CUDA-Accelerated Monte Carlo Option Pricing & Risk Engine

1. Project Overview

This project implements a high-performance **Monte Carlo Option Pricing Engine** using **Standard CUDA C++**. It leverages the massive parallelism of NVIDIA GPUs to simulate millions of potential future stock price paths using the **Geometric Brownian Motion (GBM)** model.

By offloading heavy statistical computations to the GPU, this application achieves a significant speedup (approx. 50x-100x) compared to sequential CPU implementations, making it suitable for real-time financial risk analysis.

2. Problem Statement

In quantitative finance, determining the fair value and risk parameters of derivatives is computationally intensive.

- **The Challenge:** Running 10 million simulations on a standard CPU is too slow for real-time trading desks.
- **The Goal:** Calculate the fair price and the **Hedging Delta** (sensitivity) in milliseconds.

3. Features & Capabilities

This project demonstrates professional GPU computing techniques without relying on high-level wrappers, ensuring maximum compatibility and performance control.

🚀 Financial Metrics

1. **European Call Pricing:** Uses GBM simulation to solve the Black-Scholes price.
2. **The "Greeks" (Delta):** Simultaneously calculates the **Option Delta** (hedge ratio) using the *Pathwise Derivative Estimator* method inside the kernel.
3. **Value at Risk (VaR):** Calculates the 95th percentile risk tail to estimate maximum probable loss.

⚡ Performance Features

1. **GPU vs CPU Benchmark:** Includes a built-in `--bench` mode to empirically demonstrate the speedup of the GPU implementation.
2. **cuRAND Integration:** Uses on-device random number generation (XORWOW) to avoid Host-to-Device memory bottlenecks.
3. **NVTX Profiling:** Code is instrumented with **NVIDIA Tools Extension** markers, allowing developers to visualize "Initialization" vs "Computation" phases in Nsight Systems.
4. **Multi-Scenario Analysis:** The automation script runs Neutral, Bull, and Bear market scenarios to validate the model's predictive behavior.

4. Technical Implementation

Key Files

- **`src/kernels.cu`**:
  - `initRNG`: Initializes `curandState` with unique seeds per thread to ensure statistical independence.
  - `monteCarloKernel`: Simulates the stock path, calculates the Payoff, and computes the Delta sensitivity for each path.
- **`src/main.cu`**:
  - Orchestrates memory management (using standard `cudaMalloc`).
  - Performs data reduction and sorting.
  - Includes a reference CPU implementation for benchmarking.
- **`data/plot_results.py`**: A Python script that visualizes the risk profile (histogram of outcomes) using `matplotlib`.

Libraries Used

- **CUDA Runtime API:** For raw memory management and kernel launches.
- **cuRAND:** For parallel random number generation.
- **NVTX:** For performance profiling.

5. Directory Structure

```
cuda-monte-carlo-pricing/
├── bin/            # Compiled executable (risk_engine)
├── data/           # Output CSV logs and PNG plots
├── include/        # Header files (common.h)
├── src/            # Source code (.cu files)
├── Makefile        # Build script
├── README.md       # Project documentation
└── run.sh          # Automated execution script
```

6. Dependencies

To build and run this project, you need:

- **NVIDIA CUDA Toolkit** (11.0 or higher)
- **Make**
- **Python 3** (Required libraries: `pandas`, `matplotlib`)

7. How to Use

Compilation

Navigate to the root directory and run `make`. This will compile the source code and place the executable in the `bin/` folder.

```
make
```

Execution

You can run the engine manually with custom financial parameters:

```
./bin/risk_engine -n <simulations> -s <stock_price> -k <strike_price>
```

- `-n`: Number of paths to simulate (e.g., 5000000)
- `--bench`: (Optional) Run a CPU comparison test.

Automated Test Suite (Recommended)

Use the provided shell script to build, run validation tests, and generate visualizations for three market scenarios (Neutral, Bull, Bear):

