

Лекция 6

Библиотека *cuBLAS*.

- Тензорные операции, произведение матриц.
- Реализация произведения матриц на основе CUDA API.
- Особенности использования библиотеки cuBLAS.
- Функции `cublas<T>gemm()`.
- Тензорные процессоры.
- Вызовы `cublas<T>gemm()` с использованием тензорных процессоров.

Матричное произведение тензоров

Произведение матриц

Умножение матриц $C_{mn} = \sum_k A_{mk} B_{kn}$

Diagram illustrating matrix multiplication:

Matrix A (M rows, K columns) is multiplied by Matrix B (K rows, N columns) to produce Matrix C (M rows, N columns).

The dimensions are labeled as follows:

- Matrix A: M строк (rows), K столцов (columns)
- Matrix B: K строк (rows), N столцов (columns)
- Matrix C: M строк (rows), N столцов (columns)

The multiplication is shown as:

$$\begin{bmatrix} A_{00} & A_{01} & A_{02} & A_{03} \\ A_{10} & A_{11} & A_{12} & A_{13} \\ A_{20} & A_{21} & A_{22} & A_{23} \end{bmatrix} \times \begin{bmatrix} B_{00} & B_{01} \\ B_{10} & B_{11} \\ B_{20} & B_{21} \\ B_{30} & B_{31} \end{bmatrix} = \begin{bmatrix} C_{00} & C_{01} \\ C_{10} & C_{11} \\ C_{20} & C_{21} \end{bmatrix}$$

A callout box indicates that the first two rows of Matrix B are K строк.

```
#include <malloc.h>
```

```
#include <ctime>
```

```
#define M 1024
```

```
#define K 1024
```

```
#define N 1024
```

```
void hMultMats(double** A, double** B, double** C){
```

```
    double acc;
```

```
    for(int m=0; m<M;m++)
```

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

```
            acc=0.0;
```

```
            for(int k=0; k<K;k++)
```

```
                acc+=A[m][k]*B[k][n];
```

```
            C[m][n]=acc;
```

```
        }
```

```
    }
```

```
void hInitMats(double** A, double** B){  
    for(int m=0; m<M;m++)  
        for(int k=0; k<K; k++)  
            A[m][k]=(double)((k+m*K)*1.0E-5);  
  
    for(int k=0; k<K;k++)  
        for(int n=0; n<N;n++)  
            B[k][n]=1.0;  
}
```

```
Int main(){  
    double **A, **B, **C;  
    A=(double**)calloc(M, sizeof(double*));  
    for(int m=0; m<M; m++)  
        A[m]=(double*)calloc(K, sizeof(double));
```

```
.....  
hInitMats(A, B);  
clock_t start=clock();  
    hMultMats(A, B, C);  
clock_t finish=clock();
```

```
.....  
    hMatOut(A, M, K);  
    hMatOut(B, K, N);  
    hMatOut(C, M, N);
```

```
.....  
}
```

```
/Lecture8/Lab8> ./lab8cpu
```

```
0          0.00128 0.00256 0.00384 0.00512 0.0064  0.00768 0.00896
```

```
1.31072 1.312    1.31328 1.31456 1.31584 1.31712 1.3184  1.31968
```

```
.....  
9.17504 9.17632 9.1776  9.17888 9.18016 9.18144 9.18272 9.184
```

```
////////////////////////////////////
```

```
1          1          1          1          1          1          1          1
```

```
1          1          1          1          1          1          1          1
```

```
.....  
////////////////////////////////////
```

```
5.23776 5.23776 5.23776 5.23776 5.23776 5.23776 5.23776 5.23776
```

```
1347.42 1347.42 1347.42 1347.42 1347.42 1347.42 1347.42 1347.42
```

```
2689.59 2689.59 2689.59 2689.59 2689.59 2689.59 2689.59 2689.59
```

```
.....  
9400.48 9400.48 9400.48 9400.48 9400.48 9400.48 9400.48 9400.48
```

Elapsed time: 4173.59 ms

```
/Lecture8/Lab8> g++ lab8cpu.cpp -pg -o lab8cpu
/Lecture8/Lab8> ./lab8cpu
/Lecture8/Lab8> ls -ltr
итого 720
-rw-r--r-- 1 malkov users 1528 Mar 16 18:27 lab8cpu.cpp
-rwxr-xr-x 1 malkov users 20496 Mar 16 19:22 lab8cpu
-rw-r--r-- 1 malkov users 1023 Mar 16 19:22 gmon.out
/Lecture8/Lab8> gprof lab8cpu gmon.out > lab8cpu.prof
```

```
/Lecture8/Lab8> vim lab8cpu.prof
```

Flat profile:

Each sample counts as 0.01 seconds.

