Mandating the Standard Library:
Clause 31 - Thread support library

With the adoption of P0788R3, we have a new way of specifying requirements for the library clauses of the standard. This is one of a series of papers reformulating the requirements into the new format. This effort was strongly influenced by the informational paper P1369R0.

The changes in this series of papers fall into four broad categories.

- Change 'participate in overload resolution' wording into "Constraints' elements
- Change 'Requires' elements into either "Mandates" or "Expects", depending (mostly) on whether or not they can be checked at compile time.
- Drive-by fixes (hopefully very few)

This paper covers Clause 31 (Thread Support Library)

The entire clause is reproduced here, but the changes are confined to a few sections:

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- thread.req.exception 31.2.2
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- thread.req.lockable.basic 31.2.5.2
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- futures.task.members 31.6.10.1
Help for the editors: The changes here can be viewed as latex sources with the following commands

git clone git@github.com:dsunder/draft.git dsunder-draft
cd dsunder-draft
git diff master..P1505-clause-31-cleanup -- source/threads.tex
31 Thread support library

31.1 General

The following subclauses describe components to create and manage threads, perform mutual exclusion, and communicate conditions and values between threads, as summarized in Table 134.

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31.2 Requirements

31.2.1 Template parameter names

Throughout this Clause, the names of template parameters are used to express type requirements. If a template parameter is named `Predicate`, `operator()` applied to the template argument shall return a value that is convertible to `bool`. If a template parameter is named `Clock`, the corresponding template argument shall be a type `C` for which `is_clock_v<C>` is true; otherwise the program is ill-formed.

31.2.2 Exceptions

Some functions described in this Clause are specified to throw exceptions of type `system_error`. Such exceptions shall be thrown if any of the function’s error conditions is detected or a call to an operating system or other underlying API results in an error that prevents the library function from meeting its specifications. Failure to allocate storage shall be reported as described in ??.

[Example: Consider a function in this clause that is specified to throw exceptions of type `system_error` and specifies error conditions that include `operation_not_permitted` for a thread that does not have the privilege to perform the operation. Assume that, during the execution of this function, an `errno` of `EPERM` is reported by a POSIX API call used by the implementation. Since POSIX specifies an `errno` of `EPERM` when “the caller does not have the privilege to perform the operation”, the implementation maps `EPERM` to an `error_condition` of `operation_not_permitted` and an exception of type `system_error` is thrown. — end example]

The `error_code` reported by such an exception’s `code()` member function shall compare equal to one of the conditions specified in the function’s error condition element.

31.2.3 Native handles

Several classes described in this Clause have members `native_handle_type` and `native_handle`. The presence of these members and their semantics is implementation-defined. [Note: These members allow implementations to provide access to implementation details. Their names are specified to facilitate portable compile-time detection. Actual use of these members is inherently non-portable. — end note]

31.2.4 Timing specifications

Several functions described in this Clause take an argument to specify a timeout. These timeouts are specified as either a `duration` or a `time_point` type as specified in ??.

Implementations necessarily have some delay in returning from a timeout. Any overhead in interrupt response, function return, and scheduling induces a “quality of implementation” delay, expressed as duration $D_i$. Ideally, this delay would be zero. Further, any contention for processor and memory resources induces a “quality of
management” delay, expressed as duration $D_m$. The delay durations can vary from timeout to timeout, but in all cases shorter is better.

3 The functions whose names end in _for take an argument that specifies a duration. These functions produce relative timeouts. Implementations should use a steady clock to measure time for these functions.\(^{329}\) Given a duration argument $D_t$, the real-time duration of the timeout is $D_t + D_i + D_m$.

4 The functions whose names end in _until take an argument that specifies a time point. These functions produce absolute timeouts. Implementations should use the clock specified in the time point to measure time for these functions. Given a clock time point argument $C_t$, the clock time point of the return from timeout should be $C_t + D_i + D_m$ when the clock is not adjusted during the timeout. If the clock is adjusted to the time $C_a$ during the timeout, the behavior should be as follows:

\[(4.1) \quad \text{if } C_a > C_t, \text{ the waiting function should wake as soon as possible, i.e., } C_a + D_i + D_m, \text{ since the timeout is already satisfied.}[Note: \text{This specification max can result in the total duration of the wait decreasing when measured against a steady clock. \text{— end note}]}\]

\[(4.2) \quad \text{if } C_a \leq C_t, \text{ the waiting function should not time out until } \text{Clock::now()} \text{ returns a time } C_n \geq C_t, \text{ i.e., waking at } C_t + D_i + D_m. [Note: \text{When the clock is adjusted backwards, this specification max can result in the total duration of the wait increasing when measured against a steady clock. When the clock is adjusted forwards, this specification max can result in the total duration of the wait decreasing when measured against a steady clock. \text{— end note}]}\]

An implementation shall return from such a timeout at any point from the time specified above to the time it would return from a steady-clock relative timeout on the difference between $C_t$ and the time point of the call to the _until function. [Note: Implementations should decrease the duration of the wait when the clock is adjusted forwards. \text{— end note}]\]

5 [Note: If the clock is not synchronized with a steady clock, e.g., a CPU time clock, these timeouts might not provide useful functionality. \text{— end note}]\]

6 The resolution of timing provided by an implementation depends on both operating system and hardware. The finest resolution provided by an implementation is called the native resolution.

7 Implementation-provided clocks that are used for these functions shall satisfy meet the Cpp17TrivialClock requirements (??). A function that takes an argument which specifies a timeout will throw if, during its execution, a clock, time point, or time duration throws an exception. Such exceptions are referred to as timeout-related exceptions. [Note: Instantiations of clock, time point and duration types supplied by the implementation as specified in ?? do not throw exceptions. \text{— end note}]\]

31.2.5 Requirements for Cpp17Lockable types [thread.req.lockable]

31.2.5.1 In general [thread.req.lockable.general]

1 An execution agent is an entity such as a thread that max can perform work in parallel with other execution agents. [Note: Implementations or users max can introduce other kinds of agents such as processes or thread-pool tasks. \text{— end note} The calling agent is determined by context, e.g., the calling thread that contains the call, and so on.\]

2 [Note: Some lockable objects are “agent oblivious” in that they work for any execution agent model because they do not determine or store the agent’s ID (e.g., an ordinary spin lock). \text{— end note}]

3 The standard library templates unique_lock (31.4.4.3), shared_lock (31.4.4.4), scoped_lock (31.4.4.2), lock_guard (31.4.4.1), lock, try_lock (31.4.5), and condition_variable_any (31.5.4) all operate on user-supplied lockable objects. The Cpp17BasicLockable requirements, the Cpp17Lockable requirements, and the Cpp17TimedLockable requirements list the requirements imposed by these library types in order to acquire or release ownership of a lock by a given execution agent. [Note: The nature of any lock ownership and any synchronization it max could entail are not part of these requirements. \text{— end note}]\]

31.2.5.2 Cpp17BasicLockable requirements [thread.req.lockable.basic]

1 A type $L$ meets the Cpp17BasicLockable requirements if the following expressions are well-formed and have the specified semantics (m denotes a value of type $L$).

\[^{329}\text{All implementations for which standard time units are meaningful must necessarily have a steady clock within their hardware implementation.} \]
m.lock()

**Effects:** Blocks until a lock can be acquired for the current execution agent. If an exception is thrown then a lock shall not have been acquired for the current execution agent.

m.unlock()

**Requirements-Expects:** The current execution agent shall hold a lock on m.

**Effects:** Releases a lock on m held by the current execution agent.

**Throws:** Nothing.

### 31.2.5.3 Cpp17Lockable requirements

A type L meets the Cpp17Lockable requirements if it meets the Cpp17BasicLockable requirements and the following expressions are well-formed and have the specified semantics (m denotes a value of type L).

m.try_lock()

**Effects:** Attempts to acquire a lock for the current execution agent without blocking. If an exception is thrown then a lock shall not have been acquired for the current execution agent.

**Return type:** bool.

**Returns:** true if the lock was acquired, false otherwise.

### 31.2.5.4 Cpp17TimedLockable requirements

A type L meets the Cpp17TimedLockable requirements if it meets the Cpp17Lockable requirements and the following expressions are well-formed and have the specified semantics (m denotes a value of type L, rel_time denotes a value of an instantiation of duration (??), and abs_time denotes a value of an instantiation of time_point (??)).

m.try_lock_for(rel_time)

**Effects:** Attempts to acquire a lock for the current execution agent within the relative timeout (31.2.4) specified by rel_time. The function shall not return within the timeout specified by rel_time unless it has obtained a lock on m for the current execution agent. If an exception is thrown then a lock shall not have been acquired for the current execution agent.

**Return type:** bool.

**Returns:** true if the lock was acquired, false otherwise.

m.try_lock_until(abs_time)

**Effects:** Attempts to acquire a lock for the current execution agent before the absolute timeout (31.2.4) specified by abs_time. The function shall not return before the timeout specified by abs_time unless it has obtained a lock on m for the current execution agent. If an exception is thrown then a lock shall not have been acquired for the current execution agent.

**Return type:** bool.

**Returns:** true if the lock was acquired, false otherwise.

### 31.3 Threads

31.3 describes components that can be used to create and manage threads. [Note: These threads are intended to map one-to-one with operating system threads. — end note]

#### 31.3.1 Header <thread> synopsis

```cpp
namespace std {
    class thread;
    
    void swap(thread& x, thread& y) noexcept;

    namespace this_thread {
        thread::id get_id() noexcept;
    }
}
```
void yield() noexcept;

template<class Clock, class Duration>
void sleep_until(const chrono::time_point<Clock, Duration>& abs_time);

template<class Rep, class Period>
void sleep_for(const chrono::duration<Rep, Period>& rel_time);

31.3.2 Class thread

The class thread provides a mechanism to create a new thread of execution, to join with a thread (i.e.,
wait for a thread to complete), and to perform other operations that manage and query the state of a
thread. A thread object uniquely represents a particular thread of execution. That representation may
be transferred to other thread objects in such a way that no two thread objects simultaneously represent
the same thread of execution. A thread of execution is detached when no thread object represents that
thread. Objects of class thread can be in a state that does not represent a thread of execution. [Note: A
thread object does not represent a thread of execution after default construction, after being moved from, or
after a successful call to detach or join. —end note]

namespace std {
    class thread {
    public:
        // types
        class id;
        using native_handle_type = implementation-defined;  // see 31.2.3

        // construct/copy/destroy
        thread() noexcept;
        template<class F, class... Args> explicit thread(F&& f, Args&&... args);
        ~thread();
        thread(const thread&) = delete;
        thread(thread&&) noexcept;
        thread& operator=(const thread&) = delete;
        thread& operator=(thread&&) noexcept;

        // members
        void swap(thread&) noexcept;
        bool joinable() const noexcept;
        void join();
        void detach();
        id get_id() const noexcept;
        native_handle_type native_handle();  // see 31.2.3

        // static members
        static unsigned int hardware_concurrency() noexcept;
    };
}

31.3.2.1 Class thread::id

namespace std {
    class thread::id {
    public:
        id() noexcept;
    }

    bool operator==(thread::id x, thread::id y) noexcept;
    bool operator!=(thread::id x, thread::id y) noexcept;
    bool operator<(thread::id x, thread::id y) noexcept;
    bool operator<=(thread::id x, thread::id y) noexcept;
    bool operator>(thread::id x, thread::id y) noexcept;
    bool operator>=(thread::id x, thread::id y) noexcept;

§ 31.3.2.1
An object of type \texttt{thread::id} provides a unique identifier for each thread of execution and a single distinct value for all \texttt{thread} objects that do not represent a thread of execution (31.3.2). Each thread of execution has an associated \texttt{thread::id} object that is not equal to the \texttt{thread::id} object of any other thread of execution and that is not equal to the \texttt{thread::id} object of any \texttt{thread} object that does not represent threads of execution.

\texttt{thread::id} is a trivially copyable class (??). The library \texttt{can} reuse the value of a \texttt{thread::id} of a terminated thread that can no longer be joined.

\begin{itemize}
\item \textbf{1} An object of type \texttt{thread::id} provides a unique identifier for each thread of execution and a single distinct value for all \texttt{thread} objects that do not represent a thread of execution (31.3.2). Each thread of execution has an associated \texttt{thread::id} object that is not equal to the \texttt{thread::id} object of any other thread of execution and that is not equal to the \texttt{thread::id} object of any \texttt{thread} object that does not represent threads of execution.
\item \texttt{thread::id} is a trivially copyable class (??). The library \texttt{can} reuse the value of a \texttt{thread::id} of a terminated thread that can no longer be joined.
\item [Note: Relational operators allow \texttt{thread::id} objects to be used as keys in associative containers. — end note]
\end{itemize}

Effects: Constructs an object of type \texttt{id}.

Ensures: The constructed object does not represent a thread of execution.

Returns: \texttt{true} only if \texttt{x} and \texttt{y} represent the same thread of execution or neither \texttt{x} nor \texttt{y} represents a thread of execution.

Effects: Inserts an unspecified text representation of \texttt{id} into \texttt{out}. For two objects of type \texttt{thread::id} \texttt{x} and \texttt{y}, if \texttt{x} == \texttt{y} the \texttt{thread::id} objects have the same text representation and if \texttt{x} != \texttt{y} the \texttt{thread::id} objects have distinct text representations.

Returns: \texttt{out}.

The specialization is enabled (??).
template<class F, class... Args> explicit thread(F&& f, Args&&... args);

Requires: F and each T_i in Args shall satisfy the Cpp17MoveConstructible requirements. INVOKE(decay-copy(std::forward<F>(f)), decay-copy(std::forward<Args>(args))...)
shall be a valid expression.

Remarks: This constructor shall not participate in overload resolution if remove_cvref_t<F> is not the same type as std::thread.

Effects: Constructs an object of type thread. The new thread of execution executes INVOKE(
decay-copy(std::forward<F>(f)), decay-copy(std::forward<Args>(args))...)
with the calls to decay-copy being evaluated in the constructing thread. Any return value from this invocation is ignored. [Note: This implies that any exceptions not thrown from the invocation of the copy of
f will be thrown in the constructing thread, not the new thread. —end note] If the invocation of
INVOKE(decay-copy(std::forward<F>(f)), decay-copy(std::forward<Args>(args))...)
terminates with an uncaught exception, terminate shall be called.

