The Upcoming Concurrency TS Version 2 for Low-Latency and Lockless Synchronization

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**Agenda**

1. Don’t we already have a Concurrency TS?
   - Why do we need a new one?
   - Implementation status

2. TS2 Hazard Pointer
   - How I learn to love C++ tricks

3. TS2 RCU
   - From C to C++ in 2500 days
Concurrency TS1: Don’t we already have a TS?

- Produced in 2015
- Produced by the Concurrency Study Group (SG1) with input from LEWG, LWG
- Separate document and is not part of ISO C++ Standard
- Goal: Eventual Inclusion into ISO C++ Standard
- Available online: http://wg21.link/n4538
- github: https://github.com/cplusplus/concurrency-ts
What was in Concurrency TS1?

- Improvements to std::future
- Latches and Barriers
- Atomic smart pointers

Join Example (Homogeneous)

```cpp
vector<future<int>> futures;
future<vector<future<int>>> ready =
    when_all(futures.begin(), futures.end());

ready.then([](future<vector<future<int>>> result) {
    vector<future<int>> v = result.get();
    for(auto& f : v) {
        assert(f.is_ready());
    }
});
```
Since Concurrency TS1?

- Improvements to std::future: some adapted into C++ 17
- Latches and Barriers: Adapted into C++ 20
- Atomic smart pointers: Adapted into C++17

WITHDRAWN
Talking about HP and RCU since 2014

1. Erwin Schrödinger’s Zoo and Werner Heisenberg’s advice
2. Increase uncertainty to get performance and scalability
3. So Procrastinate away! Use Structured Deferral
4. Shared_ptr vs atomic_shared_ptr vs hazard pointers vs Read Copy Update (RCU)
5. Hazard Pointers
6. Read Copy Update
7. A Concurrency Toolkit for C++
Since 2014, slow as we need to do C++17, 20

• But also we need to learn how to convert from C to C++ interface
• learn new and interesting C++ idioms
• learn new Library conventions
• work with tight schedule
• grow older, kids graduate
• changed jobs, company
To TS or not to TS: that is the question

Whether 'tis nobler in the mind to suffer. The slings and arrows of outrageous fortune, Or to take arms against a sea of troubles. And by opposing end them.
The role of TSes from P0939/P2000 Directions

We recommend

- Use TSs for library components.
- Don’t use TSs for a language feature unless the feature is a mostly self-contained unit.
- Don’t use a TS simply to delay; it doesn’t simplify later decision making. Have a concrete and articulated criteria for completion.

WG 21 Direction Group
TS vs IS: question TS should answer

- Is there an implementation?
- Is it a Library or Language proposal, or involve both aspects?
- Is the proposal a foundational proposal, meaning many other C++ aspects/proposal depend on it, and/or it depends on many other C++ aspects/proposals?
- Is it independent of aspects of the language.
- Are there competing design proposals?
- Is the proposal complicated or large that you fear there will be error in design decision?
- Is it a research idea?
- Is there substantial invention?
- Can it be staged?
- Is there a subpart that deserves to be in IS?
- Is the wording complicated or unconventional?

- Will the proposal benefit from early integration (can be applied to a WP)?
- Will you get feedback/testing only after TS publication or IS publication?
- Is there a motivation to slow down a proposal?
- Explicitly state the acceptance criteria for the TS into IS?
- Are you juggling a large number of related or dependent proposals (other proposals that depend on this proposal)?
- Are you aiming for user feedback?
- Are you aiming for implementation feedback?
- Is there a scheduling concern to make C++xx for it or its dependents?
Proposal for DG advisory

- WGs SGs decide on TS or IS route and write proposal supporting direction
- The key question:
  - WHAT ARE we hoping to LEARN through a TS must be clearly specified.
  - WHAT ARE the exit criteria of the TS to IS must be clearly specified.
- Other questions should be asked will follow to support your conclusion.
- The previous page are questions the DG may ask. And you should think about.
- We urge SGs to explicitly poll for this and their supporting reasons
- DG will offer non-binding advisory in some cases as
  - whether TS or IS route is preferred, or have you considered an SG
  - In some cases an SG vs TS vs IS continuum needs to be considered
- Please weigh our opinion as part of your decision process
- direction@lists.isocpp.org.
What is in Concurrency TS2?

