Read-Copy Update (RCU)

Authors:
Paul McKenney, Michael Wong, Maged M. Michael, Andrew Hunter, Daisy Hollman, JF Bastien, Hans
Boehm, David Goldblatt, Frank Birbacher, Erik Rigtorp, Tomasz Kamiński, Olivier Giroux, David Vernet,
Timur Doumler

e-mail:
paulmckrcu@gmail.com, michael@codeplay.com, maged.michael@acm.org, andrewwhunter@gmail.com,
dhollman@google.com, cxx@jfbastien.com, hboehm@google.com, davidtgoldblatt@gmail.com,
frank.birbacher@gmail.com, erik@rigtorp.se, tomaszkam@gmail.com, ogiroux@apple.com, dvernet@meta.com,
papers@timur.audio
## Contents

1 **Introduction** 1
   1.1 Proposed Entry to C++26 IS ................................. 1
   1.2 Feature-Test Macro ........................................ 3
   1.3 Comparison Tables ......................................... 3
   1.4 History ..................................................... 5
   1.5 Source-Code Access ........................................ 8
   1.6 Acknowledgments .......................................... 10

2 **Safe reclamation** 11
   2.1 General ..................................................... 11
   2.2 Read-copy update (RCU) ................................. 12
1 Introduction

We propose RCU for inclusion into C++26. This paper contains proposed rationale to support RCU into C++26 as well as the interface and wording for RCU, a technique for safe deferred reclamation. We further propose that the wording in Section 2.2 be adopted as a new “Safe reclamation” chapter of the IS, and we anticipate that hazard pointers would be covered by another section of this same chapter.

The purpose of adding RCU to the IS is to provide a small number of known-good implementations of RCU in standard libraries. RCU is easy to get wrong, and one purpose standard libraries is to provide good implementations of things that are easy to get wrong.

1.1 Proposed Entry to C++26 IS

A near-superset of this proposal is implemented in the Folly RCU library. This library has been used in production for several years, so we have good implementation experience for the proposed variant of RCU.

This proposal is identical to that in Concurrency TS 2. We expect that the proposal in Concurrency TS 2 will change over time, for example, adding some of the features that are present in the Folly RCU library or in the Linux kernel. Such features might include:

1. Multiple RCU domains. For example, SRCU provides these in the Linux kernel. However, RCU was in the Linux kernel for four years before this was needed, so it is not in this proposal for C++26.

2. Special-purpose RCU implementations. For example, the Linux kernel has specialized implementations for preemptible environments, single-CPU systems, as well as additional implementations required by the Linux kernel’s tracing and extended Berkeley Packet Filter (eBPF) use cases. However, none of these seem applicable to userspace applications, so none of them are in this proposal for C++26.

3. Polling grace-period-wait APIs. These allow non-blocking algorithms to interface with RCU grace periods, for example, in the Linux kernel, they allow NMI handlers to do RCU updates. (NMI handlers could do RCU readers from the get-go.) However, RCU was in the Linux kernel for more than a decade before such APIs were needed, so they are not in this proposal for C++26.

4. Async-friendly APIs for RCU’s blocking APIs. These might leverage the aforementioned polling APIs. However, more work is required to determine exactly what support is required, so they are not in this proposal for C++26. In the meantime, async code can avoid rcu_synchronize() in favor of rcu_retire(), with the scheduled deleter interacting as needed with async. Although there is no similar asynchronous variant of rcu_barrier(), one could be created if it is shown to be useful. One reason for doubting its utility is that rcu_barrier() tends to be used for cleanup operations.

5. A free function similar to rcu_retire() that uses an rcu_obj_base if available, but which invokes rcu_retire() if not. (Suggested by Tomasz Kamiński.) However, this facility has not yet been spotted in the wild, so it is not in this proposal for C++26.

6. A memory allocator might be supplied for the use of rcu_retire(). Please note that if different allocators can be supplied to different calls to rcu_retire(), then there must be a way to tag the allocated memory with the corresponding deleter. However, this facility has not yet been spotted in the wild, so it is not in this proposal for C++26.

In the meantime, users needing full control over memory allocation can use the rcu_obj_base class’s .retire() member function. With this intrusive approach, RCU need never allocate memory.

In their turn, library implementers have a number of rcu_retire() memory-provisioning strategies at their disposal given the current RCU API proposed for C++26:

a) Never allocate. Instead, on each call to rcu_retire(), invoke rcu_synchronize() then invoke the deleter.

b) Preallocate at least two blocks of memory, each containing some reasonable number of slots to record retired objects awaiting deletion. Each block must also inherit from rcu_obj_base. Fill in slots of the current block until either it fills, memory runs low, or some reasonable period of time has elapsed, then pass that block to .retire(). Switch to the next block. When a given block’s deleter is invoked, in turn invoke the deleter on each slot and then make the block available for
use by subsequent `rcu_retire()` invocations. If `rcu_retire()` runs out of blocks, fall back to strategy #a.

c) Proceed as in strategy #b, but if `rcu_retire()` runs out of blocks, allocate some more. If memory allocation fails, fall back to strategy #a.

d) Proceed as in strategy #c, but free blocks if a glut builds up.

e) Proceed as in strategy #d, but free each block within its deleter.

