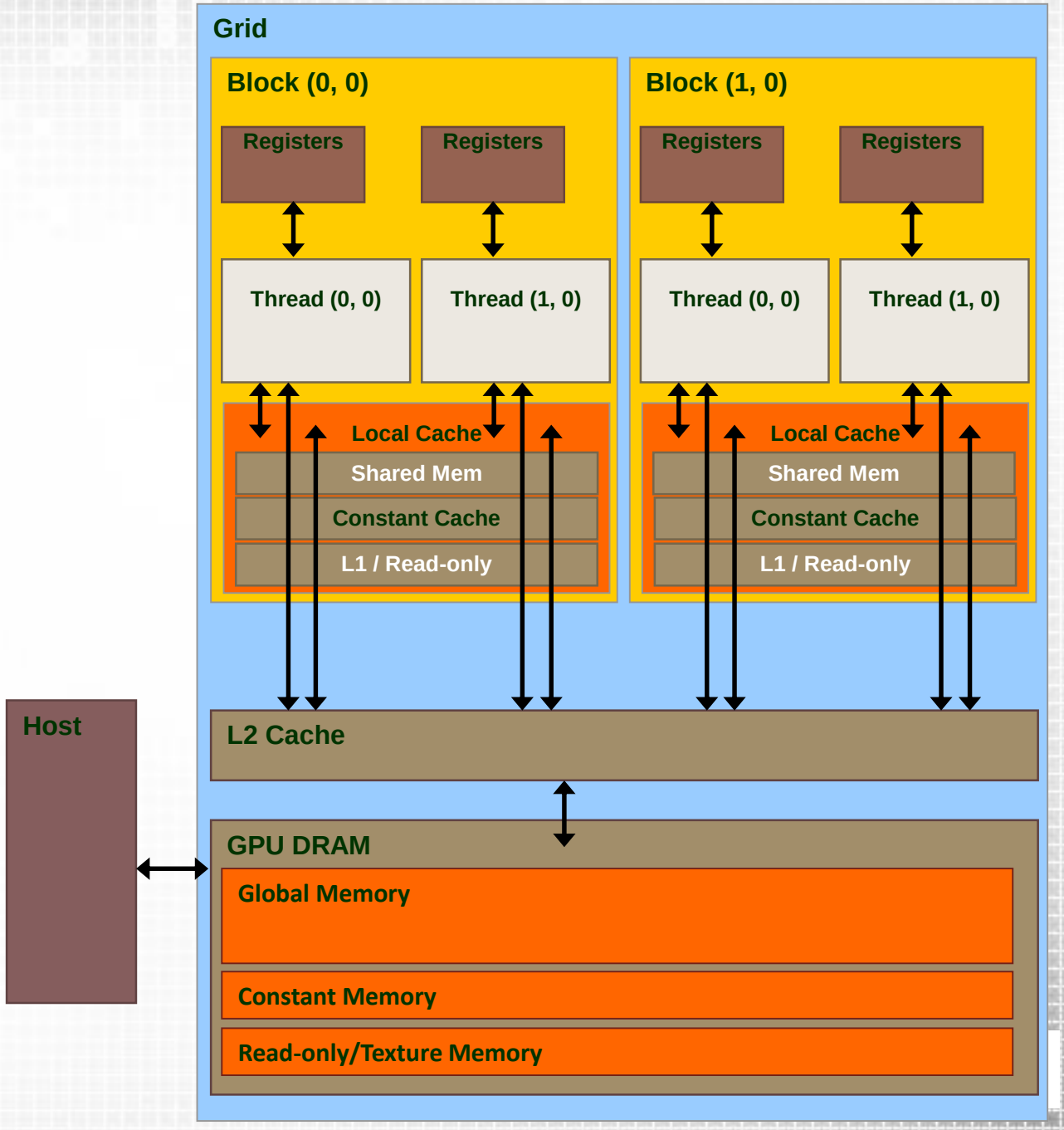
Memory Latencies

- What is the cost of accessing each area of memory?
  - On chip caches are MUCH lower latency

	Cost (cycles)
Register	1
Global	200-800
Shared memory	~1
L1	1
Constant	~1 (if cached)
Read-only (tex)	1 if cached (same as global if not)