• Several synchronization primitives for locked-free programming on concurrent data structures. These are cell, hazard ptr and RCU. These extend the existing shared_ptr and the proposed atomic_shared_ptr which all have safe reclamation facilities. As such we also propose moving shared_ptr and atomic<shared<ptr>> to this new location. We suspect this part may be controversial, so would ask for discussion on this topic.

• P1122R4 - Proposed Wording for Concurrent Data Structures: Read-Copy-Update (RCU)
Concurrent TS2 in future

Concurrent TS2 is an ongoing WIP but might contain the following which has been making its way through WG21/SG1:

- Data structures such as Concurrent queues, counters,
- Asymmetric fences
- What about executors?

Plan to be in cpluplus github

- [https://github.com/cplusplus/concurrency-ts2](https://github.com/cplusplus/concurrency-ts2)

Become an IS

- Will it still look like the TS?
33: Concurrency Utilities Library

33.1 General Concepts
- 33.1.1 Thread Support
- 33.1.2 Executor Support

33.2 Safe Reclamation
- 33.2.1 Hazard Pointers
- 33.2.2 RCU
- 33.2.3 Latest/Snapshot?
- 33.2.4 Asymmetric fences
To learn or not to learn?

• What did we learn?
• What were the exit criteria?
• What is the exit vehicle?
• Will it still look like the TS in the IS (exit vehicle)?
• What is there still to learn?
• When will we stop learning?
• What is implementation status?
• Did the TS process work for us?
Hazard Pointers in Concurrency TS2, C++26, and beyond
Hazard Pointers in a Nutshell

Used to protect access to objects that may be concurrently removed.

A hazard pointer is a single-writer multi-reader pointer.

If a hazard pointer points to an object before its removal, then the object will not be reclaimed as long as the hazard pointer remains unchanged.

Features:

- Fast and scalable protection
- Supports arbitrarily long protection

Protect object A
Set a hazard pointer to point to A if A is not removed then it is safe to use A

Remove and reclaim object A
Remove A if no hazard pointers point to A then it is safe to reclaim A
Hazard Pointers TS2 Interface

Components:
- Hazard pointers
- Objects protectable by hazard pointers
- Domain(s) to manage hazard pointers and retired objects
class hazard_pointer_domain {
public:
    hazard_pointer_domain() noexcept;
    explicit hazard_pointer_domain(pmr::polymorphic_allocator<byte> poly_alloc) noexcept;
    hazard_pointer_domain(const hazard_pointer_domain&) = delete;
    hazard_pointer_domain& operator=(const hazard_pointer_domain&) = delete;
    ~hazard_pointer_domain();
};

hazard_pointer_domain& hazard_pointer_default_domain() noexcept;

// For synchronous reclamation
void hazard_pointer_clean_up(hazard_pointer_domain& domain = hazard_pointer_default_domain()) noexcept;
template <typename T, typename D = default_delete<T>>
class hazard_pointer_obj_base {
    public:
        void retire(
            D d = D(),
            hazard_pointer_domain& domain = hazard_pointer_default_domain()) noexcept;
    void retire(hazard_pointer_domain& domain) noexcept;
};
class hazard_pointer {
public:
    hazard_pointer() noexcept; // Empty
    hazard_pointer(hazard_pointer&&) noexcept;
    hazard_pointer& operator=(hazard_pointer&&) noexcept;
    ~hazard_pointer();
    [[nodiscard]] bool empty() const noexcept;
    template <typename T> T* protect(const atomic<T*>& src) noexcept;
    template <typename T> bool try_protect(T* & ptr, const atomic<T*>& src) noexcept;
    template <typename T> void reset_protection(const T* ptr) noexcept;
    void swap(hazard_pointer&) noexcept;
};

