

Thrust

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Diving In



```
#include <thrust/host_vector.h>
#include <thrust/device_vector.h>
#include <thrust/sort.h>

int main(void)
{
    // generate 16M random numbers on the host
    thrust::host_vector<int> h_vec(1 << 24);
    thrust::generate(h_vec.begin(), h_vec.end(), rand);

    // transfer data to the device
    thrust::device_vector<int> d_vec = h_vec;

    // sort data on the device
    thrust::sort(d_vec.begin(), d_vec.end());

    // transfer data back to host
    thrust::copy(d_vec.begin(), d_vec.end(), h_vec.begin());

    return 0;
}
```

Objectives



- **Programmer productivity**
 - Rapidly develop complex applications
 - Leverage parallel primitives
- **Encourage generic programming**
 - Don't reinvent the wheel
 - E.g. one reduction to rule them all
- **High performance**
 - With minimal programmer effort
- **Interoperability**
 - Integrates with CUDA C/C++ code

What is Thrust?

- **C++ template library for CUDA**
 - Mimics Standard Template Library (STL)
- **Containers**
 - `thrust::host_vector<T>`
 - `thrust::device_vector<T>`
- **Algorithms**
 - `thrust::sort()`
 - `thrust::reduce()`
 - `thrust::inclusive_scan()`
 - Etc.

Containers



- **Make common operations concise and readable**
 - **Hides `cudaMalloc`, `cudaMemcpy` and `cudaFree`**

```
// allocate host vector with two elements
thrust::host_vector<int> h_vec(2);

// copy host vector to device
thrust::device_vector<int> d_vec = h_vec;

// manipulate device values from the host
d_vec[0] = 13;
d_vec[1] = 27;

std::cout << "sum: " << d_vec[0] + d_vec[1] << std::endl;

// vector memory automatically released w/ free() or cudaFree()
```

- **Compatible with STL containers**
 - Eases integration
 - `vector`, `list`, `map`, ...

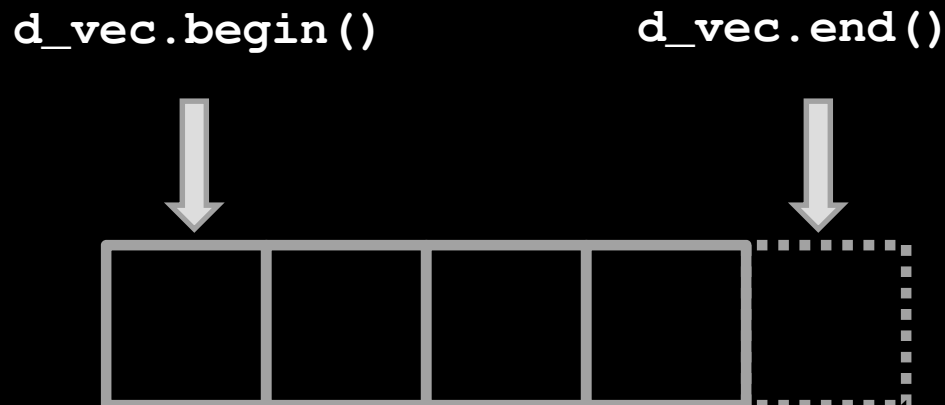
```
// list container on host
std::list<int> h_list;
h_list.push_back(13);
h_list.push_back(27);

// copy list to device vector
thrust::device_vector<int> d_vec(h_list.size());
thrust::copy(h_list.begin(), h_list.end(), d_vec.begin());

// alternative method
thrust::device_vector<int> d_vec(h_list.begin(), h_list.end());
```

- Sequences defined by pair of iterators

```
// allocate device vector  
thrust::device_vector<int> d_vec(4);  
  
d_vec.begin(); // returns iterator at first element of d_vec  
d_vec.end()    // returns iterator one past the last element of d_vec  
  
// [begin, end) pair defines a sequence of 4 elements
```



