Concurrency in C++11

- Introduction
- Basics: futures, threads, “tasks”
- Synchronization: mutexes, locks, atomics

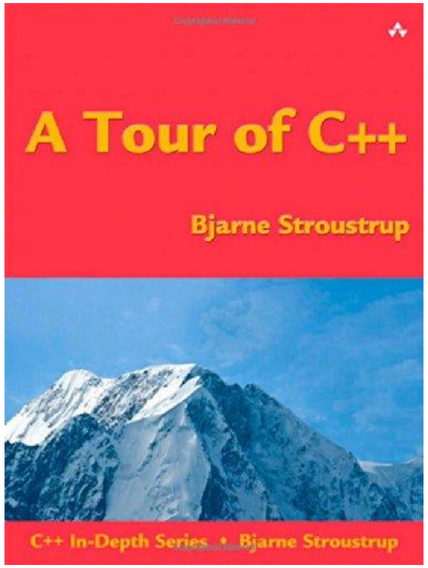
```
// This is code
assert(true && "You can read C++");
```

This is a link: http://en.cppreference.com/w/

Dmitry N. Petrov is...

- Staff software engineer at Intel Labs
- R&D: C/C++ since 2001, Java since 2004
- Compilers & development tools
- Electronic design automation
- System programming

C++ at a glance



- “Minimum overhead”
  - “High-level assembler with classes”
- Almost backward compatible with ANSI C (C89)
- Latest standard: C++11
  - Earlier known as C++0x
- Well-known desktop and server applications, embedded software, ...
- Complex compared to modern “productivity languages” (Java, C#, scripting languages, …)

Concurrency in C++ before C++11

- Essentially sequential abstract machine
  - No concurrent memory model definition
  - Required compiler-specific tricks and non-portable APIs to enable concurrency
- OpenMP, MPI
- POSIX (pthread), WinAPI, …
- Boost.Thread
  - C++11 concurrency API is based on Boost.Thread

Some important C++11 features

- Range-based for

```
std::vector<std::string> strings;
// ...
for (const std::string & s : strings) {
   std::cout << s << std::endl;
}
```

- 'auto': type inference for local variables

```
auto x = foo(a, b, c);
```

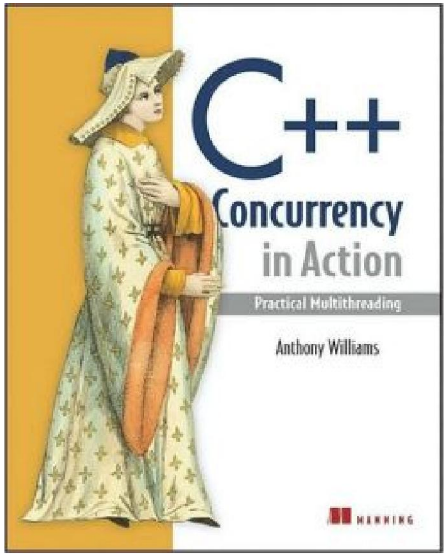
- Lambdas: anonymous functor objects

```
auto f = [](int i) { return i + 1; };

std::function<int(int)> ff = [](int i) -> int { return i + 1; };

std::cout << f(41) << std::endl;
```

Good Bedroom Reading



Anthony Williams

C++ Concurrency in Action: Practical Multithreading

C++11 concurrency from the Boost.Thread maintainer

See also

- Herb Sutter posts on concurrency and C++11
  - http://herbsutter.com/category/concurrency/
- C++ Concurrency
  - Channel9 Herb Sutter video from C++ and Beyond 2012
  - http://channel9.msdn.com/Shows/Going+Deep/C-and-Beyond-2012-Herb-Sutter-Concurrency-and-Parallelism

Before you start coding…

- Make it work. Make it right. Make it fast.
  - Premature optimization is the root of all evil
- Stop worrying and use the library
- Performance is measurable
  - Local optimizations can be global “pessimizations”
  - Profile your code
- Debugging & testing concurrent code is **hard**
  - Defensive coding, paired programming, code review, …

“Hello, world!”: now with C++11 concurrency

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

int main(int argc, char ** argv) {
     auto hello = std::async([] { std::cout << "Hello, "; });
     auto world = std::async([] { std::cout << "world!"; return 42; });
     hello.wait();
     int magic = world.get();
}
```

- This program will print something
  - Usually “Hello, world!”
- hello and world are “futures”
  - Asynchronous or deferred operations with or without result
  - std::future<T>
- [] { … } – lambda without captured values and arguments
- std::async submits task to run-time

<future>:
std::future<T>

- High-level abstraction for deferred computation
- wait() - waits for the completion
- get() - waits for the completion and returns result (or re-throws an exception)
- ~future() disposes shared state
- std::async(f, args)
  std::async(policy, f, args)
  - Exact behavior determined by the run-time library
  - policy: std::launch: { async, deferred[, sync, any] }

<thread>:
std::thread

- std::thread – single thread of execution
- join() - waits until thread completion
- detach() - let the thread execute independently
- **NB:** thread MUST be joined or detached before dtor
- **NB:** if a thread function throws an exception, program is terminated

“Hello, world!”: now with threads

