FLATIRON INSTITUTE

Lambda Functions & Standard Template Library

Nils Wentzell
Oct 20, 2022

Lambda Functions

A simple Example

C++

```cpp
auto l = [](int i) { return i+1; };
int u = l(2);
```

Python

```python
l = lambda i : i + 1
u = l(2)
```

Lambda Functions

Integrate a generic function on the interval [0, 1]

```
double integrate(auto f) {
  double r = 0.0;
  for (auto x: {0.0, 0.1, …,0.9}) r += 0.1*f(x);
  return r;
}

double r1 = integrate( cos );

double r2 = integrate( [](double x){ return cos(2*x); } );

double r3 = integrate( [r2](double y){ return pow(y, r2); } );  // y^r2
```

$$\int_0^1 dx \cos(2x)$$

Capture it first

FLATIRON INSTITUTE

Syntax

[captures] (params) -> ret { statements; }

[captures]

What outside variables are available, by value or by reference.

(params)

How to invoke it.

-> ret

Return type. Will be `auto` deduced if omitted.

{ statements; }

The body of the lambda function.

Different ways to capture

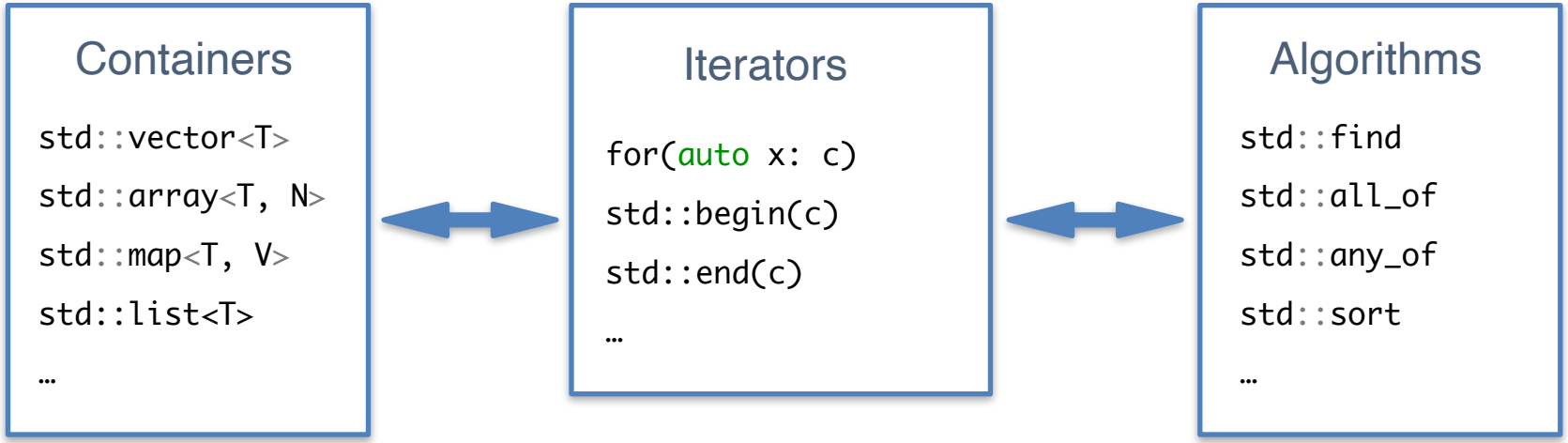
[captures] (params) -> ret { statements; }

[captures]

- `[a]` Capture `a` by copy
- `[&a]` Capture `a` by reference
- `[&]` Capture all by reference
- `[a,&]` Capture `a` by copy and others by reference
- …

Standard Template Library (STL)

- Library of generic Containers & Algorithms
- Generic Iterator Interface allows for interoperability



STL Containers

en.cppreference.com/w/cpp/container

Sequence containers

Sequence containers implement data structures which can be accessed sequentially.

array (C++11)	static contiguous array (class template)
vector	dynamic contiguous array (class template)
deque	double-ended queue (class template)
forward_list (C++11)	singly-linked list (class template)
list	doubly-linked list (class template)

Cover most use-cases!

