Programming Parallel Computers

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Part 4B:
GPU programming with CUDA

GPU programming with CUDA

- We will use NVIDIA GPUs and **CUDA** programming environment
  - CUDA code ≈ C++ code with some extensions
  - compile with **nvcc**, run as usual
- Just compiling your code with **nvcc** doesn't do anything yet
  - ***your `main()` function still runs on the CPU!***
- In your program, you need to specify what the GPU should do
  - you define a so-called ***"kernel"*** function
  - ***you explicitly ask the GPU to run the "kernel" with many threads!***

CUDA basics

What we would like to parallelize

```
for (int i = 0; i < 100; ++i) {
    for (int j = 0; j < 128; ++j) {
        foo(i, j);
    }
}
```

GPU should run these operations, preferably in parallel:

- foo(0, 0)
- foo(0, 1)
- foo(0, 2)
- foo(0, 3)

 . . .

- foo(99, 127)

CUDA basics

Parallel GPU solution

GPU

```
__global__ void mykernel() {
    int i = blockIdx.x;
    int j = threadIdx.x;
    foo(i, j);
}
```

Which thread am I?

CPU

```
int main() {
    mykernel<<<100, 128>>>();
}
```

Create 100 blocks, each with 128 threads, and let them all run function mykernel!

GPU will run these operations, possibly in parallel:

- foo(0, 0)
- foo(0, 1)
- foo(0, 2)
- foo(0, 3)

. . .

- foo(99, 127)

CUDA basics

Parallel GPU solution

GPU

```
__global__ void mykernel() {
   int i = blockIdx.x;
   int j = threadIdx.x;
   foo(i, j);
}
```

CPU

```
int main() {
   mykernel<<<100, 128>>>();
}
```

Equivalent sequential code

```
int main() {
   for (int i = 0; i < 100; ++i) {
      for (int j = 0; j < 128; ++j) {
         foo(i, j);
      }
   }
}
```

Example: split evenly

- What is the best way to **split 1^5, 2^5, 3^5, …, 30^5 in two parts** such that their **sums** are as close to each other as possible?

1^5	2^5	3^5	4^5	5^5	6^5	7^5	8^5	9^5	10^5
11^5	12^5	13^5	14^5	15^5	16^5	17^5	18^5	19^5	20^5
21^5	22^5	23^5	24^5	25^5	26^5	27^5	28^5	29^5	30^5

Example: split evenly

- What is the best way to **split 1^5, 2^5, 3^5, …, 30^5 in two parts** such that their **sums** are as close to each other as possible?

$1^5 \quad 2^5 \quad 4^5 \quad 6^5 \quad 10^5$
$11^5 \quad 12^5 \quad 13^5 \quad 15^5 \quad 17^5 \quad 19^5$
$21^5 \quad 22^5 \quad 23^5 \quad 24^5 \quad 27^5 \quad 30^5$

sum: 67 830 947

$3^5 \quad 5^5 \quad 7^5 \quad 8^5 \quad 9^5$
$14^5 \quad 16^5 \quad 18^5 \quad 20^5$
$25^5 \quad 26^5 \quad 28^5 \quad 29^5$

sum: 66 156 478

Example: split evenly

- What is the best way to **split 1^5, 2^5, 3^5, …, 30^5 in two parts** such that their **sums** are as close to each other as possible?

1^5 2^5 4^5 6^5 10^5

11^5 12^5

21^5 22^5

sum: 67 830 947

9^5

0^5

26^5 28^5 29^5

sum: 66 156 478

This clearly isn't optimal — how to find the best solution?

Example: split evenly

- What is the best way to **split 1^5, 2^5, 3^5, …, 30^5 in two parts** such that their **sums** are as close to each other as possible?