7. APIs could be provided to allow the user control over when deleters are scheduled and in what context they are invoked. Possibilities for this control include special worker threads, a “perform RCU reclamation now” function, use of timer handlers, or use of non-thread executors. In the meantime, implementations can choose to invoke deleters from `rcu_synchronize()` and `rcu_barrier()`. They may also choose to invoke deleters from `.retire()` and `rcu_retire()`, but doing so restricts users from acquiring a given resource when invoking these functions that is also acquired in a deleter passes to either of these functions. However, there is very little implementation experience with such a facility, with the only C++ example being the Folly library, which permits an executor to be associated with a newly created `rcu_domain`, which the Folly library provides as an extension to the functionality proposed for initial standardization. This facility is thus not included in this proposal for C++26.

8. Memory-allocator interfaces providing RCU-mediated typesafe memory could be provided similar to the Linux kernel’s `SLAB_TYPESAFE_BY_RCU`. In this scheme, an object from such an allocator can be freed and reallocated immediately, even in presence of pre-existing region of RCU protection. However, given such a region, such an object cannot be reallocated as some other type. The object can change type only after all pre-existing regions of RCU protection complete. The readers must do some sort of verification, for example, mediated by reference counting, locking, or sequence locking. However, a C++ implementation of this facility has not yet been spotted in the wild, so it is not in this proposal for C++26.

9. In order to wait for all pre-existing regions of RCU protection, the implementation must find them all. There are a number of ways of doing this, including: (1) Having `rcu_domain::lock` make the running thread known to RCU if it is not already known (used by one of the userspace RCU implementations), (2) Providing some means for iterating over all threads (used by some Linux-kernel RCU flavors), and (3) Using a hashing or sharding technique to track readers independently of the running threads (used by some textbook implementations adapted for small constrained systems). One alternative not explicitly supported by this initial proposal is to provide thread-registration API members. There is implementation experience with this technique, for example, the C-language userspace RCU provide `rcu_register_thread()` and `rcu_unregister_thread()` to cause userspace RCU’s grace-period computation to start or stop paying attention to the calling `std::thread`, respectively. However, the only C++ implementation experience that we are aware of is in the Folly library. This facility is thus not included in this proposal for C++26, however, later proposals might draw on additional Folly-library experience over time.

10. Numerous efficiency-oriented APIs. For but one example, the Linux kernel has an alternative `rcu_access_pointer()` that can be used in place of `rcu_dereference()` (Linux-kernelese for “consume load”) when the resulting pointer will not be dereferenced (for example, when it is only going to be compared to `NULL`). But it is not clear which (if any) of these would be accepted into the Linux kernel today, given the properties of modern computer hardware. Therefore, these are not in this proposal for C++26.

11. A future version of the standard might say something about memory-leak detectors. In the meantime, an RCU user can ensure clean shutdown as follows:

   a) Ceasing to invoke both `.retire()` and `rcu_retire()`.

   b) Invoking `rcu_barrier()`.

Implementations wishing to assist users in this task may invoke `rcu_barrier()` before destructing the default `rcu_domain` object, but after destructing all user objects. Any standard-library invocations of `.retire()` and `rcu_retire()` would also need to be carried out before destructing the default `rcu_domain` object. Users of implementations that do not assist in this manner should further refrain from invoking either `.retire()` or `rcu_retire()`, whether directly or indirectly, from the destructor of a global static object.
Table 1: High-Level Comparison of Deferred-Reclamation Techniques

<table>
<thead>
<tr>
<th>Property</th>
<th>Reference Counting</th>
<th>Hazard Pointers</th>
<th>RCU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Readers</td>
<td>Slow and unscalable</td>
<td>Fast and scalable</td>
<td>Fast and scalable</td>
</tr>
<tr>
<td>Unreclaimed Objects</td>
<td>Bounded</td>
<td>Bounded</td>
<td>Unbounded</td>
</tr>
<tr>
<td>Traversal Retries?</td>
<td>If object deleted</td>
<td>If object deleted</td>
<td>Never</td>
</tr>
<tr>
<td>Reclamation latency?</td>
<td>Fast</td>
<td>Slow</td>
<td>Slow</td>
</tr>
</tbody>
</table>

