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Vector and Wavefront Policies

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# Motivation

Vector parallelism is insufficiently supported by the current Parallelism TS ([N4578](http://www.open-std.org/JTC1/SC22/WG21/docs/papers/2016/n4578.html)). The Parallelism TS does offer the par\_unseq policy, and there is some interest in a variant that restricts execution to a single thread; the result of such a restriction is the unseq policy proposed in this paper. Alas, this policy, though it allows a vectorization (exploiting vector hardware), it is excessively permissive and fails to express the necessaryrequirements for an important set of vectorizable loops of practical interest. As defined in N4507, par\_unseq allows:

“The invocation of element access functions ... are permitted to execute in an unordered fashion in unspecified threads and unsequenced with respect to one another within each thread. [*Note*: this means that multiple function object invocations may be interleaved on a single thread. – *end note* ]”

Merely constraining par\_unseq to a single thread still allows permissive interleaving that would give undefined semantics to loops in the aforementioned set.

Here is a short example that falls in the gap, using for\_loop from [P0075](http://www.open-std.org/JTC1/SC22/WG21/docs/papers/2016/p0075r1.pdf) with vector\_policy proposed in this paper:

void binomial(int n, float y[]) {

for\_loop( **vec**, 0, n, [&](int i) {

y[i] += y[i+1];

});

}

The call to for\_loop is equivalent, except with more relaxed sequencing, to:

void binomial(int n, float y[]) {

for( int i=0; i<n; ++i )

y[i] += y[i+1];

}

The for\_loop example cannot safely use unseq or par\_unseq instead of vec, because that would result in unsequenced reads and writes of the same element of y when n≥2. Subsequent sections show some more examples that require vec instead of unseq.

The proposals in this paper are targeted for a future parallelism TS.

# Change History

## Changes from R3 to R4

**From Core review in Toronto:**

* Removed vagueness from the definition of “evaluation A *contains* evaluation B”.
* Added definition of *ordered before*, which is used to correct the definition of *vertical antecedent* so that it no longer breaks when subexpressions are unsequenced or indeterminately sequenced.
* Fixed erroneous initial condition for establishing *horizontally matched*.
* Fixed uses of the term *horizontal antecedent* (replaced by *horizontally matched*), which were left over from an earlier revision.

## Changes from R2 to R3

* R2 with the following revisions was approved by LEWG on Wednesday morning, 2016-06-22, and by EWG on Thursday morning, 2016-06-23, in Oulu. There was concern in EWG whether the description of wavefront execution is sufficient for creating a fresh implementation from the spec.
* Rename vec\_off to no\_vec.
* Add noexcept to no\_vec. Add note indicating that if function invoked by no\_vec throws, then terminate is called, consistent with vector\_policy execution.
* Delete self-assignment operator for ordered\_update\_t.
* Add const to all members of ordered\_update\_t.
* Add noexcept to all members of ordered\_update\_t.
* Add note indicating that members of ordered\_update\_t typically return by value.
* Applied name changes from [P0413r0](http://www.open-std.org/JTC1/SC22/WG21/docs/papers/2016/p0413r0.pdf).

## Changes from R1 to R2

* As requested by SG1, removed ordered scatter rule. See section 6.5 for more details.
* Added non-normative clarifying notes to the description of wavefront execution.

## Changes from R0 to R1

* Changed formal specification of wavefront ordering to use a much simpler *horizontal match* formulation instead of labeling each evaluation with a LIFO context.
* Added ordered\_update and its helper class ordered\_update\_t.
* Changed vec\_off(f) to return result of f() instead of discarding it.
* Separated the controversial “ordered scatters” rule from the rest of the proposal, so that it can be voted on separately.

# Execution policies for vectorization

## Unsequenced and vector execution policies

This paper proposes adding two new execution policies to the Parallelism TS, assuming the adoption of P0075. These policies add support for execution with relaxed sequencing restricted to a single OS thread:

* An unsequenced\_policy class and constant unseq analogous to the other policy types and constants in the Parallelism TS, with sequencing semantics similar to parallel\_unsequenced\_policy, but limited to a single OS thread.
* A vector\_policy class and constant vec that is similar to the policy above, but guarantees stronger sequencing, compatible with classic work in the field of vectorization. This policy is restricted to the indexed-based loop templates proposed in P0075.

