GPGPU programming on example of CUDA

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Outline

CPU
- CPU Architecture

GPU
- GPU Architecture

CUDA Architecture
- Existing GPGPU frameworks

GPU programming
- Data types and kernel
- Grid, blocks, threads, memory

Examples
- Parallel HelloWorld
- N body problem (no interaction) $O(N)$
- N body problem with interaction $O(N^2)$

Summary
- Out of the main track

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CPU Architecture

CPU = Central Processing Unit

- ALU - Arithmetic Logic Unit
- Registers - integral memory of CPU (data)
- IR - instruction register (processor instructions)
- PC - program counter (point in processor instruction list)

CPU working scheme

CPU was assumed to be sequential[1]:

- fetch - get an instruction to be executed (PC)
- decode - translate the instruction to elementary CPU instructions
- execute - execute all instructions using ALU
- writeback - save result (i.e. using registers)

[1] http:en.wikipedia.orgwikiCentral_processing_unit

Parallel computing and CPU:

Parallel computing and CPU:

- instrukcji level (instruction pipelining, superscalar pipeline) - use of latency of parts of fundamental sequence
- threads level (Multiple Instructions-Multiple Data) - from few processors (1960) to multi-core (2001 r.)
- data level (Single Instruction-Multiple Data) - vector CPUs, useful to special kind of problems

Source: 'Wikipedia'

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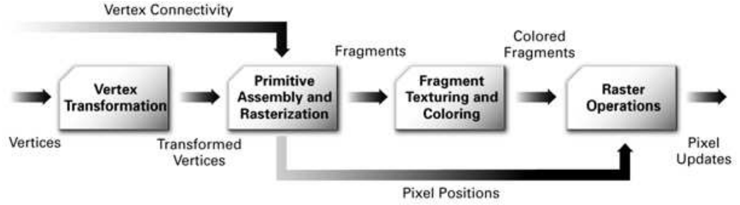
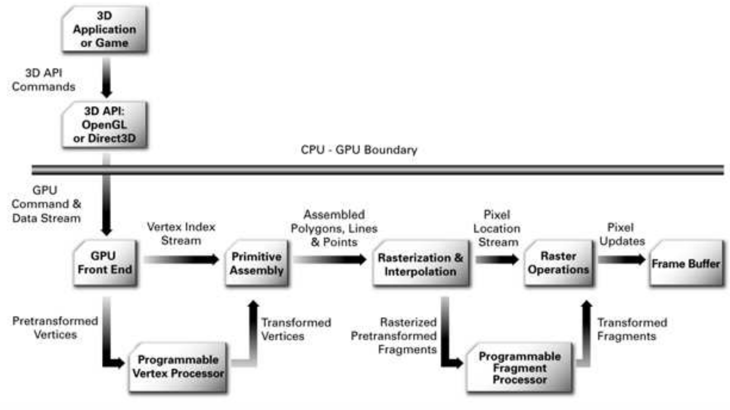
Graphics pipeline (1)



Source: 'The Cg Tutorial', nVidia

Graphics pipeline (2)



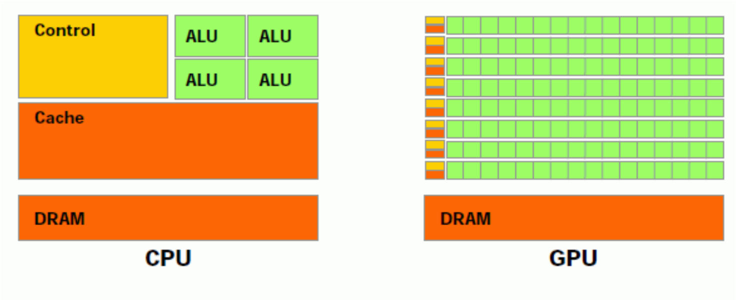
Source: 'The Cg Tutorial', nVidia

GPU - Graphics Processor Unit

GPU processor was optimized to run parts of graphics pipeline:

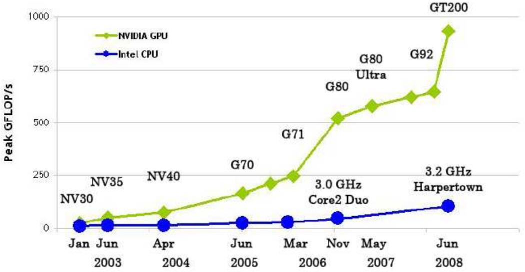
- the same procedure on many many elements
- SIMD (Single Instruction-Multiple Data) architecture
- transistors used to run many floating point operations (more than to optimize memory access like in CPUs)
- programmable shaders (vertex/pixel shaders)
- high level shader languages (CG, HLSL, GLSL)

