Transactional Language Constructs for C++ TS

vs.

WG21 SG5 C++ Standard TM Sub-Group
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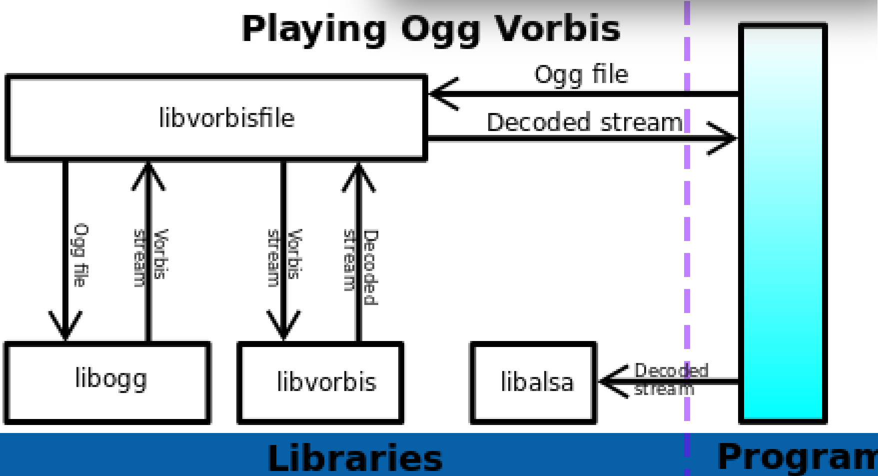
Transactional memory benefits

- **As easy to use as coarse-grain locks**
- **Scale as well as fine-grain locks**
- **Composition:**
  - **Safe & scalable composition of software modules**
  - **Locks don't compose**



Acknowledgement and Disclaimer

- Numerous people internal and external to the original C++ TM Drafting Group, WG21 SG5 TM group, 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!**
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Agenda

- **STM, HTM, HybridTM**
- Birth of a specification
- Design Goals
- Motivation for SG5 in C++ Standard
  - Use cases
  - Usability
  - Performance
- Language Constructs
  - Transactions, atomic and synchronized
  - Race-free semantics
  - Unsafe statements
  - Attributes
  - Transaction expressions and try blocks
  - Cancel
  - Exception handling
- SG5 Progress

Where were you in 1993?

- John Major was Prime Minister of Great Britain
- Brian Mulroney, Kim Campbell, Jean Chrétien were Prime Ministers of Canada
- Bill Clinton was the President Of U.S.
- EU was formally established by the Treaty of Maastricht, Helmut Kohl and Francois Mitterand
- Intel Pentium chip was the hot chip
- World Wide Web Mosaic browser was the hottest software around
- Maurice Herlihy and Elliot Moss wrote
  - Transactional Memory: Architectural support for lock free data structures
  - And then got < 10 citations/yr UNTIL 2005: not impressive
  - 2005: Multicore is coming: there is no more free-lunch!
  - Now you get 80000 hits on google, 2.7 mil on Bing

Where is transactions in 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

Transactional Memory

- Transactions appear to execute atomically
- A transactional memory implementation may allow transactions to run concurrently but the results must be equivalent to some sequential execution
- Just a form of optimistic speculation

Example

```
Initially, a == 1, b == 2, c == 3
```

T1

```
atomic {
  a = 2;
  b = a + 1;
  c = b + 1;
}
```

T2

```
atomic {
  r1 = a;
  r2 = b;
  r3 = c;
}
```

```
T2 then T1 r1==1, r2==2, r3==3
```

```
T1 then T2 r1==2, r2==3, r3==4
```

T1	T2
	r1 = 1
a = 2;	
b = 3;	
	r2 = 3;
	r3 = 3
c = 4;	

```
Incorrect r1==1, r2==3, r3==3
```

Lock elision

```
synchronized {
 node.next = succ;
 node.prev = pred;
 node.pred = node;
 node.next = node;
}
```

Why TM?

- A transaction is an atomic sequence of steps
- Intended to replace common use of locks
- A better way to build lock-free data structures
  - CAS, LL/SC only works on a memory location, or at best a contiguous memory atomically
  - But there is no way to atomically alter a set of non-contiguous memory locations

What is Transactional Memory (Again) ?