The first policy has strictly weaker sequencing guarantees than the second. The following lattice summarizes the strength of their guarantees relative to each other and existing policies, with the weakest guarantees at the top.

seq

par

**unseq**

par\_unseq

**vec**

No compiler extensions are necessary for correct implementation; since an implementation is free to implement any policy higher on the lattice via a policy lower on the lattice, serial execution is always allowed. The goal, however, is for the implementation to exploit parallel hardware, especially vector units, for improved performance. Some combination of OpenMP directives and vendor-specific hooks are likely to be used for implementing algorithms with either policy.[[1]](#footnote-2)

The ability to constrain execution to a single OS thread is commonly useful for avoiding resource interference with multi-threading designs.

Having two new policies, instead of one, and restricting vec to for\_loop resolves a fundamental conflict. The unseq policy is generally useful and straightforward to define for the parallel algorithms in the Parallelism TS, but fails to capture guarantees critical to an important class of loops. Conversely, vec is critically useful for an important class of loops and definable for for\_loop, but seems impractical to generalize to the parallel algorithms in a way that is both well-defined and beneficial to exploit.

## Extensibility of Policies

Though we don’t propose it for standardization at this time, we note that vector\_policy could be subclassed to provide additional information from the programmer to the compiler. Providing this information as static const member of integral type would enable cognizant compilers to find it a compile time, as in the following example:

struct my\_policy: vector\_policy {

static const int **safelen** = 8;

static const bool **vectorize\_remainder** = true;

};

for\_loop( my\_policy(), 0, 1912, [&](int i) {

Z[i+8] = Z[i]\*A;

});

Here, safelen is a *semantic* piece of information, similar to a safelen clause in OpenMP 4.0, that says that the (i+9)th[[2]](#footnote-3) application of the function cannot start until the ith and prior applications complete. For programmers to rely on this in portable code would require standardizing it.

In contrast, vectorize\_remainder is a performance hint, and could remain vendor specific.

# Wavefront Application

Our proposed vector\_policy gives programmers classic “vector loop” evaluation order guarantees when used with function template for\_loop from P0075. We abstract the evaluation order by defining “wavefront[[3]](#footnote-4) application*”*. Intuitively, the *wavefront application* of a function *f* over a sequence of argument listsapplies *f* to each argument list in a way that keeps preceding applications from falling behind later application. This property distinguishes our vector\_policy from our unsequenced\_policy. The wavefront property has two benefits:

* It enables exploiting “forward dependencies”, a common technique in classic vector codes.
* It implies that vector\_policy is safe to use on any loop that could be auto-vectorized.

For example, consider:[[4]](#footnote-5)

void f() {

extern float U[], V[], A, B;

for\_loop( vec, 1, 999, [&](int i) {

V[i] = U[i+1]\*A;

U[i] = V[i-1]+B;

});

}

For this code to have the same side effects with vec as with the seq policy, it is imperative that the load of U[*k*] preceded a store into U[*k*] in a later iteration, and likewise that the store into V[*k*] precede the load of V[*k*] in a later iteration. Our wavefront semantics coupled with the subscript patterns give those guarantees. With the more relaxed ordering of our unsequenced\_policy (or the existing parallel\_policy or parallel\_unsequenced\_policy) the programmer would need to fission the loop into two loops, with the consequent penalty of increasing consumption of memory bandwidth.

Wavefront application provides the **necessary** conditions for vectorization on classic “long vector” machines in the tradition of Cray and Convex, vectorization on “short vector” architectures (such as Intel® SSE, Intel® AVX, ARM® NEON, and Freescale® AltiVec), as well as software pipelining and unroll-and-interleave optimizations, without introducing relaxations that would be harmful for some loops.

## Horizontal Matching

Precisely defining “ahead” and “behind” can be tricky for functions with control flow that repeats evaluation of an expression. We solve the problem by refining the sequencing rules from N4237 to handle cyclic control flow. Our refinement uses “horizontal matching” that distinguish evaluating the same expression or statement during different trips though a loop or in different invocations of a callee. Furthermore, unstructured control flows (gotos and switch statements like in “[Duff’s device](https://en.wikipedia.org/wiki/Duff%27s_device)”) are handled by temporarily disabling synchronization guarantees across iterations, but in a way that limits the disabling to within a certain scope. While disabled, the vec policy temporarily acts like the unseq policy (i.e., the sequencing guarantees are relaxed).