```
#include <iostream>
#include <thread>

int main(int argc, char ** argv) {
    std::thread hello([] { std::cout << "Hello, "; });
    std::thread world([] { std::cout << "world!"; });
    hello.join();
    world.join();
}
```

- This will also print something (usually “Hello, world!”)

<thread>: std::this_thread

- yield() – suspends current thread
- std::thread::id get_id()
- sleep_for(duration)
  sleep_until(abs_time)

- No standard way to interrupt or terminate a thread from outside
  - Boost.Thread (look for EXTENSION): http://www.boost.org/doc/libs/1_56_0/doc/html/thread/thread_management.html

See also

- std::packaged_task<R(Args)>
  - Something (callable + arguments) that can be invoked (asynchronously)
- std::shared_future<T>
  - Future that can be shared (e.g., between multiple consumer threads)

Threads vs Tasks

- Thread: system-level resource, managed by OS
  - This is std::thread
  - Problem: oversubscription – OS threads are expensive
    - Usually threads are long-lived objects organized in execution pools
- Task: abstract “something” that should be executed [asynchronously]
  - Somewhat close to std::future
- Unlike Java, C++ standard library provides no abstraction for “task execution engine” and related parallel programming patterns
  - Vendor-specific & proprietary libraries are widely used
  - Intel TBB: https://www.threadingbuildingblocks.org/
  - Microsoft Concurrency Run-Time: http://msdn.microsoft.com/en-us/library/dd504870.aspx

Intel TBB code example

```
#include "tbb/tbb.h"
// ...

void process_file(const std::string & name) {
      // ...
}

void process_files(const std::vector<std::string> & file_names, std::size_t n) {
      parallel_for(blocked_range<size_t>(0, n),
            [&file_names](const blocked_range<size_t> & r) {
                  for (std::size_t i : r) {
                        process_file(file_names.at(i));
                  }
            });
}
```

- [&file_names]… – capture file_names by reference
- See TBB user guide at https://www.threadingbuildingblocks.org/

Synchronization

- You should already know something about...
  - Data races
  - Mutexes
  - Locks
  - Deadlocks & livelocks
  - Atomic operations
- SC-DRF memory model
  - Sequentially Consistent for Data Race-Free code
  - Related operations are seen in the same order
    - Unless there is a data race
  - Required by language standard since C++11

Reordering

- Basic operations: READ(x), WRITE(x)
  - 'x' is “memory location”
- Compiler can reorder operations
- Processor can reorder operations
- Memory (cache, etc) can reorder operations

- **Without synchronization you can't make any assumptions about shared mutable objects**

Memory locations

- Values of fundamental data types occupy exactly one memory location, regardless of their size

```
char foo, bar;        // Two different memory locations
```

- Adjacent bit fields of non-zero width share the same memory location

```
struct gizmo_42_regs {
  unsigned r0 : 4;    // 'r0' and 'r1' share the same
  unsigned r1 : 4;    //   "memory location"
  unsigned _0 : 0;    // ===== separator =====
  unsigned r2 : 4;    // 'r2' and 'r3' share the same
  unsigned r3 : 4;    //   "memory location"
};
```

<mutex>: std::mutex

- Good old mutex
- lock()
- try_lock()
- unlock()

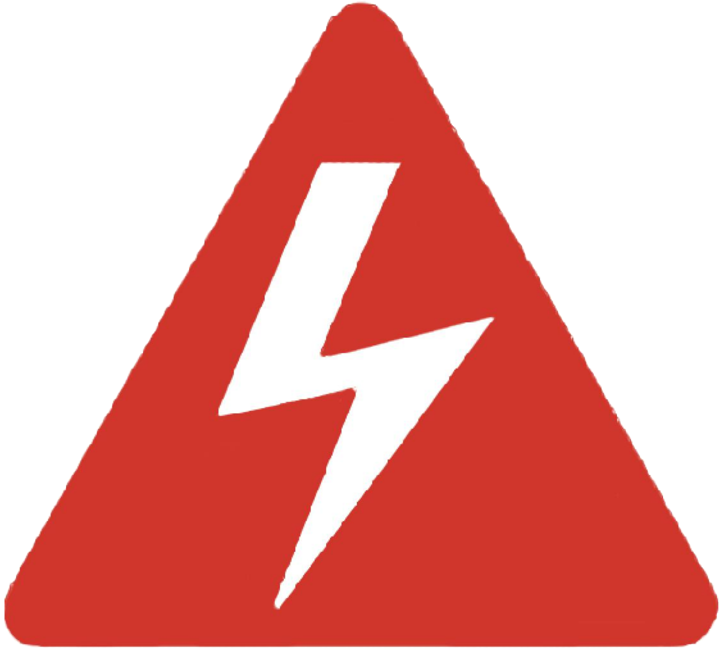
- std::lock(L1, …, Ln) – lock L1, …, Ln using deadlock avoidance algorithm

Code example