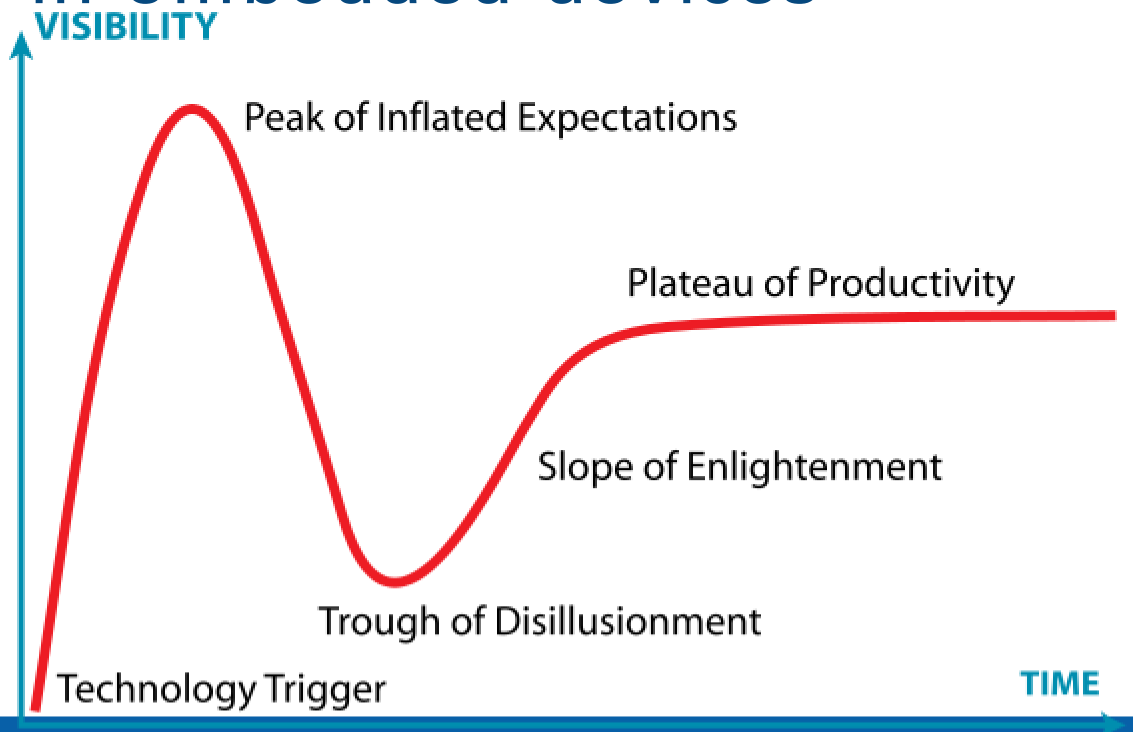
- ACI(D) properties of a transaction make it easier to ensure that shared memory programs are correct.
  - *Atomic*: each transaction either commits (it takes effect) or aborts (its effects are discarded).
  - *Consistent* (or *serializable*): they appear to take effect in a one-at-a-time order.
  - *Isolated* from other operations: the effects are not seen until the transaction has committed.
  - *(Durable*: their effects are persistent.)

Reasons for “I Hate TM”

- STM could be inefficient (most serious)
  - Improving rapidly, FUD, we were asked to address this
- TM will Never catch on, just use functional program
  - New programming style vs legacy
- Shared Mem is doomed, TM is evil because it makes Shared mem easier to use
- What concurrency software crisis? Nothing wrong with what we do today.
- It’s too early
- TM still does not make your application parallel

Mission creep and Hype Cycle

- Now it is viewed as panacea for how hard it is to program multicore
- Can it help power consumptions?
- Use in embedded devices



Language support

- Clojure
- Scala
- Haskell
- Perl
- Python
- Caml
- Java
- C/C++

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  - Unsafe statements
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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

Draft specification of transactional language constructs for C++

- 2008: Discussions by Intel, Sun, IBM started in July
- 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
- 2013: close to wording for a C++ Technical Specification

Today's talk: part motivation and part tutorial

If time permits: part future specification

What is hard about adding TM to C++

- Conflict with C++ 0x 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

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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
- Restrict constructs to enable static error detection
  - Ease of debugging is more important than flexibility
- When in doubt, leave choice to the programmer
  - Abort or irrevocable actions?
  - Commit-on-exception or rollback-on-exception?

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Overview

- **Use cases**: where is TM most useful?
- **Usability**: is TM easier than locks?
- **Performance**: is TM fast enough?

Use Cases

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 &lt;class T>
void f(T &x, T y) {
  unique_lock&lt;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 ***<u>all</u>*** generic code, even those with irrevocable operations, we need (something like) relaxed transactions.

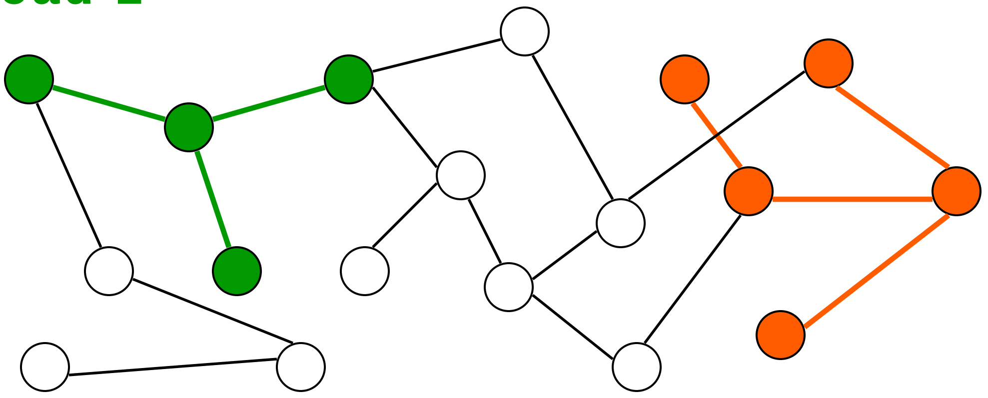
TM Patterns and Use Cases

- 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

Irregular Structures

- Irregular structures with low conflict frequency
  - E.g., graph applications (minimum spanning forest sparse graph, VPR and FPGA)
  - Advantages: concurrency and ease of deadlock-avoidance, ease of programming

