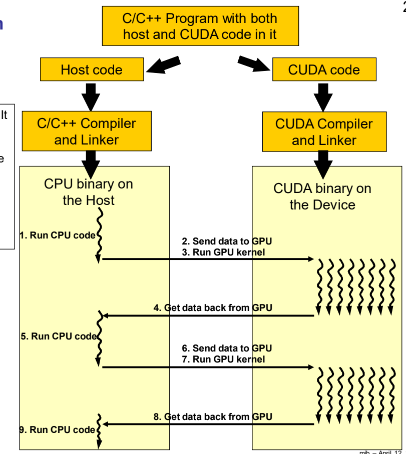
Nvidia's Compute Unified Device Architecture (CUDA)

Oregon State University
Mike Bailey
mjb@cs.oregonstate.edu

The CUDA Paradigm

CUDA is an NVIDIA-only product. It is very popular, and got the whole GPU-as-CPU ball rolling, which has resulted in other packages like OpenCL.

CUDA also comes with several libraries that are highly optimized for applications such as linear algebra and deep learning.



CUDA wants you to break the problem up into Pieces

If you were writing in **C/C++**, you would say:

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

If you were writing in **CUDA**, you would say:

```
__global__
void
ArrayMult( float *dA, float *dB, float *dC )
{
        int gid = blockIdx.x*blockDim.x + threadIdx.x;
        dC[gid] = dA[gid] * dB[gid];
}
```

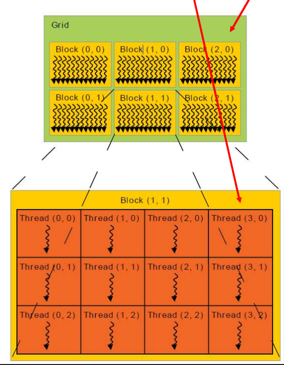
Think of this as having an implied for-loop around it, looping through all possible values of *gid*

Organization: Blocks are Arranged in Grids

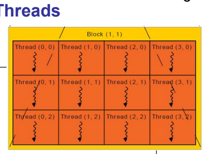
- The GPU's workload is divided into a **Grid of Blocks**
- Each Block's workload is divided into a **Grid of Threads**

Grid of Blocks

Grid of Threads

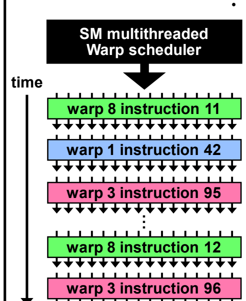


A Block is made up of a Grid of Threads



- The threads in a block each have *Thread ID* numbers within the Block
- Your CUDA program will use these Thread IDs to select work to do and pull the right data from memory
- Threads share data and synchronize while doing their share of the work
- Every **32** threads constitute a *"Warp"*. Each thread in a Warp simultaneously executes the same instruction on different pieces of data.
- But, it is likely that a Warp's execution will need to stop at some point, waiting for a memory access. This would make the execution go idle – bad! So, it is worthwhile to have multiple Warps worth of threads available so that when one Warp blocks, another Warp can be swapped in.
- The threads in a *Thread Block* can cooperate with each other by:
  - Synchronizing their execution
  - Efficiently sharing data through a low latency shared memory
- Threads from different blocks cannot cooperate

Scheduling



- The hardware implements low-overhead Warp switching
  - A Warp whose next instruction has operands ready for consumption is eligible to be executed.
  - All threads in one Warp execute the same instruction at any given time, but on different data.
  - Threads in different Warps will usually be executing different instructions at any given time

This tells you that there needs to be a bunch of Warps to work on so that something is always ready to run
If you can help it, these should be multiples of 32.

Threads Can Access Various Types of Storage

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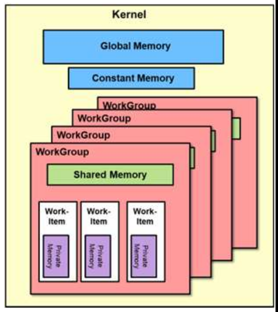
- Each thread has access to:
  - Its own R/W per-thread registers
  - Its own R/W per-thread private memory
- Each thread has access to:
  - Its block's R/W per-block shared memory
- Each thread has access to:
  - The entire R/W per-grid global memory
  - The entire read-only per-grid constant memory
  - The entire read-only per-grid texture memory
- The CPU can read and write global and, constant memories