GPU and CPU architectures



Source: 'nVidia CUDA, Programming Guide 2.2', nVidia

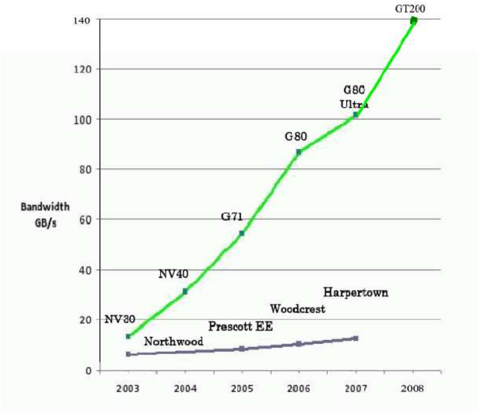
Performance (1)



GT200 = GeForce GTX 280	G71 = GeForce 7900 GTX	NV35 = GeForce FX 5950 Ultra
G92 = GeForce 9800 GTX	G70 = GeForce 7800 GTX	NV30 = GeForce FX 5800
G80 = GeForce 8800 GTX	NV40 = GeForce 6800 Ultra	

Source: 'nVidia CUDA, Programming Guide 2.2', nVidia

Performance (2)



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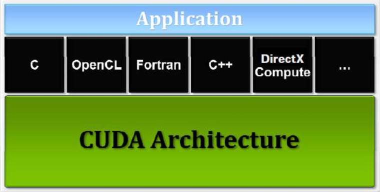
Frameworks

- Begin of GPGPU, calculations with programable shader units
- Today - two frameworks dedicated to GPU programming (ATI, nVidia)
- More: OpenCL - open standard
  for parallel computations (Khronos group)

What is that CUDA, actually?

CUDA, Compute Unified Device Architecture:

- high level language based on c/c++
- programming API
- dedicated compiler (nvcc)
- memory model

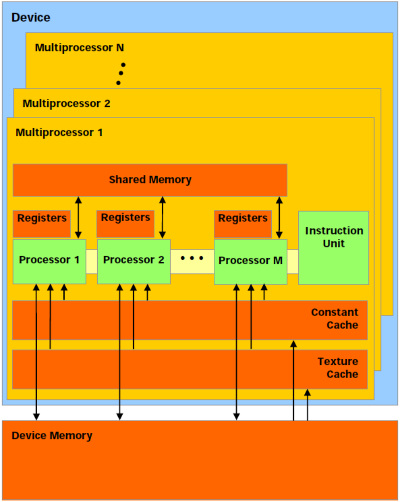


In future CUDA will be maintained from the level of any language (Source: 'nVidia CUDA, Programming Guide 2.2', nVidia).

Memory model in CUDA architecture

Different memory types in CUDA:

- shared memory (16kb)
- texture cache
- constant cache
- device memory (gb)



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CUDA Programming(1)

- new vector data types:

  char1, char2, char3, char4, int1, uint1, int2, uint2, int3, uint3, int4, uint4, float1, float2, float3, float4, double1, double2, dim3 (+ many more)

CUDA Programming(2)

- example for float3:

```
float3 w=make_float3(0.1, 2.2, 4.0);
float a = w.x + w.z;      // a = 4.1
```

- vector data types don't have implemented arithmetic operators
- one may try this (speed?):

```
__device__ float3 operator+(const float3 &a,
const float3 &b)
{
  return make_float3(a.x+b.x, a.y+b.y, a.z+b.z);
}
```

- in practice - one should be aware about memory access!

Kernel, declaration and call (1)

- in CUDA programs for GPU are called *kernels*
- code of kernels are placed in .cu files
- *Kernel* is declared in similar way to c functions
- keyword describing level from which kernel may be called (from CPU function, other kernel, etc.)