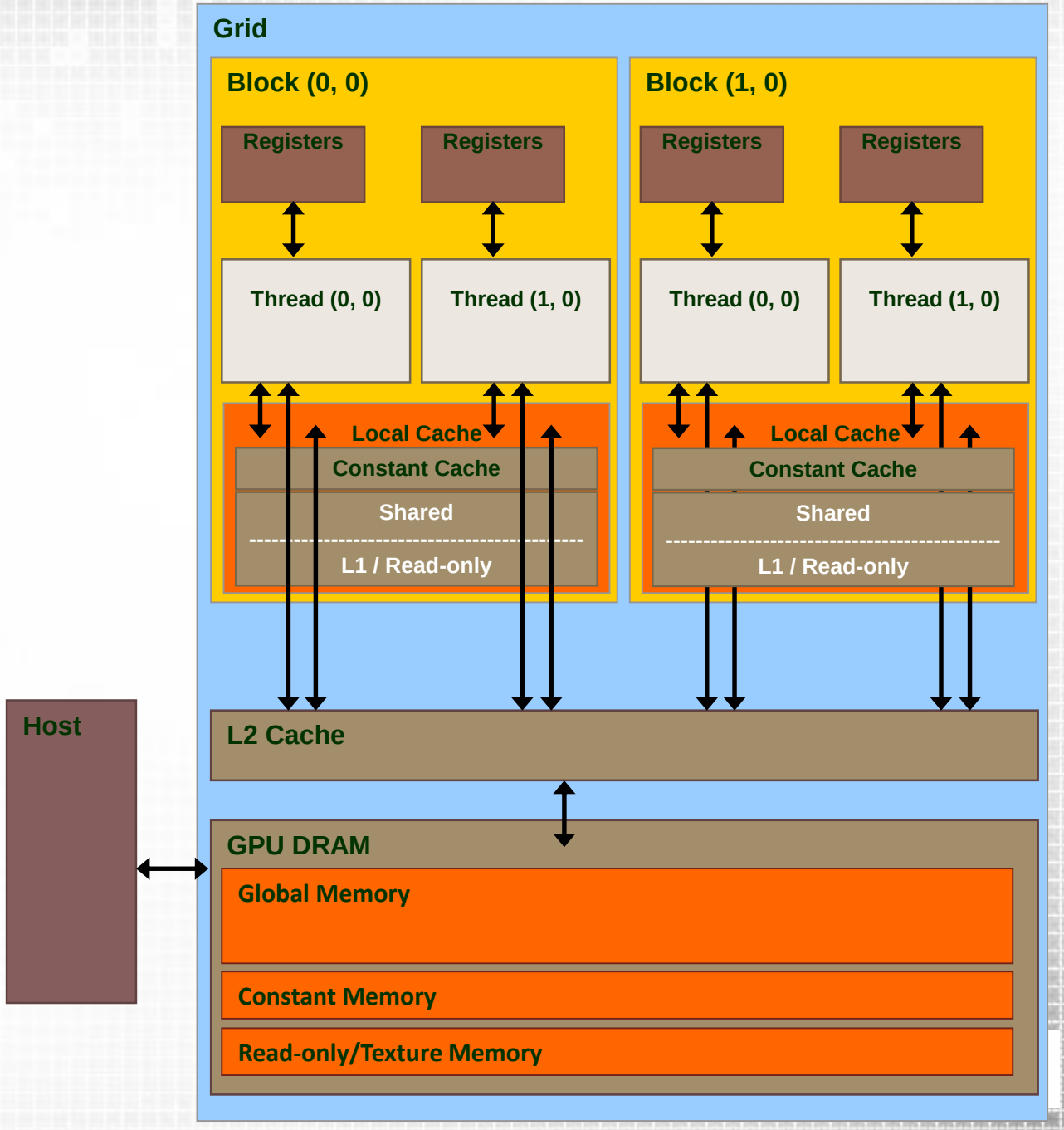
Maxwell/Pascal

- Each Thread has access to
  - **Registers**
  - **Local memory**
  - Main DRAM Memory via L2 cache
    - Global Memory
      - Can be read via Unified Data Cache
    - Constant Memory
      - Via **L2 cache** and per **block Constant cache**
    - Unified L1/Texture Cache
      - Same cache used for read only or texture reads
    - Dedicated Shared Memory
      - User configurable cache



Volta

- Each Thread has access to
  - Registers
  - Local memory
  - Main DRAM Memory via L2 cache
    - Global Memory
      - Can be read via Unified Data Cache
    - Constant Memory
      - Via L2 cache and per block Constant cache
    - **Unified Shared/L1/Texture Cache**
      - Same cache used for read only or texture reads
      - Amount of shared memory configurable at runtime



