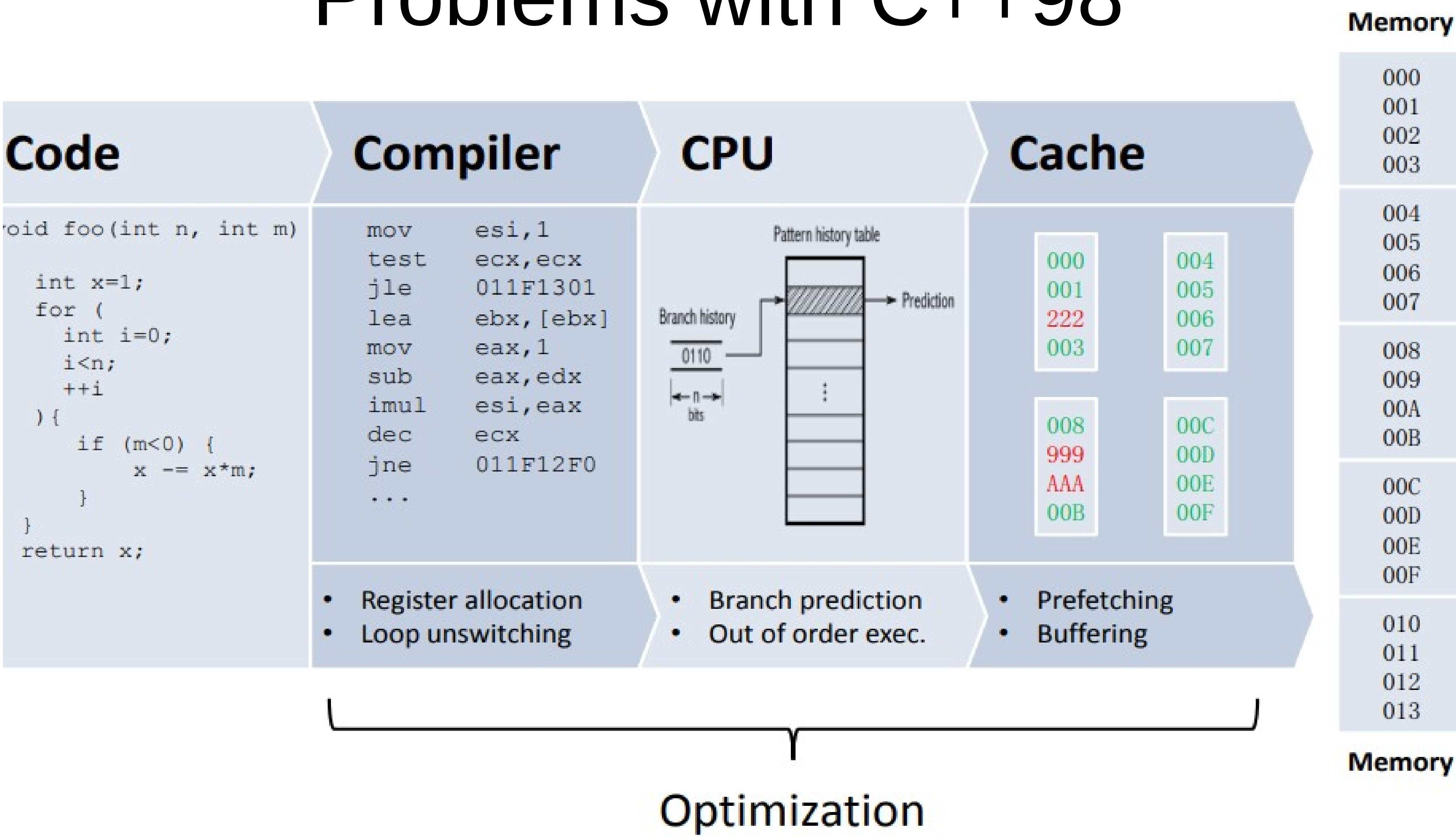
Concurrent programming in C++11

Multithreading is just one damn thing after, before, or simultaneous with another. --Andrei Alexandrescu

- Problems with C++98 memory model
- Double-checked locking pattern
- C++11 memory model
- Atomics
- Std::thread
- Mutex/Lock
- Conditional variable
- Future/Promise/Async

Problems with C++98



Valentin Ziegler, Fabio Fracassi C++ Memory Model (Meeting C++ Berlin, 2014)
https://www.think-cell.com/en/career/talks/pdf/think-cell_talk_memorymodel.pdf

Problems with C++98

```
int X = 0;
int Y = 0;

// thread 1                              // thread 2
int r1 = X;                              int r2 = Y;
if ( 1 == r1 )                           if ( 1 == r2 )
    Y = 1;                                   X = 1;

// can it be at the end of execution  r1 == r2 == 1 ?
```

Problems with C++98

```
struct S { char a; char b; };
struct S s = { 'a', 'b' };

// thread 1
s.a = 'x';

// thread 1 may compiled:
struct S tmp = x;
tmp.a = 'x';
s = tmp;
```

```
// thread 2
s.b = 'y';

// thread 2 may be compiled:
struct S tmp = x;
tmp.b = 'y';
s = tmp;
```

```
// can the result be { 'a', 'y' } or { 'x', 'b' }?
```

Problems with C++98

Hans Böhm: Threads cannot be implemented as a library
https://dl.acm.org/doi/10.1145/1065010.1065042

Francesco Zappa Nardelli EuroLLVM 2015
https://llvm.org/devmtg/2015-04/slides/CConcurrency_EuroLLVM2015.pdf

Singleton pattern

```
// in singleton.h:
class Singleton
{
public:
    static Singleton *instance();
    void other_method();
    // other methods ...
private:
    static Singleton *pinstance;
};

// in singleton.cpp:
Singleton *Singleton::pinstance = 0;

Singleton *Singleton::instance()
{
    if ( 0 == pinstance )
    {
        pinstance = new Singleton;  // lazy initialization
    }
    return pinstance;
}

// Usage:

   Singleton::istance()-> other_method();
```

Thread safe singleton construction

```
// in singleton.h:
class Singleton
{
public:
    static Singleton *instance();
    void other_method();
    // other methods ...
private:
    static Singleton *pinstance;
    static Mutex      lock_;
};

// in singleton.cpp:
Singleton *Singleton::pinstance = 0;

Singleton *Singleton::instance()
{
    Guard<Mutex> guard(lock_);  // constructor acquires lock_: not efficient
    // this is now the critical section
    if ( 0 == pinstance )
    {
        pinstance = new Singleton;  // lazy initialization
    }
    return pinstance;
} // destructor releases lock_
```

Thread safe singleton construction?

```
// in singleton.h:
class Singleton
{
public:
    static Singleton *instance();
    void other_method();
    // other methods ...
private:
    static Singleton *pinstance;
    static Mutex      lock_;
};

// in singleton.cpp:
Singleton *Singleton::pinstance = 0;

Singleton *Singleton::instance()
{
    // this is now the critical section
    if ( 0 == pinstance )
    {
        Guard<Mutex> guard(lock_);  // constructor acquires lock_: too late!
        // this is now the critical section
        pinstance = new Singleton;  // lazy initialization
    }
    return pinstance;
} // destructor releases lock_
```