Horizontal matching is fully defined and further explained in the proposed wording section (Section 7.6). For the next section, it suffices to understand that horizontal matching formalizes an intuitive notion of matching up corresponding evaluations in a sensible way. For example, given this code:

for\_loop(par, 0, 4, [&](int k){

if (k % 2)

f(k);

else

g(k);

h(k);

}

the rules horizontally match each row of evaluations shown in the table below.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Expression** | **k=0** | **k=1** | **k=2** | **k=3** |
| x % 2 | 0 % 2 | 1 % 2 | 2 % 2 | 3 % 2 |
| f(x) |  | f(1) |  | f(3) |
| g(x) | g(0) |  | g(2) |  |
| h(x) | h(0) | h(1) | h(2) | h(3) |

Executions of iterative statements are matched by matching each iteration in turn, giving up after at least one loop quits. Unstructured control-flow turns off matching until it becomes structured again. We defer the details of when this happens to the proposed wording section (7.6).

## Ordering Rules for Wavefront Application

### High-level view

The invocations of element access functions in our for\_loop template from P0075 invoked with an execution policy of type vector\_policy are permitted to execute in an unordered fashion in the calling thread, unsequenced with respect to one another within the calling thread, but restricted by the “wavefront application” ordering constraints formalized in the proposed wording in Section 7.6.

Figure 1 sketches the rule for the ith and jth invocations of the element access function, where i<j. The subscripted letters denote expression evaluations or statement executions. Dashed lines denote “horizontally matched”; solid arrows denote “sequenced before”. Our rules require that if either black partial triangle exists, then the blue sequenced-before relationship must be enforced to complete the triangle.

Ai

Bi

~~B~~

Bj

′

Aj

Ai

Bj

~~B′~~

′

Figure 1 Horizontally matched and sequenced before relationships

Thus the jth iteration cannot get ahead of the ith iteration.

### Wavefront ordering for loops within the element access function

Consider the following vector for\_loop invocation with a serial for loop nested within the element-access function (a lambda expression, in this case):

for\_loop( vec, 0, 2, [&](int i) {

for( int m=i; m<2; ++m )

A[m][i] = 1;

B[i]++;

});

The definition of horizontal matching distinguishes the three evaluations of m<2 and two evaluations of A[m][i] as five separate evaluations (in the case of i=0), as if the inner loop were unrolled. The dashed lines in Figure 2 show the horizontally matched relationships and the solid arrows show some of the resulting sequenced-before relationships. Evaluations of ++m and 1 were omitted for brevity. Left side are evaluations for i=0; right side for i=1. As traditional with such diagrams, we omit some of the arrows inferable via transitive closure.

m<2

A[m][i]

m<2

A[m][i]

m<2

m<2

A[m][i]

m<2

B[i]++

B[i]++

Figure 2 Horizontal Matching in a loop

Two evaluations are horizontally matched if their *vertical antecedents* (see proposed wording in Section 7.6) are horizontally matched. It is critical that *vertical antecedent*, unlike *sequenced before*, is *not* a transitive relationship, so the first evaluation of m<2 in the first column is *not* horizontally matched with the second evaluation of m<2 in the second column because their vertical antecedents are not horizontally matched.

If evaluations for different iterations of the inner loop were not distinguished, evaluation of the expression m<2 would be sequenced before A[m][i] across applications and *vice-versa*, resulting in arrows from every expression evaluation on the left to every expression evaluation on the right, which would imply serial execution order.

Note that the rules *do* produce sequenced-before relationships from each evaluation within the nested loop to evaluation of B[i]++ immediately following the loop. This property is called “re-convergence” and is important for maximizing vector parallelism.

# Functions for strengthening wavefront ordering

*Note that if* [*P0335*](http://www.open-std.org/JTC1/SC22/WG21/docs/papers/2016/p0335r0.pdf) *is accepted, then the two functions described here would become member functions of* vector\_policy::context\_token*.*

## no\_vec

It is sometimes useful to force serial sequencing of a region of code. We define a template function no\_vec for this purpose. Here is an example:

extern int\* p;

for\_loop( **vec**, 0, n, [&](int i) {

y[i] += y[i+1];

if(y[i]<0) {

**no\_vec**([]{

\*p++ = i;

});

}

});

The updates \*p++=i will occur in the same order as if the policy were seq.

Note that we may want to rename this function to ordered if [P0335](http://www.open-std.org/JTC1/SC22/WG21/docs/papers/2016/p0335r0.pdf) is accepted and this function becomes a member of the context token. For now, LEWG felt that ordered is not a good name to have at std namespace.

