Atomic minimum/maximum

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1 Abstract

Add integer max and min operations to the set of operations supported in <atomic>. There are minor adjustments to function naming necessitated by the fact that max and min do not exist as infix operators.

2 Changelog

— Revision R5, published 2024-02-12
3 Introduction

This proposal extends the atomic operations library to add atomic maximum/minimum operations. These were originally proposed for C++ in [N3696] as particular cases of a general “priority update” mechanism, which atomically combined reading an object’s value, computing a new value and conditionally writing this value if it differs from the old value.

In revision R2 of this paper we have proposed atomic maximum/minimum operations where it is unspecified whether or not the store takes place if the new value happens to be the same as the old value. This has caused contention in LEWG, but upon further discussion in SG1 turned out to be unnecessary - as discussed in section 5.

4 Background and motivation

Atomic addition (fetch-and-add) was introduced in the NYU Ultracomputer [Gottlieb 1982], has been implemented in a variety of hardware architectures, and has been standardized in C and C++. Atomic maximum/minimum operations (fetch-and-max, fetch-and-min) have a history almost as long as atomic addition, e.g. see [Lipovski 1988], and have also been implemented in various hardware architectures but are not currently standard in C and C++. This proposal fills the gap in C++.
Atomic maximum/minimum operations are useful in a variety of situations in multithreaded applications:

— optimal implementation of lock-free shared data structures - as in the motivating example later in this paper
— reductions in data-parallel applications: for example, OpenMP supports maximum as a reduction operation
— recording the maximum so far reached in an optimization process, to allow unproductive threads to terminate
— collecting statistics, such as the largest item of input encountered by any worker thread.

Atomic maximum/minimum operations already exist in several other programming environments, including OpenCL, and in some hardware implementations. Application need, and availability, motivate providing these operations in C++.

The proposed language changes add atomic max/min to <atomic> for builtin types, including integral and pointer (but not floating point).

5 The problem of conditional write

The existing atomic operations (e.g. fetch_and) have the effect of a read-modify-write, irrespective of whether the value changes. This is how atomic max/min are defined in several APIs (OpenCL, CUDA, C++AMP, HCC) and in several hardware architectures (ARM, RISC-V). However, some hardware (POWER) implements atomic max/min as an atomic read-and-conditional-store. If we look at an example CAS-loop implementation of this proposal, it is easy to see why such read-and-conditional-store can be more efficient.

Following the discussion in SG1 the authors are convinced that a similar implementation can be conforming, with some adjustments (example presented in 5.3), without the catch all wording such as “it is unspecified whether or not the store takes place”.

Note

Example polyfill implementations listed below rely on a simple helper function whose task is to adjust memory_order to make it a valid operand for the load operations:

```cpp
constexpr inline memory_order drop_release(memory_order m) noexcept {
    return (m == memory_order_release ? memory_order_relaxed
            : ((m == memory_order_acq_rel || m == memory_order_seq_cst) ? memory_order_acquire
                : m));
}
```

5.1 Example CAS-loop implementation with read-and-conditional-store

This implementation skips writes entirely if pv is already equal to max(v, t). It does not conform with the read-modify-write semantics, which this paper proposes:

```cpp
template <typename T>
T atomic_fetch_max_explicit(atomic<T>* pv,
    typename atomic<T>::value_type v,
    memory_order m) noexcept {
    auto const mr = drop_release(m);
    auto t = pv->load(mr);
    while (max(v, t) != t) {
        if (pv->compare_exchange_weak(t, v, m, mr))
            break;
    }
    return t;
}
```
5.2 Example CAS-loop implementation with read-modify-write

This implementation is performing an unconditional store, which means all writers need exclusive cache line access. Although conforming with the read-modify-write semantics, this may result in excessive writer contention:

```cpp
template <typename T>
T atomic_fetch_max_explicit(atomic<T>* pv,
    typename atomic<T>::value_type v,
    memory_order m) noexcept {
    auto const mr = drop_release(m);
    auto t = pv->load(mr);
    while (!pv->compare_exchange_weak(t, max(v, t), m, mr))
        ;
    return t;
}
```

5.3 Example improved CAS-loop implementation with read-modify-write

This implementation is based on read-and-conditional-store, with an added extra step to ensure that a store does take place at least once, if required:

— if the user requested memory order is not a release, then store is not required
— otherwise, add a dummy write such as fetch_add(0, m) and use its result.

