The Thrust Library

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The Thrust Library
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Getting Started
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Basic iterators
constant_iterator
counting_iterator
transform_iterator
permutation_iterator
zip_iterator
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Thrust is the CUDA analog of the Standard Template Library (STL) of C++. It comes with any installation of CUDA 4.2 and above and features:

- Dynamic data structures
- An encapsulation of GPU/CPU communication, memory management, and other low-level tasks.
- High-performance GPU-accelerated algorithms such as sorting and reduction

- Emerged from Komrade (deprecated) in 2009
- Maintained primarily by Jared Hoberock and Nathan Bell of NVIDIA.

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vector1.cu I

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

int main(void){

  // H has storage for 4 integers
  thrust::host_vector<int> H(4);

  // initialize individual elements
  H[0] = 14;
  H[1] = 20;
  H[2] = 38;
  H[3] = 46;

  // H.size() returns the size of vector H
  std::cout << "H has size " << H.size() << std::endl;

  // print contents of H
  for(int i = 0; i < H.size(); i++)
    std::cout << "H[" << i << "] = " << H[i] << std::endl;

  // resize H
  H.resize(2);
  std::cout << "H now has size " << H.size() << std::endl;

  // Copy host_vector H to device_vector D
  thrust::device_vector<int> D = H;

  // elements of D can be modified
```


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vector1.cu II

```
    D[0] = 99;
    D[1] = 88;

    // print contents of D
    for(int i = 0; i < D.size(); i++)
      std::cout << "D[" << i << "] = " << D[i] << std::endl;

    // H and D are automatically deleted when the function returns
    return 0;
}
```


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Output of vector1.cu I

```
[landau@impact1 vector1]$ make
nvcc vector1.cu -o vector1
[landau@impact1 vector1]$ ./vector1
H has size 4
H[0] = 14
H[1] = 20
H[2] = 38
H[3] = 46
H now has size 2
D[0] = 99
D[1] = 88
[landau@impact1 vector1]$
```

- Thrust takes care of `malloc()`, `cudaMalloc()`, `free()`, and `cudaFree()` for you without sacrificing performance.
- The "=" operator does a cudaMemcpy() if one vector is on the host and one is on the device.
- `thrust::` and `std::` clarify the *namespace* of the function after the double colon. For example, we need to distinguish between `thrust::copy()` and `std::copy()`.
- The "<<" operator sends a value to an output stream, an alternative to `printf()`.

vector2.cu I

```
#include <thrust/host_vector.h>
#include <thrust/device_vector.h>
#include <thrust/copy.h>
#include <thrust/fill.h>
#include <thrust/sequence.h>
#include <iostream>

int main(void){
  // initialize all ten integers of a device_vector to 1
  thrust::device_vector <int> D(10, 1);

  // set the first seven elements of a vector to 9
  thrust::fill(D.begin(), D.begin() + 7, 9);

  // initialize a host_vector with the first five elements of D
  thrust::host_vector<int> H(D.begin(), D.begin() + 5);

  // set the elements of H to 0, 1, 2, 3, ...
  thrust::sequence(H.begin(), H.end());

  // copy all of H back to the beginning of D
  thrust::copy(H.begin(), H.end(), D.begin());

  // print D
  for(int i = 0; i < D.size(); i++)
    std::cout << "D[" << i << "] = " << D[i] << std::endl;

  return 0;
}
```

Output of vector2.cu I

```
[landau@impact1 vector2]$ make
nvcc vector2.cu -o vector2
[landau@impact1 vector2]$ ./vector2
D[0] = 0
D[1] = 1
D[2] = 2
D[3] = 3
D[4] = 4
D[5] = 9
D[6] = 9
D[7] = 1
D[8] = 1
D[9] = 1
[landau@impact1 vector2]$
```


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Assignment

- `thrust::copy()` copies a section of one vector into a section of another.
- `thrust::fill()` sets a range of elements to some fixed value.
- `thrust::sequence()` assigns equally-spaced values to a section of a vector.

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The Vector Template Classes

- Declaring vectors:
  - `thrust::device_vector<T> D;` creates a vector `D` with entries of data type `T` on the device.
  - The analogous declaration for host vectors is `thrust::host_vector<T> H;`.
- An object `D` of the vector template class includes the following features:
  - A dynamic linear array of elements of type `T`.
  - Two *iterators*:
    - `D.begin()`
    - `D.end()`

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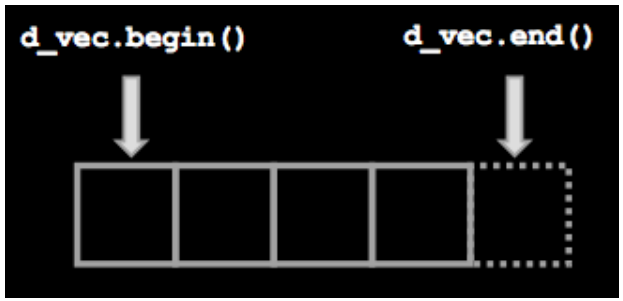
An iterator is a pointer with a C++ wrapper around it. The wrapper contains additional information, such as whether the vector is stored on the host or the device.

