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Working Draft, Technical Specification for C++ Extensions for Parallelism, Revision 1

Note: this is an early draft. It's known to be incomplet and incorrekt, and it has lots of bad formatting.

Contents

1	General	3
1.1	Scope	3
1.2	Normative references	3
1.3	Namespaces and headers	3
1.4	Terms and definitions	3
2	Execution policies	4
2.1	In general	4
2.2	Header <code><experimental/execution_policy></code> synopsis	4
2.3	Execution policy type trait	5
2.4	Sequential execution policy	5
2.5	Parallel execution policy	6
2.6	Vector execution policy	6
2.7	Dynamic execution policy	7
2.7.1	<code>execution_policy</code> construct/assign/swap	7
2.7.2	<code>execution_policy</code> object access	8
2.8	Execution policy specialized algorithms	8
2.9	Execution policy objects	8
3	Parallel exceptions	9
3.1	Exception reporting behavior	9
3.2	Header <code><experimental/exception></code> synopsis	9
4	Parallel algorithms	10
4.1	In general	10
4.1.1	Effect of execution policies on parallel algorithm execution	10
4.1.2	<code>ExecutionPolicy</code> algorithm overloads	12
4.2	Novel algorithms	13
4.2.1	Header <code><experimental/algorithm></code> synopsis	13
4.2.2	For each	13
4.2.3	Header <code><experimental/numeric></code> synopsis	14
4.2.4	Reduce	15
4.2.5	Exclusive scan	16
4.2.6	Inclusive scan	17

1 General

[parallel.general]

1.1 Scope

[parallel.general.scope]

This Technical Specification describes requirements for implementations of an interface that computer programs written in the C++ programming language may use to invoke algorithms with parallel execution. The algorithms described by this Technical Specification are realizable across a broad class of computer architectures.

This Technical Specification is non-normative. Some of the functionality described by this Technical Specification may be considered for standardization in a future version of C++, but it is not currently part of any C++ standard. Some of the functionality in this Technical Specification may never be standardized, and other functionality may be standardized in a substantially changed form.

The goal of this Technical Specification is to build widespread existing practice for parallelism in the C++ standard algorithms library. It gives advice on extensions to those vendors who wish to provide them.

1.2 Normative references

[parallel.general.references]

The following reference document is indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

- ISO/IEC 14882:2011, Programming Languages – C++

ISO/IEC 14882:2011 is herein called the C++ Standard. The library described in ISO/IEC 14882:2011 clauses 17-30 is herein called the C++ Standard Library. The C++ Standard Library components described in ISO/IEC 14882:2011 clauses 25 and 26.7 are herein called the C++ Standard Algorithms Library.

Unless otherwise specified, the whole of the C++ Standard Library introduction [lib.library] is included into this Technical Specification by reference.

1.3 Namespaces and headers

[parallel.general.namespaces]

Since the extensions described in this Technical Specification are experimental and not part of the C++ Standard Library, they should not be declared directly within namespace `std`. Unless otherwise specified, all components described in this Technical Specification are declared in namespace `std::experimental::parallel`.

[*Note:* Once standardized, the components described by this Technical Specification are expected to be promoted to namespace `std`. – *end note*]

Unless otherwise specified, references to other entities described in this Technical Specification are assumed to be qualified with `std::experimental::parallel`, and references to entities described in the C++ Standard Library are assumed to be qualified with `std::`.

Extensions that are expected to eventually be added to an existing header `<meow>` are provided inside the `<experimental/meow>` header, which shall include the standard contents of `<meow>` as if by

```
#include <meow>
```

1.4 Terms and definitions

[parallel.general.defns]

For the purposes of this document, the terms and definitions given in the C++ Standard and the following apply.

A *parallel algorithm* is a function template described by this Technical Specification declared in namespace `std::experimental::parallel` with a formal template parameter named `ExecutionPolicy`.

2 Execution policies [parallel.execpol]

2.1 In general [parallel.execpol.general]

This subclause describes classes that represent *execution policies*. An *execution policy* is an object that expresses the requirements on the ordering of functions invoked as a consequence of the invocation of a standard algorithm. Execution policies afford standard algorithms the discretion to execute in parallel.