Iterators



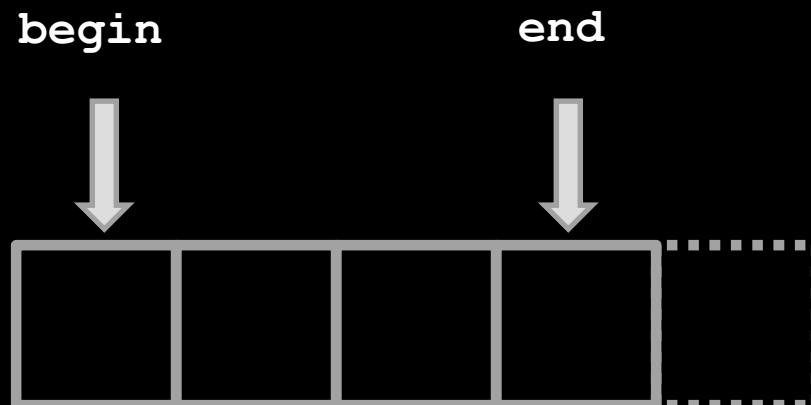
- Iterators act like pointers

```
// allocate device vector
thrust::device_vector<int> d_vec(4);

thrust::device_vector<int>::iterator begin = d_vec.begin();
thrust::device_vector<int>::iterator end   = d_vec.end();

int length = end - begin; // compute size of sequence [begin, end)

end = d_vec.begin() + 3; // define a sequence of 3 elements
```



- Use iterators like pointers

```
// allocate device vector
thrust::device_vector<int> d_vec(4);

thrust::device_vector<int>::iterator begin = d_vec.begin();

*begin = 13;           // same as d_vec[0] = 13;
int temp = *begin;    // same as temp = d_vec[0];

begin++;              // advance iterator one position

*begin = 25;          // same as d_vec[1] = 25;
```

Iterators



- Track memory space (host/device)
 - Guides algorithm dispatch

```
// initialize random values on host
thrust::host_vector<int> h_vec(1000);
thrust::generate(h_vec.begin(), h_vec.end(), rand);

// copy values to device
thrust::device_vector<int> d_vec = h_vec;

// compute sum on host
int h_sum = thrust::reduce(h_vec.begin(), h_vec.end());

// compute sum on device
int d_sum = thrust::reduce(d_vec.begin(), d_vec.end());
```

- Convertible to raw pointers

```
// allocate device vector
thrust::device_vector<int> d_vec(4);

// obtain raw pointer to device vector's memory
int * ptr = thrust::raw_pointer_cast(&d_vec[0]);

// use ptr in a CUDA C kernel
my_kernel<<<N/256, 256>>>(N, ptr);

// Note: ptr cannot be dereferenced on the host!
```

- Wrap raw pointers with `device_ptr`

```
int N = 10;

// raw pointer to device memory
int * raw_ptr;
cudaMalloc((void **) &raw_ptr, N * sizeof(int));

// wrap raw pointer with a device_ptr
thrust::device_ptr<int> dev_ptr(raw_ptr);

// use device_ptr in thrust algorithms
thrust::fill(dev_ptr, dev_ptr + N, (int) 0);

// access device memory through device_ptr
dev_ptr[0] = 1;

// free memory
cudaFree(raw_ptr);
```

Namespaces

- **C++ supports namespaces**
 - Thrust uses `thrust` namespace
 - `thrust::device_vector`
 - `thrust::copy`
 - STL uses `std` namespace
 - `std::vector`
 - `std::list`
- **Avoids collisions**
 - `thrust::sort()`
 - `std::sort()`
- **For brevity**
 - `using namespace thrust;`

Recap



- **Containers**

- Manage host & device memory
- Automatic allocation and deallocation
- Simplify data transfers

- **Iterators**

- Behave like pointers
- Keep track of memory spaces
- Convertible to raw pointers

- **Namespaces**

- Avoids collisions

C++ Background



● Function templates

```
// function template to add numbers (type of T is variable)
template< typename T >
T add(T a, T b)
{
    return a + b;
}

// add integers
int x = 10; int y = 20; int z;
z = add<int>(x,y);    // type of T explicitly specified
z = add(x,y);        // type of T determined automatically

// add floats
float x = 10.0f; float y = 20.0f; float z;
z = add<float>(x,y); // type of T explicitly specified
z = add(x,y);        // type of T determined automatically
```

C++ Background



● Function objects (Functors)

```
// templated functor to add numbers
```

```
template< typename T >  
class add  
{  
    public:  
    T operator() (T a, T b)  
    {  
        return a + b;  
    }  
};
```

```
int x = 10; int y = 20; int z;  
add<int> func; // create an add functor for T=int  
z = func(x,y); // invoke functor on x and y
```

```
float x = 10; float y = 20; float z;  
add<float> func; // create an add functor for T=float  
z = func(x,y); // invoke functor on x and y
```