%	cumulative	self	self	total		
time	secs	secs	calls	s/call	s/call	name
100.40	3.98	3.98	1	3.98	3.98	hMultMats(double**, double**, double**)
0.25	3.99	0.01	1	0.01	0.01	hInitMats(double**, double**)

.....

```
#include <malloc.h>
```

```
#define M 1024
```

```
#define K 1024
```

```
#define N 1024
```

```
#define BLOCK_DIM 32
```

```
__global__ void gMultMats(float* A, float* B, float* C){
```

```
    int n=threadIdx.x + blockIdx.x*blockDim.x;
```

```
    int m=threadIdx.y + blockIdx.y*blockDim.y;
```

```
    float acc=0.0;
```

```
    for(int k=0; k<K; k++)
```

```
        acc+=A[k+m*K]*B[n+k*N];
```

```
    C[n+m*N]=acc;
```

```
}
```



```
__global__ void glnit(float* D, int s){  
    int j=threadIdx.x + blockIdx.x*blockDim.x;  
    int i=threadIdx.y + blockIdx.y*blockDim.y;  
    int J=blockDim.x*gridDim.x;  
  
    D[j+i*J]=s*(float)((j+i*J)*1.0E-5)+(1-s)*1.0f;  
}
```

```
int main(){  
    float *A, *B, *C;  
    cudaMalloc((void**)&A, M*K*sizeof(float));
```

```
.....  
    glnit<<<dim3(K/32, M/32),dim3(32,32)>>>(A,1);
```

```
    cudaDeviceSynchronize();
```

```
    glnit<<<dim3(N/32, K/32),dim3(32,32)>>>(B,0);
```

```
    cudaDeviceSynchronize();
```

```
    cudaMemset(C, 0, M*N*sizeof(REAL));
```

```
    gMultMats<<<dim3(N/BLOCK_DIM, M/BLOCK_DIM),  
                dim3(BLOCK_DIM, BLOCK_DIM)>>>(A,B,C);
```

```
    cudaDeviceSynchronize();
```

```
    hMatOut(A, M, K);  
.....
```

```
/Lecture8/Lab8> ./lab8gpu
```

```
0          0.00128 0.00256 0.00384 0.00512 0.0064  0.00768 0.00896
1.31072 1.312    1.31328 1.31456 1.31584 1.31712 1.3184  1.31968

.....
9.17504 9.17632 9.1776  9.17888 9.18016 9.18144 9.18272 9.184
////////////////////////////////////
1          1          1          1          1          1          1          1
1          1          1          1          1          1          1          1

.....
////////////////////////////////////
5.23776 5.23776 5.23776 5.23776 5.23776 5.23776 5.23776 5.23776
1347.42 1347.42 1347.42 1347.42 1347.42 1347.42 1347.42 1347.42
2689.59 2689.59 2689.59 2689.59 2689.59 2689.59 2689.59 2689.59

.....
9400.48 9400.48 9400.48 9400.48 9400.48 9400.48 9400.48 9400.48
```

```
/Lecture8/Lab8> nvprof ./lab8gpu
```

Type	Time(%)	Time	Calls	Avg	Min	Max	Name
GPU activities:							
63.25%	3.9720ms	1	3.9720ms	3.9720ms	3.9720ms	3.9720ms	gMultMats(float*, float*, float*)
1.90%	119.46us	2	59.728us	59.648us	59.808us	59.808us	glnit(float*, int)

$3.98s * 1000 / 3.9720 = 1002.0141$

Ускорение в тысячу раз! 🤖

Библиотека cuBLAS

(*Basic Linear Algebra Subroutines*)

- Хранение по столбцам (column-major storage), совместимость с Фортраном, для копирования и инициализации матриц следует использовать специальный API.
- Линейная индексация массивов;
- Имена функций образуются по схеме: cublas<T><function>. Например, **cublasSgemm**, тип данных *float*, *generic/general matrix-matrix* умножение плюс сложение: $C = \alpha AB + \beta C$

