Multithreaded C11 & C++11: the Dawn of new Standards (and a preview of upcoming Transactional Memory TS)

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C/C++ Standard

Acknowledgement and Disclaimer

- Numerous people internal and external, in industry and academia, have made contributions, influenced ideas, written part of this presentations, and offered feedbacks to form part of this talk.
- I even lifted this acknowledgement and disclaimer from some of them.
- But I claim all credit for errors, and stupid mistakes. **These are mine, all mine!**
- Any opinions expressed in this presentation are my opinions and do not necessarily reflect the opinions of IBM.

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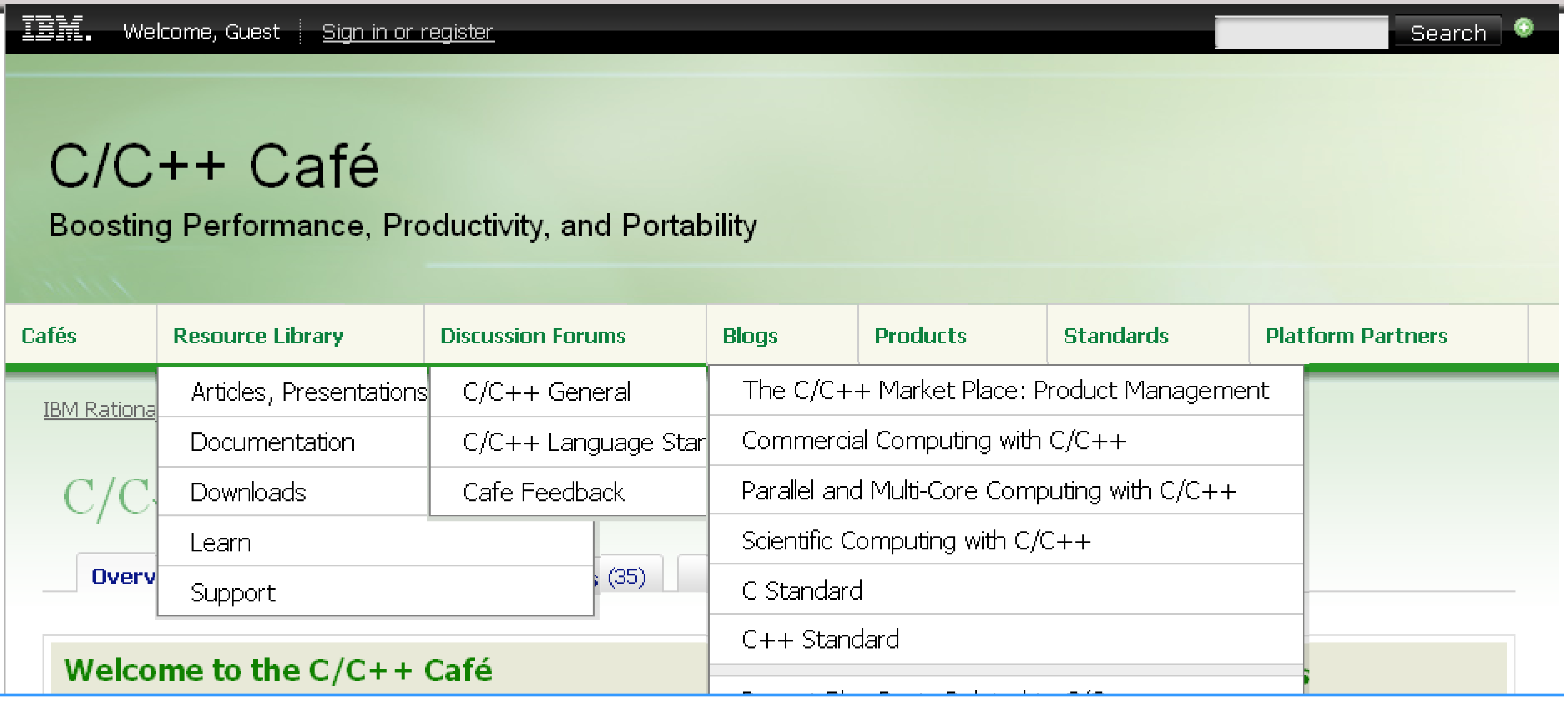

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Agenda

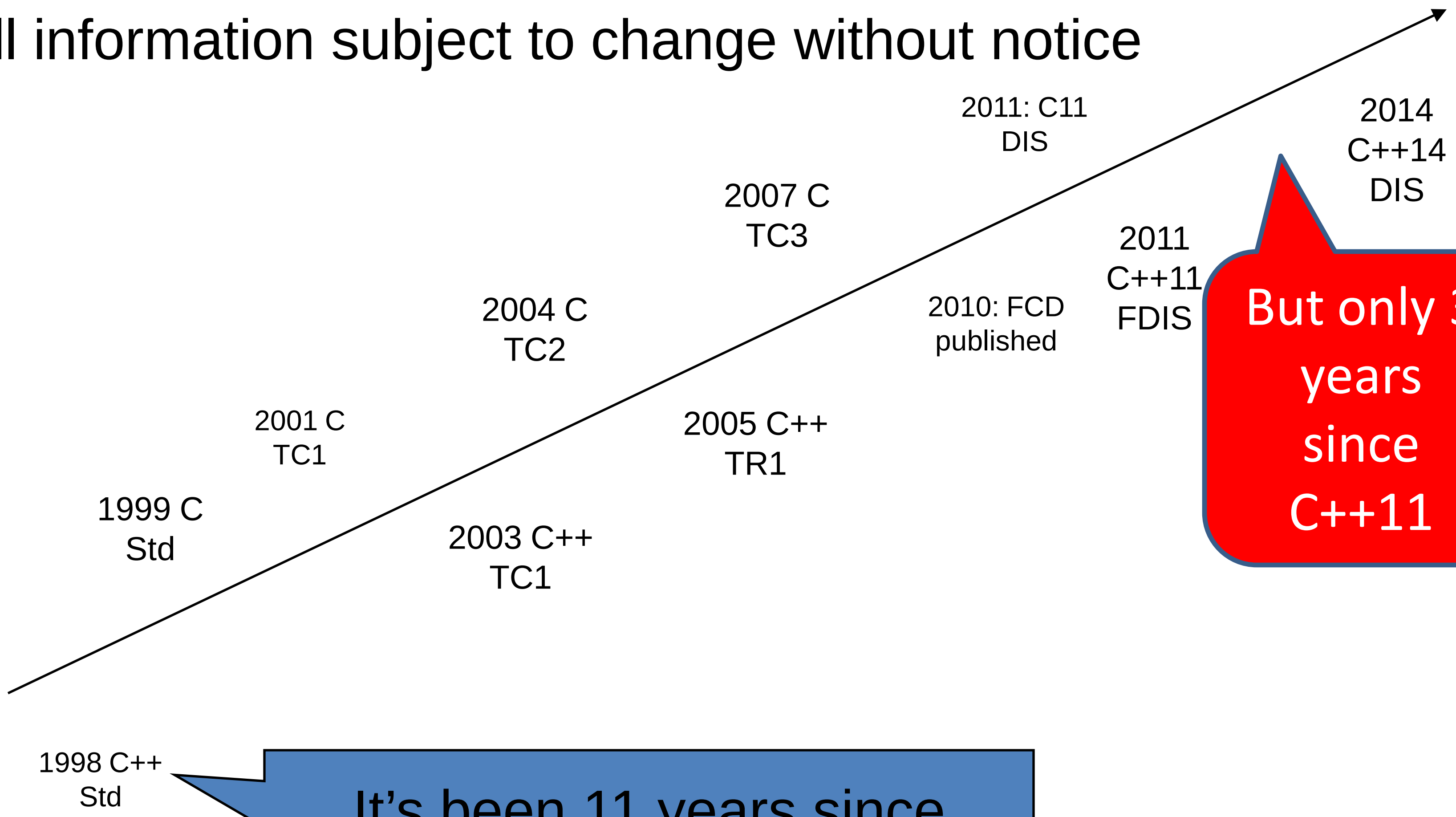
- C11, C++11, C++14, SG5 TM goals and timelines
- C++ Standard Transactional Memory status
- Multithreading support in C11 and C++11
- The problems of Concurrency before C/C++ 11
- Language support
- Memory Model
- Fragen?

Where were you in 1998?

- Google was incorporated and hires its first employee
- Paypal founded, Amazon buys IMDB
- XML published
- Intel Pentium II: 0.45 GFLOPS
- No SIMD: SSE came in Pentium III
- No GPUs: GPU came out a year later
- The fastest computer was Sandia's ASCI Red at 1.8 Tflops (9152 cores)
- C++98 became the new JTC1/SC22/WG21 C++ Standard
- A year later, C99 became the WG14 C Standard

C and C++ Standard Progress

All information subject to change without notice



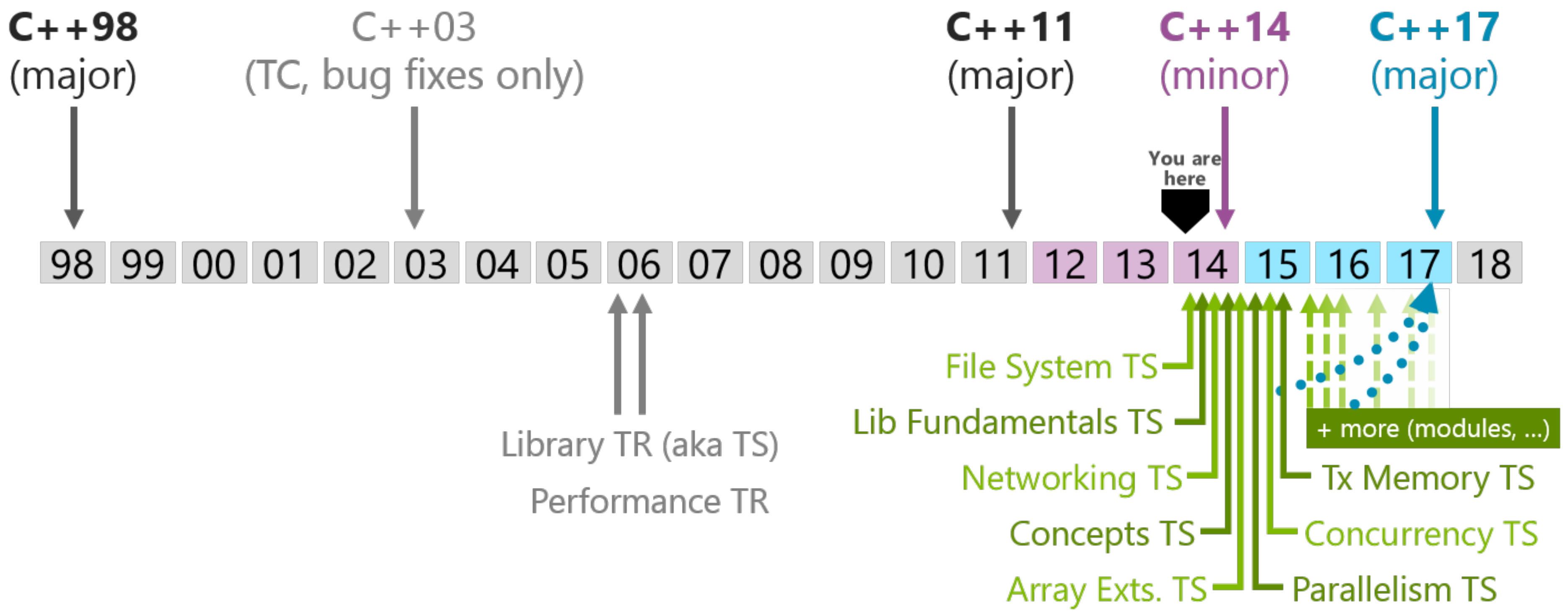
But only 3 years since C++11

It's been 11 years since C++98/C99 to C++11/C11!

ISO/IEC JTC1 ballot stages

Stage	IS	TS	Level	Ballot Period	Requirements & Notes
10 Proposal	NP	NP	SC22	3 mo	5 NBs agree to actively participate
30 Committee	CD	PDTS	SC22	2, 3, or 4 mo 3-6 mo	Principal comment stage
40 Enquiry	DIS	DTS	JTC1 / ITTF	5 mo 3-6 mo	2/3 Yes, ≤1/4 No majority
50 Approval	FDIS	—	JTC1 / ITTF	2 mo	No comments 2/3 Yes, ≤1/4 No

C++14 DIS, 8 TS's under develpoment (by Herb Sutter)

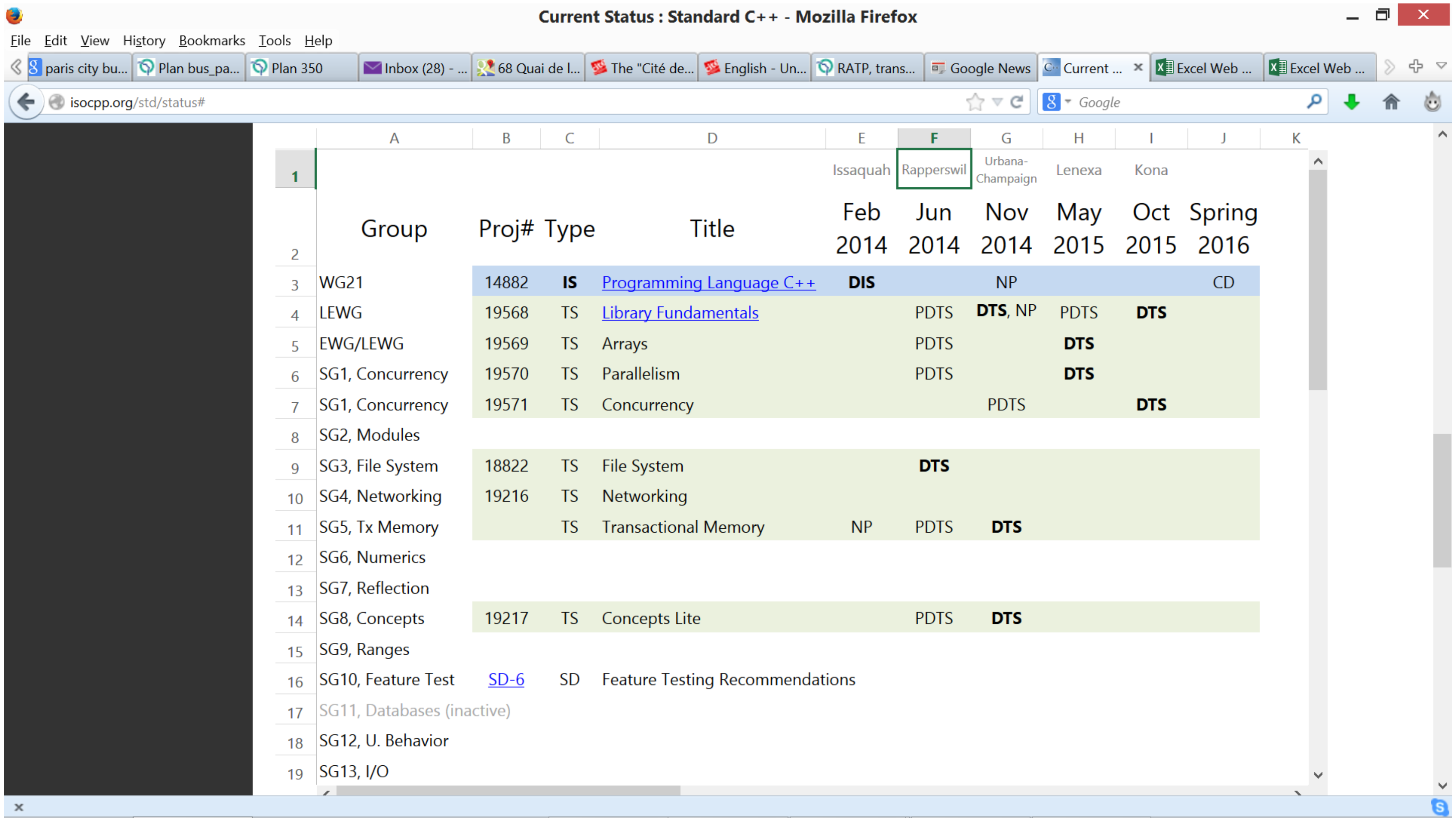


C++14 is approved (photos by Chandler Carruth)

Current Project Details

- **Programming Language C++ IS: Richard Smith.** This is the main C++ Standard project.
- **File System TS: Beman Dawes.** Work based on Boost.Filesystem v3, including file and directory iteration.
- **Library Fundamentals TS: Jeffrey Yasskin.** A set of standard library extensions for vocabulary types like optional<> and other fundamental utilities.
- **Networking TS: Kyle Kloepper.** A small set of network-related libraries including support for network byte order transformation and URIs.
- **Concepts TS: Andrew Sutton.** Extensions for template type checking.
- **Arrays TS: Lawrence Crowl.** Language and library extensions related to arrays, including runtime-sized arrays (aka arrays of runtime bound) and dynarray<>.
- **Parallelism TS: Jared Hoberock.** Initially includes a Parallel STL library with support for parallel algorithms to exploit multiple cores, and vectorizable algorithms to exploit CPU and other vector units.
- **Concurrency TS: Artur Laksberg.** Initially includes library support for executors and non-blocking extensions to std::future. Additionally may include language extensions like await, and additional libraries such as concurrent hash containers and latches.
- ***Transactional Memory TS: Michael Wong.*** *A promising way to deal with mutable shared memory, that is expected to be more usable and scalable than current techniques based on atomics and mutexes.*

Project Time line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isocpp.org/std/status#

	A	B	C	D	E	F	G	H	I	J
1					Issaquah	Rapperswil	Urbana-Champaign	Lenexa	Kona	
2	Group	Proj#	Type	Title	Feb 2014	Jun 2014	Nov 2014	May 2015	Oct 2015	Spring 2016
3	WG21	14882	**IS**	Programming Language C++	**DIS**		NP			CD
4	LEWG	19568	TS	Library Fundamentals		PDTS	**DTS**, NP	PDTS	**DTS**	
5	EWG/LEWG	19569	TS	Arrays		PDTS		**DTS**		
6	SG1, Concurrency	19570	TS	Parallelism		PDTS		**DTS**		
7	SG1, Concurrency	19571	TS	Concurrency			PDTS		**DTS**	
8	SG2, Modules									
9	SG3, File System	18822	TS	File System		**DTS**				
10	SG4, Networking	19216	TS	Networking						
11	SG5, Tx Memory		TS	Transactional Memory	NP	PDTS	**DTS**			
12	SG6, Numerics									
13	SG7, Reflection									
14	SG8, Concepts	19217	TS	Concepts Lite		PDTS	**DTS**			
15	SG9, Ranges									
16	SG10, Feature Test	SD-6	SD	Feature Testing Recommendations						
17	SG11, Databases (inactive)									
18	SG12, U. Behavior									
19	SG13, I/O									

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Why do we need a TM language?