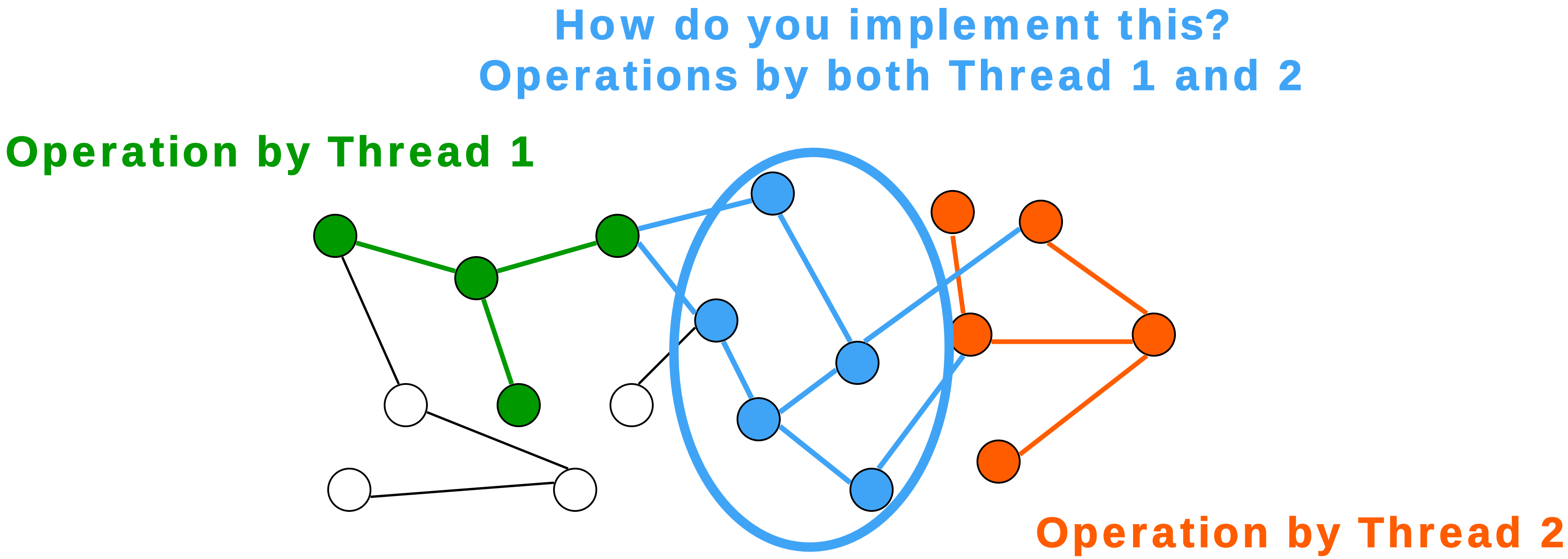
Operation by Thread 1



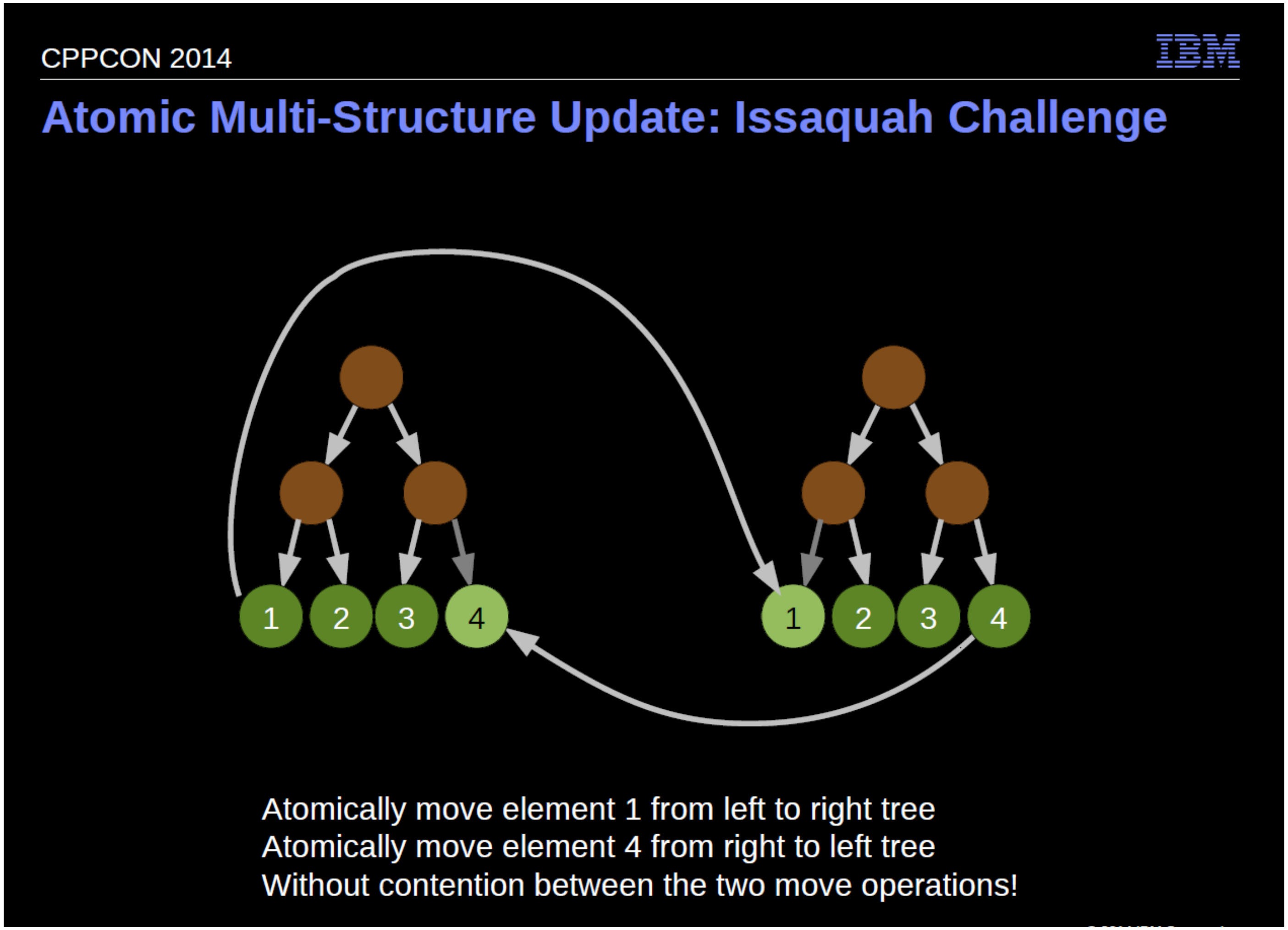
Operation by Thread 2

Why Not Locks?