This is demonstrated below:

```cpp
template <typename T>
T atomic_fetch_max_explicit(atomic<T>* pv,
    typename atomic<T>::value_type v,
    memory_order m) noexcept {
    auto const mr = drop_release(m);
    auto t = (mr != m) ? pv->fetch_add(0, m) : pv->load(mr);
    while (max(v, t) != t) {
        if (pv->compare_exchange_weak(t, v, m, mr))
            return t;
    }
    return t;
}
```

A subtle difference between this and the previous implementation is that, in this case, an extra “dummy” store can take place. The authors argue that this difference in behaviour is unobservable in the standard C++ memory model.

Similarly, given an architecture which implements atomic minimum/maximum in hardware with read-and-conditional-store semantics, a conforming read-modify-write fetch_max() can be implemented with very little overhead.

For this reason and for consistency with all other atomic instructions, we have decided to use read-modify-write semantics for the proposed atomic minimum/maximum.

6 Infix operators in <atomic> and min/max

The current <atomic> provides atomic operations in several ways:

— as a named non-member function template e.g. atomic_fetch_add returning the old value
— as a named member function template e.g. atomic<T>::fetch_add() returning the old value
— as an overloaded compound operator e.g. atomic<T>::operator+=() returning the new value
Adding ‘max’ and ‘min’ versions of the named functions is straightforward. Unlike the existing atomics, max/min operations exist in signed and unsigned flavors. The atomic type determines the operation. There is precedent for this in C, where all compound assignments on atomic variables are defined to be atomic, including sign-sensitive operations such as divide and right-shift.

The overloaded operator `atomic<T>::operator key = (n)` is defined to return the new value of the atomic object. This does not correspond directly to a named function. For `max` and `min`, we have no infix operators to overload. So if we want a function that returns the new value we would need to provide it as a named function. However, for all operators the new value can be obtained as `fetch_key(n) key n`, (the standard defines the compound operator overloads this way) while the reverse is not true for non-invertible operators like ‘and’ or ‘max’.

Thus new functions returning the new result would add no significant functionality other than providing one-to-one equivalents to `<atomic>` existing compound operator overloads. Revision R2 of this paper tentatively suggested such functions, named `replace_key` (following some of the early literature on atomic operations - [Kruskal 1986] citing [Draughon 1967]). Having discussed this in SG1, the authors have decided not to propose addition of extra functions and correspondingly they have been removed in revision R3. This same result can be obtained by the user with a simple expression such as `max(v.fetch_max(x), x)` or `min(v.fetch_min(x), x)`.

During the discussion in SG1, it was suggested that a new paper could be written proposing `key_fetch` functions returning new values. This is not such a paper.

7 Motivating example

Atomic fetch-and-max can be used to implement a lockfree bounded multi-consumer, multi-producer queue. Below is an example based on [Gong 1990]. Note, the original paper assumed existence of `EXCHANGE` operation which in practice does not exist on most platforms. Here this was replaced by a two-step read and write, in addition to translation from C to C++. For this reason the correctness proof from [Gong 1990] does not apply.

```cpp
template <typename T, size_t Size>
struct queue_t {
    static_assert(std::is_nothrow_default_constructible_v<T>);
    static_assert(std::is_nothrow_copy_constructible_v<T>);
    static_assert(std::is_nothrow_swappable_v<T>);

    using elt = T;
    static constexpr int size = Size;

    struct entry {
        elt item {};
        // a queue element
        std::atomic<int> tag {-1};
        // its generation number
    };

    entry elts[size] = {};
    // a bounded array
    std::atomic<int> back {-1};

    friend void enqueue(queue_t& queue, elt x) noexcept {
        int i = queue.back.load() + 1; // get a slot in the array for the new element
        while (true) {
            // exchange the new element with slots value if that slot has not been used
            int empty = -1;
            // expected tag for an empty slot
            auto& e = queue.elts[i % size];
            // use two-step write: first store an odd value while we are writing the new element
            if (std::atomic_compare_exchange_strong(&e.tag, &empty, (i / size) * 2 + 1)) {
                using std::swap;
                swap(x, e.item);
                e.tag.store((i / size) * 2); // done writing, switch tag to even (ie. ready)
            }
        } // done writing, switch tag to even (ie. ready)
    }
};
```
break;
}
++i;
}
std::atomic_fetch_max(&queue.back, i); // reset the value of back
}

