GPU Programming

Imperative And Functional Approaches

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The multicore era

The number of cores is rising with each generation of CPU or GPU

- Avoid the power wall:
  Increased frequency - increases power consumption.
- Avoid the Instruction level parallelism (ILP) wall:
  Finding and utilising ILP is getting more and more difficult.
- Avoid the Memory wall:
  Increasing speed gap between memory chips and processors.

Modern processors and Accelerators

- NVIDIA GTX 680: GPU
  8 * Multiprocessor (* 192 compute units, called CUDA cores)
- Intel Xeon Phi: Accelerator
  60 x86 cores
  512 bits wide SIMD (16 floats)
- Intel Ivy Bridge: Heterogeneous CPU-GPU
  2 - 6 x86 CPU cores
  6 or 16 GPU "execution units"

New ways of programming

- GPUs:
  - Accelerate: Embedded in Haskell [4].
  - CUDA: NVIDIA's C dialect for their GPUs [1].
  - Nikola: Embedded in Haskell [6].
  - Obsidian: Embedded in Haskell [5].
  - OpenCL: A platform independent "CUDA".
  - Thrust: C++ library [9].

New ways of programming

- Intel Xeon Phi:
  - Use old tools such as: OpenMP, OpenMPI.

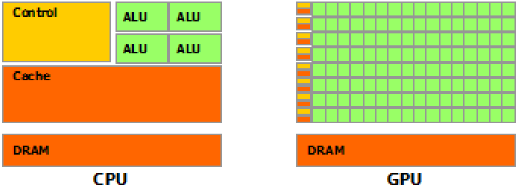
New ways of programming

- Heterogeneous:
  - ArBB: Intel Array building blocks [8]
  - EmbArBB: Haskell embedding of ArBB [11]
  - OpenCL: Can be compiled for both CPU and GPU.
  - Language combinations: CUDA + MPI.

GPUs: The device

- Memory
- Computation
- Cooling
- Connection to Host

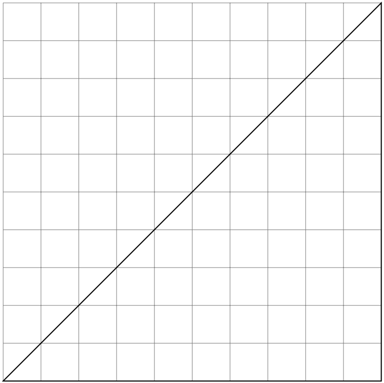
GPUs: Compared to CPUs



[1]

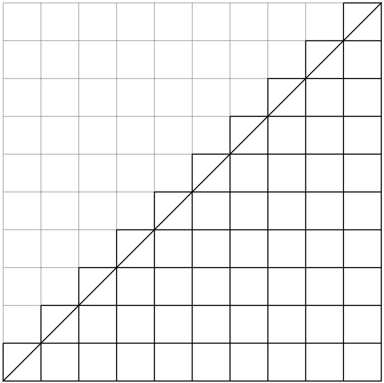
[1] image source:
http://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html

GPUs: The graphics roots



Built for drawing triangles.

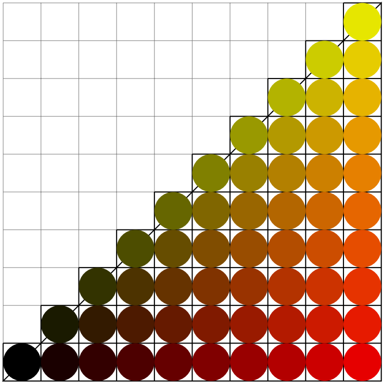
GPUs: The graphics roots



Built for drawing triangles.

For each pixel, a small program is executed.

GPUs: The graphics roots

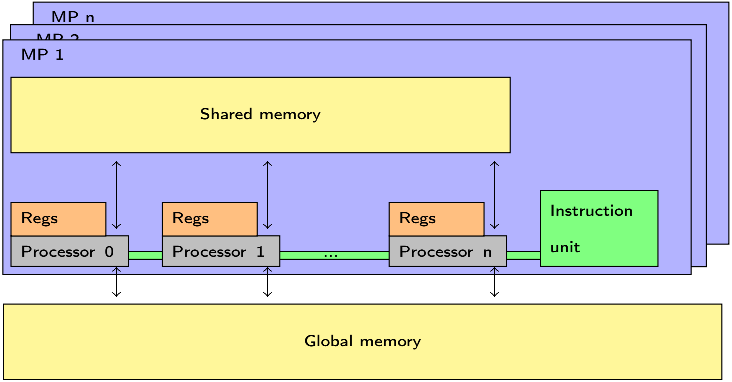


Built for drawing triangles.