## ordered\_update

The class template ordered\_update\_t and function template ordered\_update enable concise expression of some common patterns that require tightening the sequencing rules. Given an lvalue x of type X, a call ordered\_update(x) returns a proxy of type ordered\_update\_t<X> that sequences assignment and update operations as if they were wrapped in no\_vec. Example patterns:

**ordered\_update**(A[B[i]]) = f(i);     *// Scatter*

**ordered\_update**(A[B[i]]) += f(i);    *// Histogram*

++**ordered\_update**(A[B[i]]);             *// Histogram*

A[i] = (**ordered\_update**(x) += f(i)); *// Prefix scan*

if(p(i)) A[**ordered\_update**(j)++] = f(i); *// Compress*

if(p(i)) v = A[**ordered\_update**(j)++]; *// Expand*

# Alternative Designs Considered

At the September, 2014 meeting in Urbana, the model of vector programming presented here was known as the *wavefront* model. Its key characteristic is that *dynamically-forward loop-carried dependencies* are honored without additional syntax. Two other models described in Urbana were the *lock-step* model and the *explicit ordering-point* model (also called the *explicit barrier* model).

[N4238](http://www.open-std.org/JTC1/SC22/WG21/docs/papers/2014/n4238.pdf) provides a detailed description of these models, but they can be briefly summarized as follows:

The **lock-step model** groups consecutive loop iterations into chunks of known size, with execution proceeding concurrently on all iterations within a chunk as if each iteration were executing the same operation at the same time (i.e., in lock step).

The **wavefront model** allows iterations to proceed at different rates, but does not allow execution of one iteration to “get behind” execution of a subsequent iteration. Consequently, later iterations can depend on progress guarantees that support dynamically-forward loop-carried dependencies, as in the following example:

extern float A[N];

parallel::for\_loop(0, N - 1, [&](int i){

*// Evaluate* f(A[i+1]) *and store the result in A[i] occurs*

*// before* A[i+1] *is modified in the next iteration.*

A[i] = f(A[i + 1]);

});

The **explicit ordering-point model** is similar to the wavefront model except that the sequencing relationships required to support dynamically-forward loop-carried dependencies would need to be made explicit by inserting *ordering point* constructs into the loop body, e.g., as in the following example.

extern float A[N];

parallel::for\_loop(0, N - 1, [&](int i){

auto tmp = f(A[i + 1]);

// *Ensure that evaluating f(A[i+1]) occurs*

// *before A[i+1] is modified in the next iteration.*

parallel::wavefront\_ordering\_pt();

A[i] = f(tmp);

});

## Previous discussions

There was consensus before Urbana that we wish our loop-like vectorization construct to have serial equivalent semantics; i.e., it should be possible to get semantically correct results by executing the code serially. This goal conflicts with the lock-step model, which requires explicit chunking of the loop and specifies a very restrictive set of valid orderings within a chunk. Moreover, lock-step execution has a semantic whereby results calculated in one iteration of the loop may be required to be available in a *previous* iteration of the loop. Because serial ordering is not a valid ordering with the lock-step model, the lock-step programming model was not considered appropriate as the primary vector programming paradigm in C++. Both the explicit and wavefront models do support serial ordering as a valid implementation choice.

The explicit and wavefront models both had consensus support in Urbana, with the explicit model having slightly stronger support than the wavefront model. The authors of this paper deliberated long and hard on the issue and, after considering many issues, the original authors of this proposal agreed that the wavefront model was the preferred model for *vector* programming, although the explicit model may still have a role to play in some sort of *low-overhead parallel* programming which has yet to be proposed.

In Kona (October 2015), the library syntax for vector loops proposed in P0075 was well received, in general, but the question of implicit versus explicit expression of inter-iteration dependencies remained stalled. Meetings with several hardware vendors and programmers with vectorization expertise reinforced our conclusion that the wavefront model, without explicit ordering points, best expresses vectorization as it historically understood. We did, however, learn that the “ordered scatter” rule in the first version of this paper is separable from the rest of the proposal in that some existing vector systems enforce ordered scatters whereas others do not. For this reason, we have labeled this rule as “optional” and would be willing to vote on it separately.

The remainder of this section is devoted to explaining our rationale for choosing the wavefront model over the explicit model for vector programming.

## The promise and disappointments of the explicit ordering-point model

Conceptually, the explicit ordering-point model is more like a parallel programming model than is the wavefront model. An ordering point would act similar to a software barrier, preventing code motion across the ordering point but allowing it between ordering points. Theoretically, less care to maintain lexical ordering would be needed in early phases of compilation thus permitting more liberal transformations.

As we analyzed this claim of better optimization, however, we discovered some issues. To be sure, there are situations where the claim is true, but there are situations where a naïve compiler could lose optimization opportunities because the ordering points are coarse-grained, and might need to be inserted in multiple places. It is possible to make the ordering points more precise, e.g., by specifying exactly the “to” and “from” points of inter-iteration dependencies. However, this would complicate the syntax in a way that we determined was too arcane and would discourage the use of vectorization.