Double checked locking pattern

```
Singleton *Singleton::instance()
{
    if ( 0 == pinstance )
    {
        Guard<Mutex> guard(lock_);  // constructor acquires lock_
        // this is now the critical section

        if ( 0 == pinstance )   // re-check pinstance
        {
            pinstance = new Singleton;  // lazy initialization
        }
    }                                  // destructor releases lock_
    return pinstance;
}



Singleton::istance()-> other_method();  // does not lock when not necessary
```

Double checked locking pattern

```
Singleton *Singleton::instance()
{
    if ( 0 == pinstance )
    {
        Guard<Mutex> guard(lock_);  // constructor acquires lock_
        // this is now the critical section

        if ( 0 == pinstance )   // re-check pinstance
        {
            pinstance = new Singleton;  // lazy initialization
        }
    }                                   // destructor releases lock_
    return pinstance;
}
```

```
Singleton::istance()-> other_method();  // does not lock when not necessary
```

Meyers and Alexandrescu: C++ and the Perils of Double-Checked Locking:
https://www.aristeia.com/Papers/DDJ_Jul_Aug_2004_revised.pdf

Problems with DCLP

```
if ( 0 == pinstance )
{
      // ...
      pinstance = new Singleton;  // atomic?
      // ...
}
return pinstance;

// might use half-initialized pointer value
Singleton::istance()-> other_method();
```

- Pointer assignment may not be atomic
  - We can observe a not null but still invalid pointer value

New expression

```
pinstance = new Singleton;  // how this is compiled?
```

- New expression include many steps
  - (1) Allocation space with ::operator new()
  - (2) Run of constructor
  - (3) Returning the pointer

- If the compiler does (1) + (3) and leaves (2) as the last step the pointer points to uninitialized memory area

Observable behavior in C++98

```
void foo()
{
    int x = 0, y = 0;       // (1)
    x = 5;                  // (2)
    y = 10;                 // (3)
    printf( "%d,%d", x, y); // (4)
}
```

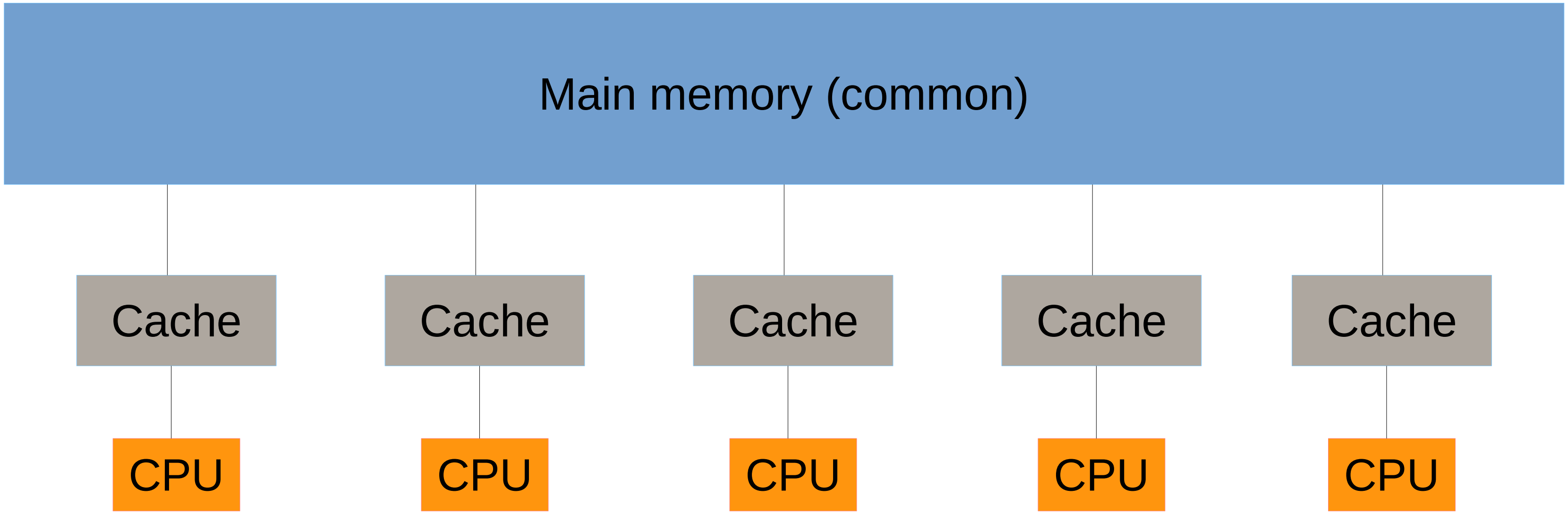
- What is visible for the outer word
  - I/O operations
  - Read/write volatile objects
- Defined by a singled-threaded mind

Sequence point

```
if ( 0 == pinstance )   // re-check pinstance
{
    // pinstance = new Singleton;
    Singleton *temp = operator new( sizeof(Singleton) );
    new (temp) Singleton;  // run the constructor
    pinstance = temp;
}
```

- The compiler can completely optimize out temp
- Even if we are using volatile temp we have issues

Modern hardware architecture



Singleton pattern

```
Singleton *Singleton::instance()
{
    Singleton *temp = pInstance;    // read pInstance

    Acquire();     // prevent visibility of later memory operations
                   // from moving up from this point

    if ( 0 == temp )
    {
        Guard<Mutex> guard(lock_);
        // this is now the critical section

        if ( 0 == pinstance )   // re-check pinstance
        {
            temp = new Singleton;

            Release();  // prevent visibility of earlier memory operations
                        // from moving down from this point

            pinstance = temp;   // write pInstance
        }
    }
    return pinstance;
}
```

C++11 memory model

- Describes the interactions of threads through memory
- Describes well defined behavior
- Constraints compiler for code generation

- C++ memory model contract
  - Programmer ensures that the program has no data race
  - System guarantees sequentially consistent execution

Terminology

- Only minimal progress guaranties are given on threads:
  - unblocked threads will make progress
  - implementation should ensure that writes in a thread should be visible in other threads "in a finite amount of time".
- The A happens before B relationship:
  - A is sequenced before B or
  - A inter-thread **happens before** B

    == there is a **synchronization point** between A and B
- Synchronization point:
  - thread creation sync with start of thread execution
  - thread completion sync with the return of join()
  - unlocking a mutex sync with the next locking of that mutex

Terminology

- Memory location
  - an object of scalar type
  - a maximal sequence of adjacent bit-fields all having non-zero width
- Data race

  A program contains **data race** if contains two actions in different threads, at least one is not "atomic" **and** neither happens before the other.
- Two threads of execution can update and access separate memory locations without interfering each others

Terminology

- Memory location
  - an object of scalar type
  - a maximal sequence of adjacent bit-fields all having non-zero width
- Data race == undefined behavior

  A program contains **data race** if contains two actions in different threads, at least one is not "atomic" **and** neither happens before the other.
- Two threads of execution can update and access separate memory locations without interfering each others

Sequential consistency

- Sequential consistent (default behavior)
  - Leslie Lamport, 1979
  - Each threads are executed in sequential order
  - The operations of each thread appear in this sequence for the other threads in that order

Sequential consistency

```
std::mutex m;
Data d;
bool flag = false;


// thread 1                  |  // thread 2
void Produce()               |  void Consume()
{                            |  {
                             |
  d = result;                |
  flag = true;               |
                             |
                             |
                             |    bool ready = flag;
                             |
                             |
                             |    if ( ready )  use(d);
}                            |  }
```

Sequential consistency

```
std::mutex m;
Data d;
bool flag = false;


// thread 1                 |  // thread 2
void Produce()              |  void Consume()
{                           |  {
                            |
  d = result;               |
  flag = true;              |
                            |
                            |
                            |    bool ready = flag;
                            |
                            |
                            |    if ( ready )  use(d);
}                           |  }
```

Data race!