Cache and Memory Sizes

	Pascal (P100) GP100	Volta (V100) GV100
Register File Size	*256KB per SM*	*256KB per SM*
Shared Memory	*64KB Dedicated*	*Configurable up to 96KB*
Constant Memory	*64KB DRAM 8KB Cache per SM*	*64KB DRAM 8KB Cache per SM*
L1/Read Only Memory	*24KB per SM Dedciated*	*Configurable up to 128KB per SM*
L2 Cache Size	*4096KB*	*6144KB*
Device Memory	*16GB*	*16GB*
DRAM Interface	*4096-bit HBM2*	*4096-bit HBM2*

Ampere (A100)
GA100

256kB

up to
164kB

192 KB

40960 KB

40GB

https://devblogs.nvidia.com/inside-volta/

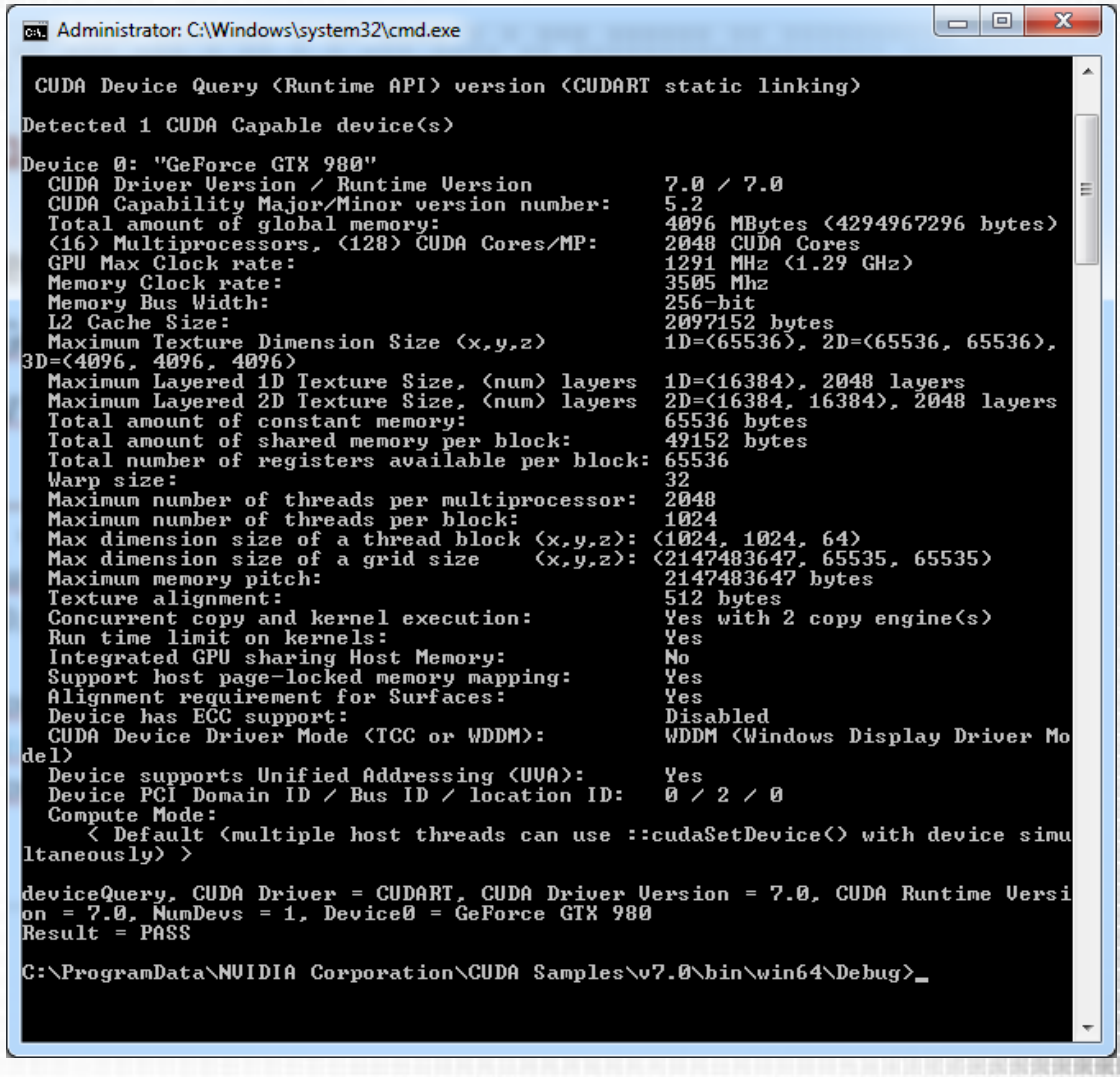
5120 bit
HBM2

The University Of Sheffield.