Table 2: Comparison Table for Reader-Writer Locking and Intrusive RCU

```cpp
With Reader-Writer Locking
struct Data /* members */;
Data* data_;
std::shared_mutex m_;

template <typename Func>
Result reader_op(Func fn) {
    std::shared_lock<std::shared_mutex> l(m_);
    Data* p = data_;
    // fn should not block too long or call update()
    return fn(p);
}

// May be called concurrently with reader_op
void update(Data* newdata) {
    Data* olddata;
    { std::unique_lock<std::shared_mutex> llock(m_);
      olddata = std::exchange(data_, newdata);
    }
    delete olddata; // reclaim *olddata immediately
}
```

```cpp
With RCU in the intrusive style
struct Data : std::rcu_obj_base<Data> /* members */;
std::atomic<Data*> data_;

template <typename Func>
Result reader_op(Func fn) {
    std::scoped_lock l(std::rcu_default_domain());
    Data* p = data_;
    // fn should not block too long or call
    // rcu_synchronize(), rcu_barrier(), or
    // rcu_retire(), directly or indirectly
    return fn(p);
}

// May be called concurrently with reader_op
void update(Data* newdata) {
    Data* olddata = data_.exchange(newdata);
    olddata->retire(); // reclaim *olddata when safe
}
```

Of course, those wanting clean shutdown should avoid the rare but real use case in which an evaluation
scheduled by `.retire()` or `rcu_retire()` unconditionally schedules another evaluation, and so on
indefinitely. Such use cases should instead include some mechanism that prevents subsequent invocations
of `.retire()` and `rcu_retire()` before the shutdown-time call to `rcu_barrier()`.

The snapshot library described in P0561R5 (“RAII Interface for Deferred Reclamation”) provides an easy-to-
use deferred-reclamation facility applying only to a single object which is intended to be based upon either
RCU or Hazard Pointers. It cannot replace either RCU or Hazard Pointers.

The Hazard Pointers library is described in P2530R3 (“Hazard Pointers for C++26”). As a very rough rule
of thumb, Hazard Pointers can be considered to be a scalable replacement for reference counters and RCU
can be considered to be a scalable replacement for reader-writer locking. A high-level comparison of reference
counting, Hazard Pointers, and RCU is displayed in Table 1.

Note that we are making this working paper available before Concurrency TS2 been published, which some
might feel is unconventional. On the other hand, Paul was asked to begin this effort in 2014, it is now 2022,
and C++ implementations have been used in production for some time, perhaps most notably the Folly RCU
library.

### 1.2 Feature-Test Macro

We propose a new feature-test macro `__cpp_lib_rcu` be added to Section 17.3.2 of the IS.

### 1.3 Comparison Tables

Although RCU can be applied to a great many use cases, its most common use case is as a replacement for
reader-writer locking. The reader-writer usage patterns most susceptible to conversion to RCU are those
where a value is computed while read-holding that lock, then used after releasing that same lock.
With Reader-Writer Locking

```cpp
struct Data /* members */ ;
Data* data_;  
std::shared_mutex m_;  
```

template<typename Func>
```cpp
Result reader_op(Func fn)  
std::shared_lock<std::shared_mutex> l(m_);  
Data* p = data_;  
// fn should not block too long or call update()  
return fn(p);  
```

// May be called concurrently with reader_op
```cpp
void update(Data* newdata)  
Data* olddata;  
std::unique_lock<std::shared_mutex> wlock(m_);  
olddata = std::exchange(data_, newdata);  
delete olddata;  // reclaim *olddata immediately
```  

Table 3: Comparison Table for Reader-Writer Locking and Non-Intrusive RCU

With RCU in the non-intrusive style

```cpp
struct Data /* members */ ;
std::atomic<Data*> data_;  
```

template<typename Func>
```cpp
Result reader_op(Func fn)  
std::scoped_lock l(std::rcu_default_domain());  
Data* p = data_;  
// fn should not block too long or call  
// rcu_synchronize(), rcu_barrier(), or  
// rcu_retire(), directly or indirectly  
return fn(p);  
```

// May be called concurrently with reader_op
```cpp
void update(Data* newdata)  
Data* olddata = data_.exchange(newdata);  
std::rcu_retire(olddata);  // reclaim *olddata when safe
```  

With RCU in the synchronous style

```cpp
struct Data /* members */ ;
std::atomic<Data*> data_;  
```

template<typename Func>
```cpp
Result reader_op(Func fn)  
std::scoped_lock l(std::rcu_default_domain());  
Data* p = data_;  
// fn should not block too long or call  
// rcu_synchronize(), rcu_barrier(), or  
// rcu_retire(), directly or indirectly  
return fn(p);  
```

// May be called concurrently with reader_op
```cpp
void update(Data* newdata)  
Data* olddata = data_.exchange(newdata);  
std::rcu_synchronize();  // wait until it’s safe  
delete olddata;  // then reclaim *olddata
```  

Table 4: Comparison Table for Reader-Writer Locking and Synchronous RCU

Table 2 compares reader-writer locking and intrusive RCU, that is, when the RCU-protected data items inherit from `std::rcu_obj_base<T>` and use the `~retire()` member function.