For each pixel, a small program is executed.

Each pixel value is computed independently.

CUDA and the GPU: Multiprocessors



CUDA and the GPU: CUDA programming model

- Single Program Multiple Threads SIMT.
- Threads are divided into *Blocks*
  - Up to 1024 threads per block. (Varies!)
  - Many blocks share a MP.
  - Threads within a block can communicate using shared memory.
  - More threads per block than processors per MP
    `__syncthreads();`

CUDA and the GPU: CUDA programming example

The Kernel:

```
__global__ void inc(float *i, float *r){

  unsigned int ix = blockIdx.x * blockDim.x + threadIdx.x;

  r[ix] = i[ix]+1;
}
```

CUDA and the GPU: CUDA glue code part 1

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

#define BLOCK_SIZE 256
#define BLOCKS 1024
#define N (BLOCKS * BLOCK_SIZE)
```

CUDA and the GPU: CUDA glue code part 2

```
int main(){

  float *v, *r;
  float *dv, *dr;

  v = (float*)malloc(N*sizeof(float));
  r = (float*)malloc(N*sizeof(float));

  //generate input data
  for (int i = 0; i < N; ++i) {
    v[i] = (float)(rand () % 1000) / 1000.0;
  }
  /* Continues on next slide */
```

CUDA and the GPU: CUDA glue code part 3

```
cudaMalloc((void**)&dv, sizeof(float) * N );
cudaMalloc((void**)&dr, sizeof(float) * N );

cudaMemcpy(dv, v, sizeof(float) * N,
           cudaMemcpyHostToDevice);
/* Continues on next slide */
```

CUDA and the GPU: CUDA glue code part 4

```
inc<<<BLOCKS, BLOCK_SIZE,0>>>(dv,dr);

cudaMemcpy(r, dr, sizeof(float) * N , cudaMemcpyDeviceToHost);

cudaFree(dv);
cudaFree(dr);
/* Continues on next slide */
```

CUDA and the GPU: CUDA glue code part 5

```
  for (int i = 0; i < N; ++i) {
    printf("%f ", r[i]);
  }
  printf("\n");

  free(v);
  free(r);
}
```

CUDA and the GPU: CUDA timing code

Add timing:

```
cudaEvent_t start,stop;

cudaEventCreate(&start);
cudaEventCreate(&stop);
```

CUDA and the GPU: CUDA timing code

Add timing:

```
cudaEvent_t start,stop;

cudaEventCreate(&start);
cudaEventCreate(&stop);
```

Wrap what you want to time with:

```
cudaEventRecord(start);
 /* This part is timed */
cudaEventRecord(stop);
cudaEventSynchronize(stop);
```

CUDA and the GPU: CUDA timing code

```
float elapsedTime;
cudaEventElapsedTime(&elapsedTime, start, stop);

printf("Time %f ms\n", elapsedTime);
```

CUDA and the GPU: Compile and run

```
> nvcc inc.cu -o inc
>./inc

1.383000 1.886000 1.777000 ...
Time 0.022432 ms
```

Haskell approaches to GPU programming

- Accelerate (Data.Array.Accelerate)
- Nikola
- Obsidian

Accelerate programming

Shapes:

```
type Dim0
type Dim1
...
```

Arrays:

```
Array sh e
```

Aliases:

```
type Scalar a = Array Dim0 a
type Vector a = Array Dim1 a
```

Accelerate programming: Example

```
dotp :: Vector Float -> Vector Float -> Acc (Scalar Float)
dotp xs ys = let xs' = use xs
                 ys' = use ys
             in fold (+) 0 (zipWith (*) xs' ys')
```

Accelerate programming: Interface