Associative containers

Associative containers implement sorted data structures that can be quickly searched ($O(\log n)$ complexity).

set	collection of unique keys, sorted by keys (class template)
map	collection of key-value pairs, sorted by keys, keys are unique (class template)
multiset	collection of keys, sorted by keys (class template)
multimap	collection of key-value pairs, sorted by keys (class template)

unordered_set (C++11)
unordered_map (C++11)
unordered_multiset (C++11)
unordered_multimap (C++11)

FLATIRON INSTITUTE

STL Containers

en.cppreference.com/w/cpp/container

array (C++11)	static contiguous array (class template)
vector	dynamic contiguous array (class template)

→ On Stack

→ On Heap

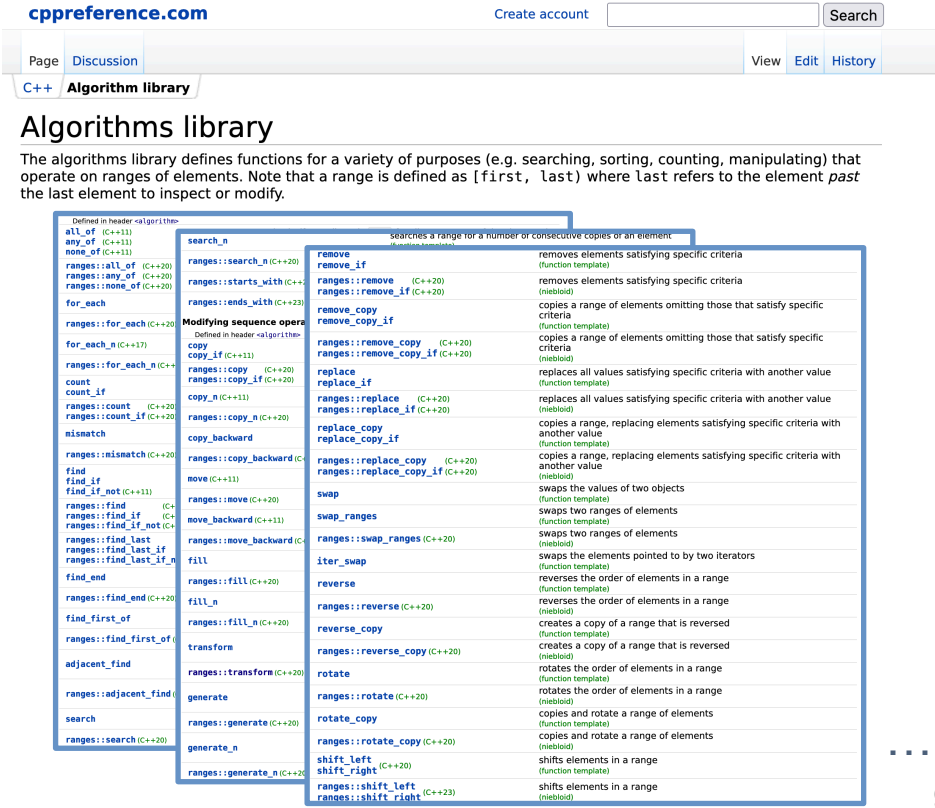
```
auto a = array<int, 3>{1, 2, 3};  // Construction
a.size();                         // How many elements?
int i = a[0];                     // Access
a[0]  = 4;                        // Assignment
for (auto x: a) …                 // Iterating
```

```
auto a = array{1, 2, 3};  // C++17: auto-deduce element-type & size
```

STL Algorithms

en.cppreference.com/w/cpp/algorithm

- Set of generic algorithms
- Widely know → easy to read
- Tested & Debugged
- Optimal Performance
- Parallel execution C++17/20
- Composable



...

std::sort

- Simple Example

```
auto v = vector{ 2, 1, 3 };
sort(begin(v), end(v)); // -> 1, 2, 3

std::ranges::sort(v); // C++20
```

- A custom sort

```
// Find traversal order from smallest to largest
auto v = vector{ 2, 1, 3, 6, 5, 4 };
```

```
// Create index vector 0, 1, 2, .. N-1
auto l = vector<int>(v.size());
iota(begin(l), end(l), 0);

sort(begin(l), end(l), [&v](int i, int j){ return v[i] < v[j]; });
// -> 1, 0, 2, 5, 4, 3
```

reduce (accumulate)

$$(v_0, \ldots, v_n) \to v_0 \square \ldots \square v_n$$

- The default case $\sum_i v_i$

```
auto v = vector{ 2, 1, 3 };
reduce(begin(v), end(v), 0); // -> 6
```

- Custom reduction $\prod_i v_i$

```
auto v = vector{ 2, 1, 3 };
reduce(begin(v), end(v), 1, [](int i, int j){ return i*j; }); // -> 6
```

reduce (accumulate)

$$(v_0, \ldots, v_n) \to v_0 \square \ldots \square v_n$$

- The default case $\sum_i v_i$

```
auto v = vector{ 2, 1, 3 };
reduce(begin(v), end(v), 0); // -> 6
```