[Example:

```
std::vector<int> v = ...

// standard sequential sort
std::sort(vec.begin(), vec.end());

using namespace std::experimental::parallel;

// explicitly sequential sort
sort(seq, v.begin(), v.end());

// permitting parallel execution
sort(par, v.begin(), v.end());

// permitting vectorization as well
sort(vec, v.begin(), v.end());

// sort with dynamically-selected execution
size_t threshold = ...
execution_policy exec = seq;
if(v.size() > threshold)
{
    exec = par;
}

sort(exec, v.begin(), v.end());
```

– end example]

[Note: Because different parallel architectures may require idiosyncratic parameters for efficient execution, implementations of the Standard Library should provide additional execution policies to those described in this Technical Specification as extensions. – end note]

2.2 Header `<experimental/execution_policy>` synopsis [parallel.execpol.synop]

```
namespace std {
namespace experimental {
namespace parallel {
    // 2.3, execution policy type trait
    template<class T> struct is_execution_policy;

    // 2.4, sequential execution policy
```

```

class sequential_execution_policy;

// 2.5, parallel execution policy
class parallel_execution_policy;

// 2.6, vector execution policy
class vector_execution_policy;

// 2.7, dynamic execution policy
class execution_policy;

// 2.8, specialized algorithms
void swap(sequential_execution_policy& a, sequential_execution_policy& b);
void swap(parallel_execution_policy& a, parallel_execution_policy& b);
void swap(vector_execution_policy& a, vector_execution_policy& b);
void swap(execution_policy& a, execution_policy& b);

// 2.9, standard execution policy objects
extern const sequential_execution_policy seq;
extern const parallel_execution_policy par;
extern const vector_execution_policy vec;
}
}
}

```

2.3 Execution policy type trait

[parallel.execpol.type]

```

namespace std {
namespace experimental {
namespace parallel {
    template<class T> struct is_execution_policy
        : integral_constant<bool, see below> { };
}
}
}

```

1. `is_execution_policy` can be used to detect parallel execution policies for the purpose of excluding function signatures from otherwise ambiguous overload resolution participation.
2. If `T` is the type of a standard or implementation-defined execution policy, `is_execution_policy<T>` shall be publicly derived from `integral_constant<bool,true>`, otherwise from `integral_constant<bool,false>`.
3. The behavior of a program that adds specializations for `is_execution_policy` is undefined.

2.4 Sequential execution policy

[parallel.execpol.seq]

```

namespace std {
namespace experimental {
namespace parallel {

class sequential_execution_policy
{
    void swap(sequential_execution_policy& other);
}
}
}

```

```
};
}
}
}
```

1. The class `sequential_execution_policy` is an execution policy type used as a unique type to disambiguate parallel algorithm overloading and require that a parallel algorithm's execution may not be parallelized.

```
void swap(sequential_execution_policy& other);
```

2. *Effects:* Swaps the state of `*this` and `other`.

2.5 Parallel execution policy

[parallel.execpol.par]

```
namespace std {
namespace experimental {
namespace parallel {

    class parallel_execution_policy
    {
        void swap(parallel_execution_policy& other);
    };
}
}
}
```

1. The class `parallel_execution_policy` is an execution policy type used as a unique type to disambiguate parallel algorithm overloading and indicate that a parallel algorithm's execution may be parallelized.

```
void swap(parallel_execution_policy& other);
```

2. *Effects:* Swaps the state of `*this` and `other`.

2.6 Vector execution policy

[parallel.execpol.vec]

```
namespace std {
namespace experimental {
namespace parallel {

    class vector_execution_policy
    {
        void swap(vector_execution_policy& other);
    };
}
}
}
```

1. The class `vector_execution_policy` is an execution policy type used as a unique type to disambiguate parallel algorithm overloading and indicate that a parallel algorithm's execution may be vectorized.

```
void swap(vector_execution_policy& other);
```

2. *Effects*: Swaps the state of **this* and *other*.