```
use :: Array sh e -> Acc (Array sh e)
map :: (Exp a -> Exp b)
    -> Acc (Array sh a)
    -> Acc (Array sh b)
zipWith :: (Exp a -> Exp b -> Exp c)
        -> Acc (Array sh a)
        -> Acc (Array sh b)
        -> Acc (Array sh c)
fold :: (Exp a -> Exp a -> Exp a)
     -> Exp a
     -> Acc (Array sh:.Int a)
     -> Acc (Array sh a)
```

And many more: `permute`, `scan` ...

Accelerate programming: More information

Ref. [4] provides more details about Accelerate and its programming model.
Recent progress in optimising accelerate programs is described in Ref. [7]. Here they mention fusion of kernels.

Nikola

- `map`
- `zipWith`

Accelerate & Nikola

- High level languages.
- Relies on code generator to produce good GPU code.

Accelerate & Nikola

- High level languages.
- Relies on code generator to produce good GPU code.
- Obsidian is slightly different...

Obsidian

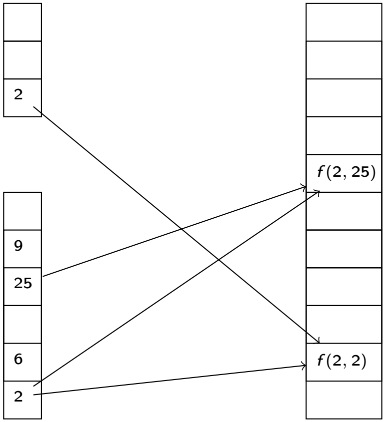
2 3

[2]game: `www.minecraft.net`
[3]lava: An embedded language for hardware design [2]

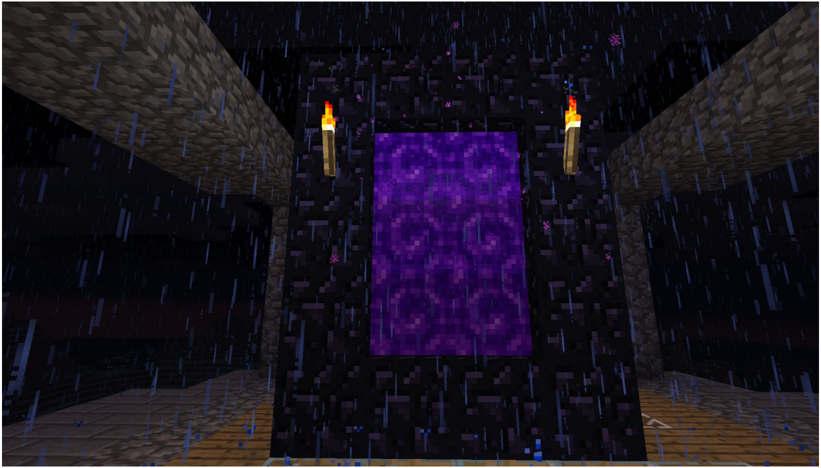
Obsidian: Goals

- Encourage experimentation.
- Combinators for parallel programming.
- Lower level than Accelerate and Nikola.
  - Programmer needs to know a little about GPUs.
  - Programmer control over how to compute on the GPU.
  - Programmer control over shared memory.
- Higher level than CUDA.
  - Not as much indexing *magic*.
  - Program describes “whole” computation.

Obsidian: Pull arrays



Obsidian: Push arrays



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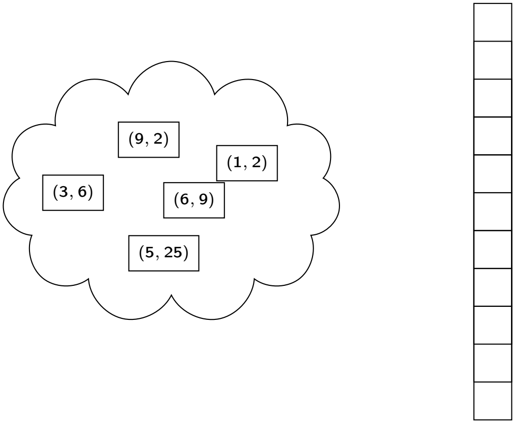

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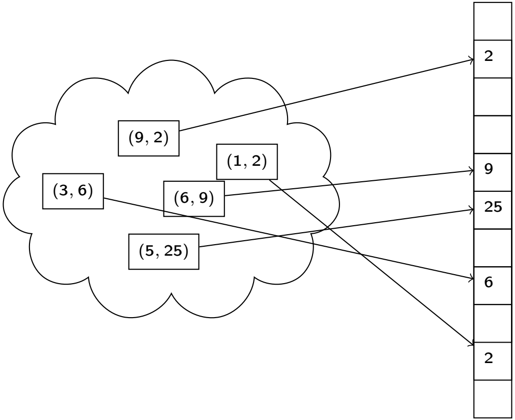
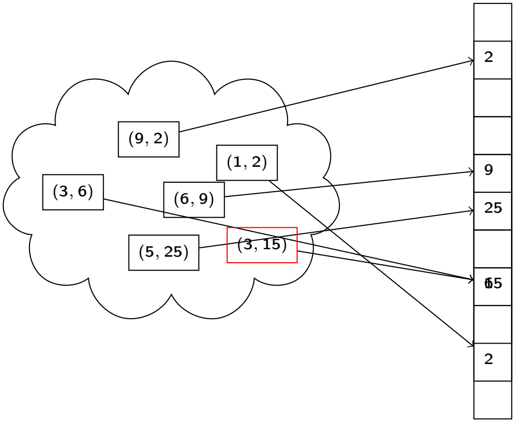


Obsidian: Push arrays



Obsidian: Example kernel