Документация: [**https://docs.nvidia.com/cuda/cublas/#**](https://docs.nvidia.com/cuda/cublas/#)

```
int main(){
```

```
// Инициализация библиотеки CUBLAS
```

```
cublasHandle_t cublas_handle;  
cublasCreate(&cublas_handle);
```

leading
dimension

```
.....  
//Копирование матрицы с числом строк num_rows и числом  
столбцов //num_cols с хоста на устройство
```

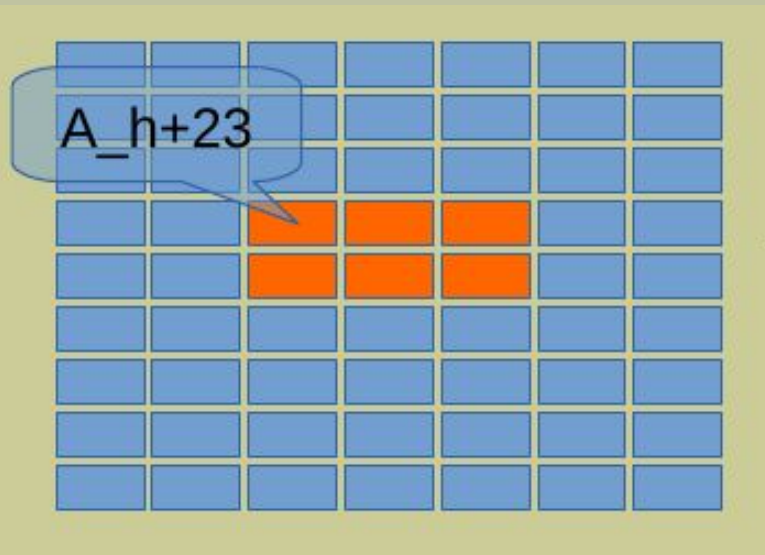
```
cublasSetMatrix(num_rows, num_cols, elem_size, A_h, Idah, A_dev, Idad);
```

```
<вызов функции cuBLAS API>
```

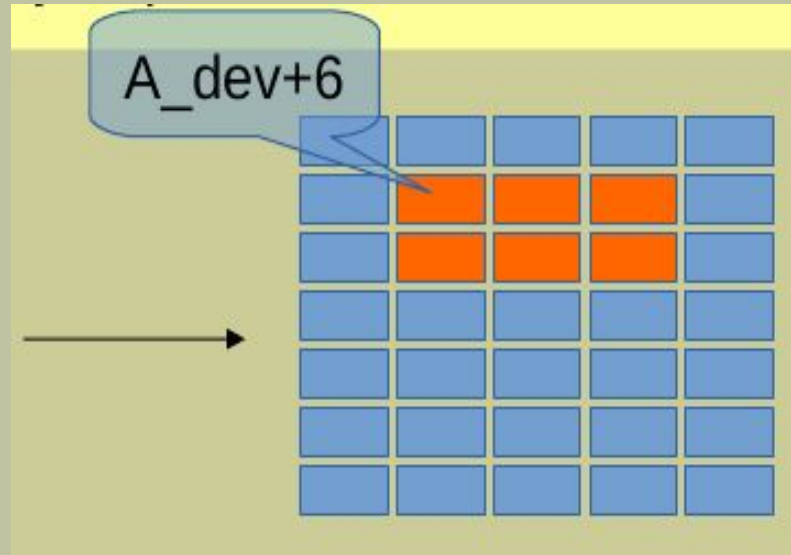
```
cublasGetMatrix(num_rows, num_cols, elem_size, A_dev, num_rows, A_h,  
num_rows);
```

```
.....  
cublasDestroy(cublas_handle);
```

```
}
```



leading dimension равно 9



leading dimension равно 7

```
void hMultMatsBlas(REAL* A, REAL* B, REAL* C){  
    cublasHandle_t cublas_handle;  
    cublasCreate(&cublas_handle);  
  
    const float alpha=1.0;  
    const float beta=0.0;  
    // cublasSetMathMode(cublas_handle, CUBLAS_TENSOR_OP_MATH);  
    cublasSgemm(cublas_handle, CUBLAS_OP_T, CUBLAS_OP_N,  
                M, N, K,  
                &alpha,  
                A, M,  
                B, K,  
                &beta,  
                C, M);  
    cublasDestroy(cublas_handle);  
}
```



```
void hMatOutBlas(REAL* D, int I, int J){  
    REAL* Dh=(REAL*)calloc(I*J, sizeof(REAL));  
    cublasGetMatrix(I, J, sizeof(REAL), D, I, Dh, I);  
    .....  
}
```

