# Nvidia's Compute Unified Device Architecture (CUDA)

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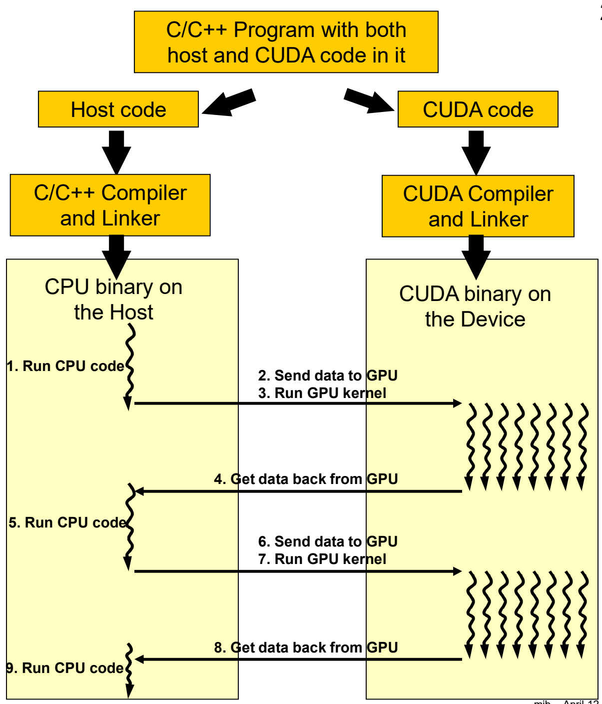
## The CUDA Paradigm




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.

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## 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*

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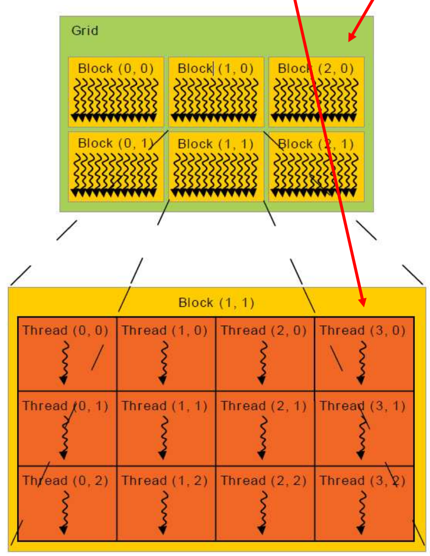
## Organization: Blocks are Arranged in Grids

- 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**

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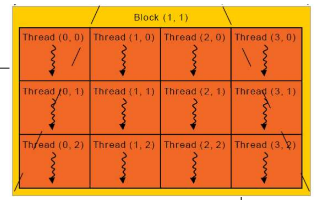
## A Block is made up of a Grid of Threads

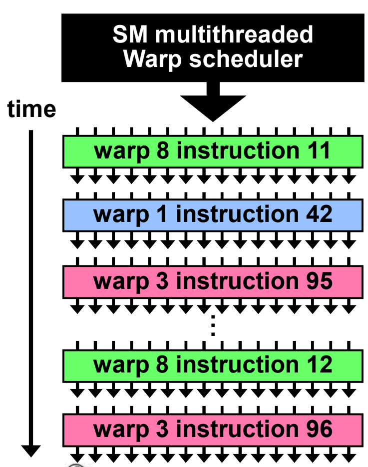



- The threads in a block each have *Thread ID* numbers within the Block
- Your CUDA program will use these Thread IDs to select work to do and pull the right data from memory
- Threads share data and synchronize while doing their share of the work
- Every **32** threads constitute a *"Warp".* Each thread 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.

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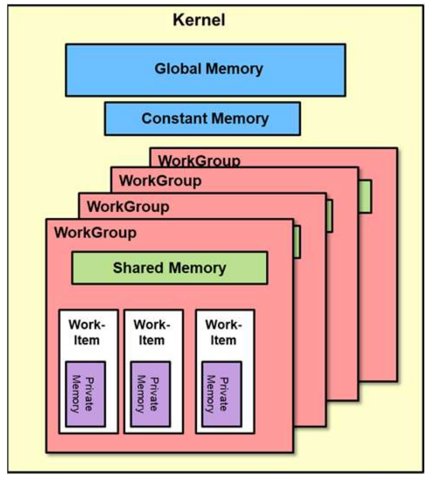
## Threads Can Access Various Types of Storage