hazard_pointer make_hazard_pointer(hazard_pointer_domain& domain = hazard_pointer_default_domain());

void swap(hazard_pointer&, hazard_pointer&) noexcept;
Usage Example

class Foo : public hazard_pointer_obj_base<Foo> { /* Foo members */ }; 

void read_and_use(const std::atomic<Foo*>& src, Func fn) { // Called frequently  
    hazard_pointer h = make_hazard_pointer();  
    Foo* ptr = h.protect(src);  
    fn(ptr); // ptr is protected 
}

void update(std::atomic<Foo*>& src, Foo* newptr) { // Called infrequently  
    Foo* oldp.ptr = src.exchange(newptr);  
    oldp.ptr->retire(); 
}
What Did We Learn in 4 Years?

• **Open source:** github.com/facebook/folly under synchronization/Hazptr.h

• **Synchronous reclamation:**
  • TS2 global cleanup is a powerful but blunt tool.
  • Folly (fast and scalable) cohort synchronous reclamation.
  • **CPPCON 2021:** Hazard pointer synchronous reclamation beyond Concurrency TS2

• **Integrated link counting:**
  • Not in TS2. Folly support for linked structures with immutable links (e.g., queues).
    Can reclaim nodes of arbitrary depth in one check of hazard pointers.

• **Hazard pointers arrays optimizations**
  • Not in TS2. Folly make_hazard_pointer_arrray<M>(), e.g., 4, 5, 6 ns vs 4, 8, 12 ns

• **Optional dedicated thread pool for asynchronous reclamation:**
  • Robustness against latency spikes and deadlock.

• **Domains:**
  • Robust default domain with expanded capabilities (cohorts, link counting, array optimization).
  • No customization needed in Folly so far.
Hazard Pointers Proposal for C++26

Minimalist useful subset of TS2:
- Supports asynchronous reclamation
- Compatible with external link counting and automatic retirement
- Strict subset of TS2 API and wording
- No custom domains (for now)
- No synchronous reclamation (for now)
- Can be extended
class hazard_pointer_domain {
public:
    hazard_pointer_domain() noexcept;
    explicit hazard_pointer_domain(
        pmr::polymorphic_allocator<byte> poly_alloc) noexcept;
    hazard_pointer_domain(const hazard_pointer_domain&) = delete;
    hazard_pointer_domain& operator=(const hazard_pointer_domain&) = delete;
    ~hazard_pointer_domain();
};

hazard_pointer_domain& hazard_pointer_default_domain() noexcept;

// For synchronous reclamation
void hazard_pointer_clean_up(
    hazard_pointer_domain& domain = hazard_pointer_default_domain()) noexcept;
template <typename T, typename D = default_delete<T> >
class hazard_pointer_obj_base {
public:
    void retire(
        D d = D(),
        hazard_pointer_domain& domain = hazard_pointer_default_domain()) noexcept;
    void retire(hazard_pointer_domain& domain) noexcept;
};
class hazard_pointer {
   public:
      hazard_pointer() noexcept; // Empty
      hazard_pointer(hazard_pointer&&) noexcept;
      hazard_pointer& operator=(hazard_pointer&&) noexcept;
      ~hazard_pointer();
      [[nodiscard]] bool empty() const noexcept;
      template <typename T> T* protect(const atomic<T*>& src) noexcept;
      template <typename T> bool try_protect(T*& ptr, const atomic<T*>& src) noexcept;
      template <typename T> void reset_protection(const T* ptr) noexcept;
      void reset_protection(nullptr_t = nullptr) noexcept;
      void swap(hazard_pointer&) noexcept;
   }

hazard_pointer make_hazard_pointer(
   hazard_pointer_domain& domain = hazard_pointer_default_domain());