Kernel, declaration and call (2)

- example declaration:

```
__global__ void doSomethingOnDevice(...)
{
   ...
}
```

where:

  - __global__ compiled for GPU, called by CPU
  - __device__ compiled for GPU, called by GPU
  - __host__ compiled for CPU, called by CPU

Kernel, declaration and call (3)

- Kernel is called in similar way as c function
- additional declaration of number of blocks in a grid and threads in the block

```
<<< ... , ... >>>
```

- example call:

```
int blockSize = 128;
int nBlocks = N/blockSize
              + (N % blockSize == 0 ? 0 : 1);

doSomethingOnDevice <<< nBlocks, blockSize >>> (...);
```

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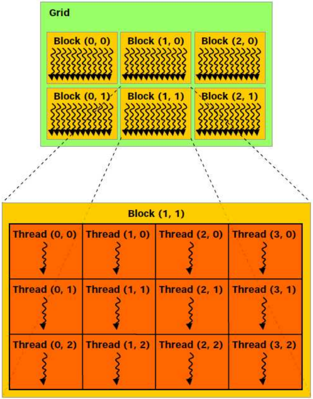
Grid, blocks, threads...

```
doSomethingOnDevice <<< nBlocks, blockSize >>> (...);
```

- creates grid of blocks (grid)
- nBlocks of blocks each
- each block consists of blockSize threads



Example ⟶

- nBlocks = dim3(3,2,1);
- blockSize = dim3(4,3,1);

Source: 'nVidia CUDA, Programming Guide 2.2', nVidia

Data declaration, memory (1)

- constants in GPU memory, i.e.

```
__constant__ float3 Gravity = {0,-1.0,0};
```

- constants in device memory, i.e.

```
__device__ float3 velocity = {0,0,0};
```

- memory shared between threads in a block

```
__shared__ float3 table[N];
```

- access to data of type __device__ from CPU, example:

```
float3 vel_host;
const char *symbol="velocity";
cudaMemcpyFromSymbol (vel_host, symbol,
sizeof(float3), 0, cudaMemcpyDeviceToHost);
```

Memory allocation and copying (CPU $\leftrightarrow$ GPU)

CPU

```
float *a_h = (float *)malloc(size);
```

GPU

```
float *a_d;
cudaMalloc((void **) &a_d, size);
```

Copying CPU $\rightarrow$ GPU

```
cudaMemcpy(a_d, a_h, size, cudaMemcpyHostToDevice);
```

Copying CPU $\leftarrow$ GPU

```
cudaMemcpy(a_h, a_d, size, cudaMemcpyDeviceToHost);
```

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Hello World

```
#include <stdio.h>
#include <cuda.h>

__device__ char napis_device[14];

__global__ void helloWorldOnDevice(void)
{
    napis_device[0] = 'H';
    napis_device[1] = 'e';
    ...
    napis_device[12] = '\n';
    napis_device[13] = 0;
}

int main(void)
{
    helloWorldOnDevice <<< 1, 1 >>> ();
    cudaThreadSynchronize();

    char napis_host[14];
    const char *symbol="napis_device";
    cudaMemcpyFromSymbol (napis_host, symbol, sizeof(char)*13, 0, cudaMemcpyDeviceToHost);

    printf("%s",napis_host);
}
```

Result: 'Hello World!' written by GPU.

Parallel version of Hello World

Parallel version of 'Hello World!':

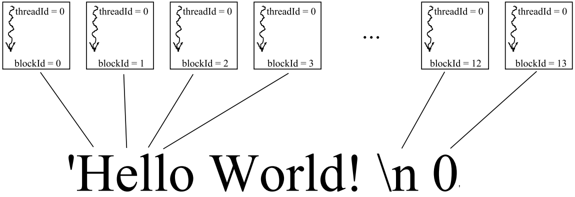
- no changes in functionality
- we split the task between cores
- let each 'Hello World!' letter will be written by different core!

(Together with Paweł Czubiński)

Parallel version of Hello World

Kernel split to 14 blocks 1 thread each:

```
helloWorldOnDevice <<< 14, 1 >>> ();
```



Hello World

```

__device__ char napis_device[14];
__constant__ __device__ char hw[] = "Hello World!\n";

__global__ void helloWorldOnDevice(void)
{
    int idx = blockIdx.x;
    napis_device[idx] = hw[idx];
}

int main(void)
{
    helloWorldOnDevice <<< 14, 1 >>> ();
    cudaThreadSynchronize();
    ...
}
```

- Result: 'Hello World!' written by GPU in parallel!
- Each letter written by different core (if there were free resources available).