C++ Background



● Generic Algorithms

```
// apply function f to sequences x, y and store result in z
template <typename T, typename Function>
void transform(int N, T * x, T * y, T * z, Function f)
{
    for (int i = 0; i < N; i++)
        z[i] = f(x[i], y[i]);
}

int N = 100;
int x[N]; int y[N]; int z[N];

add<int> func; // add functor for T=int

transform(N, x, y, z, func); // compute z[i] = x[i] + y[i]

transform(N, x, y, z, add<int>()); // equivalent
```

Algorithms



- **Thrust provides many standard algorithms**
 - Transformations
 - Reductions
 - Prefix Sums
 - Sorting
- **Generic definitions**
 - **General Types**
 - Built-in types (`int`, `float`, ...)
 - User-defined structures
 - **General Operators**
 - reduce with `plus` operator
 - scan with `maximum` operator

● General types and operators

```
#include <thrust/reduce.h>

// declare storage
device_vector<int>    i_vec = ...
device_vector<float> f_vec = ...

// sum of integers (equivalent calls)
reduce(i_vec.begin(), i_vec.end());
reduce(i_vec.begin(), i_vec.end(), 0, plus<int>());

// sum of floats (equivalent calls)
reduce(f_vec.begin(), f_vec.end());
reduce(f_vec.begin(), f_vec.end(), 0.0f, plus<float>());

// maximum of integers
reduce(i_vec.begin(), i_vec.end(), 0, maximum<int>());
```

● General types and operators

```
struct negate_float2
{
    __host__ __device__
    float2 operator()(float2 a)
    {
        return make_float2(-a.x, -a.y);
    }
};

// declare storage
device_vector<float2> input = ...
device_vector<float2> output = ...

// create functor
negate_float2 func;

// negate vectors
transform(input.begin(), input.end(), output.begin(), func);
```

● General types and operators

```
// compare x component of two float2 structures
struct compare_float2
{
    __host__ __device__
    bool operator()(float2 a, float2 b)
    {
        return a.x < b.x;
    }
};

// declare storage
device_vector<float2> vec = ...

// create comparison functor
compare_float2 comp;

// sort elements by x component
sort(vec.begin(), vec.end(), comp);
```

● Operators with State

```
// compare x component of two float2 structures
struct is_greater_than
{
    int threshold;

    is_greater_than(int t) { threshold = t; }

    __host__ __device__
    bool operator()(int x) { return x > threshold; }
};

device_vector<int> vec = ...

// create predicate functor (returns true for x > 10)
is_greater_than pred(10);

// count number of values > 10
int result = count_if(vec.begin(), vec.end(), pred);
```

Recap



- **Algorithms**
 - **Generic**
 - Support general types and operators
 - **Statically dispatched based on iterator type**
 - Memory space is known at compile time
 - **Have default arguments**
 - `reduce(begin, end)`
 - `reduce(begin, end, init, binary_op)`

Fancy Iterators

- Behave like “normal” iterators
 - Algorithms don't know the difference
- Examples
 - `constant_iterator`
 - `counting_iterator`
 - `transform_iterator`
 - `permutation_iterator`
 - `zip_iterator`

Fancy Iterators

- `constant_iterator`
 - Mimics an infinite array filled with a constant value

```
// create iterators
constant_iterator<int> begin(10);
constant_iterator<int> end = begin + 3;

begin[0]    // returns 10
begin[1]    // returns 10
begin[100] // returns 10

// sum of [begin, end)
reduce(begin, end); // returns 30 (i.e. 3 * 10)
```