```
// 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
```



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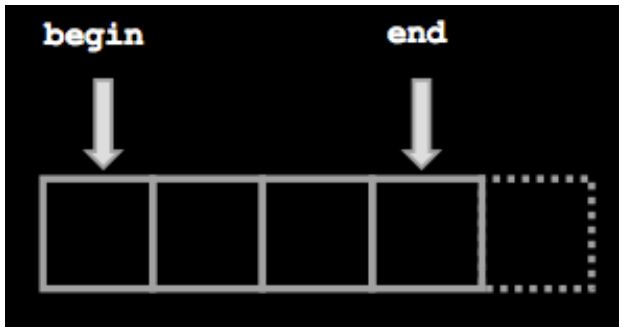
Iterators act like pointers.

```
// 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 the length of the vector

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



```
// 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;
```

Wrap pointers to make iterators.

```
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_iter(raw_ptr); // dev_iter is now an
      iterator pointing to device memory
thrust::fill(dev_iter, dev_iter + N, (int) 0); // access device memory
      through device_ptr

dev_iter[0] = 1;

// free memory
cudaFree(raw_ptr);
```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Unwrap iterators to extract 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!
```

constant_iterator

A constant_iterator is a pointer with some constant value associated with it.

```
#include <thrust/iterator/constant_iterator.h>
...
// create iterators
thrust::constant_iterator<int> first(10);
thrust::constant_iterator<int> last = first + 3;

first[0]; // returns 10
first[1]; // returns 10
first[100]; // returns 10

// sum of [first, last)
thrust::reduce(first, last); // returns 30 (i.e. 3 * 10)
```

counting_iterator

A counting_iterator is a pointer with the value <some constant> + <offset> associated with it.

```
#include <thrust/iterator/counting_iterator.h>
...

// create iterators
thrust::counting_iterator<int> first(10);
thrust::counting_iterator<int> last = first + 3;

first[0]; // returns 10
first[1]; // returns 11
first[100]; // returns 110

// sum of [first, last)
thrust::reduce(first, last); // returns 33 (i.e. 10 + 11 + 12)
```

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transform_iterator I

A transform_iterator is a pointer with the value <some function>(<vector entry>) associated with it.

```
#include <thrust/iterator/transform_iterator.h>
...
thrust::device_vector <int> vec(3);
vec[0] = 10;
vec[1] = 20;
vec[2] = 30;

// create iterator
thrust::transform_iterator <int> first =
  thrust::make_transform_iterator(vec.begin(), negate<int>());

thrust::transform_iterator <int> last =
  thrust::make_transform_iterator(vec.end(), negate<int>());

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

thrust::reduce(first, last); // returns -60 (i.e. -10 + -20 + -30)

//same thing:
thrust::reduce(
  thrust::make_transform_iterator(
    vec.begin(), negate<int>()),
  thrust::make_transform_iterator(
```

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transform_iterator II

```
    vec.end(), negate<int>()));
```

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permutation_iterator I

A permutation_iterator is a pointer associated with a permuted vector.

```
#include <thrust/iterator/permutation_iterator.h>
...
thrust::device_vector <int> map(4);
map[0] = 3;
map[1] = 1;
map[2] = 0;
map[3] = 5;

thrust::device_vector <int> source(6);
source[0] = 10;
source[1] = 20;
source[2] = 30;
source[3] = 40;
source[4] = 50;
source[5] = 60;

typedef thrust::device_vector<int>::iterator indexIter;

thrust::permutation_iterator<indexIter, indexIter> pbegin =
  thrust::make_permutation_iterator(
    source.begin(), map.begin())

thrust::permutation_iterator<indexIter, indexIter> pend =
  thrust::make_permutation_iterator(
    source.end(), map.end())

int p0 = pbegin[0] // source[map[0]] = 40
```

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permutation_iterator II

```
int p1 = pbegin[1] // source[map[1]] = 20

int sum = thrust::reduce(pbegin, pend)

/* sum =
 * source[map[0]] + source[map[1]] + source[map[2]] + source[map[3]] =
 * source[3] + source[1] + source[0] + source[5] =
 * 40 + 20 + 10 + 60 =
 * 130 */
```


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zip_iterator I

A zip_iterator is a pointer associated with a vector of tuples.