Sequential consistency

```
std::mutex m;
Data d;
bool flag = false;


// thread 1                     |  // thread 2
void Produce()                  |  void Consume()
{                               |  {
  m.lock();                     |
  d = result;                   |
  flag = true;                  |
  m.unlock();                   |
                                |    m.lock();
                                |    bool ready = flag;
                                |    m.unlock();
                                |
                                |    if ( ready )  use(d);
}                               |  }
```

Sequential consistency

```
std::mutex m;
Data d;
bool flag = false;


// thread 1                  |  // thread 2
void Produce()               |  void Consume()
{                            |  {
  m.lock();                  |    bool ready;
  d = result;                |
  flag = true;               |
  m.unlock();                |
                             |    m.lock();
                             |    bool ready = flag;
                             |    m.unlock();
                             |
                             |    if ( ready )  use(d);
}                            |  }
```

Synchronized with

Sequential consistency

```
std::mutex m;
Data d;
bool flag = false;


// thread 1                    |  // thread 2
void Produce()                 |  void Consume()
{                              |  {
  m.lock();                    |    bool ready;
  d = result;                  |
  flag = true;                 |
  m.unlock();                  |
                               |    m.lock();
                               |    bool ready = flag;
                               |    m.unlock();
                               |
                               |    if ( ready )  use(d);
}                              |  }
```

Happens before

Synchronized with

Sequential consistency

```
std::mutex m;
Data d;
bool flag = false;


// thread 1                  |  // thread 2
void Produce()               |  void Consume()
{                            |  {
  m.lock();                  |    bool ready;
  d = result;                |
  flag = true;               |
  m.unlock();                |
                             |    m.lock();
                             |    bool ready = flag;
                             |    m.unlock();
                             |
                             |    if ( ready )  use(d);
}                            |  }
```

Happens before

Synchronized with

Sequential consistency

```
std::mutex m;
Data d;
bool flag = false;

// thread 1                     |  // start of thread 2
void Produce()                  |  void Consume()
{                               |  {
  m.lock();                     |    bool ready;
  d = result;                   |
  flag = true;                  |
  m.unlock();                   |
                                |    m.lock();
                                |    bool ready = flag;
                                |    m.unlock();
                                |
                                |    if ( ready )  use(d);
}                               |  }
```

Happens before

Synchronized with

Sequential consistency

```
std::mutex m;
Data d;
std::atomic<bool> flag = false;


// thread 1                    |       // thread 2
void Produce()                 |  void Consume()
{                              |  {
  m.lock();                    |    bool ready;
  d = result;                  |
  flag.store(true);            |
  m.unlock();                  |
                               |    m.lock();
                               |    bool ready = flag.load();
                               |    m.unlock();
                               |
                               |    if ( ready )  use(d);
}                              |  }
```

Sequential consistency

```
std::mutex m;
Data d;
std::atomic<bool> flag = false;


// thread 1                    |       // thread 2
void Produce()                 |   void Consume()
{                              |   {
  m.lock();                    |     bool ready;
  d = result;                  |
  flag.store(true);            |
  m.unlock();                  |
                               |     m.lock();
                               |     bool ready = flag.load();
                               |     m.unlock();
                               |
                               |     if ( ready )  use(d);
}                              |   }
```

C++11 memory model

```
int x, y;

// thread 1        |        // thread 2
x = 1;             |        cout << y << ", ";
y = 2;             |        cout << x << endl;
```

```
  In C++03  not even Undefined Behavior

  In C++11  Undefined Behavior
```

C++11 memory model

```
std::atomic<int> x, y;

// thread 1      |       // thread 2
x.store(1);      |       cout << y.load() << ", ";
y.store(2);      |       cout << x.load() << endl;


// Equivalent to:

int x, y;
mutex x_mutex, y_mutex;

// thread 1      |       // thread 2
x_mutex.lock()   |       y_mutex.lock();
x = 1;           |       cout << y << ", ";
x_mutex.unlock() |       y_mutex.unlock();
y_mutex.lock()   |       x_mutex.lock();
y = 2;           |       cout << x << endl;
y_mutex.unlock() |       x_mutex.unlock();
```

C++11 memory model (default)

```
std::atomic<int> x, y;
x.store(0); y.store(0);

// thread 1         |        // thread 2
x.store(1);         |        cout << y.load() << ", ";
y.store(2);         |        cout << x.load() << endl;
```

```
Result can be:
```

```
0 0
2 1
0 1
// never prints: 2 0
```

```
Sequential consistency:   atomics == atomic load/store + ordering
```

Memory ordering

- memory_order_seq_cst   (default)
- memory_order_consume
- memory_order_acquire
- memory_order_release
- memory_order_acq_rel
- memory_order_relaxed

X86/x86_64 does not require additional instructions to implement acquire-release ordering

Relaxed memory order

- Each memory location has a total modification order
  - But this may be not observable directly
- Memory operations performed by
  - The same thread and
  - On the same memory location

  are not reordered with respect of modification order

Relaxed memory order

```
std::atomic<int> x, y;

// relaxed
// thread 1                          |  // thread 2
x.store(1, memory_order_relaxed); |  cout << y.load(memory_order_relaxed) << ", ";
y.store(2, memory_order_relaxed); |  cout << x.load(memory_order_relaxed) << endl;

// Defined, atomic, but not ordered, result may be:
0 0
2 1
0 1
2 0
```

Relaxed memory order

```
// read-modify-write

std::atomic<int> x;

// relaxed
// thread 1
int i = x.load();                       // current value of x

While ( ! x.compare_exchange_weak( i,   // expected value of x, i is updated on failure
                                  i+1,  // desired value of x
                                  memory_order_relaxed
                                 )
      ) ; // try it again on failure



// equivalent solution

x.fetch_add( 1, memory_order_relaxed);
```