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Different Types of CUDA Memory

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Memory	Location	Who Uses
Registers	On-chip	One thread
Private	On-chip	One thread
Shared	On-chip	All threads in that block
Global	Off-chip	All threads + Host
Constant	Off-chip	All threads + Host

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Thread Rules

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- Each Thread has its own registers and private memory
- Each Block can use at most some maximum number of registers, divided equally among all Threads
- Threads can share local memory with the other Threads in the same Block
- Threads can synchronize with other Threads in the same Block
- Global and Constant memory is accessible by all Threads in all Blocks
- 192 or 256 are good numbers of Threads per Block (multiples of the Warp size)

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A CUDA Thread can Query where it Fits in its "Community" of Threads and Blocks

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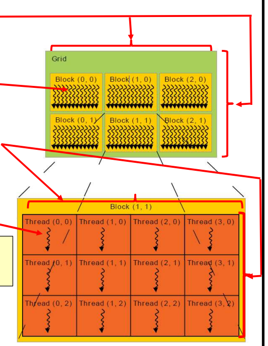
- `dim3 gridDim;`
  - Dimensions of the blocks in this grid
- `dim3 blockIdx;`
  - This block's indexes within this grid
- `dim3 blockDim;`
  - Dimensions of the threads in this block
- `dim3 threadIdx;`
  - This thread's indexes within the block

Note: It is as if dim3 is defined as:
typedef int[3] dim3;
(it's not really – it is actually defined within the CUDA compiler)



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A CUDA Thread needs to know where it Lives in its "Community" of Threads and Blocks

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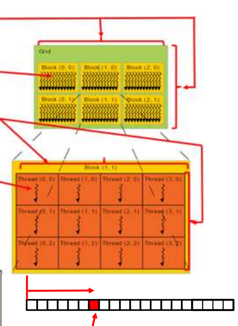
- `dim3 gridDim;`
  - Dimensions of the blocks in this grid
- `dim3 blockIdx;`
  - This block's indexes within this grid
- `dim3 blockDim;`
  - Dimensions of the threads in this block
- `dim3 threadIdx;`
  - This thread's indexes within the block

For a 1D problem:
int blockThreads = blockIdx.x*blockDim.x;
int gid = blockThreads + threadIdx.x;
C[gid] = A[gid]*B[gid];



For a 2D problem:
int blockNum = blockIdx.y*gridDim.x + blockIdx.x;
int blockThreads = blockNum*blockDim.x*blockDim.y;
int gid = blockThreads + threadIdx.y*blockDim.x + threadIdx.x;
C[gid] = A[gid]*B[gid];

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Types of CUDA Functions

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	Executed on the:	Only callable from the:
`__device__ float DeviceFunc()`	GPU	GPU
`__global__ void KernelFunc()`	GPU	Host
`__host__ float HostFunc()`	Host	Host

`__global__` defines a kernel function – it must return `void`

Note: "__" is 2 underscore characters

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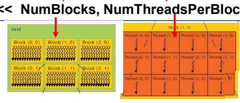
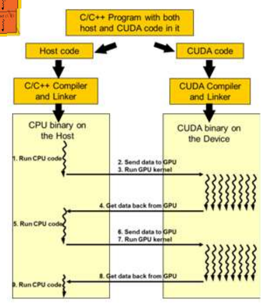
The C/C++ Program Calls a CUDA Kernel using a Special <<<…>>> Syntax

These are called "chevrons"

dim3 dim3

KernelFunction<<< NumBlocks, NumThreadsPerBlock >>>(arg1, arg2, …) ;

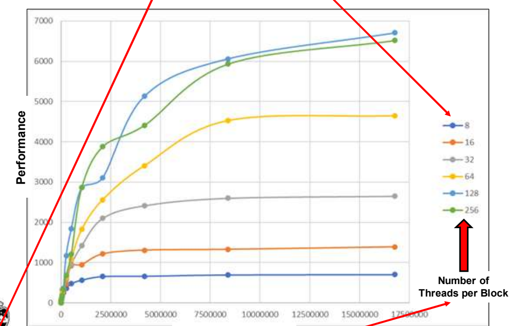




Note that this is just like calling the C/C++ function:
KernelFunction(arg1, arg2, …) ;
except that we have designated it to run on the GPU with a particular block/thread configuration.