- TM requires language support
- Hardware here and now
- Multiple projects extend C++ with TM constructs
- Adoption requires common TM language extensions

What is hard about adding TM to C++

- Conflict with C++ 11 memory model and atomics
- Support member initializer syntax
- Support C++ expressions
- Work with legacy code
- Structured block nesting
- Multiple entry and exit from transactions
- Polymorphism
- Exceptions

Project History

- 2008: every other week discussions by Intel, Sun/Oracle, IBM started in July, joined by HP, Redhat, academics
- 2009: Version 1.0 released in August
- 2011: Version 1.1 fixes problems in 1.0, exceptions
- 2012: Brought proposal to C++Std SG1; became SG5, demonstrated use-cases, performance data
- 2013: Presented to Evolution WG as a proposed C++ Technical Specification
- 2014: Approved by Evolution WG; voted in Full group to start New Proposal as a Technical Specification

Active members

- Hans Boehm, hans.boehm@hp.com
- Justin Gottschlich, justin.gottschlich@intel.com
- Victor Luchangco, victor.luchangco@oracle.com
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- Michael Spear, spear@cse.lehigh.edu
- Michael Wong, michaelw@ca.ibm.com

Commercial Hardware TMs

- Azul Systems’ HTM (phased out?)
- AMD ASF (unknown status)
- Sun’s Rock (cancelled)
- IBM’s Blue Gene/Q (2011)
- Intel’s TSX (code named Haswell) (2012)
- IBM’s zEC12 (2012)
- IBM Power8 (2014)

- HTM will only improve existing STM performance

Commercial/OS Compilers

- Sun Studio (for Rock)
- Intel STM
- IBM AlphaWorks STM (for BG)
- GNU 4.7
- IBM xlC z/OS v1R13 compiler

Design goals

Build on the C++11 specification

- Follow established patterns and rules
- “Catch fire” semantics for racy programs

Enable easy adoption

- Minimize number of new keywords
- Do not break existing non-transactional code

Have constructs to enable static error detection and runtime selection

- Ease of debugging is important but so is flexibility

When in doubt, leave choice to the programmer

- Abort or irrevocable actions?
- Commit-on-exception or rollback-on-exception?

Locks are Impractical for Generic Programming=callback

Thread 1:

```
m1.lock();
m2.lock();
…
```

+

Thread 2:

```
m2.lock();
m1.lock();
…
```

= *deadlock*

Easy. Order Locks.

Now let's get slightly more real:

What about Thread 1 +

A thread running `f()`*:*

```
template <class T>
void f(T &x, T y) {
  unique_lock<mutex> _(m2);
  x = y;
}
```

?

What locks does `x = y` acquire?

What locks does `x = y` acquire?

- Depends on the type `T` of `x` and `y`.
  - The author of `f()` shouldn't need to know.
    - That would violate modularity.
  - But lets say it's `shared_ptr<TT>`.
    - Depends on locks acquired by `TT`'s destructor.
    - Which probably depends on its member destructors.
    - Which I definitely shouldn't need to know.
    - But which might include a `shared_ptr<TTT>`.
      - Which acquires locks depending on `TTT`'s destructor.
      - Whose internals I definitely have no business knowing.
      - …
- And this was for an unrealistically simple `f()`!
- We have no realistic rules for avoiding deadlock!
  - In practice: Test & fix?

```
template <class T>
void f(T &x, T y) {
   unique_lock<mutex> _(m2);
   x = y;
}
```

Transactions Naturally Fit Generic Programming Model

- Composable, no ordering constraints

f() implementation:

```
template <class T>
void f(T &x, T y) {
   transaction {
   x = y;
   }
}
```

Class implementation:

```
class ImpT
{
   ImpT& operator=(ImpT T& rhs)
   {
      transaction {
         // handle assignment
      }
   }
};
```

Impossible to deadlock

The Problem

- **Popular belief:** *enforced locking ordering can avoid deadlock.*

- We show this is essentially impossible with C++ template programming.

- *Template programming is pervasive in C++. Thus, template programming needs TM.*

Don’t We Know This Already?

- Perhaps, but impact has been widely underestimated.
  - Templates are everywhere in C++.
- Move TM debate away from performance; focus on convincingly correct code.
- Relevant because of C++11 and SG5.
- Generic Programming Needs Transactional Memory by Gottschlich & Boehm, Transact 2013

Conclusion

- Given C++11, generic programming needs TM more than ever.

- To avoid deadlocks in ***all*** generic code, even those with irrevocable operations, we need (something like) relaxed transactions.

TM Patterns and Use Cases

- Top four uses cases:
  1. Irregular structures with low conflict frequency
  2. Low conflict structures with high read-sharing and complex operations
  3. Read-mostly structures with frequent read-only operations
  4. Composable modular structures and functions

Current Status of SG5 TM

- EWG Approved to start a NP for a TS 16/6/1/0/0
- LEWG Approved 8/3/2/0/0
- Formal motion for New Proposal TS approved INCITS: 25/0/0 and ISO: 7/0/0
  - Based on N3919 as indicated content
  - 3 sets of Balloting for 12 months to become and official TS
- Continue telecon every other week to create a first TS Working Draft for Rapperswil, Switzerland
- Aimed for Final DTS for 2015
- Continue working on enhancements for further TS

Support for TM in C++ std library

- enable users to use transactional constructs in the first TS delivery of SG5
- Started with std::list
- Make it transaction-safe
  - Enables use with atomic blocks
- Open source collaboration welcome on github
  - https://github.com/mfs409/tm_stl

2014: SG5 TM Language in a nutshell (N3919)

1 construct for transactions

1. Compound Statements

2 Keywords for different types of TX

atomic_noexcept | atomic_commit | atomic_cancel {<compound-statement> }

synchronized {<compound-statement> }

1 Function/function pointer keyword

transaction_safe

-must be a keyword because it conveys necessary semantics on type

1 Function/function pointer attribute

[[transaction_unsafe]]

-provides static checking and performance hints, so it can be an attribute

What is transaction-safe?

- From N3919, what is a transaction-safe operation?
  - Operations in which system can guarantee atomicity
- excluding:
  - Access to volatile data
  - Assembly instructions
  - Calls to functions that violate atomicity
- Examples of functions that violate atomicity
  - Synchronization: operations on locks/ mutexes and C++11 atomics
  - Certain I/O functions

– More info in:
  - http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2014/n3919.pdf

atomic Examples

```
class Account {
  int bal;
 public:
  Account(int initbal) { bal = initbal;
     };
  void deposit(doublex) {
    atomic_noexcept {
      this.bal += x;
    }
  };
  double balance() { return bal; }
}
```

```
void transfer(Account
   a1, a2; int x;) {
  atomic_noexcept {
    a1.deposit(-x);
    a2.deposit(x);
  }
};
```

synhronized examples

```
int i = 0;
void f() {
  transaction_relaxed {
    if (unlikely_condition)
      std::cerr << "oops" << std::endl;
    ++i;
  }
}
```

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Is this legal C++03 syntax?

```
template<class T> using Vec = vector<T,My_alloc<T>>;
Vec<double> v = { 2.3, 1.2, 6.7, 4.5 };
//sort(v);
for(auto p = v.begin(); p!=v.end(); ++p)
        cout << *p << endl;
```

Hello Concurrent World

```
#include <iostream>
#include <thread> //#1
void hello() //#2
{
    std::cout<<"Hello Concurrent World"<<std::endl;
}
int main()
{
    std::thread t(hello); //#3
    t.join(); //#4
}
```

Can you do this with TLS before C11/C++11?

```
extern std::string f(); //returns “Hello”
  from another TU
std::string foo(std::string const& s2) {
  __thread std::string s=f();
  s+=s2;
  return s;
 }
```

Is this valid C++ today? Are these equivalent?

```
int x = 0;
atomic<int> y = 0;
```
Thread 1:
```
   x = 17;
   y.store(1,
   memory_order_release);
   // or:      y.store(1);
```

Thread 2:
```
   while
   (y.load(memory_order_acquire
   ) != 1)
   // or:      while (y.load()
   != 1)

   assert(x == 17);
```

```
int x = 0;
atomic<int> y = 0;
```
Thread 1:
```
   x = 17;
   y = 1;
```
Thread 2:
```
   while (y != 1)
        continue;
   assert(x == 17);
```

C++11, C11

- C++0x: Codename for the planned new standard for the C++ programming language
  - Will replace existing ISO/IEC 14882 standard published in 1998 (C++98) and updated in 2003 (C++03)
  - Many new features to core language
  - Many library features: most of C++ Technical Report 1 (TR1)
  - FDIS in March 2011
  - X=A,B,C,D,E,F?
  - C++11 ratified Dec 2012

X=B!

- C1x: Codename for the planned new standard for the C programming language
  - Will replace existing ISO/IEC 9899 standard published in 1999
  - DIS in March 2011
  - C11 ratified Dec 2012

Status of Language Standards as of 1H 2013

- C11 ratified Dec 2011,
  - starting work on next C
- C++11 ratified Dec 2011,
  - starting work on C++2014/2017/2022

•Much more advanced concurrency

- Creation of isocpp.org Foundation to promote Std C++ and centralize latest knowledge

•Michael Wong is Founding Director & VP

•IBM is Founding Member

Organization & Sponsors

- Three goals:
  - Handle money: Pay for site development and maintenance by accept funds from sponsors (but not general public).
  - Hold copyright/license: We need Pearson to be able to publish an edited version of the wiki FAQ as a *C++ FAQs 3e* book/e-book.
  - Have a clear board: We need to make it clear "who this is," who is involved and directing the effort.

- "Standard C++ Foundation" 501c(6)
  - Founding sponsors: Some subset of { AAPL, Boost/BoostPro, Bloomberg, C&B, FB, GOOG, IBM, INTL, MSFT, TAMU, … }
    - Gold: $10K/year
    - Silver:$5K/year
    - Bronze:$1K?year
  - Board of directors:
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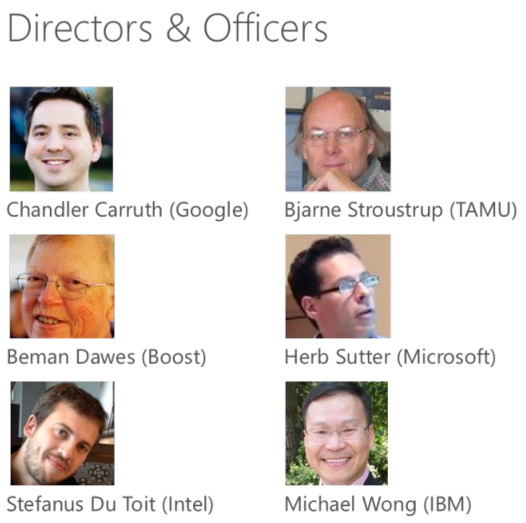


Sum of all things **C11** & C++11

Atomic operations
Right Angle Brackets
General Attributes
Multi-threading Library
Member Initializers
Lambda
PODs unstrung
Explicit Virtual Overrides
long long
Extern template
tuples
Strongly Typed Enums
Namespace Association
User-defined Literals
unique_ptr,forward_list,
regular expressions
Generalized Constant
Raw.unicode String Literals
Thread-Local Storage
Expressions
type_trait names
Delegating Constructors,
New function declaration syntax
static_assert
Garbage Collection
memory model
Alignment
hash tables
Extended friend Declarations
Decltype
Rvalue Reference
hash tables
nullptr
enhanced binder
Unrestricted Unions
Data-Dependency Orderin
random numbers
Auto type inference
Variadic Templates
range-based for-loop
Initializer lists
Template aliases
generalized functors
Local Classes more Usefu
Inheriting Constructors
Extending sizeof
Explicit Conversion Operators
__func__
Forward Declaration of Enums
Propagating exceptions
Defaulted and Deleted Functions
variadic macros, empty macro argument,
Dynamic initialization and concurrency
Universal Character Names in Literals
enhanced member pointer adaptor
SFINAE problem for expressions
char16_t,char32_t
concatenation of mixed char and wchar literals
Unicode Strings UTF8 Literals
extended integer types

C++11 Library

- Start with original C++98 library
  - Improved performance with rvalue reference
  - Used variadic templates to improve compile time
  - Potential binary incompatibility with C++98 library strings
  - Reference counting not allowed
- Added 13/14 TR1 libraries
  - Reference wrapper, smart ptrs, return type determination, enhanced member pointer adapter, enhanced binder, generalized functors, type traits, random numbers, tuples, fixed size array, hash tables, regular expressions, C99 cmpat
- Added threading, unique_ptr,forward_list, many new algorithms

Sum of all things C11

- Alignment specification
  - _Alignas specifier
  - Alignof operator
  - Aligned_alloc funcioin
  - <stdalign.h> header
- _Noreturn function specifier
- Type-generic expressions
  - _Generic keyword
- Multithreading support
  - _Thread_local storage class specifier
- Improved unicode (UTF16/32/8)
- Remove gets
- Macros for querying suboral floating point number and number of digits the type is able to store
- Anonymous structs/unions
- Static assertions
- Exclusive create-and-open mode for fopen
- Quick_exit
- Macros for construction of complex values

- Optional features new from C99
  - Analyzability (Annex L)
  - Bounds Checking (Annex K)
  - Multithreading <threads.h>
  - Atomic primitives and types Mstdatomic.h> and _Atomic type qualifier
- Optional features optional in C99
  - IEC 60559 floating point arithmetic (Annex F)
  - IEC 60559 compatible complex arithmetic (Annex G)
- Optional features mandatory in C99
  - Complex types (mandatory for hosted)
  - Variable length arrays