2.7 Dynamic execution policy

[parallel.execpol.dynamic]

```
namespace std {
namespace experimental {
namespace parallel {

class execution_policy
{
public:
    // 2.7.1, construct/assign/swap
    template<class T> execution_policy(const T& exec);
    template<class T> execution_policy& operator=(const T& exec);
    void swap(execution_policy& other);

    // 2.7.2, object access
    const type_info& target_type() const;
    template<class T> T* target();
    template<class T> const T* target() const;
};
}
}
}
```

1. The class `execution_policy` is a dynamic container for execution policy objects. `execution_policy` allows dynamic control over standard algorithm execution.

[*Example*:

```
std::vector<float> sort_me = ...

std::execution_policy exec = std::seq;

if(sort_me.size() > threshold)
{
    exec = std::par;
}

std::sort(exec, sort_me.begin(), sort_me.end());
```

– *end example*]

2. Objects of type `execution_policy` shall be constructible and assignable from objects of type `T` for which `is_execution_policy<T>::value` is true.

2.7.1 `execution_policy` construct/assign/swap

[parallel.execpol.con]

```
template<class T> execution_policy(const T &exec);
```

1. *Effects*: Constructs an `execution_policy` object with a copy of `exec`'s state.

2. *Requires:* `is_execution_policy<T>::value` is true

```
template<class T> execution_policy& operator=(const T& exec);
```

3. *Effects:* Assigns a copy of `exec`'s state to `*this`.

4. *Returns:* `*this`.

5. *Requires:* `is_execution_policy<T>::value` is true

```
void swap(execution_policy& other);
```

1. *Effects:* Swaps the stored object of `*this` with that of `other`.

2.7.2 execution_policy object access

[parallel.execpol.access]

```
const type_info& target_type() const;
```

1. *Returns:* `typeid(T)`, such that `T` is the type of the execution policy object contained by `*this`.

```
template<class T> T* target();
```

```
template<class T> const T* target() const;
```

2. *Returns:* If `target_type() == typeid(T)`, a pointer to the stored execution policy object; otherwise a null pointer.

3. *Requires:* `is_execution_policy<T>::value` is true

2.8 Execution policy specialized algorithms

[parallel.execpol.algorithms]

```
void swap(sequential_execution_policy& a, sequential_execution_policy& b);
void swap(parallel_execution_policy& a, parallel_execution_policy& b);
void swap(vector_execution_policy& a, vector_execution_policy& b);
void swap(execution_policy& a, execution_policy& b);
```

1. *Effects:* `a.swap(b)`.

2.9 Execution policy objects

[parallel.execpol.objects]

```
namespace std {
namespace experimental {
namespace parallel {
    constexpr sequential_execution_policy seq = sequential_execution_policy();
    constexpr parallel_execution_policy par = parallel_execution_policy();
    constexpr vector_execution_policy vec = vector_execution_policy();
}
}
}
```

1. The header `<execution_policy>` declares a global object associated with each type of execution policy defined by this technical specification.

3 Parallel exceptions

[parallel.exceptions]

3.1 Exception reporting behavior

[parallel.exceptions.behavior]

1. If temporary memory resources are required by the algorithm and none are available, the algorithm throws a `std::bad_alloc` exception.
2. During the execution of a standard parallel algorithm, if the application of a function object terminates with an uncaught exception, the behavior of the program is determined by the type of execution policy used to invoke the algorithm:

- If the execution policy object is of type `vector_execution_policy`, `std::terminate` shall be called.
- If the execution policy object is of type `sequential_execution_policy` or `parallel_execution_policy`, the execution of the algorithm terminates with an `exception_list` exception. All uncaught exceptions thrown during the application of user-provided function objects shall be contained in the `exception_list`.