Table 3 compares reader-writer locking and non-intrusive RCU, that is, when the RCU-protected data items do not inherit from `std::rcu_obj_base<T>` and instead use the `std::rcu_retire()` free function.

Table 4 compares reader-writer locking and synchronous RCU, that is, when the RCU updater does an explicit wait for readers. When using this style, RCU-protected data items need not inherit from `std::rcu_obj_base<T>`.  

§ 1.3
1.4 History

More detailed history may be found here: https://github.com/paulmckrcu/wg21-rcu-C-26.git.

1.4.1 Changes From D2545R4 to P2545R4

These changes were requested at the March 8, 2023 Library Working Group teleconference:

— Correct the name of P2530R3 to “Hazard Pointers for C++26” (but on own volition).
— Add a 2.2.4.1 section to avoid a hanging paragraph.
— Change 2.2.4.3 immutable name from [safercl.rcu.domain.nonmembers] to [safercl.rcu.domain.func].
— Eliminate the “Updater free function” section in favor of pulling rcu_synchronize, rcu_barrier, and rcu_retire into 2.2.4.3.
— Adjust section references, including refactoring the history list for the March 1, 2023 Library Working Group teleconference to be less dependent on low-level \LaTeX labels.

1.4.2 Changes From P2545R3 to D2545R4

These changes were requested at the March 1, 2023 Library Working Group teleconference:

— Title changed from “Why RCU Should be in C++26” to “Read-Copy Update (RCU)”.
— Guessed at the updated title for the hazard-pointers paper.
— Added a detailed change history for the February 8, 2023 Library Working Group review at the Issaquah meeting.
— 2.2.1p2: Added “it has” to produce “... and that base is public and non-virtual, and it has no base classes of type ...”
— 2.2.3p8: Changed “deleter” to italized fixed font to indicate an expository identifier. Also changed “if that evaluation throws an exception” to “if that evaluation exits via an exception”.
— 2.2.4:
  — Add try_lock() in order to meet the requirements of Cpp17Lockable instead of Cpp17BasicLockable.
  This change allows the user to add RCU readers to a list of locks that are to be acquired in a deadlock-free manner. This is strictly a convenience to the user (RCU readers cannot deadlock).
  — Change “the function lock” to just “lock”.
  — Change “the function unlock” to just “unlock”.
  — Change “the default object” to “a static-duration object”.
  — Add a note stating that neither of rcu_synchronize and rcu_barrier imply the other.
  — Refactor the mandates, preconditions (AKA expects), and effects clauses for rcu_retire.
  — Rely on common Library wording to avoid special rcu_retire wording for bad_alloc subclasses.

1.4.3 Changes From P2545R2 to P2545R3

Most of these changes were motivated by an LWG review of parallel sections of P2530R3 (“Hazard Pointers for C++26”) that was carried out at the 2023 Issaquah meeting.

— Editorial updates.
— Add additional non-normative user advice for use of memory-leak detectors.
— Add non-normative user advice for interacting with async code.
— Use immutable references to sections of the IS.
— Remove “A client-supplied template argument” from the description of rcu_obj_base. (Given that D is a parameter, it is clearly supplied by the client.)
— Add the other five constructors, assignment operators, and destructor to rcu_obj_base.
— Expand the point about parameter T being an incomplete type to include the fact that it must be complete before any resulting specialization of rcu_obj_base is referenced.
— Move the point about .retire(), .unlock(), and rcu_retire() invoking scheduled evaluations from remarks to normative text. The point about potential deadlock remains in a non-normative note.
— Convert from \( L' \) and \( U' \) to \( L2 \) and \( U2 \), respectively.
— Note that \texttt{rcu\_obj\_base} must be non-virtual.
— Updates based on February 8 LWG review:
  — 2.2.1p3.1: Added a comma.
  — 2.2.1p6: Deleted “such” from “any other such scheduled evaluation”.
  — 2.2.3: Remove “\texttt{const}” in order to produce a valid move constructor and a valid move-assignment operator.
  — Moved 2.2.3p1 and 2.2.3p3 to follow 2.2.3p4, so that these became 2.2.3p3, 2.2.3p4, and 2.2.3p2, respectively.
  — 2.2.3p7: Removed “The expression \texttt{deleter(addressof(x))} has well-defined behavior and does not throw an exception.”
  — 2.2.3p8: Added “the behavior is undefined if that evaluation throws an exception”.
  — Note 1 following 2.2.3p8: Put “retire” into code font.