Moreover, some expressions that are handled naturally in the wavefront model but are difficult to express using explicit ordering points. Assuming arrays A and B and loop control variable i, the expression,

A[i] = 2\*A[i + 1];

requires that A[1] in iteration 1 not be modified until its value has been read in iteration 0. With the explicit ordering-point model, an ordering point would need to be inserted between the read of A[i+1] and the modification of A[i]:

auto tmp = A[i + 1];

parallel::wavefront\_ordering\_pt();

A[i] = 2\*tmp;

Not only is the above workaround somewhat ugly and potentially error prone, but it show one of several warts that are exposed when the explicit ordering-point model is examined closely. It is not clear how many more such warts are necessary to express the entire body of vectorizable code.

Finally, the explicit model was touted as a way to express a form of parallelism more general than SIMD vectorization and software pipelining (e.g., a low-overhead parallelism that could be implemented on SIMT GPUs). While this idea has some merit, it is somewhat speculative at this point. It is not clear that the model is sufficiently rich to express the desired semantics. It is our opinion that a generalized low-overhead parallelism that can be implemented with multiple mechanisms (including SIMD) should be the subject of a future proposal, after the issues have been thoroughly explored, and with a couple of implementations. We should not hold up support for vectorization pending such exploration.

## Existing Practice

The wavefront model is a formalization of the model that has been used for SIMD and long-vector architectures for decades [1][2][2]. It has been analyzed and refined in the technical literature and it has been implemented in many compilers and in many programming languages including C, C++, and Fortran (via OpenMP as well as proprietary annotations).

The experts in vector programming are familiar with the wavefront model; to them, it’s what vector programming looks like. Even if we were to all agree that the explicit model is easier to learn than the wavefront model (and that is certainly not obvious), **we don’t want to standardize something that is hostile to experts**.

## Using vec with Other Algorithms

We considered applying vec to all algorithms in the Parallelism TS but we felt that it was not clear what that would mean and that assigning an arbitrary meaning would give the programmer a mistaken impression of usability. We might give vec a meaning to more algorithms in the future, if and when we identify a reasonable meaning for them.

## Ordered scatters

Previous revisions of this paper proposed a vec rule to ensure that “scatters” behave in a way consistent with serial semantics. For example, given:

void f() {

extern float A[], B[];

extern int P[], Q[];

for\_loop( vec, 0, 1000, [&](int i) {

A[P[i]] = B[Q[i]];

});

}

This “ordered scatter” rule would have ensured that the result is the same as for replacing vec with seq, even if there are duplicate values in array P. In contrast, this example has undefined behavior if unseq is used and P has duplicate values, even if all elements of B are identical, because there would be unsequenced modifications of the same element of A. The inclusion of this rule would have reduced the uses of ordered\_update and would have made it less likely to create program errors that result in undefined behavior. However, for architectures that support only unordered scatter instructions, the compiler would have to prove, for every store, that collisions are not possible in order to avoid serializing the store. Moreover, although ordered\_update would not have been needed for an assignment like the above, it would still be needed for read-modify-write operations (e.g., increment), so things like the histogram pattern would not have benefited from this rule. SG1 voted to remove this rule in at the 2016-02 meeting in Jacksonville.

# C++ Proposed Wording

The proposed edits are with respect to the current Parallelism TS assuming the adoption of P0075 and P0413.

## Feature test macros

Add the following row to Table 1 in section 1.5 [parallel.general.features]

|  |  |  |
| --- | --- | --- |
| **Name** | **Value** | **Header** |
| \_\_cpp\_lib\_experimental\_execution\_vector\_policy | 201606 | <experimental/algorithm> <experimental/execution> |

**Editorial note:** The format of this section of the TS should probably be changed to match that of the Library Fundamentals TS, which has a 6-column table that includes the name of the specific feature and the document number that proposed it.

## Header <experimental/execution> synopsis

Add the following to section 2.2 [parallel.execution.synopsis] (in nested namespace execution):

class vector\_policy;

class unsequenced\_policy;

## Add new execution policies

And add the following subsections:

**2.x Vector execution policy [parallel.execution.vec]**

class vector\_policy{ *unspecified* };

The class vector\_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, but must respect wavefront evaluation order.

**2.x Unsequenced execution policy [parallel.execution.unseq]**

class unsequenced\_policy{ *unspecified* };

The class unsequenced\_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.