Synchronization: The completion of the invocation of the constructor synchronizes with the beginning
of the invocation of the copy of f.

Ensures: get_id() != id(). *this represents the newly started thread.

Throws: system_error if unable to start the new thread.

Error conditions:
— resource_unavailable_try_again — the system lacked the necessary resources to create another
thread, or the system-imposed limit on the number of threads in a process would be exceeded.

thread(thread&& x) noexcept;

Effects: Constructs an object of type thread from x, and sets x to a default constructed state.

Ensures: x.get_id() == id() and get_id() returns the value of x.get_id() prior to the start of
construction.

31.3.2.3 Destructor [thread.thread.destr]
~thread();

If joinable(), calls terminate(). Otherwise, has no effects. [Note: Either implicitly detaching or
joining a joinable() thread in its destructor could result in difficult to debug correctness (for detach)
or performance (for join) bugs encountered only when an exception is thrown. Thus the programmer
must ensure that the destructor is never executed while the thread is still joinable. —end note]

31.3.2.4 Assignment [thread.thread.assign]
thread& operator=(thread&& x) noexcept;

Effects: If joinable(), calls terminate(). Otherwise, assigns the state of x to *this and sets x to a
default constructed state.

Ensures: x.get_id() == id() and get_id() returns the value of x.get_id() prior to the assignment.

Returns: *this.

31.3.2.5 Members [thread.thread.member]
void swap(thread& x) noexcept;

Effects: Swaps the state of *this and x.

bool joinable() const noexcept;

Returns: get_id() != id().

void join();

Effects: Blocks until the thread represented by *this has completed.

Synchronization: The completion of the thread represented by *this synchronizes with (?) the
corresponding successful join() return. [Note: Operations on *this are not synchronized. —end
note]
Ensures: The thread represented by *this has completed. get_id() == id().

Throws: system_error when an exception is required (31.2.2).

Error conditions:

(7.1) — resource_deadlock_would_occur — if deadlock is detected or get_id() == this_thread::get_id().
(7.2) — no_such_process — if the thread is not valid.
(7.3) — invalid_argument — if the thread is not joinable.

void detach();

Effects: The thread represented by *this continues execution without the calling thread blocking. When detach() returns, *this no longer represents the possibly continuing thread of execution. When the thread previously represented by *this ends execution, the implementation shall releases any owned resources.

Ensures: get_id() == id().

Throws: system_error when an exception is required (31.2.2).

Error conditions:

(11.1) — no_such_process — if the thread is not valid.
(11.2) — invalid_argument — if the thread is not joinable.

id get_id() const noexcept;

Returns: A default constructed id object if *this does not represent a thread, otherwise this_thread::get_id() for the thread of execution represented by *this.

31.3.2.6 Static members

unsigned hardware_concurrency() noexcept;

Returns: The number of hardware thread contexts. [Note: This value should only be considered to be a hint. — end note] If this value is not computable or well-defined, an implementation should return 0.

31.3.2.7 Specialized algorithms

void swap(thread& x, thread& y) noexcept;

Effects: As if by x.swap(y).

31.3.3 Namespace this_thread

namespace std::this_thread {
    thread::id get_id() noexcept;

    void yield() noexcept;
    template<class Clock, class Duration>
        void sleep_until(const chrono::time_point<Clock, Duration>& abs_time);
    template<class Rep, class Period>
        void sleep_for(const chrono::duration<Rep, Period>& rel_time);
}

thread::id this_thread::get_id() noexcept;

Returns: An object of type thread::id that uniquely identifies the current thread of execution. No other thread of execution shall has this id and this thread of execution shall always have has this id. The object returned shall does not compare equal to a default constructed thread::id.

void this_thread::yield() noexcept;

Effects: Offers the implementation the opportunity to reschedule.

Synchronization: None.
template<class Clock, class Duration>
void sleep_until(const chrono::time_point<Clock, Duration>& abs_time);

*Effects:* Blocks the calling thread for the absolute timeout (31.2.4) specified by `abs_time`.
*Synchronization:* None.
*Throws:* Timeout-related exceptions (31.2.4).

template<class Rep, class Period>
void sleep_for(const chrono::duration<Rep, Period>& rel_time);

*Effects:* Blocks the calling thread for the relative timeout (31.2.4) specified by `rel_time`.
*Synchronization:* None.
*Throws:* Timeout-related exceptions (31.2.4).

### 31.4 Mutual exclusion

This subclause provides mechanisms for mutual exclusion: mutexes, locks, and call once. These mechanisms ease the production of race-free programs (??).

#### 31.4.1 Header `<mutex>` synopsis

namespace std {
  class mutex;
  class recursive_mutex;
  class timed_mutex;
  class recursive_timed_mutex;

  struct defer_lock_t { explicit defer_lock_t() = default; };
  struct try_to_lock_t { explicit try_to_lock_t() = default; };
  struct adopt_lock_t { explicit adopt_lock_t() = default; };

  inline constexpr defer_lock_t defer_lock { };
  inline constexpr try_to_lock_t try_to_lock { };
  inline constexpr adopt_lock_t adopt_lock { };

  template<class Mutex> class lock_guard;
  template<class... MutexTypes> class scoped_lock;
  template<class Mutex> class unique_lock;

  template<class Mutex>
  void swap(unique_lock<Mutex>& x, unique_lock<Mutex>& y) noexcept;

  template<class L1, class L2, class... L3> int try_lock(L1&, L2&, L3&...);
  template<class L1, class L2, class... L3> void lock(L1&, L2&, L3&...);

  struct once_flag;

  template<class Callable, class... Args>
  void call_once(once_flag& flag, Callable&& func, Args&&... args);
}

#### 31.4.2 Header `<shared_mutex>` synopsis

namespace std {
  class shared_mutex;
  class shared_timed_mutex;
  template<class Mutex> class shared_lock;

  template<class Mutex>
  void swap(shared_lock<Mutex>& x, shared_lock<Mutex>& y) noexcept;
}

§ 31.4.2
31.4.3 Mutex requirements [thread.mutex.requirements]

31.4.3.1 In general [thread.mutex.requirements.general]

1 A mutex object facilitates protection against data races and allows safe synchronization of data between execution agents (31.2.5). An execution agent owns a mutex from the time it successfully calls one of the lock functions until it calls unlock. Mutexes can be either recursive or non-recursive, and can grant simultaneous ownership to one or many execution agents. Both recursive and non-recursive mutexes are supplied.

31.4.3.2 Mutex types [thread.mutex.requirements.mutex]

1 The mutex types are the standard library types `mutex`, `recursive_mutex`, `timed_mutex`, `recursive_timed_mutex`, `shared_mutex`, and `shared_timed_mutex`. They shall satisfy the requirements set out in this subclause. In this description, \( m \) denotes an object of a mutex type.

2 The mutex types shall satisfy the \( \text{Cpp17Lockable} \) requirements (31.2.5.3).

3 The mutex types shall be \( \text{Cpp17DefaultConstructible} \) and \( \text{Cpp17Destructible} \). If initialization of an object of a mutex type fails, an exception of type `system_error` shall be thrown. The mutex types shall not be copyable nor movable.

4 The error conditions for error codes, if any, reported by member functions of the mutex types shall be as follows:

   - \( \text{resource unavailable try again} \) — if any native handle type manipulated is not available.
   - \( \text{operation not permitted} \) — if the thread does not have the privilege to perform the operation.
   - \( \text{invalid argument} \) — if any native handle type manipulated as part of mutex construction is incorrect.

5 The implementation shall provide lock and unlock operations, as described below. For purposes of determining the existence of a data race, these behave as atomic operations (??). The lock and unlock operations on a single mutex shall appear to occur in a single total order. [Note: This can be viewed as the modification order (??) of the mutex. — end note] [Note: Construction and destruction of an object of a mutex type need not be thread-safe; other synchronization should be used to ensure that mutex objects are initialized and visible to other threads. — end note]

6 The expression \( m.\text{lock()} \) shall be well-formed and have has the following semantics:

   \[\text{Requires:} \text{Expects:}\] If \( m \) is of type `mutex`, `timed_mutex`, `shared_mutex`, or `shared_timed_mutex`, the calling thread does not own the mutex.

   \[\text{Effects:}\] Blocks the calling thread until ownership of the mutex can be obtained for the calling thread.

   \[\text{Ensures:}\] The calling thread owns the mutex.

   \[\text{Return type:} \text{void}.\]

   \[\text{Synchronization:} \text{Prior unlock()} operations on the same object shall synchronize with (??) this operation.\]

   \[\text{Throws:} \text{system_error} \text{when an exception is required (31.2.2).}\]

   \[\text{Error conditions:}\]

   - \( \text{operation not permitted} \) — if the thread does not have the privilege to perform the operation.
   - \( \text{resource deadlock would occur} \) — if the implementation detects that a deadlock would occur.

14 The expression \( m.\text{try_lock()} \) shall be well-formed and have has the following semantics:

   \[\text{Requires:} \text{Expects:}\] If \( m \) is of type `mutex`, `timed_mutex`, `shared_mutex`, or `shared_timed_mutex`, the calling thread does not own the mutex.

   \[\text{Effects:} \text{Attempts to obtain ownership of the mutex for the calling thread without blocking. If ownership is not obtained, there is no effect and try_lock()} immediately returns. An implementation may fail to obtain the lock even if it is not held by any other thread. [Note: This spurious failure is normally uncommon, but allows interesting implementations based on a simple compare and exchange (??). — end note] An implementation should ensure that try_lock() does not consistently return \text{false} in the absence of contending mutex acquisitions.\]

   \[\text{Return type:} \text{bool}.\]

   \[\text{Returns:} \text{true if ownership of the mutex was obtained for the calling thread, otherwise false.}\]

§ 31.4.3.2 9
19  **Synchronization:** If `try_lock()` returns `true`, prior `unlock()` operations on the same object synchronize with (??) this operation. [Note: Since `lock()` does not synchronize with a failed subsequent `try_lock()`, the visibility rules are weak enough that little would be known about the state after a failure, even in the absence of spurious failures. — end note]

20  **Throws:** Nothing.

21  The expression `m.unlock()` shall be well-formed and has the following semantics:

22  **Require—Expect:** The calling thread shall own the mutex.

23  **Effects:** Releases the calling thread’s ownership of the mutex.

24  **Return type:** `void`.

25  **Synchronization:** This operation synchronizes with (??) subsequent lock operations that obtain ownership on the same object.

26  **Throws:** Nothing.

### 31.4.3.2.1 Class mutex

```cpp
namespace std {
    class mutex {
    public:
        constexpr mutex() noexcept;  
        ~mutex();

        mutex(const mutex&) = delete;  
        mutex& operator=(const mutex&) = delete;

        void lock();
        bool try_lock();
        void unlock();

        using native_handle_type = implementation-defined;  
        // see 31.2.3

        native_handle_type native_handle();  
        // see 31.2.3
    };
}
```

1  The class `mutex` provides a non-recursive mutex with exclusive ownership semantics. If one thread owns a mutex object, attempts by another thread to acquire ownership of that object will fail (for `try_lock()`) or block (for `lock()`) until the owning thread has released ownership with a call to `unlock()`.

2  [Note: After a thread A has called `unlock()`, releasing a mutex, it is possible for another thread B to lock the same mutex, observe that it is no longer in use, unlock it, and destroy it, before thread A appears to have returned from its unlock call. Implementations are required to handle such scenarios correctly, as long as thread A doesn’t access the mutex after the unlock call returns. These cases typically occur when a reference-counted object contains a mutex that is used to protect the reference count. — end note]

3  The class `mutex` shall satisfy all of the mutex requirements (31.4.3). It shall be a standard-layout class (??).

4  [Note: A program may deadlock if the thread that owns a mutex object calls `lock()` on that object. If the implementation can detect the deadlock, a `resource_deadlock_would_occur` error condition may be observed. — end note]

5  The behavior of a program is undefined if it destroys a mutex object owned by any thread or a thread terminates while owning a mutex object.

### 31.4.3.2.2 Class recursive_mutex

```cpp
namespace std {
    class recursive_mutex {
    public:
        recursive_mutex();
        ~recursive_mutex();

        recursive_mutex(const recursive_mutex&) = delete;
        recursive_mutex& operator=(const recursive_mutex&) = delete;
    };
}
```

§ 31.4.3.2.2
The class `recursive_mutex` provides a recursive mutex with exclusive ownership semantics. If one thread owns a `recursive_mutex` object, attempts by another thread to acquire ownership of that object will fail (for `try_lock()`) or block (for `lock()`) until the first thread has completely released ownership.

The class `recursive_mutex` shall satisfy all of the mutex requirements (31.4.3). It shall be a standard-layout class (??).

A thread that owns a `recursive_mutex` object may acquire additional levels of ownership by calling `lock()` or `try_lock()` on that object. It is unspecified how many levels of ownership may be acquired by a single thread. If a thread has already acquired the maximum level of ownership for a `recursive_mutex` object, additional calls to `try_lock()` shall fail, and additional calls to `lock()` shall throw an exception of type `system_error`. A thread shall call `unlock()` once for each level of ownership acquired by calls to `lock()` and `try_lock()`. Only when all levels of ownership have been released may ownership be acquired by another thread.

The behavior of a program is undefined if:

1. it destroys a `recursive_mutex` object owned by any thread or
2. a thread terminates while owning a `recursive_mutex` object.

### 31.4.3.3 Timed mutex types

The timed mutex types are the standard library types `timed_mutex`, `recursive_timed_mutex`, and `shared_timed_mutex`. They shall meet the requirements set out below. In this description, `m` denotes an object of a mutex type, `rel_time` denotes an object of an instantiation of `duration` (??), and `abs_time` denotes an object of an instantiation of `time_point` (??).

The timed mutex types shall satisfy the `Cpp17TimedLockable` requirements (31.2.5.4).

