

Parallel Programming

Introduction to CUDA C/C++

Part I

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Data parallelism

- Question: Why modern software applications run slowly?
- Answer: too much data to process
 - Image-processing apps: million to trillions of pixels
 - Molecular dynamics apps: Thousands to billions of atoms
- Organizing the computation around the data such that we can execute the resulting independent computations in parallel to complete the overall job faster—often much faster.



CUDA C/C++: is extended-C/C++, allows us to write a program running on both CPU (sequential parts) and **GPU (massively parallel parts)**

```
#include <iostream>
#include <algorithm>

using namespace std;

#define N 1024
#define RADIUS 3
#define BLOCK_SIZE 16

__global__ void stencil_1d(int *in, int *out) {
    __shared__ int temp[BLOCK_SIZE * 2 * RADIUS];
    int gindex = threadIdx.x + blockIdx.x * blockDim.x;
    int lindex = threadIdx.x + RADIUS;

    // Read input elements into shared memory
    temp[lindex] = in[gindex - RADIUS];
    temp[lindex + BLOCK_SIZE] = in[gindex + BLOCK_SIZE];
}

// Synchronize (ensure all the data is available)
__syncthreads();

// Apply the stencil
int result = 0;
for (int offset = -RADIUS; offset <= RADIUS; offset++)
    result += temp[lindex + offset];

// Store the result
out[gindex] = result;
}

void fill_ints(int *x, int n) {
    fill_n(x, n, 1);
}

int main(void) {
    int *in, *out; // host copies of a, b, c
    int *d_in, *d_out; // device copies of a, b, c
    int size = (N + 2 * RADIUS) * sizeof(int);

    // Alloc space for host copies and setup values
    in = (int *)malloc(size); fill_ints(in, N + 2 * RADIUS);
    out = (int *)malloc(size); fill_ints(out, N + 2 * RADIUS);

    // Alloc space for device copies
    cudaMalloc((void **)&d_in, size);
    cudaMalloc((void **)&d_out, size);

    // Copy to device
    cudaMemcpy(d_in, in, size, cudaMemcpyHostToDevice);
    cudaMemcpy(d_out, out, size, cudaMemcpyHostToDevice);

    // Launch stencil_1d() kernel on GPU
    stencil_1d(<<<N/BLOCK_SIZE,BLOCK_SIZE>>>)(d_in + RADIUS,
    d_out + RADIUS);

    // Copy result back to host
    cudaMemcpy(out, d_out, size, cudaMemcpyDeviceToHost);

    // Cleanup
    free(in); free(out);
    cudaFree(d_in); cudaFree(d_out);
    return 0;
}
```

parallel function

serial code

parallel code

serial code



Host = CPU
(+ memory)



Device = GPU



A simple CUDA program: adding 2 vectors

- Adding 2 vectors sequentially using host
- Adding 2 vectors in parallel using device: each thread on device are responsible for computing an element in the sum vector, and all these threads run in parallel
- Who win?