One of my own Experiments with Number of Threads Per Block

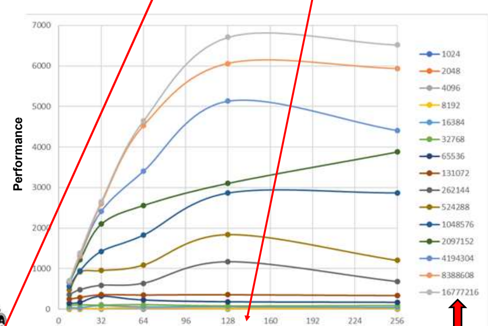
KernelFunction<<< NumBlocks, NumThreadsPerBlock >>>(arg1, arg2, …) ;



NumBlocks = DataSetSize / NumThreadsPerBlock

One of my own Experiments with Number of Threads Per Block

KernelFunction<<< NumBlocks , NumThreadsPerBlock >>>(arg1, arg2, …) ;



NumBlocks = DataSetSize / NumThreadsPerBlock

Getting CUDA Programs to Run under Linux

This is the Makefile we use:

```
CUDA_PATH      =    /usr/local/apps/cuda/cuda-10.1
CUDA_BIN_PATH  =    $(CUDA_PATH)/bin
CUDA_NVCC      =    $(CUDA_BIN_PATH)/nvcc

arrayMul:           arrayMul.cu
                    $(CUDA_NVCC) -o arrayMul  arrayMul.cu
```

This is the path where the CUDA tools are loaded on our Oregon State University systems.

Or, without the Makefile syntax:

```
/usr/local/apps/cuda/cuda-10.1/bin/nvcc  -o  arrayMul  arrayMul.cu
```

We also have the CUDA-11 and CUDA-12 tools loaded for your use. You can use them if you want. Bur, given the wide breadth of different Nvidia cards around campus, **CUDA-10** seems to be the one that will run ***everywhere***! I recommend you use it.

Getting CUDA Programs to Run under Visual Studio

1. Install Visual Studio if you haven't already. If you are an OSU student, go to:

https://azureforeducation.microsoft.com/devtools

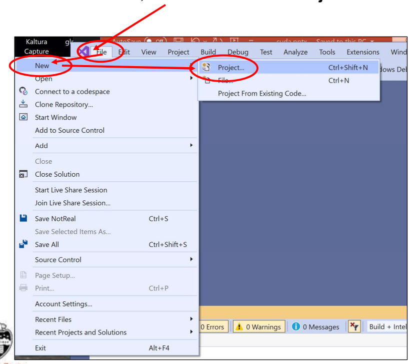
Click the blue **Sign In** button on the right.
Login using your ONID@oregonstate.edu username and password.
Install ***Visual Studio 2022 Enterprise***

2. Install the CUDA toolkit for Windows. It is available here:

https://developer.nvidia.com/cuda-downloads?target_os=Windows&target_arch=x86_64&target_version=11&target_type=exe_local

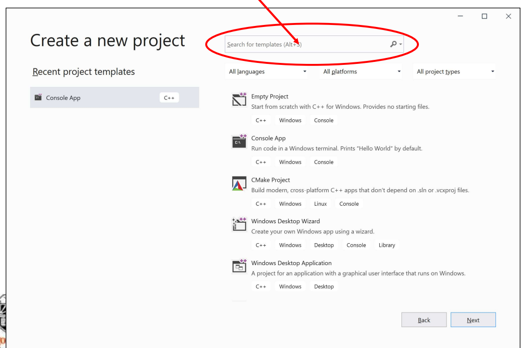
Getting CUDA Programs to Run under Visual Studio

From the main screen, click **File → New → Project…**



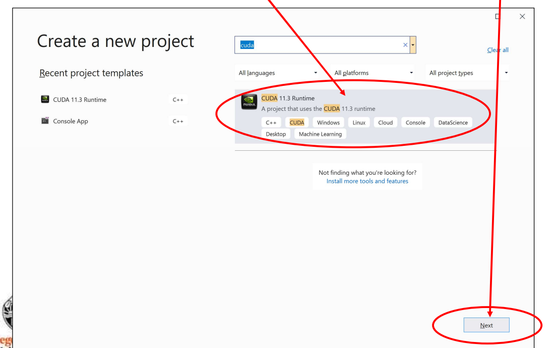
Getting CUDA Programs to Run under Visual Studio

