CS 677: Parallel Programming for Many-core Processors
Lecture 1

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Objectives

• Learn how to program massively parallel processors and achieve
  – High performance
  – Functionality and maintainability
  – Scalability across future generations

• Acquire technical knowledge required to achieve above goals
  – Principles and patterns of parallel programming
  – Processor architecture features and constraints
  – Programming API, tools and techniques
Important Points

• This is an elective course. You chose to be here.

• Expect to work and to be challenged.

• If your programming background is weak, you will probably suffer.

• This course will evolve to follow the rapid pace of progress in GPU programming. It is bound to always be a little behind...
Important Points II

• At any point ask me WHY?
• You can ask me anything about the course in class, during a break, in my office, by email.
  – If you think a homework is taking too long or is wrong.
  – If you can’t decide on a project.
  – Etc. etc.
Logistics

• Class webpage:
  http://www.cs.stevens.edu/~mordohai/classes/cs677_s14.html

• Office hours: Tuesdays 5-6pm and by email

• Evaluation:
  – Homework assignments (40%)
  – Participation (5%)
  – Midterm (15%)
  – Final project (40%)
Project

• Pick topic BEFORE middle of the semester
• I will suggest ideas and datasets, if you can’t decide
• Deliverables:
  – Project proposal
  – Presentation in class
  – Poster in CS department event
  – Final report (around 8 pages)
Project Examples

- k-means
- Perceptron
- Boosting
  - General
  - Face detector (group of 2)
- Mean Shift
- Normal estimation for 3D point clouds
More Ideas

• Look for parallelizable problems in:
    – Image processing
    – Cryptanalysis
    – Graphics
    • GPU Gems
    – Nearest neighbor search

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</tbody>
</table>
Even More…

- Particle simulations
- Financial analysis
- MCMC
- Games/puzzles
Resources

• Textbook

• Slides and more
Online Resources

• NVIDIA. The NVIDIA CUDA Programming Guide.

• NVIDIA. CUDA Reference Manual.

• CUDA Toolkit
Lecture Overview

• Scaling up computational power
• GPUs
• Introduction to CUDA
• CUDA programming model
Moore’s Law (paraphrased)

“The number of transistors on an integrated circuit doubles every two years.”
- Gordon E. Moore
Serial Performance Scaling is Over

• **Cannot** continue to scale processor frequencies
  – no 10 GHz chips

• **Cannot** continue to increase power consumption
  – cannot melt chip

• **Can** continue to increase transistor density
  – as per Moore’s Law
How to Use Transistors?

• Instruction-level parallelism
  – out-of-order execution, speculation, ...
  – vanishing opportunities in power-constrained world

• Data-level parallelism
  – vector units, SIMD execution, ...
  – increasing ... SSE, AVX, Cell SPE, Clearspeed, GPU

• Thread-level parallelism
  – increasing ... multithreading, multicore, manycore
  – Intel Core2, AMD Phenom, Sun Niagara, STI Cell, NVIDIA Fermi, ...

16
Why Massively Parallel Processing?

- A quiet revolution and potential build-up
  - Computation: TFLOPs vs. 100 GFLOPs

- GPU in every PC - massive volume & potential impact
Why Massively Parallel Processing?

- A quiet revolution and potential build-up
  - Bandwidth: $\sim 10x$

- GPU in every PC - massive volume & potential impact
The “New” Moore’s Law

- Computers no longer get faster, just wider
- You *must* re-think your algorithms to be parallel!
- Data-parallel computing is most scalable solution
  - Otherwise: refactor code for 2 cores 4 cores 8 cores 16 cores…
  - You will always have more data than cores - build the computation around the data
Generic Multicore Chip

- Handful of processors each supporting ~1 hardware thread
- On-chip memory near processors (cache, RAM, or both)
- Shared global memory space (external DRAM)
Generic Manycore Chip

- Many processors each supporting many hardware threads
- On-chip memory near processors (cache, RAM, or both)
- Shared global memory space (external DRAM)
Enter the GPU

- Massive economies of scale
- Massively parallel
Graphics in a Nutshell

• Make great images
  – intricate shapes
  – complex optical effects
  – seamless motion