[*Note:* For example, the number of invocations of the user-provided function object in `for_each` is unspecified. When `for_each` is executed sequentially, only one exception will be contained in the `exception_list` object – *end note*]

[*Note:* These guarantees imply that, unless the algorithm has failed to allocate memory and terminated with `std::bad_alloc`, all exceptions thrown during the execution of the algorithm are communicated to the caller. It is unspecified whether an algorithm implementation will “forge ahead” after encountering and capturing a user exception. – *end note*]

[*Note:* The algorithm may terminate with the `std::bad_alloc` exception even if one or more user-provided function objects have terminated with an exception. For example, this can happen when an algorithm fails to allocate memory while creating or adding elements to the `exception_list` object – *end note*]

- If the execution policy object is of any other type, the behavior is implementation-defined.

3.2 Header <experimental/exception> synopsis

[parallel.exceptions.synop]

```
namespace std {
namespace experimental {
namespace parallel {
    class exception_list : public exception
    {
    public:
        typedef exception_ptr          value_type;
        typedef const value_type&      reference;
        typedef const value_type&      const_reference;
        typedef implementation-defined const_iterator;
        typedef const_iterator        iterator;
        typedef typename iterator_traits<const_iterator>::difference_type difference_type;
        typedef size_t                size_type;

        size_t size() const;
        iterator begin() const;
        iterator end() const;

    private:
```

```

    std::list<exception_ptr> exceptions_; // exposition only
};
}
}
}

```

1. The class `exception_list` is a container of `exception_ptr` objects parallel algorithms may use to communicate uncaught exceptions encountered during parallel execution to the caller of the algorithm.
2. The type `exception_list::const_iterator` shall fulfill the requirements of `ForwardIterator`.

```
size_t size() const;
```

2. *Returns:* The number of `exception_ptr` objects contained within the `exception_list`.
3. *Complexity:* Constant time.

```
exception_list::iterator begin() const;
```

4. *Returns:* An iterator referring to the first `exception_ptr` object contained within the `exception_list`.

```
exception_list::iterator end() const;
```

5. *Returns:* An iterator which is the past-the-end value for the `exception_list`.

4 Parallel algorithms

[parallel.alg]

4.1 In general

[parallel.alg.general]

This clause describes components that C++ programs may use to perform operations on containers and other sequences in parallel.

4.1.1 Effect of execution policies on parallel algorithm execution [parallel.alg.general.exec]

1. Parallel algorithms have template parameters named `ExecutionPolicy` which describe the manner in which the execution of these algorithms may be parallelized and the manner in which they apply user-provided function objects.
2. The applications of function objects in parallel algorithms invoked with an execution policy object of type `sequential_execution_policy` execute in sequential order in the calling thread.
3. The applications of function objects in parallel algorithms invoked with an execution policy object of type `parallel_execution_policy` are permitted to execute in an unordered fashion in unspecified threads, and indeterminately sequenced within each thread. [*Note:* It is the caller's responsibility to ensure correctness, for example that the invocation does not introduce data races or deadlocks. — *end note*]

[*Example:*

```

using namespace std::experimental::parallel;
int a[] = {0,1};
std::vector<int> v;
for_each(par, std::begin(a), std::end(a), [&](int i) {
    v.push_back(i*2+1);
});

```

The program above has a data race because of the unsynchronized access to the container `v` — *end example*

[*Example:*

```
using namespace std::experimental::parallel;
std::atomic<int> x = 0;
int a[] = {1,2};
for_each(par, std::begin(a), std::end(a), [](int n) {
    x.fetch_add(1, std::memory_order_relaxed);
    // spin wait for another iteration to change the value of x
    while (x.load(std::memory_order_relaxed) == 1) { }
});
```

The above example depends on the order of execution of the iterations, and is therefore undefined (may deadlock). — *end example*

[*Example:*

```
using namespace std::experimental::parallel;
int x;
std::mutex m;
int a[] = {1,2};
for_each(par, std::begin(a), std::end(a), [&](int) {
    m.lock();
    ++x;
    m.unlock();
});
```

The above example synchronizes access to object `x` ensuring that it is incremented correctly. — *end example*

4. The applications of function objects in parallel algorithms invoked with an execution policy of type `vector_execution_policy` are permitted to execute in an unordered fashion in unspecified threads, and unsequenced within each thread. [*Note:* as a consequence, function objects governed by the `vector_execution_policy` policy must not synchronize with each other. Specifically, they must not acquire locks. — *end note*]

[*Example:*

```
using namespace std::experimental::parallel;
int x;
std::mutex m;
int a[] = {1,2};
for_each(vec, std::begin(a), std::end(a), [&](int) {
    m.lock();
    ++x;
    m.unlock();
});
```

The above program is invalid because the applications of the function object are not guaranteed to run on different threads.