- 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

| 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

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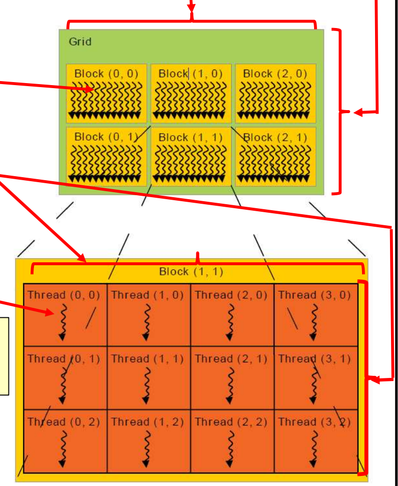
## A CUDA Thread can Query where it Fits in its "Community" of Threads and Blocks

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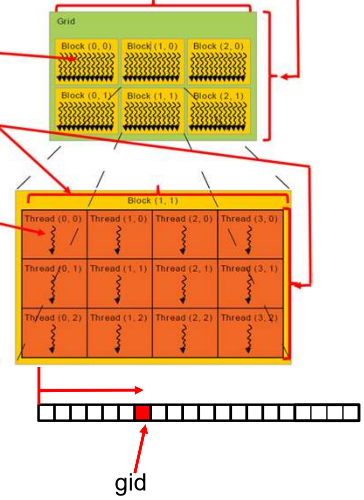
## A CUDA Thread needs to know where it Lives in its "Community" of Threads and Blocks

- `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];





## Types of CUDA Functions

| | 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`

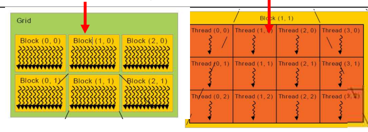
Note: "__" is *2* underscore characters

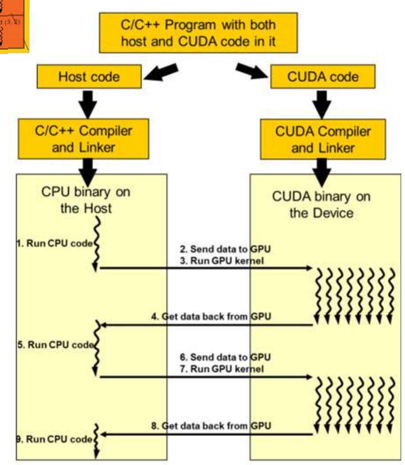
## The C/C++ Program Calls a CUDA Kernel using a Special <<<…>>> Syntax

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.

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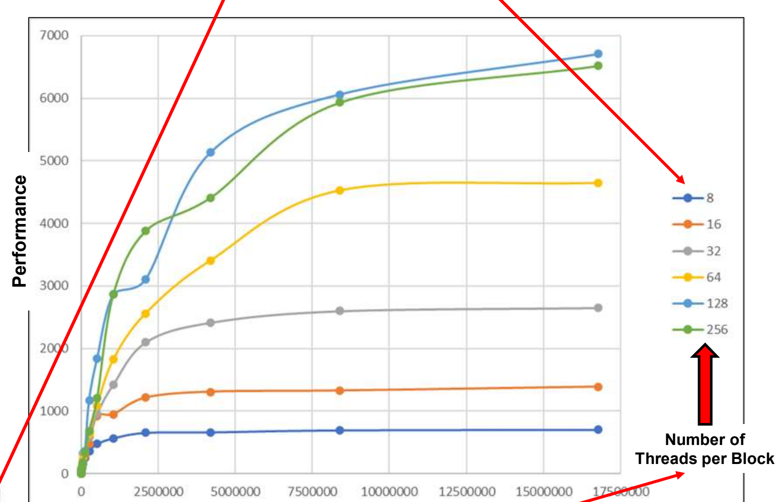
## One of my own Experiments with Number of Threads Per Block

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




**NumBlocks = DataSetSize / NumThreadsPerBlock**

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## One of my own Experiments with Number of Threads Per Block

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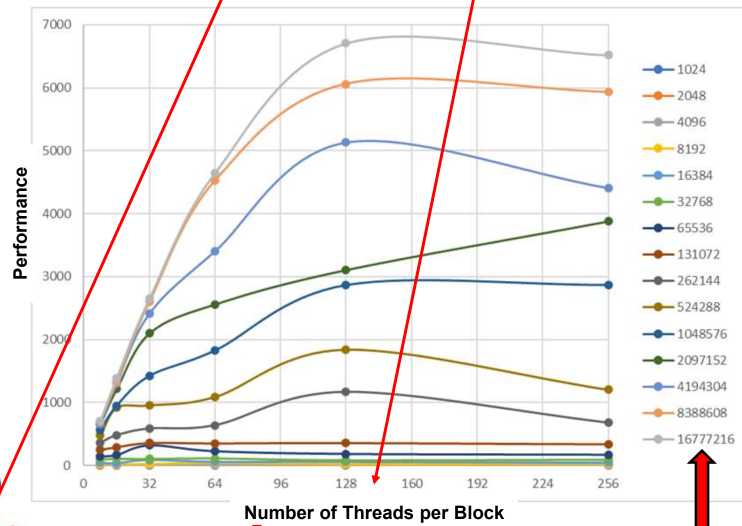
**KernelFunction<<< NumBlocks , NumThreadsPerBlock >>>( arg1, arg2, … ) ;**




**Dataset Size**

**NumBlocks = DataSetSize / NumThreadsPerBlock**

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## Getting CUDA Programs to Run under Linux

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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.