• Make them fast
  – invent clever techniques
  – use every trick imaginable
  – build monster hardware

Eugene d'Eon, David Luebke, Eric Enderton
In Proc. EGSR 2007 and GPU Gems 3
The Graphics Pipeline

- Vertex Transform & Lighting
- Triangle Setup & Rasterization
- Texturing & Pixel Shading
- Depth Test & Blending
- Framebuffer
The Graphics Pipeline

- Vertex Transform & Lighting
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The Graphics Pipeline

1. Vertex Transform & Lighting
2. Triangle Setup & Rasterization
3. Texturing & Pixel Shading
4. Depth Test & Blending
5. Framebuffer
The Graphics Pipeline

- Vertex Transform & Lighting
- Triangle Setup & Rasterization
- Texturing & Pixel Shading
- Depth Test & Blending
- Framebuffer
The Graphics Pipeline

- Key abstraction of real-time graphics
- Hardware used to look like this
- One chip/board per stage
- Fixed data flow through pipeline
The Graphics Pipeline

- Everything had fixed function, with a certain number of modes
- Number of modes for each stage grew over time
- Hard to optimize HW
- Developers always wanted more flexibility
The Graphics Pipeline

- Remains a key abstraction
- Hardware used to look like this
- Vertex & pixel processing became programmable, new stages added
- GPU architecture increasingly centers around shader execution
The Graphics Pipeline

- Exposing an (at first limited) instruction set for some stages

- Limited instructions & instruction types and no control flow at first

- Expanded to full Instruction Set Architecture
Why GPUs scale so nicely

• Workload and Programming Model provide lots of parallelism
• Applications provide large groups of vertices at once
  – Vertices can be processed in parallel
  – Apply same transform to all vertices
• Triangles contain many pixels
  – Pixels from a triangle can be processed in parallel
  – Apply same shader to all pixels
• Very efficient hardware to hide serialization bottlenecks
With Moore’s Law...
More Efficiency

• Note that we do the **same thing** for lots of pixels/vertices

• A warp = 32 threads launched together

• Usually, execute together as well
Early GPGPU

• All this performance attracted developers
• To use GPUs, re-expressed their algorithms as graphics computations
• Very tedious, limited usability
• Still had some very nice results

• This was the lead up to CUDA
GPU Evolution

- **High throughput computation**
  - GeForce GTX 280: 933 GFLOPS
  - GeForce 600 series (Kepler): 2×2811 GFLOPS
- **High bandwidth**
  - GeForce GTX 280: 140 GB/s
  - GeForce 600 series (Kepler): 2×192 GB/s
- **High availability to all**
  - 180+ million CUDA-capable GPUs in the wild
Lessons from Graphics Pipeline

- **Throughput** is paramount
  - must paint every pixel within frame time
  - scalability
  - video games have strict time requirements: bare minimum: $2 \text{ Mpixels} \times 60 \text{ fps} \times 2 = 240 \text{ Mthread/s}$

- Create, run, & retire **lots of threads** very rapidly
  - measured 14.8 Gthread/s on `increment()` kernel (2010)

- Use **multithreading** to hide latency
  - 1 stalled thread is OK if 100 are ready to run
Why is this different from a CPU?

• Different goals produce different designs
  – GPU assumes work load is highly parallel
  – CPU must be good at everything, parallel or not

• CPU: minimize latency experienced by 1 thread
  – big on-chip caches
  – sophisticated control logic

• GPU: maximize throughput of all threads
  – # threads in flight limited by resources => lots of resources (registers, bandwidth, etc.)
  – multithreading can hide latency => skip the big caches
  – share control logic across many threads
CPUs and GPUs have fundamentally different design philosophies.
Architecture of a CUDA-capable GPU
SMs and SPs

- **SM**: Streaming Multiprocessor
- **SP**: Streaming Processor (core)
SM Multiprocessor

- 32 CUDA Cores per SM (512 total)
- Direct load/store to memory
  - High bandwidth (Hundreds GB/sec)
- 64KB of fast, on-chip RAM
  - Software or hardware-managed
  - Shared amongst CUDA cores
  - Enables thread communication
Key Architectural Ideas