Device Query

- What are the specifics of my GPU?
  - Use `cudaGetDeviceProperties`
  - E.g.
    - `deviceProp.sharedMemPerBlock`
  - CUDA SDK deviceQry example

```
int deviceCount = 0;
cudaGetDeviceCount(&deviceCount);
for (int dev = 0; dev < deviceCount; ++dev)
{
    cudaSetDevice(dev);
    cudaDeviceProp deviceProp;
    cudaGetDeviceProperties(&deviceProp, dev);
    …
}
```



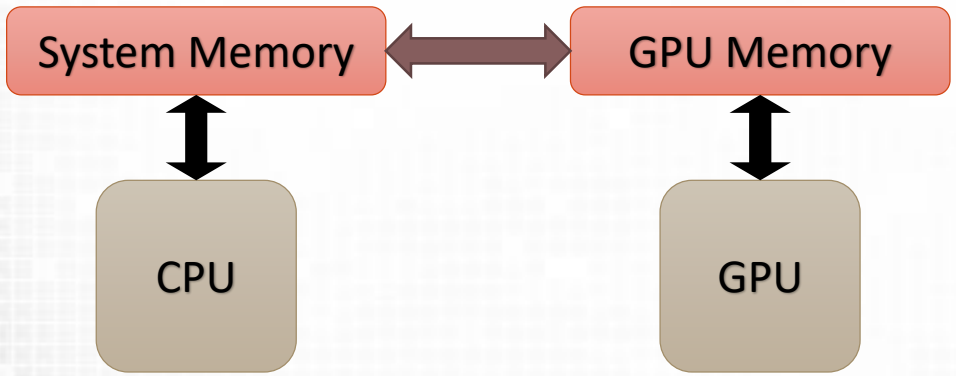
- ❑Memory Hierarchy Overview
- ❑Global Memory
- ❑Constant Memory
- ❑Texture and Read-only Memory
- ❑Roundup & Performance Timing

Dynamic vs Static Global Memory

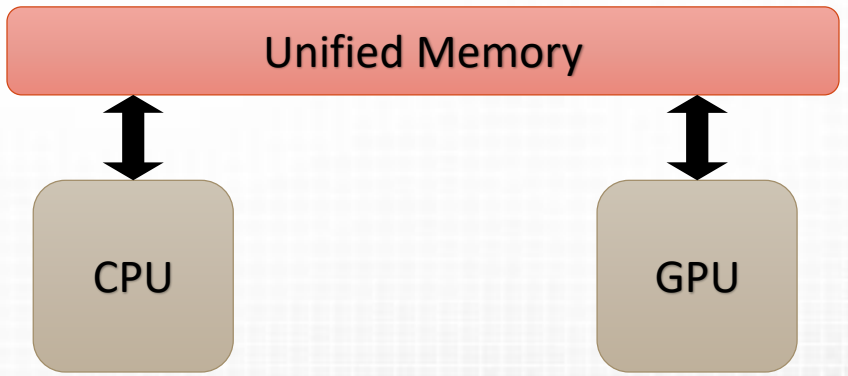
- In the previous lab we dynamically defined GPU memory
  - Using `cudaMalloc()`
- You can also statically define (and allocate) GPU global memory
  - Using `__device__` qualifier 호스트가 부를수 없는 디바이스 함수 / 함수의 반환 타입이 제한되지 X
  - Requires memory copies are performed using `cudaMemcpyToSymbol` or `cudaMemcpyFromSymbol`
  - See example from last weeks lecture
- This is the difference between the following in C
  - `int my_static_array[1024];`
  - `int *my_dynamic_array = (int*) malloc(1024*sizeof(int));`

Unified Memory

- So far the developer view is that GPU and CPU have separate memory
  - Memory must be explicitly copied
  - Deep copies required for complex data structures
- Unified Memory changes that view



CUDA 6.0+
Kepler+



Unified Memory Example

C Code

```
void sortfile(FILE *fp, int N) {
  char *data;
  data = (char *)malloc(N);

  fread(data, 1, N, fp);

  qsort(data, N, 1, compare);


  use_data(data);

  free(data);
}
```

CUDA (6.0+) Code

```
void sortfile(FILE *fp, int N) {
  char *data;
  cudaMallocManaged(&data, N);

  fread(data, 1, N, fp);

  gpu_qsort(data, N, 1, compare);
  cudaDeviceSynchronize();

  use_data(data);

  cudaFree(data);
}
```

- CUDA의 디바이스 함수는 호스트 스레드와 동시에 실행 (OpenCL 커널 실행과 동일)
- 호스트-디바이스간 동기화를 위해 cudaDeviceSynchronize (OpenCL: clFinish)