```
inc :: SPull EFloat -> SPull EFloat
inc = fmap (+1)
```

Obsidian: Example grid

```
incG :: DPull EFloat -> DPush Grid EFloat
incG arr = mapG (return . inc) (splitUp 256 arr)
```

Obsidian: Example grid

```
incG :: DPull EFloat -> DPush Grid EFloat
incG arr = mapG (return . inc) (splitUp 256 arr)

splitUp :: Word32 -> DPull a -> DPull (SPull a)
splitUp n arr =
  mkPullArray (m `div` fromIntegral n) $ \i ->
    mkPullArray n $ \j -> arr ! (i * fromIntegral n + j)
  where
    m = len arr
```

Obsidian: Example code generation

```
input :: DPull EFloat
input = namedGlobal "apa" (variable "X")

getIncG = putStrLn $ genKernel "inc" incG input
```

Obsidian: Example code generation

```
input :: DPull EFloat
input = namedGlobal "apa" (variable "X")

getIncG = putStrLn $ genKernel "inc" incG input

> getIncG
__global__ void inc(float* input0,uint32_t n0,float* output0){

    uint32_t t0 = ((blockIdx.x*256)+threadIdx.x);
    output0[t0] = (input0[t0]+1.0);


}
```

Obsidian: Example shared memory

```
incG :: DPull EFloat -> DPush Grid EFloat
incG arr = mapG (force . inc) (splitUp 256 arr)
```

Obsidian: Example shared memory

```
incG :: DPull EFloat -> DPush Grid EFloat
incG arr = mapG (force . inc) (splitUp 256 arr)

> getIncG
__global__ void inc(float* input0,uint32_t n0,float* output0){

    uint32_t t1 = ((blockIdx.x*256)+threadIdx.x);
    extern __shared__ uint8_t sbase[];
    ((float*)sbase)[threadIdx.x] = (input0[t1]+1.0);
    __syncthreads();
    output0[t1] = ((float*)sbase)[threadIdx.x];


}
```

Obsidian: Recap

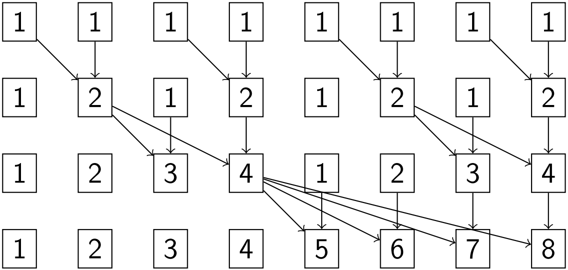
- Arrays: Push and Pull
  - With static (`SPull`, `SPush`) and dynamic (`DPull`, `DPush`) lengths.
- Push arrays have a parameter `Thread`, `Block` or `Grid`.
- ```
  mapG :: ASize l
        =>(SPull a -> BProgram (SPull b))
        -> Pull l (SPull a) -> Push Grid l b
  ```
- ```
  force :: (Pushable p, Array p, MemoryOps a)
         => p Word32 a -> BProgram (Pull Word32 a)
  ```

Obsidian: prefix sums (Scan)

Given a associative operator $\oplus$, and an array $\{a_0, a_1, \cdots, a_{n-1}\}$ the prefix sums operation results in
$\{a_0, (a_0 \oplus a_1), \cdots, a_0 \oplus a_1 \oplus \cdots \oplus a_{n-1}\}$

This operation can be implemented on parallel hardware and can be used in the implementation of many algorithms, see Ref. [3] for more info.

Obsidian: Sklansky [10]



Obsidian: Sklansky implementation