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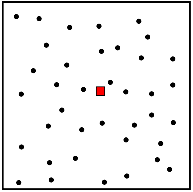
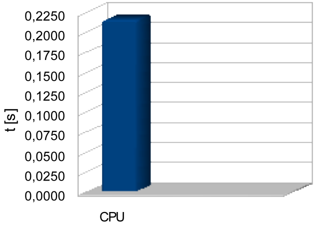
N body problem (no interaction) $O(N)$



- N non interacting material points
- gravity force $g = (0, g_y, 0)$
- $+$ attraction to specified point
- computational loop:
  1. force calculation 2. integration of equations of motion
- a little number of FLOPS per memory access!
- linear complexity growth - O(N)

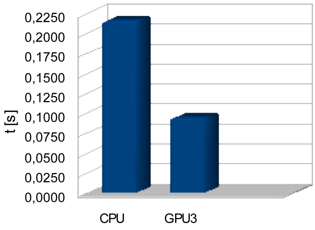
Solution 1. CPU

```
for(int i=0; i < N; i++)
{

  DIST = sqrt( (_ATR.x - pos[i].x)*(_ATR.x - pos[i].x)
         + (_ATR.y - pos[i].y)*(_ATR.y - pos[i].y));

  if(DIST)
  {
    ATRF.x = KD * ((_ATR.x - pos[i].x))/DIST;
    ATRF.y = KD * ((_ATR.y - pos[i].y))/DIST;
  }

  vel[i].x = vel[i].x + (G.x + ATRF.x) * dt;
  vel[i].y = vel[i].y + (G.y + ATRF.y) * dt;

  pos[i].x = pos[i].x + vel[i].x * dt;
  pos[i].y = pos[i].y + vel[i].y * dt;

  if(pos[i].x >1) {pos[i].x = 1; vel[i].x = -vel[i].x;}
  if(pos[i].y >1) {pos[i].y = 1; vel[i].y = -vel[i].y;}
  if(pos[i].x <-1) {pos[i].x = -1; vel[i].x = -vel[i].x;}
  if(pos[i].y <-1) {pos[i].y = -1; vel[i].y = -vel[i].y;}

}
```



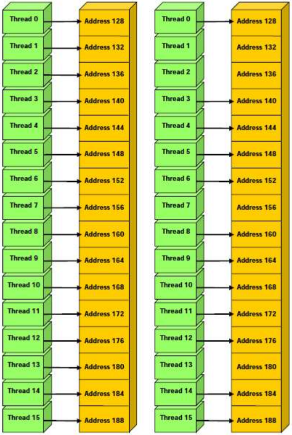
Solution 2. GPU, float3

```
__global__ void movepartOnDevice
(float3* posvbo, float3 *vel, ...)
{
  int idx = blockIdx.x*blockDim.x + threadIdx.x;

  float3 posidx;
  float3 velidx;

  (...)

  if (idx < _N)
  {
    posidx = posvbo[idx];
    velidx = vel[idx];

      // ------------------------------------
      // Here: loop as in CPU code, exchange
      // pos[i] -> posidx
      // vel[i] -> velidx
      // ------------------------------------

    posvbo[idx] = posidx;
    vel[idx] = velidx;
  }
}
```



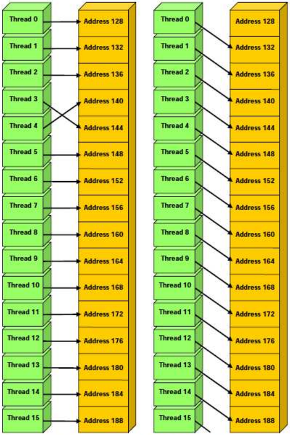
- x2
- memory access!

Coalesced memory access



Left: coalesced `float` memory access, resulting in a single memory transaction.
Right: coalesced `float` memory access (divergent warp), resulting in a single memory transaction.

Figure 5-1. Examples of Coalesced Global Memory Access Patterns

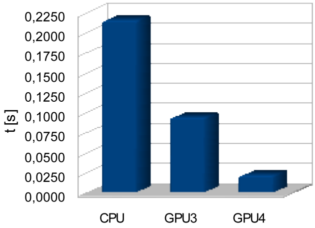


Left: non-sequential `float` memory access, resulting in 16 memory transactions.
Right: access with a misaligned starting address, resulting in 16 memory transactions.