These changes nevertheless need LWG review, given that there might be both typos and subtle differences between hazard pointers and RCU that require different modifications to the RCU paper.

1.4.4 Changes From P2545R1 to P2545R2
— Prototype a private constructor for \texttt{rcu\_domain} in response to guidance during 2022 Kona LEWG review. (Minor wording change.)
— Record straw polls from 2022 Kona LEWG review and from September 2022 virtual LEWG review.
— Update “Tony Tables” to “Comparison Tables” in response to guidance during 2022 Kona LEWG review.
— Mention a number of longer-term possible changes:
  — Provide means for user to control the context in which deleters are invoked and the timing of their invocation.
  — RCU-mediated typesafe memory, perhaps similar to the Linux kernel’s \texttt{SLAB\_TYPESAFE\_BY\_RCU}.
  — Manual thread registration for threads other than \texttt{std::thread}, in response to discussions during 2022 Kona LEWG review.
  — Give user and implementer advice on \texttt{rcu\_retire()} metadata handling.
  — Interactions with memory-leak detectors.

1.4.5 Kona 2022
This paper updates P2545R1 based on discussions in LEWG and offline at the Kona meeting. Notes may be found here:
— https://docs.google.com/document/d/1QWFqwcJ6W2Q0Yr0ofyigU6Ej-XiNLQfTuTuf_6PZLZk/edit#
— https://github.com/cplusplus/papers/issues/1206#issuecomment-1310849132

LEWG straw polls were as shown in the following sections.

1.4.5.1 Poll 1
Remove the defaulted \texttt{rcu\_domain} parameter from \texttt{rcu\_synchronize}, \texttt{rcu\_barrier}, \texttt{rcu\_retire}, and \texttt{rcu\_obj\_base::retire}.

\begin{tabular}{|c|c|c|c|c|}
\hline
SF & F & N & A & SA \\
\hline
4 & 5 & 12 & 1 & 0 \\
\hline
\end{tabular}

Attendance: 23 (in-person) + 7 (online)
# of Authors: 2
Author Position: 2 x N
Outcome: No consensus
1.4.5.2 Poll 2
Remove `rcu_domain` (but keep `rcu_default_domain` that returns a BasicLockable object).

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
<td>8</td>
<td>1</td>
<td>7</td>
</tr>
</tbody>
</table>

Attendance: 22 (in-person) + 7 (online)
# of Authors: 2
Author Position: 2 x WA
Outcome: No consensus

1.4.5.3 Poll 3
Send P2545R1 (why RCU should be in C++26) to Library for C++26 classified as B3 - addition, to be confirmed with a Library Evolution electronic poll.

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>7</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Attendance: 25 (in-person) + 7 (remote)
# of Authors: 2
Author Position: 2 x SF
Outcome: Consensus
Statement from “weakly against” voter: I want to get rid of the object and have a private constructor. (Addressed by making the constructor private.)

1.4.5.4 Action Items
— Add a section discussing thread registration (done).
— Get feedback from implementers.
— Bikeshed `rcu_obj_base`.
— Make `rcu_domains` constructor private (done).

1.4.6 September 20 2022 LEWG Teleconference
This paper updates P2545R0 based on discussions at LEWG and offlist. Notes may be found here:
— https://wiki.edg.com/bin/view/Wg21telecons2022/P2545?twiki_redirect_cache=93b9b23e9c2596b6802a09fd3b3f
— https://github.com/cplusplus/papers/issues/1206#issuecomment-1256428844

1.4.6.1 Poll
RCU should target the International Standard instead of the Concurrency Technical Specification v2.

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>7</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Attendance: 25
# of Authors: 4
Author Position: 4 x SF
Outcome: Consensus in favor.
Statements from “weakly against” voters:
— More fleshed out motivation could change my “A” to “F”.
— More evidence of existing practice might change my mind.
Added motivation and existing practice to address these statements.

1.4.7 Changes From P2545R0 to P2545R1
These changes to P2545R0 resulted in P2545R1, based on discussions in virtual SG1 and LEWG meetings:
— Add “Tony Tables” for intrusive, non-intrusive, and synchronous use cases.
— Switch from experimental to `std::` namespace.
— Provide rationale for adding RCU to the IS.
— Add a feature-test macro.
— Add a list of C++ RCU implementations.
— Add Fedor Pikus quote about large concurrent applications and inadvertent uses of RCU.
— Add a list of publications showing performance benefits of RCU.
— Mention a number of longer-term possible changes:
  — Async-friendly RCU APIs.
  — A free function similar to \texttt{rcu_retire()} that uses an \texttt{rcu_obj_base} if available and invokes \texttt{rcu_retire()} if not.