Fancy Iterators

- `counting_iterator`
 - Mimics an infinite array with sequential values

```
// create iterators
counting_iterator<int> begin(10);
counting_iterator<int> end = begin + 3;

begin[0]    // returns 10
begin[1]    // returns 11
begin[100]  // returns 110

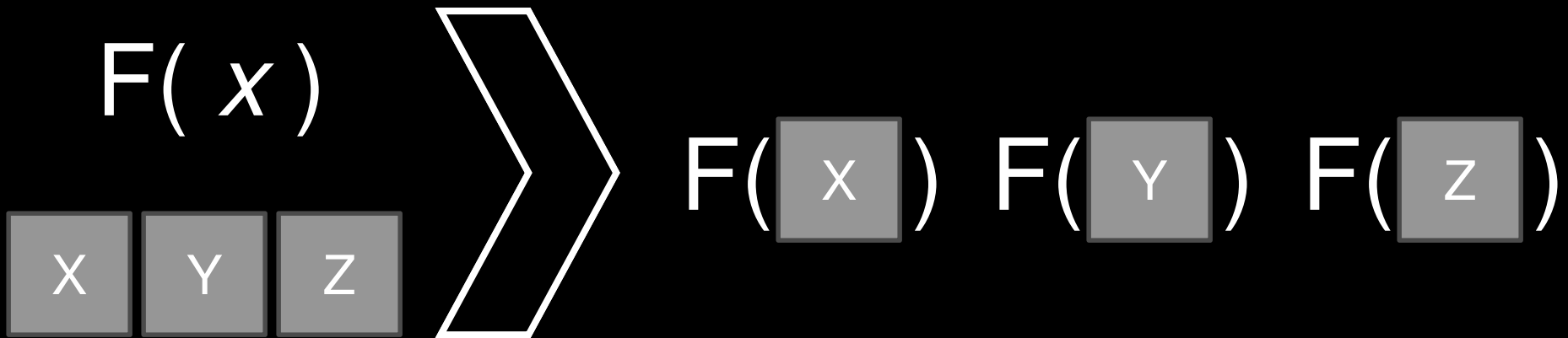
// sum of [begin, end)
reduce(begin, end); // returns 33 (i.e. 10 + 11 + 12)
```



Fancy Iterators



- `transform_iterator`
 - Yields a transformed sequence
 - Facilitates kernel fusion



Fancy Iterators

- `transform_iterator`
 - Conserves memory capacity and bandwidth

```
// initialize vector
device_vector<int> vec(3);
vec[0] = 10; vec[1] = 20; vec[2] = 30;

// create iterator (type omitted)
begin = make_transform_iterator(vec.begin(), negate<int>());
end    = make_transform_iterator(vec.end(),    negate<int>());

begin[0] // returns -10
begin[1] // returns -20
begin[2] // returns -30

// sum of [begin, end)
reduce(begin, end); // returns -60 (i.e. -10 + -20 + -30)
```

Fancy Iterators



- `zip_iterator`
 - Looks like an array of structs (AoS)
 - Stored in structure of arrays (SoA)



Fancy Iterators



● zip_iterator

```
// initialize vectors
device_vector<int>  A(3);
device_vector<char> B(3);
A[0] = 10;  A[1] = 20;  A[2] = 30;
B[0] = 'x'; B[1] = 'y'; B[2] = 'z';

// create iterator (type omitted)
begin = make_zip_iterator(make_tuple(A.begin(), B.begin()));
end    = make_zip_iterator(make_tuple(A.end(),   B.end()));

begin[0] // returns tuple(10, 'x')
begin[1] // returns tuple(20, 'y')
begin[2] // returns tuple(30, 'z')

// maximum of [begin, end)
maximum< tuple<int, char> > binary_op;
reduce(begin, end, begin[0], binary_op); // returns tuple(30, 'z')
```

Best Practices



- **Fusion**
 - **Combine related operations together**
- **Structure of Arrays**
 - **Ensure memory coalescing**
- **Implicit Sequences**
 - **Eliminate memory accesses**

Fusion



- **Combine related operations together**
 - **Conserves memory bandwidth**
- **Example: SNRM2**
 - **Square each element**
 - **Compute sum of squares and take `sqrt()`**

● Unoptimized implementation

```
// define transformation f(x) -> x^2
struct square
{
    __host__ __device__
    float operator()(float x)
    {
        return x * x;
    }
};

float snrm2_slow(device_vector<float>& x)
{
    // without fusion
    device_vector<float> temp(x.size());
    transform(x.begin(), x.end(), temp.begin(), square());

    return sqrt( reduce(temp.begin(), temp.end()) );
}
```

- **Optimized implementation (3.8x faster)**

```
// define transformation f(x) -> x^2
struct square
{
    __host__ __device__
    float operator()(float x)
    {
        return x * x;
    }
};

float snrm2_fast(device_vector<float>& x)
{
    // with fusion
    return sqrt( transform_reduce(x.begin(), x.end(),
                                square(), 0.0f, plus<float>()));
}
```

