ECE 277: GPU Programming
Final Project Presentation

CUDA-Accelerated GPT-2 Inference Optimization

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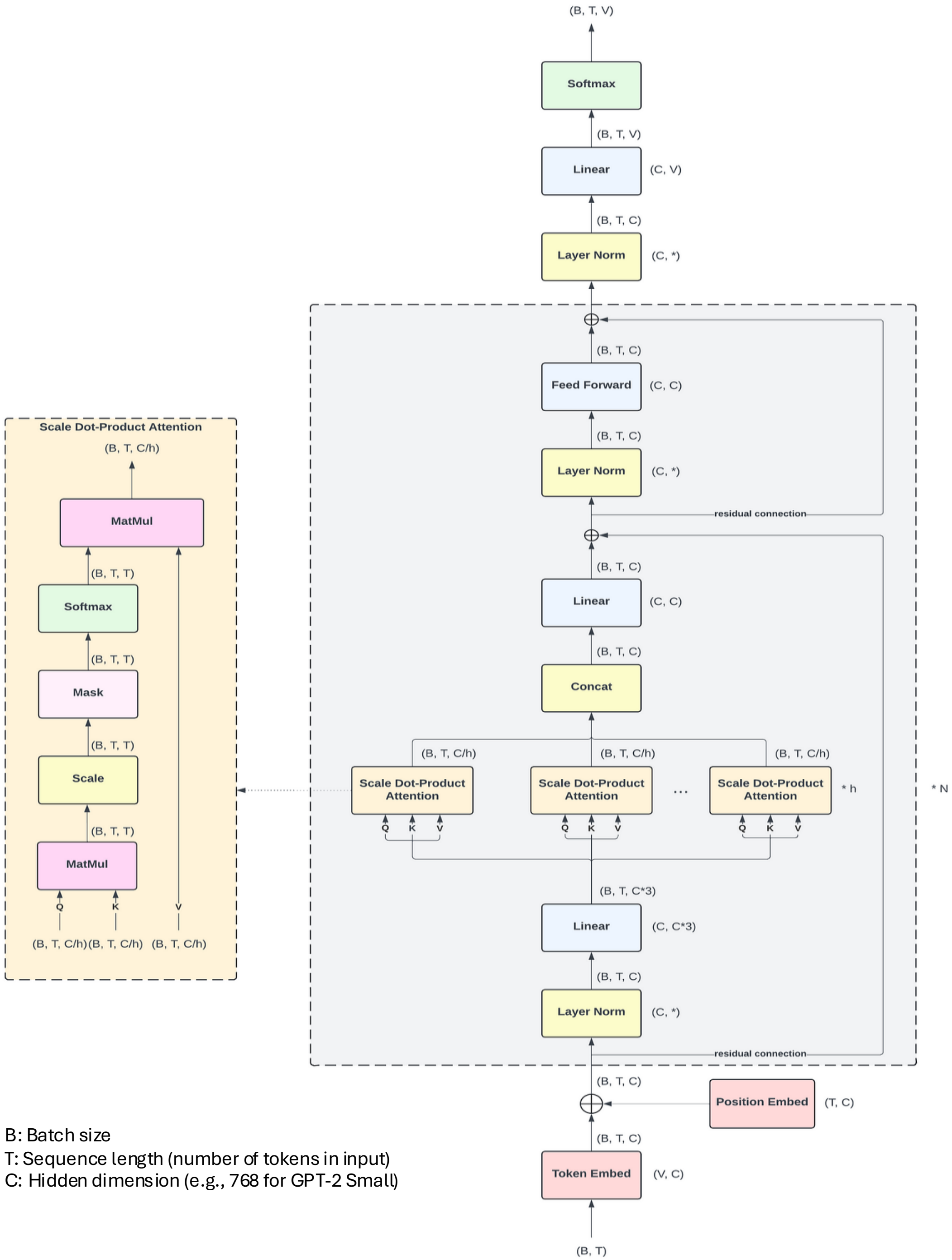
Problem statement