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## 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:

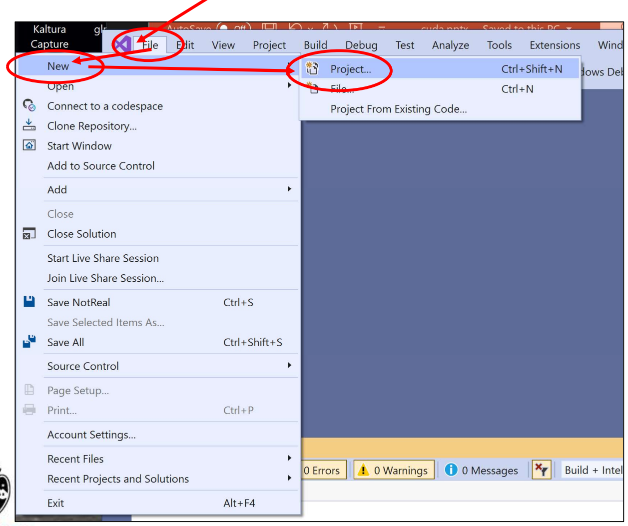
**https://developer.nvidia.com/cuda-downloads?target_os=Windows&target_arch=x86_64&target_version=11&target_type=exe_local**



## Getting CUDA Programs to Run under Visual Studio



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



# Getting CUDA Programs to Run under Visual Studio

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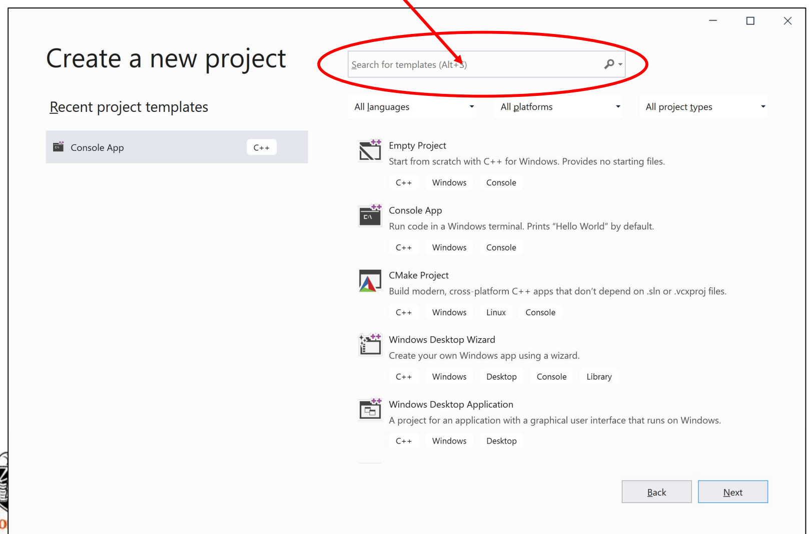
Then, in this *templates* box, type: **CUDA**

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# Getting CUDA Programs to Run under Visual Studio

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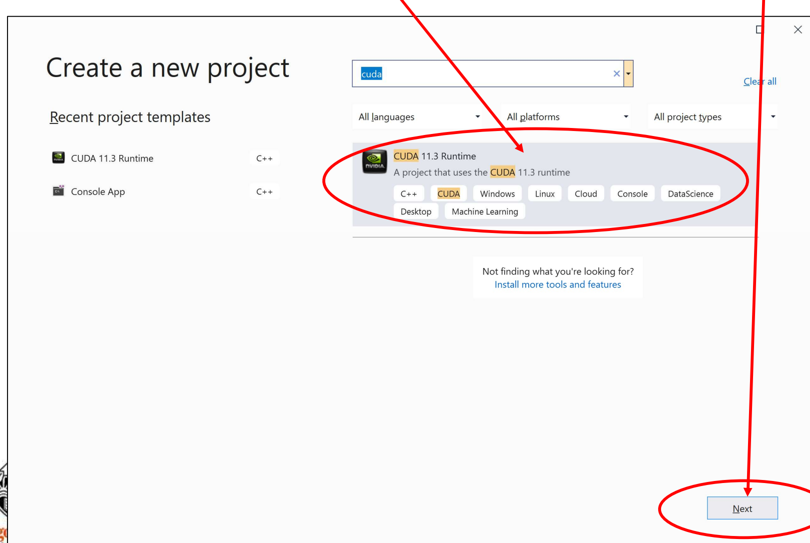
After a few seconds, you will then see this. Click **Next**.