friend auto dequeue(queue_t & queue) noexcept -> elt {
while (true) {
  // keep trying until an element is found
  int range = queue.back.load(); // search up to back slots
  for (int i = 0; i <= range; i++) {
    int ready = (i / size) * 2; // expected even tag for ready slot
    auto & e = queue.elts[i % size];
    // use two-step read: first store -2 while we are reading the element
    if (std::atomic_compare_exchange_strong(&e.tag, &ready, -2)) {
      using std::swap;
      elt ret{};
      swap(ret, e.item);
      e.tag.store(-1); // done reading, switch tag to -1 (ie. empty)
      return ret;
    }
  }
}
};

8 Implementation experience

The required intrinsics have been added to Clang.

9 Benchmarks

We have implemented benchmark bench and made it available on [Github].

— bench is finding a maximum value from a PRNG. We were able to achieve acceptably low standard deviation of results for this test. The selected PRNG is a linear distribution 2e9 wide, using 10'000 PRNG samples per run. In this benchmark, the fetch_max updates were relatively infrequent.

We have measured the nanosecond time of different implementations of:

atomic_fetch_max_explicit(&max, i, std::memory_order_acquire)

where i is generated by a PRNG. The benchmarks capture the cost of contention to max from varying number of cores. The benchmarks were run on AWS EC2 instance type c7g.16xlarge (i.e. 64 cores ARMv8.4 Graviton3 CPU). The machine was running Linux kernel 6.1 and was configured for complete isolation of cores 1-63. We used core 0 only when running the benchmark across all 64 cores, in which case the samples from this core were dropped (to avoid the noise caused by the normal operating system operation).

The benchmark parameters were:

— -m 0.5 : maximum std. deviation for PRNG cost calibration
— -i 1e6 : number of iterations (this translates to 100 runs, each sampling the PRNG 10'000 times)

The table below compares two fetch_max implementations:

— -t t : CAS-loop based algorithm presented in 5.3 (we call it “smart”)
During benchmarking, we have observed that the time of read-and-conditional-store CAS-loop algorithm (as presented in 5.2, we call it “weak” in the benchmarks) was almost immeasurable, irrespective of the number of cores. We explain this by how rarely the PRNG sampling benchmark updates the max value. Similarly the “smart” algorithm with std::memory_order_release had shown to be very fast, irrespective of the number of cores.

10 Note on pointer operations

It was pointed out that the semantics of pointer operations is not clear in the revision 3 of this paper. The new wording in revision 4 makes it clear that the new atomic operations perform computation as-if by max and min algorithms, which also work on pointers if these point the same complete object (or array), see [expr.rel] remark 4. The intent is to give fetch_max and fetch_min the same semantics, including the requirements.

This is in apparent divergence from other atomic operations which are guaranteed not to create undefined behaviour (e.g. “If the result is not a representable value for its type (7.1), the result is unspecified, but the operations otherwise have no undefined behavior.” for floating point and “The result may be an undefined address, but the operations otherwise have no undefined behavior.” for pointers). Note that fetch_max and fetch_min in principle do not create new values as opposed to other atomic functions; the result of the function is either an old value of the atomic object or a new value, as provided by the caller. Hence there’s less demand for an “escape clause” for potentially “undefined address” (there likely isn’t one).

If this proposal is accepted and we gain more experience with existing implementations of fetch_max and fetch_min, plausibly an “escape clause” similar to ones quoted above might be added in the future revisions of C++ e.g. by allowing comparison of unrelated pointers. At this moment we aren’t certain that such hypothetical clause would be implementable; furthermore a user with a need for such operation could use conversion to and from uintptr_t instead (and deal with the fallout of using resulting pointer).