void swap(hazard_pointer&, hazard_pointer&) noexcept;
Hazard Pointers Proposal for C++26

template <typename T, typename D = default_delete<T>>
class hazard_pointer_obj_base {
  public:
    void retire(D d = D()) noexcept;
  
  class hazard_pointer {
    public:
      hazard_pointer() noexcept; // Empty
      hazard_pointer(hazard_pointer&&) noexcept;
      hazard_pointer& operator=(hazard_pointer&&) noexcept;
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      template <typename T> void reset_protection(const T* ptr) noexcept;
      void reset_protection(nullptr_t = nullptr) noexcept;
      void swap(hazard_pointer&) noexcept;
    
    hazard_pointer make_hazard_pointer();
    
    void swap(hazard_pointer&, hazard_pointer&) noexcept;
  };

hazard_pointer make_hazard_pointer();
Hazard Pointers Beyond C++26

- Hazard pointer array optimization
  - In heavy use in Folly for ~4 years. Simple.
- Synchronous reclamation
  - Folly cohort synchronous reclamation: In heavy use in Folly for 3+ years.
  - Global cleanup as in TS2?
  - Other variations?
  - CPPCON 2021: Hazard pointer synchronous reclamation beyond Concurrency TS2
- Integrated link counting
  - In heavy use in Folly for ~4 years. Formal wording may not be simple.
- Domains:
  - Custom domain allocators as in TS2?
  - WiredTiger Feedback: Separate checking protection from reclamation.
  - Folly experience: Robust default domain. No custom domains needed so far.
RCU in Concurrency TS 2
C++ RCU: A Learning Experience

My previous C++ project had been in 1990

My initial attempt at RCU bindings in C++ thus used “virtual”

This resulted in some pointed feedback
Again With Curiously Recurring Template Pattern

Diagnostic-driven development leads to this dubious code:

```cpp
struct foo: std::rcu_obj_base<foo> {
    int a;
};
```

Actually, RCU will be in an experimental namespace rather than std::, but I am being optimistic!
Again With Curiously Recurring Template Pattern

Diagnostic-driven development leads to this dubious code:

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    int a;
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```

But it compiles?
Again With Curiously Recurring Template Pattern

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```cpp
struct foo: std::rcu_obj_base<foo> {
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But it compiles? And it works???
Again With Curiously Recurring Template Pattern

Diagnostic-driven development leads to this dubious code:

```cpp
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    int a;
};
```

But it compiles? And it works???

The magic of CRTP!!!
Mutually Assured Education

- My knowledge of C++ was and is limited
- Others’ knowledge of RCU was and is limited
- Therefore, lots of discussion and code samples
  - https://github.com/paulmckrcu/RCUCPPbindings Test/paulmck
  - Many thanks to my many teachers, especially those who taught in code:
    - Arthur J. O’Dwyer, Daisy Hollman, and Izzy Muerte
- And lots of discussions afterwards
  - Too many to fit on a slide, but see authors and contributors to many papers
A Little Bike-Shedding Along the Way

Wikimedia Commons User SeppVei
A Little Bike-Shedding Along the Way

- `template<T>` replaced museum-piece abstract classes ;-)
- `synchronize_rcu()` to `rcu_synchrnoize()` for consistency
- RAII: `rcu_reader` to a `Cpp17BasicLockable rcu_domain`
- Deleters may be invoked directly from a `retire` call
  - Late-breaking news: May need to inform users of this (more on this later)
- Non-intrusive `rcu_retire()` (now in Linux kernel...)


RCU RAII Readers

- As C++ developers might expect:

```cpp
void an_rcu_reader()
{
    do_something_before_reader();
    std::unique_lock<std::rcu_domain> rdru(std::rcu_default_domain());
    do_something_within_reader();
}

void wait_for_rcu_readers()
{
    rcu_synchronize();
}
```
As RCU users might expect:
RCU RAII Readers

• As C++ developers might expect, but more succinctly:

```cpp
void an_rcu_reader()
{
    do_something_before_reader();
    std::unique_lock<std::rcu_domain> rdru();
    do_something_within_reader();
}
```

• Except that not all the world can live within the confines of an RCU RAII reader...
RCU Non-RAII Readers

• And another fine example of diagnostic-driven development!