```
sklansky :: Int -> SPull EFloat -> BProgram (SPull EFloat)
sklansky 0 arr = return arr
sklansky n arr =
  do
    let arr1 = binSplit (n-1) (fan (+)) arr
    arr2 <- force arr1
    sklansky (n-1) arr2
```

Obsidian: Sklansky implementation

```
sklansky :: Int -> SPull EFloat -> BProgram (SPull EFloat)
sklansky 0 arr = return arr
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    let arr1 = binSplit (n-1) (fan (+)) arr
    arr2 <- force arr1
    sklansky (n-1) arr2

fan :: Choice a => (a -> a -> a) -> SPull a -> SPull a
fan op arr = a1 `conc` fmap (op (last a1)) a2
  where (a1,a2) = halve arr
```

Obsidian: Many Sklansky

```
sklanskyG :: DPull EFloat -> DPush Grid EFloat
sklanskyG arr = mapG (sklansky 8) (splitUp 256 arr)
```

Obsidian: Sklansky generated code

```
__global__ void sklansky(float* input0,uint32_t n0,float* output0){

    uint32_t t2 = ((blockIdx.x*32)+((threadIdx.x&4294967294)|(threadIdx.x&1)));
    uint32_t t9 = ((threadIdx.x&4294967292)|(threadIdx.x&3));
    uint32_t t14 = ((threadIdx.x&4294967288)|(threadIdx.x&7));
    uint32_t t19 = ((threadIdx.x&4294967280)|(threadIdx.x&15));
    extern __shared__ __attribute__ ((aligned(16))) uint8_t sbase[];
    ((float*)sbase)[threadIdx.x] =
      (((threadIdx.x&1)<1) ? input0[t2] :
           (input0[((blockIdx.x*32)+((threadIdx.x&4294967294)|0))]+input0[t2]));
    __syncthreads();
    ((float*)(sbase+128))[threadIdx.x] =
      (((threadIdx.x&3)<2) ? ((float*)sbase)[t9] :
           (((float*)sbase)[((threadIdx.x&4294967292)|1)]+((float*)sbase)[t9]));
    __syncthreads();
    ((float*)sbase)[threadIdx.x] =
      (((threadIdx.x&7)<4) ? ((float*)(sbase+128))[t14] :
           (((float*)(sbase+128))[((threadIdx.x&4294967288)|3)]+((float*)(sbase+128))[t14]));
    __syncthreads();
    ((float*)(sbase+128))[threadIdx.x] =
      (((threadIdx.x&15)<8) ? ((float*)sbase)[t19] :
           (((float*)sbase)[((threadIdx.x&4294967280)|7)]+((float*)sbase)[t19]));
    __syncthreads();
    ((float*)sbase)[threadIdx.x] =
      ((threadIdx.x<16) ? ((float*)(sbase+128))[threadIdx.x] :
        (((float*)(sbase+128))[15]+((float*)(sbase+128))[threadIdx.x]));
    __syncthreads();
    output0[((blockIdx.x*32)+threadIdx.x)] = ((float*)sbase)[threadIdx.x];

}
```

Next time

- More about arrays:
  - What is a pull array, really ?
  - What is a push array, really ?
- Programs:
  - `TProgram`
  - `BProgram`
  - `GProgram`
- Implementation:
  - Library functions.
  - Code generation.

End

CUDA programming manual.
`http://docs.nvidia.com/cuda/cuda-c-programming-guide/`.

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