1.4.8 Older History
This paper updates P2545R0 based on discussions in SG1 and LEWG.
P2545R0 was derived from N4895, which was in turn based on P1122R4.
P1122R4 is a successor to the RCU portion of P0566R5, in response to LEWG’s Rapperswil 2018 request that the two techniques be split into separate papers.

This is proposed wording for Read-Copy-Update [P0461], which is a technique for safe deferred resource reclamation for optimistic concurrency, useful for lock-free data structures. Both RCU and hazard pointers have been progressing steadily through SG1 based on years of implementation by the authors, and are in wide use in MongoDB (for Hazard Pointers), Facebook, and Linux OS (RCU).

We originally decided to do both papers’ wording together to illustrate their close relationship, and similar design structure, while hopefully making it easier for the reader to review together for this first presentation. As noted above, they have been split on the committee’s request.

This wording is based P0566r5, which in turn was based on that of on n4618 draft [N4618].

1.5 Source-Code Access
This section presents C++ reference implementations, other C++ implementations, additional implementations and use cases, and performance implications.

Counting the two reference implementation, this section points out eleven implementations of RCU-like mechanisms in C++.

1.5.1 Reference C++ Implementations
The Folly library is open source, and its RCU implementation may be accessed here:

There is an additional reference implementation of this proposal. Unlike the Folly library’s version, this reference implementation is not production quality. However, it is quite a bit simpler, having delegated the difficult parts to the C-language userspace RCU library:
— https://github.com/paulmck/rcu/RCUCPPbindings/tree/master/Test/paulmck
— https://librcu.org

1.5.2 Other C++ Implementations
Maxim Khizhinsky added a C++ implementation of RCU to his libcds around 2017. URL: https://github.com/khizmax/libcds/tree/master/cds/urcu

Avi Kivity added a C++ implementation of RCU to the OSv kernel in 2010. URL: https://github.com/cloudius-systems/osv/blob/master/include/osv/rcu.hh

Google uses an internally developed C++ RCU implementation alluded to by Andrew Hunter’s and Geoffrey Romer’s P0561 C++ working paper. This implementation makes use of restartable sequences in addition to facilities defined in the standard. URL: https://www.open-std.org/jtc1/sc22/wg21/docs/papers/2020/p0561r5.html

Isaac Gelado and Michael Garland describe use of a CUDA/C++ RCU in GPU programming in their 2019 PPoPP paper entitled “Throughput-Oriented GPU Memory Allocation”. URL: https://dl.acm.org/doi/10.1145/3293883.3295727

In 2016, Pedro Ramalhete and Andreia Correia produced a C++ prototype implementation of RCU in the ConcurrencyFreaks GitHub repository. URL: https://github.com/pramalhe/ConcurrencyFreaks/tree/master/Cpp/papers/gracesharingurcu This appeared in the August 2017 issue of ACM SIGPLAN Notices. URL: https://dl.acm.org/doi/abs/10.1145/3155284.3019021

Peter Goodman produced a prototype C++ implementation of RCU in his GitHub repository in 2012. URL: https://github.com/pgoodman/rcu


Gamsa et al. describe an RCU-like implementation within the Tornado and K42 research operating systems, both of which were coded in C++. Sections 5.2 and 5.3 of their 1999 OSDI paper entitled “Tornado: Maximizing Locality and Concurrency in a Shared Memory Multiprocessor Operating System” gives an overview of their RCU-like mechanism for providing what they call “existence guarantees”. URL: https://www.usenix.org/legacy/events/osdi99/full_papers/gamsa/gamsa.pdf

There are implementations of RCU-like mechanisms in proprietary applications, but these cannot be divulged to the committee without the permission of their respective copyright holders. However, in the words of Fedor Pikus:

> In fact, you may already be using the RCU approach in your program without realizing it! Wouldn’t that be cool? But careful now: you may be already using the RCU approach in your program in a subtly wrong way. I’m talking about the kind of way that makes your program pass every test you can throw at it and then crash in front of your most important customer (but only when they run their most critical job, not when you try to reproduce the problem).

URL: https://cppcon2017.sched.com/event/BgtF/read-copy-update-then-what-rcu-for-non-kernel-programmers

With these words, Fedor has pinpointed a major motivation for adding RCU to the C++ standard: To provide a smaller number of known-good RCU implementations to C++ users.