- **What is GPT-2?**
  - A transformer-based language model for natural language processing tasks.
  - It is used for text generation, summarization and other NLP tasks
  - GPT-2 inference is computationally expensive operation.
  - Latency issues for real-time applications.
- **Goal**:
  - Accelerate key computations with GPU for real-time performance.
  - Focus on optimizing performance-critical components:
    1. Layer Norm
    2. Softmax
    3. Attention



B: Batch size
T: Sequence length (number of tokens in input)
C: Hidden dimension (e.g., 768 for GPT-2 Small)

1.Layer Norm

A technique that normalizes the inputs across the feature dimension within a layer to stabilize training and improve convergence.

$$\text{LayerNorm}[x] = \frac{x - \mathrm{E}[x]}{\sqrt{\mathrm{Var}[x] + \epsilon}} * \gamma + \beta,$$

Each thread processes a subset of the array.

```
__global__
void layernorm_kernel(float* out, float* x, float* w, float* b, int C){
int idx = threadIdx.x; //Thread indexing
float mean = 0;
__shared__ float s_mean[256]; //Shared memory allocation
__shared__ float s_var[256]; //Shared memory allocation
s_mean[idx] = 0.0f;
s_var[idx] = 0.0f;
__syncthreads();

for(int i = idx;i<C;i+=blockDim.x){
s_mean[idx] += x[i];
}
__syncthreads();
if(idx == 0){
float m = 0;
for(int i = 0;i<blockDim.x;i++){
m += s_mean[i];
}
m /= C;
s_mean[0] = m;
}
__syncthreads();
```

Each thread accumulates partial sums for mean and stores them in shared memory(**s_mean**).

These partial sums are reduced to compute the overall mean.

```
mean = s_mean[0];
for(int i = idx;i<C;i+=blockDim.x){
float diff = x[i] - mean;
s_var[idx] += diff * diff;
}
__syncthreads();
if(idx == 0){
float v = 0;
for(int i = 0;i<blockDim.x;i++){
v += s_var[i];
}
v /= C;
s_var[0] = v;
}
__syncthreads();
float var = s_var[0];
float scale = 1.0 / sqrt(var + 1e-6);
for(int i = idx;i<C;i+=blockDim.x){
out[i] = (x[i] - mean) * scale * w[i] + b[i];
}
}

void layernorm_gpu(float* out, float* x, float* w, float* b, int C){
int numThreads = 256;
int block = 1;
layernorm_kernel<<<block,numThreads>>>(out,x,w,b,C);
}
```

Each thread accumulates partial variance for variance and stores them in shared memory(**s_var**).

These partial variance are reduced to compute the overall variance.

Each thread normalizes its portion of x, applies scaling (w), and adds the bias (b), writing the result to out.

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Debug x64 Local Windows Debugger Live Share

attention.cu layernorm.cu softmax.cu

attention (Global Scope) isequal(float * a, float * b, int n)

```
using namespace std;

void rand_init(float* x, int n) {
    for (int i = 0; i < n; i++) {
        x[i] = (float)rand() / RAND_MAX;
    }
}

void isequal(float* a, float* b, int n) {
    float maxval = -INFINITY;
    for (int i = 0; i < n; i++) {
        maxval = fmaxf(maxval, fmaxf(a[i], b[i]));
    }
    float eps = 1e-5;

    for (int i = 0; i < n; i++) {
        if (fabs(a[i] - b[i]) > eps * (maxval + 1)) {
            cout << "Mismatches" << endl;
            for (int j = i; j < min(n, i + 10); j++) {
                cout << a[j] << " " << b[j] << endl;
            }
            return;
        }
    }
    cout << "Results match " << endl;
    for (int i = 0; i < 4; i++) {
        cout << a[i] << " " << b[i] << endl;
    }
}

void softmax(float* x, int N) {
    float max = x[0];
    for (int i = 1; i < N; i++) {
        if (x[i] > max) {
            max = x[i];
        }
    }
    float sum = 0;
```