- Custom reduction $\prod_i v_i$

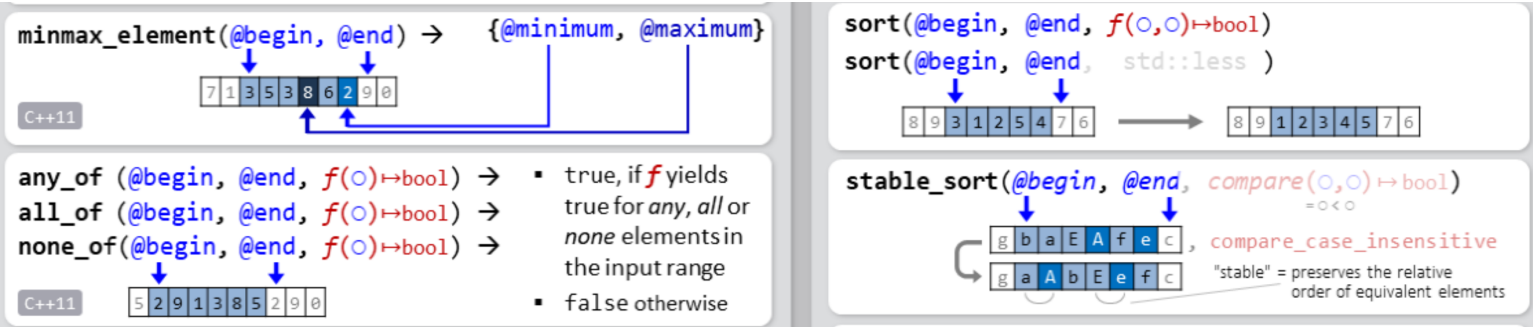
```
auto v = vector{ 2, 1, 3 };
reduce(begin(v), end(v), 1, multiplies<>{});
```

en.cppreference.com/w/cpp/header/functional

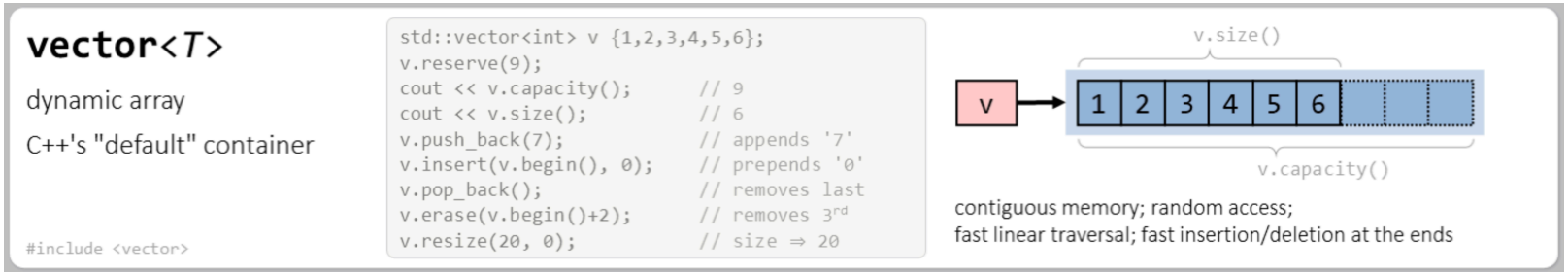
STL Cheat Sheets

hackingcpp.com/cpp/cheat_sheets.html

Algorithms



Containers



and much more…

A note on Parallelism

en.cppreference.com/w/cpp/algorithm/execution_policy_tag_t

- Most STL Algorithms can be easily run in parallel

```
auto v = vector<int>(1e5, 1);
reduce(begin(v), end(v), 0);
```

```
#include <execution>
auto v = vector<int>(1e5, 1);
return reduce(std::execution::par, begin(v), end(v), 0);
```

Composable Algorithms

C++20

en.cppreference.com/w/cpp/algorithm/ranges

Example

Run this code

```
#include <vector>
#include <ranges>
#include <iostream>

int main()
{
    std::vector<int> ints{0,1,2,3,4,5};
    auto even = [](int i){ return 0 == i % 2; };
    auto square = [](int i) { return i * i; };

    for (int i : ints | std::views::filter(even) | std::views::transform(square)) {
        std::cout << i << ' ';
    }
}
```