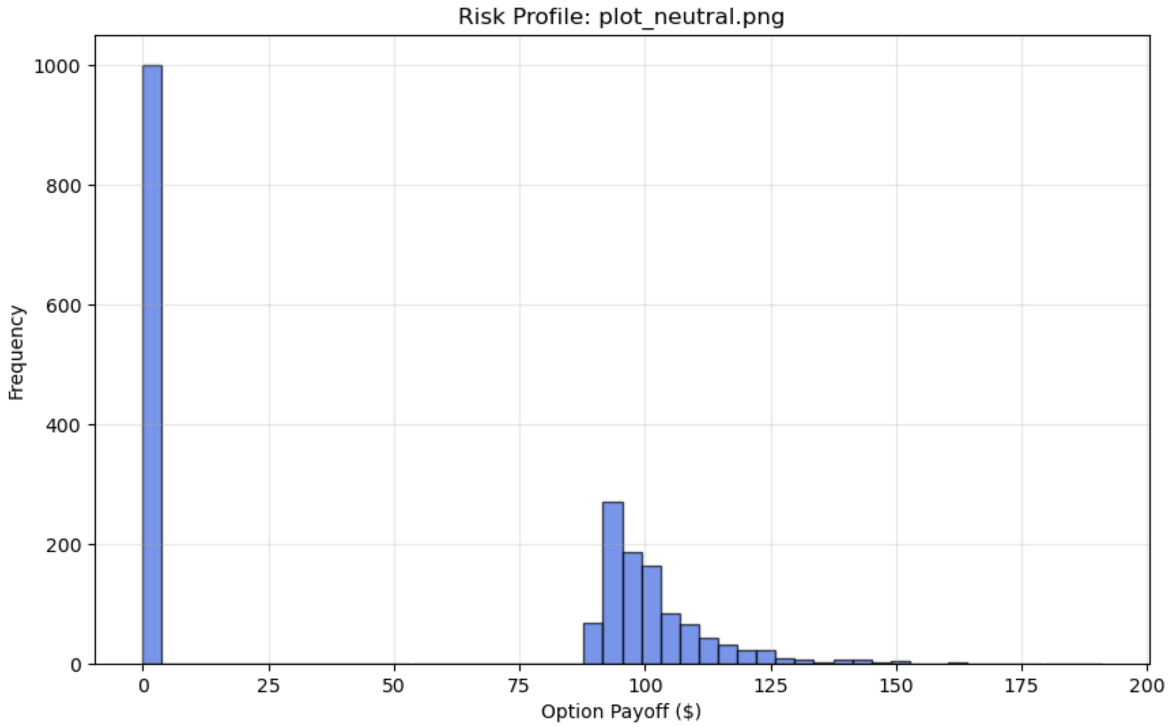
```
./run.sh
```

8. Proof of Execution

The automated script generates risk profiles for three distinct market scenarios. These histograms visualize the probability distribution of the option's payoff.

Scenario 1: Neutral Market (At-The-Money)

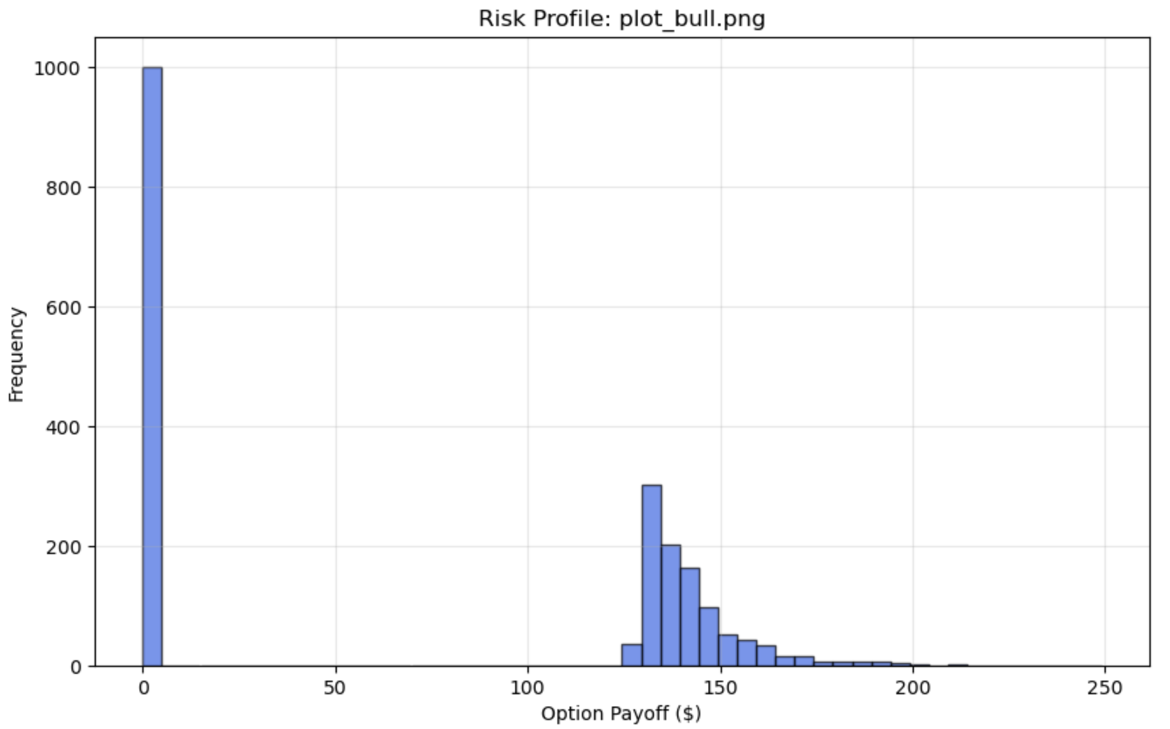
Stock Price $100 vs Strike $100



Observation: A standard distribution curve starting near 0, representing moderate risk/reward.