Figure 5-2. Examples of Global Memory Access Patterns That Are Non-Coalesced for Devices of Compute

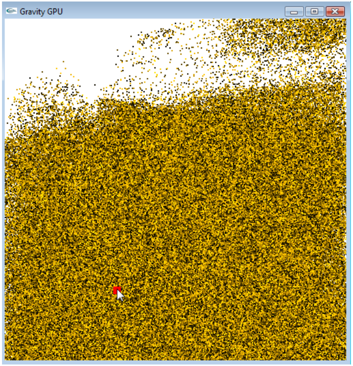
Solution 3. GPU, float4

```
__global__ void movepartOnDevice
(float4* posvbo, float4 *vel, ...)
{
  int idx = blockIdx.x*blockDim.x + threadIdx.x;

  float4 posidx;
  float4 velidx;

  (...)

  if (idx < _N)
  {
    posidx = posvbo[idx];
    velidx = vel[idx];

      // -----------------------------------
      // Here: loop as in CPU code, exchange
      // pos[i] -> posidx
      // vel[i] -> velidx
      // -----------------------------------


    posvbo[idx] = posidx;
    vel[idx] = velidx;
  }
}
```



- x10
- order of magnitude!

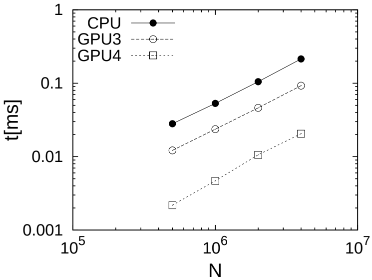
Complexity O(N), OpenGL visualization, GPU vs CPU



- 0.5 milion of points
- realtime visualization
- OpenGL
- GL Utility Toolkit (GLUT)
- Vertex Buffer Object (VBO)

[run]

Complexity O(N), comparison



- linear complexity
- GPU→device memory > CPU→host memory.
- coalesced access → x10!

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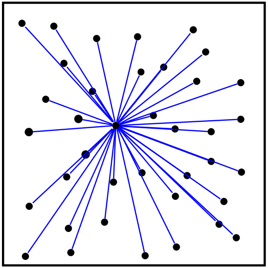
N body problem with interaction $O(N^2)$

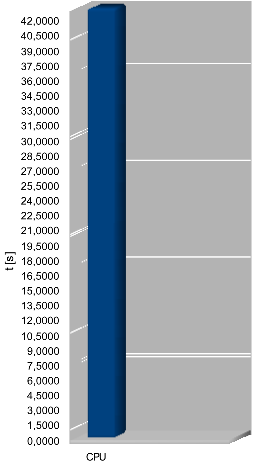
- N interacting point masses
- pairwise interaction
- computational loop:

1. force calculation (double)
2. integration of equations of motion



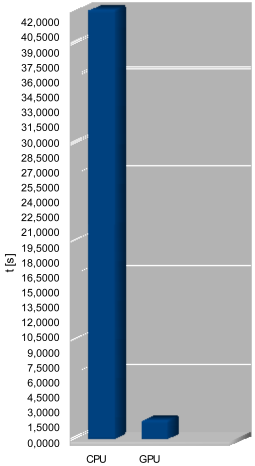
Solution 1. CPU, N=32000

```
(...)

for(int i=0; i < N; i++)
for(int j=0; j < N; j++)
{
  n.x = pos[j].x - pos[i].x;
  n.y = pos[j].y - pos[i].y;

  DIST = sqrt(n.x * n.x + n.y * n.y + EPS2);

  // fg = n*G*m1m2/r**3

  forc[i].x += (n.x * BIGG / DIST*DIST*DIST);
  forc[i].y += (n.y * BIGG / DIST*DIST*DIST);

}

(...)
```



Solution 2. GPU, N=32000

```
__global__ void moveparticlesOnDevice
(float4* posvbo, float4 *vel, ...)
{
  int idx = blockIdx.x*blockDim.x + threadIdx.x;
  (...)
  if (idx<_N)
  {
    posidx = posvbo[idx];

    forc.x = 0;
    forc.y = 0;

    for(int j=0; j < _N; j++)
    {
        // fg = n*G*m1m2/r**3
        // between posidx, and posvbo[j]
        // (analogy to CPU code)
        (...)
    }
  }

  (...)
}
```