- If conflicts arise, fine-graining locking can lead to deadlocks or degraded performance

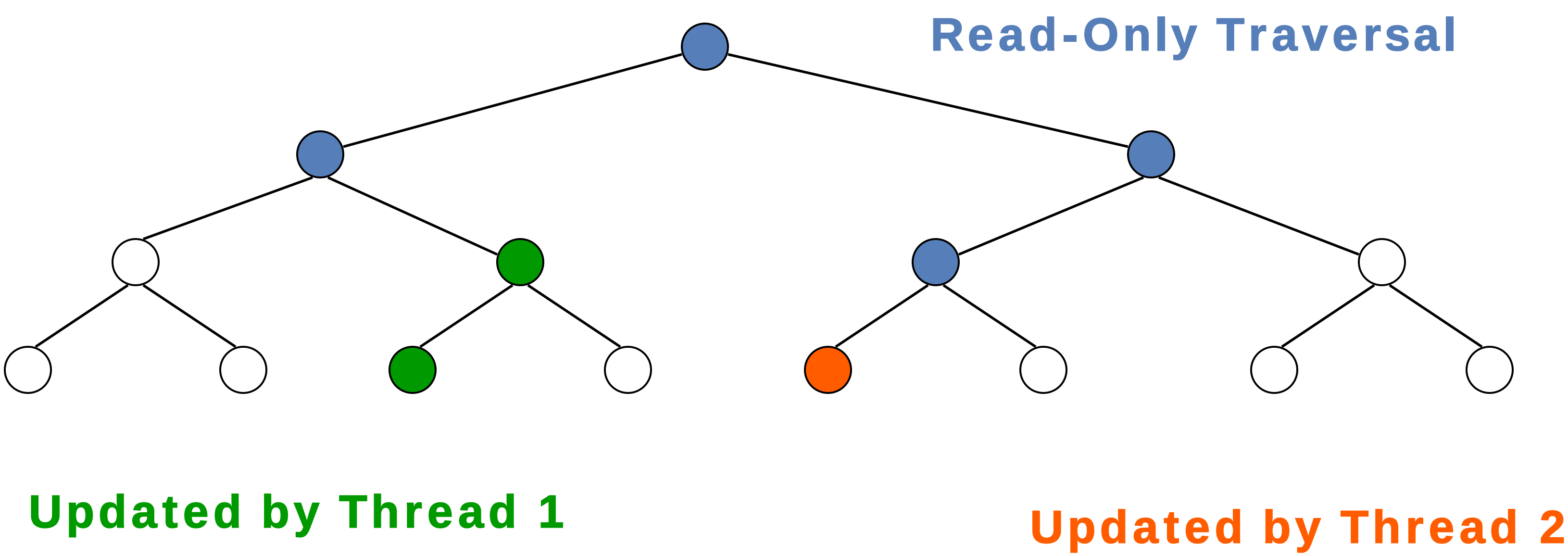


Paul McKenny's RCU talk



The Issaquah Challenge: Low Conflict Structures

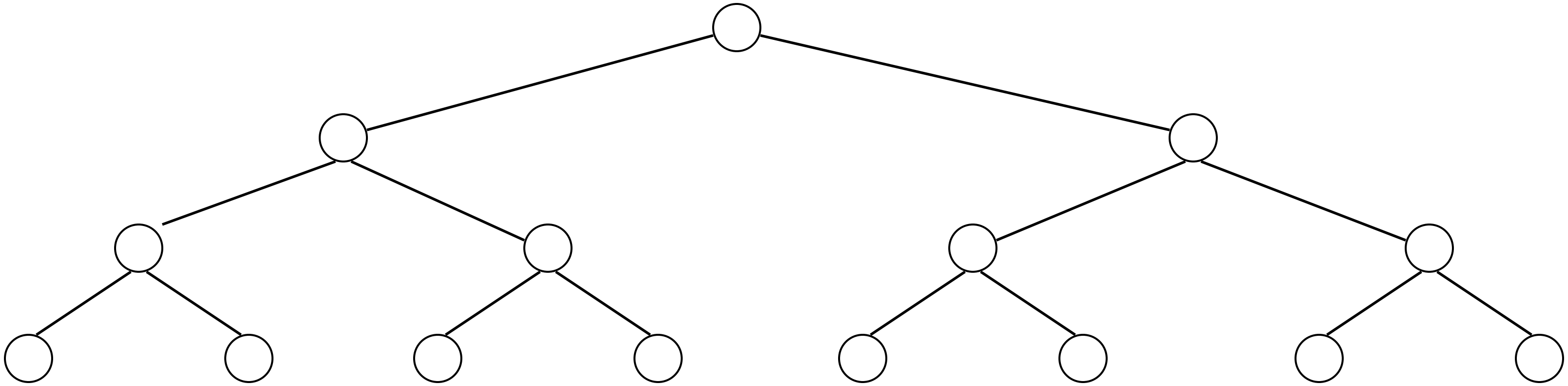
- Low conflict structures with high read-sharing and complex operations
  - E.g. red-black trees, AVL trees
  - Advantages: ease of parallelization, high concurrency, low cache coherence traffic, ease of programming