Removed or Deprecated features

C++

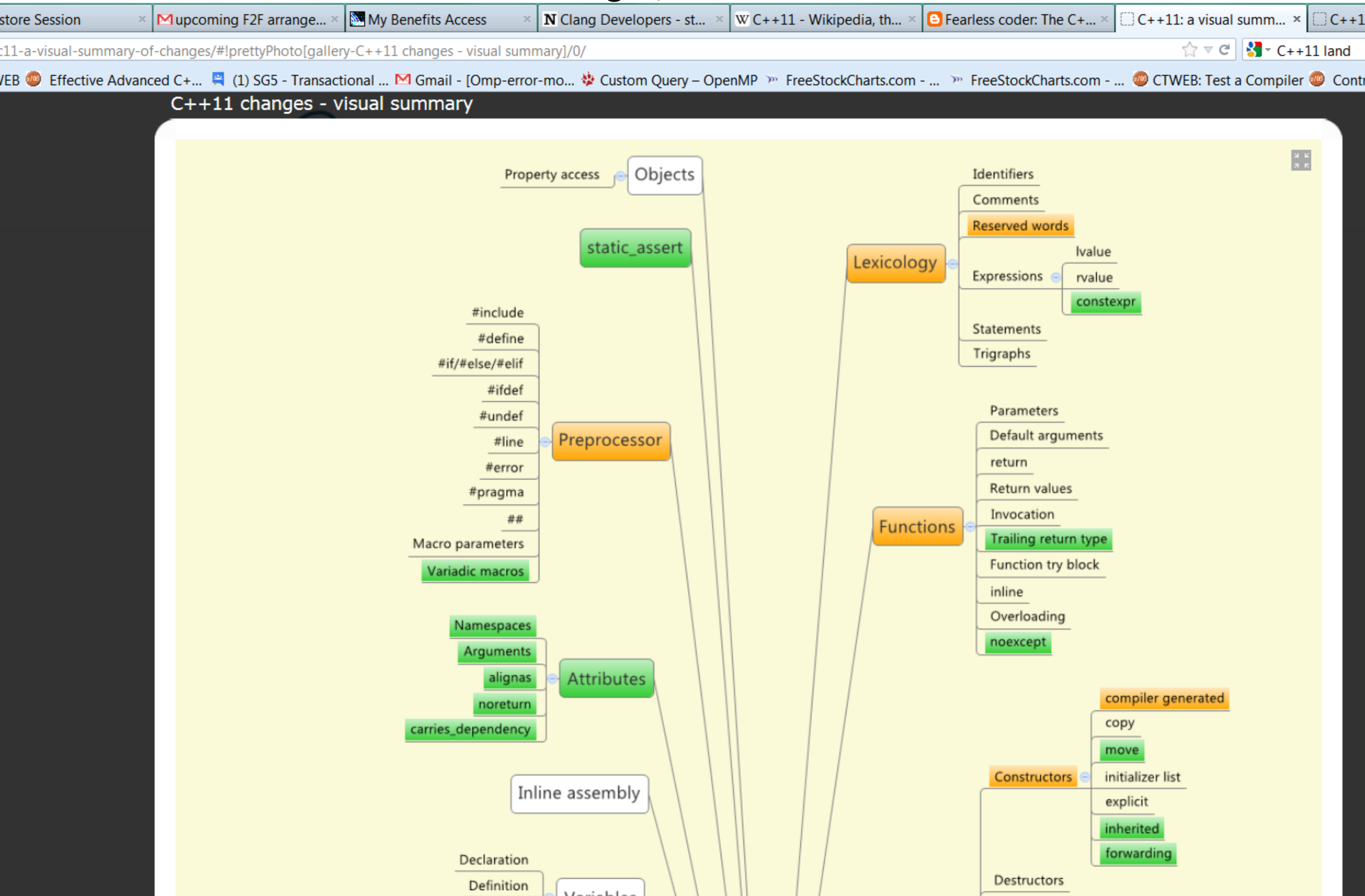
- Auto as a storage class
- Export semantics
- Register semantics
- Exception specification
- Auto_ptr
- Bind1st/bind2nd
- bool++
- See Clause D

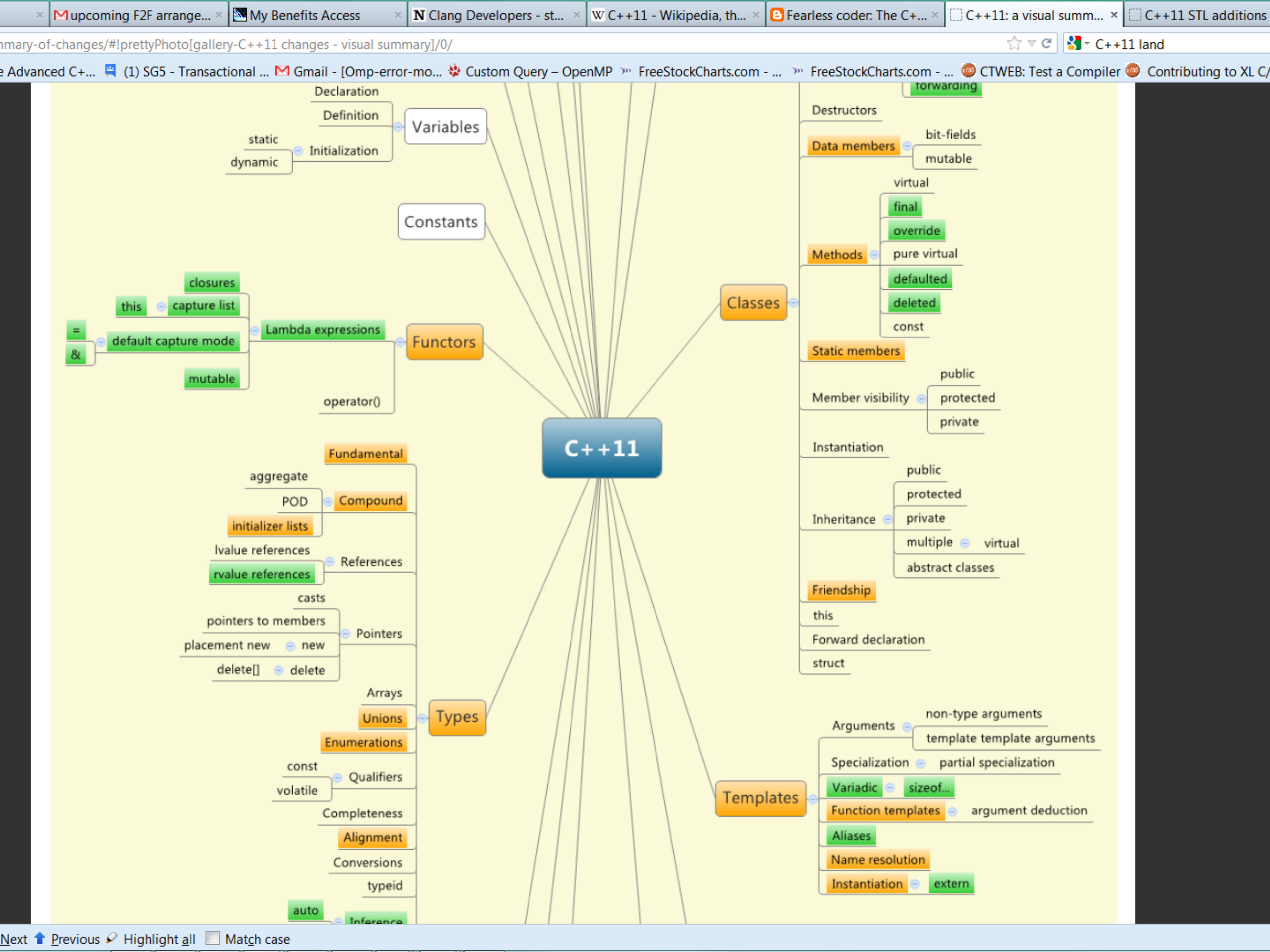
C

- Gets

C++11 land: http://fearlesscoder.blogspot.ca/2012/01/c11-lands.html

What changed in C++11: http://cpprocks.com/c11-a-visual-summary-of-changes/

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Custom Query – OpenMP
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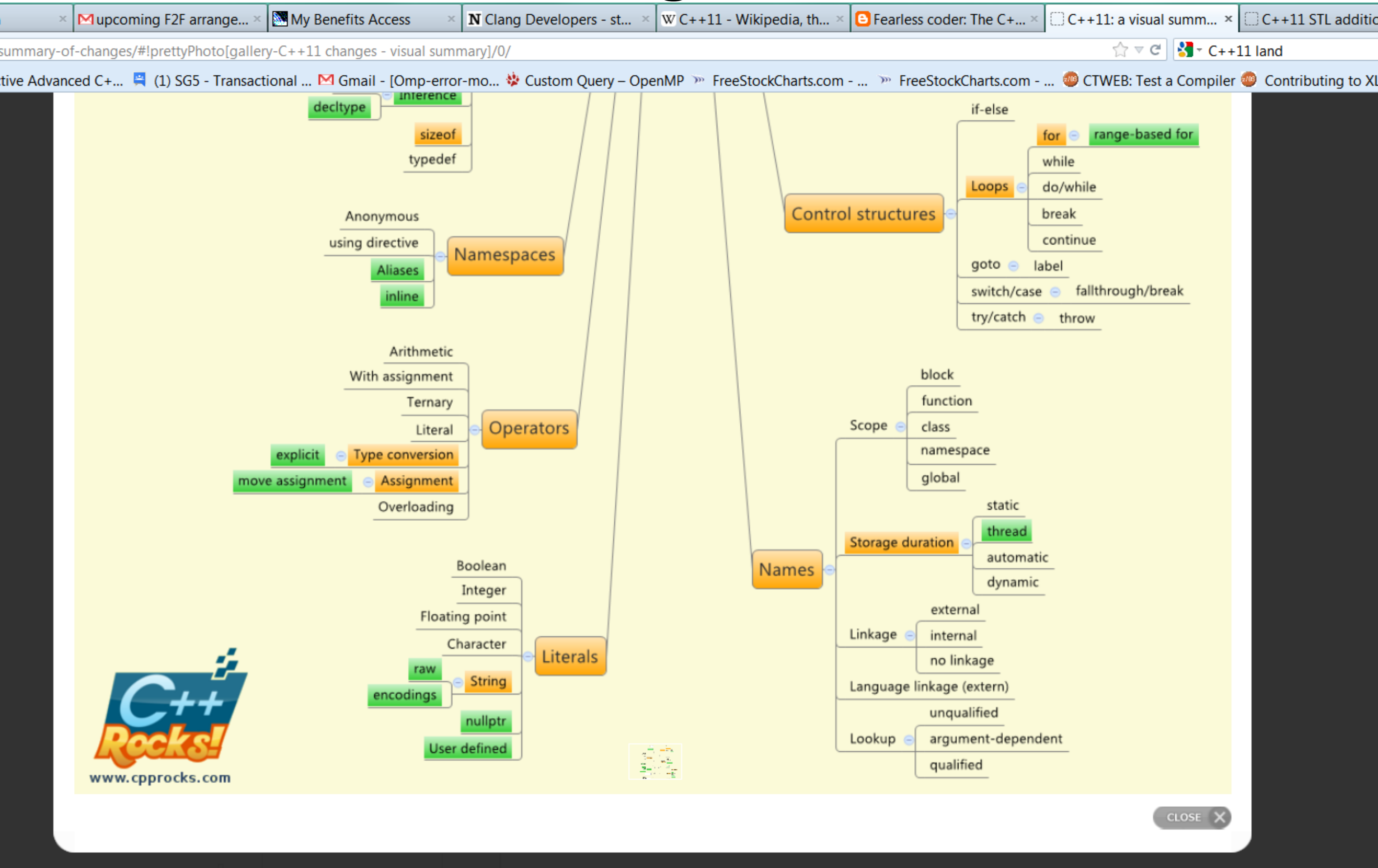
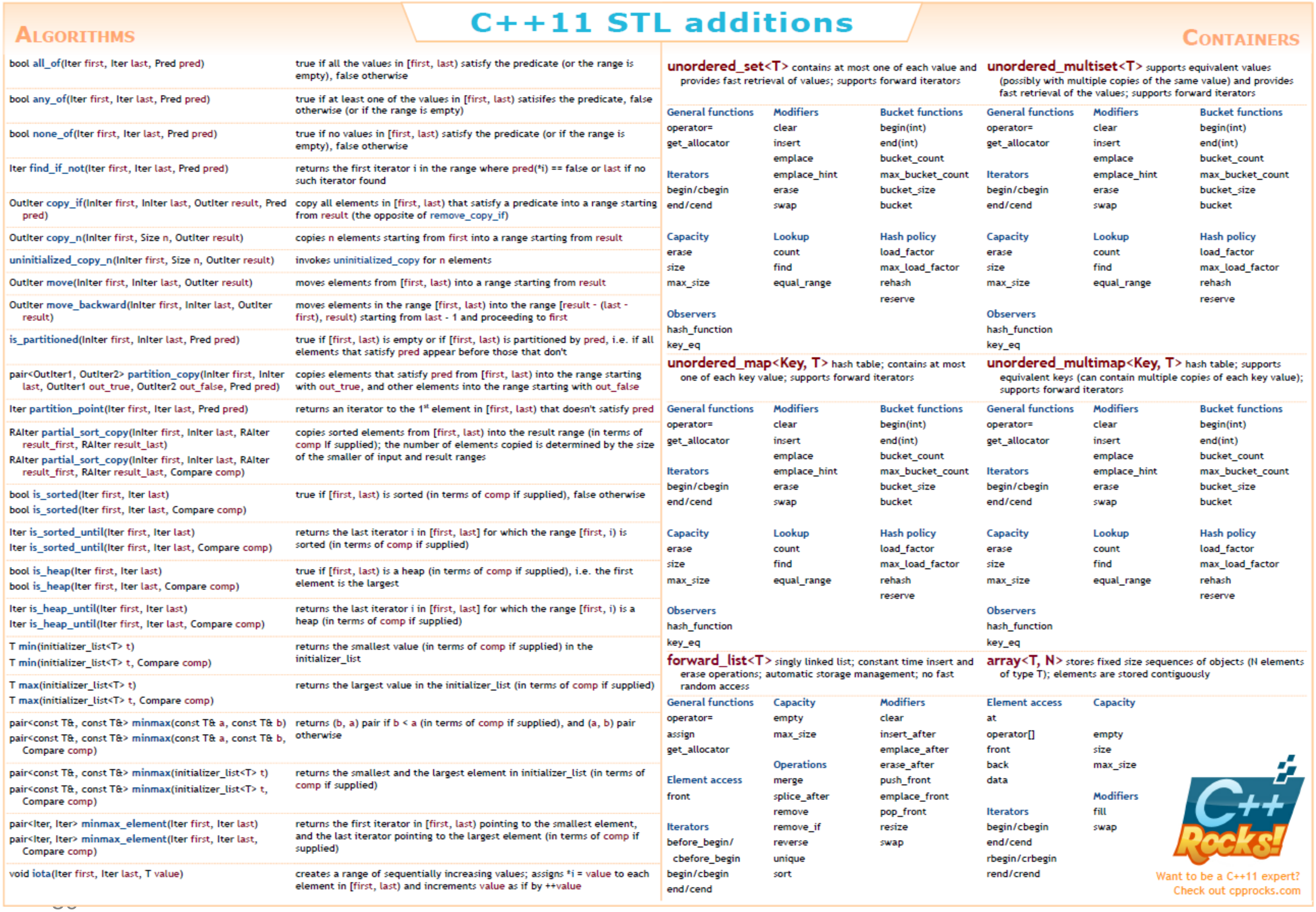
Contributing to XL C/
C++11
Variables
Declaration
Definition
Initialization
static
dynamic
Constants
Functors
Lambda expressions
closures
capture list
this
default capture mode
=
&
mutable
operator()
Types
Fundamental
Compound
aggregate
POD
initializer lists
References
lvalue references
rvalue references
Pointers
casts
pointers to members
new
placement new
delete
delete[]
Arrays
Unions
Enumerations
Qualifiers
const
volatile
Completeness
Alignment
Conversions
typeid
Inference
auto
Classes
forwarding
Destructors
Data members
bit-fields
mutable
Methods
virtual
final
override
pure virtual
defaulted
deleted
const
Static members
Member visibility
public
protected
private
Instantiation
Inheritance
public
protected
private
multiple
virtual
abstract classes
Friendship
this
Forward declaration
struct
Templates
Arguments
non-type arguments
template template arguments
Specialization
partial specialization
Variadic
sizeof...
Function templates
argument deduction
Aliases
Name resolution
Instantiation
extern
Next
Previous
Highlight all
Match case