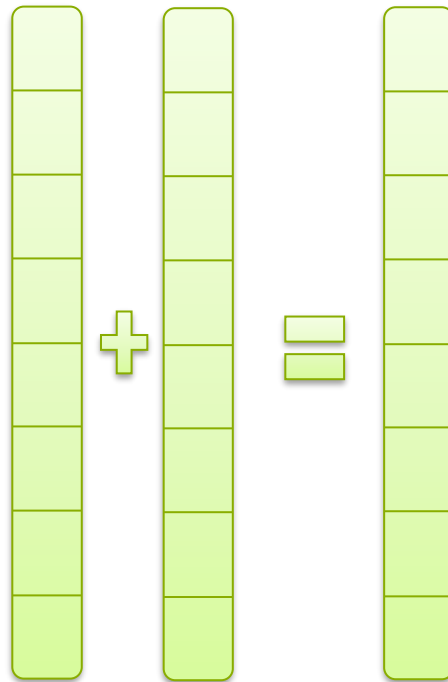


Image source: NVIDIA. CUDA C/C++ Basics

```
int main(int argc, char **argv)
{
    int n; // Vector size
    float *in1, *in2; // Input vectors
    float *out; // Output vector

    // Input data into n
    ...

    // Allocate memories for in1, in2, out
    ...

    // Input data into in1, in2
    ...

    // Add vectors (on host)
    addVecOnHost(in1, in2, out, n);

    // Free memories
    ...

    return 0;
}
```

```
void addVecOnHost(float* in1, float* in2, float* out, int n)
{
    for (int i = 0; i < n; i++)
        out[i] = in1[i] + in2[i];
}
```

```

int main(int argc, char **argv)
{
    int n; // Vector size
    float *in1, *in2; // Input vectors
    float *out; // Output vector

    // Input data into n
    ...

    // Allocate memories for in1, in2, out
    ...

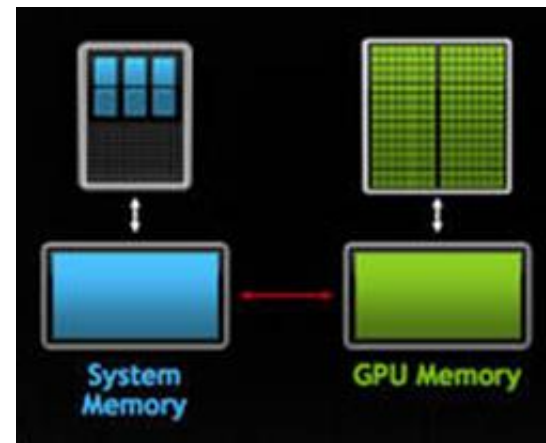
    // Input data into in1, in2
    ...

    // Add vectors (on host)
    addVecOnHost(in1, in2, out, n);

    // Free memories
    ...

    return 0;
}

```



```

// Host allocates memories on device
...

// Host copies data to device memories
...

// Host invokes kernel function to add vectors
on device
...

// Host copies result from device memory
...

// Host frees device memories
...

```

// Host allocates memories on device

```
float *d_in1, *d_in2, *d_out;  
cudaMalloc(&d_in1, n * sizeof(float));  
cudaMalloc(&d_in2, n * sizeof(float));  
cudaMalloc(&d_out, n * sizeof(float));
```

// Host copies data to device memories

...

// Host invokes kernel function to add vectors on device

...

// Host copies result from device memory

...

// Host frees device memories

...

// Host allocates memories on device

```
float *d_in1, *d_in2, *d_out;  
cudaMalloc(&d_in1, n * sizeof(float));  
cudaMalloc(&d_in2, n * sizeof(float));  
cudaMalloc(&d_out, n * sizeof(float));
```

// Host copies data to device memories

```
cudaMemcpy(d_in1, in1, n * sizeof(float), cudaMemcpyHostToDevice);  
cudaMemcpy(d_in2, in2, n * sizeof(float), cudaMemcpyHostToDevice);
```

// Host invokes kernel function to add vectors on device

...

// Host copies result from device memory

...

// Host frees device memories

...

// Host allocates memories on device

```
float *d_in1, *d_in2, *d_out;  
cudaMalloc(&d_in1, n * sizeof(float));  
cudaMalloc(&d_in2, n * sizeof(float));  
cudaMalloc(&d_out, n * sizeof(float));
```

// Host copies data to device memories

```
cudaMemcpy(d_in1, in1, n * sizeof(float), cudaMemcpyHostToDevice);  
cudaMemcpy(d_in2, in2, n * sizeof(float), cudaMemcpyHostToDevice);
```

// Host invokes kernel function to add vectors on device

...

// Host copies result from device memory

```
cudaMemcpy(out, d_out, n * sizeof(float), cudaMemcpyDeviceToHost);
```

// Host frees device memories

...