- **SIMT** (Single Instruction Multiple Thread) execution
  - threads run in groups of 32 called **warps**
  - threads in a warp share instruction unit (IU)
  - HW automatically handles divergence

- Hardware multithreading
  - HW resource allocation & thread scheduling
  - HW relies on threads to hide latency

- Threads have all resources needed to run
  - any warp not waiting for something can run
  - context switching is (basically) free
Enter CUDA

• Scalable parallel programming model

• Minimal extensions to familiar C/C++ environment

• Heterogeneous serial-parallel computing
Motivation

45X
cell phone safety simulations

17X
fluid mechanics (Matlab)

100X
astrophysics

13–457X
MRI reconstruction

110–240X
molecular modeling applications

35X
Gene sequence matching
**CUDA: Scalable parallel programming**

- Augment C/C++ with minimalist abstractions
  - let programmers focus on parallel algorithms
  - *not* mechanics of a parallel programming language

- Provide straightforward mapping onto hardware
  - good fit to GPU architecture
  - maps well to multi-core CPUs too

- Scale to 100s of cores & 10,000s of parallel threads
  - GPU threads are lightweight – create / switch is free
  - GPU needs 1000s of threads for full utilization
Key Parallel Abstractions in CUDA

- Hierarchy of concurrent threads
- Lightweight synchronization primitives
- Shared memory model for cooperating threads
Hierarchical structure of concurrent threads

- **Parallel kernels** composed of many threads
  - all threads execute the same sequential program

- Threads are grouped into **thread blocks**
  - threads in the same block can cooperate

- Threads/blocks have unique IDs
CUDA Model of Parallelism

- CUDA virtualizes the physical hardware
  - a thread is a virtualized scalar processor (registers, PC, state)
  - a block is a virtualized multiprocessor (threads, shared memory)

- Scheduled onto physical hardware without pre-emption
  - threads/blocks launch & run to completion
  - blocks should be independent
NOT: Flat Multiprocessor

- Global synchronization isn’t cheap
- Global memory access times are expensive
NOT: Distributed Processors

- Distributed computing is a different setting
- cf. BSP (Bulk Synchronous Parallel) model, MPI
Control Flow Divergence
Heterogeneous Computing

Multicore CPU

Manycore GPU
CUDA Programming Model
Overview

• CUDA programming model - basic concepts and data types

• CUDA application programming interface - basic

• Simple examples to illustrate basic concepts and functionalities

• Performance features will be covered later
CUDA - C with no shader limitations

- Integrated host+device app C program
  - Serial or modestly parallel parts in **host** C code
  - Highly parallel parts in **device** SPMD kernel C code

```
Serial Code (host)

Parallel Kernel (device)
KernelA<<< nBlk, nTid >>>(args);

Serial Code (host)

Parallel Kernel (device)
KernelB<<< nBlk, nTid >>>(args);
```
CUDA Devices and Threads

• A compute device
  – Is a coprocessor to the CPU or host
  – Has its own DRAM (device memory)
  – Runs many threads in parallel
  – Is typically a GPU but can also be another type of parallel processing device

• Data-parallel portions of an application are expressed as device kernels which run on many threads

• Differences between GPU and CPU threads
  – GPU threads are extremely lightweight
    • Very little creation overhead
  – GPU needs 1000s of threads for full efficiency
    • Multi-core CPU needs only a few
G80 - Graphics Mode

• The future of GPUs is programmable processing
• So – build the architecture around the processor
G80 CUDA mode - A Device Example

- Processors execute computing threads
- New operating mode/HW interface for computing
Extended C

• **Declspecs**
  - global, device, shared, local, constant

  ```c
  __device__ float filter[N];
  __global__ void convolve (float *image) {
    __shared__ float region[M];
    ...
    region[threadIdx] = image[i];
    __syncthreads()
    ...
    image[j] = result;
  }
  ```

• **Keywords**
  - threadIdx, blockIdx

• **Intrinsics**
  - __syncthreads

• **Runtime API**
  - Memory, symbol, execution management

  ```c
  // Allocate GPU memory
  void *myimage; cudaMalloc(myimage, bytes)
  ```

• **Function launch**

  ```c
  // 100 blocks, 10 threads per block
  convolve<<<100, 10>>> (myimage);
  ```
Arrays of Parallel Threads