What changed in C++11



What changed in C++11 STL:http://cpprocks.com/cpp11-stl-additions



C++11 STL additions

Algorithms

bool all_of(Iter first, Iter last, Pred pred)	true if all the values in [first, last) satisfy the predicate (or the range is empty), false otherwise
bool any_of(Iter first, Iter last, Pred pred)	true if at least one of the values in [first, last) satisifes the predicate, false otherwise (or if the range is empty)
bool none_of(Iter first, Iter last, Pred pred)	true if no values in [first, last) satisfy the predicate (or if the range is empty), false otherwise
Iter find_if_not(Iter first, Iter last, Pred pred)	returns the first iterator i in the range where pred(*i) == false or last if no such iterator found
OutIter copy_if(InIter first, InIter last, OutIter result, Pred pred)	copy all elements in [first, last) that satisfy a predicate into a range starting from result (the opposite of remove_copy_if)
OutIter copy_n(InIter first, Size n, OutIter result)	copies n elements starting from first into a range starting from result
uninitialized_copy_n(InIter first, Size n, OutIter result)	invokes uninitialized_copy for n elements
OutIter move(InIter first, InIter last, OutIter result)	moves elements from [first, last) into a range starting from result
OutIter move_backward(InIter first, InIter last, OutIter result)	moves elements in the range [first, last) into the range [result - (last - first), result) starting from last - 1 and proceeding to first
is_partitioned(InIter first, InIter last, Pred pred)	true if [first, last) is empty or if [first, last) is partitioned by pred, i.e. if all elements that satisfy pred appear before those that don't
pair<OutIter1, OutIter2> partition_copy(InIter first, InIter last, OutIter1 out_true, OutIter2 out_false, Pred pred)	copies elements that satisfy pred from [first, last) into the range starting with out_true, and other elements into the range starting with out_false
Iter partition_point(Iter first, Iter last, Pred pred)	returns an iterator to the 1st element in [first, last) that doesn't satisfy pred
RAIter partial_sort_copy(InIter first, InIter last, RAIter result_first, RAIter result_last) RAIter partial_sort_copy(InIter first, InIter last, RAIter result_first, RAIter result_last, Compare comp)	copies sorted elements from [first, last) into the result range (in terms of comp If supplied); the number of elements copied is determined by the size of the smaller of input and result ranges
bool is_sorted(Iter first, Iter last) bool is_sorted(Iter first, Iter last, Compare comp)	true if [first, last) is sorted (in terms of comp if supplied), false otherwise
Iter is_sorted_until(Iter first, Iter last) Iter is_sorted_until(Iter first, Iter last, Compare comp)	returns the last iterator i in [first, last] for which the range [first, i) is sorted (in terms of comp if supplied)
bool is_heap(Iter first, Iter last) bool is_heap(Iter first, Iter last, Compare comp)	true if [first, last) is a heap (in terms of comp if supplied), i.e. the first element is the largest
Iter is_heap_until(Iter first, Iter last) Iter is_heap_until(Iter first, Iter last, Compare comp)	returns the last iterator i in [first, last] for which the range [first, i) is a heap (in terms of comp if supplied)
T min(initializer_list<T> t) T min(initializer_list<T> t, Compare comp)	returns the smallest value (in terms of comp if supplied) in the initializer_list
T max(initializer_list<T> t) T max(initializer_list<T> t, Compare comp)	returns the largest value in the initializer_list (in terms of comp if supplied)
pair<const T&, const T&> minmax(const T& a, const T& b) pair<const T&, const T&> minmax(const T& a, const T& b, Compare comp)	returns (b, a) pair if b < a (in terms of comp if supplied), and (a, b) pair otherwise
pair<const T&, const T&> minmax(initializer_list<T> t) pair<const T&, const T&> minmax(initializer_list<T> t, Compare comp)	returns the smallest and the largest element in initializer_list (in terms of comp if supplied)
pair<Iter, Iter> minmax_element(Iter first, Iter last) pair<Iter, Iter> minmax_element(Iter first, Iter last, Compare comp)	returns the first iterator in [first, last) pointing to the smallest element, and the last iterator pointing to the largest element (in terms of comp if supplied)
void iota(Iter first, Iter last, T value)	creates a range of sequentially increasing values; assigns *i = value to each element in [first, last) and increments value as if by ++value

Containers

unordered_set<T> contains at most one of each value and provides fast retrieval of values; supports forward iterators

General functions	Modifiers	Bucket functions
operator=	clear	begin(int)
get_allocator	insert	end(int)
	emplace	bucket_count
Iterators	emplace_hint	max_bucket_count
begin/cbegin	erase	bucket_size
end/cend	swap	bucket
Capacity	**Lookup**	**Hash policy**
erase	count	load_factor
size	find	max_load_factor
max_size	equal_range	rehash
		reserve
Observers		
hash_function		
key_eq		

unordered_multiset<T> supports equivalent values (possibly with multiple copies of the same value) and provides fast retrieval of the values; supports forward iterators

General functions	Modifiers	Bucket functions
operator=	clear	begin(int)
get_allocator	insert	end(int)
	emplace	bucket_count
Iterators	emplace_hint	max_bucket_count
begin/cbegin	erase	bucket_size
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erase	count	load_factor
size	find	max_load_factor
max_size	equal_range	rehash
		reserve
Observers		
hash_function		
key_eq		

unordered_map<Key, T> hash table; contains at most one of each key value; supports forward iterators

General functions	Modifiers	Bucket functions
operator=	clear	begin(int)
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Iterators	emplace_hint	max_bucket_count
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erase	count	load_factor
size	find	max_load_factor
max_size	equal_range	rehash
		reserve
Observers		
hash_function		
key_eq		

unordered_multimap<Key, T> hash table; supports equivalent keys (can contain multiple copies of each key value); supports forward iterators

General functions	Modifiers	Bucket functions
operator=	clear	begin(int)
get_allocator	insert	end(int)
	emplace	bucket_count
Iterators	emplace_hint	max_bucket_count
begin/cbegin	erase	bucket_size
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Capacity	**Lookup**	**Hash policy**
erase	count	load_factor
size	find	max_load_factor
max_size	equal_range	rehash
		reserve
Observers		
hash_function		
key_eq		

forward_list<T> singly linked list; constant time insert and erase operations; automatic storage management; no fast random access

General functions	Capacity	Modifiers
operator=	empty	clear
assign	max_size	insert_after
get_allocator		emplace_after
	Operations	erase_after
Element access	merge	push_front
front	splice_after	emplace_front
	remove	pop_front
Iterators	remove_if	resize
before_begin/ cbefore_begin	reverse	swap
begin/cbegin	unique	
end/cend	sort	

array<T, N> stores fixed size sequences of objects (N elements of type T); elements are stored contiguously

Element access	Capacity
at	
operator[]	empty
front	size
back	max_size
data	
	Modifiers
Iterators	fill
begin/cbegin	swap
end/cend	
rbegin/crbegin	
rend/crend	

Want to be a C++11 expert?
Check out cpprocks.com

Concurrency in C11/C++11

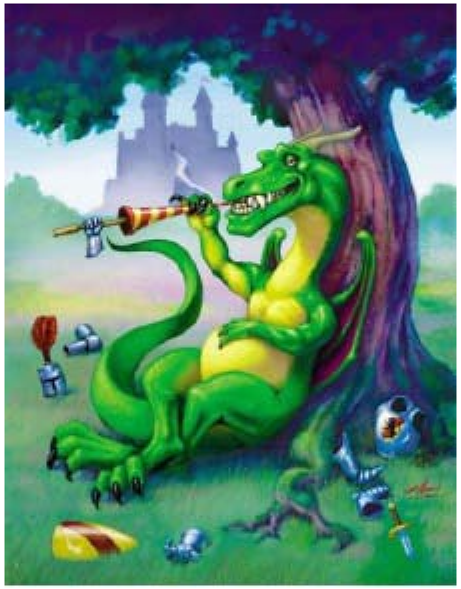
- C99/C++98/03: does not have concurrency
- C++11 is in Final Draft International Standard on 2011
- C11 is in Draft International Standard in 2011
- C++11 have multithreading support
  – Memory model, atomics API
  – Language support: TLS, static init, termination, lambda function
  – Library support: thread start, join, terminate, mutex, condition variable
  – Advanced abstractions: basic futures, thread pools
- C11 will have similar memory model, atomics API. TLS, static init/termination
  – Some minor differences like __Atomic qualifier

Introduction to concurrency

- Why do we need to standardize concurrency
  - Multi-core processors
  - Solutions for very large problems
  - Internet programming
- Standardize existing practice
  - C++ threads=OS threads
  - shared memory
  - Loosely based on POSIX, Boost thread
  - Does not replace other specifications
    - MPI, OpenMP, UPC, autoparallelization
  - Can help existing advanced abstractions
    - TBB, PPL, Cilk,

Concurrency core/library

- Core: what does it mean to share memory and how it affects variables
  - TLS
  - Static duration variable initialization/destruction
  - Memory model
  - Atomic types and operations
    - Lock-free programing
  - Fences
  - *Dependence based Ordering*
- Library
  - How to create/synchronize/terminate threads,
  - Thread , mutex , locks
    - RAII for locking, type safe
  - *propagate exceptions*
  - *A few advanced abstraction*
    - *Async() , promises and futures*



What we got

- Low level support to enable higher abstractions
  - Thread pools, TM
- Ease of programming
  - Writing correct concurrent code is hard
  - Lots of concurrency in modern HW, more than you imagine
- Portability with the same natural syntax
  - Not achievable before
- Uncompromising Performance
- Stable memory model
- System level interoperability
  - C++ shares threads with other languages

What we did not get

- All the nifty, higher parallel abstractions
  - TM, thread pools, futures, parallel STL
- Complete Compatibility between C and C++
- Total insolation from programmer mistakes

The grand scheme of Concurrency

	Asynchronus Agents	Concurrent collections	Mutable shared state
summary	tasks that run independently and communicate via messages	operations on groups of things, exploit parallelism in data and algorithm structures	avoid races and synchronizing objects in shared memory
examples	GUI,background printing, disk/net access	trees, quicksorts, compilation	locked data(99%), lock-free libraries (wizards), atomics (experts)
key metrics	responsiveness	throughput, many core scalability	race free, lock free
requirement	isolation, messages	low overhead	composability
today's abstractions	thread,messages	thread pools, openmp	locks, lock hierarchies
future abstractions	futures, active objects	chores, parallel STL, PLINQ	transactional memory, declarative support for locks

Memory Model and Consistency model, a quick tutorial

- Sequential Consistency (SC)

Sequential consistency was originally defined in 1979 by Leslie Lamport as follows:

- "… the result of any execution is the same as if the reads and writes occurred in some order, and the operations of each individual processor appear in this sequence in the order specified by its program"
- But chip/compiler designers can be annoyingly helpful:
- It can be more expensive to do exactly what you wrote.
- Often they'd rather do something else, that could run faster.

Sequential Consistency: a tutorial

- The semantics of the single threaded program is defined by the program order of the statements. This is the strict sequential order. For example:

```
x = 1;
r1 = z;
y = 1;
r2 = w;
```

Sequential Consistency for program understanding

- Suppose we have two threads. Thread 1 is the sequence of statement above. Thread 2 is:

Thread 1:	Thread2:
x = 1;	w=1;
r1 = z;	r3=y;
y = 1;	z=1;
r2 = w;	r4=x;

(All variables are initialized to zero.)

- 2 of 4! Possible interleavings:

x = 1;	x=1;
w = 1;	w=1;
r1 = z;	r3=y;
r3 = y;	z=1;
y = 1;	r4=x;
z = 1;	r1=z;
r2 = w;	y=1;
r4 = x;	r2=w;

Now add fences to control reordering

Thread 1:

```
x = 1;
r1 = z;
fence();
y = 1;
r2 = w;
```

Thread2:

```
w=1;
r3=y;
fence();
z=1;
r4=x;
```

Is r3==1 and r4==1 possible?

Is r1==1 and r2==1 possible?

Agenda

- C11, C++11, C++14, SG5 TM goals and timelines
- C++ Standard Transactional Memory status
- Multithreading support in C11 and C++11
- The problems of Concurrency before C/C++ 11
- Language support
- Memory Model
- Fragen?

Memory Model and instruction reordering

- Definitions:
- Instruction reordering: When a program executes instructions, especially memory reads and writes, in an order that is different than the order specified in the program's source code.
- Memory model: Describes how memory reads and writes may appear to be executed relative to their program order.
- Affects the valid optimizations that can be performed by compilers, physical processors, and caches.

Memory Model and Consistency model

- Sequential Consistency (SC)

Sequential consistency was originally defined in 1979 by Leslie Lamport as follows:

- "… the result of any execution is the same as if the reads and writes occurred in some order, and the operations of each individual processor appear in this sequence in the order specified by its program"
- But chip/compiler designers can be annoyingly helpful:
- It can be more expensive to do exactly what you wrote.
- Often they'd rather do something else, that could run faster.

Problems for concurrency in 2005

- How much and what kind of reordering is allowed?
  - For programmer understanding?
  - For better performance
- What motivates each paragraph of clause 1.10, and Chap 29 of the C++0x Standard

1. The entire software/hardware stack
2. Languages and compilers
3. Volatile
4. Compiler-generated data races
5. C++ destructors
6. Thread libraries
7. C++ Standard Library
8. Thread-safe C libraries
9. Broken C++ idioms

Problem1: Hardware at the bottom of the stack

- Everything from threads implementations to user code depends on memory consistency/ordering:
- Canonical Example (assume all init with 0, all shared variables):

Thread 1	Thread 2
x=1;	y=1;
r1=y; //reads 0	r2=x; //reads 0

Can both r1 and r2 be 0?

- Intuitively (or under sequential consistency) no; some thread executes first.
- In practice, yes; compilers, thread library and hardware can reorder.
- Most hardware will allow this outcome because they have write buffers!

Hardware at the bottom of the stack

- The hardware doesn't implement what we tell it is fundamentally a problem
  - If we understand HW rules and can use them to implement a usable programming model
- Widely held belief
  - Weaker memory models (e.g. allowing this) is fine, since
    - We only pay for ordering (special fence instructions) when needed
      - Should be cheaper
    - Fence instructions get us sequential consistency exactly when we need it

Transformations: in the name of speed

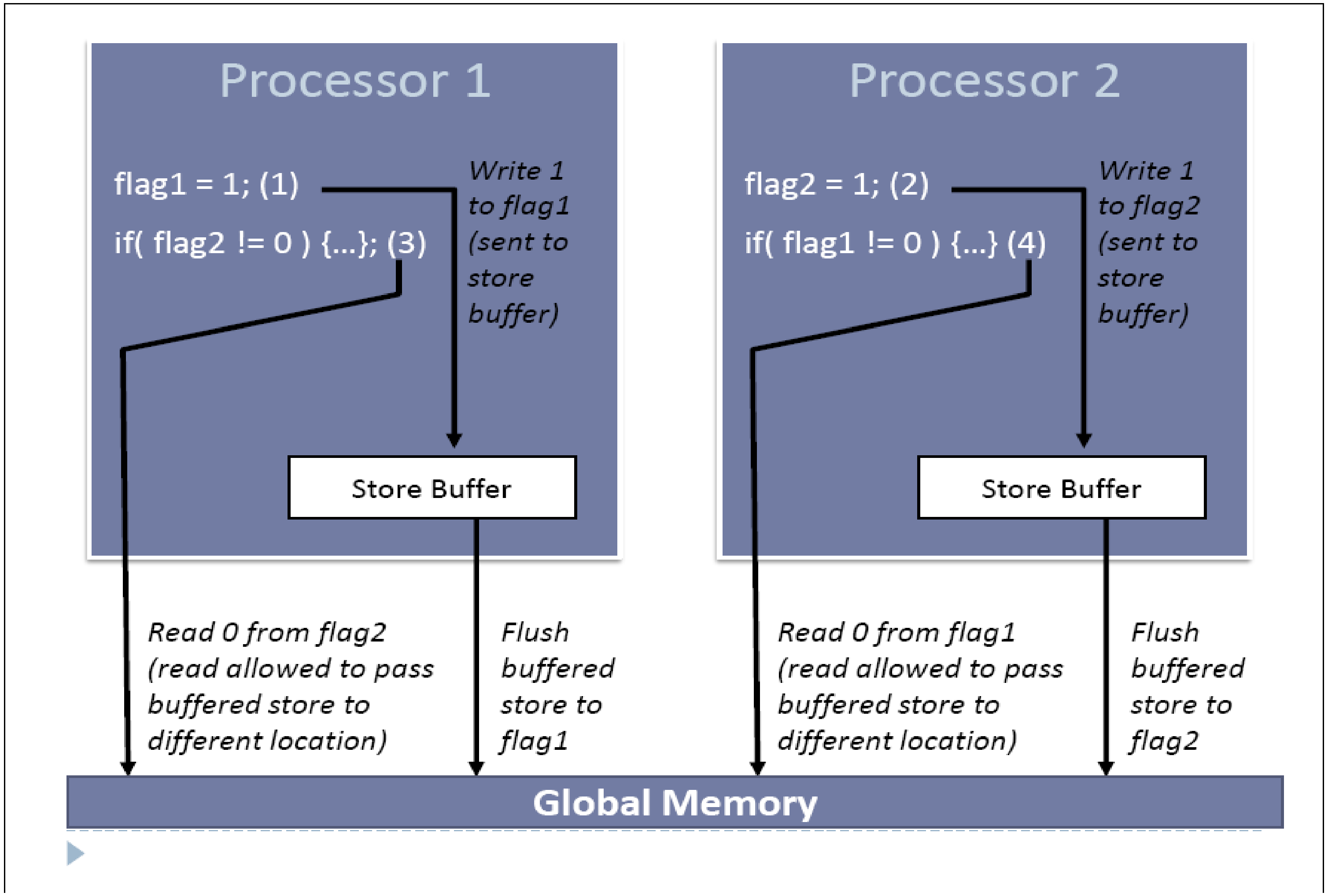
- Reordering, invention, removal
- Entire stack:
  - Source code
  - Compiler
  - Hardware
  - Cache
  - Execution

Dekker's and Peterson's Algorithms

- Consider (flags are shared and atomic, initially zero):

  Thread 1:
  ```
  flag1 = 1;               // a: declare intent to enter
  if( flag2 != 0 ) { ... } // b: detect and resolve contention
  // enter critical section
  ```
  Thread 2:
  ```
  flag2 = 1;               // c: declare intent to enter
  if( flag1 != 0 ) { ... } // d: detect and resolve contention
  // enter critical section
  ```
- Could both threads enter the critical region?
- Maybe:If a can pass b, and c can pass d, we could get b->d->a->c.
- Solution 1 (good): Use a suitable atomic type (e.g., Java/.NET "volatile", C++0x std::atomic<>) for the flag variables.
- Solution 2 (good?): Use system locks instead of rolling your own.
- Solution 3 (harder but fast): Write a memory barrier after a and c.