Implications of CUDA Unified Managed Memory

- Simpler porting of code
- Memory is only *virtually* unified
  - GPU still has discrete memory
  - It still has to be transferred via PCIe (or NVLINK)
- Easier management of data to and from the device
  - Explicit memory movement is not required
  - Similar to the way the OS handles virtual memory
- Issues
  - Requires look ahead and paging to ensure memory is in the correct place (and synchronised)
  - It is not as fast as hand tuned code which has finer explicit control over transfers
- *We will manage memory movement ourselves!*

- ❑Memory Hierarchy Overview
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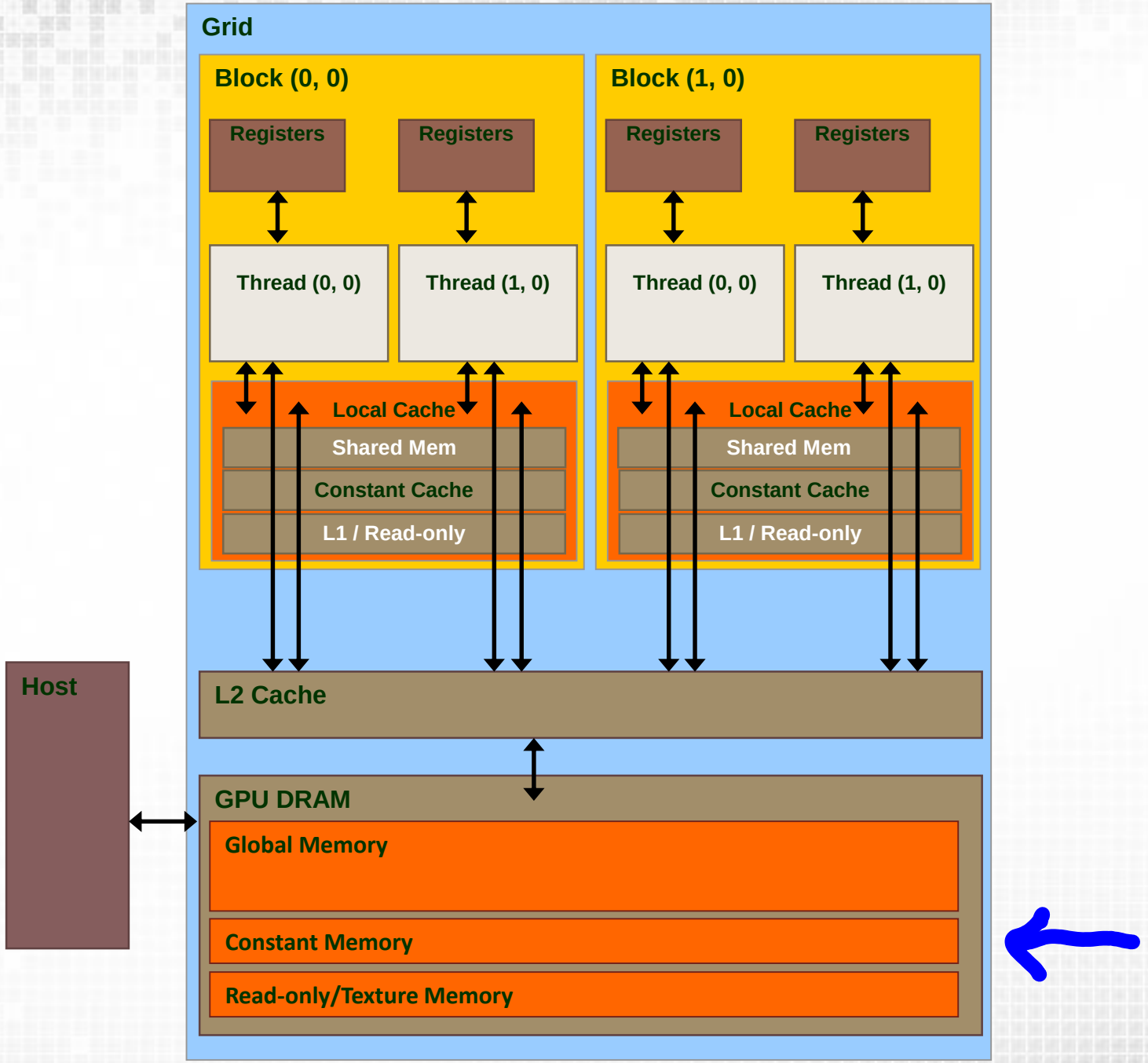
- ❑Constant Memory
- ❑Texture and Read-only Memory
- ❑Roundup & Performance Timing



Constant Memory

- Constant Memory
  - Stored in the devices global memory
  - Read through the per SM constant cache
  - Set at runtime
  - When using correctly only 1/16 of the traffic compared to global loads
- When to use it?
  - When small amounts of data are **read only**
  - When values are **broadcast** to threads in a half warp (of 16 threads)
  - Very fast when cache hit
  - Very slow when no cache hit
- How to use
  - Must be **statically** (compile-time) defined as a symbol using `__constant__` qualifier
  - Value(s) must be copied using **cudaMemcpytoSymbol**.