11 Note on floating point operations

Following the discussion in Varna ’23 plenary, also carried on the reflector, the authors decided to remove the proposed fetch_min and fetch_max from the floating point specializations (that is, proposed wording in sections [atomics.types.float] and [atomics.ref.float]).

Floating point types do not receive the same treatment in std::min and std::max as other types do (due to the presence of NaN values and signed zero), hence they would have to be either defined using different means, or at the very least worded differently. Since there already is implementation experience regarding the use of std::fmin and std::fmax in atomic operations on floating point numbers, and a new paper [P3008] is being...
prepared to propose the relevant addition in the standard, trying to nail down the semantics based on `std::min` and `std::max` in this proposal seems counterproductive.

## 12 Acknowlegements

This paper benefited from discussion with Mario Torrecillas Rodriguez, Nigel Stephens, Nick Maclaren, Olivier Giroux, Gašper Ažman and Jens Maurer.

## 13 Changes to the C++ standard

The following text outlines the proposed changes, based on [N4917].

### 17 Language support library [support]

#### 17.3 Implementation properties [support.limits]

#### 17.3.2 Header `<version>` synopsis

*Add feature test macro:*

```cpp
#define __cpp_lib_atomic_min_max 202XXXL // also in <atomic>
```

### 33 Concurrency support library [thread]

#### 33.5 Atomic operations [atomics]

#### 33.5.2 Header `<atomic>` synopsis [atomics.syn]

*Add following functions, immediately below `atomic_fetch_xor_explicit`:*

```cpp
namespace std {
  // 33.5.9, non-member functions
  ...

  template<class T>
  T atomic_fetch_max(volatile atomic<T>*,
                     typename atomic<T>::value_type) noexcept;

  template<class T>
  T atomic_fetch_max(atomic<T>*,
                     typename atomic<T>::value_type) noexcept;

  template<class T>
  T atomic_fetch_max_explicit(volatile atomic<T>*,
                               typename atomic<T>::value_type,
                               memory_order) noexcept;

  template<class T>
  T atomic_fetch_max_explicit(atomic<T>*,
                            typename atomic<T>::value_type,
                            memory_order) noexcept;

  template<class T>
  T atomic_fetch_min(volatile atomic<T>*,
                     typename atomic<T>::value_type) noexcept;

  template<class T>
  T atomic_fetch_min(atomic<T>*,
                     typename atomic<T>::value_type) noexcept;

  template<class T>
  T atomic_fetch_min_explicit(volatile atomic<T>*,
                             typename atomic<T>::value_type,
                             memory_order) noexcept;

  template<class T>
  T atomic_fetch_min_explicit(atomic<T>*,
                           typename atomic<T>::value_type,
                           memory_order) noexcept;

  ...

```
```cpp
T atomic_fetch_min_explicit(atomic<T>*, // freestanding
typename atomic<T>::value_type,
memory_order) noexcept;
...
}

33.5.7 Class template atomic_ref [atomics.ref.generic]

33.5.7.3 Specializations for integral types [atomics.ref.int]

— Add following public functions, immediately below `fetch_xor`:

```cpp
namespace std {
    template <> struct atomic_ref<integral> {
        ...
        integral fetch_max(integral, memory_order = memory_order::seq_cst) const noexcept;
        integral fetch_min(integral, memory_order = memory_order::seq_cst) const noexcept;
        ...
    };
}

— Change remark 6:

Remarks: Except for `fetch_max` and `fetch_min`, for signed integer types, the result is as if the object value and parameters were converted to their corresponding unsigned types, the computation performed on those types, and the result converted back to the signed type.

[Note 2: There are no undefined results arising from the computation. — end note]

— Add remark 7 immediately below:

Remarks: For `fetch_max` and `fetch_min`, the maximum and minimum computation is performed as if by `max` and `min` algorithms [alg.min.max], respectively, with the object value and the first parameter as the arguments.