## Execution policy objects

Add to [parallel.execution.objects] (in nested namespace execution):

constexpr vector\_policy vec{};

constexpr unsequenced\_policy unseq{};

## Exception reporting behavior

Edit 3.1 [parallel.exeptions.behavior] paragraph 2 as shown:

* If the execution policy object is of type class vector\_policy, unsequenced\_policy, or parallel\_unsequenced\_policy, std::terminate shall be called.

## Wavefront Application

New subsection to add to section 4.1. Shaded text is explanatory and not part of the formal wording.

**Wavefront Application [parallel.alg.general.wavefront]**

For the purpose of this section, an *evaluation* is a value computation or side effect of an expression, or an execution of a statement. Initialization of a temporary object is considered a subexpression of the expression that necessitates the temporary object.

An evaluation A *contains* an evaluation B if:

* A and B are not potentially concurrent ([intro.races]); and
* the start of A is the start of B or the start of A is sequenced before the start of B; and
* the completion of B is the completion of A or the completion of B is sequenced before the completion of A.

[*Note*: This includes evaluations occurring in function invocations. --  *end note*]

An evaluation A is *ordered before* an evaluation B if A is deterministically sequenced before B. [*Note:* If A is indeterminately sequenced with respect to B or A and B are unsequenced, then A is not ordered before B and B is not ordered before A. The ordered before relationship is transitive. – *end note*]

For an evaluation A ordered before an evaluation B, both contained in the same invocation of an element access function, A is a *vertical antecedent* of B if:

* there exists an evaluation S such that:
  + S contains A, and
  + S contains all evaluations C (if any) such that A is ordered before C and C is ordered before B,
  + but S does not contain B, and
* control reached B from A without executing any of the following:
  + a goto statement or asm declaration that jumps to a statement outside of S, or
  + a switch statement executed within S that transfers control into a substatement of a nested selection or iteration statement, or
  + a throw [*Note*: even if caught – *end note*], or
  + a longjmp.

[*Note*: Vertical antecedentis an irreflexive, antisymmetric, nontransitive relationship between two evaluations. Informally, A is a vertical antecedent of B if A is sequenced immediately before B or A is nested zero or more levels within a statement S that immediately precedes B – *end note*]

The first major bullet above describes what could informally be called “immediately precedes”. If A and B are part of the *same* statement, then A is a vertical antecedent of B only if there is nothing sequenced between them. If A and B are part of *different* statements, then A is a vertical antecedent of B if, by popping out zero or more levels of nesting, you find a point where the statement *containing* A immediately precedes B. This is the point of re-convergence after a control-flow divergence.

The second major bullet is needed to handle cases where re-convergence is difficult or impossible to establish. In those cases, the guarantees degenerate to those provided by the unsequenced\_policy until convergence is re-established at the end of the block containing both the jump statement and the jumped-to statement.

In the following, *X*i and *X*j refer to evaluations of the *same* expression or statement contained in the application of an element access function corresponding to the ith and jth elements of the input sequence. [*Note:* There might be several evaluations *X*k, Yk, etc. of a single expression or statement in application *k*, for example, if the expression or statement appears in a loop within the element access function. – *end note*]

*Horizontally matched* is an equivalence relationship between two evaluations of the same expression. An evaluation Bi is *horizontally matched* with an evaluation Bj if:

* both are the first evaluations in their respective applications of the element access function, or
* there exist horizontally matched evaluations Ai and Aj that are vertical antecedents of evaluations Bi and Bj, respectively.

[*Note*: *Horizontally matched* establishes a theoretical *lock-step* relationship between evaluations in different applications of an element access function. *– end note*]

The rules for establishing the horizontally matched relationship match evaluations in one application with corresponding evaluations in a separate application of the element access function. The nature of the rules are such that even nested loops work correctly. For example, given:

*b*;  
 while ( *e* )  
 *stmt*;  
 *c*;

where *bi* is horizontally matched with *bj*. Intuitively, we would expect the kth evaluation of *ei* to be horizontally matched with the kth evaluation of *ej*, assuming both evaluations happen. Even if one of the invocations executes *e* more times than the other, all evaluations of *ei* and *ej* are vertical antecedents of *ci* and *cj*, respectively, so the horizontally matched relationship is re-established for *ci* and *cj*.

Let *f* be a function called for each argument list in a sequence of argument lists. *Wavefront application* of *f* requires that evaluation Ai be sequenced before evaluation Bj if i < j and:

* Ai is sequenced before some evaluation Bi and Bi is horizontally matched with Bj, or
* Ai is horizontally matched with some evaluation Aj and Aj is sequenced before Bj.