Constant Memory Broadcast

- …. When values are **broadcast** to threads in a half warp (groups of 16 threads)

```
__constant__ int my_const[16];

__global__ void vectorAdd() {
int i = blockIdx.x;

int value = my_const[i % 16];
}
```

```
__constant__ int my_const[16];

__global__ void vectorAdd() {
int i = blockIdx.x * blockDim.x + threadIdx.x;

int value = my_const[i % 16];
}
```

Which is good use of constant memory?

Constant Memory

- Question: Should I convert `#define` to constants?
  - E.g. `#define MY_CONST 1234`
- Answer: No
  - Leave alone
  - `#defines` are embed in the code by pre-processors
  - They don't take up registers as they are embed within the instruction space
    - i.e. are replaced with literals by the pre-processor
- Only replace constants that may change at runtime (but not during the GPU programs)

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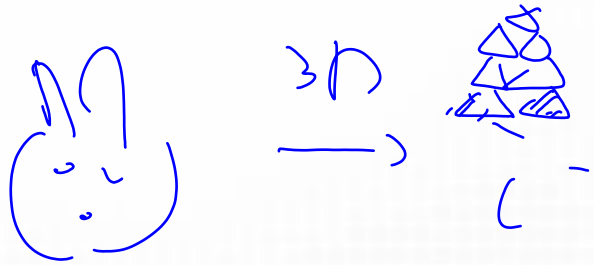
Read-only and Texture Memory

- Separate in Kepler but unified with L1 thereafter
  - Same use case but used in different ways

- When to use read-only or texture
  - When data is read only
  - Good for bandwidth limited kernels
  - Regular memory accesses with good locality (think about the way textures are accessed)
  - Texture cache can outperform read only cache for certain scenarios
    - Normalisation/interpolation
    - 2D and 3D loads
  - Read only cache can outperform texture cache
    - Loads of 4 byte values



- Two Methods for utilising Read-only/Texture Memory
  - Bind memory to texture (or use advanced bindless textures in CUDA 5.0+)
  - Hint the compiler to load via read-only cache

텍스쳐를 처리할때는 원래의 3d 객체 위에 2d 텍스쳐를 입힘. 이 때 하나의 2d 텍스쳐가 여러번 참조될 경우가 많기 때문에 텍스쳐 메모리라고 따로 이름붙여서 사용.
https://forums.developer.nvidia.com/t/texture-memory-when-to-use/12607

Texture Memory Binding

- Known as bound texture (or texture reference method)

```
#define N 1024
texture<float, 1, cudaReadModeElementType> tex;

__global__ void kernel() {
  int i = blockIdx.x * blockDim.x + threadIdx.x;
  float x = tex1Dfetch(tex, i);
}


int main() {
  float *buffer;
  cudaMalloc(&buffer, N*sizeof(float));
  cudaBindTexture(0, tex, buffer, N*sizeof(float));
  kernel << <grid, block >> >();
  cudaUnbindTexture(tex);
  cudaFree(buffer);
}
```

Texture Memory Binding

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#define N 1024
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__global__ void kernel() {
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  cudaBindTexture(0, tex, buffer, N*sizeof(float));
  kernel << <grid, block >> >();
  cudaUnbindTexture(tex);
  cudaFree(buffer);
}
```

Must be either;

- `char`, `short`, `long`, `long long`, `float` or `double`

Vector Equivalents are also permitted e.g.

- `uchar4`

Texture Memory Binding

- Known as bound texture (or texture reference method)

```
#define N 1024
texture<float, 1, cudaReadModeElementType> tex;

__global__ void kernel() {
  int i = blockIdx.x * blockDim.x + threadIdx.x;
  float x = tex1Dfetch(tex, i);
}


int main() {
  float *buffer;
  cudaMalloc(&buffer, N*sizeof(float));
  cudaBindTexture(0, tex, buffer, N*sizeof(float));
  kernel << <grid, block >> >();
  cudaUnbindTexture(tex);
  cudaFree(buffer);
}
```

Dimensionality:

- cudaTextureType1D (1)
- cudaTextureType2D (2)
- cudaTextureType3D (3)
- cudaTextureType1DLayered (4)
- cudaTextureType2DLayered (5)
- cudaTextureTypeCubemap (6)
- cudaTextureTypeCubemapLayered (7)

Texture Memory Binding

- Known as bound texture (or texture reference method)