Acquire – release memory order

- A store-release operation **synchronizes** with all load-acquire operations reading a stored value
- Operations preceding the store-release in the releasing thread **happens before** operations following the load-acquire
- On some platforms acquire-release is cheaper than sequention consistency

```
std::mutex m; Data d;
std::atomic<bool> flag = false;

// thread 1                         |  // thread 2
void Produce()                      |  void Consume()
{                                   |  {
  d = result;                       |
  flag.store(true,                  |    bool ready =
   memory_order_release);           |         flag.load(memory_order_acquire);
                                    |    if ( ready )  use(d);
}                                   |  }
```

Acquire – release memory order

- A store-release operation **synchronizes** with all load-acquire operations reading a stored value
- Operations preceding the store-release in the releasing thread **happens before** operations following the load-acquire
- On some platforms acquire-release is cheaper than sequention consistency

```
std::mutex m; Data d;
std::atomic<bool> flag = false;

// thread 1                          |  // thread 2
void Produce()                       |  void Consume()
{                                    |  {
  d = result;                        |
  flag.store(true,                   |    bool ready =
   memory_order_release);            |    flag.load(memory_order_acquire);
                                     |    if ( ready )  use(d);
}                                    |  }
```

Acquire – release memory order

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- Operations preceding the store-release in the releasing thread **happens before** operations following the load-acquire
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```
std::mutex m; Data d;
std::atomic<bool> flag = false;

// thread 1                          |  // thread 2
void Produce()                       |  void Consume()
{                                    |  {
  d = result;                        |
  flag.store(true,                   |    bool ready =
   memory_order_release);            |    flag.load(memory_order_acquire);
                                     |    if ( ready ) use(d);
}                                    |  }
```

Acquire – release memory order

- A store-release operation **synchronizes** with all load-acquire operations reading a stored value
- Operations preceding the store-release in the releasing thread **happens before** operations following the load-acquire
- On some platforms acquire-release is cheaper than sequention consistency

```
std::mutex m; Data d;
std::atomic<bool> flag = false;

// thread 1                          |  // thread 2
void Produce()                       |  void Consume()
{                                    |  {
  d = result;                        |
  flag.store(true,                   |    bool ready =
   memory_order_release);            |    flag.load(memory_order_acquire);
                                     |    if ( ready )  use(d);
}                                    |  }
```

Acquire – release memory order

```
// acquire-release
// thread 1                      |  // thread 2
x.store(1, memory_order_release); |  cout << y.load(memory_order_acquire) << ", ";
y.store(2, memory_order_release); |  cout << x.load(memory_order_acquire) << endl;

// In C++11 Defined and the result can be:
0 0
2 1
0 1
// never prints: 2 0, but can be faster than strict ordering.
// results may be different in more complex programs
```

Consume – release memory order

- Operations preceding the store-release in the releasing thread **happens before** an operation X in the consuming thread where X has a **data dependency** on the loaded value

```
int d = 0;
std::atomic<int *> ptr = std::nullptr;

// thread 1                          |  // thread 2
void Produce()                       |  void Consume()
{                                    |  {
  d = 42                             |    int *p;
  ptr.store(&d,                      |
   memory_order_release);            |    if (p= ptr.load(memory_order_consume))
                                     |    {
                                     |      assert ( 42 == *p );
                                     |
                                     |      assert ( 42 ==  d );
                                     |    }
}                                    |  }
```

Consume – release memory order

- Operations preceding the store-release in the releasing thread **happens before** an operation X in the consuming thread where X has a **data dependency** on the loaded value

```
int d = 0;
std::atomic<int *> ptr = std::nullptr;

// thread 1                        |  // thread 2
void Produce()                     |  void Consume()
{                                  |  {
  d = 42                           |    int *p;
  ptr.store(&d,                    |
   memory_order_release);          |    if (p= ptr.load(memory_order_consume))
                                   |    {
                                   |      assert ( 42 == *p );
                                   |
                                   |      assert ( 42 ==  d );
                                   |    }
}                                  |  }
```

Consume – release memory order

- Operations preceding the store-release in the releasing thread **happens before** an operation X in the consuming thread where X has a **data dependency** on the loaded value

```
int d = 0;
std::atomic<int *> ptr = std::nullptr;

// thread 1                        |  // thread 2
void Produce()                     |  void Consume()
{                                  |  {
  d = 42                           |    int *p;
  ptr.store(&d,                    |
   memory_order_release);          |    if (p= ptr.load(memory_order_consume))
                                   |    {
                                   |      assert ( 42 == *p );  // ok
                                   |
                                   |      assert ( 42 ==  d );
                                   |    }
}                                  |  }
```

Consume – release memory order

- Operations preceding the store-release in the releasing thread **happens before** an operation X in the consuming thread where X has a **data dependency** on the loaded value

```
int d = 0;
std::atomic<int *> ptr = std::nullptr;

// thread 1                          |  // thread 2
void Produce()                       |  void Consume()
{                                    |  {
  d = 42                             |    int *p;
  ptr.store(&d,                      |
   memory_order_release);            |    if (p= ptr.load(memory_order_consume))
                                     |    {
                                     |      assert ( 42 == *p );  // ok
                                     |
                                     |      assert ( 42 ==  d );  // DATA RACE
                                     |    }
}                                    |  }
```

std::thread

```
class thread
{
public:
  typedef native_handle ...;
  typedef id ...;

  thread() noexept;                // does not represent a thread
  thread( thread&& other) noexept; // move constructor
  ~thread();                       // if joinable() calls std::terminate()

  template <typename Function, typename... Args> // copies args to thread local
  explicit thread( Function&& f, Arg&&... args); // then execute f with args

  thread(const thread&) = delete;  // no copy
  thread& operator=(thread&& other) noexept;  // move
  void swap( thread& other);  // swap

  bool joinable() const; // thread object owns a physical thread
  void join();           // blocks current thread until *this finish
  void detach();         // separates physical thread from the thread object

  std::thread::id get_id() const;             // std::this_thread
  static unsigned int hardware_concurrency();  // supported concurrent threads
  native_handle_type native_handle();          // e.g. thread id
};
```

Usage of std::thread

```
void f( int i, const std::string&);
{
    std::cout << "Hello concurrent world" << std::endl;
}

int main()
{
    int i = 3;
    std::string s("Hello");

    // Will copy both i and s
    // We can prevent the copy by using reference wrapper
    // std::thread t( f, std::ref(i), std::ref(s));
    std::thread t( f, i, s);

    // if the thread destructor runs and the thread is joinable, than
    // std::system_error will be thrown.
    // Use join() or detach() to avoid that.
    t.join();

    return 0;
}
```

Issue with join()

- If the thread destructor called when the thread is still *joinable* std::system_error will be thrown
- Alternatives are not really feasible:
- Implicit join:
  - The destructor waits until the thread execution is completed
  - Hard-to detect performance issues
- Implicit detach
  - The destructor may run, but the underlying thread is still under execution
  - We may destroy resources still used by the thread
- Scoped_thread or thread_strategy parameters

Scoped thread