The expression `m.try_lock_for(rel_time)` shall be well-formed and have the following semantics:

**Requires: ** If `m` is of type `timed_mutex` or `shared_timed_mutex`, the calling thread does not own the mutex.

**Effects:** The function attempts to obtain ownership of the mutex within the relative timeout (31.2.4) specified by `rel_time`. If the time specified by `rel_time` is less than or equal to `rel_time.zero()`, the function attempts to obtain ownership without blocking (as if by calling `try_lock()`). The function shall return within the timeout specified by `rel_time` only if it has obtained ownership of the mutex object. [Note: As with `try_lock()`, there is no guarantee that ownership will be obtained if the lock is available, but implementations are expected to make a strong effort to do so. — end note]

**Return type:** `bool`.

**Returns:** `true` if ownership was obtained, otherwise `false`.

**Synchronization:** If `try_lock_for()` returns `true`, prior `unlock()` operations on the same object synchronize with (??) this operation.

**Throws:** Timeout-related exceptions (31.2.4).

The expression `m.try_lock_until(abs_time)` shall be well-formed and have the following semantics:

**Requires-** **Expects:** If `m` is of type `timed_mutex` or `shared_timed_mutex`, the calling thread does not own the mutex.

**Effects:** The function attempts to obtain ownership of the mutex. If `abs_time` has already passed, the function attempts to obtain ownership without blocking (as if by calling `try_lock()`). The function shall return before the absolute timeout (31.2.4) specified by `abs_time` only if it has obtained ownership of the mutex object. [Note: As with `try_lock()`, there is no guarantee that ownership will be obtained if the lock is available, but implementations are expected to make a strong effort to do so. — end note]

**Return type:** `bool`. 

§ 31.4.3.3 11
14 Returns: true if ownership was obtained, otherwise false.

15 Synchronization: If try_lock_until() returns true, prior unlock() operations on the same object synchronize with (??) this operation.

16 Throws: Timeout-related exceptions (31.2.4).

31.4.3.3.1 Class timed_mutex
namespace std {
    class timed_mutex {
    public:
        timed_mutex();
        ~timed_mutex();
        timed_mutex(const timed_mutex&) = delete;
        timed_mutex& operator=(const timed_mutex&) = delete;
        timed_mutex(const timed_mutex&) = delete;
        timed_mutex& operator=(const timed_mutex&) = delete;

        void lock(); // blocking
        bool try_lock();
        template<class Rep, class Period>
            bool try_lock_for(const chrono::duration<Rep, Period>& rel_time);
        template<class Clock, class Duration>
            bool try_lock_until(const chrono::time_point<Clock, Duration>& abs_time);
        void unlock();

        using native_handle_type = implementation-defined; // see 31.2.3
        native_handle_type native_handle(); // see 31.2.3
    }
};

1 The class timed_mutex provides a non-recursive mutex with exclusive ownership semantics. If one thread owns a timed_mutex object, attempts by another thread to acquire ownership of that object will fail (for try_lock() or block (for lock(), try_lock_for(), and try_lock_until())) until the owning thread has released ownership with a call to unlock() or the call to try_lock_for() or try_lock_until() times out (having failed to obtain ownership).

2 The class timed_mutex shall satisfy all of the timed mutex requirements (31.4.3.3). It shall be a standard-layout class (??).

3 The behavior of a program is undefined if:

3.1 — it destroys a timed_mutex object owned by any thread,

3.2 — a thread that owns a timed_mutex object calls lock(), try_lock(), try_lock_for(), or try_lock_until() on that object, or

3.3 — a thread terminates while owning a timed_mutex object.

31.4.3.3.2 Class recursive_timed_mutex
namespace std {
    class recursive_timed_mutex {
    public:
        recursive_timed_mutex();
        ~recursive_timed_mutex();
        recursive_timed_mutex(const recursive_timed_mutex&) = delete;
        recursive_timed_mutex& operator=(const recursive_timed_mutex&) = delete;

        void lock(); // blocking
        bool try_lock() noexcept;
        template<class Rep, class Period>
            bool try_lock_for(const chrono::duration<Rep, Period>& rel_time);
        template<class Clock, class Duration>
            bool try_lock_until(const chrono::time_point<Clock, Duration>& abs_time);
        void unlock();

    § 31.4.3.3.2
The class `recursive_timed_mutex` provides a recursive mutex with exclusive ownership semantics. If one thread owns a `recursive_timed_mutex` object, attempts by another thread to acquire ownership of that object will fail (for `try_lock()` or block (for `lock()`, `try_lock_for()`, and `try_lock_until()` until the owning thread has completely released ownership or the call to `try_lock_for()` or `try_lock_until()` times out (having failed to obtain ownership).

The class `recursive_timed_mutex` shall satisfy all of the timed mutex requirements (31.4.3.3). It shall be a standard-layout class (?). A thread that owns a `recursive_timed_mutex` object can acquire additional levels of ownership by calling `lock()`, `try_lock()`, `try_lock_for()`, or `try_lock_until()` on that object. It is unspecified how many levels of ownership can be acquired by a single thread. If a thread has already acquired the maximum level of ownership for a `recursive_timed_mutex` object, additional calls to `try_lock()`, `try_lock_for()`, or `try_lock_until()` shall fail, and additional calls to `lock()` shall throw an exception of type `system_error`. A thread shall call `unlock()` once for each level of ownership acquired by calls to `lock()`, `try_lock()`, `try_lock_for()`, and `try_lock_until()`. Only when all levels of ownership have been released ownership of the object be acquired by another thread.

The behavior of a program is undefined if:

- it destroys a `recursive_timed_mutex` object owned by any thread, or
- a thread terminates while owning a `recursive_timed_mutex` object.

### 31.4.3.4 Shared mutex types

The standard library types `shared_mutex` and `shared_timed_mutex` are shared mutex types. Shared mutex types shall satisfy the requirements of mutex types (31.4.3.2), and additionally shall satisfy the requirements set out below. In this description, `m` denotes an object of a shared mutex type.

In addition to the exclusive lock ownership mode specified in 31.4.3.2, shared mutex types provide a shared lock ownership mode. Multiple execution agents can simultaneously hold a shared lock ownership of a shared mutex type. But no execution agent shall hold a shared lock while another execution agent holds an exclusive lock on the same shared mutex type, and vice-versa. The maximum number of execution agents which can share a shared lock on a single shared mutex type is unspecified, but shall be at least 10000. If more than the maximum number of execution agents attempt to obtain a shared lock, the excess execution agents shall block until the number of shared locks are reduced below the maximum amount by other execution agents releasing their shared lock.

The expression `m.lock_shared()` shall be well-formed and have the following semantics:

**Requires:** The calling thread has no ownership of the mutex.

**Effects:** Blocks the calling thread until shared ownership of the mutex can be obtained for the calling thread. If an exception is thrown then a shared lock shall not have been acquired for the current thread.

**Ensures:** The calling thread has a shared lock on the mutex.

**Return type:** `void`.

**Synchronization:** Prior `unlock()` operations on the same object shall synchronize with this operation.

**Throws:** `system_error` when an exception is required (31.2.2).

**Error conditions:**

- `operation_not_permitted` — if the thread does not have the privilege to perform the operation.
- `resource_deadlock_would_occur` — if the implementation detects that a deadlock would occur.

The expression `m.unlock_shared()` shall be well-formed and have the following semantics:

**Requires:** The calling thread holds a shared lock on the mutex.

**Effects:** Releases a shared lock on the mutex held by the calling thread.

**Return type:** `void`. 
Synchronization: This operation synchronizes with subsequent lock() operations that obtain ownership on the same object.

Throws: Nothing.

The expression `m.try_lock_shared()` shall be well-formed and have has the following semantics:

Requires - Expects: The calling thread has no ownership of the mutex.

Effects: Attempts to obtain shared ownership of the mutex for the calling thread without blocking. If shared ownership is not obtained, there is no effect and try_lock_shared() immediately returns. An implementation may fail to obtain the lock even if it is not held by any other thread.

Return type: bool.

Returns: true if the shared ownership lock was acquired, false otherwise.

Synchronization: If try_lock_shared() returns true, prior unlock() operations on the same object synchronize with this operation.

Throws: Nothing.

31.4.3.4.1 Class shared_mutex

```cpp
namespace std {
    class shared_mutex {
        public:
            shared_mutex();
            ~shared_mutex();
            shared_mutex(const shared_mutex&) = delete;
            shared_mutex& operator=(const shared_mutex&) = delete;

            // exclusive ownership
            void lock(); // blocking
            bool try_lock();
            void unlock();

            // shared ownership
            void lock_shared(); // blocking
            bool try_lock_shared();
            void unlock_shared();

            using native_handle_type = implementation-defined; // see 31.2.3
            native_handle_type native_handle(); // see 31.2.3
        }
    }
}
```

The class shared_mutex provides a non-recursive mutex with shared ownership semantics.

The class shared_mutex shall satisfy satisfies all of the shared mutex requirements (31.4.3.4). It shall be a standard-layout class (??).

The behavior of a program is undefined if:

1. it destroys a shared_mutex object owned by any thread,
2. a thread attempts to recursively gain any ownership of a shared_mutex, or
3. a thread terminates while possessing any ownership of a shared_mutex.

shared_mutex may can be a synonym for shared_timed_mutex.

31.4.3.5 Shared timed mutex types

The standard library type shared_timed_mutex is a shared timed mutex type. Shared timed mutex types shall satisfy the requirements of timed mutex types (31.4.3.3), shared mutex types (31.4.3.4), and additionally shall satisfy the requirements set out below. In this description, m denotes an object of a shared timed mutex type, rel_type denotes an object of an instantiation of duration (??), and abs_time denotes an object of an instantiation of time_point (??).
The expression `m.try_lock_shared_for(rel_time)` shall be well-formed and have the following semantics:

**Requires—Expects:** The calling thread has no ownership of the mutex.

**Effects:** Attempts to obtain shared lock ownership for the calling thread within the relative timeout (31.2.4) specified by `rel_time`. If the time specified by `rel_time` is less than or equal to `rel_time.zero()`, the function attempts to obtain ownership without blocking (as if by calling `try_lock_shared()`). The function shall return within the timeout specified by `rel_time` only if it has obtained shared ownership of the mutex object. [Note: As with `try_lock()`, there is no guarantee that ownership will be obtained if the lock is available, but implementations are expected to make a strong effort to do so. — end note] If an exception is thrown then a shared lock shall not have been acquired for the current thread.

**Return type:** `bool`.

**Returns:** `true` if the shared lock was acquired, `false` otherwise.

**Synchronization:** If `try_lock_shared_for()` returns `true`, prior `unlock()` operations on the same object synchronize with (??) this operation.

**Throws:** Timeout-related exceptions (31.2.4).

The expression `m.try_lock_shared_until(abs_time)` shall be well-formed and have the following semantics:

**Requires—Expects:** The calling thread has no ownership of the mutex.

**Effects:** The function attempts to obtain shared ownership of the mutex. If `abs_time` has already passed, the function attempts to obtain shared ownership without blocking (as if by calling `try_lock_shared()`). The function shall return before the absolute timeout (31.2.4) specified by `abs_time` only if it has obtained shared ownership of the mutex object. [Note: As with `try_lock()`, there is no guarantee that ownership will be obtained if the lock is available, but implementations are expected to make a strong effort to do so. — end note] If an exception is thrown then a shared lock shall not have been acquired for the current thread.

**Return type:** `bool`.

**Returns:** `true` if the shared lock was acquired, `false` otherwise.

**Synchronization:** If `try_lock_shared_until()` returns `true`, prior `unlock()` operations on the same object synchronize with (??) this operation.

**Throws:** Timeout-related exceptions (31.2.4).

### 31.4.3.5.1 Class shared_timed_mutex

```cpp
class shared_timed_mutex {
public:
    shared_timed_mutex();
    ~shared_timed_mutex();

    shared_timed_mutex(const shared_timed_mutex&) = delete;
    shared_timed_mutex& operator=(const shared_timed_mutex&) = delete;

    // exclusive ownership
    void lock();       // blocking
    bool try_lock();
    template<class Rep, class Period>
        bool try_lock_for(const chrono::duration<Rep, Period>& rel_time);
    template<class Clock, class Duration>
        bool try_lock_until(const chrono::time_point<Clock, Duration>& abs_time);
    void unlock();

    // shared ownership
    void lock_shared();  // blocking
    bool try_lock_shared();
    template<class Rep, class Period>
        bool try_lock_shared_for(const chrono::duration<Rep, Period>& rel_time);
};
```

§ 31.4.3.5.1
A lock is an object that holds a reference to a lockable object and can unlock the lockable object during the lock’s destruction (such as when leaving block scope). An execution agent can use a lock to aid in managing ownership of a lockable object in an exception safe manner. A lock is said to own a lockable object if it is currently managing the ownership of that lockable object for an execution agent. A lock does not manage the lifetime of the lockable object it references. [Note: Locks are intended to ease the burden of unlocking the lockable object under both normal and exceptional circumstances. —end note]

Some lock constructors take tag types which describe what should be done with the lockable object during the lock’s construction.

namespace std {
    struct defer_lock_t {};// do not acquire ownership of the mutex
    struct try_to_lock_t {};// try to acquire ownership of the mutex
    // without blocking
    struct adopt_lock_t {};// assume the calling thread has already
    // obtained mutex ownership and manage it

    inline constexpr defer_lock_t defer_lock {};
    inline constexpr try_to_lock_t try_to_lock {};
    inline constexpr adopt_lock_t adopt_lock {};
}

### 31.4.4.1 Class template `lock_guard`

An object of type `lock_guard` controls the ownership of a lockable object within a scope. A `lock_guard` object maintains ownership of a lockable object throughout the `lock_guard` object’s lifetime. The behavior of a program is undefined if the lockable object referenced by `pm` does not exist for the entire lifetime of the `lock_guard` object. The supplied `Mutex` type shall satisfy the `Cpp17BasicLockable` requirements.
explicit lock_guard(mutex_type& m);

2  **Requires—Expects:** If *mutex_type* is not a recursive mutex, the calling thread does not own the mutex *m*.

3  **Effects:** Initializes *pm* with *m*. Calls *m.lock()*.

lock_guard(mutex_type& m, adopt_lock_t);

4  **Requires—Expects:** The calling thread owns the mutex *m*.

5  **Effects:** Initializes *pm* with *m*.

6  **Throws:** Nothing.

~lock_guard();

7  **Effects:** As if by *pm.unlock()*.