```
#define N 1024
texture<float, 1, cudaReadModeElementType> tex;

__global__ void kernel() {
  int i = blockIdx.x * blockDim.x + threadIdx.x;
  float x = tex1Dfetch(tex, i);
}


int main() {
  float *buffer;
  cudaMalloc(&buffer, N*sizeof(float));
  cudaBindTexture(0, tex, buffer, N*sizeof(float));
  kernel << <grid, block >> >();
  cudaUnbindTexture(tex);
  cudaFree(buffer);
}
```

Value normalization:

- cudaReadModeElementType
- cudaReadModeNormalizedFloat
  - Normalises values across range

Texture Memory Binding on 2D Arrays

```
#define N 1024
texture<float, 2, cudaReadModeElementType> tex;

__global__ void kernel() {
  int x = blockIdx.x * blockDim.x + threadIdx.x;
  int y = blockIdx.y * blockDim.y + threadIdx.y;
  float v = tex2D (tex, x, y);
}

int main() {
  float *buffer;
  cudaMalloc(&buffer, W*H*sizeof(float));
  cudaChannelFormatDesc desc = cudaCreateChannelDesc<float>();
  cudaBindTexture2D(0, tex, buffer, desc, W,
                    H, W*sizeof(float));
  kernel << <grid, block >> >();
  cudaUnbindTexture(tex);
  cudaFree(buffer);
}
```

- Use tex2D rather than tex1Dfetch for CUDA arrays
- Note that last arg of **cudaBindTexture2D** is pitch
  - Row size not != total size

Read-only Memory

- No textures required
- Hint to the compiler that the data is read-only without pointer aliasing
  - Using the `const` and `__restrict__` qualifiers
  - Suggests the compiler should use `__ldg` but does not guarantee it
- Not the same as `__constant__`
  - Does not require broadcast reading

```
#define N 1024

__global__ void kernel(float const* __restrict__ buffer) {
  int i = blockIdx.x * blockDim.x + threadIdx.x;
  float x1 = buffer[i];
  float x2 = __ldg(buffer[i]);
}


int main() {
  float *buffer;
  cudaMalloc(&buffer, N*sizeof(float));
  kernel << <grid, block >> >(buffer);
  cudaFree(buffer);
}
```

Probably read through read only cache

Definitely read through read only cache

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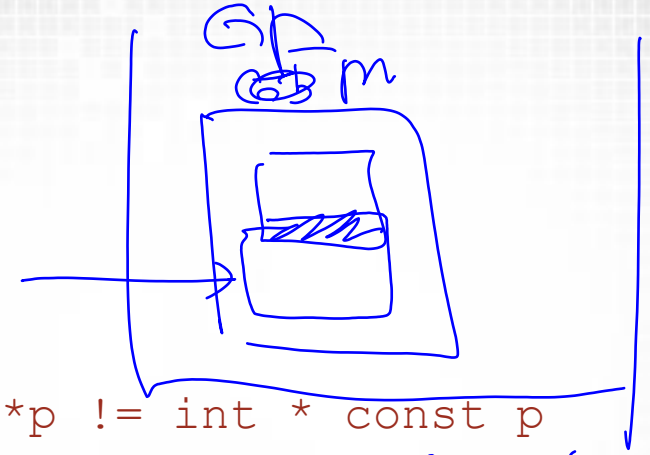
CUDA qualifiers summary

libcu++
C++20 SIMD (draft)
C++23 SIMD



- Where can a variable be accessed?
  - Is declared inside the kernel?
    - Then the host can not access it
    - Lifespan ends after kernel execution
  - Is declared outside the kernel
    - Then the host can access it (via `cudaMemcpyToSymbol`)

Kitchen Sink

- What about pointers?
  - They can point to anything
  - BUT are <u>not</u> typed on memory space
  - Be careful not to confuse the compiler

Remember!

```
const int *p != int * const p
```

West const East const

```
__device__ int my_global;
__constant__ int my_constant;

__global__ void my_kernel() {
  int my_local;

  int *ptr1 = &my_global;
  int *ptr2 = &my_local;
  const int *ptr3 = &my_constant;
}
```

CUDA의 포인터
- Variable type qualifier.
- 변수가 선언되면 해당 변수가 생성되는 메모리 공간을 지정

```
if (something)
  ptr1 = &my_global;
else
  ptr1 = &my_local;
```

Performance Measurements

- How can we benchmark our CUDA code?
- Kernel Calls are asynchronous
  - If we use a standard CPU timer it will measure only launch time not execution time
  - We could call `cudaDeviceSynchronise()` but this will stall the entire GPU pipeline
- Alternative: CUDA Events
  - Events are created with `cudaEventCreate()`
  - Timestamps can be set using `cudaEventRecord()`
  - `cudaEventElapsedTime()` sets the time in *ms* between the two events.