```
class scoped_thread   // Anthony Williams
{
    std::thread t;
public:
    explicit scoped_thread(std::thread t_): t(std::move(t_))
    {
        if(!t.joinable())
            throw std::logic_error("No thread");
    }
    ~scoped_thread()
    {
        t.join();
    }
    scoped_thread(scoped_thread const&)=delete;
    scoped_thread& operator=(scoped_thread const&)=delete;
};

struct func;

void f()
{
    int some_local_state;
    scoped_thread t(std::thread(func(some_local_state)));
    do_something_in_current_thread();
}
```

Usage of std::thread

```
struct func
{
    int& i;
    func(int& i_) : i (i_) { }

    void operator()()
    {
        for(unsigned int j=0; j < 1000000; ++j)
        {
            do_something(i);  // i refers to a destroyed variable
        }
    }
};

void oops()
{
    int some_local_state=0;

    func my_func(some_local_state);

    std::thread my_thread(my_func);

    my_thread.detach();  // don't wait the thread to finish
}  // i is destroyed, but the thread is likely still running..
```

std::thread works with containers

```
void do_work(unsigned id);

void f()
{
    std::vector<std::thread> threads;
    for(unsigned i=0;i<20;++i)
    {
        threads.push_back(std::thread(do_work,i));
    }
    std::for_each(threads.begin(),threads.end(),
                  std::mem_fn(&std::thread::join));
}
```

std::thread works with containers

```
// std::thread::id identifiers returned by std::this_thread::get_id()
// it returns std::thread::id() if there is no associated thread.
std::thread::id master_thread;
void some_core_part_of_algorithm()
{
    if(std::this_thread::get_id()==master_thread)
    {
        do_master_thread_work();
    }
    do_common_work();
}


// gives a hint about the available cores. Be aware of
// “oversubscription", i.e. using more threads than cores we have.
std::thread::hardware_concurency()
```

Syncronization objects: mutex

```cpp
#include <mutex>

void f()
{
    std::mutex m;
    int sh;  // shared data
    // ...
    m.lock();
    // manipulate shared data:
    sh+=1;
    m.unlock();
}


void g()
{
    std::mutex m;
    int sh;  // shared data
    // ...
    if ( m.try_lock() )
    {
      // manipulate shared data:
      sh+=1;
      m.unlock();
    }
}
```

```cpp
// Recursive mutex
std::recursive_mutex m;
int sh;  // shared data

void h(int i)
{
    // ...
    m.lock();
    // manipulate shared data:
    sh+=1;
    if (--i>0) f(i);
    m.unlock();
    // ...
}
```

Syncronization objects: timed mutex

```
void f1()
{
    std::timed_mutex m;
    int sh;  // shared data
    // ...
    if (m.try_lock_for(std::chrono::seconds(10)))
    {
      // manipulate shared data:
      sh+=1;
      m.unlock();
    }
    else
      // we didn't get the mutex; do something else
}
void f2()
{
    std::timed_mutex m;
    int sh;  // shared data
    // ...
    if (m.try_lock_until(midnight))
    {
      // manipulate shared data:
      sh+=1;
      m.unlock();
    }
    else
      // we didn't get the mutex; do something else
}
```

RAII support

```
#include <list>
#include <mutex>
#include <algorithm>

std::list<int> l;
std::mutex     m;

void add_to_list(int value);
{
    // lock acquired - with RAII style lock management
    std::lock_guard< std::mutex > guard(m);
    l.push_back(value);
}   // lock released
```

Pointers or references pointing out from the guarded area may be an issue!

Can this go dead-locked?

```
bool operator<( T const& lhs, T const& rhs)
{
    if ( &lhs == &rhs )
      return false;

    std::lock_guard< std::mutex > guard(lhs.m)
    std::lock_guard< std::mutex > guard(rhs.m)

    return lhs.data < rhs.data;
}
```

Can this go dead-locked?

```
bool operator<( T const& lhs, T const& rhs)
{
    if ( &lhs == &rhs )
      return false;

    std::lock_guard< std::mutex > guard(lhs.m)
    std::lock_guard< std::mutex > guard(rhs.m)

    return lhs.data < rhs.data;
}



// thread1          |           thread2

    a < b           |            b < a
```

Correct solution

```
bool operator<( T const& lhs, T const& rhs)
{
    if ( &lhs == &rhs )
        return false;

    // std::lock - lock two or more mutexes
    std::lock( lhs.m, rhs.m);
    std::lock_guard< std::mutex >  lock_lhs( lhs.m, std::adopt_lock);
    std::lock_guard< std::mutex >  lock_rhs( rhs.m, std::adopt_lock);

    return lhs.data < rhs.data;
}

// attempts to lock in unspecified order
template <class Lockable1, class Lockable2, class Lockable3, ...>
void std::lock( Lockable1 m1, Lockable2 m2, Lockable3 m3, ...);

// attempts to lock in left-to-right order
// returns -1 on success, otherwise the index of first failed
template <class Lockable1, class Lockable2, class Lockable3, ...>
int std::try_lock( Lockable1 m1, Lockable2 m2, Lockable3 m3, ...);
```

Unique_lock with defer_lock

```
bool operator<( T const& lhs, T const& rhs)
{
    if ( &lhs == &rhs )
        return false;

    // std::unique_locks constructed with defer_lock can be locked
    // manually, by using lock() on the lock object ...
    std::unique_lock< std::mutex >  lock_lhs( lhs.m, std::defer_lock);
    std::unique_lock< std::mutex >  lock_rhs( rhs.m, std::defer_lock);
    // lock_lhs.owns_lock() now false

    // ... or passing to std::lock
    std::lock( lock_lhs, lock_rhs);  // designed to avoid dead-lock
    // also there is an unlock() memberfunction

    // lock_lhs.owns_lock() now true
    return lhs.data < rhs.data;
}
```

Unique_lock only moveable

```
std::unique_lock<std::mutex> get_lock()
{
    extern std::mutex some_mutex;
    std::unique_lock<std::mutex> lk(some_mutex);
    prepare_data();
    return lk; // same as std::move(lk),
              // return does not require std::move
}

void process_data()
{
    std::unique_lock<std::mutex> lk(get_lock());
    do_something();
}
```

Shared_lock in C++14

```
std::shared_timed_mutex m;
my_data d;

void reader()
{
    std::shared_lock<std::shared_timed_mutex>  rl(m);
    read_only(d);
}

void writer()
{
    std::lock_guard<std::shared_timed_mutex>   wl(m);
    write(d);
}
```

Use of shared_timed_mutex may have worse performance

Mutex management

```
lock_guard
   C++11: Simple scoped wrapper around a mutex
          Non-copyable, non-movable

unique_lock
   C++11: Simple scoped wrapper around a mutex
          Non-copyable,
          Movable: unique_lock(unique_lock&&) operator=(unique_lock&&)
          unlock()

shared_lock
   C++14: lock the mutex in shared mode e.g shared_timed_mutex (c++14)
          Non-copyable, movable

scoped_lock
   C++17: variadic template class RAII to own one or more mutexes
          Non-copyable, owning multiple mutexes with std::lock()
```

Concurrent singleton