- We will solve this with a **naive brute force algorithm**
- First with **CPUs with a sequential program**
- Then with **GPUs with a massively parallel program**

Example: split evenly

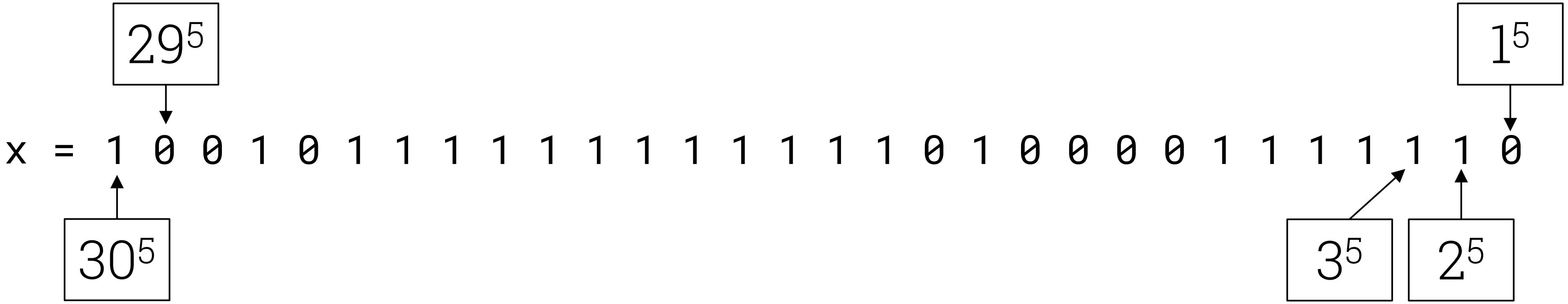
- What is the best way to **split 1^5, 2^5, 3^5, …, 30^5 in two parts** such that their **sums** are as close to each other as possible?

- Algorithms: just try out all **2^{30} cases** and see what is best

Example: split evenly

Each case is represented as a **30-bit binary number *x***

Bit 0 in position *i*: number $(i + 1)^5$ in the **first part**



Bit 1 in position *i*: number $(i + 1)^5$ in the **second part**

```
inline int p5(int i) { return i * i * i * i * i; }

inline int value(int x) {
    int a = 0;
    for (int i = 0; i < 30; ++i) {
        if (x & (1 << i)) {
            a += p5(i+1);
        } else {
            a -= p5(i+1);
        }
    }
    return abs(a);
}
```

x = one way to split our numbers

value(x) = absolute difference between the sum of the first part and the sum of the second part

```
inline int p5(int i) { return i * i * i * i * i; }

inline int value(int x) {
    int a = 0;
    for (int i = 0; i < 30; ++i) {
        if (x & (1 << i)) {
            a += p5(i+1);
        } else {
            a -= p5(i+1);
        }
    }
    return abs(a);
}
```

Find $0 \le x < 2^{30}$ that minimizes value(x)

Sequential CPU solution

```
constexpr int total = 1 << 30;
int best_x = 0;
int best_v = value(best_x);
for (int x = 0; x < total; ++x) {
    int v = value(x);
    if (v < best_v) {
        best_x = x;
        best_v = v;
    }
}
```

Find $0 \le x < 2^{30}$ that minimizes value(x)

GPU: splitting work

- We have got $\mathbf{2^{30}}$ cases to check
- How many ***blocks*** to create?
- How many ***threads*** per block?
- How many cases does one thread check?

GPU: splitting work

- We have got **2^{30}** cases to check
- How many ***blocks*** to create?
- How many ***threads*** per block?
- If we have e.g. **2^{30}** threads in total, each thread will only check **1** case
  - too little useful work per thread
  - too much overhead e.g. in launching kernel, communicating result

GPU: splitting work

- We have got **2^{30}** cases to check
- ***Blocks:***
  - we need to have lots of blocks ready for execution
  - our choice here: **2^{10}** = 1024 blocks
- ***Threads per block:***
  - reasonable block size is a multiple of one **warp** = 32 threads
  - our choice here: **2^{6}** = 64 threads
- Each thread will need to check $2^{30} / (2^{10} \cdot 2^{6}) =$ **2^{14}** cases

GPU: splitting work

Block index
(highest 10 bits)

Current iteration inside one thread
(lowest 14 bits)

```
x = 1 0 0 1 0 1 1 1 1 1 1 1 1 1 1 1 1 0 1 0 0 0 0 1 1 1 1 1 1 0
```

Thread index
(next 6 bits)

GPU: coordination between threads

- Let’s keep things as simple as possible
- Allocate one word of GPU memory per thread
- ***GPU: each thread will write its local optimum in GPU memory***
- Copy results from GPU memory to CPU memory
- ***CPU: find the best split among local optima***

```
__global__ void mykernel(int* r) {
    int x3 = blockIdx.x;
    int x2 = threadIdx.x;
```