### 31.4.4.2 Class template scoped_lock

```cpp
namespace std {
    template<class... MutexTypes>
    class scoped_lock {
    public:
        using mutex_type = Mutex;  // If MutexTypes... consists of the single type Mutex
        explicit scoped_lock(MutexTypes&... m);
        explicit scoped_lock(adopt_lock_t, MutexTypes&... m);
        ~scoped_lock();

        scoped_lock(const scoped_lock&) = delete;
        scoped_lock& operator=(const scoped_lock&) = delete;

    private:
        tuple<MutexTypes&...> pm;  // exposition only
    };
}
```

An object of type *scoped_lock* controls the ownership of lockable objects within a scope. A *scoped_lock* object maintains ownership of lockable objects throughout the *scoped_lock* object's lifetime (??). The behavior of a program is undefined if the lockable objects referenced by *pm* do not exist for the entire lifetime of the *scoped_lock* object. When sizeof...(MutexTypes) is 1, the supplied *Mutex* type shall satisfy the *Cpp17BasicLockable* requirements (31.2.5.2). Otherwise, each of the mutex types shall satisfy the *Cpp17Lockable* requirements (31.2.5.3).

```cpp
explicit scoped_lock(MutexTypes&... m);

2  **Requires—Expects:** If a *MutexTypes* type is not a recursive mutex, the calling thread does not own the corresponding mutex element of *m*.

3  **Effects:** Initializes *pm* with tie(*m...*). Then if sizeof...(MutexTypes) is 0, no effects. Otherwise if sizeof...(MutexTypes) is 1, then *m.lock()*(). Otherwise, lock(*m...*).

explicit scoped_lock(adopt_lock_t, MutexTypes&... m);

4  **Requires—Expects:** The calling thread owns all the mutexes in *m*.

5  **Effects:** Initializes *pm* with tie(*m...*).

6  **Throws:** Nothing.

~scoped_lock();

7  **Effects:** For all *i* in [0, sizeof...(MutexTypes)), get<i>(*pm*).unlock().

### 31.4.4.3 Class template unique_lock

```cpp
namespace std {
    template<class Mutex>
    class unique_lock {
    public:
        using mutex_type = Mutex;
```
unique_lock() noexcept;
explicit unique_lock(mutex_type& m);
unique_lock(mutex_type& m, defer_lock_t) noexcept;
unique_lock(mutex_type& m, try_to_lock_t);
unique_lock(mutex_type& m, adopt_lock_t);
template<class Clock, class Duration>
  unique_lock(mutex_type& m, const chrono::time_point<Clock, Duration>& abs_time);
template<class Rep, class Period>
  unique_lock(mutex_type& m, const chrono::duration<Rep, Period>& rel_time);
~unique_lock();
unique_lock(const unique_lock&) = delete;
unique_lock& operator=(const unique_lock&) = delete;
unique_lock(unique_lock&& u) noexcept;
unique_lock& operator=(unique_lock&& u);

void lock();
bool try_lock();
template<class Rep, class Period>
  bool try_lock_for(const chrono::duration<Rep, Period>& rel_time);
template<class Clock, class Duration>
  bool try_lock_until(const chrono::time_point<Clock, Duration>& abs_time);
void unlock();

void swap(unique_lock& u, unique_lock& y) noexcept;

An object of type unique_lock controls the ownership of a lockable object within a scope. Ownership of the lockable object can be acquired at construction or after construction, and can be transferred, after acquisition, to another unique_lock object. Objects of type unique_lock are not copyable but are movable. The behavior of a program is undefined if the contained pointer pm is not null and the lockable object pointed to by pm does not exist for the entire remaining lifetime (??) of the unique_lock object. The supplied Mutex type shall meet the Cpp17BasicLockable requirements (31.2.5.2).

[Note: unique_lock<Mutex> meets the Cpp17BasicLockable requirements. If Mutex meets the Cpp17Lockable requirements (31.2.5.3), unique_lock<Mutex> also meets the Cpp17Lockable requirements; if Mutex meets the Cpp17TimedLockable requirements (31.2.5.4), unique_lock<Mutex> also meets the Cpp17TimedLockable requirements. — end note]
explicit unique_lock(mutex_type& m);

    Requires: If mutex_type is not a recursive mutex the calling thread does not own the mutex.
    Effects: Constructs an object of type unique_lock and calls m.lock().
    Ensures: pm == addressof(m) and owns == true.

unique_lock(mutex_type& m, defer_lock_t) noexcept;

    Effects: Constructs an object of type unique_lock.
    Ensures: pm == addressof(m) and owns == false.

unique_lock(mutex_type& m, try_to_lock_t);

    Mandates: The supplied Mutex type meets the Cpp17Lockable requirements (31.2.5.3).
    Requires: The supplied Mutex type shall satisfy the Cpp17Lockable requirements (31.2.5.3)
    Expects: If mutex_type is not a recursive mutex the calling thread does not own the mutex.
    Effects: Constructs an object of type unique_lock and calls m.try_lock().
    Ensures: pm == addressof(m) and owns == res, where res is the value returned by the call to m.try_lock().

unique_lock(mutex_type& m, adopt_lock_t);

    Requires: The calling thread owns the mutex.
    Effects: Constructs an object of type unique_lock.
    Ensures: pm == addressof(m) and owns == true.
    Throws: Nothing.

template<class Clock, class Duration>
unique_lock(mutex_type& m, const chrono::time_point<Clock, Duration>& abs_time);

    Mandates: The supplied Mutex type meets the Cpp17TimedLockable requirements (31.2.5.4).
    Requires: The supplied Mutex type shall satisfy the Cpp17TimedLockable requirements (31.2.5.4).
    Effects: Constructs an object of type unique_lock and calls m.try_lock_until(abs_time).
    Ensures: pm == addressof(m) and owns == res, where res is the value returned by the call to m.try_lock_until(abs_time).

template<class Rep, class Period>
unique_lock(mutex_type& m, const chrono::duration<Rep, Period>& rel_time);

    Mandates: The supplied Mutex type meets the Cpp17TimedLockable requirements (31.2.5.4).
    Requires: The supplied Mutex type shall satisfy the Cpp17TimedLockable requirements (31.2.5.4).
    Effects: Constructs an object of type unique_lock and calls m.try_lock_for(rel_time).
    Ensures: pm == addressof(m) and owns == res, where res is the value returned by the call to m.try_lock_for(rel_time).

unique_lock(unique_lock&& u) noexcept;

    Ensures: pm == u_p.pm and owns == u_p.owns (where u_p is the state of u just prior to this construction), u.pm == 0 and u.owns == false.

unique_lock& operator=(unique_lock&& u);

    Effects: If owns calls pm->unlock().
    Ensures: pm == u_p.pm and owns == u_p.owns (where u_p is the state of u just prior to this construction), u.pm == 0 and u.owns == false.

[Note: With a recursive mutex it is possible for both *this and u to own the same mutex before the assignment. In this case, *this will own the mutex after the assignment and u will not. — end note]

Throws: Nothing.

§ 31.4.4.3.1
~unique_lock();

Effects: If owns calls pm->unlock().

### 31.4.4.3.2 Locking

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

Effects: As if by pm->lock().

Ensures: owns == true.

Throws: Any exception thrown by pm->lock(). system_error when an exception is required (31.2.2).

Error conditions:

- operation_not_permitted — if pm is nullptr.
- resource_deadlock_would_occur — if on entry owns is true.

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

Requires: Mandates: The supplied Mutex shall satisfy meets the Cpp17Lockable requirements (31.2.5.3).

Effects: As if by pm->try_lock().

Returns: The value returned by the call to try_lock().

Ensures: owns == res, where res is the value returned by the call to try_lock().

Throws: Any exception thrown by pm->try_lock(). system_error when an exception is required (31.2.2).

Error conditions:

- operation_not_permitted — if pm is nullptr.
- resource_deadlock_would_occur — if on entry owns is true.

```cpp
template<class Clock, class Duration>
bool try_lock_until(const chrono::time_point<Clock, Duration>& abs_time);
```

Requires: Mandates: The supplied Mutex type shall satisfy meets the Cpp17TimedLockable requirements (31.2.5.4).

Effects: As if by pm->try_lock_until(abs_time).

Returns: The value returned by the call to try_lock_until(abs_time).

Ensures: owns == res, where res is the value returned by the call to try_lock_until(abs_time).

Throws: Any exception thrown by pm->try_lock_until(). system_error when an exception is required (31.2.2).

Error conditions:

- operation_not_permitted — if pm is nullptr.
- resource_deadlock_would_occur — if on entry owns is true.

```cpp
template<class Rep, class Period>
bool try_lock_for(const chrono::duration<Rep, Period>& rel_time);
```

Requires: Mandates: The supplied Mutex type shall satisfy meets the Cpp17TimedLockable requirements (31.2.5.4).

Effects: As if by pm->try_lock_for(rel_time).

Returns: The value returned by the call to try_lock_until(rel_time).

Ensures: owns == res, where res is the value returned by the call to try_lock_until(rel_time).

Throws: Any exception thrown by pm->try_lock_for(). system_error when an exception is required (31.2.2).

Error conditions:

- operation_not_permitted — if pm is nullptr.
- resource_deadlock_would_occur — if on entry owns is true.
void unlock();

23   Effects: As if by pm->unlock().
24   Ensures: owns == false.
25   Throws: system_error when an exception is required (31.2.2).
26   Error conditions:

(26.1) — operation_not_permitted — if on entry owns is false.

31.4.4.3.3 Modifiers

void swap(unique_lock& u) noexcept;

1   Effects: Swaps the data members of *this and u.

mutex_type* release() noexcept;

2   Returns: The previous value of pm.
3   Ensures: pm == 0 and owns == false.

template<class Mutex>
void swap(unique_lock<Mutex>& x, unique_lock<Mutex>& y) noexcept;

4   Effects: As if by x.swap(y).

31.4.4.3.4 Observers

bool owns_lock() const noexcept;

1   Returns: owns.

explicit operator bool() const noexcept;

2   Returns: owns.

mutex_type *mutex() const noexcept;

3   Returns: pm.

31.4.4.4 Class template shared_lock

namespace std {

template<class Mutex>
class shared_lock {
public:
    using mutex_type = Mutex;

    // 31.4.4.4.1, construct/copy/destroy
    shared_lock() noexcept;
    explicit shared_lock(mutex_type& m);     // blocking
    shared_lock(mutex_type& m, defer_lock_t) noexcept;
    shared_lock(mutex_type& m, try_to_lock_t);
    shared_lock(mutex_type& m, adopt_lock_t);
    template<class Clock, class Duration>
    shared_lock(mutex_type& m, const chrono::time_point<Clock, Duration>& abs_time);
    template<class Rep, class Period>
    shared_lock(mutex_type& m, const chrono::duration<Rep, Period>& rel_time);
    ~shared_lock();

    shared_lock(const shared_lock&) = delete;
    shared_lock& operator=(const shared_lock&) = delete;

    shared_lock(shared_lock& u) noexcept;
    shared_lock& operator=(shared_lock& u) noexcept;

    // 31.4.4.4.2, locking
    void lock();          // blocking
    bool try_lock();
template<class Rep, class Period>
  bool try_lock_for(const chrono::duration<Rep, Period>& rel_time);

template<class Clock, class Duration>
  bool try_lock_until(const chrono::time_point<Clock, Duration>& abs_time);

void unlock();

// 31.4.4.4.3, modifiers
void swap(shared_lock& u) noexcept;
mutex_type* release() noexcept;

// 31.4.4.4, observers
bool owns_lock() const noexcept;
explicit operator bool () const noexcept;
mutex_type* mutex() const noexcept;

private:
  mutex_type* pm;
  // exposition only
  bool owns;
  // exposition only
};

template<class Mutex>
  void swap(shared_lock<Mutex>& x, shared_lock<Mutex>& y) noexcept;

1 An object of type shared_lock controls the shared ownership of a lockable object within a scope. Shared
ownership of the lockable object may be acquired at construction or after construction, and may be
transferred, after acquisition, to another shared_lock object. Objects of type shared_lock are not copyable
but are movable. The behavior of a program is undefined if the contained pointer pm is not null and the
lockable object pointed to by pm does not exist for the entire remaining lifetime of the shared_lock
object. The supplied Mutex type shall satisfy the shared mutex requirements (31.4.3.5).

[Note: shared_lock<Mutex> meets the Cpp17TimedLockable requirements (31.2.5.4). — end note]

31.4.4.4.1 Constructors, destructor, and assignment [thread.lock.shared.cons]

shared_lock() noexcept;
  Effects: Constructs an object of type shared_lock.
  Ensures: pm == nullptr and owns == false.

explicit shared_lock(mutex_type& m);
  Requires-Expects: The calling thread does not own the mutex for any ownership mode.
  Effects: Constructs an object of type shared_lock and calls m.lock_shared().
  Ensures: pm == addressof(m) and owns == true.

shared_lock(mutex_type& m, defer_lock_t) noexcept;
  Effects: Constructs an object of type shared_lock.
  Ensures: pm == addressof(m) and owns == false.

shared_lock(mutex_type& m, try_to_lock_t);
  Requires-Expects: The calling thread does not own the mutex for any ownership mode.
  Effects: Constructs an object of type shared_lock and calls m.try_lock_shared().
  Ensures: pm == addressof(m) and owns == res where res is the value returned by the call to
  m.try_lock_shared().

shared_lock(mutex_type& m, adopt_lock_t);
  Requires-Expects: The calling thread has shared ownership of the mutex.
  Effects: Constructs an object of type shared_lock.
  Ensures: pm == addressof(m) and owns == true.
template<class Clock, class Duration>
    shared_lock(mutex_type& m,
        const chrono::time_point<Clock, Duration>& abs_time);

    Requires: The calling thread does not own the mutex for any ownership mode.
    Effects: Constructs an object of type shared_lock and calls m.try_lock_shared_until(abs_time).
    Ensures: pm == addressof(m) and owns == res where res is the value returned by the call to m.try_lock_shared_until(abs_time).

template<class Rep, class Period>
    shared_lock(mutex_type& m,
        const chrono::duration<Rep, Period>& rel_time);

    Requires: The calling thread does not own the mutex for any ownership mode.
    Effects: Constructs an object of type shared_lock and calls m.try_lock_shared_for(rel_time).
    Ensures: pm == addressof(m) and owns == res where res is the value returned by the call to m.try_lock_shared_for(rel_time).

~shared_lock();
    Effects: If owns calls pm->unlock_shared().

shared_lock(shared_lock&& sl) noexcept;
    Ensures: pm == sl_p.pm and owns == sl_p.owns (where sl_p is the state of sl just prior to this construction), sl.pm == nullptr and sl.owns == false.

shared_lock& operator=(shared_lock&& sl) noexcept;
    Effects: If owns calls pm->unlock_shared().
    Ensures: pm == sl_p.pm and owns == sl_p.owns (where sl_p is the state of sl just prior to this assignment), sl.pm == nullptr and sl.owns == false.

31.4.4.4.2 Locking

void lock();
    Effects: As if by pm->lock_shared().
    Ensures: owns == true.
    Throws: Any exception thrown by pm->lock_shared(). system_error when an exception is required (31.2.2).
    Error conditions:
        — operation_not_permitted — if pm is nullptr.
        — resource_deadlock_would_occur — if on entry owns is true.

bool try_lock();
    Effects: As if by pm->try_lock_shared().
    Returns: The value returned by the call to pm->try_lock_shared().
    Ensures: owns == res, where res is the value returned by the call to pm->try_lock_shared().
    Throws: Any exception thrown by pm->try_lock_shared(). system_error when an exception is required (31.2.2).
    Error conditions:
        — operation_not_permitted — if pm is nullptr.
        — resource_deadlock_would_occur — if on entry owns is true.

template<class Clock, class Duration>
    bool try_lock_until(const chrono::time_point<Clock, Duration>& abs_time);
    Effects: As if by pm->try_lock_shared_until(abs_time).
Returns: The value returned by the call to `pm->try_lock_shared_until(abs_time)`.

Ensures: `owns == res`, where `res` is the value returned by the call to `pm->try_lock_shared_until(abs_time)`.

Throws: Any exception thrown by `pm->try_lock_shared_until(abs_time)`. `system_error` when an exception is required (31.2.2).

Error conditions:

- operation_not_permitted — if `pm` is `nullptr`.
- resource_deadlock_would_occur — if on entry `owns` is true.