TM Use Example

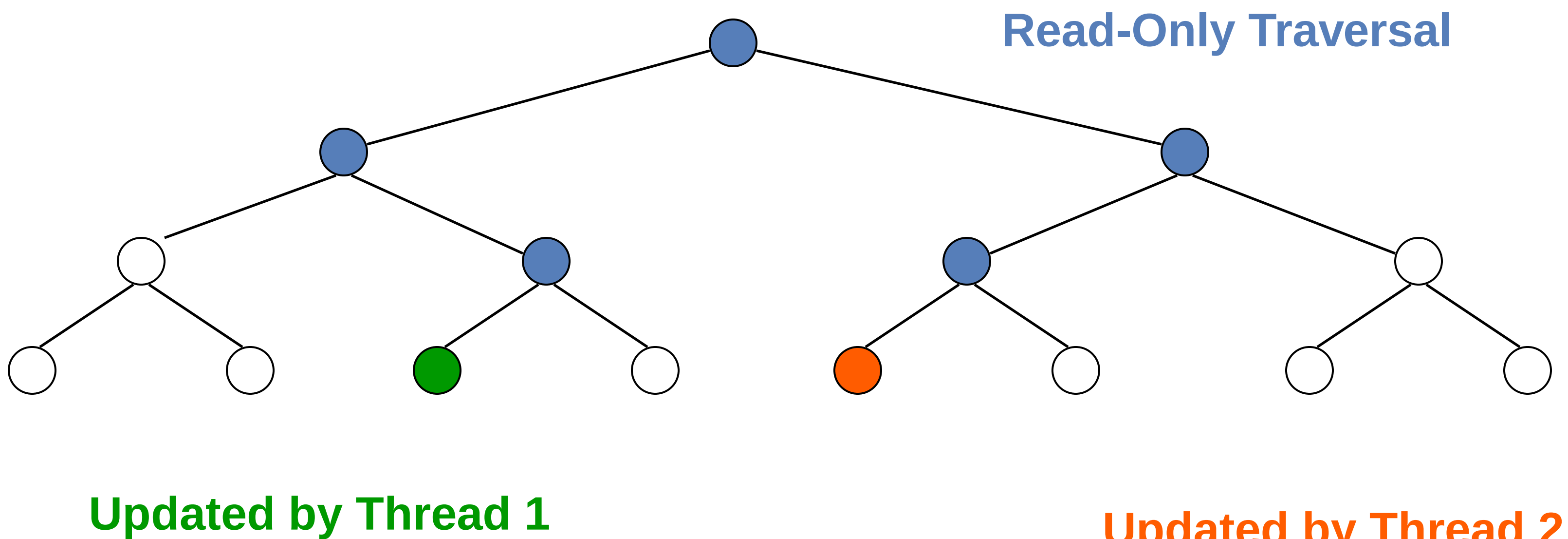
- E.g., trees, graphs
- Unsynchronized operations

```
void insert(Item &x);
void delete(Item &x);
```



TM Use Example

- Concurrency in low conflict cases
- Without complex fine-grained design
- Thread 1:
  `atomic_cancel { tree.insert(x); }`
- Thread 2:
  `atomic_noexcept { tree.delete(y); }`



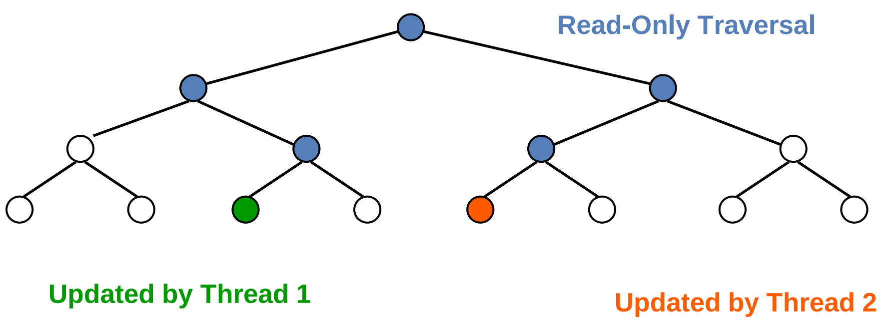
TM Use Example

- Composability and exception atomicity
- Thread 1:

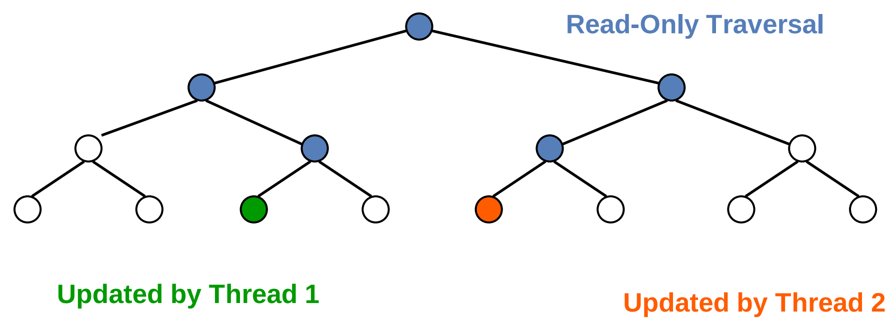
```
atomic_cancel {
  tree1.delete(x);
  tree2.insert(x);
}
```