— *end example*

[*Note:* the application of the function object may result in two consecutive calls to `m.lock` on the same thread, which may deadlock — *end note*]

[*Note:* The semantics of the `parallel_execution_policy` or the `vector_execution_policy` invocation allow the implementation to fall back to sequential execution if the system cannot parallelize an algorithm invocation due to lack of resources. – *end note.*]

5. If they exist, a parallel algorithm invoked with an execution policy object of type `parallel_execution_policy` or `vector_execution_policy` may apply iterator member functions of a stronger category than its specification requires. In this case, the application of these member functions are subject to provisions 3. and 4. above, respectively.

[*Note:* For example, an algorithm whose specification requires `InputIterator` but receives a concrete iterator of the category `RandomAccessIterator` may use `operator[]`. In this case, it is the algorithm caller's responsibility to ensure `operator[]` is race-free. – *end note.*]

6. Algorithms invoked with an execution policy object of type `execution_policy` execute internally as if invoked with instances of type `sequential_execution_policy`, `parallel_execution_policy`, or an implementation-defined execution policy type depending on the dynamic value of the `execution_policy` object.
7. The semantics of parallel algorithms invoked with an execution policy object of implementation-defined type are unspecified.

4.1.2 ExecutionPolicy algorithm overloads

[`parallel.alg.overloads`]

1. Parallel algorithms coexist alongside their sequential counterparts as overloads distinguished by a formal template parameter named `ExecutionPolicy`. This template parameter corresponds to the parallel algorithm's first function parameter, whose type is `ExecutionPolicy&&`.
2. Unless otherwise specified, the semantics of `ExecutionPolicy` algorithm overloads are identical to their overloads without.
3. Parallel algorithms have the requirement `is_execution_policy<ExecutionPolicy>::value` is `true`.
4. The algorithms listed in table 1 shall have `ExecutionPolicy` overloads.

<code>adjacent_find</code>	<code>for_each</code>	<code>none_of</code>	<code>search</code>
<code>all_of</code>	<code>for_each_n</code>	<code>nth_element</code>	<code>search_n</code>
<code>any_of</code>	<code>generate</code>	<code>partial_sort</code>	<code>set_difference</code>
<code>copy</code>	<code>generate_n</code>	<code>partial_sort_copy</code>	<code>set_intersection</code>
<code>copy_if</code>	<code>includes</code>	<code>partition</code>	<code>set_symmetric_difference</code>
<code>copy_n</code>	<code>inclusive_scan</code>	<code>partition_copy</code>	<code>set_union</code>
<code>count</code>	<code>inplace_merge</code>	<code>reduce</code>	<code>sort</code>
<code>count_if</code>	<code>is_heap</code>	<code>remove</code>	<code>stable_partition</code>
<code>equal</code>	<code>is_partitioned</code>	<code>remove_copy</code>	<code>stable_sort</code>
<code>exclusive_scan</code>	<code>is_sorted</code>	<code>remove_copy_if</code>	<code>swap_ranges</code>
<code>fill</code>	<code>is_sorted_until</code>	<code>remove_if</code>	<code>transform</code>
<code>fill_n</code>	<code>lexicographical_compare</code>	<code>replace</code>	<code>uninitialized_copy</code>
<code>find</code>	<code>max_element</code>	<code>replace_copy</code>	<code>uninitialized_copy_n</code>
<code>find</code>	<code>merge</code>	<code>replace_copy_if</code>	<code>uninitialized_fill</code>
<code>find_end</code>	<code>min_element</code>	<code>reverse</code>	<code>uninitialized_fill_n</code>

find_first_of	minmax_element	reverse_copy	unique
find_if	mismatch	rotate	unique_copy
find_if_not	move	rotate_copy	

Table 1: Table of parallel algorithms

4.2 Novel algorithms

[parallel.alg.novel]

This subclause describes novel algorithms introduced by this technical specification.