### 1.5.3 Other Use Cases

The C-language userspace RCU library appeared around 2009. The QEMU project created its own version of this library in 2015. URL: https://liburcu.org

A list of additional RCU implementations in a variety of languages may be found in Sections 9.5.5, 9.5.5.2, and 9.6.3.3 of “Is Parallel Programming Hard, And, If So, What Can You Do About It?”. URL: https://kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook-e2.pdf

RCU is used heavily in the Linux kernel:


### 1.5.4 Performance Implications

RCU provides the best results in read-mostly situations involving linked data structures, and is most often used as a replacement for reader-writer locking. Experience in the Linux kernel indicates that well over half of the situations to which reader-writer locking is applied can be handled by RCU. RCU has provided orders-of-magnitude performance and scalability improvements in many situations, a few of which are listed below:

1. https://lwn.net/Kernel/Index/#Read-copy-update
5. https://www.linuxjournal.com/article/6993
9. https://docs.google.com/document/d/1X0lThx80K0ZgLmVoXiR4Zr0URHrXK6NyLRbeX3Xac/edit?usp=sharing

Additional information may be found in Section 9.5.4 of the aforementioned “Is Parallel Programming Hard, And, If So, What Can You Do About It?”.

1.6 Acknowledgments

We owe special thanks to Jens Maurer, Arthur O’Dwyer, and Geoffrey Romer for their many contributions to this effort.
2 Safe reclamation

2.1 General

This clause adds safe-reclamation techniques, which are most frequently used to straightforwardly resolve access-deletion races.
2.2 Read-copy update (RCU) [safercrl.rcu]

2.2.1 General [safercrl.rcu.general]

1 RCU is a synchronization mechanism that can be used for linked data structures that are frequently read, but seldom updated. RCU does not provide mutual exclusion, but instead allows the user to schedule specified actions such as deletion at some later time.

2 A class type \( T \) is \textit{rcu-protectable} if it has exactly one base class of type \textit{rcu_obj_base}<\( T, D \)> for some \( D \), and that base is public and non-virtual, and it has no base classes of type \textit{rcu_obj_base}<\( X, Y \)> for any other combination \( X, Y \). An object is rcu-protectable if it is of rcu-protectable type.

3 An invocation of \textit{unlock} \( U \) on an \textit{rcu_domain} \( \text{dom} \) corresponds to an invocation of \textit{lock} \( L \) on \( \text{dom} \) if \( L \) is sequenced before \( U \) and either

\( (3.1) \) — no other invocation of \textit{lock} on \( \text{dom} \) is sequenced after \( L \) and before \( U \), or

\( (3.2) \) — every invocation of \textit{unlock} \( U_2 \) on \( \text{dom} \) such that \( L \) is sequenced before \( U_2 \) and \( U_2 \) is sequenced before \( U \) corresponds to an invocation of \textit{lock} \( L_2 \) on \( \text{dom} \) such that \( L \) is sequenced before \( L_2 \) and \( L_2 \) is sequenced before \( U_2 \).

[Note 1: This pairs nested locks and unlocks on a given domain in each thread. — end note]

4 A \textit{region of RCU protection} on a domain \( \text{dom} \) starts with a \textit{lock} \( L \) on \( \text{dom} \) and ends with its corresponding \textit{unlock} \( U \).

5 Given a region of RCU protection \( R \) on a domain \( \text{dom} \) and given an evaluation \( E \) that scheduled another evaluation \( F \) in \( \text{dom} \), if \( E \) does not strongly happen before the start of \( R \), the end of \( R \) strongly happens before evaluating \( F \).

6 The evaluation of a scheduled evaluation is potentially concurrent with any other scheduled evaluation. Each scheduled evaluation is evaluated at most once.

2.2.2 Header \texttt{<rcu>} synopsis [safercrl.rcu.syn]

```cpp
namespace std {
  // 2.2.3, class template rcu_obj_base
  template<class T, class D = default_delete<T>>
  class rcu_obj_base;

  // 2.2.4, class rcu_domain
  class rcu_domain;
  rcu_domain& rcu_default_domain() noexcept;
  void rcu_synchronize(rcu_domain& dom = rcu_default_domain()) noexcept;
  void rcu_barrier(rcu_domain& dom = rcu_default_domain()) noexcept;
  template<class T, class D = default_delete<T>>
  void rcu_retire(T* p, D d = D(), rcu_domain& dom = rcu_default_domain());
}
```

2.2.3 Class \texttt{rcu_obj_base} [safercrl.rcu.base]

Objects of type \( T \) to be protected by RCU inherit from a specialization of \texttt{rcu_obj_base}<\( T, D \)>.

```cpp
template<class T, class D = default_delete<T>>
class rcu_obj_base {
  public:
    void retire(D d = D(), rcu_domain& dom = rcu_default_domain()) noexcept;
  protected:
    rcu_obj_base() = default;
    rcu_obj_base(const rcu_obj_base&) = default;
    rcu_obj_base(rcu_obj_base&&) = default;
    rcu_obj_base& operator=(const rcu_obj_base&) = default;
    rcu_obj_base& operator=(rcu_obj_base&&) = default;
    ~rcu_obj_base() = default;
  private:
    D deleter; // exposition only
};
```

1 The behavior of a program that adds specializations for \texttt{rcu_obj_base} is undefined.
2. T may be an incomplete type. It shall be complete before any member of the resulting specialization of `rcu_obj_base` is referenced.