What really happens when you are not looking


Processor 1
flag1 = 1; (1)
if(flag2 != 0) {…}; (3)
Write 1 to flag1 (sent to store buffer)
Store Buffer
Read 0 from flag2 (read allowed to pass buffered store to different location)
Flush buffered store to flag1
Processor 2
flag2 = 1; (2)
if(flag1 != 0) {…} (4)
Write 1 to flag2 (sent to store buffer)
Store Buffer
Read 0 from flag1 (read allowed to pass buffered store to different location)
Flush buffered store to flag2
Global Memory

Memory Ordering and fences in 2006

- Some architectures have underspecified memory ordering
  - Confusion
  - Interesting consequences, X86
    - Gcc __sync_synchronize() full memory barrier erroneously generates no-op
    - P4 lfence, sfence instructions appeared to be no-ops in most user code, but the loads and stores are already ordered

Performance

- Performance of fences and syncs was often neglected
  - More then 100 cycle, best case on P4
  - Encourages
    - Clever sync avoidance techniques=bugs
  - Can easiy be much more expensive then sequential consistency everywhere(PA-RISC)
- Some Memory models in which it appeared that fences could not enforce sequential consistency
  - This means Java memory model is not really implementable

Independent Reads with Independent Writes

- x,y init to 0, add fences between every instruction

Thread 1	Thread2	Thread3	Thread4
x=1;	y=1;	r1=x;(1)	r3=y;(1)
		fence;	fence;
		r2=y;(0)	r4=x;(0)
		x set first!	y set first!

Can this be both true?

Architecture in late 2007

- Intel and AMD published Memory models
- IBM has published PowerPC Atomic operations
  - http://www.rdrop.com/users/paulmck/scalability/paper/N2745r.2009.02.27a.html
- Can get sequential consistency examples like the preceding one on X86
  - But stores to x and y in T1 and T2 need to be implemented with xchg
    - Many JVMs will need to be fixed because they didn’t know this rule when they were written
- Most other vendors are paying attention

Problem 2: Languages and Compilers

- Programming rules are unclear, some languages more then others
  - Java is in best shape since fix in 2005
  - .Net and OpenMP need to be clearer
  - C99 and C++98 has no rules! Other then volatile, sequence points
  - C++11 will hopefully be the best

C++11 programming rules:

- No simultaneous access from two threads to ordinary shared variables if one access is a write, ie data races are outlawed
  - Posix C has this rule too, explored in Sarita Adve’s Ph.D thesis
  - This rule dates back to at least Ada83
- No Data races solves many problems:
  - can’t tell whether compiler reorders ordinary memory operations
    - If you could tell, observing thread would race with updating thread
    - Can’t tell whether hardware reorders memory operations (as long as locks are handled)
  - C/C++ compilers may rely on the absence of asynchronous changes. This may have weird side effects

Consequence of “no async changes” compiler assumption:

```
unsigned x;
If (x<3) {
 // async x change
 switch (x) {
     case 0: …
   case 1: …
   case 2: …
 }
}
```

- Assume switch statement compiled as branch table
- May assume x is in range
- Async change to x causes wild branch
  - Not just wrong value

C and C++ thread realities before standardization

- Common attitude that data races aren't so bad
  - Frequently used idioms rely on benign data races:
    - Approximate counters sometimes without locking an update, and read asynchronously
    - Double-checked locking: lazy init that reads flag outside of critical section
  - Or nonportanle atomic (interlocked, __sync) operations
    - Eg. Reference counting
  - Not well-defined, and read accesses generally appear as data races to compiler
    - This can result in crashed, reads of half-updated values, uninitialized data
    - But locks are expensive enough that this is often impractical to avoid

Problem 3: A Volatile Market

- 2005 java:

```
volatile x_init:
x=1;
//possible fence here
x_init=true;
```

This gurantees that x becomes visible to other threads before x_init.

Volatile

- OpenMP 2.5 and 3.0 Revision 11 Clause 1.4, Pg 15 Line 26-31

  The volatile keyword in the C and C++ languages specifies a consistency mechanism that is related to the OpenMP memory consistency mechanism in the following way: a reference that reads the value of an object with a volatile-qualified type behaves as if there were a flush operation on that object at the previous sequence point, while a reference that modifies the value of an object with a volatile-qualified type behaves as if there were a flush operation on that object at the next sequence point.

POSIX Pthread C binding

- David Butenof:

“volatile … provide[s] no help whatsoever in making code ‘thread safe’”

C++ 11 WP solution

- Concurrent access to special atomic objects is allowed
  - atomic <int>
- Really just a communication issue
- Eliminates all benign data races in C++
- C++ volatile continues to have nothing to do with threads
- Java volatile= C++ atomic
- C++ volatile != Jave volatile

Problem 4: Compiler generated data races

- Compiler may generate code that adds data races!
  - When small struct fields are updated
  - Optimizations leading to spurious writes of old values
  - C++03 allows this!

Adjacent bitfield memory

- Given a global s of type struct { int a:9; int b:7; }:

  Thread 1:

  {lock<mutex> hold(aMutex);s.a = 1;}

  Thread 2:

  {lock<mutex> hold(bMutex);s.b = 1;}
- Is there a race? Yes in C++0x, in pthreads
  - **It may be impossible to generate code that will update the bits of** a **without updating the bits of** b**, and vice versa.**
  - **C++0x will say that this is a race. Adjacent bitfields are one "object."**

Adjacent scalar types

- What about two global variables char c; and char d;?
  Thread 1:
  {lock<mutex> hold(cMutex);c = 1;}
  Thread 2:
  {lock<mutex> hold(dMutex);d = 1;}
- Is there a race? No ideally and in C++0x, but maybe today in pthreads
- Say the system lays out c then d contiguously, and transforms “d = 1” to:
  char tmp[4];   // 32-bit scratchpad
  memcpy(&tmp[0], &c, 4);// read 32 bits starting at c
  tmp[2] = 1;// set only the bits of d
  memcpy(&c, &tmp[0], 4);// write 32 bits back
- Oops: Thread 2 now silently also writes to c without holding cMutex.

Other things that go Bump in the night

- There are many transformations. Here are two common ones.
- Speculation:
  - **Say the system (compiler, CPU, cache, …) speculates that a condition may be true (e.g., branch prediction), or has reason to believe that a condition is often true (e.g., it was true the last 100 times we executed this code).**
  - **To save time, we can optimistically start further execution based on that guess. If it's right, we saved time. If it's wrong, we have to undo any speculative work.**
- Register allocation:
  - **Say the program updates a variable** x **in a tight loop. To save time: Load** x **into a register, update the register, and then write the final value to** x**.**
- Key issue: The system must not invent a write to a variable that wouldn't be written to (in an SC execution).
- If the programmer can't see all the variables that get written to, they can't possibly know what locks to take.

Eliding locks

- Consider (where x is a shared variable, cond does not change):

  ```
  if( cond )lock x
  ...
  if( cond )use x
  ...
  if( cond )unlock x
  ```
- Q: Is this pattern safe?
- A: In theory, yes. In reality, maybe not…

Write speculation

- Consider (where x is a shared variable):

  ```
  if( cond )x = 42;
  ```

- Say the system (compiler, CPU, cache, …) speculates (predicts, guesses, measures) that cond (may be, will be, often is) true. Can this be transformed to:

  ```
  r1 = x;             // read what's there
  x = 42;             // perform an optimistic write
  if( !cond)          // check if we guessed wrong
    x = r1;           // oops: back-out write is not SC
  ```

- In theory, No… but on some implementations, Maybe.
  - **Same key issue: Inventing a write to a location that would never be written to in an SC execution.**
  - **If this happens, it can break patterns that conditionally take a lock.**

Lessons learned

- All bets are off in a race:
  - Prefer to use locks **to avoid races and nearly all memory model weirdness, despite the flaws of locks. (In the future: TM?)**
  - **Avoid lock-free code. It's for wizards only, even using SC atomics.**
  - **Avoid fences even more. They're even harder, even full fences.**
- Conditional locks:
  - **Problem: Your code conditionally takes a lock, but your system changes a conditional write to be unconditional.**
  - **Option 1: In code like we've seen, replace one function having a doOptionalWorkflag with two functions (possibly overloaded):**
    - **One function always takes the lock and does the** x**-related work.**
    - **One function never takes the lock or touches x.**
  - **Option 2: Pessimistically take a lock for any variables you *mention anywhere* in a region of code**.
  - **Even if updates are conditional, and by SC reasoning you could believe you won't reach that code on some paths and so won't need the lock.**

C++11 WP solution:

- Subject to “no data races” rule:
  - Each update affects a “memory location”
    - Scalar value, or contiguous sequence of bitfields
  - Define exactly which assignments can be “seen” by each reference to a memory location
  - For ordinary (non-atomic) references, there must be exactly one, for atomics there can be several
  - A reference to x.d after completion of both threads must see a value of 1
  - The preceding implementation of bit-field assignments is incorrect
  - Assignments s.a and s.b bitfields may still interfere

Non-terminating loops

- Some kinds of code hoisting are problematic.
- Stores may not be advanced across potentially nonterminating loops.
- Example:

```
for (T*p = q; p != 0; p = p -> next) ++count;
x = 42;
```

- Uncommon? But analysis is commonly wrong.

Subtle implication of the C++11 rule

- No speculative writes

```
int count; //global , may be shared between threads
for (p=q; p!=0; p=p->next)
  if (p->data>0) ++ count;
```

- Cannot transform into

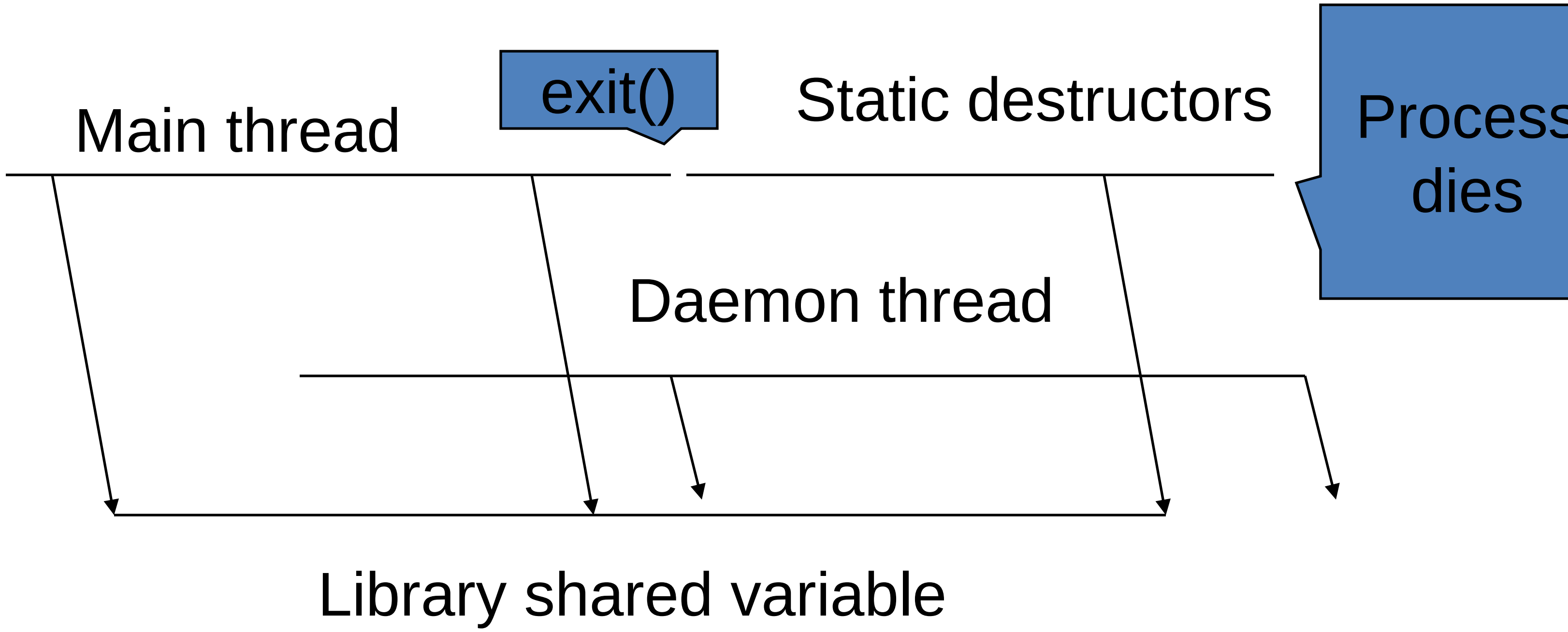
```
int count; //global , may be shared
reg=count;
for (p=q; p!=0; p=p->next)
  if (p->data>0) ++ reg;
count=reg; //may spuriously assign to count
```

Consequence

- Outlaws some useful optimizations,
- Gives programmer a simple and consistent story
- Prevents really mysterious compiler-introduced program bugs
- Outlawed optimizations can often be replaced by others

Problem 5: C++ destructors

- We just needed assignments to break things



- Even standard library is unsafe to use after exit()
- except that threads may return after main() calls exit()

C++11 WP solution

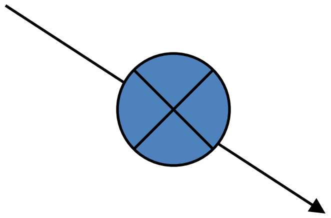
- Only partial solution:
- 1. Shutdown all threads before process exit
  - Hard if they are waiting for I/O
- 2. OR execute only special cleanups before exit (but not destructors) A way to kill a process without making libraries unusable,

  . i.e. without running static destructors.
- The former is hard:
  - **Need to shut down threads blocked on I/O**
  - **Tried and failed to get something that played with Posix cancellation.**
- Quick_exit() gives us the latter.
  - **Something between exit() and _exit()**

Problem 6: Thread libraries

- Have to limit reordering of memory operations with respect to synchronization operations:

```
lock();
tmp=x;
x=tmp+1;
unlock();
```

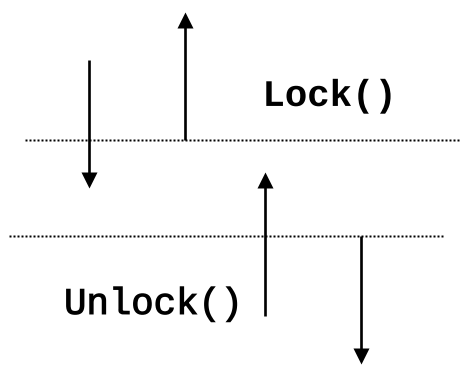
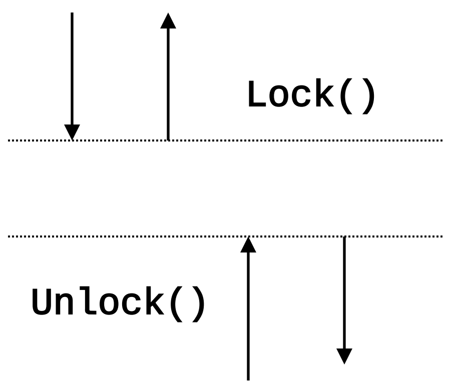
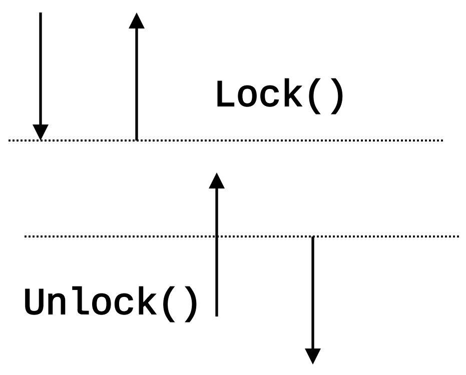


- Done in 2 ways
  - Compiler treats synchronization functions as opaque
    - As though they might change x
  - Synchronization routines contain expensive fence

```
tmp=x;
lock();
x=tmp+1;
unlock();
```

What reordering should we allow?