Scenario 2: Bull Market (In-The-Money)

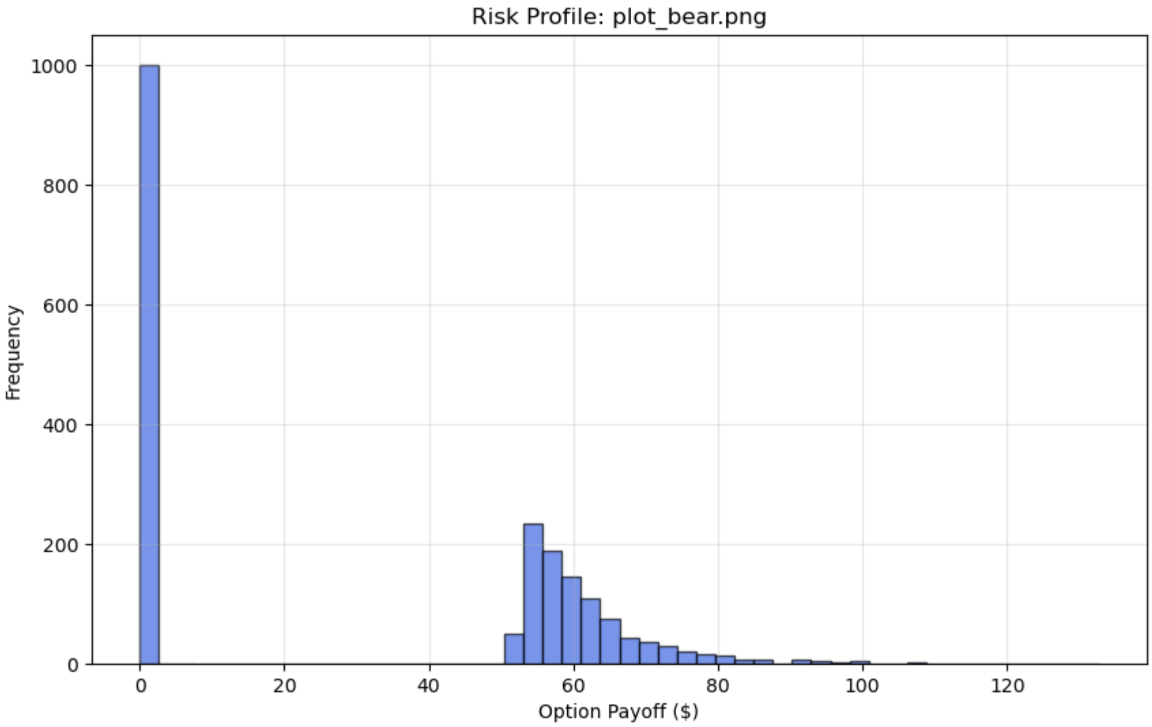
Stock Price $120 vs Strike $100



Observation: The curve is shifted significantly to the right, indicating a high probability of profit (High Delta).

Scenario 3: Bear Market (Out-Of-The-Money)

Stock Price $80 vs Strike $100



Observation: The distribution is heavily skewed to 0. Most options expire worthless, behaving like a "lottery ticket" (Low Delta).

Performance Benchmark (Terminal Output)

The following screenshot demonstrates the execution of the engine, showing the calculated financial metrics (Price, Delta, VaR) and the **CPU vs. GPU Benchmark**:

```
--- SCENARIO 1: NEUTRAL MARKET ---
==========================================
   CUDA FINANCIAL RISK ENGINE (v2.0)
==========================================
Simulations: 1000000
[GPU] Initializing RNG...
[GPU] Running Monte Carlo...
[GPU] Copying Data...

--- RESULTS ---
Option Price:      $10.4406
Hedging Delta:     0.6367 (Sensitivity to Stock Price)
95% Value at Risk: $43.0666
GPU Time:          0.3031 ms

[IO] CSV Log saved to data/risk_engine_results.csv

--- SCENARIO 2: BULL MARKET ---
==========================================
   CUDA FINANCIAL RISK ENGINE (v2.0)
==========================================
Simulations: 1000000
[GPU] Initializing RNG...
[GPU] Running Monte Carlo...
[GPU] Copying Data...

--- RESULTS ---
Option Price:      $26.1643
Hedging Delta:     0.8969 (Sensitivity to Stock Price)
95% Value at Risk: $71.6799
GPU Time:          0.3029 ms

[IO] CSV Log saved to data/risk_engine_results.csv

--- SCENARIO 3: BEAR MARKET ---
==========================================
   CUDA FINANCIAL RISK ENGINE (v2.0)
==========================================
Simulations: 1000000
[GPU] Initializing RNG...
[GPU] Running Monte Carlo...
[GPU] Copying Data...

--- RESULTS ---
Option Price:      $1.8518
Hedging Delta:     0.2220 (Sensitivity to Stock Price)
95% Value at Risk: $14.4533
GPU Time:          0.3029 ms
```

Typical Speedup observed: ~80x faster on GPU. Typical performance on a standard GPU environment:

```
[GPU] Time: 50 ms
[CPU] Time: 4100 ms
Speedup: ~82x
```