- Thread 2:

```
atomic_cancel {
  tree2.delete(y);
  tree1.insert(y);
}
```



Tree 1



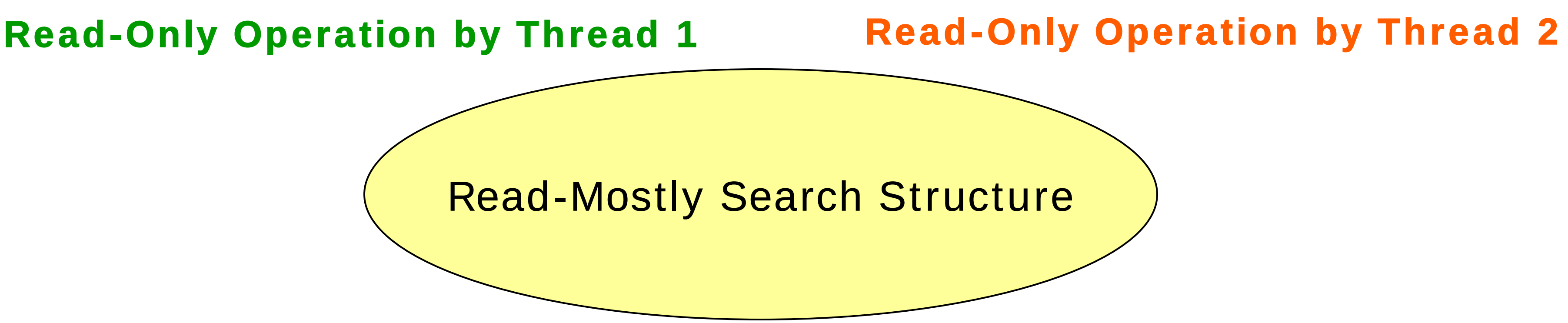
Tree 2

Best conditions for TM

- Low inherent conflict
  - TM is capable of high concurrency
- Irregular structures and operations
  - Easy to use TM
  - Difficult for fine-grained locking
- Composite operations
  - Easy using TM. Difficult using locks

Read-Mostly Structures

- Read-mostly structures with frequent read-only operations
  - E.g. search structures
  - Advantages: high concurrency, read-only operations avoid writing (avoid unnecessary cache coherence traffic)



Composition / Modularity

- composable modular structures and functions
  - Advantages: modular design, code maintainability, ease of programming (e.g., using STL)

```
__transaction {
  // Search an arbitrary structure A for an item with an arbitrary key K
  // If found, remove that item (X) from A
  X = remove(A,K);
  if (X != NULL)
  {
     // Depending on X's value, insert X in an arbitrary structure B
     B = f(X->Value);
     insert(B,X);
  }
}
```

Usability

Two User Studies

- Is Transactional Programming Actually Easier?
  - Chris Rossbach, Owen Hofmann, Emmett Witchel
  - 3-year study of undergrad class (237 students)
  - presented at PPoPP 2010
- A Study of TM vs. Locks in Practice
  - Victor Pankratius, Ali-Reza Adl-Tabatabai
  - 6 groups, each with 2 Masters students
  - presented at SPAA 2011

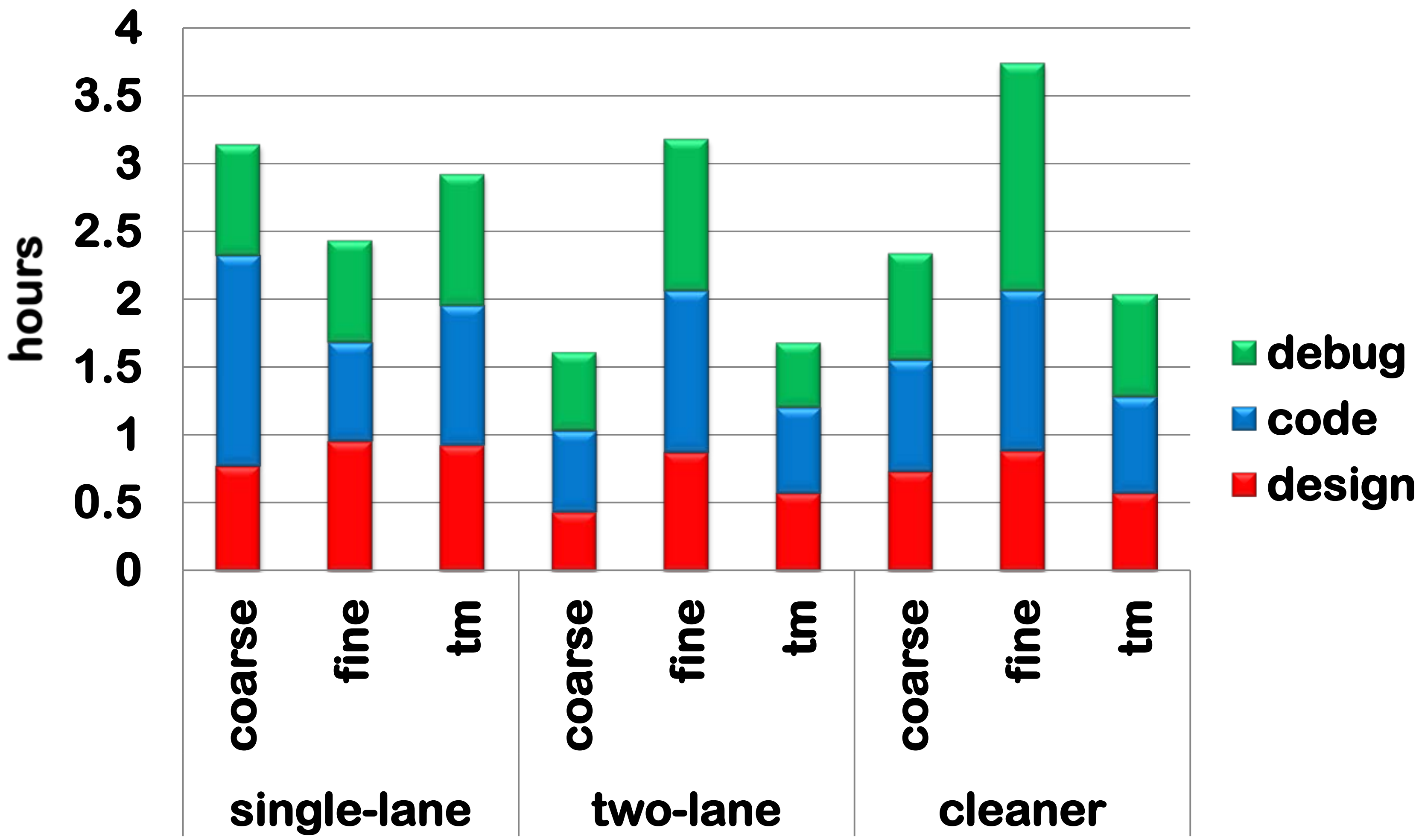
Is Transactional Programming Actually Easier?