```cpp
template<class Rep, class Period>
bool try_lock_for(const chrono::duration<Rep, Period>& rel_time);
```

Effects: As if by `pm->try_lock_shared_for(rel_time)`.

Returns: The value returned by the call to `pm->try_lock_shared_for(rel_time)`.

Ensures: `owns == res`, where `res` is the value returned by the call to `pm->try_lock_shared_for(rel_time)`.

Throws: Any exception thrown by `pm->try_lock_shared_for(rel_time)`. `system_error` when an exception is required (31.2.2).

Error conditions:

- operation_not_permitted — if `pm` is `nullptr`.
- resource_deadlock_would_occur — if on entry `owns` is true.

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

Effects: As if by `pm->unlock_shared()`.

Ensures: `owns == false`.

Throws: `system_error` when an exception is required (31.2.2).

Error conditions:

- operation_not_permitted — if on entry `owns` is false.

31.4.4.3 Modifiers

```cpp
void swap(shared_lock& sl) noexcept;
```

Effects: Swaps the data members of `*this` and `sl`.

```cpp
mutex_type* release() noexcept;
```

Returns: The previous value of `pm`.

Ensures: `pm == nullptr` and `owns == false`.

```cpp
template<class Mutex>
void swap(shared_lock<Mutex>& x, shared_lock<Mutex>& y) noexcept;
```

Effects: As if by `x.swap(y)`.

31.4.4.4 Observers

```cpp
bool owns_lock() const noexcept;
```

Returns: `owns`.

```cpp
explicit operator bool() const noexcept;
```

Returns: `owns`.

```cpp
mutex_type* mutex() const noexcept;
```

Returns: `pm`.
31.4.5 Generic locking algorithms

```
template<class L1, class L2, class... L3> int try_lock(L1&, L2&, L3&...);
```

1. **Requires**  
   Each template parameter type shall satisfy the Cpp17Lockable requirements.  
   **Mandates:** The Cpp17Lockable requirements.  
   **[Note: The unique_lock class template meets these requirements when suitably instantiated. — end note]**

2. **Effects:** Calls try_lock() for each argument in order beginning with the first until all arguments have been processed or a call to try_lock() fails, either by returning false or by throwing an exception. If a call to try_lock() fails, unlock() is called for all prior arguments with no further calls to try_lock().

3. **Returns:** -1 if all calls to try_lock() returned true, otherwise a zero-based index value that indicates the argument for which try_lock() returned false.

```
template<class L1, class L2, class... L3> void lock(L1&, L2&, L3&...);
```

4. **Requires**  
   Each template parameter type shall satisfy the Cpp17Lockable requirements.  
   **Mandates:** The Cpp17Lockable requirements.  
   **[Note: The unique_lock class template meets these requirements when suitably instantiated. — end note]**

5. **Effects:** All arguments are locked via a sequence of calls to lock(), try_lock(), or unlock() on each argument. The sequence of calls does not result in deadlock, but is otherwise unspecified.  
   **[Note: A deadlock avoidance algorithm such as try-and-back-off must be used, but the specific algorithm is not specified to avoid over-constraining implementations. — end note]**

   If a call to lock() or try_lock() throws an exception, unlock() is called for any argument that had been locked by a call to lock() or try_lock().

31.4.6 Call once

31.4.6.1 Struct once_flag

```
namespace std {
  struct once_flag {
    constexpr once_flag() noexcept;
    once_flag(const once_flag&) = delete;
    once_flag& operator=(const once_flag&) = delete;
  };
}
```

1. The class once_flag is an opaque data structure that call_once uses to initialize data without causing a data race or deadlock.

```
constexpr once_flag() noexcept;
```

2. **Effects:** Constructs an object of type once_flag.

3. **Synchronization:** The construction of a once_flag object is not synchronized.

4. **Ensures:** The object’s internal state is set to indicate to an invocation of call_once with the object as its initial argument that no function has been called.

31.4.6.2 Function call_once

```
template<class Callable, class... Args>
void call_once(once_flag& flag, Callable&& func, Args&&... args);
```

1. **Requires**  
   INVOLVE(std::forward<Callable>(func), std::forward<Args>(args)...)
   (see ??) shall be a valid expression.  
   **Mandates:**

2. **Effects:** An execution of call_once that does not call its func is a passive execution. An execution of call_once that calls its func is an active execution. An active execution shall call INVOLVE( std::forward<Callable>(func), std::forward<Args>(args)...). If such a call to func throws an exception the execution is exceptional, otherwise it is returning. An exceptional execution shall propagate the exception to the caller of call_once. Among all executions of call_once for any given once_flag: at most one shall be a returning execution; if there is a returning execution, it shall be the last active execution; and there are passive executions only if there is a returning execution.  
   **[Note:
Passive executions allow other threads to reliably observe the results produced by the earlier returning execution. — end note

Synchronization: For any given once_flag: all active executions occur in a total order; completion of an active execution synchronizes with (??) the start of the next one in this total order; and the returning execution synchronizes with the return from all passive executions.

Throws: system_error when an exception is required (31.2.2), or any exception thrown by func.

[Example:

```cpp
// global flag, regular function
void init();
std::once_flag flag;

void f() {
    std::call_once(flag, init);
}

// function static flag, function object
struct initializer {
    void operator()();
};
void g() {
    static std::once_flag flag2;
    std::call_once(flag2, initializer());
}

// object flag, member function
class information {
    std::once_flag verified;
    void verifier();
public:
    void verify() { std::call_once(verified, &information::verifier, *this); }
};

— end example]

31.5 Condition variables [thread.condition]

Condition variables provide synchronization primitives used to block a thread until notified by some other thread that some condition is met or until a system time is reached. Class condition_variable provides a condition variable that can only wait on an object of type unique_lock<mutex>, allowing the implementation to be more efficient. Class condition_variable_any provides a general condition variable that can wait on objects of user-supplied lock types.

Condition variables permit concurrent invocation of the wait, wait_for, wait_until, notify_one and notify_all member functions.

The executions of notify_one and notify_all shall be atomic. The executions of wait, wait_for, and wait_until shall be performed in three atomic parts:

1. the release of the mutex and entry into the waiting state;
2. the unblocking of the wait; and
3. the reacquisition of the lock.

The implementation shall behaves as if all executions of notify_one, notify_all, and each part of the wait, wait_for, and wait_until executions are executed in a single unspecified total order consistent with the "happens before" order.

Condition variable construction and destruction need not be synchronized.

31.5.1 Header <condition_variable> synopsis [condition_variable.syn]

```cpp
namespace std {
    class condition_variable;
    class condition_variable_any;
}
void notify_all_at_thread_exit(condition_variable& cond, unique_lock<mutex> lk);

enum class cv_status { no_timeout, timeout };

31.5.2 Non-member functions

void notify_all_at_thread_exit(condition_variable& cond, unique_lock<mutex> lk);

Requires: lk is locked by the calling thread and either

1. no other thread is waiting on cond, or
2. lk.mutex() returns the same value for each of the lock arguments supplied by all concurrently
   waiting (via wait, wait_for, or wait_until) threads.

Effects: Transfers ownership of the lock associated with lk into internal storage and schedules cond to
be notified when the current thread exits, after all objects of thread storage duration associated with
the current thread have been destroyed. This notification shall be as equivalent to:

lk.unlock();
cond.notify_all();

Synchronization: The implied lk.unlock() call is sequenced after the destruction of all objects with
thread storage duration associated with the current thread.

[Note: The supplied lock will be held until the thread exits, and care should be taken to ensure that
this does not cause deadlock due to lock ordering issues. After calling notify_all_at_thread_exit
it is recommended that the thread should be exited as soon as possible, and that no blocking or
time-consuming tasks are run on that thread. — end note]

[Note: It is the user’s responsibility to ensure that waiting threads do not erroneously assume that the
thread has finished if they experience spurious wakeups. This typically requires that the condition being
waited for is satisfied while holding the lock on lk, and that this lock is not released and reacquired
prior to calling notify_all_at_thread_exit. — end note]

31.5.3 Class condition_variable

namespace std {

class condition_variable {

public:

condition_variable();
~condition_variable();

condition_variable(const condition_variable&) = delete;
condition_variable& operator=(const condition_variable&) = delete;

void notify_one() noexcept;
void notify_all() noexcept;
void wait(unique_lock<mutex>& lock);

template<class Predicate>
void wait(unique_lock<mutex>& lock, Predicate pred);

template<class Clock, class Duration>
cv_status wait_until(unique_lock<mutex>& lock,
const chrono::time_point<Clock, Duration>& abs_time);

template<class Clock, class Duration, class Predicate>
bool wait_until(unique_lock<mutex>& lock,
const chrono::time_point<Clock, Duration>& abs_time,
Predicate pred);

template<class Rep, class Period>
cv_status wait_for(unique_lock<mutex>& lock,
const chrono::duration<Rep, Period>& rel_time);

template<class Rep, class Period, class Predicate>
bool wait_for(unique_lock<mutex>& lock,
const chrono::duration<Rep, Period>& rel_time,
Predicate pred);

};
The class `condition_variable` shall be a standard-layout class.

```cpp
condition_variable();
```

**Effects:** Constructs an object of type `condition_variable`.

**Throws:** `system_error` when an exception is required (31.2.2).

**Error conditions:**

1. `resource_unavailable_try_again` — if some non-memory resource limitation prevents initialization.

```cpp
~condition_variable();
```

**Requires: Expects:** There shall be no thread blocked on `*this`. [Note: That is, all threads shall have been notified; they may have subsequently block on the lock specified in the wait. This relaxes the usual rules, which would have required all wait calls to happen before destruction. Only the notification to unblock the wait needs to happen before destruction. The user should take care to ensure that no threads wait on `*this` once the destructor has been started, especially when the waiting threads are calling the wait functions in a loop or using the overloads of `wait`, `wait_for`, or `wait_until` that take a predicate. — end note]

**Effects:** Destroys the object.

```cpp
void notify_one() noexcept;
```

**Effects:** If any threads are blocked waiting for `*this`, unblocks one of those threads.

```cpp
void notify_all() noexcept;
```

**Effects:** Unblocks all threads that are blocked waiting for `*this`.

```cpp
void wait(unique_lock<mutex>& lock);
```

**Requires: Expects:** `lock.owns_lock()` is `true` and `lock.mutex()` is locked by the calling thread, and either

1. no other thread is waiting on this `condition_variable` object or
2. `lock.mutex()` returns the same value for each of the `lock` arguments supplied by all concurrently waiting (via `wait`, `wait_for`, or `wait_until`) threads.

**Effects:**

1. Atomically calls `lock.unlock()` and blocks on `*this`.
2. When unblocked, calls `lock.lock()` (possibly blocking on the lock), then returns.
3. The function will unblock when signaled by a call to `notify_one()` or a call to `notify_all()`, or spuriously.

**Remarks:** If the function fails to meet the postcondition, `terminate()` shall be called. [Note: This can happen if the re-locking of the mutex throws an exception. — end note]

**Ensures:** `lock.owns_lock()` is `true` and `lock.mutex()` is locked by the calling thread.

**Throws:** Nothing.