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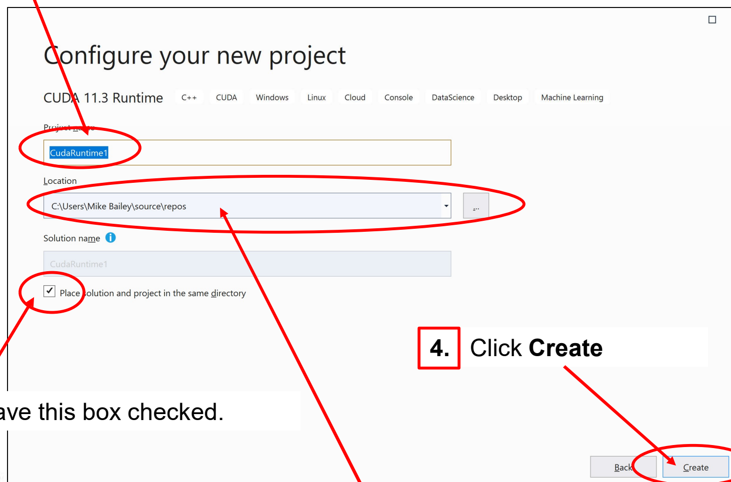
## Getting CUDA Programs to Run under Visual Studio



**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.

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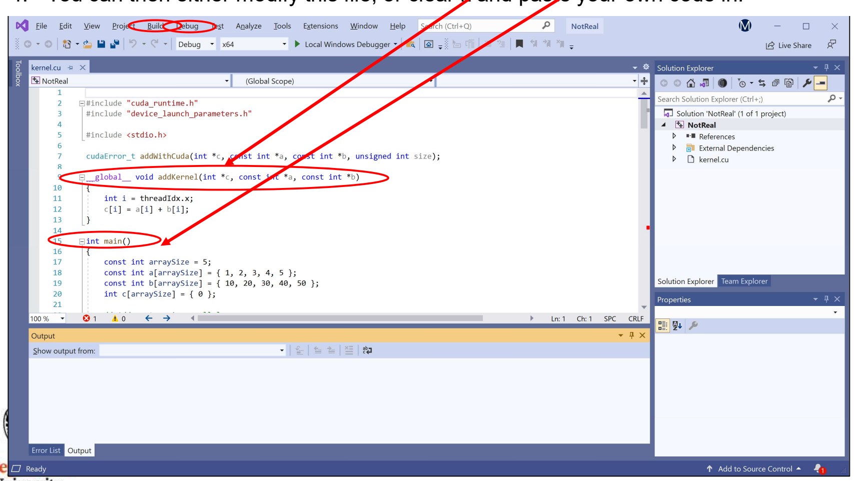
## Getting CUDA Programs to Run under Visual Studio



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.

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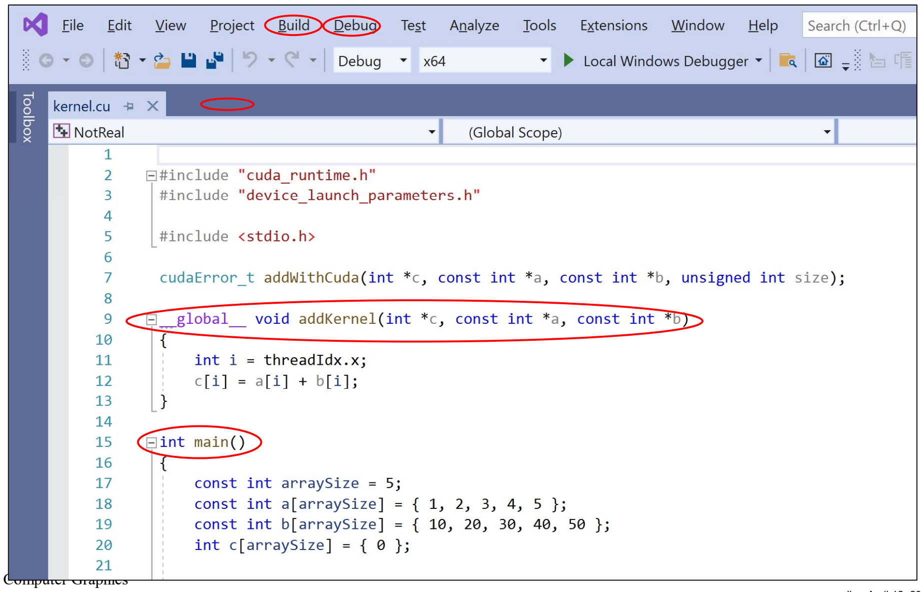
# Getting CUDA Programs to Run under Visual Studio








# 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 );
```