```
#include <thrust/device_vector.h>
#include <thrust/tuple.h>
#include <thrust/iterator/zip_iterator.h>
#include <iostream>

#include <thrust/iterator/zip_iterator.h>

int main(){
  thrust::device_vector<int> int_v(3);
  int_v[0] = 0; int_v[1] = 1; int_v[2] = 2;

  thrust::device_vector<float> float_v(3);
  float_v[0] = 0.0; float_v[1] = 1.0; float_v[2] = 2.0;

  thrust::device_vector<char> char_v(3);
  char_v[0] = 'a'; char_v[1] = 'b'; char_v[2] = 'c';

  // typedef these iterators for shorthand
  typedef thrust::device_vector<int>::iterator   IntIterator;
  typedef thrust::device_vector<float>::iterator FloatIterator;
  typedef thrust::device_vector<char>::iterator  CharIterator;

  // typedef a tuple of these iterators
  typedef thrust::tuple<IntIterator, FloatIterator, CharIterator>
      IteratorTuple;
```

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zip_iterator II

```
  // typedef the zip_iterator of this tuple
  typedef thrust::zip_iterator<IteratorTuple> ZipIterator;

  // finally, create the zip_iterator
  ZipIterator iter(thrust::make_tuple(int_v.begin(), float_v.begin(),
       char_v.begin()));

  *iter;   // returns (0, 0.0, 'a')
  iter[0]; // returns (0, 0.0, 'a')
  iter[1]; // returns (1, 1.0, 'b')
  iter[2]; // returns (2, 2.0, 'c')

  thrust::get<0>(iter[2]); // returns 2
  thrust::get<1>(iter[0]); // returns 0.0
  thrust::get<2>(iter[1]); // returns 'b'

  // iter[3] is an out-of-bounds error
}
```


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Containers are fancy data storage classes used in the Standard Template Library (STL), the CPU C++ analogue of Thrust. Examples of containers include:

- `vector`
- `deque`
- `list`
- `tack`
- `queue`
- `priority_queue`
- `set`
- `multiset`
- `map`
- `multimap`
- `biset`

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container.cu I

Thrust only implements vectors, but it's still compatible with the rest of STL's template classes:

```
#include <thrust/device_vector.h>
#include <thrust/copy.h>
#include <list>
#include <vector>

int main(void){
  // create an STL list with 4 values
  std::list<int> stl_list;
  stl_list.push_back(10);
  stl_list.push_back(20);
  stl_list.push_back(30);
  stl_list.push_back(40);

  // initialize a device_vector with the list
  thrust::device_vector <int> D(stl_list.begin(), stl_list.end());

  // copy a device_vector into an STL vector
  std::vector<int> stl_vector(D.size());
  thrust::copy(D.begin(), D.end(), stl_vector.begin());

  return 0;
}
```

Output:

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container.cu II

```
[landau@impact1 container]$ make
nvcc container.cu -o container
[landau@impact1 container]$ ./container
[landau@impact1 container]$
```

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Transformations

- A transformation is the application of a function to each element within a range of elements in a vector. The results are stored as a range of elements in another vector.
- Examples:
  - `thrust::fill()`
  - `thrust::sequence()`
  - `thrust::replace()`
  - `thrust::transform()`

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transformations.cu I

```
#include <thrust/device_vector.h>
#include <thrust/transform.h>
#include <thrust/sequence.h>
#include <thrust/copy.h>
#include <thrust/fill.h>
#include <thrust/replace.h>
#include <thrust/functional.h>
#include <iostream>

int main(void) {
  // allocate three device_vectors with 10 elements
  thrust::device_vector <int> X(10);
  thrust::device_vector <int> Y(10);
  thrust::device_vector <int> Z(10);

  // initialize X to 0,1,2,3, ....
  thrust::sequence(X.begin(), X.end());

  // compute Y = -X
  thrust::transform(X.begin(), X.end(), Y.begin(), thrust::negate<int>()
      );

  // fill Z with twos
  thrust::fill(Z.begin(), Z.end(), 2);

  // compute Y = X mod 2
  thrust::transform(X.begin(), X.end(), Z.begin(),
                    Y.begin(), thrust::modulus<int>());

  // replace all the ones in Y with tens
```


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transformations.cu II

```
    thrust::replace(Y.begin(), Y.end(), 1, 10);

    // print Y
    thrust::copy(Y.begin(), Y.end(), std::ostream_iterator<int>(std::cout,
          "\n"));
    return 0;
}
```

Output:

```
[landau@impact1 transformations]$ make
nvcc transformations.cu -o transformations
[landau@impact1 transformations]$ ./transformations
0
10
0
10
0
10
0
10
0
10
[landau@impact1 transformations]$
```

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Reductions

A reduction algorithm uses a binary operation to reduce an input vector to a single value. For example, here are equivalent ways to code the pairwise sum:

```
int sum = thrust::reduce(D.begin(), D.end(),
  (int) 0, thrust::plus<int>());

int sum = thrust::reduce(D.begin(), D.end(),
  (int) 0);

int sum = thrust::reduce(D.begin(), D.end())
```

- The third argument is the starting value of the reduction.
- The fourth argument is the binary operation that defines the kind of reduction.

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Counting

Another reduction: use `thrust::count()` to count the number of times a value appears in a vector

```
#include <thrust/count.h>
#include <thrust/device_vector.h>
...

// put three 1s in a device_vector
thrust::device_vector <int> vec(5,0);

vec [1] = 1;
vec [3] = 1;
vec [4] = 1;

// count the 1s
int result = thrust::count(vec.begin(), vec.end(), 1);
// result is three
```

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Scans

A scan, also called a prefix-sum, applies a function to multiple sub-ranges of a vector and returns the result in a vector of the same size. The default function is addition.

```
#include <thrust/scan.h>
...
int data[6] = {1, 0, 2, 2, 1, 3};
thrust::inclusive_scan(data, data + 6, data);

/* data[0] = data[0]
 * data[1] = data[0] + data[1]
 * data[2] = data[0] + data[1] + data[2]
 * ...
 * data[5] = data[0] + data[1] +     + data[5]
 */

// data is now {1, 1, 3, 5, 6, 9}
```


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Scans

There are *exclusive scans* in addition to *inclusive scans*:

```
#include <thrust/scan.h>
...
int data[6] = {1, 0, 2, 2, 1, 3};
thrust::exclusive_scan(data, data + 6, data);

/* data[0] = 0
 * data[1] = data[0]
 * data[2] = data[0] + data[1]
 * ...
 * data[5] = data[0] + data[1] + ... + data[4]
 */

// data is now {0, 1, 1, 3, 5, 6}
```


The Thrust Library

Will Landau
Prof. Jarad Niemi

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Reordering

The "Reordering" utilities provides subletting and partitioning tools:

- `thrust::copy_if()`: copy the elements that make some logical function return true.
- `thrust::partition()`; reorder a vector such that values returning true precede values returning false.
- `thrust::remove()` and `remove_if()`: remove elements that return false.
- `thrust::unique()`: remove duplicates in a vector.

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```cpp
#include <thrust/partition.h>
...

struct is_even{
  __host__ __device__ bool operator()(const int &x){
    return (x % 2) == 0;
  }
};

int main(){
  int A[] = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
  const int N = sizeof(A)/sizeof(int);
  thrust::partition(A, A + N,
                    is_even());

  // A is now {2, 4, 6, 8, 10, 1, 3, 5, 7, 9}
  return 0;
}
```


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Sorting I

thrust::sort():

```
#include <thrust/sort.h>
...
const int N = 6;
int A[N] = {1, 4, 2, 8, 5, 7};
thrust::sort(A, A + N);
// A is now {1, 2, 4, 5, 7, 8}
```

thrust::sort_by_key():

```
#include <thrust/sort.h>
...
const int N = 6;
int keys[N] = { 1, 4, 2, 8, 5, 7};
char values[N] = {'a', 'b', 'c', 'd', 'e', 'f'};
thrust::sort_by_key(keys, keys + N, values);
// keys is now { 1, 2, 4, 5, 7, 8}
// values is now {'a', 'c', 'b', 'e', 'f', 'd'}
```

thrust::stable_sort():

Sorting II

```
#include <thrust/sort.h>
...
const int N = 6;
int keys[N] = { 1, 4, 2, 8, 5, 7};
char values[N] = {'a', 'b', 'c', 'd', 'e', 'f'};
thrust::sort_by_key(keys, keys + N, values);
// keys is now { 1, 2, 4, 5, 7, 8}
// values is now {'a', 'c', 'b', 'e', 'f', 'd'}
```

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Materials

These slides, a tentative syllabus for the whole lecture series, and all example code are available at `https://github.com/wlandau/gpu`.

After logging into you home directory on impact1, type:

```
git clone https://github.com/wlandau/gpu
```

into the command line to download all the materials.

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Sources

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3. CUDA Toolkit 4.2 Thrust Quick Start Guide. March 2012. http://developer.download.nvidia.com/compute/DevZone/docs/html/CUDALibraries/doc/Thrust_Quick_Start_Guide.pdf