• Function to start an RCU reader:

```cpp
std::unique_lock<std::rcu_domain> start_deferred_reader()
{
    std::unique_lock<std::rcu_domain> new_rdr(std::rcu_default_domain());
    return std::move(new_rdr);
}
```

• Function to end an RCU reader:

```cpp
void end_deferred_reader(std::unique_lock<std::rcu_domain> old_rdr)
{
}
Invoking RCU Non-RAII Readers

• Whenever the spirit std::move()s you:

```cpp
void an_rcu_reader()
{
    do_something_before_reader();
    auto rdr = std::move(start_deferred_reader()); // rcu_read_lock();
    do_something_within_reader();
    end_deferred_reader(std::move(rdr));           // rcu_read_unlock();
    do_something_after_reader();
}
```

• But why not just add a pair of curly braces???
Why RCU Non-RAII Readers?

Diagram showing the structure of RCU with a root node, internal nodes, and leaf objects, each with a lock.
Why RCU Non-RAII Readers?

- Use RCU to protect a search structure, and locking on objects

```cpp
void update_object(int key) {
    auto rdr = std::move(start_deferred_reader()); // rcu_read_lock();
    auto p& = find_object(key);
    if (needs_update(p)) {
        std::lock_guard<std::mutex> guard(p.objmutex);
        end_deferred_reader(std::move(rdr)); // rcu_read_unlock();
        if (needs_update(p))
            do_rcu_unsafe_locked_update(p);
    } else {
        end_deferred_reader(std::move(rdr)); // rcu_read_unlock();
    }
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    }
}
```
What Future Learnings Might There Be?

• QEMU developers’ on deleters being invoked from `rcu_retire()`:
  • Don’t do that!!! We hate the resulting deadlocks!!!
What `rcu_retire()` deadlocks???

• If any lock is acquired by any deleter, that lock cannot be held across any call to `.retire()` or `rcu_retire()`!

```cpp
void hapless_retire_invoker(Foo *p)
{
    std::lock_guard<std::mutex> guard(mymutex);
    rcu_retire(p);
    // Which might invoke deleters.
    // And if any of those deleters acquire mymutex, game over!!!
}
```
What Future Learnings Might There Be?

• QEMU developers’ on deleters being invoked from rcu_retire():
  • Don’t do that!!! We hate the resulting deadlocks!!!
  • But some environments don’t have much choice
  • Perhaps a static function? If it returns false, no such deadlocks!
    
    ```cpp
    bool rcu_deleters_from_retire(rcu_domain& dom = rcu_default_domain()) noexcept;
    ```
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• Additional unique_lock/lock_guard constructors for RCU?
• Some users might want a rough count of outstanding deleters
• Multiple instances of rcu_domain? Later...
• And there is still memory_order_consume...
What Future Learnings Might There Be?

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• Additional unique_lock/lock_guard constructors for RCU?
• Some users might want a rough count of outstanding deleters
• Multiple instances of rcu_domain? Later...
• And there is still memory_order_consume...
• None of which are on critical path to IS
Final Words
The IRONY: it is not lost on us SG1 Concurrency SG will have 2 concurrency TSes in the github repository concurrently
What is in Concurrency TS2?

• Several synchronization primitives for locked-free programming on concurrent data structures. These are cell, hazard ptr and RCU. These extend the existing shared_ptr and the proposed atomic_shared_ptr which all have safe reclamation facilities. As such we also propose moving shared_ptr and atomic<shared<ptr>> to this new location. We suspect this part may be controversial, so would ask for discussion on this topic.

• P1122R4 - Proposed Wording for Concurrent Data Structures: Read-Copy-Update (RCU)
BACKUP