```
class thread_safe_stack {
        std::vector<std::string> data;
        std::mutex data_mtx;
public:
        // ...

        void push(const std::string & x) {
                data_mtx.lock();
                data.push_back(x);
                data_mtx.unlock();
        }

        std::string pop() {
                data_mtx.lock();
                std::string top;
                if (!data.empty()) {
                        top = data.back();
                        data.pop_back();
                }
                data_mtx.unlock();
                return top;
        }
};
```



RAII & Object lifetime

- RAII = “Resource Allocation Is Initialization”
  - Classes have constructor(s) and destructor
  - Resources are usually disposed in dtor
  - ➔ Resource lifetime = owner object lifetime

```
void foo() {
   // ...
   my_class x; // Default ctor: 'my_class::my_class()'
   // ...
   // 'x' goes out of scope
   //     => (implicit) dtor: 'my_class::~my_class()'
}
```

- Java: try-finally
- C#: using

RAII & Exception safety

- Exceptions complicate reasoning about possible execution paths
- Think about invariants for methods
- RAII
  - All resources allocated should be owned by someone
  - Dtors will be invoked during call stack unwinding

<mutex>: std::lock_guard

- RAII object representing lock
- Locks in ctor, unlocks in dtor

Code example

```
class thread_safe_stack {
    std::vector<std::string> data;
    std::mutex data_mtx;

public:

    // ...

    void push(std::string x) {
        std::lock_guard<std::mutex> lock(data_mtx);
        data.push_back(x);
    }

    std::string pop() {
        std::lock_guard<std::mutex> lock(data_mtx);
        std::string top;
        if (!data.empty()) {
            top = data.back();
            data.pop_back();
        }
        return top;
    }
};
```

data_mtx is locked here

data_mtx is locked here

<mutex>: std::unique_lock

- RAII object representing a lock
- (Usually) locks in ctor, unlocks in dtor
- Can defer lock with special ctor
- Can unlock before dtor
- std::unique_lock(mutex)
- lock(), try_lock(), unlock()
- **Use std::lock_guard unless you really need to unlock “in the middle” / defer locking**

<condition_variable>: std::condition_variable

- Event notification mechanism
  - E.g., “there are messages ready for processing”
- wait(std::unique_lock<std::mutex>& lock)
  1. Releases lock (that’s why std::unique_lock)
  2. Blocks current execution thread T
  3. Waits for notification
  4. Reacquires lock, resumes thread T
- wait(std::unique_lock<std::mutex>& lock, pred)
  - waits until a predicate is satisfied.
  Equivalent to:
  `while(!pred()) { wait(lock); }`

<condition_variable>: std::condition_variable

- notify_one() – notifies some waiting thread
- notify_all() – notifies all waiting threads

- **NB:** lost notifications are similar to deadlocks
  - Use notify_all() before “make it fast” phase

Example: producer / consumer

```
std::mutex fifo_mutex;
std::queue<Sample> data_fifo;
std::condition_variable data_rdy;
```

```
Sample produce();
void process(const Sample &);
bool is_last(const Sample &);
```

```
void producer_thread() {
  while (true) {
    const Sample s = produce();
    std::lock_guard<std::mutex>
        lk(fifo_mutex);
    data_fifo.push(s);
    data_rdy.notify_all();
    if (is_last(s)) break;
  }
}
```

```
void consumer_thread() {
  while (true) {
    std::unique_lock<std::mutex>
        lk(fifo_mutex);
    data_rdy.wait(lk,
        [] { return !data_fifo.empty(); });
    const Sample s = data_fifo.front();
    data_fifo.pop();
    lk.unlock();
    process(s);
    if (is_last(s)) break;
  }
}
```

See also

- std::shared_lock
- std::defer_lock
- std::adopt_lock

To lock or not to lock?

- Minimize shared mutable state
  - Tasks, actors, …
- Provide good (concurrency-aware) API
  - High-level operations (transactions), not steps