[*Note:* *Wavefront application* guarantees that parallel applications i and j execute such that progress on application j never gets *ahead* of application i. – *end note*] [*Note:* The relationships between Ai and Bi and between Aj and Bj are *sequenced before*, not *vertical antecedent*. -- end note]

The two bullets describe the two triangles in Figure 1.

## Effect of execution policies on algorithm execution

To section 4.1.2 [parallel.alg.general.exec], add:

The invocations of element access functions in parallel algorithms invoked with an execution policy of type unsequenced\_policy are permitted to execute in an unordered fashion in the calling thread, unsequenced with respect to one another within the calling thread.

The invocations of element access functions in parallel algorithms invoked with an execution policy of type vector\_policy are permitted to execute in an unordered fashion in the calling thread, unsequenced with respect to one another within the calling thread, subject to the constraints of wavefront application (See 7.6 [parallel.alg.general.wavefront]) order for the last argument to for\_loop or for\_loop\_strided.

## Header <experimental/algorithm> synopsis

Add the following to 4.3.1 [parallel.alg.ops.synopsis]:

namespace std {

namespace experimental {

namespace parallel {

inline namespace v2 {

template<typename F>

auto no\_vec(F&& f) noexcept -> decltype(f());

template<class T>

class ordered\_update\_t;

template <class T>

ordered\_update\_t<T> ordered\_update(T& ref) noexcept;

}}}}

## no\_vec

Add this function to section 4.3 [parallel.alg.ops]:

**4.3.x No\_vec [parallel.alg.novec]**

template<typename F>

auto no\_vec(F&& f) noexcept -> decltype(f());

*Effects*: Evaluates std::forward<F>(f)(). If two calls to no\_vec are horizontally matched within a wavefront application of an element access function over input sequence S, then the evaluation of f() in the application for one element in S is sequenced before the evaluation f() in the application for a subsequent element in S; otherwise (for other execution policies) there is no effect on sequencing.

*Returns*: the result of the evaluation of f().

*Note:* If f() exits via an exception, then terminate will be called, consistent with all other potentially-throwing operations invoked within vector\_policy execution.

## ordered\_update

Add these subsections to section 4.3 [parallel.alg.ops]

**4.3.x Ordered update class [parallel.alg.ordupdate.class]**

template<class T>

class ordered\_update\_t {

T& ref; // exposition only

public:

ordered\_update\_t(T& loc) noexcept;

ordered\_update(const ordered\_update&) = delete;

template <class U>

auto operator=(U rhs) const noexcept;

template <class U>

   auto operator+=(U rhs) const noexcept;

template <class U>

   auto operator-=(U rhs) const noexcept;

template <class U>

   auto operator\*=(U rhs) const noexcept;

template <class U>

   auto operator/=(U rhs) const noexcept;

template <class U>

   auto operator%=(U rhs) const noexcept;

template <class U>

   auto operator>>=(U rhs) const noexcept;

template <class U>

   auto operator<<=(U rhs) const noexcept;

template <class U>

   auto operator&=(U rhs) const noexcept;

template <class U>

   auto operator^=(U rhs) const noexcept;

template <class U>

   auto operator|=(U rhs) const noexcept;

  auto operator++() const noexcept;

  auto operator++(int) const noexcept;

  auto operator--() const noexcept;

  auto operator--(int) const noexcept;

};

An object of type ordered\_update\_t<T> is a proxy for an object of type T intended to be used within a parallel application of an element access function using a policy object of type vector\_policy. Simple increments, assignments and compound assignments to the object are forwarded to proxied object, but are sequenced as though executed within a no\_vec invocation. [*Note*: The return-value deduction of the forwarded operations results in these operators returning by value, not reference. This formulation prevents accidental collisions on accesses to the return value. – *end note*]

ordered\_update\_t(T& loc) noexcept;

*Effect*: Initialize *ref* with loc.

template <class U>

auto operator=(U rhs) const noexcept;

*Effects:* equivalent to return no\_vec([&]{ return ref = std::move(rhs); })

template <class U>

auto operator+=(U rhs) const noexcept;

template <class U>

auto operator-=(U rhs) const noexcept;

template <class U>

auto operator\*=(U rhs) const noexcept;

template <class U>

auto operator/=(U rhs) const noexcept;

template <class U>

auto operator%=(U rhs) const noexcept;

template <class U>

auto operator>>=(U rhs) const noexcept;

template <class U>

auto operator<<=(U rhs) const noexcept;

template <class U>

auto operator&=(U rhs) const noexcept;

template <class U>

auto operator^=(U rhs) const noexcept;

template <class U>

auto operator|=(U rhs) const noexcept;