- Reordering of memory operations with respect to critical sections:

Expected(&java)	Naive pthreads	Optimized pthreads
		

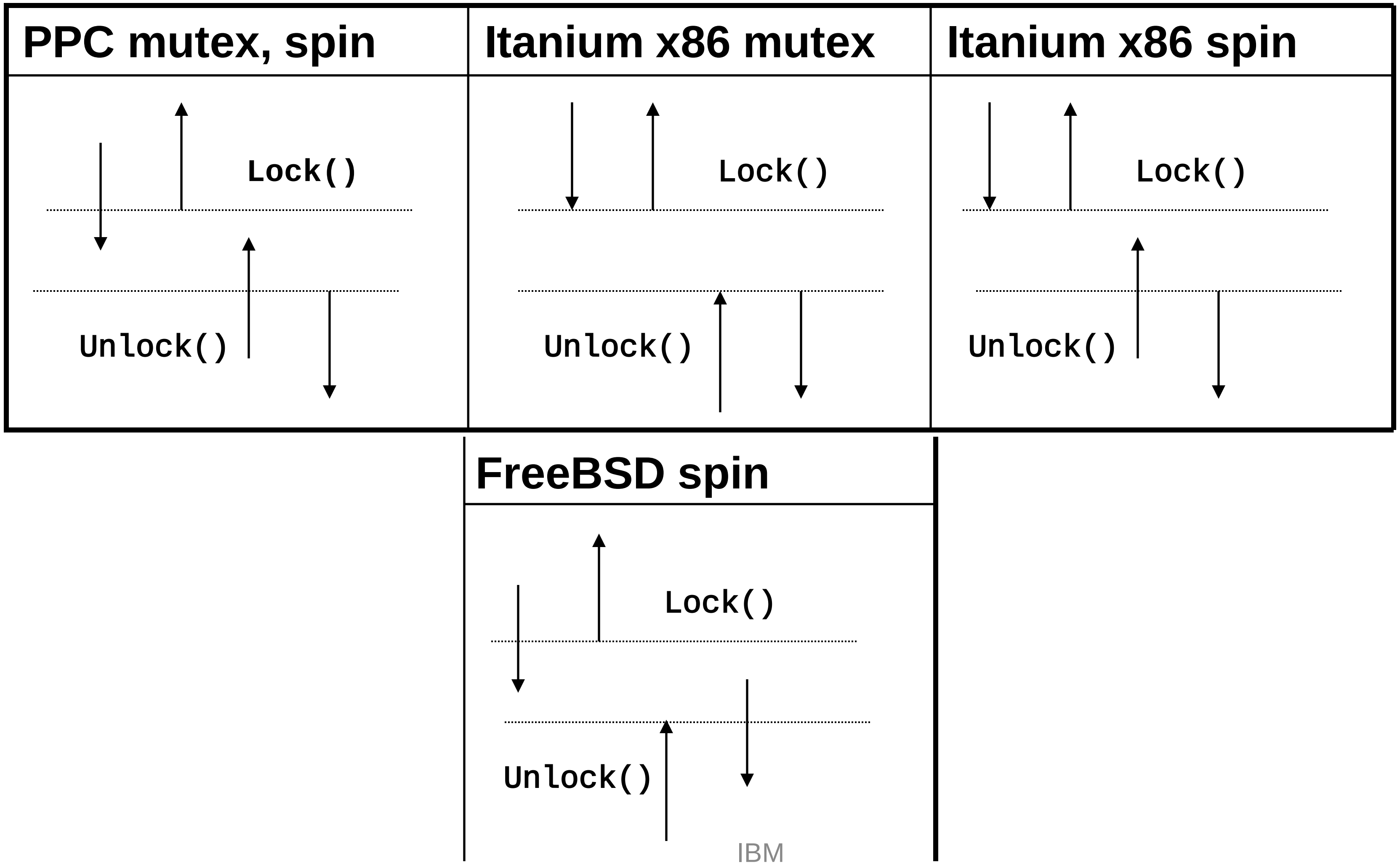
Trylock, why pthread doesn't allow expected reordering

- Some awful code would break (Don't write code like this!):

```
Thread 1            Thread 2
X=42;               while (trylock() == SUCCESS)
lock();                     unlock();
                    assert (x==42);
```

- Reordering thread 1 statements is wrong
  - Can't move into a lock
- Only recognized recently

Some open source pthread lock implementations 2006



C++11 WP solution:

- Movement into critical section is allowed in both directions
- Trylock() may fail even if lock is available
  - Problematic examples are now clearly incorrect, achieved our goal
  - But library vendors are informally discouraged from taking advantage of this
    - Worsens performance
- Allows the standard to guarantee that memory operation reordering is invisible for data-race-free programs
  - That don't use some low level library facilities
  - Such data-race-free programs behave as though thread steps are simply interleaved

Problem 7: C++ Standard Libraries

- General Wisdom about locks in container libraries
  - Lock in the client
  - Only client knows about sharing the right granularity
  - Unexpected library-based locking causes:
    - Performance problems and deadlocks
- But
  - Original Java collections like vectors are synchronized
    - Including individual element access
  - As is Posix putc
    - But not C++ STL containers

C++11 solution

- Follow de facto STL convention
  - Containers do not visibly acquire locks by default
  - **Containers behave like scalars:**
    - **Two operations on a container conflict if one of them logically updates the container.**
    - **Allocation doesn't count as update.**
    - **User-invisible updates require internal locking.**
    - **Other locking is the clients reponsibility.**
  - **This seems to be the de facto standard.**
    - **except for I/O?**
  - **Basic_string and reference counting?**
    - **ABI change?**

Problem 8: thread –safe C library

- Four levels of MT safe attributes for library interfaces.
- 1) Unsafe
  - Contains global and static data that are not protected. User should make sure only one thread at time to execute the call.

Unsafe Function	Reentrant counterpart
ctime	ctime_r
localtime	localtime_r
asctime	asctime_r
gmtime	gmtime_r
ctermid	ctermid_r
getlogin	getlogin_r
rand	rand_r
readdir	readdir_r
strtok	strtok_r
tmpnam	tmpnam_r

Use MT-Safe Routines

- 2) Safe
  - Global and static data are protected. Might not provide any concurrency between calls made by different threads.
    - Example: malloc in libc(3c)
- 3) MT-Safe
  - Safe and can provide a reasonable amount of concurrency.

Use MT-Safe Routines

- 4) Async-signal-safe
  - Can be safely called from a signal handler.
  - Example:
    - Not async-signal-safe: malloc(), pthread_getspecific()
    - Async-signal-safe: open(), read()

Problem 9: broken C++ idioms

- Singleton pattern
- Lazy initialization
- Reference counts

Why not drop down to threads?

- Shared data are a problem and we try to use locks
- Double Checking singleton pattern

```
Singleton& Singleton::Instance() {
    if (!pInstance_) // 1
    { pInstance_ = new Singleton; // 2 }
    return *pInstance_; // 3 }
```

Locking solution with threads

- While the thread assigns to pInstance_, all other stop in guard's constructor
- Each call to Instance incurs locking and unlocking the synchronization object

```
Singleton& Singleton::Instance() {
   // mutex_ is a mutex object //
    Lock manages the mutex Lock
    guard(mutex_);
   if (!pInstance_) {
   pInstance_ = new Singleton; }
     return *pInstance_;
 }
```

Double-checked locking pattern

```
Singleton& Singleton::Instance() {
      if (!pInstance_) // 1
      { // 2
            Guard myGuard(lock_); // 3
            if (!pInstance_) // 4
            { pInstance_ = new Singleton; }
     }
     return *pInstance_;
}
```

Example: Lazy Initialization

- The Sequential Version

```
typedef struct
{
    int data1;
    int data2;
    ...
} A;
```

```
A *init_single_A()
{
  static A *single_A;
  if (single_A == NULL) {
     single_A = malloc(sizeof(A));
     single_A->data1 = ...;
     ...
  }
  return single_A;
}
```

It does not work in mt applications.

Example: Lazy Initialization Multithreaded Version

```
A *init_single_A()
{
  static A *single_A;
  lock();
  if (single_A == NULL) {
     single_A = malloc(sizeof(A));
     single_A->data1 = ...;
     ...
  }
  unlock();
  return single_A;
}
```

Not efficient

```
A *init_single_A()
{
  static A *single_A;
  A *temp = single_A;
  if (temp == NULL) {
     lock();
     if (single_A == NULL) {
         temp = malloc(sizeof(A));
         temp->data1 = ...;
         ...
         single_A = temp;
     }
    unlock();
  }
  return temp;
}
```

May be broken

Double-checked Locking

```
A *p = init_single_A();
... = p->data1;
```

```
A *init_single_A()
{
  static A *single_A;
  A *temp = single_A;
  if (temp == NULL) {
     lock();
     if (single_A == NULL) {
         temp = malloc(sizeof(A));
         temp->data1 = ...;
         ...

         single_A = temp;
     }
    unlock();
  }
  return temp;
}
```

The compiler may reorder these two writes.

Even if the compiler does not reorder them, a thread on another processor may perceive the two writes in a different order.

Therefore, a thread on another processor may read wrong value of single_A->data1.

Fixing DCL

```
A *init_single_A()
{
   static A *single_A;
   A *temp = single_A;
   if (temp == NULL) {
       lock();
       if (single_A == NULL) {
            temp = malloc(sizeof(A));
            temp->data1 = ...;
            ...
            memory_barrier();
            single_A = temp;
       }
      unlock();
   }
   return temp;
}
```

A possible fix.

Still broken on some architectures, e.g. PowerPC.

Memory Consistency Model

- Pthreads
  - No formal specification
  - Shared accesses must be synchronized by calling pthread synchronization functions.
- C++/C
  - C++03/C99:Assumes single thread program execution.
    - “volatile” restricts compiler optimization, but it does not address the memory consistency issue.
  - C++11/C11: Memory model for multithreaded C++ will be in C++11.

Memory Consistency Model

- OpenMP
  - Detailed clarification. No formal specification.
    - Each thread has a temporary view of shared memory.
    - A flush operation restricts the ordering of memory operations and synchronizes a thread's temporary view with shared memory. All threads must observe any two flush operations with overlapping variable lists in sequential order.

Memory Consistency Model

- Java: revised and clarified by JSR-133
  - Volatile variables
  - Final variables
  - Immutable objects (objects whose fields are only set in their constructor)
  - Thread-and memory-related JVM functionality and APIs such as class initialization, asynchronous exceptions, finalizers, thread interrupts, and the sleep, wait, and join methods of class Thread

C++11 solution

- Avoid writing codes that have deliberate data races.
  It is tricky and difficult to understand and debug.
- Use atomics on init variable

Agenda

- C11, C++11, C++14, SG5 TM goals and timelines
- C++ Standard Transactional Memory status
- Multithreading support in C11 and C++11
- The problems of Concurrency before C/C++ 11
- Language support
- Memory Model
- Fragen?

Can you do this today with TLS?

```
extern std::string f(); //returns “Hello”
  from another TU
std::string foo(std::string const& s2) {
  __thread std::string s=f();
  s+=s2;
  return s;
 }
```

Non-atomic Variables

- Thread Local Storage (TLS)
- Static duration variables
  - Dynamic initialization
  - Destruction

Thread local storage variable

- Adopt existing practice

  __thread int a;
- Introduce new storage duration
  - Thread duration

  thread_local int var =3 ; //C++

  _Thread_local int var=5; //C
- Unique to each thread
- Accessible from every thread
- Address is not constant

Extend TLS

- Existing practice only supports static initialization and trivial destructors

```
std::string foo(std::string const& s2) {
    thread_local std::string s="hello";
    s+=s2;
    return s; }
```

- Want to extend it to dynamic initializers and destructors

```
      thread_local vector<int> var=f();
```

- Dynamic initialization allows lazy init
- OS support may be needed

Initialization of static-duration variables

- Dynamic initialization is tricky
  – No syntax to order most initializations
- Without synchronization, potential data races
- With synchronization, potential deadlock
- Examine 2 kinds:
  – Function local statics
  – globals

Function-local static storage

- Initialization implicitly synchronized
  - While not holding any locks
- New algorithm contributed by Mike Burrows from Google

```
void bar() {
    static my_class z(42+foo()); // initialization is thread-safe
    z.do_stuff();
}
```

Do not use a mutex during Initialization?

- Constructor declared as constexpr and satisfies the requirements for constant initialization
- Such objects are guaranteed to be init before any code is run as part of static init phase

```
class my_class {
	int i;
	public:
		constexpr my_class():i(0){}
		my_class(int i_):i(i_){}
		void do_stuff(); };
my_class x; // static initialization with constexpr constructor
int foo();
my_class y(42+foo()); // dynamic initialization
void f()
{ y.do_stuff(); // is y initialized? }
```

Global variable

- Initialization implicitly synchronized
- Concurrent initialization enabled
- Initialization may not use a dynamically initialized object defined outside the translation unit

```
extern vector<int> e;
vector <int> u; //OK, default init
vector <int> v(u); //OK within this TU
vector <int> w(e); //undefined, outside of this TU
```

If you have to dynamically initialize…

- When std::call_once is used with an instance of std::once_flag, function is called exactly once

```
my_class* p=0;
std::once_flag p_flag;
void create_instance() {
    p=new my_class(42+foo()); }
void baz() {
    std::call_once(p_flag,create_instance); p->do_stuff(); }
```

destruction

- First terminate all threads
- Execute destructors in a concurrent reverse of initialization
- Interleave namespace-scope vars with function-scope static vars
- Same restriction on use of vars outside current TU

Agenda

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- Memory Model
- Fragen?