Output:

```
0 4 16
```

Summary

- Algorithms + Lambdas are incredibly useful!
- In particular `transform_reduce`
  - `reduce, transform, inclusive_scan, adjacent_difference, adjacent_find`
- Even more powerful and expressive in C++20/23
  - Parallel execution, Compact Syntax, Composability (Ranges)

transform

$v_i \to f(v_i)$ $(v_i, w_i) \to g(v_i, w_i)$

- Squaring elements $v_i \to v_i^2$

```
auto v = vector{ 2, 1, 3 };
transform(begin(v), end(v), begin(v),
  [](int i){ return i * i; });
```

- Logical or $(v_i, w_i) \to v_i \,||\, w_i$

```
vector<bool> a, b;
transform(begin(a), end(a), begin(b), begin(a),
  [](bool l, bool r){ return l || r; });
```

transform

$v_i \to f(v_i)$ $(v_i, w_i) \to g(v_i, w_i)$

- Squaring elements $v_i \to v_i^2$

```
auto v = vector{ 2, 1, 3 };
transform(cbegin(v), cend(v), begin(v),
  [](int i){ return i * i; });
```

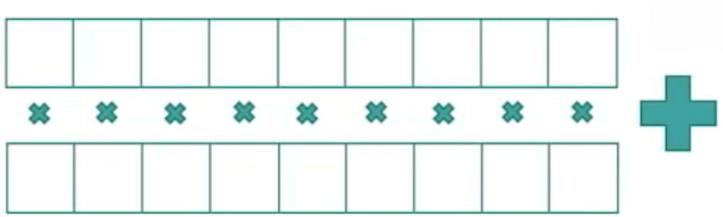
- Logical or $(v_i, w_i) \to v_i \,||\, w_i$

```
vector<bool> a, b;
transform(begin(a), end(a), begin(b), begin(a),
  logical_or<>{});
```

transform_reduce (inner_product)

$$(v_0, \ldots, v_n) \to f(v_0) \square \ldots \square f(v_n)$$

$$(v_0, \ldots, v_n), (w_0, \ldots, w_n) \to g(v_0, w_0) \square \ldots \square g(v_n, w_n)$$



- A vector product $\sum_i v_i w_i$

```
vector<double> x, y;
// ...
transform_reduce(begin(x), end(x), begin(y), 0.0);
```

- Vector Distance $\sum_i (v_i - w_i)^2$

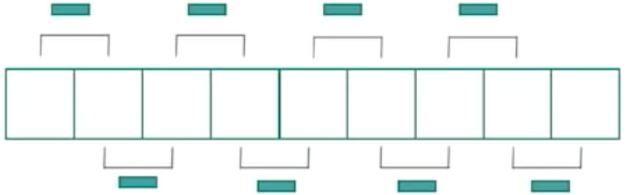
```
vector<int> v, w;
// ...
transform_reduce(begin(v), end(v), begin(w), 0,
  [](int i, int j) -> int { return (i - j) * (i - j); },
  std::plus<>{});
```

Other useful algorithms

`inclusive_scan` (`partial_sum`)

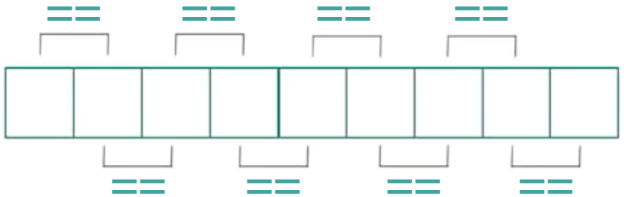
$v_i \to v_0 \square \ldots \square v_i$ Why not `partial_reduce` ?

`adjacent_difference`



$v_0 \to v_0 \qquad v_i \to v_{i-1} \square v_i$

`adjacent_find`



all_of and any_of

- All values greater 10?

```
vector<int> v;
all_of(begin(v), end(v), [](int i){ return i > 10; });
```

- Any values negative?

```
vector<double> x;
any_of(begin(x), end(x), [](double d){ return d < 0.; });
```

iota and generate

github.com/TRIQS/triqs/blob/2.2.x/test/itertools/itertools.cpp

github.com/TRIQS/triqs/blob/2.2.x/itertools/itertools.hpp

- A range of integers

```
auto v = vector<int>(10);
iota(begin(v), end(v), 0);
// 0 1 2 3 4 5 6 7 8 9
```

```
itertools::range(0,10);
```

- A list of squares

```
auto v = vector<int>(10);
generate(begin(v), end(v),
  [i = 0] () mutable { ++i; return i*i; });
// 1 4 9 16 25 36 49 64 81 100
```