“NVIDIA GeForce RTX 2060”

Ускорение по отношению к алгоритму на основе *CUDA API* на *GPU 7.68*.

```
~/Lecture8/Lab8blas> nvprof ./lab8blas
```

```
16.51% 516.96us   1  516.96us 516.96us 516.96us
                                volta_sgemm_128x64_tn
3.81% 119.39us   2  59.695us 59.552us 59.839us
                                glnit(float*, int)
```

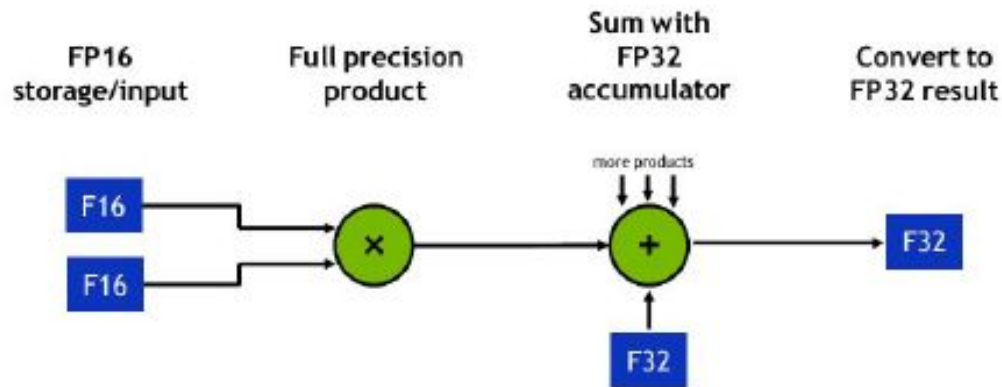
“GeForce GTX 1050”

```
~/WORKSHOP/PGP-2023> nvprof ./lab8blas
```

```
.....
41.49% 1.3640ms   1  1.3640ms 1.3640ms 1.3640ms
                                sgemm_128x128x8_NT_vec
9.28% 305.00us   2  152.50us 152.36us 152.65us
                                glnit(float*, int)
```

Нейронные процессоры:

- специализированные микросхемы, “заточенные” на ускорение алгоритмов машинного обучения;
- аппаратная реализация GEMM ($C = \alpha AB + \beta C$);
- вычисления со смешанной точностью (FP16, FP32, FP64);
- перемножение матриц размерности 4x4, 8x8, 16x16 за один такт;



*GETTING STARTED WITH
TENSOR CORES IN HPC*
Vishal Mehta, NVIDIA
Super Computing, 2019

Google TPU,
Huawei Ascend 310 / Ascend 910,

.....

NVIDIA Tensor Cores.

V100: 64 GEMM за такт, архитектура Volta (Nvidia Tesla V100), sm_70;
TU100-104: архитектура Turing (Geforce RTX 20*), sm_75;
A100: 256 GEMM за такт, архитектура Ampere (Geforce RTX 30*), sm_80.

WMMA, <https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html#wmma>;
cuBLAS, <https://docs.nvidia.com/cuda/cublas/>;
CUTLASS, <https://nvidia.github.io/cutlass/>;
cuTENSOR, <https://docs.nvidia.com/cuda/cutensor/>;
cuDNN, <https://developer.nvidia.com/cudnn>;
TensorFlow, <https://www.tensorflow.org/>,
<https://docs.nvidia.com/deeplearning/frameworks/tensorflow-user-guide/>;
PyTorch, <https://pytorch.org/>.

1. CUTENSOR A CUDA Library for High-Performance Tensor Primitives, Paul Springer, November 20th 2019.
2. GETTING STARTED WITH TENSOR CORES IN HPC, Vishal Mehta, NVIDIA Super Computing, 2019
3. CUTLASS: CUDA TEMPLATE LIBRARY FOR DENSE LINEAR ALGEBRA AT ALL LEVELS AND SCALES, Jeng Bai-Cheng (Ryan), 21 Nov.
4. VOLTA TENSOR CORE TRAINING ORNL, August 2019.
5. Stefano Markidis et al. NVIDIA Tensor Core Programmability, Performance & Precision, arXiv:1803.04014 [cs.DC], (2018). <https://doi.org/10.48550/arXiv.1803.04014>.