// Host allocates memories on device

```
float *d_in1, *d_in2, *d_out;  
cudaMalloc(&d_in1, n * sizeof(float));  
cudaMalloc(&d_in2, n * sizeof(float));  
cudaMalloc(&d_out, n * sizeof(float));
```

// Host copies data to device memories

```
cudaMemcpy(d_in1, in1, n * sizeof(float), cudaMemcpyHostToDevice);  
cudaMemcpy(d_in2, in2, n * sizeof(float), cudaMemcpyHostToDevice);
```

// Host invokes kernel function to add vectors on device

...

// Host copies result from device memory

```
cudaMemcpy(out, d_out, n * sizeof(float), cudaMemcpyDeviceToHost);
```

// Host frees device memories

```
cudaFree(d_in1);  
cudaFree(d_in2);  
cudaFree(d_out);
```

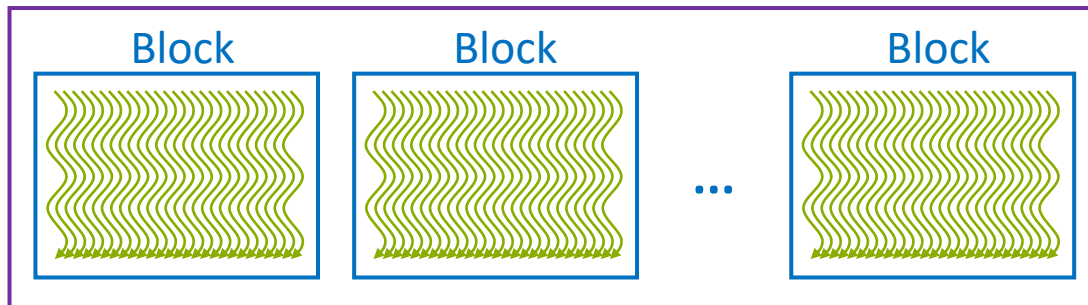
```
// Host allocates memories on device  
float *d_in1, *d_in2, *d_out;  
cudaMalloc(&d_in1, n * sizeof(float));  
cudaMalloc(&d_in2, n * sizeof(float));  
cudaMalloc(&d_out, n * sizeof(float));
```

```
// Host copies data to device memories  
cudaMemcpy(d_in1, in1, n * sizeof(float), cudaMemcpyHostToDevice);  
cudaMemcpy(d_in2, in2, n * sizeof(float), cudaMemcpyHostToDevice);
```

```
// Host invokes kernel function to add vectors on device  
dim3 blockSize(256); // For simplicity, you can temporarily view blockSize as a number  
dim3 gridSize((n - 1) / blockSize.x + 1); // Similarity, view gridSize as a number  
addVecOnDevice<<<gridSize, blockSize>>>(d_in1, d_in2, d_out, n);
```

This command creates on device a bunch of threads (called **grid**) executing the addVecOnDevice function in parallel; these threads are organized into gridSize groups or **blocks**, each group/block consists of blockSize threads

Grid



...

// Host invokes kernel function to add vectors on device

```
dim3 blockSize(256);
```