```cpp
template<class Predicate>
void wait(unique_lock<mutex>& lock, Predicate pred);
```

**Requires: Expects:** `lock.owns_lock()` is `true` and `lock.mutex()` is locked by the calling thread, and either

1. no other thread is waiting on this `condition_variable` object or
2. `lock.mutex()` returns the same value for each of the `lock` arguments supplied by all concurrently waiting (via `wait`, `wait_for`, or `wait_until`) threads.
Effects: Equivalent to:

\[
\text{while (!pred())}
\text{wait(lock);}\]

Remarks: If the function fails to meet the postcondition, \text{terminate()} \text{shall be} called (\text{??}). [Note: This can happen if the re-locking of the mutex throws an exception. — end note]

Ensures: lock.owns_lock() is true and lock.mutex() is locked by the calling thread.

Throws: Any exception thrown by \text{pred}.

template<class Clock, class Duration>
cv_status wait_until(unique_lock<mutex>& lock,
  const chrono::time_point<Clock, Duration>& abs_time);

Requires-Expects: lock.owns_lock() is true and lock.mutex() is locked by the calling thread, and either

(19.1) — no other thread is waiting on this \text{condition_variable} object or
(19.2) — lock.mutex() returns the same value for each of the lock arguments supplied by all concurrently waiting (via \text{wait, wait_for, or wait_until}) threads.

Effects:

(20.1) — Atomically calls lock.unlock() and blocks on *this.
(20.2) — When unblocked, calls lock.lock() (possibly blocking on the lock), then returns.
(20.3) — The function will unblock when signaled by a call to notify_one(), a call to notify_all(), expiration of the absolute timeout (31.2.4) specified by \text{abs_time}, or spuriously.
(20.4) — If the function exits via an exception, lock.lock() \text{shall be} called prior to exiting the function.

Remarks: If the function fails to meet the postcondition, \text{terminate()} \text{shall be} called (\text{??}). [Note: This can happen if the re-locking of the mutex throws an exception. — end note]

Ensures: lock.owns_lock() is true and lock.mutex() is locked by the calling thread.

Returns: \text{cv_status::timeout} if the absolute timeout (31.2.4) specified by \text{abs_time} expired, otherwise \text{cv_status::no_timeout}.

Throws: Timeout-related exceptions (31.2.4).

template<class Rep, class Period>
cv_status wait_for(unique_lock<mutex>& lock,
  const chrono::duration<Rep, Period>& rel_time);

Requires-Expects: lock.owns_lock() is true and lock.mutex() is locked by the calling thread, and either

(25.1) — no other thread is waiting on this \text{condition_variable} object or
(25.2) — lock.mutex() returns the same value for each of the lock arguments supplied by all concurrently waiting (via \text{wait, wait_for, or wait_until}) threads.

Effects: Equivalent to:

\[
\text{return wait_until(lock, chrono::steady_clock::now() + rel_time);}\]

Returns: \text{cv_status::timeout} if the relative timeout (31.2.4) specified by \text{rel_time} expired, otherwise \text{cv_status::no_timeout}.

Remarks: If the function fails to meet the postcondition, \text{terminate()} \text{shall be} called (\text{??}). [Note: This can happen if the re-locking of the mutex throws an exception. — end note]

Ensures: lock.owns_lock() is true and lock.mutex() is locked by the calling thread.

Throws: Timeout-related exceptions (31.2.4).

template<class Clock, class Duration, class Predicate>
bool wait_until(unique_lock<mutex>& lock,
  const chrono::time_point<Clock, Duration>& abs_time,
Predicate pred);

**Requires—Expects:** lock.owns_lock() is true and lock.mutex() is locked by the calling thread, and either

— no other thread is waiting on this condition_variable object or

— lock.mutex() returns the same value for each of the lock arguments supplied by all concurrently waiting (via wait, wait_for, or wait_until) threads.

**Effects:** Equivalent to:

```cpp
while (!pred())
    if (wait_until(lock, abs_time) == cv_status::timeout)
        return pred();
    return true;
```

**Remarks:** If the function fails to meet the postcondition, terminate() shall be called (??). [Note: This can happen if the re-locking of the mutex throws an exception. — end note]

**Ensures:** lock.owns_lock() is true and lock.mutex() is locked by the calling thread.

[Note: The returned value indicates whether the predicate evaluated to true regardless of whether the timeout was triggered. — end note]

**Throws:** Timeout-related exceptions (31.2.4) or any exception thrown by pred.

```cpp
template<class Rep, class Period, class Predicate>
bool wait_for(unique_lock<mutex>& lock,
              const chrono::duration<Rep, Period>& rel_time,
              Predicate pred);
```

**Requires—Expects:** lock.owns_lock() is true and lock.mutex() is locked by the calling thread, and either

— no other thread is waiting on this condition_variable object or

— lock.mutex() returns the same value for each of the lock arguments supplied by all concurrently waiting (via wait, wait_for, or wait_until) threads.

**Effects:** Equivalent to:

```cpp
return wait_until(lock, chrono::steady_clock::now() + rel_time, std::move(pred));
```

[Note: There is no blocking if pred() is initially true, even if the timeout has already expired. — end note]

**Remarks:** If the function fails to meet the postcondition, terminate() shall be called (??). [Note: This can happen if the re-locking of the mutex throws an exception. — end note]

**Ensures:** lock.owns_lock() is true and lock.mutex() is locked by the calling thread.

[Note: The returned value indicates whether the predicate evaluates to true regardless of whether the timeout was triggered. — end note]

**Throws:** Timeout-related exceptions (31.2.4) or any exception thrown by pred.

### 31.5.4 Class condition_variable_any

A Lock type shall satisfy the Cpp17BasicLockable requirements (31.2.5.2). [Note: All of the standard mutex types meet this requirement. If a Lock type other than one of the standard mutex types or a unique_lock wrapper for a standard mutex type is used with condition_variable_any, the user should ensure that any necessary synchronization is in place with respect to the predicate associated with the condition_variable_any instance. — end note]

```cpp
namespace std {
    class condition_variable_any {
        public:
            condition_variable_any();
            ~condition_variable_any();

            condition_variable_any(const condition_variable_any&) = delete;
            condition_variable_any& operator=(const condition_variable_any&) = delete;
    }
}
```
void notify_one() noexcept;
void notify_all() noexcept;
template<class Lock>
void wait(Lock& lock);
template<class Lock, class Predicate>
void wait(Lock& lock, Predicate pred);

template<class Lock, class Clock, class Duration>
cv_status wait_until(Lock& lock, const chrono::time_point<Clock, Duration>& abs_time);
template<class Lock, class Clock, class Duration, class Predicate>
bool wait_until(Lock& lock, const chrono::time_point<Clock, Duration>& abs_time, Predicate pred);
template<class Lock, class Rep, class Period>
cv_status wait_for(Lock& lock, const chrono::duration<Rep, Period>& rel_time);
template<class Lock, class Rep, class Period, class Predicate>
bool wait_for(Lock& lock, const chrono::duration<Rep, Period>& rel_time, Predicate pred);
};
}

condition_variable_any();

Effects: Constructs an object of type condition_variable_any.

Throws: bad_alloc or system_error when an exception is required (31.2.2).

Error conditions:
(4.1) — resource_unavailable_try_again — if some non-memory resource limitation prevents initialization.
(4.2) — operation_not_permitted — if the thread does not have the privilege to perform the operation.

~condition_variable_any();

Requires—Expects: There shall be no thread blocked on *this. [Note: That is, all threads shall have been notified; they may subsequently block on the lock specified in the wait. This relaxes the usual rules, which would have required all wait calls to happen before destruction. Only the notification to unblock the wait needs to happen before destruction. The user should take care to ensure that no threads wait on *this once the destructor has been started, especially when the waiting threads are calling the wait functions in a loop or using the overloads of wait, wait_for, or wait_until that take a predicate. — end note]

Effects: Destroys the object.

void notify_one() noexcept;

Effects: If any threads are blocked waiting for *this, unblocks one of those threads.

void notify_all() noexcept;

Effects: Unblocks all threads that are blocked waiting for *this.

template<class Lock>
void wait(Lock& lock);

Effects:
(9.1) — Atomically calls lock.unlock() and blocks on *this.
(9.2) — When unblocked, calls lock.lock() (possibly blocking on the lock) and returns.
(9.3) — The function will unblock when signaled by a call to notify_one(), a call to notify_all(), or spuriously.

Remarks: If the function fails to meet the postcondition, terminate() shall have been called (??). [Note: This can happen if the re-locking of the mutex throws an exception. — end note]

Ensures: lock is locked by the calling thread.

Throws: Nothing.
template<class Lock, class Predicate>
    void wait(Lock& lock, Predicate pred);

Effects: Equivalent to:
    while (!pred())
        wait(lock);

template<class Lock, class Clock, class Duration>
    cv_status wait_until(Lock& lock, const chrono::time_point<Clock, Duration>& abs_time);

Effects:
(14.1) — Atomically calls `lock.unlock()` and blocks on `*this`.
(14.2) — When unblocked, calls `lock.lock()` (possibly blocking on the lock) and returns.
(14.3) — The function will unblock when signaled by a call to `notify_one()`, a call to `notify_all()`,
expiration of the absolute timeout (31.2.4) specified by `abs_time`, or spuriously.
(14.4) — If the function exits via an exception, `lock.lock()` shall beis called prior to exiting the function.

Remarks: If the function fails to meet the postcondition, `terminate()` shall beis called (??). [Note:
This can happen if the re-locking of the mutex throws an exception. — end note]

Ensures: `lock` is locked by the calling thread.

Returns: `cv_status::timeout` if the absolute timeout (31.2.4) specified by `abs_time` expired, otherwise
          `cv_status::no_timeout`.

Throws: Timeout-related exceptions (31.2.4).

template<class Lock, class Rep, class Period>
    cv_status wait_for(Lock& lock, const chrono::duration<Rep, Period>& rel_time);

Effects: Equivalent to:
    return wait_until(lock, chrono::steady_clock::now() + rel_time);

Returns: `cv_status::timeout` if the relative timeout (31.2.4) specified by `rel_time` expired, otherwise
          `cv_status::no_timeout`.

Remarks: If the function fails to meet the postcondition, `terminate()` shall beis called (??). [Note:
This can happen if the re-locking of the mutex throws an exception. — end note]

Ensures: `lock` is locked by the calling thread.

Throws: Timeout-related exceptions (31.2.4).

template<class Lock, class Clock, class Duration, class Predicate>
    bool wait_until(Lock& lock, const chrono::time_point<Clock, Duration>& abs_time, Predicate pred);

Effects: Equivalent to:
    while (!pred())
        if (wait_until(lock, abs_time) == cv_status::timeout)
            return pred();
        return true;

[Note: There is no blocking if `pred()` is initially `true`, or if the timeout has already expired. — end note]

[Note: The returned value indicates whether the predicate evaluates to `true` regardless of whether the
    timeout was triggered. — end note]

template<class Lock, class Rep, class Period, class Predicate>
    bool wait_for(Lock& lock, const chrono::duration<Rep, Period>& rel_time, Predicate pred);

Effects: Equivalent to:
    return wait_until(lock, chrono::steady_clock::now() + rel_time, std::move(pred));
31.6 Futures [futures]

31.6.1 Overview [futures.overview]

31.6 describes components that a C++ program can use to retrieve in one thread the result (value or exception) from a function that has run in the same thread or another thread. [Note: These components are not restricted to multi-threaded programs but can be useful in single-threaded programs as well. — end note]

31.6.2 Header <future> synopsis [future.syn]

```cpp
namespace std {
    enum class future_errc {
        broken_promise = implementation-defined,
        future_already_retrieved = implementation-defined,
        promise_already_satisfied = implementation-defined,
        no_state = implementation-defined
    };

    enum class launch : unspecified {
        async = unspecified,
        deferred = unspecified,
        implementation-defined
    };

    enum class future_status {
        ready,
        timeout,
        deferred
    };

    template<> struct is_error_code_enum<future_errc> : public true_type { };
	error_code make_error_code(future_errc e) noexcept;
	error_condition make_error_condition(future_errc e) noexcept;

    const error_category& future_category() noexcept;

    class future_error;

    template<class R> class promise;
    template<class R> class promise<R&>;
    template<> class promise<void>;

    template<class R>
    void swap(promise<R>& x, promise<R>& y) noexcept;

    template<class R, class Alloc>
    struct uses_allocator<promise<R>, Alloc>;

    template<class R> class future;
    template<class R> class future<R&>;
    template<> class future<void>;

    template<class R> class shared_future;
    template<class R> class shared_future<R&>;
    template<> class shared_future<void>;

    template<class> class packaged_task;  // not defined
    template<class R, class... Args>
    class packaged_task<R(ArgTypes...)>;

    template<class R, class... Args>
    void swap(packaged_task<R(ArgTypes...)>&, packaged_task<R(ArgTypes...)>&) noexcept;

    template<class F, class... Args>
    [[nodiscard]] future<invoke_result_t<decay_t<F>, decay_t<Args>...>>
    async(F&& f, Args&& args);
```
The enum type `launch` is a bitmask type (??) with elements `launch::async` and `launch::deferred`. [Note: Implementations can provide bitmasks to specify restrictions on task interaction by functions launched by `async()` applicable to a corresponding subset of available launch policies. Implementations can extend the behavior of the first overload of `async()` by adding their extensions to the launch policy under the “as if” rule. —end note]

The enum values of `future_errc` are distinct and not zero.

### 31.6.3 Error handling

```cpp
const error_category& future_category() noexcept;
```

**Returns:** A reference to an object of a type derived from class `error_category`.

The object’s `default_error_condition` and equivalent virtual functions shall behave as specified for the class `error_category`. The object’s `name` virtual function shall return a pointer to the string "future".

```cpp
error_code make_error_code(future_errc e) noexcept;
```

**Returns:** `error_code(static_cast<int>(e), future_category())`.