```
cudaEvent_t start, stop;
cudaEventCreate(&start);
cudaEventCreate(&stop);

cudaEventRecord(start);
my_kernel <<<(N /TPB), TPB >>>();
cudaEventRecord(stop);

cudaEventSynchronize(stop);
float milliseconds = 0;
cudaEventElapsedTime(&milliseconds,
                     start, stop);

cudaEventDestroy(start);
cudaEventDestroy(stop);
```

Summary

- The CUDA Memory Hierarchy varies between hardware generations
- Utilisation of local caches can have a big impact on the expected performance (1 cycle vs. 100s)
- Global memory can be declared statically or dynamically
- Constant cache good for small read only data accessed in broadcast by *nearby* threads
- Read-Only cache is larger than constant cache but does not have broadcast performance of constant cache
- Kernel variables are not available outside of the kernel

Acknowledgements and Further Reading

- http://devblogs.nvidia.com/parallelforall/cuda-pro-tip-kepler-texture-objects-improve-performance-and-flexibility/
- Mike Giles (Oxford): Different Memory and Variable Types
  - https://people.maths.ox.ac.uk/gilesm/cuda/
- Jared Hoberock: CUDA Memories
  - https://code.google.com/p/stanford-cs193g-sp2010/wiki/ClassSchedule
- CUDA Programming Guide
  - http://docs.nvidia.com/cuda/cuda-c-programming-guide/#texture-memory

NVIDIA Ampere Architecture in-depth: https://developer.nvidia.com/blog/nvidia-ampere-architecture-in-depth/

Google Compute Engine A2 (In Development)
Amazon EC2 P3 (In Service): https://aws.amazon.com/ko/ec2/instance-types/p3/
Microsoft ND A100 v4 VM (In Development)

https://mkblog.co.kr : 한글로 잘 정리된 GPU 관련 블로그

https://docs.nvidia.com/ngc/index.html

Bindless Textures (Advanced)

```
#define N 1024

__global__ void kernel(cudaTextureObject_t tex) {
  int i = blockIdx.x * blockDim.x + threadIdx.x;
  float x = tex1Dfetch(tex, i);
}

int main() {
  float *buffer;
  cudaMalloc(&buffer, N*sizeof(float));

  cudaResourceDesc resDesc;
  memset(&resDesc, 0, sizeof(resDesc));
  resDesc.resType = cudaResourceTypeLinear;
  resDesc.res.linear.devPtr = buffer;
  resDesc.res.linear.desc.f = cudaChannelFormatKindFloat;
  resDesc.res.linear.desc.x = 32; // bits per channel
  resDesc.res.linear.sizeInBytes = N*sizeof(float);

  cudaTextureDesc texDesc;
  memset(&texDesc, 0, sizeof(texDesc));
  texDesc.readMode = cudaReadModeElementType;

  cudaTextureObject_t tex;
  cudaCreateTextureObject(&tex, &resDesc, &texDesc, NULL);
  kernel << <grid, block >> >(tex);
  cudaDestroyTextureObject(tex);
  cudaFree(buffer);
}
```

- Texture Object Approach (Kepler+ and CUDA 5.0+)
- Textures only need to be created once
  - No need for binding an unbinding
- Better performance than binding
  - Small kernel overhead
- More details in programming guide
  - http://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html#texture-object-api

Address and Filter Modes (Bindless Textures)

- `addressMode`: Dictates what happened when address are out of bounds. E.g.
  - `cudaAddressModeClamp`: in which case addresses out of bounds will be clamped to range
  - `cudaAddressModeWrap`: in which case addressed out of bounds will wrap
- `filterMode`: Allows values read from the texture to be filtered. E.g.
  - `cudaFilterModeLinear`: Linearly interpolates between points
  - `cudaFilterModePoint`: Gives the value at the specific texture point

```
cudaTextureObject_t tex;
cudaCreateTextureObject(&tex, &resDesc, &texDesc, NULL);
tex.addressMode = cudaAddressModeClamp;
```

Bindless Textures

```
texture<float, 1, cudaReadModeElementType> tex;
tex.addressMode = cudaAddressModeClamp;
```

Bound Textures