4.2.1 Header <experimental/algorithm> synopsis

[parallel.alg.novel.algorithm.synop]

```

namespace std {
namespace experimental {
namespace parallel {
    template<class ExecutionPolicy,
             class InputIterator, class Function>
    InputIterator for_each(ExecutionPolicy&& exec,
                        InputIterator first, InputIterator last,
                        Function f);
    void for_each(ExecutionPolicy&& exec,
                 InputIterator first, InputIterator last,
                 Function f);
    template<class InputIterator, class Size, class Function>
    Function for_each_n(InputIterator first, Size n,
                      Function f);
    InputIterator for_each_n(InputIterator first, Size n,
                           Function f);
    template<class ExecutionPolicy,
            class InputIterator, class Size, class Function>
    InputIterator for_each_n(ExecutionPolicy&& exec, InputIterator first, Size n,
                          Function f);
}
}
}

```

4.2.2 For each

[parallel.alg.novel.foreach]

```

template<class ExecutionPolicy,
        class InputIterator, class Function>
InputIterator for_each(ExecutionPolicy&& exec,
                    InputIterator first, InputIterator last,
                    Function f);
void for_each(ExecutionPolicy&& exec,
             InputIterator first, InputIterator last,
             Function f);

```

1. *Effects:* Applies `f` to the result of dereferencing every iterator in the range `[first,last)`. [Note: If the type of `first` satisfies the requirements of a mutable iterator, `f` may apply nonconstant functions through the dereferenced iterator. – end note]
2. ~~Returns: first + (last – first).~~

3. *Complexity*: Applies `f` exactly `last - first` times.
4. *Remarks*: If `f` returns a result, the result is ignored.
5. *Note*: Unlike its sequential form, the parallel overload of `for_each` does not return a copy of its Function parameter, since parallelization may not permit efficient state accumulation.

```
template<class InputIterator, class Size, class Function>
Function for_each_n(InputIterator first, Size n,
Function f);
InputIterator for_each_n(InputIterator first, Size n,
Function f);
```

1. *Requires*: Function shall meet the requirements of `MoveConstructible` [*Note*: Function need not meet the requirements of `CopyConstructible`. – end note]
2. *Effects*: Applies `f` to the result of dereferencing every iterator in the range `[first, first + n)`, starting from `first` and proceeding to `first + n - 1`. [*Note*: If the type of `first` satisfies the requirements of a mutable iterator, `f` may apply nonconstant functions through the dereferenced iterator. – end note]
3. *Returns*: ~~`std::move(f)`~~`first + n`.
4. *Complexity*: Applies `f` exactly `n` times.
5. *Remarks*: If `f` returns a result, the result is ignored.

```
template<class ExecutionPolicy,
class InputIterator, class Size, class Function>
InputIterator for_each_n(ExecutionPolicy&& exec,
InputIterator first, Size n,
Function f);
```

1. *Requires*: ~~Function shall meet the requirements of `MoveConstructible` [*Note*: Function need not meet the requirements of `CopyConstructible`. – end note]~~
2. *Effects*: ~~Applies `f` to the result of dereferencing every iterator in the range `[first, first + n)`, starting from `first` and proceeding to `first + n - 1`. [*Note*: If the type of `first` satisfies the requirements of a mutable iterator, `f` may apply nonconstant functions through the dereferenced iterator. – end note]~~
3. *Returns*: ~~`first + n`~~.
4. *Complexity*: ~~Applies `f` exactly `n` times.~~
5. *Remarks*: ~~If `f` returns a result, the result is ignored.~~