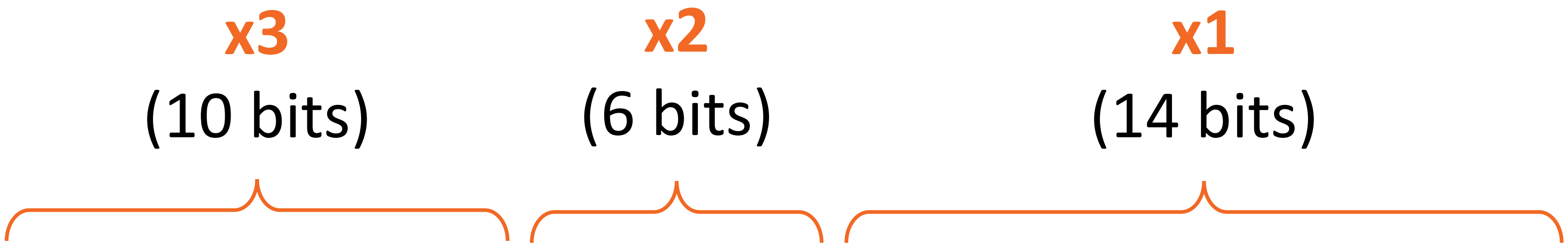
What is my part of search space?

$$x = \overbrace{1\ 0\ 0\ 1\ 0\ 1\ 1\ 1\ 1\ 1}^{\substack{\textbf{x3} \\ \text{(10 bits)}}}\ \overbrace{1\ 1\ 1\ 1\ 1\ 1}^{\substack{\textbf{x2} \\ \text{(6 bits)}}}\ \overbrace{1\ 0\ 1\ 0\ 0\ 0\ 0\ 1\ 1\ 1\ 1\ 1\ 1\ 0}^{\substack{\textbf{x1} \\ \text{(14 bits)}}}$$

```
}
```

```
__global__ void mykernel(int* r) {
    int x3 = blockIdx.x;
    int x2 = threadIdx.x;
```

What is my part of search space?



```
x = 1 0 0 1 0 1 1 1 1 1 1 1 1 1 1 1 1 0 1 0 0 0 0 1 1 1 1 1 1 0
```

```
    r[(x3 << 6) | x2] = best_x;
}
```

Save best solution in my part of search space

```
__global__ void mykernel(int* r) {
    int x3 = blockIdx.x;
    int x2 = threadIdx.x;
    int best_x = 0;
    int best_v = value(best_x);
    for (int x1 = 0; x1 < iterations; ++x1) {
        int x = (x3 << 20) | (x2 << 14) | x1;
        int v = value(x);
        if (v < best_v) {
            best_x = x;
            best_v = v;
        }
    }
    r[(x3 << 6) | x2] = best_x;
}
```

What is my part of search space?

Mostly normal sequential C++ code here

Save best solution in my part of search space

```
constexpr int blocks = 1 << 10;
constexpr int threads = 1 << 6;

int* rGPU = NULL;
cudaMalloc((void**)&rGPU, blocks * threads * sizeof(int));

mykernel<<<blocks, threads>>>(rGPU);

std::vector<int> r(blocks * threads);
cudaMemcpy(r.data(), rGPU, blocks * threads * sizeof(int),
           cudaMemcpyDeviceToHost);
cudaFree(rGPU);

// Find x in r that
// minimizes value(x)
```

```
constexpr int blocks = 1 << 10;
constexpr int threads = 1 << 6;

int* rGPU = NULL;
cudaMalloc((void**)&rGPU, blocks * threads * sizeof(int));

mykernel<<<blocks, threads>>>(rGPU);

std::vector<int> r(blocks * threads);
cudaMemcpy(r.data(), rGPU, blocks * threads * sizeof(int),
           cudaMemcpyDeviceToHost);
cudaFree(rGPU);

// Find x in r that
// minimizes value(x)
```

Allocate GPU memory for result

```
constexpr int blocks = 1 << 10;
constexpr int threads = 1 << 6;

int* rGPU = NULL;
cudaMalloc((void**)&rGPU, blocks * threads * sizeof(int));

mykernel<<<blocks, threads>>>(rGPU);

std::vector<int> r(blocks * threads);
cudaMemcpy(r.data(), rGPU, blocks * threads * sizeof(int),
           cudaMemcpyDeviceToHost);
cudaFree(rGPU);

// Find x in r that
// minimizes value(x)
```