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Output

Show output from: Build

```
1>Done building project "softmax.vcxproj".
2>Done building project "layernorm.vcxproj".
3>attention.vcxproj -> H:\FinalProject_\build\Src\gpt2\Debug\attention.exe
3>Done building project "attention.vcxproj".
4>------ Skipped Build: Project: ALL_BUILD, Configuration: Debug x64 ------
4>Project not selected to build for this solution configuration
========== Build: 3 succeeded, 0 failed, 1 up-to-date, 1 skipped ==========
```

Solution Explorer

Search Solution Explorer (Ctrl+;)

- Solution 'Final' (5 of 5 projects)
  - ALL_BUILD
  - attention
  - layernorm
  - softmax
    - References
    - External Dependencies
    - CMake Rules
    - Object Files
    - Source Files
      - softmax.cu
    - CMakeLists.txt
  - ZERO_CHECK

Solution Explorer Git Changes

Properties

attention Project Properties

Misc	
(Name)	attention
Project Dependencies	
Project File	H:\FinalProject_\build\Src\gpt2\atte
Root Namespace	

(Name)
Specifies the project name.

2.Softmax

$$\mathrm{softmax}(x_i) = \frac{e^{x_i}}{\sum_{j=1}^{N} e^{x_j}}$$

Each thread processes a subset of the array.

```
__global__ void softmax_kernel(float* x, int N) {
int idx = threadIdx.x; //Thread indexing
__shared__ float smax[1024]; //Shared memory allocation
__shared__ float ssum[1024]; //Shared memory allocation
smax[idx] = -FLT_MAX;
ssum[idx] = 0.0f;
__syncthreads();

for (int i = idx; i < N; i += blockDim.x) {
smax[idx] = fmaxf(smax[idx], x[i]);
}
__syncthreads();
if (idx == 0) {
float maxval = -FLT_MAX;
for (int i = 0; i < blockDim.x; i++) {
maxval = fmaxf(maxval, smax[i]);
}
smax[0] = maxval;
}
__syncthreads();
```

Each thread computes a partial maximum using **strided access** within the loop. And stores them in shared memory(**s_max**).

Reduction in shared memory for the global maximum.

```
float maxval = smax[0];
float local_sum = 0.0f;
for (int i = idx; i < N; i += blockDim.x) {
x[i] = expf(x[i] - maxval);
local_sum += x[i];
}
ssum[idx] = local_sum;
__syncthreads();
if (idx == 0) {
float sum = 0.0f;
for (int i = 0; i < blockDim.x; i++) {
sum += ssum[i];
}
ssum[0] = sum;
}
__syncthreads();
float sum = ssum[0];
for (int i = idx; i < N; i += blockDim.x) {
x[i] /= sum;
}
}

void softmax_gpu(float* x, int N) {
int numThreads = 1024;
softmax_kernel<<<1, numThreads>>>(x, N);
}
```

Threads compute exp(x[i] - maxval) for their segment. Local sums stored in shared memory.

Thread 0 accumulates partial sums into the global sum.