4.2.3 Header `<experimental/numeric>` synopsis

[parallel.alg.novel.numeric.synop]

```
namespace std {
namespace experimental {
namespace parallel {
template<class InputIterator>
typename iterator_traits<InputIterator>::value_type
reduce(InputIterator first, InputIterator last);
template<class InputIterator, class T>
T reduce(InputIterator first, InputIterator last T init);
```

```

template<class InputIterator, class T, class BinaryOperation>
    T reduce(InputIterator first, InputIterator last, T init,
             BinaryOperation binary_op);

template<class InputIterator, class OutputIterator>
    OutputIterator
        exclusive_scan(InputIterator first, InputIterator last,
                       OutputIterator result);
template<class InputIterator, class OutputIterator,
        class T>
    OutputIterator
        exclusive_scan(InputIterator first, InputIterator last,
                       OutputIterator result,
                       T init);
template<class InputIterator, class OutputIterator,
        class T, class BinaryOperation>
    OutputIterator
        exclusive_scan(InputIterator first, InputIterator last,
                       OutputIterator result,
                       T init, BinaryOperation binary_op);

template<class InputIterator, class OutputIterator>
    OutputIterator
        inclusive_scan(InputIterator first, InputIterator last,
                       OutputIterator result);
template<class InputIterator, class OutputIterator,
        class BinaryOperation>
    OutputIterator
        inclusive_scan(InputIterator first, InputIterator last,
                       OutputIterator result,
                       BinaryOperation binary_op);
template<class InputIterator, class OutputIterator,
        class T, class BinaryOperation>
    OutputIterator
        inclusive_scan(InputIterator first, InputIterator last,
                       OutputIterator result,
                       T init, BinaryOperation binary_op);
}
}
}

```

4.2.4 Reduce

[parallel.alg.novel.reduce]

```

template<class InputIterator>
    typename iterator_traits<InputIterator>::value_type
        reduce(InputIterator first, InputIterator last);

```

1. *Returns:* `reduce(first, last, typename iterator_traits<InputIterator>::value_type(0), {})`
2. *Requires:* `typename iterator_traits<InputIterator>::value_type(0), {}` shall be a valid expression. The `operator+` function associated with `iterator_traits<InputIterator>::value_type` shall have associativity and commutativity.
`operator+` shall not invalidate iterators or subranges, nor modify elements in the range `[first, last)`.

3. *Complexity*: $O(\text{last} - \text{first})$ applications of `operator+`.
4. *Note*: The primary difference between `reduce` and `accumulate` is that the behavior of `reduce` may be non-deterministic for non-associative or non-commutative `operator+`.

```
template<class InputIterator, class T>
T reduce(InputIterator first, InputIterator last, T init);
```

1. *Returns*: `reduce(first, last, init, plus<>())`
2. *Requires*: The `operator+` function associated with `T` shall not invalidate iterators or subranges, nor modify elements in the range `[first,last)`.
3. *Complexity*: $O(\text{last} - \text{first})$ applications of `operator+`.
4. *Note*: The primary difference between `reduce` and `accumulate` is that the behavior of `reduce` may be non-deterministic for non-associative or non-commutative `operator+`.

```
template<class InputIterator, class T, class BinaryOperation>
T reduce(InputIterator first, InputIterator last, T init,
        BinaryOperation binary_op);
```

1. *Returns*: The result of the generalized sum of `init` and the elements in the range `[first,last)`. Sums of elements are evaluated with `binary_op`. The order of operands of the sum is unspecified.
2. *Requires*: `binary_op` shall have associativity and commutativity. `binary_op` shall not invalidate iterators or subranges, nor modify elements in the range `[first,last)`.
3. *Complexity*: $O(\text{last} - \text{first})$ applications of `binary_op`.
4. *Note*: The primary difference between `reduce` and `accumulate` is that the behavior of `reduce` may be non-deterministic for non-associative or non-commutative `operator+`.

