

# Code Optimizations

Jiří Filipovič

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# Vector Reduction

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There is flow dependency across iterations.

- we cannot compute completely parallel
- addition is (at least in theory :-)) associative
- so, we do not need to add numbers in sequential order

# Parallel Algorithm

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We can work in parallel now:

- four additions in the first step
- two additions in the second step
- one addition in the third step

In summary, we perform  $n - 1$  additions in  $\log_2 n$  parallel steps!

# Parallel Algorithm

We have found the parallel algorithm

- the same number of additions as the serial algorithm
- in logarithmic time (if we have enough cores)

We add results of previous additions

- flow-dependency across threads
- we need global barrier



# Naive Approach

The simplest scheme of the algorithm:

- for even  $i$ ,  $i < n$  perform  $v[i] += v[i+1]$
- repeat for  $n \neq 2$  until  $n > 1$

The performance is not ideal

- $2n$  numbers loaded from global memory
- $n$  numbers stored to global memory
- $\log_2 n$  kernel invocations

We have three memory accesses to one arithmetic operation and considerable kernel invocation overhead.

# Exploiting Data Locality

We can add more than pairs during single kernel call.

- each block  $bx$  loads  $m$  numbers into shared memory
- it reduces the input (in shared memory in  $\log_2 m$  steps)
- it stores only one number containing  $\sum_{i=m \cdot bx}^{m \cdot bx + m - 1} v_i$

Reduces both memory transfers and number of kernel invocations

- number of loads:  $n + \frac{n}{m} + \frac{n}{m^2} + \dots + \frac{n}{m^{\log_m n}} = (n - 1) \frac{m}{m - 1}$
- approximately  $n + \frac{n}{m}$  numbers read,  $\frac{n}{m}$  written
- $\log_m n$  kernel invocations

# Implementation 1

```

__global__ void reduce1(int *v){
    extern __shared__ int sv[];

    unsigned int tid = threadIdx.x;
    unsigned int i = blockIdx.x*blockDim.x + threadIdx.x;
    sv[tid] = v[i];
    __syncthreads();

    for(unsigned int s=1; s < blockDim.x; s *= 2) {
        if (tid % (2*s) == 0)
            sv[tid] += sv[tid + s];
        __syncthreads();
    }

    if (tid == 0)
        v[blockIdx.x] = sv[0];
}

```

# Performance

Beware modulo operation.

High degree of divergence

- during the first iteration, only half of threads is working
- during the second iteration, only quarter of threads is working
- etc.

Performance on GTX 280: 3.77 GB/s (0.94 MElem/s).

# Implementation 2

We will modify indexation

```
for (unsigned int s = 1; s < blockDim.x; s *= 2) {  
    int index = 2 * s * tid;  
    if (index < blockDim.x)  
        sv[index] += sv[index + s];  
    __syncthreads();  
}
```

Performance: 8.33 GB/s (2.08 MElem/s).

The code is free of modulo and divergence, but generates shared memory bank conflicts.

# Implementation 3

So we can try another indexing...

```
for (unsigned int s = blockDim.x/2; s > 0; s >>= 1) {
    if (tid < s)
        sv[tid] += sv[tid + s];
    __syncthreads();
}
```

No divergence and no conflicts.

Performance 16.34 GB/s (4.08 MElem/s).

Half of threads do not compute...

# Implementation 4

We can add numbers during loading them from global memory.

```
unsigned int i = blockIdx.x*(blockDim.x*2) + threadIdx.x;  
sv[tid] = v[i] + v[i+blockDim.x];
```

Performance 27.16 GB/s (6.79 MElem/s).

There is no problem with data access, but the performance is still low – we will focus to instructions.

# Implementation 5

The number of active threads decreases during computation in shared memory.

- in the last six iterations, only the last warp is active
- the warp is synchronized implicitly on GPUs with c.c.  $< 7.0$ , so we do not need `__syncthreads()`
  - we need volatile variable in this case
- condition `if(tid < s)` does not spare any computation

So we can unroll the last warp...