Threads divide their computed exponentials by the global sum.

```
using namespace std;

void rand_init(float* x, int n) {
    for (int i = 0; i < n; i++) {
        x[i] = (float)rand() / RAND_MAX;
    }
}

void isequal(float* a, float* b, int n) {
    float maxval = -INFINITY;
    for (int i = 0; i < n; i++) {
        maxval = fmaxf(maxval, fmaxf(a[i], b[i]));
    }
    float eps = 1e-5;

    for (int i = 0; i < n; i++) {
        if (fabs(a[i] - b[i]) > eps * (maxval + 1)) {
            cout << "Mismatches" << endl;
            for (int j = i; j < min(n, i + 10); j++) {
                cout << a[j] << " " << b[j] << endl;
            }
            return;
        }
    }
    cout << "Results match " << endl;
    for (int i = 0; i < 4; i++) {
        cout << a[i] << " " << b[i] << endl;
    }
}

void softmax(float* x, int N) {
    float max = x[0];
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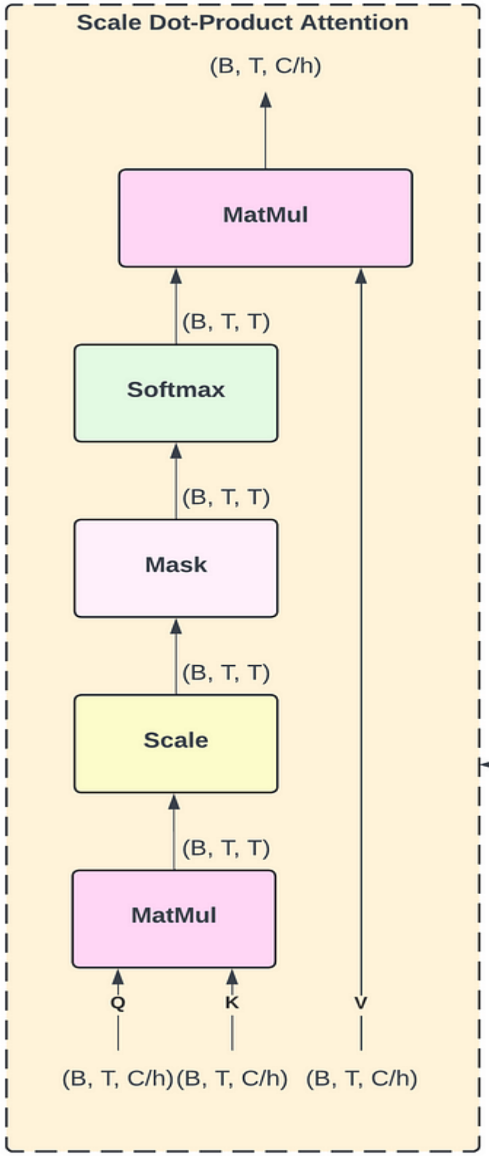
3. Attention Block

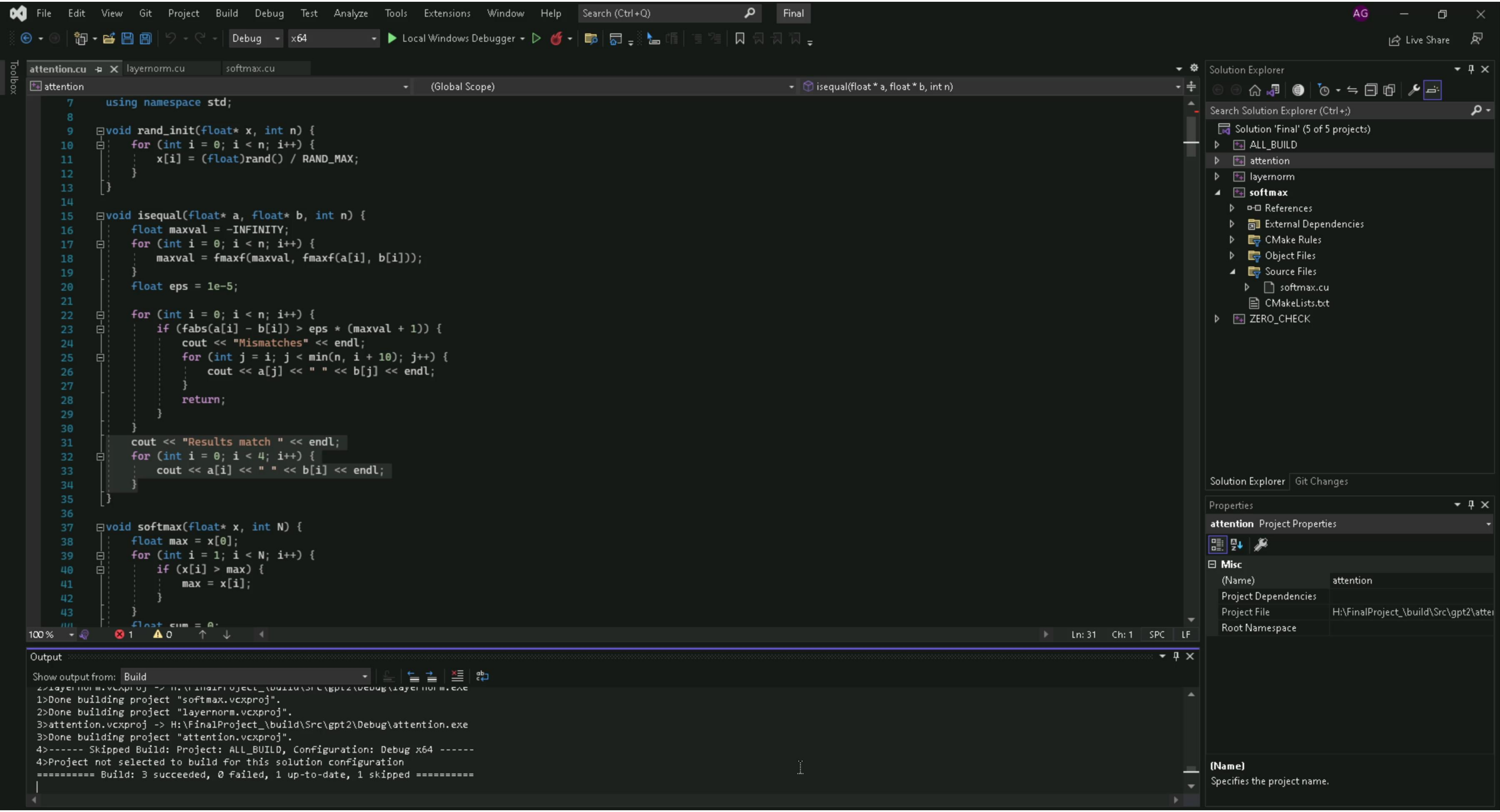
- The attention mechanism helps models focus on the most relevant parts of the input sequence when generating output.

1. **Head Size Calculation**:
   - Compute head_size = C / NH to divide the total number of features (C) evenly across the attention heads (NH).
2. **Key and Value Cache Population**:
   - The fill_cache kernel reorganizes keys and values from the qkv tensor into key_cache and value_cache.
   - This cache is reshaped to ensure memory coalescing for subsequent attention calculations.
3. **Attention Score Computation**: *att = q * K^T*
   - The compute_att_kernel computes the dot product of the query vector (q) with the key matrix (K^T) for each head.
   - Threads are parallelized across the time steps (T) and attention heads (NH).
4. **Softmax Normalization**:
   - The softmax_kernel normalizes the attention scores in-place to ensure they sum to 1.