Structure of Arrays (SoA)

- **Array of Structures (AoS)**
 - Often does not obey coalescing rules
 - `device_vector<float3>`
- **Structure of Arrays (SoA)**
 - Obeys coalescing rules
 - Components stored in separate arrays
 - `device_vector<float> x, y, z;`
- **Example: Rotate 3d vectors**
 - SoA is 2.8x faster

Structure of Arrays (SoA)



```
struct rotate_float3
{
    __host__ __device__
    float3 operator() (float3 v)
    {
        float x = v.x;
        float y = v.y;
        float z = v.z;

        float rx = 0.36f*x + 0.48f*y + -0.80f*z;
        float ry = -0.80f*x + 0.60f*y + 0.00f*z;
        float rz = 0.48f*x + 0.64f*y + 0.60f*z;

        return make_float3(rx, ry, rz);
    }
};
```

...

```
device_vector<float3> vec(N);

transform(vec.begin(), vec.end(),
          vec.begin(),
          rotate_float3());
```

Structure of Arrays (SoA)



```
struct rotate_tuple
{
    __host__ __device__
    tuple<float, float, float> operator() (tuple<float, float, float> v)
    {
        float x = get<0>(v);
        float y = get<1>(v);
        float z = get<2>(v);

        float rx = 0.36f*x + 0.48f*y + -0.80f*z;
        float ry = -0.80f*x + 0.60f*y + 0.00f*z;
        float rz = 0.48f*x + 0.64f*y + 0.60f*z;

        return make_tuple(rx, ry, rz);
    }
};

...

device_vector<float> x(N), y(N), z(N);

transform(make_zip_iterator(make_tuple(x.begin(), y.begin(), z.begin())),
          make_zip_iterator(make_tuple(x.end(), y.end(), z.end())),
          make_zip_iterator(make_tuple(x.begin(), y.begin(), z.begin())),
          rotate_tuple());
```

Implicit Sequences

- **Avoid storing sequences explicitly**
 - **Constant sequences**
 - [1, 1, 1, 1, ...]
 - **Incrementing sequences**
 - [0, 1, 2, 3, ...]
- **Implicit sequences require no storage**
 - `constant_iterator`
 - `counting_iterator`
- **Example**
 - **Index of the smallest element**

Implicit Sequences



```
// return the smaller of two tuples
struct smaller_tuple
{
    tuple<float,int> operator() (tuple<float,int> a, tuple<float,int> b)
    {
        if (a < b)
            return a;
        else
            return b;
    }
};

int min_index(device_vector<float>& vec)
{
    // create explicit index sequence [0, 1, 2, ... )
    device_vector<int> indices(vec.size());
    sequence(indices.begin(), indices.end());

    tuple<float,int> init(vec[0],0);
    tuple<float,int> smallest;

    smallest = reduce(make_zip_iterator(make_tuple(vec.begin(), indices.begin())),
                    make_zip_iterator(make_tuple(vec.end(), indices.end())),
                    init,
                    smaller_tuple());

    return get<1>(smallest);
}
```

Implicit Sequences



```
// return the smaller of two tuples
struct smaller_tuple
{
    tuple<float,int> operator() (tuple<float,int> a, tuple<float,int> b)
    {
        if (a < b)
            return a;
        else
            return b;
    }
};

int min_index(device_vector<float>& vec)
{
    // create implicit index sequence [0, 1, 2, ... )
    counting_iterator<int> begin(0);
    counting_iterator<int> end(vec.size());

    tuple<float,int> init(vec[0],0);
    tuple<float,int> smallest;

    smallest = reduce(make_zip_iterator(make_tuple(vec.begin(), begin)),
                     make_zip_iterator(make_tuple(vec.end(), end)),
                     init,
                     smaller_tuple());

    return get<1>(smallest);
}
```


Recap



- **Best Practices**
 - **Fusion**
 - 3.8x faster
 - **Structure of Arrays**
 - 2.8x faster
 - **Implicit Sequences**
 - 3.4x faster

Additional Resources



● Thrust

- Homepage
- Quick Start Guide
- Documentation
- Examples
- MegaNewtons (blog)
- thrust-users (mailing list)

● Other

- NVIDIA Research
- CUDA