Is this valid C++ today? Are these equivalent?

```
int x = 0;
atomic<int> y = 0;
```
Thread 1:
```
   x = 17;
   y.store(1,
   memory_order_release);
   // or:      y.store(1);
```

Thread 2:
```
   while
   (y.load(memory_order_acquire
   ) != 1)
   // or:      while (y.load()
   != 1)

   assert(x == 17);
```

```
int x = 0;
atomic<int> y = 0;
```
Thread 1:
```
   x = 17;
   y = 1;
```
Thread 2:
```
   while (y != 1)
        continue;
   assert(x == 17);
```

Memory Model

- One of the most important aspect of C++0x /C1x is almost invisible to most programmers
  - memory model
    - How threads interact through memory
    - What assumptions the compiler is allowed to make when generating code
    - 2 aspects
      - How things are laid out in memory
      - What happens when two threads access the same memory location and one of them is a modfy
        - » Data race
        - » Modification order

Memory Model

- Locks and atomic operations communicate non-atomic writes between two threads
- Volatile is not atomics
- Memory races cause undefined behavior
- Some optimizations are no longer legal
- Compiler may assume some loops terminate

Message shared memory

- Writes are explicitly communicated
  - Between pairs of threads
  - Through a lock or an atomic variable
- The mechanism is acquire and release
  - One thread releases its memory writes
    - V=32; atomic_store_explicit(&a,3, memory_order_release);
  - Another thread acquires those writes
    - i=atomic_load_explicit(&a, memory_order_acquire); i+v;

What is a memory location

- A non-bitfield primitive data object
- A sequence of adjacent bitfields
  - Not separated by a structure boundary
  - Not interrupted by the null bitfield
  - Avoid expensive atomic read-modify-write operations on bitfields

Data race condition

- A non-atomic write to a memory location in one thread
- A non-atomic read from or write to that same location in another thread
- With no happens-before relations between them
- Is undefined behaviour

Effect on compiler optimization

- Some rare optimizations are restricted
  - Fewer speculative writes
  - Fewer speculative reads
- Some common optimizations can be augmented
  - They may assume that loops terminate
  - Nearly always true

Atomics: To Volatile or Not Volatile

- Too much history in volatile to change its meaning
- It is not used to indicate atomicity like Java
- Volatile atomic means something from the environment may also change this in addition to another thread

Requirements on atomics

- Static initialization
- Reasonable implementation on current hardware
- Relative novices can write working code
- Experts can performance efficient code

Consistency problem

- X and y are atomic and initially 0
  - Thread 1: x=1;
  - Thread 2: y=1;
  - Thread 3: if (x==1 && y==0)
  - Thread 4: if (x==0 && y==1)
- Are both conditions exclusive?
  - Is there a total store order?
- The hardware/software system may not provide it
- Programming is harder without it

Consistency models

- Sequentially consistent
  - What is observed is consistent with a sequential ordering of all events in the system
    - But comes with a very heavy cost
- Weaker models
  - More complex to code for some
    - But very efficient
- What we decided
  - Default is sequential consistency
  - But allow weaker semantics explicitly

Atomic Design

- Want shared variables
  - **that can be concurrently updated without introducing data race,**
  - **that are atomically updated and read**
    - **half updated states are not visible,**
- that are implemented without lock overhead whenever the hardware allows,
- that provide access to hardware atomic read-modify write (fetch-and-add, xchg, cmpxchg) instructions whenever possible.

Race Free semantics and Atomic Memory operations

- If a program has a race, it has undefined behavior
  - This is sometimes known as “catch fire” semantics
  - No compiler transformation is allowed to introduce a race
    - no invented writes
    - Possibly fewer speculative stores **and (potentially) loads**
- There are atomic memory operations that don’t cause races
  - Can be used to implement locks/mutexes
  - Also useful for lock-free algorithms
- Atomic memory operations are expressed as library function calls
  - Reduces need for new language syntax

Atomic Operations and Type

- Data race: if there is no enforced ordering between two accesses to a single memory location from separate threads, one or both of those accesses is not atomic, and one or both is a write, this is a data race, and causes undefined behavior.
- These types avoid undefined behavior and provide an ordering of operations between threads

Standard Atomic Types

- #include <cstdatomic>
- atomic_flag
- Integral types:
  - atomic_char, atomic_schar, atomic_uchar, atomic_short, atomic_ushort, atomic_int, atomic_uint, atomic_long, atomic_ulong, atomic_llong, atomic_ullong atomic_char16_t, atomic_char32_t, atomic_wchar_t
- Typedefs like those in <cstdint>
  - atomic_int_least8_t, atomic_uint_least8_t, atomic_int_least16_t, atomic_uint_least16_t, atomic_int_least32_t, atomic_uint_least32_t, atomic_int_least64_t, atomic_uint_least64_t, atomic_int_fast8_t, atomic_uint_fast8_t, atomic_int_fast16_t, atomic_uint_fast16_t, atomic_int_fast32_t, atomic_uint_fast32_t, atomic_int_fast64_t, atomic_uint_fast64_t, atomic_intptr_t, atomic_uintptr_t, atomic_size_t, atomic_ssize_t, atomic_ptrdiff_t, atomic_intmax_t, atomic_uintmax_t
- is_lock_free();
- Non-copyable, non-assignable

Minimal atomics

- Need 1 primitive data types that is a must, most modern hardware has instructions to implement the atomic operations
  - **for small types**
  - **and bit-wise comparison, assignment (which we require)**
  - atomic_flag type

```
static std::atomic_flag v1= ATOMIC_FLAG_INIT
If (atomic_flag_test_and_set(&v1))
    atomic_flag_clear(&v1);
```

- For other types, hardware, atomic operations may be emulated with locks.
  - Sometimes this isn.t good enough:
    - across processes, in signal/interrupt handlers.
  - is_lock_free() returns false if locks are used, and operations may block.
- Operations on variable have attributes, which can be explicit
  - Acquire=get other memory writes
  - Release=give my memory writes
  - Acq_and_rel=Acquire and release at the same time
  - Relaxed=no acquire or released, non-deterministic, not synchronizing with the rest of memory, but still sequential view of that variable
  - Seq-cst=Fully ordered,extra ordering semantics beyond acquire and releases, this is sequentially consistent
  - Consumed=dependecy-based ordering

Std::atomic<bool>

- Most basic std::atomic_bool, can be built from a non-atomic bool
- Can be constructed, initiialized, assigned from a plain bool
- assignment operator from a non-atomic bool does not return a reference to the object assigned to, but it returns a bool with the value assigned (like all other atomic types).
  - prevents code that depended on the result of the assignment to have to explicitly load the value, potentially getting a modified result from another thread.
- replace the stored value with a new one and retrieve the original value
- a plain non-modifying query of the value with an implicit conversion to plain bool
- RMW operation that stores a new value if the current value is equal to an expected value is compare_exchange_{weak/strong}();
- If we have spurious failure:

```
bool expected=false; extern atomic_bool b; // set somewhere else
while(!b.compare_exchange_weak(expected,true) && !expected);
```

- May not be lock free, need to check per instance

Basic atomics

- atomic<bool>
  - Load, store, swap, cas
- atomic<int>
  - Load, store, swap, cas
  - Fetch-and-(add, sub, and, or, xor)
- atomic<void *>
  - Load, store, swap, cas
  - Fetch-and-(add, sub)

Std::atomic<integral>

- this adds fetch_and, fetch_or, fetch_xor, and compound assignments like:
- +=,-=,&=,^=, pre and post increment and decrement
- missing division, multiplication and shift operations, but atomic integrals are usually used as counters or bit masks, this is not a big loss
- all semantics match fetch_add and fetch_sub for atomic_address: returns old value
- the compound assignments return new value
- ++x increments the variable and returns new value, x++ increments the variable and returns old value
- result is the value of the associated integral type

Std::atomic <> template

- std::atomic<> to create an atomic user-defined type
- Specializations for integral types derived from std::atomic_integral_type, and pointer types
- Main benefit of the template is atomic variants of user-defined types, can't be just any UDT, it must fit this criteria:
  - must have trivial copy-assignment operator: no virtual functions or virtual bases and must use the compiler-generated copt-assignment operator
  - every base class and non-static data member of UDT must also have a trivial copy-assignment operator
  - Must be bitwise equality comparable
- Only have
  - load(), store()
- Assignment and conversion to the UDT
  - exchange(), compare_exchange_weak(), compare_exchange_strong()
  - assignment from and conversion to an instance of type T

Atomic templates

- Makes an atomic type from a non-atomic type
  - Must be bitwise copyable and comparable
- Defined specializations for basic types and pointers
- Suggested specializations for alignment and size

```
atomic <int *> aip = {0};
aip=ip; aip+=4;
atomic <small_type> ag={ …. };
while (!ag.compare_swap(&ag, &g.g+4));
atomic<circus > ac; //works, but not recommended
```

Atomic freedom

- Lock-free
  - Robust to crashes
  - Someone will make progress
  - C++14: “shall” obstruction-free and “should” for lock-free
- Wait-free
  - Operations completed in a bounded time
  - Cas vs ll/sc
- Address-free
  - Atomicity does not depend on using the same address

Lock-free atomics

- Large atomics have no hardware support
  - Implemented with locks
- Locks and signals don’t mix
  - Test for lock-free
- Compile-time macros for basic types
  - Always lock-free
  - Never lock-free
- RTTI for each type

Wait-free atomics

- Hard to implement without direct HW support
  - Resulting programs is usually HW-specific
  - Hard to be portable anyway
- IBM argued against it since ll/sc is not wait-free
- Few who write this seemed to cared anyway
  - No requirement for it
  - No query about it

Address-free atomics

- Memory may not have a consistent address
  - Processes sharing memory may not have the same address for that memory
  - Memory may be mapped into the address space twice
- Atomic operations must be address-free to work
  - One small tool for inter-process communication
- A lock-free operation is address-free
  - Not clear we can say this in a std way
  - But we will make our intent clear

Compiler Impact

- Memory model does not say how to make an application thread safe
  - Assumption is that source presented to compiler is thread safe
  - Undefined semantics for code with any data races
- Memory model describes legal transformations on already safe code
  - Compiler may not introduce any data races
- Memory model concerned with performance
  - Limited set of optimizations disallowed – may introduce data race
  - Allows some memory optimizations across locks
- Quality implementation
  - Most implementations already support a low quality implementation
  - Acquire/release operations seen as calls to opaque global functions – All shared variables may be referenced and modified

atomics

```
atomic<int> alp; alp=4; alp+=3;
atomic<int> current;
int desired, expected=current.load();
do desired=function(expected);
while(!current.compare_exchange_weak(expect
   ed, desired));
```

Race Free semantics and Atomic Memory operations

- If a program has a race, it has undefined behavior
  - This is sometimes known as “catch fire” semantics
  - No compiler transformation is allowed to introduce a race
    - no invented writes
    - Possibly fewer speculative stores **and (potentially) loads**
- There are atomic memory operations that don’t cause races
  - Can be used to implement locks/mutexes
  - Also useful for lock-free algorithms
- Atomic memory operations are expressed as library function calls
  - Reduces need for new language syntax

Memory Ordering Operations

```
enum memory_order {
    Memory_order_consumed,
    memory_order_relaxed,   // just atomic, no constraint
    memory_order_release,
    memory_order_acquire,
    memory_order_acq_rel,   // both acquire and release
    memory_order_seq_cst }; // sequentially consistent
                            // (even stronger than cq_rel)
```

- Every atomic operation has a default form, implicitly using `seq_cst`, and a form with an explicit order argument
- When specified, argument is expected to be just an enum constant

Memory Ordering Constraints

- Sequential Consistency
  - **Single total order for all SC ops on all variables**
  - **default**
- Acquire/Release
  - **Pairwise ordering rather than total order**
  - **Independent Reads of Independent Writes don't require synchronization between CPUs**
- Relaxed Atomics
  - **Read or write data without ordering**
  - **Still obeys happens-before**

Operations available on atomic types

	atomic_flag	bool/others	T*	integral
test_and_set, clear	Y			
is_lock_free		Y	Y	Y
load, store, exchange, compare_exchange_weak+strong		Y	Y	Y
fetch_add (+=), fetch_sub (-=), ++, --			Y	Y
fetch_or (|=), fetch_and (&=), fetch_xor (^=)				Y

Sequencing redefined for serial program

- Sequence points are … gone!
- Sequence are now defined by ordering relations
  - Sequence-before
  - Indeterminately-sequenced
- A write/write or read/write pair relations
  - That are not sequenced before
  - That are not indeterminately-sequenced
  - Results in undefined behaviour

Sequencing extended for parallel programs

- Sequenced-before
  - Provides intra-thread ordering
- Synchronizes with (Acquire and release)
  - Provide inter-thread ordering
- Happens-before relation
  - Between memory operations in different threads

Sequenced before

- If a memory update or side-effect *a is-sequenced-before* another memory operation or side-effect *b*,
  - then informally *a* must appear to be completely evaluated before *b* in the sequential execution of a single thread, e.g. all accesses and side effects of *a* must occur before those of *b*.
  - We will say that a subexpression *A* of the source program *is-sequenced-before* another subexpression *B* of the same source program to indicate that all side-effects and memory operations performed by an execution of *A* occur-before those performed by the corresponding execution of *B*, i.e. as part of the same execution of the smallest expression that includes them both.
- We propose roughly that wherever the current standard states that there is a sequence point between *A* and *B*, we instead state that *A* is-sequenced-before *B*. This will constitute the precise definition of *is-sequenced-before* on subexpressions, and hence on memory actions and side effects.

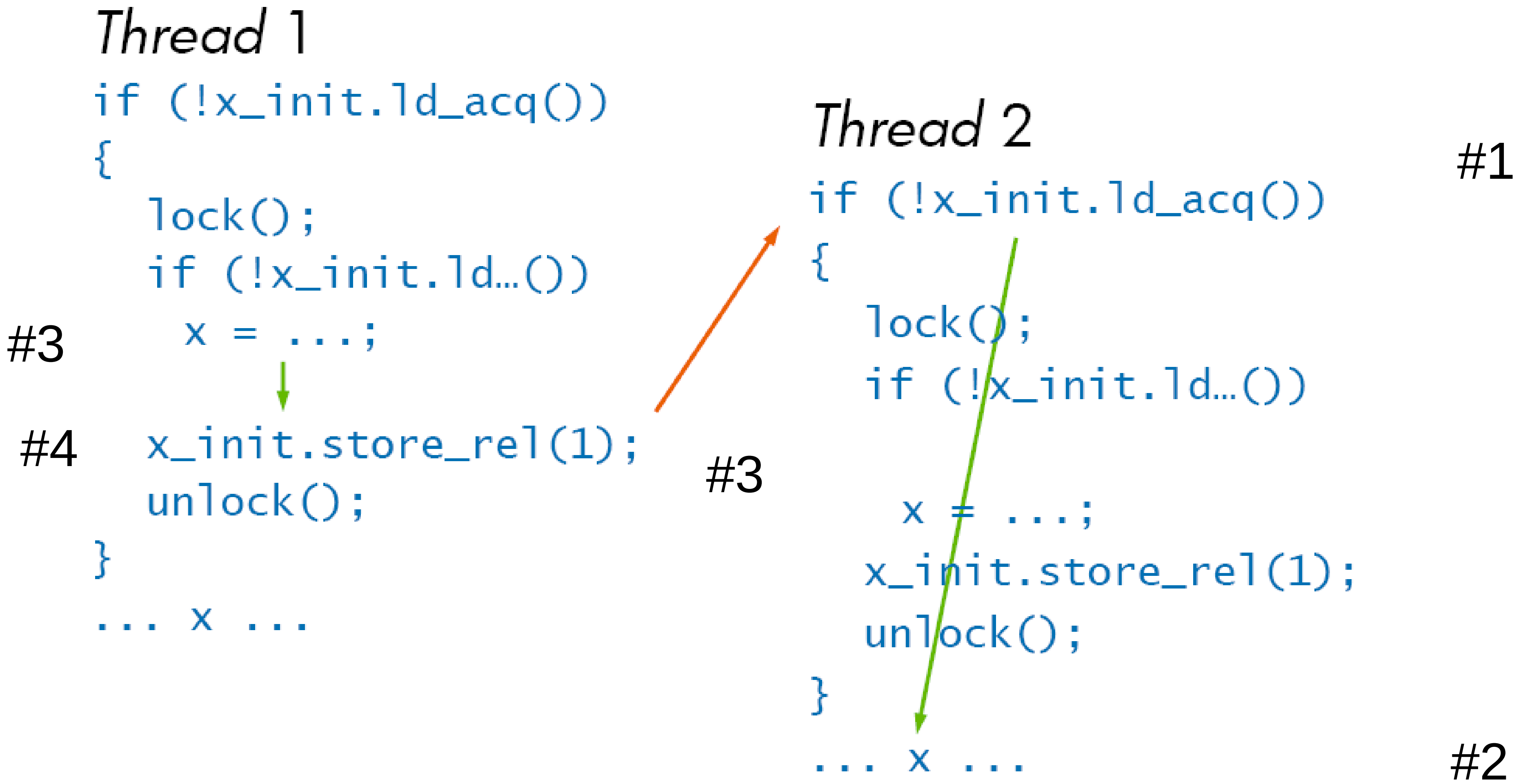
Synchronizes with

- only between operations on atomic types
- operations on a data structure (locking a mutex) might provide this relationship if the data structire contains atomic types, and the operations on that data structure perform the appropriate operations internally
- definition:
  - **a suitably-tagged atomic write operation on a variable x synchronizes-with a suitably-tagged atomic read operation on x that reads the value stored by (a) that write, (b) a subsequent atomic write operation on x by the same thread that performed the initial write, or (c) an atomic read-modify-write operation on x (such as fetch_add() or compare_exchange_weak()) by any thread, that read the value written.**
- Store-release synchronizes-with a load-acquire

Happens before

- It specifies which operations see the effects of which other operations.
- An evaluation A happens before an evaluation B if:
  - **A is sequenced before B, or**
  - **A synchronizes with B, or**
  - **for some evaluation X, A happens before X and X happens before B.**