# Implementation 5

```

float mySum = 0;

for (unsigned int s = blockDim.x/2; s > 32; s >>= 1){
    if (tid < s)
        sv[tid] = mySum = mySum + sv[tid + s];
    __syncthreads();
}

if (tid < 32){
    volatile float *s = sv;
    s[tid] = mySum = mySum + s[tid + 32]; __syncthreads();
    s[tid] = mySum = mySum + s[tid + 16]; __syncthreads();
    s[tid] = mySum = mySum + s[tid + 8]; __syncthreads();
    s[tid] = mySum = mySum + s[tid + 4]; __syncthreads();
    s[tid] = mySum = mySum + s[tid + 2]; __syncthreads();
    s[tid] = mySum = mySum + s[tid + 1];
}

```

We save time in all warps (the last warp is simpler, others exits earlier from the for loop).

Performance: 37.68 GB/s (9.42 MElem/s).

# Implementation 5

For c.c. 3.0 or greater, we can use warp shuffle:

```
if (tid < 32){
    mySum += sdata[tid + 32]; __syncthreads();
    for (int offset = warpSize/2; offset > 0; offset /= 2)
        mySum += __shfl_down_sync(mySum, offset);
}
```

# Implementation 6

Can we unroll the for loop?

If we know the number of iterations, we can unroll it

- the number of iterations depends on the block size

Can we implement it generically?

- algorithm uses blocks of size  $2^n$
- the block size is upper-bound
- if we know the block size during compilation, we can use a template

```
template <unsigned int blockSize>
__global__ void reduce6(int *v)
```

# Implementation 6

Conditions using `blockSize` are evaluated during compilation:

```

if (blockSize >= 512){
    if (tid < 256)
        sv[tid] += sv[tid + 256];
    __syncthreads();
}
if (blockSize >= 256){
    if (tid < 128)
        sv[tid] += sv[tid + 128];
    __syncthreads();
}
if (blockSize >= 128){
    if (tid < 64)
        sv[tid] += sv[tid + 64];
    __syncthreads();
}

```

Performance: 50.64 GB/s (12.66 MElem/s).

# Implementation 7

Can we implement faster algorithm?

Let's reconsider the complexity:

- $\log n$  parallel steps
- $n - 1$  additions
- time complexity for  $p$  threads running in parallel (using  $p$  processors):  $\mathcal{O}\left(\frac{n}{p} + \log n\right)$

Cost of parallel computation

- defined as number of processors multiplied by time complexity
- if we assign one thread to one data element, we get  $p = n$
- and the cost is  $\mathcal{O}(n \cdot \log n)$
- which is not efficient

# Implementation 7

## Decreasing the cost

- we use  $\mathcal{O}\left(\frac{n}{\log n}\right)$  threads
- each thread performs  $\mathcal{O}(\log n)$  sequential steps
- after that, it performs  $\mathcal{O}(\log n)$  parallel steps
- time complexity is the same
- the cost is  $\mathcal{O}(n)$

## What it means in practice?

- we reduce overhead of the computation (e.g., integer arithmetics)
- advantage if we have much more threads that is needed to saturate GPU

# Implementation 7

We modify loading into shared memory

```
unsigned int gridSize = blockSize*2*gridDim.x;
sv[tid] = 0;

while(i < n){
    sv[tid] += v[i] + v[i+blockSize];
    i += gridSize;
}
__syncthreads();
```

Performance: 77.21 GB/s (19.3 MElem/s).

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You can find those implementations in CUDA SDK.



# Intra-kernel Optimizations

The compiler optimizes each kernel separately, so it may miss some optimization opportunities.

- kernel fusion – gluing code from several kernels into one kernel
- kernel fission – splitting a kernel into several smaller kernels

# Kernel fusion

## Performance impact of kernel fusion

- reduce kernel execution overhead
- may add more parallelism
- allow more scalar code optimizations: common subexpression elimination, loop fusion, condition fusion
- reduce global memory transfers if kernels are flow-dependent or input-dependent

## Correctness

- no flow dependency between thread blocks
- shared memory and registers locality has to be maintained

# Kernel fission

Kernel fission reduces resources consumption

- increases occupancy
- may allow to use algorithms which would be inefficient when run in one kernel (e.g., if part of the algorithm uses different amount of parallelism or different amount of resources)
- more complicated and divergent codes may be separated (e.g., handling array boundaries)

Correctness

- much easier, we just need to transfer data between new kernels

# Problem Choice

Before we start with code acceleration, we should consider carefully, if it is meaningful.

The accelerated code should be

- critical for application performance (profile... and profile on real data)
- large enough (usually not ideal for relatively simple but latency critical application)
- parallelizable (problematic, e.g., in simulation of a small system evolving for a long time)
- sufficient number of flops to memory transfers (consider slow PCI-E)

# Problem Choice

Do we optimize running time or power consumption?