```cpp
error_condition make_error_condition(future_errc e) noexcept;
```

**Returns:** `error_condition(static_cast<int>(e), future_category())`.

### 31.6.4 Class `future_error`

```cpp
namespace std {
    class future_error : public logic_error {
        public:
            explicit future_error(future_errc e);

            const error_code& code() const noexcept;
            const char* what() const noexcept;

        private:
            error_code ec_; // exposition only
        };
    }
```

**Explicit future_error(future_errc e);**

**Effects:** Constructs an object of class `future_error` and initializes `ec_` with `make_error_code(e)`.

**Returns:** `ec_`.

**Const char* what() const noexcept;**

**Returns:** An `ntbs` incorporating `code().message()`.

### 31.6.5 Shared state

Many of the classes introduced in this subclause use some state to communicate results. This *shared state* consists of some state information and some (possibly not yet evaluated) result, which can be a (possibly void) value or an exception. [Note: Futures, promises, and tasks defined in this clause reference such shared state. —end note]

[Note: The result can be any kind of object including a function to compute that result, as used by `async` when policy is `launch::deferred`. —end note]

An *asynchronous return object* is an object that reads results from a shared state. A *waiting function* of an asynchronous return object is one that potentially blocks to wait for the shared state to be made ready. If a
waiting function can return before the state is made ready because of a timeout (31.2.5), then it is a **timed waiting function**, otherwise it is a **non-timed waiting function**.

An **asynchronous provider** is an object that provides a result to a shared state. The result of a shared state is set by respective functions on the asynchronous provider. [Note: Such as promises or tasks. — end note] The means of setting the result of a shared state is specified in the description of those classes and functions that create such a state object.

When an asynchronous return object or an asynchronous provider is said to release its shared state, it means:

1. **(5.1)** if the return object or provider holds the last reference to its shared state, the shared state is destroyed; and
2. **(5.2)** the return object or provider gives up its reference to its shared state; and
3. **(5.3)** these actions will not block for the shared state to become ready, except that it **can** block if all of the following are true: the shared state was created by a call to `std::async`, the shared state is not yet ready, and this was the last reference to the shared state.

When an asynchronous provider is said to make its shared state ready, it means:

1. **(6.1)** first, the provider marks its shared state as ready; and
2. **(6.2)** second, the provider unblocks any execution agents waiting for its shared state to become ready.

When an asynchronous provider is said to abandon its shared state, it means:

1. **(7.1)** first, if that state is not ready, the provider
   - **(7.1.1)** stores an exception object of type `future_error` with an error condition of `broken.promise` within its shared state; and then
   - **(7.1.2)** makes its shared state ready;
2. **(7.2)** second, the provider releases its shared state.

A shared state is **ready** only if it holds a value or an exception ready for retrieval. Waiting for a shared state to become ready **can** invoke code to compute the result on the waiting thread if so specified in the description of the class or function that creates the state object.

Calls to functions that successfully set the stored result of a shared state synchronize with (??) calls to functions successfully detecting the ready state resulting from that setting. The storage of the result (whether normal or exceptional) into the shared state synchronizes with (??) the successful return from a call to a waiting function on the shared state.

Some functions (e.g., `promise::set_value_at_thread_exit`) delay making the shared state ready until the calling thread exits. The destruction of each of that thread’s objects with thread storage duration (??) is sequenced before making that shared state ready.

Access to the result of the same shared state **can** conflict (??). [Note: This explicitly specifies that the result of the shared state is visible in the objects that reference this state in the sense of data race avoidance (??). For example, concurrent accesses through references returned by `shared_future::get()` (31.6.8) must either use read-only operations or provide additional synchronization. — end note]

### 31.6.6 Class template `promise`

```cpp
namespace std {
    template<class R>
    class promise {
public:
        promise();
        template<class Allocator>
        promise(allocator_arg_t, const Allocator& a);
        promise(promise&& rhs) noexcept;
        promise(const promise& rhs) = delete;
        ~promise();

        // assignment
        promise& operator=(promise&& rhs) noexcept;
        promise& operator=(const promise& rhs) = delete;
        void swap(promise& other) noexcept;
    }
}
```
The implementation shall provide the template `promise` and two specializations, `promise<R&>` and `promise<void>`. These differ only in the argument type of the member functions `set_value` and `set_value_at_thread_exit`, as set out in their descriptions, below.

The `set_value`, `set_exception`, `set_value_at_thread_exit`, and `set_exception_at_thread_exit` member functions behave as though they acquire a single mutex associated with the promise object while updating the promise object.

```cpp
template<class R>
void swap(promise<R>& x, promise<R>& y) noexcept;

template<class R, class Alloc>
struct uses_allocator<promise<R>, Alloc>;
```

1. The implementation shall provide the template `promise` and two specializations, `promise<R&>` and `promise<void>`. These differ only in the argument type of the member functions `set_value` and `set_value_at_thread_exit`, as set out in their descriptions, below.

2. The `set_value`, `set_exception`, `set_value_at_thread_exit`, and `set_exception_at_thread_exit` member functions behave as though they acquire a single mutex associated with the promise object while updating the promise object.

```cpp
template<class R, class Alloc>
struct uses_allocator<promise<R>, Alloc> : true_type { };
```

3. Requires: Alloc shall satisfy meets the Cpp17Allocator requirements (Table ??).

```cpp
promise();
```

4. Effects: Constructs a promise object and creates a shared state. The second constructor uses the allocator `a` to allocate memory for the shared state.

```cpp
template<class Allocator>
promise(allocator_arg_t, const Allocator& a);
```

5. Effects: Constructs a new promise object and transfers ownership of the shared state of `rhs` (if any) to the newly-constructed object.

6. Ensures: `rhs` has no shared state.

```cpp
~promise();
```

7. Effects: Abandons any shared state (31.6.5).

```cpp
promise& operator=(promise&& rhs) noexcept;
```

8. Effects: Abandons any shared state (31.6.5) and then as if `promise(std::move(rhs)).swap(*this)`.

9. Returns: *this.

```cpp
void swap(promise& other) noexcept;
```

10. Effects: Exchanges the shared state of *this and other.

11. Ensures: *this has the shared state (if any) that other had prior to the call to swap. other has the shared state (if any) that *this had prior to the call to swap.

```cpp
future<R> get_future();
```

12. Returns: A future<R> object with the same shared state as *this.

```cpp
§ 31.6.6
```

13. Synchronization: Calls to this function do not introduce data races (??) with calls to `set_value`, `set_exception`, `set_value_at_thread_exit`, or `set_exception_at_thread_exit`. [Note: Such calls need not synchronize with each other. — end note]
Throws: `future_error` if `*this` has no shared state or if `get_future` has already been called on a `promise` with the same shared state as `*this`.

Error conditions:

(15.1) `future_already_retrieved` if `get_future` has already been called on a `promise` with the same shared state as `*this`.

(15.2) `no_state` if `*this` has no shared state.

```cpp
void promise::set_value(const R& r);
void promise::set_value(R&& r);
void promise<R&>::set_value(R& r);
void promise<void>::set_value();
```

Effects: Atomically stores the value `r` in the shared state and makes that state ready (31.6.5).

Throws:

(17.1) `future_error` if its shared state already has a stored value or exception, or

(17.2) for the first version, any exception thrown by the constructor selected to copy an object of `R`, or

(17.3) for the second version, any exception thrown by the constructor selected to move an object of `R`.

Error conditions:

(18.1) `promise_already_satisfied` if its shared state already has a stored value or exception.

(18.2) `no_state` if `*this` has no shared state.

```cpp
void set_exception(exception_ptr p);
```

Requires: `p` is not null.

Effects: Atomically stores the exception pointer `p` in the shared state and makes that state ready (31.6.5).

Throws: `future_error` if its shared state already has a stored value or exception.

Error conditions:

(22.1) `promise_already_satisfied` if its shared state already has a stored value or exception.

(22.2) `no_state` if `*this` has no shared state.

```cpp
void promise::set_value_at_thread_exit(const R& r);
void promise::set_value_at_thread_exit(R&& r);
void promise<R&>::set_value_at_thread_exit(R& r);
void promise<void>::set_value_at_thread_exit();
```

Effects: Stores the value `r` in the shared state without making that state ready immediately. Schedules that state to be made ready when the current thread exits, after all objects of thread storage duration associated with the current thread have been destroyed.

Throws:

(24.1) `future_error` if its shared state already has a stored value or exception, or

(24.2) for the first version, any exception thrown by the constructor selected to copy an object of `R`, or

(24.3) for the second version, any exception thrown by the constructor selected to move an object of `R`.

Error conditions:

(25.1) `promise_already_satisfied` if its shared state already has a stored value or exception.

(25.2) `no_state` if `*this` has no shared state.

```cpp
void set_exception_at_thread_exit(exception_ptr p);
```

Requires: `p` is not null.

Effects: Stores the exception pointer `p` in the shared state without making that state ready immediately. Schedules that state to be made ready when the current thread exits, after all objects of thread storage duration associated with the current thread have been destroyed.

Throws: `future_error` if an error condition occurs.

Error conditions:
template<class R>
    void swap(promise<R>& x, promise<R>& y) noexcept;

30
    Effects: As if by x.swap(y).

31.6.7 Class template future

The class template future defines a type for asynchronous return objects which do not share their shared state with other asynchronous return objects. A default-constructed future object has no shared state. A future object with shared state can be created by functions on asynchronous providers (31.6.5) or by the move constructor and shares its shared state with the original asynchronous provider. The result (value or exception) of a future object can be set by calling a respective function on an object that shares the same shared state.

1 [Note: Member functions of future do not synchronize with themselves or with member functions of shared_future. — end note]

2 The effect of calling any member function other than the destructor, the move-assignment operator, share, or valid on a future object for which valid() == false is undefined. [Note: It is valid to move from a future object for which valid() == false. — end note] [Note: Implementations should detect this case and throw an object of type future_error with an error condition of future_errc::no_state. — end note]

namespace std {
    template<class R>
    class future {
        public:
            future() noexcept;
            future(future&&) noexcept;
            future(const future& rhs) = delete;
            ~future();
            future& operator=(const future& rhs) = delete;
            future& operator=(future&&) noexcept;
            shared_future<R> share() noexcept;

                // retrieving the value
                see below get();

                // functions to check state
                bool valid() const noexcept;

                void wait() const;
                template<class Rep, class Period>
                    future_status wait_for(const chrono::duration<Rep, Period>& rel_time) const;
                template<class Clock, class Duration>
                    future_status wait_until(const chrono::time_point<Clock, Duration>& abs_time) const;
    };
}

4 The implementation shall provide the template future and two specializations, future<R&> and future<void>. These differ only in the return type and return value of the member function get, as set out in its description, below.

future() noexcept;

5 Effects: Constructs an empty future object that does not refer to a shared state.

6 Ensures: valid() == false.

future(future&& rhs) noexcept;

7 Effects: Move constructs a future object that refers to the shared state that was originally referred to by rhs (if any).

8 Ensures:
(8.1) — valid() returns the same value as rhs.valid() prior to the constructor invocation.

(8.2) — rhs.valid() == false.

-future();

Effects:

(9.1) — Releases any shared state (31.6.5);

(9.2) — destroys *this.

future& operator=(future&& rhs) noexcept;

Effects:

(10.1) — Releases any shared state (31.6.5).

(10.2) — move assigns the contents of rhs to *this.

Ensures:

(11.1) — valid() returns the same value as rhs.valid() prior to the assignment.

(11.2) — rhs.valid() == false.

shared_future<R> share() noexcept;

Returns: shared_future<R>(std::move(*this)).

Ensures: valid() == false.

R future::get();
R& future<R&>::get();
void future<void>::get();

[Note: As described above, the template and its two required specializations differ only in the return type and return value of the member function get. — end note]

Effects:

(15.1) — wait()s until the shared state is ready, then retrieves the value stored in the shared state;

(15.2) — releases any shared state (31.6.5).

Returns:

(16.1) — future::get() returns the value v stored in the object’s shared state as std::move(v).

(16.2) — future<R&>::get() returns the reference stored as value in the object’s shared state.

(16.3) — future<void>::get() returns nothing.

Throws: The stored exception, if an exception was stored in the shared state.

Ensures: valid() == false.

bool valid() const noexcept;

Returns: true only if *this refers to a shared state.

void wait() const;

Effects: Blocks until the shared state is ready.

template<class Rep, class Period>
future_status wait_for(const chrono::duration<Rep, Period>& rel_time) const;

Effects: None if the shared state contains a deferred function (31.6.9), otherwise blocks until the shared state is ready or until the relative timeout (31.2.4) specified by rel_time has expired.

Returns:

(22.1) — future_status::deferred if the shared state contains a deferred function.

(22.2) — future_status::ready if the shared state is ready.

(22.3) — future_status::timeout if the function is returning because the relative timeout (31.2.4) specified by rel_time has expired.

Throws: timeout-related exceptions (31.2.4).
### 31.6.8  Class template `shared_future` [futures.shared_future]

The class template `shared_future` defines a type for asynchronous return objects which may share their shared state with other asynchronous return objects. A default-constructed `shared_future` object has no shared state. A `shared_future` object with shared state can be created by conversion from a `future` object and shares its shared state with the original asynchronous provider (31.6.5) of the shared state. The result (value or exception) of a `shared_future` object can be set by calling a respective function on an object that shares the same shared state.

1. **Note:** Member functions of `shared_future` do not synchronize with themselves, but they synchronize with the shared state. — *end note*

2. The effect of calling any member function other than the destructor, the move-assignment operator, the copy-assignment operator, or valid() on a `shared_future` object for which valid() == false is undefined. **Note:** It is valid to copy or move from a `shared_future` object for which valid() is false. — *end note*

3. **Note:** Implementations should detect this case and throw an object of type `future_error` with an error condition of `future_errc::no_state`. — *end note*

```cpp
namespace std {
    template<class R>
    class shared_future {
    public:
        shared_future() noexcept;
        shared_future(const shared_future& rhs) noexcept;
        shared_future(future<R>&&) noexcept;
        shared_future(shared_future&& rhs) noexcept;
        ~shared_future();
        shared_future& operator=(const shared_future& rhs);
        shared_future& operator=(shared_future&& rhs);

        // retrieving the value
        see below get() const;

        // functions to check state
        bool valid() const noexcept;

        void wait() const;

        template<class Rep, class Period>
        future_status wait_for(const chrono::duration<Rep, Period>& rel_time) const;

        template<class Clock, class Duration>
        future_status wait_until(const chrono::time_point<Clock, Duration>& abs_time) const;
    };
}
```

4. The implementation shall provides the template `shared_future` and two specializations, `shared_future<R&>` and `shared_future<void>`. These differ only in the return type and return value of the member function `get`, as set out in its description, below.