Then, in this *templates* box, type: **CUDA**



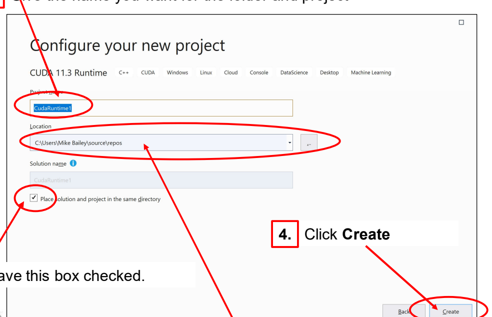
Getting CUDA Programs to Run under Visual Studio

After a few seconds, you will then see this. Click **Next**.



Getting CUDA Programs to Run under Visual Studio

2. Give the name you want for the folder and project



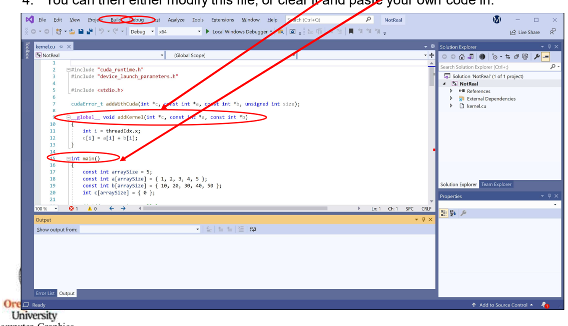
4. Click **Create**

3. Leave this box checked.

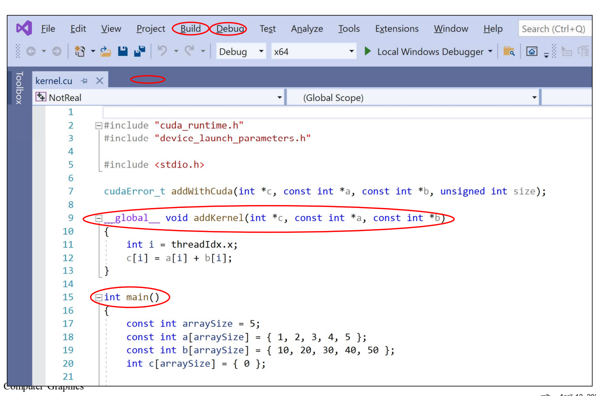
1. Navigate to the folder you want to contain this project folder.

Getting CUDA Programs to Run under Visual Studio

1. Visual Studio then "writes" a program for you. It has both CUDA and C++ code in it. Its structure looks just like our notes' examples.
2. You can click **Build** → **Build** to compile it, both the C++ and the CUDA code.
3. You can click **Debug** → **Start Without Debugging** to run it.
4. You can then either modify this file, or clear it and paste your own code in.



Getting CUDA Programs to Run under Visual Studio



Using CUDA and OpenMP Together

This is the Makefile we use on Linux:

```
CUDA_PATH       =   /usr/local/apps/cuda/cuda-10.1
CUDA_BIN_PATH   =   $(CUDA_PATH)/bin
CUDA_NVCC       =   $(CUDA_BIN_PATH)/nvcc

arrayMul:           arrayMul.cu
                    $(CUDA_NVCC) -o arrayMul  arrayMul.cu -Xcompiler -fopenmp
```

Or, on Linux, but without the Makefile syntax:

```
/usr/local/apps/cuda/cuda-10.1/bin/nvcc  -o  arrayMul  arrayMul.cu  -Xcompiler  -fopenmp
```

Or, in Visual Studio:

1. Go to the Project menu ⟶ Project Properties
2. Change the setting Configuration Properties ⟶ C/C++ ⟶ Language ⟶ OpenMP Support to **"Yes (/openmp)"**

We also have the CUDA-11 and CUDA-12 tools loaded for your use. You can use them if you want. Bur, given the wide breadth of different Nvidia cards around campus, **CUDA-10** seems to be the one that will run ***everywhere***! I recommend you use it.

Using Multiple GPU Cards with CUDA

```
int  deviceCount;
cudaGetDeviceCount(  &deviceCount  );

. . .

int device;         // 0  ≤  device  ≤  deviceCount - 1
cudaSetDevice( device );
```

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