   - Employs warp-level reductions (warpReduceMax and warpReduceSum) for efficient summation and normalization.
5. **Weighted Sum (Attention * Value)**:
   - The compute_out_kernel computes the weighted sum of the values (V) based on the normalized attention scores (att) to produce the output tensor (out).



Cuda optimization techniques used

- **Memory Coalescing**
  - **Fill Cache Kernel:** Rearranges keys and values into a layout that enables coalesced memory access during attention computation.
  - Access patterns are aligned for efficient global memory reads and writes.
- **Parallelism**
  - Each CUDA block handles one attention head.
  - Threads within a block handle computations for time steps (TTT) or head size (HSHSHS).
- **Warp-Level Primitives**
  - **Softmax Kernel:** Utilizes __shfl_sync for warp-level reductions to compute max and sum values efficiently.
  - Reduces latency for operations like summation and normalization.
- **Shared Memory Usage**
  - **Softmax Kernel:** Uses shared memory for intermediate storage of max and sum values.
  - Reduces global memory transactions, improving speed.
- **Loop Unrolling**
  - **Dot Product and Weighted Sum Kernels:** Loops over head size and sequence positions are unrolled to maximize instruction-level parallelism.
- **Thread Count Management**
  - Caps threads per block at 1024 to comply with hardware constraints.
  - Dynamically adjusts the number of threads for sequence positions (pos) and head size (HS).



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attention.cu
layernorm.cu
softmax.cu
attention
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attention Project Properties
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(Name)
Specifies the project name.

Performance Bench Marking

	Layer-Norm	Softmax	Attention
CPU	0.0072ms	2.1551ms	5.4209ms
GPU	0.3502ms	1.6969ms	1.4694ms

Thank you!

Thank you!