```cpp
shared_future() noexcept;
```

5. **Effects:** Constructs an empty `shared_future` object that does not refer to a shared state.

6. **Ensures:** valid() == false.
shared_future(const shared_future& rhs) noexcept;

Effects: Constructs a shared_future object that refers to the same shared state as rhs (if any).

Ensures: valid() returns the same value as rhs.valid().

shared_future(future<R>&& rhs) noexcept;
shared_future(shared_future&& rhs) noexcept;

Effects: Move constructs a shared_future object that refers to the shared state that was originally referred to by rhs (if any).

Ensures:

(10.1) valid() returns the same value as rhs.valid() returned prior to the constructor invocation.
(10.2) rhs.valid() == false.

~shared_future();

Effects:

(11.1) Releases any shared state (31.6.5);
(11.2) destroys *this.

shared_future& operator=(shared_future&& rhs) noexcept;

Effects:

(12.1) Releases any shared state (31.6.5);
(12.2) move assigns the contents of rhs to *this.

Ensures:

(13.1) valid() returns the same value as rhs.valid() returned prior to the assignment.
(13.2) rhs.valid() == false.

shared_future& operator=(const shared_future& rhs) noexcept;

Effects:

(14.1) Releases any shared state (31.6.5);
(14.2) assigns the contents of rhs to *this. [Note: As a result, *this refers to the same shared state as rhs (if any). — end note]

Ensures: valid() == rhs.valid().

const R& shared_future::get() const;
R& shared_future<R&>::get() const;
void shared_future<void>::get() const;

[Note: As described above, the template and its two required specializations differ only in the return type and return value of the member function get. — end note]

[Note: Access to a value object stored in the shared state is unsynchronized, so programmers should apply only those operations on R that do not introduce a data race (??). — end note]

Effects: wait()s until the shared state is ready, then retrieves the value stored in the shared state.

Returns:

(19.1) shared_future::get() returns a const reference to the value stored in the object’s shared state. [Note: Access through that reference after the shared state has been destroyed produces undefined behavior; this can be avoided by not storing the reference in any storage with a greater lifetime than the shared_future object that returned the reference. — end note]
(19.2) shared_future<R&>::get() returns the reference stored as value in the object’s shared state.
(19.3) shared_future<void>::get() returns nothing.

Throws: The stored exception, if an exception was stored in the shared state.

bool valid() const noexcept;

Returns: true only if *this refers to a shared state.
void wait() const;

Effects: Blocks until the shared state is ready.

template<class Rep, class Period>
future_status wait_for(const chrono::duration<Rep, Period>& rel_time) const;

Effects: None if the shared state contains a deferred function (31.6.9), otherwise blocks until the shared
state is ready or until the relative timeout (31.2.4) specified by rel_time has expired.

Returns:
(24.1) — future_status::deferred if the shared state contains a deferred function.
(24.2) — future_status::ready if the shared state is ready.
(24.3) — future_status::timeout if the function is returning because the relative timeout (31.2.4) specified
by rel_time has expired.

Throws: timeout-related exceptions (31.2.4).

template<class Clock, class Duration>
future_status wait_until(const chrono::time_point<Clock, Duration>& abs_time) const;

Effects: None if the shared state contains a deferred function (31.6.9), otherwise blocks until the shared
state is ready or until the absolute timeout (31.2.4) specified by abs_time has expired.

Returns:
(27.1) — future_status::deferred if the shared state contains a deferred function.
(27.2) — future_status::ready if the shared state is ready.
(27.3) — future_status::timeout if the function is returning because the absolute timeout (31.2.4)
specified by abs_time has expired.

Throws: timeout-related exceptions (31.2.4).

31.6.9 Function template async

The function template async provides a mechanism to launch a function potentially in a new thread and
provides the result of the function in a future object with which it shares a shared state.

template<class F, class... Args>
[[nodiscard]] future<invoke_result_t<decay_t<F>, decay_t<Args>...>>
async(F&& f, Args&&... args);

template<class F, class... Args>
[[nodiscard]] future<invoke_result_t<decay_t<F>, decay_t<Args>...>>
async(launch policy, F&& f, Args&&... args);

Requires: Mandates: F and each Tj in Args shall satisfy the Cpp17MoveConstructible requirements, and

\[
\text{INVOKED}(\text{decay-copy}(\text{std::forward}\langle F\rangle(f)), \text{decay-copy}(\text{std::forward}\langle \text{Args}\rangle(\text{args}))) \quad // \text{see } ??, \text{31.3.2.2}
\]

shall be a valid expression.

Effects: The first function behaves the same as a call to the second function with a policy argument of
launch::async | launch::deferred and the same arguments for F and Args. The second function creates a shared state that is associated with the returned future object. The further behavior of the
second function depends on the policy argument as follows (if more than one of these conditions
applies, the implementation may choose any of the corresponding policies):

(3.1) — If launch::async is set in policy, calls \text{INVOKED}(\text{decay-copy}(\text{std::forward}\langle F\rangle(f)), \text{decay-copy}(\text{std::forward}\langle \text{Args}\rangle(\text{args}))) \quad (??, \text{31.3.2.2}) as if in a new thread of execution represented by a thread object with the calls to \text{decay-copy} being evaluated in the thread that called
async. Any return value is stored as the result in the shared state. Any exception propagated
from the execution of \text{INVOKED}(\text{decay-copy}(\text{std::forward}\langle F\rangle(f)), \text{decay-copy}(\text{std::forward}
<\text{Args}\rangle(\text{args}))) \quad ...) is stored as the exceptional result in the shared state. The thread object
is stored in the shared state and affects the behavior of any asynchronous return objects that reference that state.
If `launch::deferred` is set in `policy`, stores `decay-copy(std::forward<F>(f))` and `decay-copy(std::forward<Args>(args))` in the shared state. These copies of `f` and `args` constitute a deferred function. Invocation of the deferred function evaluates `INVOKE(std::move(g), std::move(xyz))` where `g` is the stored value of `decay-copy(std::forward<F>(f))` and `xyz` is the stored copy of `decay-copy(std::forward<Args>(args))`. Any return value is stored as the result in the shared state. Any exception propagated from the execution of the deferred function is stored as the exceptional result in the shared state. The shared state is not made ready until the function has completed. The first call to a non-timed waiting function (31.6.5) on an asynchronous return object referring to this shared state shall invoke the deferred function in the thread that called the waiting function. Once evaluation of `INVOKE(std::move(g), std::move(xyz))` begins, the function is no longer considered deferred. [Note: If this policy is specified together with other policies, such as when using a `policy` value of `launch::async | launch::deferred`, implementations should defer invocation or the selection of the policy when no more concurrency can be effectively exploited. —end note]

If no value is set in the launch policy, or a value is set that is neither specified in this document nor by the implementation, the behavior is undefined.

Returns: An object of type `future<invoke_result_t<decay_t<F>, decay_t<Args>...>>` that refers to the shared state created by this call to `async`. [Note: If a future obtained from `async` is moved outside the local scope, other code that uses the future should be aware that the future’s destructor can block for the shared state to become ready. —end note]

Synchronization: Regardless of the provided `policy` argument,

1. the invocation of `async` synchronizes with (??) the invocation of `f`. [Note: This statement applies even when the corresponding `future` object is moved to another thread. —end note]; and
2. the completion of the function `f` is sequenced before (??) the shared state is made ready. [Note: `f` might not be called at all, so its completion might never happen. —end note]

If the implementation chooses the `launch::async` policy,

1. a call to a waiting function on an asynchronous return object that shares the shared state created by this `async` call shall block until the associated thread has completed, as if joined, or else time out (31.3.2.5);
2. the associated thread completion synchronizes with (??) the return from the first function that successfully detects the ready status of the shared state or with the return from the last function that releases the shared state, whichever happens first.

Throws: `system_error` if `policy == launch::async` and the implementation is unable to start a new thread, or `std::bad_alloc` if memory for the internal data structures could not be allocated.

Error conditions:

1. `resource_unavailable_try_again` — if `policy == launch::async` and the system is unable to start a new thread.

[Example:

```cpp
int work1(int value);
int work2(int value);
int work(int value) {
    auto handle = std::async([=]{ return work2(value); });
    int tmp = work1(value);
    return tmp + handle.get(); // #1
}
```

[Note: Line #1 might not result in concurrency because the `async` call uses the default policy, which can use `launch::deferred`, in which case the lambda might not be invoked until the `get()` call; in that case, `work1` and `work2` are called on the same thread and there is no concurrency. —end note] —end example]

31.6.10 Class template `packaged_task` [futures.task]

The class template `packaged_task` defines a type for wrapping a function or callable object so that the return value of the function or callable object is stored in a future when it is invoked.
When the `packaged_task` object is invoked, its stored task is invoked and the result (whether normal or exceptional) stored in the shared state. Any futures that share the shared state will then be able to access the stored result.

```cpp
namespace std {
  template<class> class packaged_task; // not defined

  template<class R, class... ArgTypes>
  class packaged_task<R(ArgTypes...)> {
  public:
    // construction and destruction
    packaged_task() noexcept;
    template<class F>
    explicit packaged_task(F&& f);
    ~packaged_task();

    // move support
    packaged_task(packaged_task&& rhs) noexcept;
    packaged_task& operator=(packaged_task&& rhs) noexcept;
    void swap(packaged_task& other) noexcept;

    bool valid() const noexcept;

    // result retrieval
    future<R> get_future();

    // execution
    void operator()(ArgTypes...);
    void make_ready_at_thread_exit(ArgTypes...);
    void reset();
  };

  template<class R, class... ArgTypes>
  void swap(packaged_task<R(ArgTypes...)>& x, packaged_task<R(ArgTypes...)>& y) noexcept;
}
```

### 31.6.10.1 Member functions

`packaged_task() noexcept;`

**Effects:** Constructs a `packaged_task` object with `Has` no shared state and no stored task.

```cpp
template<class F>
packaged_task(F&& f);
```

**Required**

`MANDATES` _INVOKE<R>(f, t₁, t₂, ..., t_N) (??), where t₁, t₂, ..., t_N are values of the corresponding types in ArgTypes..., shall be a valid expression. Invoking a copy of f shall behave the same as invoking f._

**Remarks:** This constructor shall not participate in overload resolution if `Constraints:`

`remove_cvref_t<F> is not the same type as packaged_task<R(ArgTypes...)>._`

**Effects:** Constructs a new `packaged_task` object with a shared state and initializes the object's stored task with `std::forward<F>(f)`. A new `packaged_task` object is created and its `shared_state` is set to `std::forward<F>(f)`.

**Throws:** Any exceptions thrown by the copy or move constructor of f, or `bad_alloc` if memory for the internal data structures could not be allocated.

`packaged_task(packaged_task&& rhs) noexcept;`

**Effects:** Constructs a new `packaged_task` object and transfers ownership of `rhs`'s shared state to `*this`, leaving `rhs` with no shared state. Moves the stored task from `rhs` to `*this`. A new `packaged_task` object is created and its `shared_state` is set to the shared state of `rhs`. The `shared_state` of `rhs` is then set to `nullptr`.

§ 31.6.10.1
Ensures: \( \text{rhs} \) has no shared state.

\[
\text{packaged_task} \& \operatorname{=} (\text{packaged_task} \& \text{rhs}) \text{ noexcept};
\]

**Effects:**

- Releases any shared state (31.6.5);
- Calls \( \text{packaged_task} (\text{std} : \text{move} (\text{rhs})) . \text{swap} (* \text{this}) \).

```cpp
def ~packaged_task():
    Effects: Abandons any shared state (31.6.5).
```

```cpp
void swap (packaged_task & \text{other}) \text{ noexcept};
```

**Effects:** Exchanges the shared states and stored tasks of \( * \text{this} \) and \( \text{other} \).

Ensures: \( * \text{this} \) has the same shared state and stored task (if any) as \( \text{other} \) prior to the call to \( \text{swap} \). \( \text{other} \) has the same shared state and stored task (if any) as \( * \text{this} \) prior to the call to \( \text{swap} \).

```cpp
bool valid() \text{ const} \text{ noexcept};
```

**Returns:** \( true \) only if \( * \text{this} \) has a shared state.

```cpp
\text{future} <\text{R}> \text{get_future}();
```

**Returns:** A \text{future} object that shares the same shared state as \( * \text{this} \).

**Synchronization:** Calls to this function do not introduce data races (??) with calls to \text{operator()} or \text{make_ready_at_thread_exit}. [*Note: Such calls need not synchronize with each other. — end note]*

**Throws:** A \text{future_error} object if an error occurs.

**Error conditions:**

- \( \text{future_already_retrieved} \) if \text{get_future} has already been called on a \text{packaged_task} object with the same shared state as \( * \text{this} \).
- \( \text{no_state} \) if \( * \text{this} \) has no shared state.

```cpp
\text{void operator()} (\text{ArgsTypes} ... \text{args});
```

**Effects:** As if by INVOKE\text{R}>(f, t_1, t_2, \ldots, t_N) (??), where \( f \) is the stored task of \( * \text{this} \) and \( t_1, t_2, \ldots, t_N \) are the values in \text{args}.... If the task returns normally, the return value is stored as the asynchronous result in the shared state of \( * \text{this} \), otherwise the exception thrown by the task is stored. The shared state of \( * \text{this} \) is made ready, and any threads blocked in a function waiting for the shared state of \( * \text{this} \) to become ready are unblocked.

**Throws:** A \text{future_error} exception object if there is no shared state or the stored task has already been invoked.

**Error conditions:**

- \( \text{promise_already_satisfied} \) if the stored task has already been invoked.
- \( \text{no_state} \) if \( * \text{this} \) has no shared state.

```cpp
\text{void make_ready_at_thread_exit} (\text{ArgsTypes} ... \text{args});
```

**Effects:** As if by INVOKE\text{R}>(f, t_1, t_2, \ldots, t_N) (??), where \( f \) is the stored task and \( t_1, t_2, \ldots, t_N \) are the values in \text{args}.... If the task returns normally, the return value is stored as the asynchronous result in the shared state of \( * \text{this} \), otherwise the exception thrown by the task is stored. In either case, this shall be done without making that state ready (31.6.5) immediately. Schedules the shared state to be made ready when the current thread exits, after all objects of thread storage duration associated with the current thread have been destroyed.

**Throws:** \text{future_error} if an error condition occurs.

**Error conditions:**

- \( \text{promise_already_satisfied} \) if the stored task has already been invoked.
- \( \text{no_state} \) if \( * \text{this} \) has no shared state.
void reset();

Effects: As if *this = packaged_task(std::move(f)), where f is the task stored in *this. [Note: This constructs a new shared state for *this. The old state is abandoned (31.6.5). — end note]

Throws:

(24.1) — bad_alloc if memory for the new shared state could not be allocated.
(24.2) — any exception thrown by the move constructor of the task stored in the shared state.
(24.3) — future_error with an error condition of no_state if *this has no shared state.

31.6.10.2 Globals [futures.task.nonmembers]

template<class R, class... ArgTypes>
void swap(packaged_task<R(ArgTypes...)>& x, packaged_task<R(ArgTypes...)>& y) noexcept;

Effects: As if by x.swap(y).