- "Sync-gallery" programming assignment
  - part of undergrad OS course
    - 2 sections in each of 3 semesters, each a year apart
    - 237 students total
  - assignment had 3 variants (see next slide)
  - each student implemented each variant 3 ways
    - coarse-grained locking, always done first
    - fine-grained locking
    - TM (library-based support only)
    - randomly assigned which of fine-grained locking or TM-based to implement first

Sync-gallery assignment

- "Rogues" shoot paint balls in "lanes" at a gallery
  - 2 rogues (one shoots red, the other blue), 16 lanes
- Four properties
  - only one rogue can shoot in a lane at a time
  - must shoot in "clean" lane
  - clean all lanes when there are no more clean lanes
  - only one thread cleaning at a time (no concurrent shooting)
- Three variants
  - rogue reserves one lane at a time, cleans all lanes if it dirties the last lane
  - same as above, except rogue reserves two lanes at a time
  - all cleaning by separate cleaner thread; coordinate via condition variable

Development Effort: year 2



Qualitative preferences: Y2

Best Syntax

Ranking	1	2	3	4
Coarse	**62%**	30%	1%	4%
Fine	6%	21%	**45%**	**40%**
TM	26%	**32%**	19%	21%
Conditions	6%	21%	29%	**40%**

Easiest to Think about

Ranking	1	2	3	4
Coarse	**81%**	14%	1%	3%
Fine	1%	**38%**	30%	29%
TM	16%	**32%**	30%	21%
Conditions	4%	14%	**40%**	**40%**

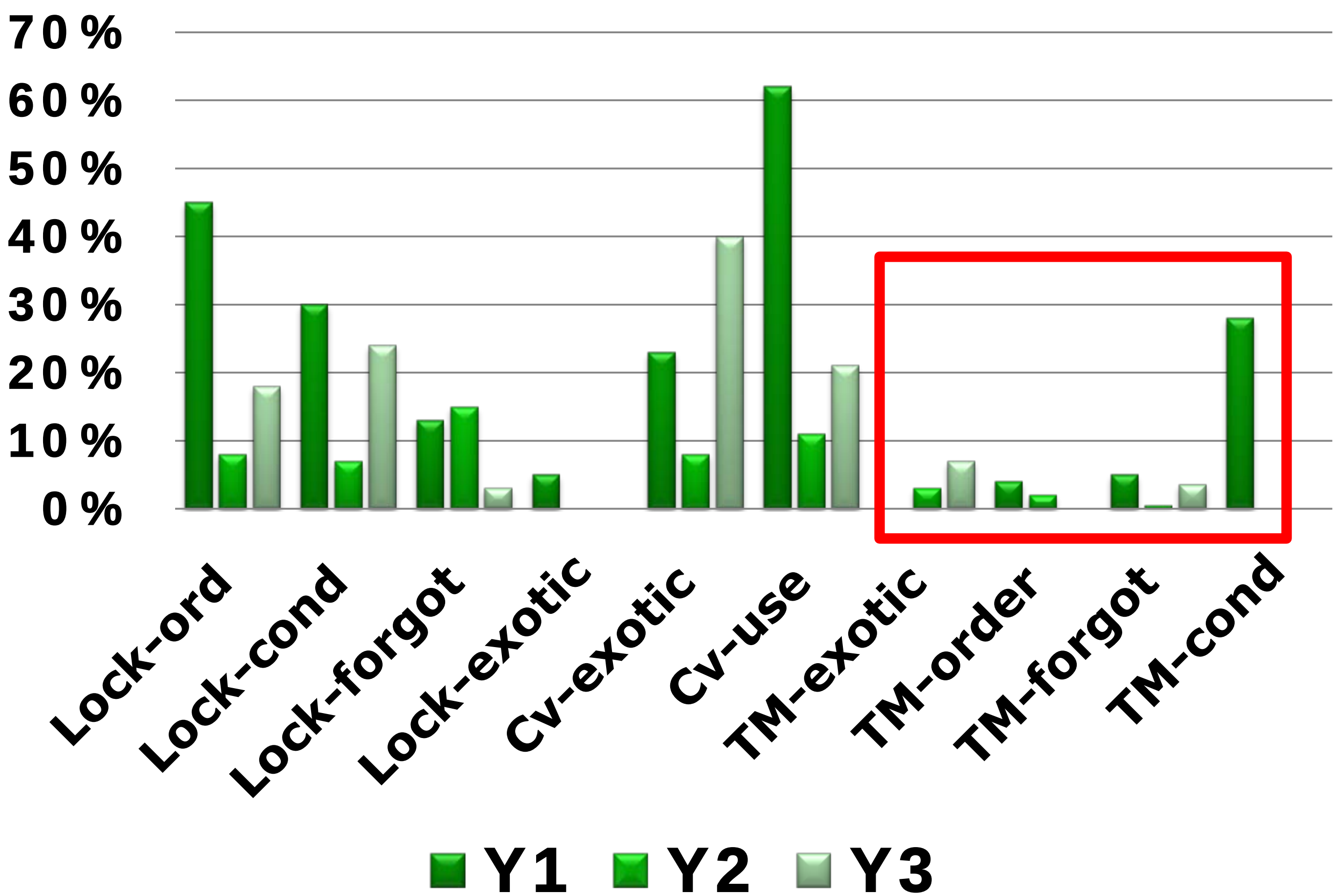
(Year 2)