```
/* Ex.1 */  if (!q.empty()) { x = q.front(); q.pop(); process(x); }
/* Ex.2 */  if (q.try_pop_front(x)) { process(x); }
```

  - Think about invariants
- Lock at proper granularity
  - Again, think about invariants

Concurrent programming patterns

- Active object
  - Replace locking operation with message submission
- Reactor
  - Receive message, spawn new task
- SPMD
  - Parallel for
  - Parallel reduce
  - Recursive fork-join
- Pipeline (special case of “Task dependency graph”)
  - F → G → H
  - Operations F, G, H are independent

Coding for concurrency

- Localize (and eliminate) mutability
  - Immutable objects are thread-safe by default
  - C++: ‘const’ discipline matters
- Minimize dependencies between tasks
  - Maximize determinism
- Group data by tasks
- Separate business logic from orchestration
  - Better testability
- Use library solutions when possible
  - Thread-safe containers, logging, …

Atomics

- **C/C++: ‘volatile’ != atomic**
- std::atomic<T>
  - compare_exchange_weak(expected, desired), compare_exchange_strong(expected, desired)
    - Basic read-modify write operation known as CAS (Compare-And-Swap)
  - operator ++, operator --, operator +=, …
- std::atomic_flag
  - test_and_set(), clear()

Example: test-and-set mutex

```
class tas_mutex {
    std::atomic_flag flag;

public:
    tas_mutex()
        : flag(ATOMIC_FLAG_INIT)
    {}

    void lock() {
        while(flag.test_and_set());
    }

    void unlock() {
        flag.clear();
    }
};
```

More on atomics

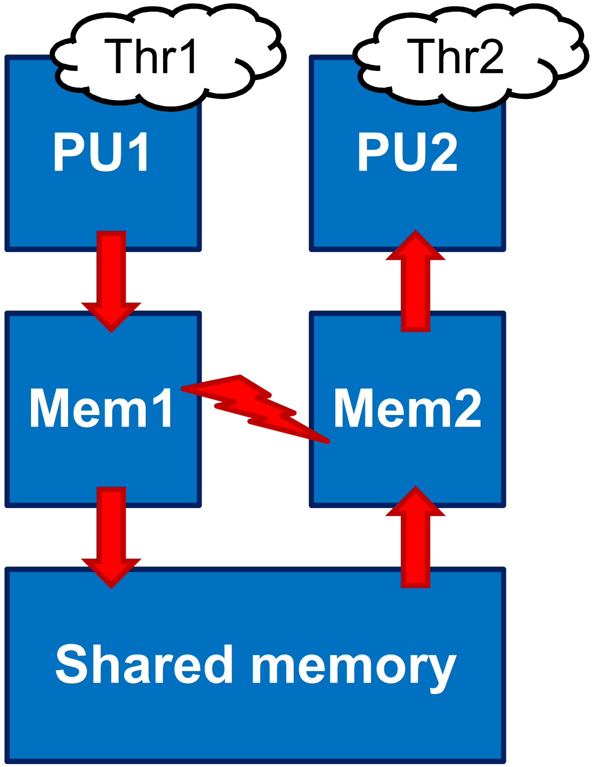
Herb Sutter: atomic<> Weapons

(Channel9 video from C++ and Beyound 2012)

1. http://channel9.msdn.com/Shows/Going+Deep/Cpp-and-Beyond-2012-Herb-Sutter-atomic-Weapons-1-of-2
2. http://channel9.msdn.com/Shows/Going+Deep/Cpp-and-Beyond-2012-Herb-Sutter-atomic-Weapons-2-of-2

Data contention

- Data propagation through memory hierarchy can be **very** slow
  - Cache ping-pong in loops
  - **Atomics (and mutexes) count, too**
- "False sharing"
  - Caches operate in cache lines
  - E.g.: naïve matrix multiplication
- Data proximity
  - Organize your data by tasks
  - Use extra padding to test for false sharing
  - TBB: cache_aligned_allocator<T>



CAS and the “ABA problem”

- Thread T writes A to shared variable X
- Thread T goes to sleep
- Someone writes B to X
- …
- Someone writes A to X
- Thread T wakes up
- Thread T sees value A of shared variable X
- Thread T happily continues

Did anyone tell you shared state is bad?

Workarounds for ABA problem

- Tagged state reference
  - <Value, Modification counter>
  - Used in Boost.Lockfree
- Special case: memory management in dynamic data structures
  - Use GC
  - Use smart node reclamation strategy
- Minimize shared state
  - Tasks, actors, …

Boost.Lockfree:
since 1.53

CAF: C++ Actor Framework
http://actor-framework.org/