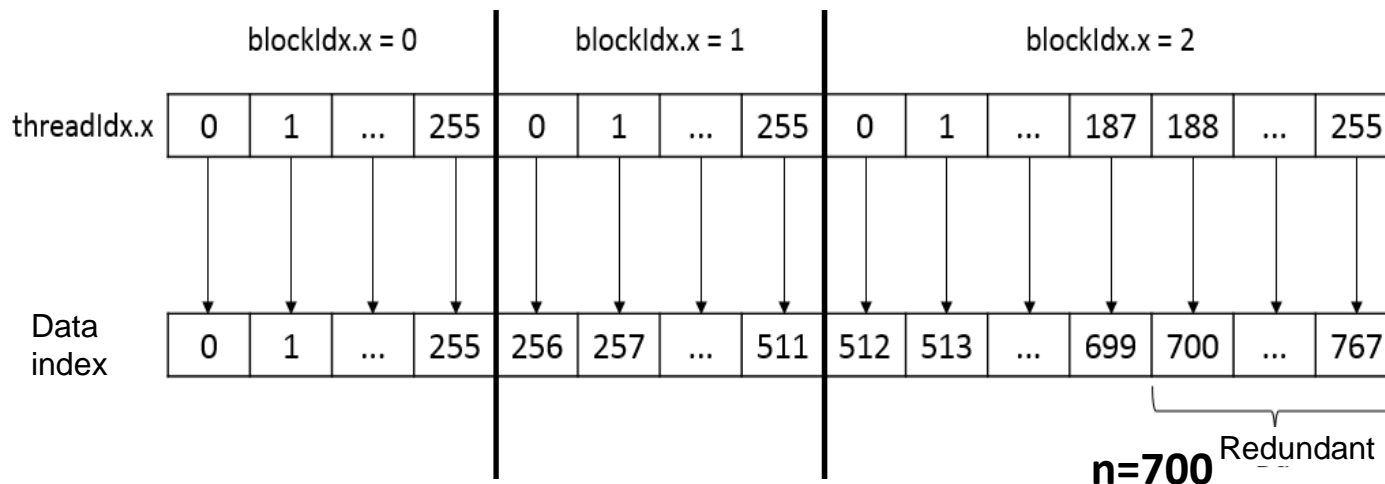
```
dim3 gridSize((n - 1) / blockSize.x + 1);
```

```
addVecOnDevice<<<gridSize, blockSize>>>(d_in1, d_in2, d_out, n);
```

...

Kernel functions must return "void"

```
__global__ void addVecOnDevice(float* in1, float* in2, float* out, int n)
{
    int i = blockIdx.x * blockDim.x + threadIdx.x;
    if (i < n)
        out[i] = in1[i] + in2[i];
}
```