Happens-before



Thread 1

```
if (!x_init.ld_acq())
{
   lock();
   if (!x_init.ld…())
     x = ...;

   x_init.store_rel(1);
   unlock();
}
... x ...
```

Thread 2

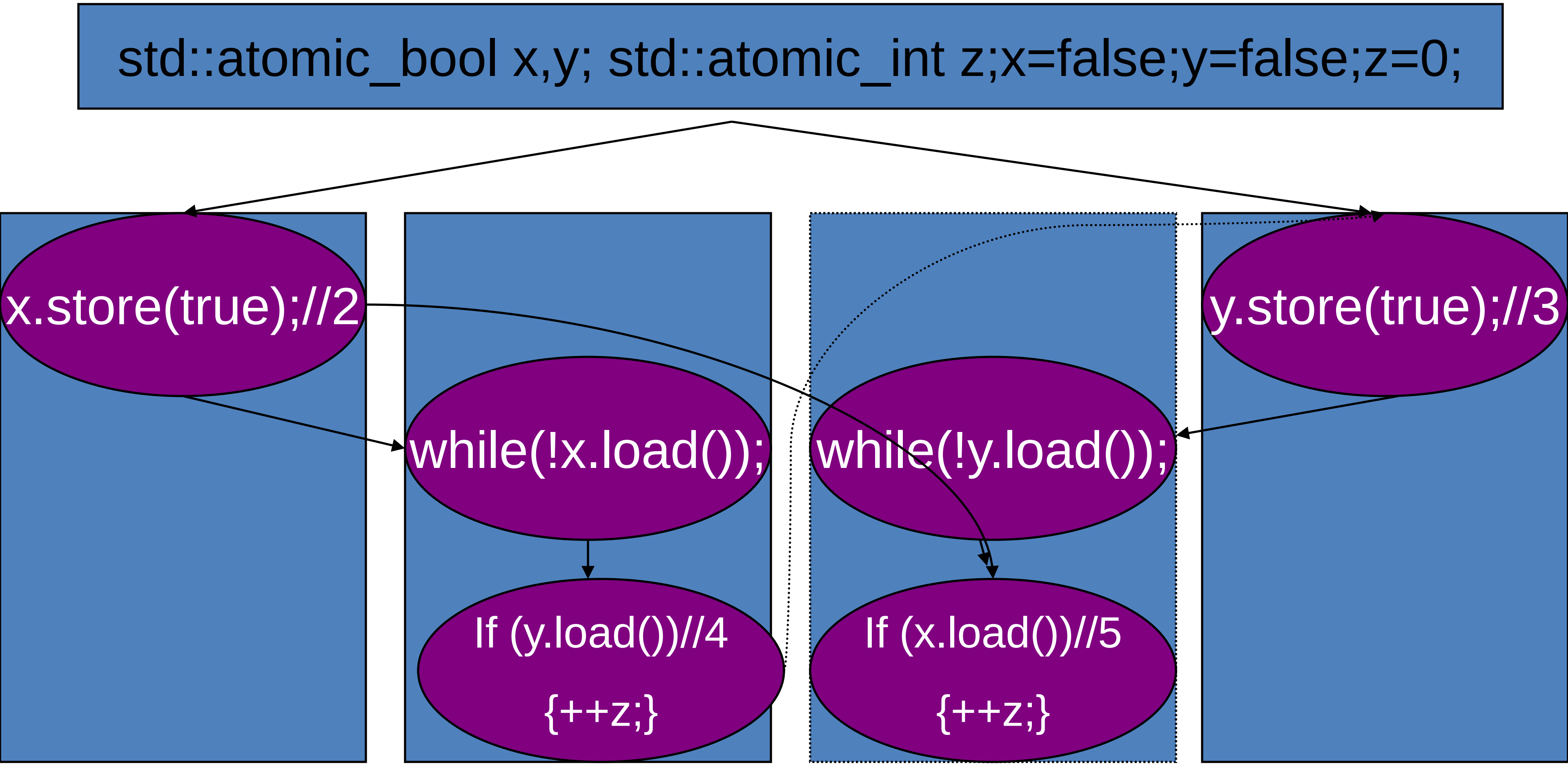
```
if (!x_init.ld_acq())
{
   lock();
   if (!x_init.ld…())

     x = ...;
   x_init.store_rel(1);
   unlock();
}
... x ...
```

Sequential Consistency implies a total ordering

```
std::atomic_bool x,y;
std::atomic_int z;
void write_x()
{
        x.store(true,std::memory_order_seq_cst); //2
}
void write_y()
{
        y.store(true,std::memory_order_seq_cst); //3
}
void read_x_then_y()
{
     while(!x.load(std::memory_order_seq_cst));
     if(y.load(std::memory_order_seq_cst)) //4
          ++z;
}
void read_y_then_x()
{
     while(!y.load(std::memory_order_seq_cst));
     if(x.load(std::memory_order_seq_cst)) //5
          ++z;
}
```

```
int main()
{
     x=false;
     y=false;
     z=0;
     std::thread a(write_x);
     std::thread b(write_y);
     std::thread c(read_x_then_y);
     std::thread d(read_y_then_x);
     a.join();
     b.join();
     c.join();
     d.join();
     assert(z.load()!=0); //1
}
```

SC and happens-before



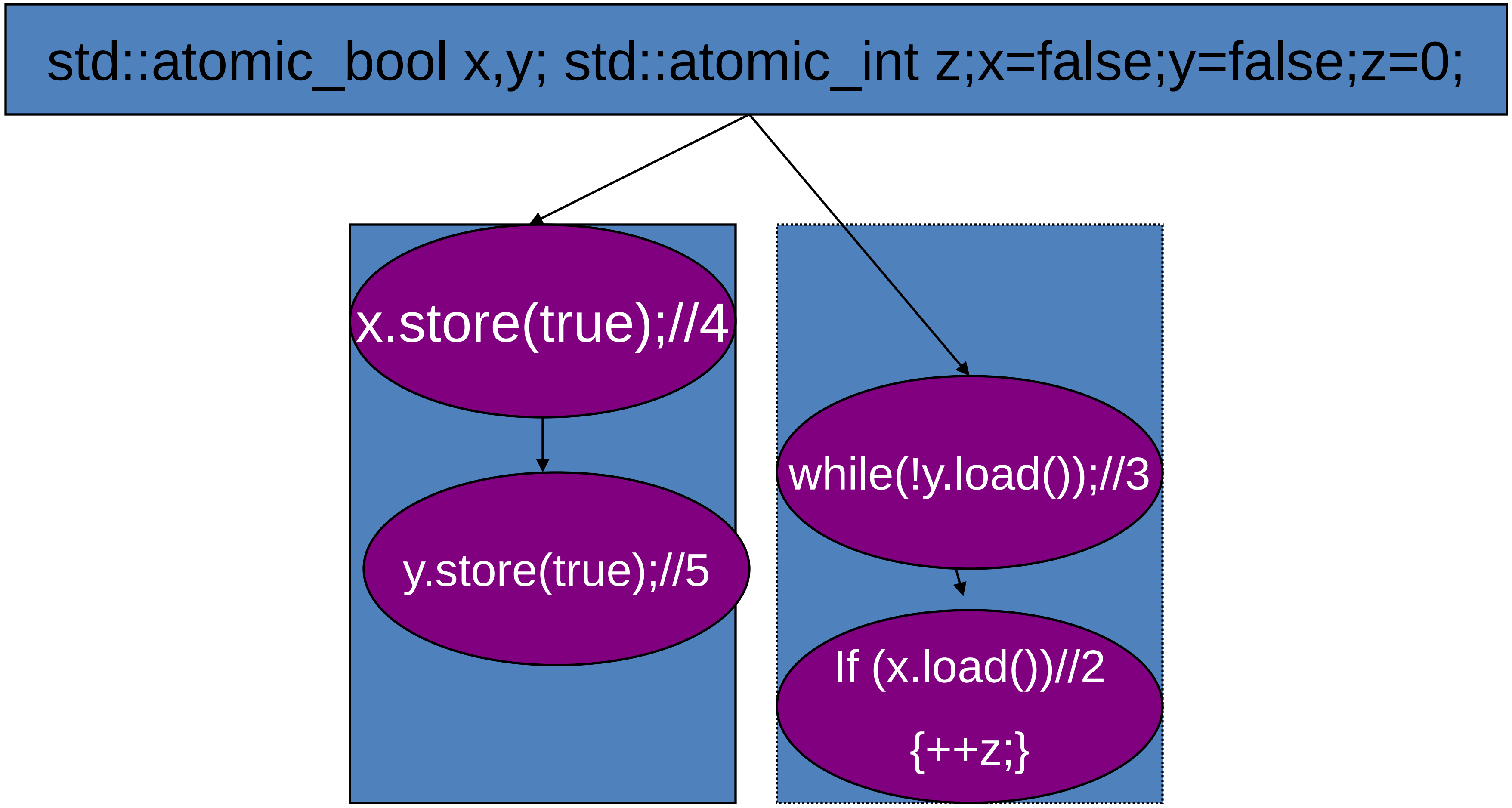
assert(z.load()!=0); //1

Relaxed operations have little ordering requirement

```
std::atomic_bool x,y;
std::atomic_int z;
void write_x_then_y()
{
    x.store(true,std::memory_order_relaxed); //4
    y.store(true,std::memory_order_relaxed); //5
}
void read_y_then_x()
{
    while(!y.load(std::memory_order_relaxed)); //3
    if(x.load(std::memory_order_relaxed)) //2
        ++z;
}
```

```
int main()
{
    x=false;
    y=false;
    z=0;
    std::thread a(write_x_then_y);
    std::thread b(read_y_then_x);
    a.join();
    b.join();
    assert(z.load()!=0); //1
}
```

Relaxed and happens-before



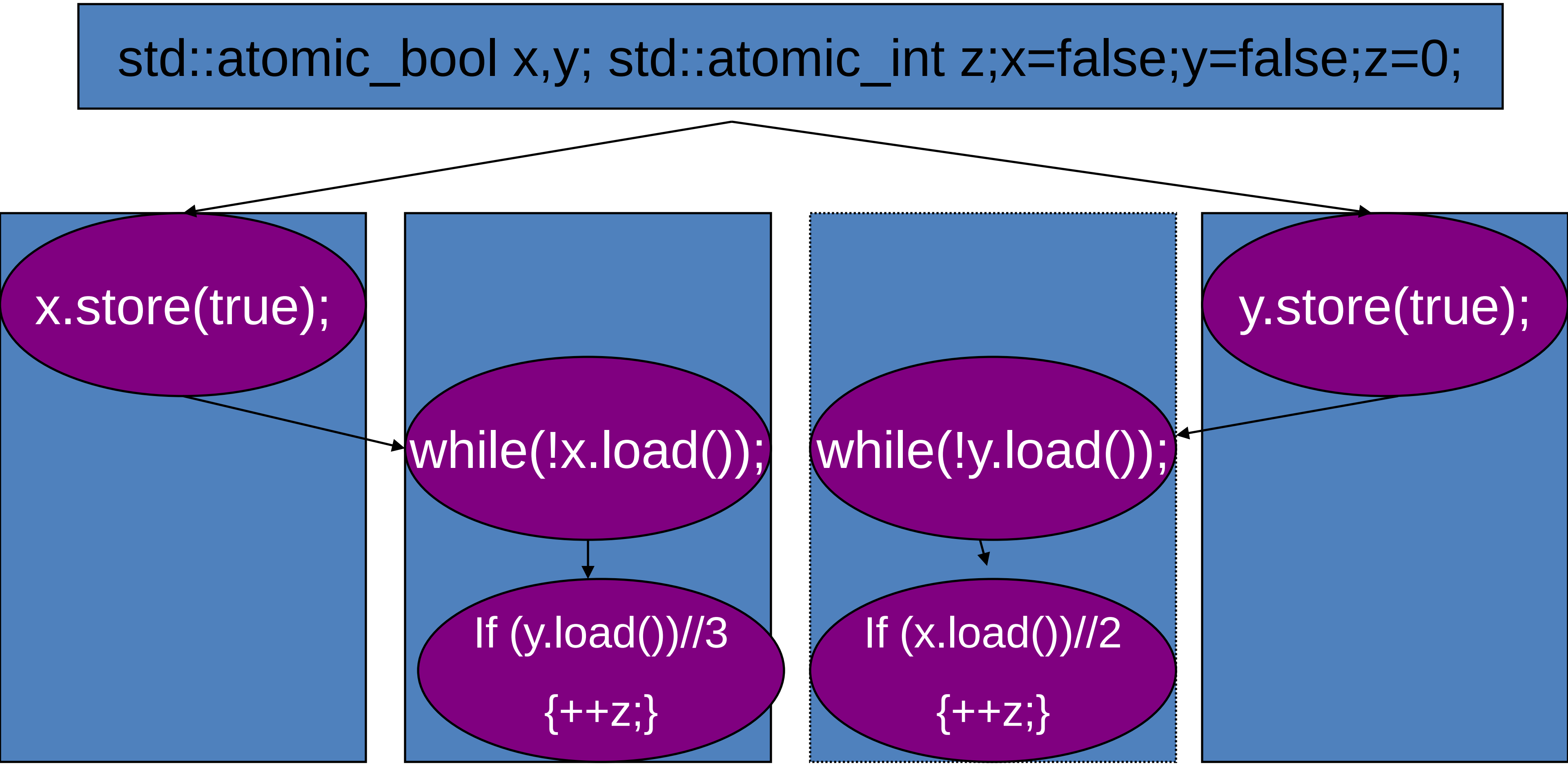
assert(z.load()!=0); //1

Acquire-Release does not mean a total ordering

```
std::atomic_bool x,y;
std::atomic_int z;
void write_x()
{
        x.store(true,std::memory_order_release);
}
void write_y()
{
        y.store(true,std::memory_order_release);
}
void read_x_then_y()
{
     while(!x.load(std::memory_order_acquire));
     if(y.load(std::memory_order_acquire)) //3
          ++z;
}
void read_y_then_x()
{
     while(!y.load(std::memory_order_acquire));
     if(x.load(std::memory_order_acquire)) //2
          ++z;
}
```

```
int main()
{
     x=false;
     y=false;
     z=0;
     std::thread a(write_x);
     std::thread b(write_y);
     std::thread c(read_x_then_y);
     std::thread d(read_y_then_x);
     a.join();
     b.join();
     c.join();
     d.join();
     assert(z.load()!=0); //1
}
```

Acquire-Release with Happens-before



assert(z.load()!=0); //1

Agenda

- C11, C++11, C++14, SG5 TM goals and timelines
- C++ Standard Transactional Memory status
- Multithreading support in C11 and C++11
- The problems of Concurrency before C/C++ 11
- Language support
- Memory Model
- Fragen?

Food for thought and Q/A

- This is the chance to get a copy before you have to pay for it:
  - **http://www.hpl.hp.com/personal/Hans_Boehm/c++mm**
  - C++ : http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2011/n3291.pdf
  - C++ (last free version): http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2011/n3242.pdf
  - C: http://www.open-std.org/jtc1/sc22/wg14/www/docs/n1570.pdf
- Participate and feedback to Compiler
  - What features/libraries interest you or your customers?
  - What problem/annoyance you would like the Std to resolve?
  - Is Special Math important to you?
  - Do you expect 0x features to be used quickly by your customers?
- Talk to me at my blog:
  - http://www.ibm.com/software/rational/cafe/blogs/cpp-standard

My blogs and email address

- OpenMP CEO: http://openmp.org/wp/about-openmp/
  My Blogs: http://ibm.co/pCvPHR
  C++11 status: http://tinyurl.com/43y8xgf
  Boost test results
  http://www.ibm.com/support/docview.wss?rs=2239&context=SSJT9L&uid=swg27006911
  C/C++ Compilers Support/Feature Request Page
  http://www.ibm.com/software/awdtools/ccompilers/support/
  http://www.ibm.com/support/docview.wss?uid=swg27005811
  STM: https://sites.google.com/site/tmforcplusplus/
- Chair of WG21 SG5 Transactional Memory
- IBM and Canada C++ Standard Head of Delegation
- ISOCPP.org Director, Vice President http://isocpp.org/wiki/faq/wg21:michael-wong
- Vice Chair of Standards Council of Canada Programming Languages
- **Tell us how you use OpenMP:**
- http://openmp.org/wp/whos-using-openmp/

Acknowledgement

- Some slides are based on committee presentations by various committee members, their proposals, and private communication

FRAGEN ?

Hat Ihnen mein Vortrag gefallen?

Ich freue mich

auf Ihr Feedback!