Allocate GPU memory for result

Launch 2^{16} threads on GPU

```
constexpr int blocks = 1 << 10;
constexpr int threads = 1 << 6;

int* rGPU = NULL;
cudaMalloc((void**)&rGPU, blocks * threads * sizeof(int));

mykernel<<<blocks, threads>>>(rGPU);

std::vector<int> r(blocks * threads);
cudaMemcpy(r.data(), rGPU, blocks * threads * sizeof(int),
           cudaMemcpyDeviceToHost);
cudaFree(rGPU);

// Find x in r that
// minimizes value(x)
```

Allocate GPU memory for result

Launch 2^{16} threads on GPU

Copy result back from GPU memory to CPU memory

```
constexpr int blocks = 1 << 10;
constexpr int threads = 1 << 6;

int* rGPU = NULL;
cudaMalloc((void**)&rGPU, blocks * threads * sizeof(int));
```

Allocate GPU memory for result

```
mykernel<<<blocks, threads>>>(rGPU);
```

Launch 2^{16} threads on GPU

```
std::vector<int> r(blocks * threads);
cudaMemcpy(r.data(), rGPU, blocks * threads * sizeof(int),
           cudaMemcpyDeviceToHost);
```

Copy result back from GPU memory to CPU memory

```
cudaFree(rGPU);
```

Free memory

```
// Find x in r that
// minimizes value(x)
```

```
constexpr int blocks = 1 << 10;
constexpr int threads = 1 << 6;

int* rGPU = NULL;
cudaMalloc((void**)&rGPU, blocks * threads * sizeof(int));

mykernel<<<blocks, threads>>>(rGPU);

std::vector<int> r(blocks * threads);
cudaMemcpy(r.data(), rGPU, blocks * threads * sizeof(int),
           cudaMemcpyDeviceToHost);
cudaFree(rGPU);

// Find x in r that
// minimizes value(x)
```

Now vector “r” contains the best result for each thread, just check which of these is the global optimum

Try it out

- Compile & link with “**nvcc**” instead of “**g++**”
- Run as usual
  - sequential CPU solution: **38 seconds**
  - parallel GPU solution: **0.3 seconds**

$$1^5 + 2^5 + 3^5 + 4^5 + 5^5 + 9^5 + 10^5 + 12^5 + 15^5 + 16^5 + 17^5 + 19^5 + 22^5 + 23^5 + 24^5 + 25^5 + 27^5 + 28^5 = 66\,993\,712$$

$$6^5 + 7^5 + 8^5 + 11^5 + 13^5 + 14^5 + 18^5 + 20^5 + 21^5 + 26^5 + 29^5 + 30^5 = 66\,993\,713$$

```
constexpr int blocks = 1 << 10;
constexpr int threads = 1 << 6;

int* rGPU = NULL;
cudaMalloc((void**)&rGPU, blocks * threads * sizeof(int));

mykernel<<<blocks, threads>>>(rGPU);

std::vector<int> r(blocks * threads);
cudaMemcpy(r.data(), rGPU, blocks * threads * sizeof(int),
           cudaMemcpyDeviceToHost);
cudaFree(rGPU);

// Find x in r that
// minimizes value(x)
```

Error checking omitted!

```
constexpr int blocks = 1 << 10;
constexpr int threads = 1 << 6;

int* rGPU = NULL;
CHECK(cudaMalloc((void**)&rGPU, blocks * threads * sizeof(int)));

mykernel<<<blocks, threads>>>(rGPU);
CHECK(cudaGetLastError());

std::vector<int> r(blocks * threads);
CHECK(cudaMemcpy(r.data(), rGPU, blocks * threads * sizeof(int),
      cudaMemcpyDeviceToHost));
CHECK(cudaFree(rGPU));

// Find x in r that
// minimizes value(x)
```

More details in the course material!

Typical program structure

- **GPU side:**
    - "**kernel**" that does one small part of work
- **CPU side:**
    - do pre-processing if needed
    - allocate GPU memory for input & output
    - copy input from CPU memory to GPU memory
    - **launch kernel** (lots of blocks, lots of threads)
    - copy result back from GPU memory to CPU memory
    - release GPU memory
    - do post-processing if needed