- A CUDA kernel is executed by an array of threads
  - All threads run the same code
  - Each thread has an ID that it uses to compute memory addresses and make control decisions

```c
float x = input[threadID];
float y = func(x);
output[threadID] = y;
```

```c
... threadID 0 1 2 3 4 5 6 7
... ```
Thread Blocks: Scalable Cooperation

• Divide monolithic thread array into multiple blocks
  – Threads within a block cooperate via shared memory, atomic operations and barrier synchronization
  – Threads in different blocks cannot cooperate

```cpp
... float x = input[threadID];
float y = func(x);
output[threadID] = y;
...
```
Block IDs and Thread IDs

- Each thread uses IDs to decide what data to work on
  - Block ID: 1D or 2D
  - Thread ID: 1D, 2D, or 3D

- Simplifies memory addressing when processing multidimensional data
  - Image processing
  - Solving PDEs on volumes
  - …

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CUDA Memory Model Overview

- **Global memory**
  - Main means of communicating R/W Data between **host** and **device**
  - Contents visible to all threads
  - Long latency access
- **We will focus on global memory for now**
  - Constant and texture memory will come later
CUDA API Highlights: Easy and Lightweight

• The API is an extension to the ANSI C programming language
  → Low learning curve

• The hardware is designed to enable lightweight runtime and driver
  → High performance
CUDA Device Memory Allocation

- **cudaMalloc()**
  - Allocates object in the device **Global Memory**
  - Requires two parameters
    - Address of a pointer to the allocated object
    - Size of allocated object
- **cudaFree()**
  - Frees object from device **Global Memory**
    - Pointer to freed object
CUDA Device Memory Allocation (cont.)

• Code example:
  – Allocate a 64 * 64 single precision float array
  – Attach the allocated storage to Md
  – “d” is often used to indicate a device data structure

```c
int TILE_WIDTH = 64;
float* Md;
int size = TILE_WIDTH * TILE_WIDTH * sizeof(float);

cudaMalloc((void**)&Md, size);
cudaFree(Md);
```
CUDA Host-Device Data Transfer

- cudaMemcpy()
  - memory data transfer
  - Requires four parameters
    - Pointer to destination
    - Pointer to source
    - Number of bytes copied
    - Type of transfer
      - Host to Host
      - Host to Device
      - Device to Host
      - Device to Device

- Asynchronous transfer
CUDA Host-Device Data Transfer (cont.)

• Code example:
  – Transfer a 64 * 64 single precision float array
  – M is in host memory and Md is in device memory
  – cudaMemcpyHostToDevice and cudaMemcpyDeviceToHost are symbolic constants

\[
\text{cudaMemcpy(Md, M, size, cudaMemcpyHostToDevice);} \\
\text{cudaMemcpy(M, Md, size, cudaMemcpyDeviceToHost);} \\
\]
CUDA Keywords
CUDA Function Declarations

<table>
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<th><strong>device</strong> float DeviceFunc()</th>
<th>Executed on the:</th>
<th>Only callable from the:</th>
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</thead>
<tbody>
<tr>
<td><strong>global</strong> void KernelFunc()</td>
<td>device</td>
<td>host</td>
</tr>
<tr>
<td><strong>host</strong> float HostFunc()</td>
<td>host</td>
<td>host</td>
</tr>
</tbody>
</table>

- __global__ defines a kernel function
  - Must return void
- __device__ and __host__ can be used together
CUDA Function Declarations (cont.)

- **__device__** functions cannot have their address taken

- For functions executed on the device:
  - No recursion
    - Recursion supported since CUDA Toolkit 3.1
  - No static variable declarations inside the function
  - No variable number of arguments
Calling a Kernel Function - Thread Creation

• A kernel function must be called with an execution configuration:

```c
__global__ void KernelFunc(...);
dim3 DimGrid(100, 50); // 5000 thread blocks
dim3 DimBlock(4, 8, 8); // 256 threads per block
size_t SharedMemBytes = 64; // 64 bytes of shared memory
KernelFunc<<< DimGrid, DimBlock, SharedMemBytes >>>(...);
```

• Any call to a kernel function is asynchronous from CUDA 1.0 on, explicit synch needed for blocking
Example: vector_addition

// compute vector sum $c = a + b$
// each thread performs one pair-wise addition

__global__ void vector_add(float* A, float* B, float* C)
{
    int i = threadIdx.x + blockDim.x * blockIdx.x;
    C[i] = A[i] + B[i];
}

int main()
{
    // initialization code
    ...
    // Launch N/256 blocks of 256 threads each
    vector_add<<< N/256, 256 >>>(d_A, d_B, d_C);
}
Example: \texttt{vector\_addition}

// compute vector sum \( c = a + b \)
// each thread performs one pair-wise addition
__global__ void vector_add(float* A, float* B, float* C)
{
    int i = threadIdx.x + blockDim.x * blockIdx.x;
    C[i] = A[i] + B[i];
}

int main()
{
    // initialization code
    ...
    // launch \( N/256 \) blocks of 256 threads each
    vector_add<<<N/256, 256>>>(d_A, d_B, d_C);
}
Example: Initialization code for vector_addition

// allocate and initialize host (CPU) memory
float *h_A = ..., *h_B = ...;

// allocate device (GPU) memory
float *d_A, *d_B, *d_C;
cudaMalloc( (void**) &d_A, N * sizeof(float));
cudaMalloc( (void**) &d_B, N * sizeof(float));
cudaMalloc( (void**) &d_C, N * sizeof(float));

// copy host memory to device
cudamemcpy( d_A, h_A, N * sizeof(float),
cudamemcpyhostToDevice );
cudamemcpy( d_B, h_B, N * sizeof(float),
cudamemcpyhostToDevice );

// launch N/256 blocks of 256 threads each
vector_add<<<N/256, 256>>>(d_A, d_B, d_C);
Running Example: Matrix Multiplication

- A simple matrix multiplication example that illustrates the basic features of memory and thread management in CUDA programs
  - Leave shared memory usage until later
  - Local, register usage
  - Thread ID usage
  - Memory data transfer API between host and device
  - Assume square matrix for simplicity
Programming Model: Square Matrix Multiplication Example

- $P = M \times N$ of size $\text{WIDTH} \times \text{WIDTH}$
- Without tiling:
  - One thread calculates one element of $P$
  - $M$ and $N$ are loaded $\text{WIDTH}$ times from global memory
Memory Layout of a Matrix in C

\[
\begin{array}{cccc}
M_{0,0} & M_{1,0} & M_{2,0} & M_{3,0} \\
M_{0,1} & M_{1,1} & M_{2,1} & M_{3,1} \\
M_{0,2} & M_{1,2} & M_{2,2} & M_{3,2} \\
M_{0,3} & M_{1,3} & M_{2,3} & M_{3,3} \\
\end{array}
\]
Matrix Multiplication
A Simple Host Version in C

// Matrix multiplication on the (CPU) host in double precision
void MatrixMulOnHost(float* M, float* N, float* P, int Width)
{
    for (int i = 0; i < Width; ++i)
        for (int j = 0; j < Width; ++j) {
            double sum = 0;
            for (int k = 0; k < Width; ++k) {
                double a = M[i * width + k];
                double b = N[k * width + j];
                sum += a * b;
            }
            P[i * Width + j] = sum;
        }
}
Step 1: Input Matrix Data Transfer (Host-side Code)

```c
void MatrixMulOnDevice(float* M, float* N, float* P, int Width)
{
  int size = Width * Width * sizeof(float);
  float *Md, *Nd, *Pd;
  ...

  1. // Allocate and Load M, N to device memory
     cudaMalloc(&Md, size);
     cudaMemcpy(Md, M, size, cudaMemcpyHostToDevice);
     cudaMemcpy(Md, M, size, cudaMemcpyHostToDevice);

     cudaMalloc(&Nd, size);
     cudaMemcpy(Nd, N, size, cudaMemcpyHostToDevice);