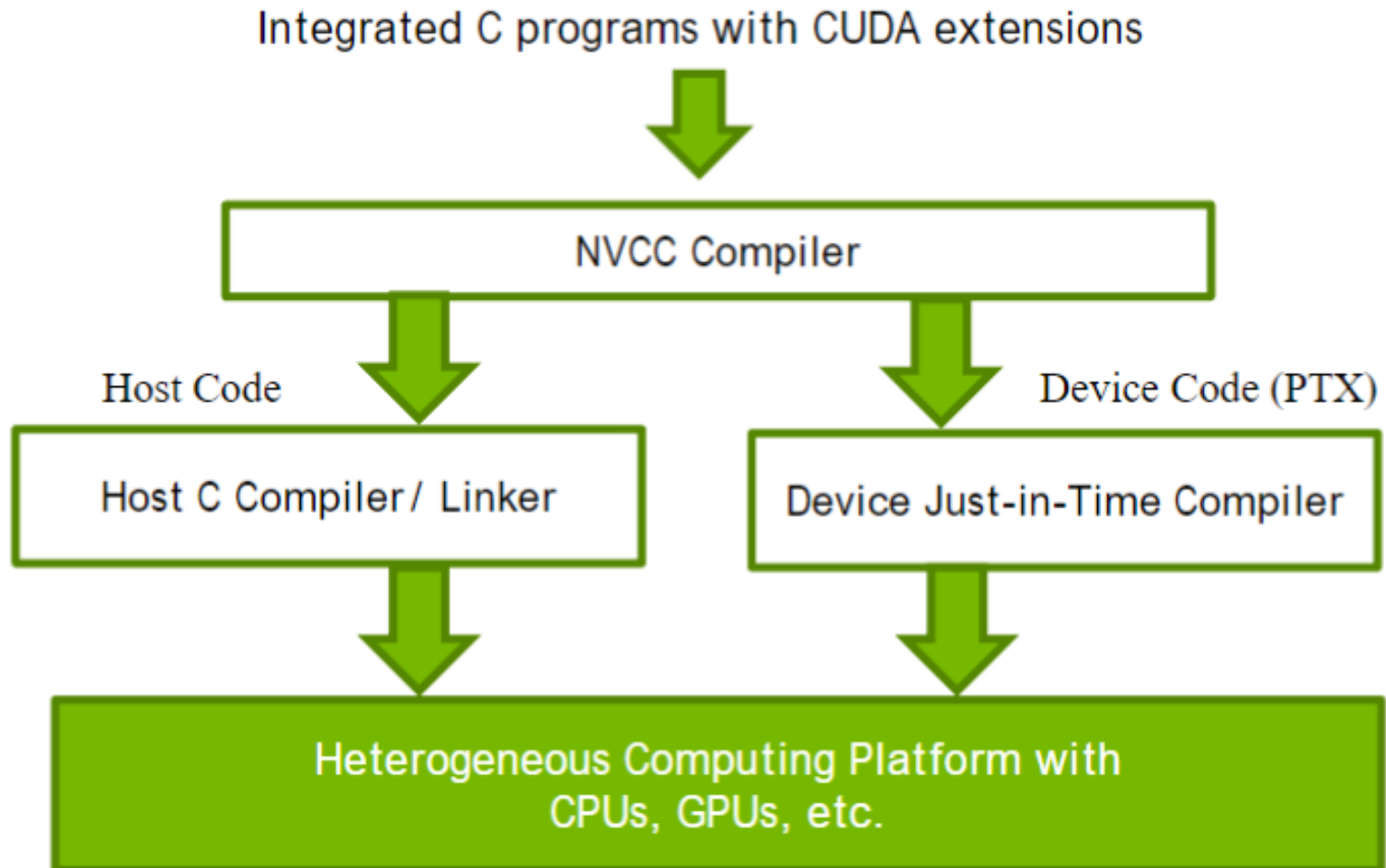
More on CUDA Function Declarations

	Callable from	Execute on	Execute by
<code>__device__ float DeviceFunc()</code>	device	device	Caller host thread
<code>__global__ void KernelFunc()</code>	host	device	New grid of device thread
<code>__host__ float HostFunc()</code>	host	host	Caller thread device

- `__global__` define a kernel function
 - A kernel function must return void
- `__device__` and `__host__` can be used together
 - Generate two versions of object code for the same function
- `__host__` is optional if use alone.

Compiling A CUDA Program

- Use NVCC (NVIDIA C compiler)



Kernel function execution is asynchronous w.r.t host by default

After host calls a kernel function to be executed on device, host will be free to do other works without waiting the kernel to be completed

...

// Host invokes kernel function to add vectors on device

```
dim3 blockSize(256);
```

```
dim3 gridSize((n - 1) / blockSize.x + 1);
```

```
addVecOnDevice<<<gridSize, blockSize>>>(d_in1, d_in2, d_out, n);
```

// Host copies result from device memory

```
cudaMemcpy(out, d_out, n * sizeof(float), cudaMemcpyDeviceToHost); // OK?
```

OK, because the cudaMemcpy function forces host to wait until the kernel finishes, only then it starts to copy

Kernel function execution is asynchronous w.r.t host by default

...

// Host invokes kernel function to add vectors on device

```
dim3 blockSize(256);
```

```
dim3 gridSize((n - 1) / blockSize.x + 1);
```

```
double start = seconds(); // seconds is my function to get the current time
```

```
addVecOnDevice<<<gridSize, blockSize>>>(d_in1, d_in2, d_out, n);
```

```
double time = seconds() - start; // OK?
```

...

Kernel function execution is asynchronous w.r.t host by default

```
...  
// Host invokes kernel function to add vectors on device  
dim3 blockSize(256);  
dim3 gridSize((n - 1) / blockSize.x + 1);  
double start = seconds(); // seconds is my function to get the current time  
addVecOnDevice<<<gridSize, blockSize>>>(d_in1, d_in2, d_out, n);  
cudaDeviceSynchronize(); // Host waits here until device completes its work  
double time = seconds() - start; // ✓  
...
```