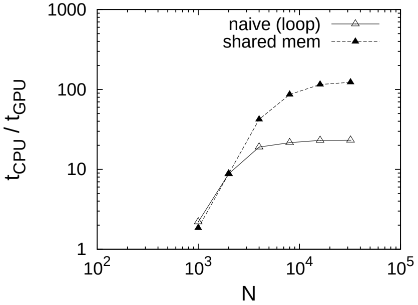
N body algorithm with shared memory

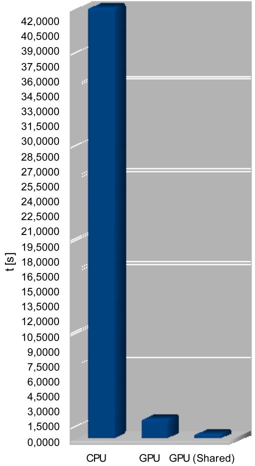
Effective algorithm of N body for CUDA:

- Lars Nyland, Mark Harris, Jan Prins
  Fast N-Body Simulation with CUDA
  GPU Gems 3

- use of shared memory
- each thread calculates N forces
- p - number of threads in a block
- each thread runs a loop which calculates N/p forces (p times)
- these N/p forces are calculated using data stored in shared memory
- thread/block -¿ place in memory mapping

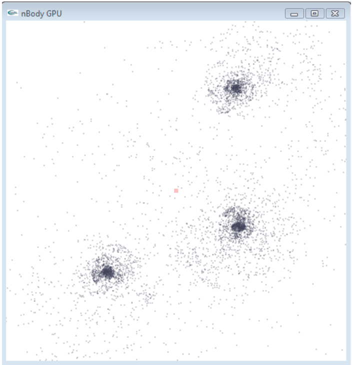
Solution 3. GPU - shared memory, N=32000





- x100!
- 2 orders of magnitude!

Complexity $O(N^2)$, OpenGL visualization, GPU vs CPU



- 5835 points
- realtime visualization
- OpenGL
- GL Utility Toolkit (GLUT)
- Vertex Buffer Object (VBO)

[run-CPU] [run-GPU]
[(GPU+CPU)]

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Summary

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- memory access optimization - crucial
- algorithm rebuilding - needed (work for programmers)
- shared memory - 16kb of registers (!)
- a lot of work - worth to do.
- Future? GTX300 - complete change of architecture? (!)

Attention: In that seminar we didn't say anything about compute capabilities, atomic operations, threads synchronization, vertex and pixel bufor, textures, loops unrolling, memory bank conflicts, warps etc..

Source: 'nVidia CUDA, Programming Guide 2.2', nVidia

Sources

- http://4.bp.blogspot.com/_hqgVFA7RYE4/SkAI1b2QGlI/AAAAAAAABd4 /Q5mhupfFHCA/s400/Hun+Sen+shaking+hand+with+Abhisit+(Reuters).jpg
- http://www.ipipan.gda.pl/ wiesiek/pjwstk/08-09/ark/wyklad-03.pdf
- http://http.developer.nvidia.com/CgTutorial/cg_tutorial_chapter01.html
- http://arstechnica.com/hardware/reviews/2008/06/nvidia-geforce-gx2-review.ars
- 'nVidia CUDA, Programming Guide 2.2', nVidia
- Wikipedia
- Zbigniew Koza, 'CUDA na Twoim biurku, czyli słów kilka na temat Compute Unified Device Architecture', Wykład

Outline

CPU
- CPU Architecture

GPU
- GPU Architecture

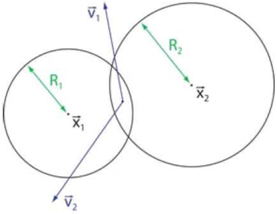
CUDA Architecture
- Existing GPGPU frameworks

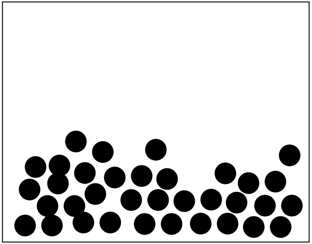
GPU programming
- Data types and kernel
- Grid, blocks, threads, memory

Examples
- Parallel HelloWorld
- N body problem (no interaction) $O(N)$
- N body problem with interaction $O(N^2)$

Summary
- Out of the main track

Out of the main track





- Simple model of granular matter:

  N. Bell, Y. Yu and P. J. Mucha,
  Particle-Based Simulation of Granular Materials,
  Eurographics/ACM SIGGRAPH (2005)

- spring interaction between masses
- Realtime, CUDA, 4096 grains, [run]

The End

Thank you for your attention!