4.2.5 Exclusive scan

[parallel.alg.novel.exclusive.scan]

```
template<class InputIterator, class OutputIterator,
        class T>
OutputIterator
exclusive_scan(InputIterator first, InputIterator last,
               OutputIterator result,
               T init);
```

1. *Returns*: `exclusive_scan(first, last, result, init, plus<>())`
2. *Requires*: The `operator+` function associated with `iterator_traits<InputIterator>::value_type` shall not invalidate iterators or subranges, nor modify elements in the ranges `[first,last)` or `[result,result + (last - first))`.
3. *Complexity*: $O(\text{last} - \text{first})$ applications of `operator+`.
4. *Notes*: The primary difference between `exclusive_scan` and `inclusive_scan` is that `exclusive_scan` excludes the *i*th input element from the *i*th sum.


```
template<class InputIterator, class OutputIterator,
        class T, class BinaryOperation>
OutputIterator
exclusive_scan(InputIterator first, InputIterator last,
               OutputIterator result,
               T init, BinaryOperation binary_op);
```

1. *Effects:* For each iterator *i* in `[result, result + (last - first))`, produces a result such that upon completion of the algorithm, `*i` yields the generalized sum of `init` and the elements in the range `[first, first + (i - result))`.

During execution of the algorithm, every evaluation of the above sum is

`binary_op(binary_op(init,A), B)` or `binary_op(A, B)`

where there exists some iterator *j* in `[first, last)` such that:

1. *A* is the partial sum of elements in the range `[j, j + n)`.
 2. *B* is the partial sum of elements in the range `[j + n, j + m)`.
 3. *n* and *m* are positive integers and `j + m < last`.
2. *Returns:* The end of the resulting range beginning at `result`.
 3. *Requires:* `binary_op` shall have associativity.
`binary_op` shall not invalidate iterators or subranges, nor modify elements in the ranges `[first,last)` or `[result,result + (last - first))`.
 4. *Complexity:* $O(\text{last} - \text{first})$ applications of `binary_op`.
 5. *Notes:* The primary difference between `exclusive_scan` and `inclusive_scan` is that `exclusive_scan` excludes the *i*th input element from the *i*th sum.

4.2.6 Inclusive scan

[parallel.alg.novel.inclusive.scan]

```
template<class InputIterator, class OutputIterator>
OutputIterator
inclusive_scan(InputIterator first, InputIterator last,
               OutputIterator result);
```

1. *Returns:* `inclusive_scan(first, last, result, plus<>())`
2. *Requires:* The `operator+` function associated with `iterator_traits<InputIterator>::value_type` shall have associativity.
`operator+` shall not invalidate iterators or subranges, nor modify elements in the ranges `[first,last)` or `[result,result + (last - first))`.
3. *Complexity:* $O(\text{last} - \text{first})$ applications of `operator+`.
4. *Notes:* The primary difference between `exclusive_scan` and `inclusive_scan` is that `exclusive_scan` excludes the *i*th input element from the *i*th sum.

```
template<class InputIterator, class OutputIterator,
        class BinaryOperation>
OutputIterator
inclusive_scan(InputIterator first, InputIterator last,
               OutputIterator result,
```

```

        BinaryOperation binary_op);

template<class InputIterator, class OutputIterator,
        class T, class BinaryOperation>
OutputIterator
    inclusive_scan(InputIterator first, InputIterator last,
                  OutputIterator result,
                  T init, BinaryOperation binary_op);

```

1. *Effects:* For each iterator *i* in `[result, result + (last - first))`, produces a result such that upon completion of the algorithm, `*i` yields the generalized sum of `init`, if it is provided as a parameter, and the elements in the range `[first, first + (i - result)]`.

During execution of the algorithm, every evaluation of the above sum is either of the corresponding form

`binary_op(binary_op(init,A), B)` or `binary_op(A, B)`

where there exists some iterator *j* in `[first, last)` such that:

1. *A* is the partial sum of elements in the range `[j, j + n)`.
 2. *B* is the partial sum of elements in the range `[j + n, j + m)`.
 3. *n* and *m* are positive integers and `j + m < last`.
2. *Returns:* The end of the resulting range beginning at `result`.
 3. *Requires:* `binary_op` shall have associativity.
`binary_op` shall not invalidate iterators or subranges, nor modify elements in the ranges `[first,last)` or `[result,result + (last - first))`.
 4. *Complexity:* $O(\text{last} - \text{first})$ applications of `binary_op`.
 5. *Notes:* The primary difference between `exclusive_scan` and `inclusive_scan` is that `inclusive_scan` includes the *i*th input element in the *i*th sum.