- accelerators are usually faster, but also have higher power consumption
- how to deal with hybrid systems (e.g., CPU, GPU and Xeon Phi)
- influences decision what to buy as well as what to use (which resources let in power-saving mode)

# Algorithm Design

## Parallelization

- we need to parallelize computational problem
- we should be aware about target architecture even in this stage (consider, e.g., graph algorithms)

It is difficult to accelerate codes on GPU:

- if threads within the warp access rather random addresses in the memory
- if threads within the warp diverges (by nature of the algorithm)
- if the parallelism is insufficient in certain parts of computation

# How to Write Bug-Free Code

Test if API and kernel calls are successful

- otherwise, errors can appear later...

The memory allocation on GPU occurs seldom

- if your modify your code in a way your kernel does not write any result, you got a result from its previous run
- clear output arrays for debugging purposes

Be aware of out-of-bounds shared memory access

- kernel usually runs successfully, but one block interferes with another

# Optimization

Start with the most important optimizations and continue with less important (so the effect of less important optimizations is not hidden). In general, this order should work well:

- PCI-E transfers reduction/overlay
- global memory access (bandwidth, latency)
- access to other types of memory
- divergence
- parallelism configuration (block size, amount of serial work per thread)
- instruction optimization

It is good idea to write your code configurable

- block size, number of serial iterations per thread, loop unrolling factor, used algorithm . . .
- use macros or templates to ease configuration of the optimizations



# Interpretation of Algorithm Performance

Some optimizations may be hidden

- e.g., optimizing instruction cannot help when code is bound by wrong global memory access
- can be reduced by applying more important optimizations earlier
- use the profiler

The optimization space is not continuous

- due to restricted amount of GPU resources
- e.g., improving efficiency of scalar code by using one more register may decrease the performance by restricting GPU occupancy

Performance is data-dependent

- data size: partition camping, underutilized GPU
- data content: sparse data with varying structure

# What is real speedup over CPU?

Comparison of a theoretical peak is basic metric

- however, the speedup can be lower
  - insufficient parallelism
  - inappropriate data structures, random access
  - PCI-E bottleneck (especially multi-GPU algorithms)
- however, the speedup can be also higher
  - frequent usage of SFUs
  - complicated vectorization on CPU
  - insufficient scaling on SMP (cache interferences, NUMA)
- different scaling of CPU and GPU with growing problem size

# Searching for Bottlenecks

The amount of arithmetic operations and memory transfers tells us what is expected to be a limit for algorithm

- sometimes bottleneck is not clear (overhead instructions, irregular memory access)
- code profiling – suitable to identify issues with instructions throughput or bad memory access pattern, more difficult to identify source of latency problems
- code modifications – more difficult and not usable in all cases, but may help to clarify some issues

# Profiling

How close is the code to the hardware limits?

- profiler shows the overall utilization of particular GPU subsystems, such as cache, global memory, FP instructions etc.

Issues identification

- profiler detects some issues, such as shared memory bank conflicts or code divergence

We can inspect a code in details

- time spent on particular instructions/C for CUDA lines of code
- we need to compile the code with flag `-lineinfo`

# Code Modifications

## Global memory performance

- we comment-out the computation
- but we need to somehow use loaded data (to disallow compiler to exclude loading)
- we can check with profiler that the same amount of data are transferred

## Instructions performance

- we comment-out data movement
- but the resulting data is needed to be stored (to disallow compiler to exclude computation)
  - but we do not want to store data. . .
  - we can move the code storing data into condition which is evaluated as false during computation (but not during compilation)
- be aware of execution overhead in the case of fast kernels

# Code Modifications

Be aware of occupancy changes

- code modifications can release some resources
- we can restrict occupancy by allocating some dummy shared memory array

Interpretation of measured times

- original kernel execution time is close to sum of computation and memory kernel time – the latency is an issue
- computation or memory kernel time dominates and is closed to original kernel time – the performance is bounded by computation or memory
- computation and memory kernel times are similar to original kernel time – we need to optimize both

# Code Modifications

## Approximation of an optimization effect

- when we already know some performance issue
- when we want to know the effect of optimization before we actually implement it
- we can modify the code without preserving original functionality, but preserving amount of work and removing performance issue
  - cannot be done in all cases
  - may show us if we really address the performance issue
  - see matrix transposition example