*Effects:* for the respective binary operator *op* (one of +, -, \*, /, %, >>, <<, &, ^, or |), equivalent to return no\_vec([&]{ return ref *op*= std::move(rhs); })

Editorial guidance needed from LWG:

1. Is the use of auto above the best way, or should we use auto with -> decltype(*expr*)? (Pablo had difficulty getting the decltype version working with clang, but is not sure if the problem was with the code or with the compiler.)
2. Is the description of the return value clear? Would it be better to break it out individually for each of the operators as in:

template <class U>

auto operator|=(U rhs) const noexcept;

*Effects:* equivalent to no\_vec([&]{ return ref |= std::move(rhs); })

Or even putting the definition in the synopsis:

template <class U>

auto operator|=(U rhs) const noexcept

{ return no\_vec([&]{ return ref |= std::move(rhs); }); }

My preferred formulation is the one current one, but Hans Boehm indicated a preference for the last one. I am concerned about verbosity and also about leaving out the word “equivalent”, since some architectures have instructions that allow, for example, ordered increment operations on a vector operand without serializing.

auto operator++() const noexcept;

*Effects:* equivalent to return no\_vec([&]{ return ++ref; })

auto operator++(int) const noexcept;

*Effects:* equivalent to return no\_vec([&]{ return ref++; })

auto operator--() const noexcept;

*Effects:* equivalent to return no\_vec([&]{ return --ref; })

auto operator--(int) const noexcept;

*Effects:* equivalent to return no\_vec([&]{ return ref--; })

**4.3.x Ordered update function template [parallel.alg.ordupdate.func]**

template <class T>

ordered\_update\_t<T> ordered\_update(T& ref) noexcept;

*Returns*: ordered\_update\_t<T>(ref)

# Acknowledgement

Olivier Giroux provided the ideas behind “horizontally matched” and “vertical antecedent”.

# References

1. [CONVEX Architecture Handbook](http://bitsavers.informatik.uni-stuttgart.de/pdf/convex/080-000120-000_CONVEX_Architecture_Handbook_1984.pdf), Document No. 080-000120-000, PDF page 222, implies that the scatter instruction has serial semantics.
2. Lee Higbie, [Vectorization and Conversion of Fortran Programs for the CRAY-1 (CFG) Compiler](http://bitsavers.informatik.uni-stuttgart.de/pdf/cray/CFT/2240207_Vectorization_and_Conversion_of_Fortran_Programs_for_the_CFT_Compiler.pdf), Undated, but seems to be from Cray-1 timeframe. PDF page 15 describes vectorization of a loop with a forward lexical dependence.
3. [Cray Assembly Language (CAL) for Cray X1 Systems Reference Manual, Section 2.6](http://docs.cray.com/books/S-2314-51/html-S-2314-51/x3724.html) says “Otherwise, the Cray X1 system guarantees that B will reference memory after A only if: ... A and B are elements of the same ordered vector scatter or zero-stride vector store.”
4. Michael Wolfe, “Loop Skewing: The Wavefront Method Revisited”, Int. J. of Parallel Programming 15(4), 1986, pp. 279-293.
5. Robert Geva and Clark Nelson, “Language Extensions for Vector loop level parallelism”, WG21 [N4237](http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2014/n4237.pdf).
6. Arch D. Robison, Pablo Halpern, Robert Geva and Clark Nelson, “Template Library for Index-Based Loops”, WG21 [P0075R1](http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2016/p0075r1.pdf).
7. Jared Hoberock (editor), “Working Draft, Technical Specification for C++ Extensions for Parallelism Version 2”, WG21 [N4578](http://www.open-std.org/JTC1/SC22/WG21/docs/papers/2016/n4578.html).
8. Pablo Halpern, “Updating Parallel Execution Policy Names in the Parallelism TS”, WG21 [P0413r0](http://www.open-std.org/JTC1/SC22/WG21/docs/papers/2016/p0413r0.pdf).

1. In particular, we implemented a performant version of vector reductions for for\_loop in LLVM by adding special intriniscs. [↑](#footnote-ref-2)
2. Yes, 9 and not 8. The wavefront semantics prevent the oldest iteration in flight from getting behind the newest iteration in flight. [↑](#footnote-ref-3)
3. The term “wavefront” for similar orderings has a long history in the field of vector and parallel programming. An example is Figure 7 from reference [4]. [↑](#footnote-ref-4)
4. The example is a toy, but the dependence pattern is similar to those in staggered finite-time finite-difference codes. [↑](#footnote-ref-5)