3. D shall be a function object type ([function.objects]) for which, given a value d of type D and a value ptr of type T*, the expression d(ptr) is valid.

4. D shall meet the requirements for `Cpp17DefaultConstructible` and `Cpp17MoveAssignable`.

5. If D is trivially copyable, all specializations of `rcu_obj_base<T,D>` are trivially copyable.

```cpp
void retire(D d = D(), rcu_domain& dom = rcu_default_domain()) noexcept;
```

6. **Mandates:** T is an rcu-protectable type.

7. ** Preconditions:** *this is a base class subobject of an object x of type T. The member function `rcu_obj_base<T,D>::retire` was not invoked on x before. The assignment to deleter does not throw an exception.

8. **Effects:** Evaluates deleter = std::move(d) and schedules the evaluation of the expression deleter(addressof(x)) in the domain dom; the behavior is undefined if that evaluation exits via an exception. May invoke scheduled evaluations in dom.

   **Note 1:** If such evaluations acquire resources held across any invocation of retire on dom, deadlock can occur. —end note

2.2.4 Class `rcu_domain` [saferc1.rcu.domain]

2.2.4.1 General [saferc1.rcu.domain.general]

This class meets the requirements of `Cpp17Lockable` ([thread.req.lockable.req]) and provides regions of RCU protection.

**Example 1:**
```cpp
std::scoped_lock<rcu_domain> rlock(rcu_default_domain());
```

**end example**

```cpp
class rcu_domain {
public:
    rcu_domain(const rcu_domain&) = delete;
    rcu_domain& operator=(const rcu_domain&) = delete;

    void lock() noexcept;
    bool try_lock() noexcept;
    void unlock() noexcept;
};
```

The functions lock and unlock establish (possibly nested) regions of RCU protection.

2.2.4.2 Member functions [saferc1.rcu.domain.members]

```cpp
void lock() noexcept;
```

1. **Effects:** Opens a region of RCU protection.

2. **Remarks:** Calls to lock do not introduce a data race ([intro.races]) involving *this.

```cpp
bool try_lock() noexcept;
```

3. **Effects:** Equivalent to lock().

4. **Returns:** true.

```cpp
void unlock() noexcept;
```

5. **Preconditions:** A call to lock that opened an unclosed region of RCU protection is sequenced before the call to unlock.

6. **Effects:** Closes the unclosed region of RCU protection that was most recently opened. May invoke scheduled evaluations in *this.

   **Note 1:** If such evaluations acquire resources held across any invocation of unlock on *this, deadlock can occur. —end note

§ 2.2.4.2
Calls to unlock do not introduce a data race involving *this.

[Note 2: Evaluation of scheduled evaluations can still cause a data race. — end note]

2.2.4.3 Non-member functions

rcu_domain& rcu_default_domain() noexcept;

Returns: A reference to a static-duration object of type rcu_domain. A reference to the same object is returned every time this function is called.

void rcu_synchronize(rcu_domain& dom = rcu_default_domain()) noexcept;

Effects: If the call to rcu_synchronize does not strongly happen before the lock opening an RCU protection region R on dom, blocks until the unlock closing R happens.

Synchronization: The unlock closing R strongly happens before the return from rcu_synchronize.

void rcu_barrier(rcu_domain& dom = rcu_default_domain()) noexcept;

Effects: May evaluate any scheduled evaluations in dom. For any evaluation that happens before the call to rcu_barrier and that schedules an evaluation E in dom, blocks until E has been evaluated.

Synchronization: The evaluation of any such E strongly happens before the return from rcu_barrier.

[Note 1: A call to rcu_barrier does not imply a call to rcu_synchronize and vice versa. — end note]

template<class T, class D = default_delete<T>>
void rcu_retire(T* p, D d = D(), rcu_domain& dom = rcu_default_domain());

Mandates: is_move_constructible_v<D> is true and the expression d(p) is well-formed.

Preconditions: D meets the Cpp17MoveConstructible and Cpp17Destructible requirements.

Effects: May allocate memory. It is unspecified whether the memory allocation is performed by invoking operator new. Initializes an object d1 of type D from std::move(d). Schedules the evaluation of d1(p) in the domain dom; the behavior is undefined if that evaluation exits via an exception. May invoke scheduled evaluations in dom.

[Note 2: If rcu_retire exits via an exception, no evaluation is scheduled. — end note]

Throws: bad_alloc or any exception thrown by the initialization of d1.

[Note 3: If scheduled evaluations acquire resources held across any invocation of rcu_retire on dom, deadlock can occur. — end note]