Тензорные ядра не активны.

```
~/Lecture8/Lab8blas> ncu --replay-mode application --metrics  
sm__pipe_tensor_cycles_active.avg.pct_of_peak_sustained_active lab8blas
```

volta_sgemm_128x64_tn, 2023-Mar-20 13:56:45, Context 1, Stream 7

Section: Command line profiler metrics

```
-----  
sm__pipe_tensor_cycles_active.avg.pct_of_peak_sustained_active    %      0  
-----
```

```
~/Lecture8/Lab8blas> nvprof ./lab8blas
```

```
.....  
11.63% 308.32us 1 308.32us 308.32us 308.32us  
                               volta_s884gemm_128x128_ldg8_f2f_tn  
4.44% 117.79us 2 58.895us 58.784us 59.007us  
                               glnit(float*, int)  
.....
```

Тензорные ядра активны.

```
~/Lecture8/Lab8blas> ncu --replay-mode application --metrics
```

```
sm__pipe_tensor_cycles_active.avg.pct_of_peak_sustained_active lab8blas
```

```
volta_s884gemm_128x128_ldg8_f2f_tn, 2023-Mar-20 12:29:27, Context 1, Stream 7  
Section: Command line profiler metrics
```

```
-----  
sm__pipe_tensor_cycles_active.avg.pct_of_peak_sustained_active  %      37.90  
-----
```

Ускорение по отношению к алгоритму на основе *CUDA API* на *GPU* 12.9.

Потеря точности.

5.23777	5.23777	5.23777
1347.41	1347.41	1347.41
2689.56	2689.56	2689.56
.....			
9400.73	9400.73	9400.73


```
void hMultMatsBlas(half* A, half* B, half* C){
```

```
.....  
const half alpha=1.0;
```

```
const half beta=0.0;
```

```
  
cublasSetMathMode(cublas_handle, CUBLAS_TENSOR_OP_MATH);
```

```
cublasHgemm(cublas_handle, CUBLAS_OP_T, CUBLAS_OP_N,
```

```
            M, N, K,
```

```
            &alpha,
```

```
            A, M,
```

```
            B, K,
```

```
            &beta,
```

```
            C, M);
```

```
cublasDestroy(cublas_handle);
```

```
}
```

```
__global__ void gInit(REAL* D, int s){
```

```
.....  
    D[j+i*J]=__float2half(s*(float)((j+i*J)*1.0E-5)+(1-s)*1.0f);  
}
```

```
int main(){
```

```
    half *A, *B, *C;
```

```
    cudaMalloc((void**)&A, M*K*sizeof(half));
```

```
.....  
    hMultMatsBlas(A,B,C);
```

```
.....  
}
```

```
.....  
fprintf(stdout, "%g\t", __half2float(Dh[i+j*I]));
```

```
.....
```

```
/Lecture8/Lab8blas> nvprof ./lab8blasH
13.92% 118.59us 2 59.295us 59.231us 59.359us
                        glnit(__half*, int)
11.68% 99.519us 1 99.519us 99.519us 99.519us
                        turing_h1688gemm_128x128_ldg8_stages_32x1_tn
```

```
~/Lecture8/Lab8blas> ncu --replay-mode application --metrics
sm__pipe_tensor_cycles_active.avg.pct_of_peak_sustained_active
lab8blas
turing_h1688gemm_128x128_ldg8_stages_32x1_tn, 2023-Mar-20 14:42:07, Context
1, Stream 7
```

Section: Command line profiler metrics

```
-----
sm__pipe_tensor_cycles_active.avg.pct_of_peak_sustained_active    %    62.27
-----
```

Тензорные ядра активны.

Потеря точности.

5.23828	5.23828.....	5.23828
1344	1344.....	.1344
2688	2688.....	.2688
.....	
9392	9392.....	.9392

Ускорение по отношению к алгоритму на основе CUDA API на GPU
39.9.

Ускорение по отношению к алгоритму на CPU **39992.36.**

В сорок тысяч раз!

ЗАДАНИЕ.

Реализовать вычисление произведения матриц на GPU, используя CUDA API (“сырой код”) и, отдельно, используя библиотеку *cuBLAS*. Сравнить время выполнения программ при различной размерности матриц.