```
template <typename T>
class MySingleton
{
public:
    std::shared_ptr<T> instance()
    {
        std::call_once( resource_init_flag, init_resource);
        return resource_ptr;
    }
private:
    void init_resource()
    {
        resource_ptr.reset( new T(...) );
    }
    std::shared_ptr<T> resource_ptr;
    std::once_flag     resource_init_flag; // can't be moved or copied
};
```

Meyers singleton

```
// Meyers singleton:
// C++11 guaranties: local static is initialized in a thread safe way
//
class MySingleton;
MySingleton& MySingletonInstance()
{
    static MySingleton _instance;
    return _instance;
}
```

Spin lock

```
bool flag;   // waiting for this flag
std::mutex m;

void wait_for_flag()
{
    std::unique_lock<std::mutex> lk(m);
    while(!flag)
    {
        lk.unlock();
        std::this_thread::sleep_for(std::chrono::milliseconds(100));
        lk.lock();
    }
}
```

Condition variable

```
std::mutex                    my_mutex;
std::queue< data_t >          my_queue;
std::conditional_variable data_cond;  // conditional variable

void producer()
{
    while ( more_data_to_produce() )
    {
        const data_t data = produce_data();
        std::lock_guard< std::mutex > prod_lock(my_mutex);  // guard the push
        my_queue.push(data);
        data_cond.notify_one(); // notify the waiting thread to evaluate cond.
    }
}

void consumer()
{
    while ( true )
    {
        std::unique_lock< std::mutex > cons_lock(my_mutex); // not lock_guard
        data_cond.wait(cons_lock,                          // returns if lamdba returns true
                  [&my_queue]{return !my_queue.empty();}); // else unlocks and waits
        data_t data = my_queue.front();  // lock is hold here to protect pop...
        my_queue.pop();
        cons_lock.unlock();                // ... until here
        consume_data(data);
    }
}
```

Condition variable

- During the wait the condition variable may check the condition any time
- But under the protection of the mutex and returns immediately if condition is true.

- Spurious wake: wake up without notification from other thread. Undefined times and frequency -> better to avoid functions with side effect (e.g. using a counter in lambda to check how many notifications were is bad)

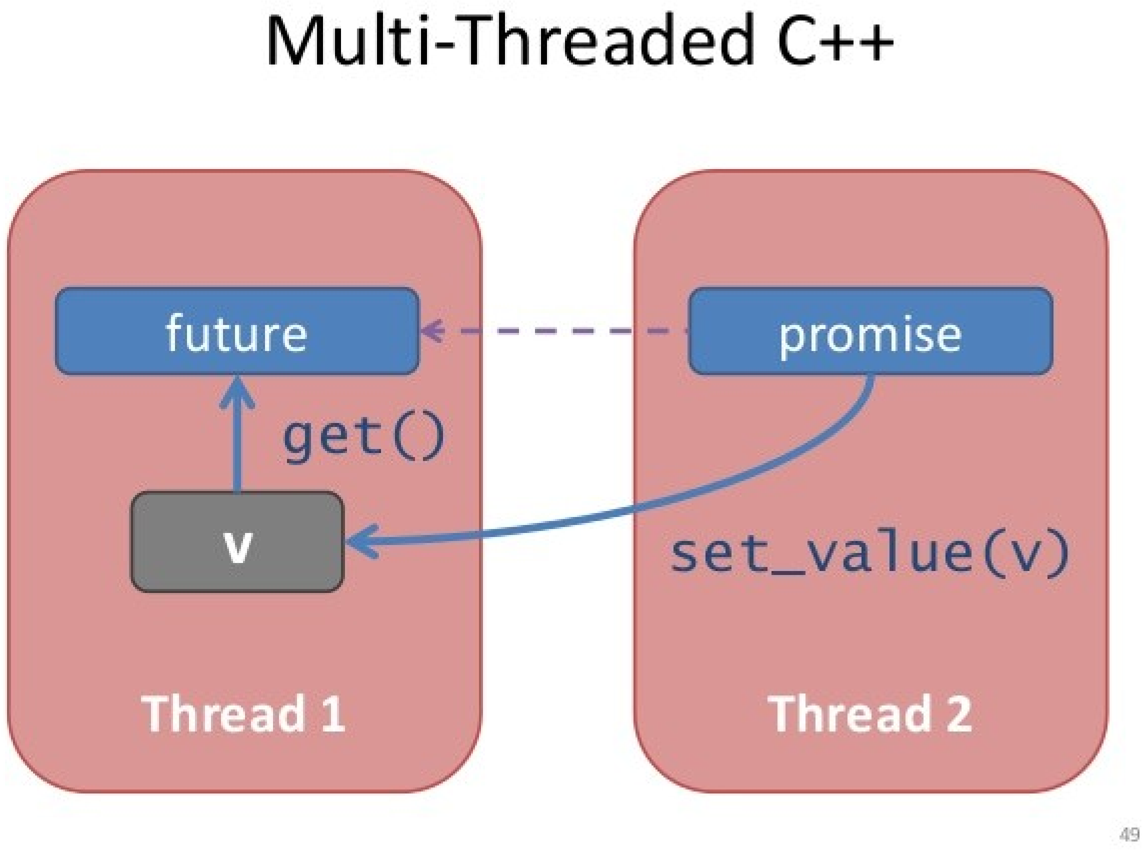
Condition variable

```
std::mutex                 my_mutex;
std::queue< data_t >       my_queue;
std::conditional_variable data_cond;  // conditional variable

void producer()
{
    while ( more_data_to_produce() )
    {
        const data_t data = produce_data();
        { // more optimal: release lock before notify
          std::lock_guard< std::mutex > prod_lock(my_mutex);  // guard the push
          my_queue.push(data);
        }
        data_cond.notify_one(); // notify the waiting thread to evaluate cond.
    }
}

void consumer()
{
    while ( true )
    {
        std::unique_lock< std::mutex > cons_lock(my_mutex); // not lock_guard
        data_cond.wait(cons_lock,                         // returns if lamdba returns true
                   [&my_queue]{return !my_queue.empty();}); // else unlocks and waits
        data_t data = my_queue.front();  // lock is hold here to protect pop...
        my_queue.pop();
        cons_lock.unlock();               // ... until here
        consume_data(data);
    }
}
```

Future

- 1976 Daniel P. Friedman and David Wise: promise
- 1977 Henry Baker and Carl Hewitt: future
- Future: a read-only placeholder view of a variable or exception
- Promise: a writeable, single assignment container (to set the future)
- Communication channel: promise → future
- std::future the
  - Only instance to refer the async event
  - Move-only
- std::shared_future
  - Multiple instances referring to the same event
  - Copiable
  - All instances will be ready on the same time

Future-Promise



std::async

```
#include <future>
#include <iostream>

int f(int);
void do_other_stuff();

int main()
{
    std::future<int> the_answer = std::async(f,1);
    do_other_stuff();
    std::cout<< "The answer is " << the_answer.get() << std::endl;
}

// The std::async() executes the task either in a new thread or on get()