Error checking when calling CUDA API functions

- It's possible that an error happens but the CUDA program still run normally and give wrong result
 - don't know where to fix bug ☹
 - to know where to fix bug, we should always check error when calling CUDA API functions
- For convenience, we can define a macro to check error and wrap it around

```
C #define CHECK(call) \
{\
    cudaError_t err = call;\
    if (err != cudaSuccess)\
    {\
        printf("%s in %s at line %d!\n", cudaGetErrorString(err), __FILE__, __LINE__); \
        exit(EXIT_FAILURE);\
    }\
}
```

// Host allocates memories on device

```
float *d_in1, *d_in2, *d_out;  
CHECK(cudaMalloc(&d_in1, n * sizeof(float)));  
CHECK(cudaMalloc(&d_in2, n * sizeof(float)));  
CHECK(cudaMalloc(&d_out, n * sizeof(float)));
```

// Host copies data to device memories

```
CHECK(cudaMemcpy(d_in1, in1, n * sizeof(float), cudaMemcpyHostToDevice));  
CHECK(cudaMemcpy(d_in2, in2, n * sizeof(float), cudaMemcpyHostToDevice));
```

// Host invokes kernel function to add vectors on device

```
dim3 blockSize(256);  
dim3 gridSize((n - 1) / blockSize.x + 1);  
addVecOnDevice<<<gridSize, blockSize>>>(d_in1, d_in2, d_out, n);
```

// Host copies result from device memory

```
CHECK(cudaMemcpy(out, d_out, n * sizeof(float), cudaMemcpyDeviceToHost));
```

// Host frees device memories

```
CHECK(cudaFree(d_in1));  
CHECK(cudaFree(d_in2));  
CHECK(cudaFree(d_out));
```

Error checking when calling kernel functions?

Read [here](#), “Handling CUDA Errors” section

Experiment: host vs device

- Generate input vectors with random values in $[0, 1]$
- Compare running time between host (`addVecOnHost` function) and device (`addVecOnDevice` function, block size 512) with different vector sizes
- GPU: GeForce GTX 560 Ti (compute capability 2.1)

Experiment: host vs device

Vec size	Host time (ms)	Device time (ms)	Host time / Device time
64			

Experiment: host vs device

Vec size	Host time (ms)	Device time (ms)	Host time / Device time
64	0.001	0.040	0.024

Experiment: host vs device

Vec size	Host time (ms)	Device time (ms)	Host time / Device time
64	0.001	0.040	0.024
256			

Experiment: host vs device

Vec size	Host time (ms)	Device time (ms)	Host time / Device time
64	0.001	0.040	0.024
256	0.002	0.018	0.118

Experiment: host vs device

Vec size	Host time (ms)	Device time (ms)	Host time / Device time
64	0.001	0.040	0.024
256	0.002	0.018	0.118
1024			

Experiment: host vs device

Vec size	Host time (ms)	Device time (ms)	Host time / Device time
64	0.001	0.040	0.024
256	0.002	0.018	0.118
1024	0.006	0.017	0.347

Experiment: host vs device

Vec size	Host time (ms)	Device time (ms)	Host time / Device time
64	0.001	0.040	0.024
256	0.002	0.018	0.118
1024	0.006	0.017	0.347
4096			

Experiment: host vs device

Vec size	Host time (ms)	Device time (ms)	Host time / Device time
64	0.001	0.040	0.024
256	0.002	0.018	0.118
1024	0.006	0.017	0.347
4096	0.030	0.017	1.775

Experiment: host vs device

Vec size	Host time (ms)	Device time (ms)	Host time / Device time
64	0.001	0.040	0.024
256	0.002	0.018	0.118
1024	0.006	0.017	0.347
4096	0.030	0.017	1.775
16384	0.127	0.017	7.403
65536	0.516	0.055	9.409
262144	1.028	0.197	5.220
1048576	3.773	0.277	13.619
4194304	13.870	0.617	22.479
16777216	55.177	1.993	27.683

Reference

- [1] Slides from *Illinois-NVIDIA GPU Teaching Kit*
- [2] Wen-Mei, W. Hwu, David B. Kirk, and Izzat El Hajj. *Programming Massively Parallel Processors: A Hands-on Approach*. Morgan Kaufmann, 2022



THE END