     // Allocate P on the device
     cudaMalloc(&Pd, size);

```
Step 3: Output Matrix Data Transfer (Host-side Code)

2. // Kernel invocation code – to be shown later
   ...

3. // Read P from the device
   cudaMemcpy(P, Pd, size, cudaMemcpyDeviceToHost);

   // Free device matrices
   cudaFree(Md); cudaFree(Nd); cudaFree(Pd);
}
Step 2: Kernel Function

// Matrix multiplication kernel – per thread code

__global__ void MatrixMulKernel(float* Md, float* Nd, float* Pd, int Width)
{

    // Pvalue is used to store the element of the matrix
    // that is computed by the thread
    float Pvalue = 0;

Step 2: Kernel Function (cont.)

for (int k = 0; k < Width; ++k) {
    float Melement = Md[threadIdx.y*Width+k];
    float Nelement = Nd[k*Width+threadIdx.x];
    Pvalue += Melement * Nelement;
}

Pd[threadIdx.y*Width+threadIdx.x] = Pvalue;
Step 2: Kernel Invocation
(Host-side Code)

// Setup the execution configuration
dim3 dimGrid(1, 1);
dim3 dimBlock(Width, Width);

// Launch the device computation threads!
MatrixMulKernel<<<dimGrid, dimBlock>>>(Md, Nd, Pd, Width);
Only One Thread Block Used

• One Block of threads computes matrix $P_d$
  – Each thread computes one element of $P_d$

• Each thread
  – Loads a row of matrix $M_d$
  – Loads a column of matrix $N_d$
  – Performs one multiply and addition for each pair of $M_d$ and $N_d$ elements
  – Compute to off-chip memory access ratio close to 1:1 (not very high)

• Size of matrix limited by the number of threads allowed in a thread block

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Handling Arbitrary Sized Square Matrices (will cover later)

- Have each 2D thread block to compute a \((\text{TILE\_WIDTH})^2\) sub-matrix (tile) of the result matrix
  - Each has \((\text{TILE\_WIDTH})^2\) threads
- Generate a 2D Grid of \((\text{WIDTH}/\text{TILE\_WIDTH})^2\) blocks

You still need to put a loop around the kernel call for cases where \(\text{WIDTH}/\text{TILE\_WIDTH}\) is greater than max grid size (64K)!

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Some Useful Information on Tools

Download CUDA Toolkit 5.0
Compilation

• Any source file containing CUDA language extensions must be compiled with NVCC

• NVCC is a compiler driver
  – Works by invoking all the necessary tools and compilers like cudacc, g++, cl, ...

• NVCC outputs:
  – C code (host CPU Code)
    • Must then be compiled with the rest of the application using another tool
  – PTX (Parallel Thread eXecution)
    • Object code directly
    • Or, PTX source, interpreted at runtime
Linking

• Any executable with CUDA code requires two dynamic libraries:
  – The CUDA runtime library (cudart)
  – The CUDA core library (cuda)
Debugging

• NVIDIA Nsight
  – Debugging and profiling tools for Visual Studio and Eclipse

• CUDA-GDB
  – For Linux

• Debuggers come with toolkit now
Device Emulation Mode (Deprecated)

- An executable compiled in device emulation mode (`nvcc -deviceemu`) runs completely on the host using the CUDA runtime
  - No need of any device and CUDA driver
  - Each device thread is emulated with a host thread

- Running in device emulation mode, one can:
  - Use host native debug support (breakpoints, inspection, etc.)
  - Access any device-specific data from host code and vice-versa
  - Call any host function from device code (e.g. `printf`) and vice-versa
  - Detect deadlock situations caused by improper usage of `__syncthreads`
Device Emulation Mode Pitfalls

• Emulated device threads execute sequentially, so simultaneous accesses of the same memory location by multiple threads could produce different results.

• Dereferencing device pointers on the host or host pointers on the device can produce correct results in device emulation mode, but will generate an error in device execution mode.
GPU Ocelot

- Emulator for Windows and Linux
  - [http://gpuocelot.gatech.edu/](http://gpuocelot.gatech.edu/)
  - Executes PTX on GPUs, including non-NVIDIA ones, and CPUs
Assignment 0

- Work through tutorial code
  - cuda_memory_model.cu
  - global_functions.cu
  - device_functions.cu
  - vector_addition.cu

==> SUBMIT BY EMAIL A SCREENSHOT OF THE VECTOR ADDITION EXAMPLE