// starts in a new thread
auto fut1 = std::async(std::launch::async, f, 1);
// run in the same thread on wait() or get()
auto fut2 = std::async(std::launch::deferred, f, 2);
// default: implementation chooses
auto fut3 = std::async(std::launch::deferred | std::launch::async, f, 3);
// default: implementation chooses
auto fut4 = std::async(f, 4);

// If no wait() or get() is called, then the task may not be executed at all.
```

std::async

```
// from cppreference.com
#include <iostream>
#include <future>
#include <thread>
#include <chrono>

int main()
{
    std::future<int> future = std::async(std::launch::async, [](){
        std::this_thread::sleep_for(std::chrono::seconds(3));
        return 8;
    });

    std::cout << "waiting...\n";
    std::future_status status;
    do {
        status = future.wait_for(std::chrono::seconds(1));
        if (status == std::future_status::deferred) {
            std::cout << "deferred\n";
        } else if (status == std::future_status::timeout) {
            std::cout << "timeout\n";
        } else if (status == std::future_status::ready) {
            std::cout << "ready!\n";
        }
    } while (status != std::future_status::ready);

    std::cout << "result is " << future.get() << '\n';
}
```

Exceptions

```
double square_root(double x)
{
    if ( x < 0 )
    {
        throw std::out_of_range("x<0");
    }
    return sqrt(x);
}

int main()
{
    std::future<double> fut = std::async( square_root, -1);
    // do something else...
    double res = fut.get(); // f becomes ready on exception and rethrows
}                           // exception object could be a copy of original
```

Exceptions

```
void asyncFun( std::promise<int> myPromise)
{
    int result;
    try
    {
        // calculate the result
        myPromise.set_value(result);
    }
    catch ( ... )
    {
        myPromise.set_exception(std::current_exception());
    }
}

// In the calling thread:
int main()
{
    std::promise<int> intPromise;
    std::future<int> intFuture = intPromise.getFuture();
    std::thread t(asyncFun, std::move(intPromise));

    // do other stuff here, while asyncFun is working

    int result = intFuture.get();  // may throw MyException
    return 0;
}
```

par_algorithms (C++17)

- Based on Intel's Threading Building Blocks (TBB)
- Extends STL algorithms with execution policy
  - std::execution::seq Sequential execution
  - std::execution::par Parallel execution
  - std::execution::par_unseq Parallel SIMD execution
  - std::execution::unseq Sequential SIMD execution

- These policies are permissions not obligations. Implementation may choose what can be parallelized
- Minimal requirement: forward iterator
- The programmer's task to ensure that element access functions will not cause dead lock or data race
- In case of paralellization and vectorization access must not use any blocking synchronization

Parallel STL

```
// Example from Stroustrup

template<class T, class V>
struct Accum     // simple accumulator function object
{
    T* b;
    T* e;
    V val;
    Accum(T* bb, T* ee, const V& vv) : b{bb}, e{ee}, val{vv} {}
    V operator() () { return std::accumulate(b,e,val); }
};

double comp(vector<double>& v)   // spawn many tasks if v is large enough
{
    if (v.size()<10000) return std::accumulate(v.begin(),v.end(),0.0);

    auto f0 {async(Accum{&v[0],&v[v.size()/4],0.0})};
    auto f1 {async(Accum{&v[v.size()/4],&v[v.size()/2],0.0})};
    auto f2 {async(Accum{&v[v.size()/2],&v[v.size()*3/4],0.0})};
    auto f3 {async(Accum{&v[v.size()*3/4],&v[v.size()],0.0})};

    return f0.get()+f1.get()+f2.get()+f3.get();
}
```

Parallel STL

```
// Example from cppreference

template<class T, class V>
struct Accum     // simple accumulator function object
{
    T* b;
    T* e;
    V val;
    Accum(T* bb, T* ee, const V& vv) : b{bb}, e{ee}, val{vv} {}
    V operator() () { return std::accumulate(b,e,val); }
};

double comp(vector<double>& v)
{
    // non-deterministic if binary_op is not associative or not commutative
    double res = std::reduce(std::execution::par, v.begin(), v.end(), 0.0);
    return res;
}
```

Vectorization

```
std::vector<int> v {1,2, ... };

int sum { std::accumulate(v.begin(), v.end(), 0) };


int sum = 0;
for ( size_t i = 0; i < v.size(); ++i)
{
    sum += v[i];
}



int sum = 0;
for ( size_t i = 0; i < v.size() / 4; i+=4)
{
    sum += v[i] + v[i+1] + v[i+2] + v[i+3];   // most CPU supports this
}
// handle if (v.size()/4) is not 0
```

accumulate() vs reduce()

```
#include <iostream>
#include <vector>

int main()
{
  std::vector<long long> v1;
  for ( int i = 0; i < 10; ++i)
  {
    v1.insert( v1.end(), {0,1,2,3,4}); // creates 50 elements
  }

  long long sum = 0;
  for ( std::size_t i = 0; i < v1.size(); ++i) // summa x^2  x in [0..49]
  {
    sum += v1[i]*v1[i];
  }

  std::cout << sum << '\n';

  return 0;
}
```

```
$ ./a.out
300
```

accumulate() vs reduce()

```
#include <iostream>
#include <numeric>
#include <vector>


std::vector<long long> v1;
auto sqrsum = [] (auto s, auto val) { return s + val * val; };

int main()
{
  for ( int i = 0; i < 10; ++i)
  {
    v1.insert( v1.end(), {0,1,2,3,4});  // creates 50 elements
  }

  auto sum1 = std::accumulate(v1.begin(), v1.end(), 0LL, sqrsum);  // classical STL



  std::cout << sum1 << '\n';
  return 0;
}
```

```
$ ./a.out
300
```

accumulate() vs reduce()

```
#include <iostream>
#include <numeric>
#include <vector>


std::vector<long long> v1;
auto sqrsum = [] (auto s, auto val) { return s + val * val; };

int main()
{
  for ( int i = 0; i < 10; ++i)
  {
    v1.insert( v1.end(), {0,1,2,3,4});  // creates 50 elements
  }
  // accumulate is guaranteed left associative
  auto sum1 = std::accumulate(v1.begin(), v1.end(), 0LL, sqrsum);  // classical STL



  std::cout << sum1 << '\n';
  return 0;
}
```

```
$ ./a.out
300
```

accumulate() vs reduce()

```
#include <iostream>
#include <numeric>
#include <vector>
#include <execution>

std::vector<long long> v1;
auto sqrsum = [] (auto s, auto val) { return s + val * val; };

int main()
{
  for ( int i = 0; i < 10; ++i)
  {
    v1.insert( v1.end(), {0,1,2,3,4});
  }
  // accumulate is guaranteed left associative
  auto sum1 = std::accumulate(v1.begin(), v1.end(), 0LL, sqrsum);
  // reduce can work parallel
  auto sum2 = std::reduce(std::execution::par, v1.begin(), v1.end(), 0LL, sqrsum);

  std::cout << sum1 << ", " << sum2 << '\n';
  return 0;
}
```

```
$ ./a.out
300, 300
```

accumulate() vs reduce()