— Bump existing remarks below new remark 7

33.5.7.5 Partial specialization for pointers [atomics.ref.pointer]

— Add following public functions, immediately below `fetch_sub`:

```cpp
namespace std {
    template <class T> struct atomic_ref<T *> {
        ...
        T* fetch_max(T *, memory_order = memory_order::seq_cst) const noexcept;
        T* fetch_min(T *, memory_order = memory_order::seq_cst) const noexcept;
    };
}

— Add remark 7 with note 1 immediately below remark 6:

Remarks: For `fetch_max` and `fetch_min`, the maximum and minimum computation is performed as if by `max` and `min` algorithms [alg.min.max], respectively, with the object value and the first parameter as the arguments.

[Note 1: If the pointers point to different complete objects (or subobjects thereof), the `<` operator does not establish a strict weak ordering ([tab:cpp17.lessthancomparable],[expr.rel]) — end note]

— Bump existing remarks below new remark 7

33.5.8 Class template atomic [atomics.types.generic]

33.5.8.3 Specializations for integers [atomics.types.int]
— Add following public functions, immediately below `fetch_xor`:

```cpp
namespace std {
    template <> struct atomic<integral> {
        ...
        integral fetch_max(integral, memory_order = memory_order::seq_cst) volatile noexcept;
        integral fetch_max(integral, memory_order = memory_order::seq_cst) noexcept;
        integral fetch_min(integral, memory_order = memory_order::seq_cst) volatile noexcept;
        integral fetch_min(integral, memory_order = memory_order::seq_cst) noexcept;
        ...
    };
}
```

— In table 146, [tab:atomic.types.int.comp], add the following entries (note empty “Op” column):

<table>
<thead>
<tr>
<th>key</th>
<th>Op</th>
<th>Computation</th>
</tr>
</thead>
<tbody>
<tr>
<td>max</td>
<td></td>
<td>maximum</td>
</tr>
<tr>
<td>min</td>
<td></td>
<td>minimum</td>
</tr>
</tbody>
</table>

— Change remark 8:

Remarks: For except for `fetch_max` and `fetch_min`, for signed integer types, the result is as if the object value and parameters were converted to their corresponding unsigned types, the computation performed on those types, and the result converted back to the signed type.

[Note 2: There are no undefined results arising from the computation. — end note]

— Add remark 9 immediately below:

Remarks: For `fetch_max` and `fetch_min`, the maximum and minimum computation is performed as if by `max` and `min` algorithms [alg.min.max], respectively, with the object value and the first parameter as the arguments.

— Bump existing remarks below new remark 9

33.5.8.5 Partial specialization for pointers [atomics.types.pointer]

— Add following public functions, immediately below `fetch_sub`:

```cpp
namespace std {
    template <class T> struct atomic<T*> {
        ...
        T* fetch_max(T*, memory_order = memory_order::seq_cst) volatile noexcept;
        T* fetch_max(T*, memory_order = memory_order::seq_cst) noexcept;
        T* fetch_min(T*, memory_order = memory_order::seq_cst) volatile noexcept;
        T* fetch_min(T*, memory_order = memory_order::seq_cst) noexcept;
        ...
    };
}
```

— In table 147, [tab:atomic.types.pointer.comp], add the following entries (note empty “Op” column):

<table>
<thead>
<tr>
<th>key</th>
<th>Op</th>
<th>Computation</th>
</tr>
</thead>
<tbody>
<tr>
<td>max</td>
<td></td>
<td>maximum</td>
</tr>
<tr>
<td>min</td>
<td></td>
<td>minimum</td>
</tr>
</tbody>
</table>
9 Remarks: For fetch_max and fetch_min, the maximum and minimum computation is performed as if by max and min algorithms [alg.min.max], respectively, with the object value and the first parameter as the arguments.

[Note 2: If the pointers point to different complete objects (or subobjects thereof), the < operator does not establish a strict weak ordering ([tab:cpp17.lessthancomparable],[expr.rel]) – end note]

Bump existing remarks below new remark 9

14 References

https://nyuscholars.nyu.edu/en/publications/programming-considerations-for-parallel-computers

https://github.com/Bronek/wg21-p0493


https://dl.acm.org/doi/10.1145/48022.48024


https://wg21.link/n3696

https://wg21.link/n4901

https://wg21.link/n4917

https://wg21.link/p3008