```
#include <iostream>
#include <numeric>
#include <vector>
#include <execution>

std::vector<long long> v1;
auto sqrsum = [] (auto s, auto val) { return s + val * val; };

int main()
{
  for ( int i = 0; i < 1000; ++i)
  {
    v1.insert( v1.end(), {0,1,2,3,4});
  }
  // accumulate is guaranteed left associative
  auto sum1 = std::accumulate(v1.begin(), v1.end(), 0LL, sqrsum);
  // reduce can work parallel
  auto sum2 = std::reduce(std::execution::par, v1.begin(), v1.end(), 0LL, sqrsum);

  std::cout << sum1 << ", " << sum2 << '\n';
  return 0;
}
```

```
$ ./a.out
30000, 30000
```

accumulate() vs reduce()

```
#include <iostream>
#include <numeric>
#include <vector>
#include <execution>

std::vector<long long> v1;
auto sqrsum = [] (auto s, auto val) { return s + val * val; };

int main()
{
  for ( int i = 0; i < 1000000; ++i)
  {
    v1.insert( v1.end(), {0,1,2,3,4});
  }
  // accumulate is guaranteed left associative
  auto sum1 = std::accumulate(v1.begin(), v1.end(), 0LL, sqrsum);
  // reduce can work parallel
  auto sum2 = std::reduce(std::execution::par, v1.begin(), v1.end(), 0LL, sqrsum);

  std::cout << sum1 << ", " << sum2 << '\n';
  return 0;
}
```

```
$ ./a.out
30000000, 59820950156796
```

accumulate() vs reduce()

```
#include <iostream>
#include <numeric>
#include <vector>
#include <execution>

std::vector<long long> v1;
auto sqrsum = [] (auto s, auto val) { return s + val * val; };  // not commutative

int main()
{
  for ( int i = 0; i < 1000000; ++i)
  {
    v1.insert( v1.end(), {0,1,2,3,4});
  }
  // accumulate is guaranteed left associative
  auto sum1 = std::accumulate(v1.begin(), v1.end(), 0LL, sqrsum);
  // reduce can work parallel
  auto sum2 = std::reduce(std::execution::par, v1.begin(), v1.end(), 0LL, sqrsum);

  std::cout << sum1 << ", " << sum2 << '\n';
  return 0;
}
```

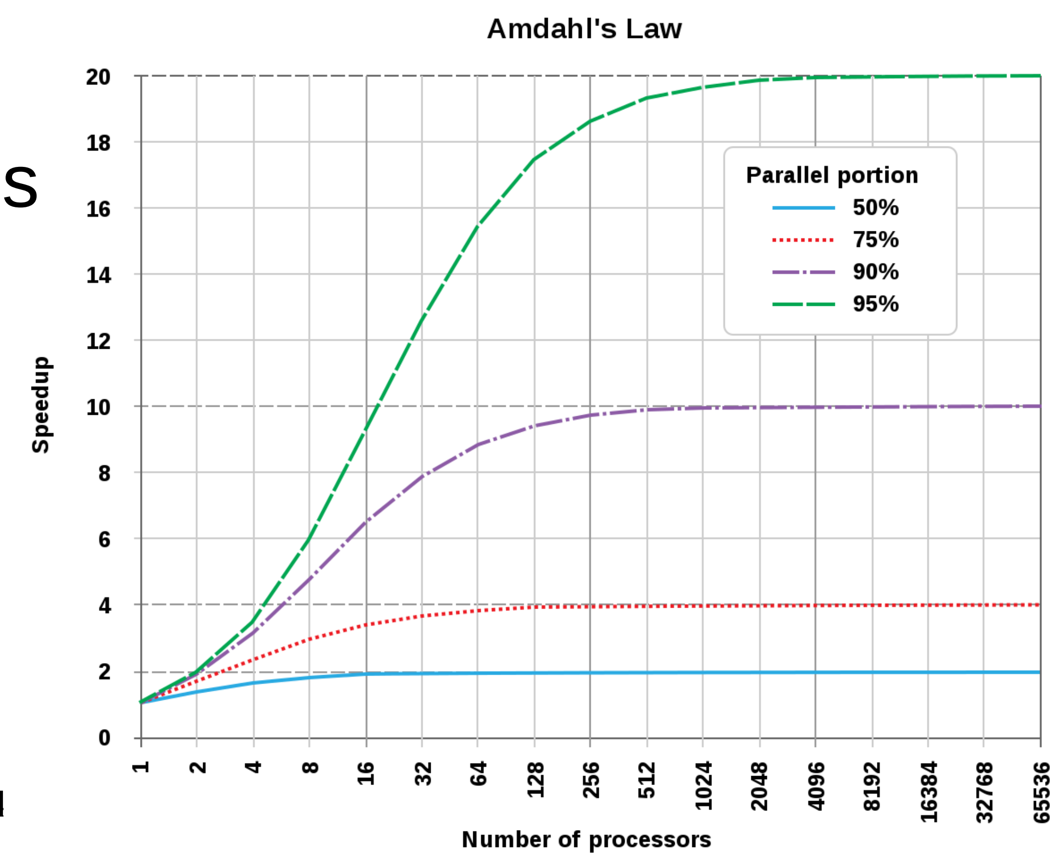
```
$ ./a.out
30000000, 59820950156796
```

accumulate() vs reduce()

```
#include <iostream>
#include <numeric>
#include <vector>
#include <execution>
#include <functional>
std::vector<long long> v1;
auto sqrsum = [] (auto s, auto val) { return s + val * val; };

int main()
{
  for ( int i = 0; i < 1000000; ++i)
  {
    v1.insert( v1.end(), {0,1,2,3,4});
  }
  // accumulate is guaranteed left associative
  auto sum1 = std::accumulate(v1.begin(), v1.end(), 0LL, sqrsum);
  auto sum2 = std::transform_reduce(std::execution::par,  // map-reduce
             v1.begin(), v1.end(), 0LL,
             std::plus<>(),
             [](auto v) { return v*v; });
  std::cout << sum1 << ", " << sum2 << '\n';
  return 0;
}

$ ./a.out
30000000, 30000000
```

Lock free programming

- Mutexes are implemented by OS features
- Improper use of locks can cause deadlock
- Locking/unlocking can cause context switch
  - Clear the cache
  - Further cache-misses
- Amdahl law
- Blocking vs non-blocking



Lock free programming

- Non-Blocking
- Lock-free
  - Non-blocking, some thread(s) may progress
  - Starvation can happen
- Wait-free
  - Lock-free, all threads are progressing
  - Every operation can be performed in a single pass
  - Steps does not cause any operations to fail

C++20

- resumable functions
  - async ... wait
- continuation
  - then()
  - when_any()
  - when_all()
- transactional memory – ???

- Critics on C++ concurrency:

  Bartosz Milewski's blog: Broken promises - C++0x futures
  http://bartoszmilewski.com/2009/03/03/broken-promises-c0x-futures/

  MeetingC++ - Hartmut Kaiser: Plain Threads are the GOTO of todays computing https://www.youtube.com/watch?v=4OCUEgSNIAY