Analyzing Programming Errors

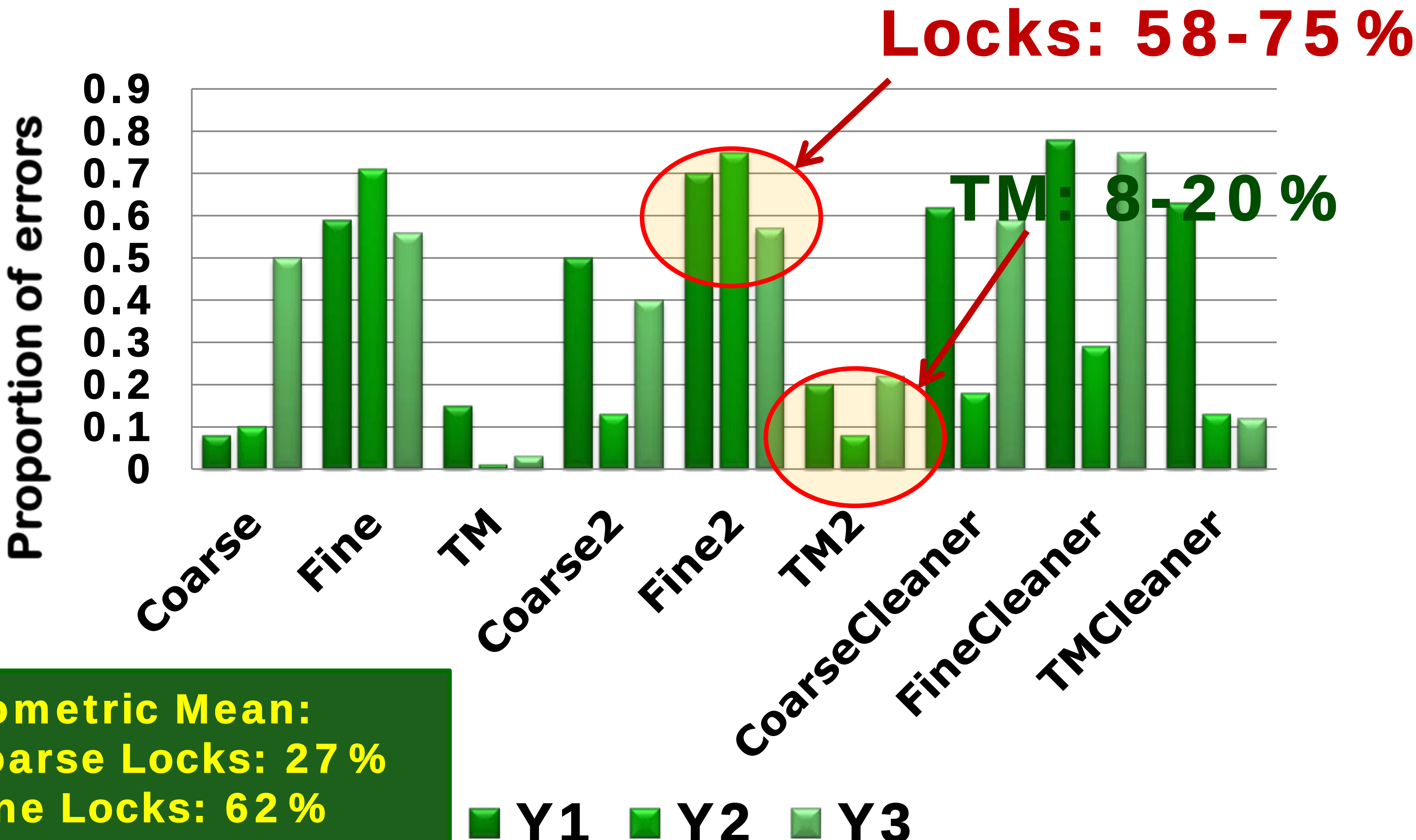
Error taxonomy: 10 classes

- **Lock-ord:** lock ordering
- **Lock-cond:** checking condition outside critical section
- **Lock-forgot:** forgotten synchronization
- **Lock-exotic**: inscrutable lock usage
- **Cv-exotic:** exotic condition variable usage
- **Cv-use:** condition variable errors
- **TM-exotic:** TM primitive misuse
- **TM-forgot:** forgotten TM synchronization
- **TM-cond**: checking conditions outside critical section
- **TM-order:** ordering in TM

Error Rates by Defect Type

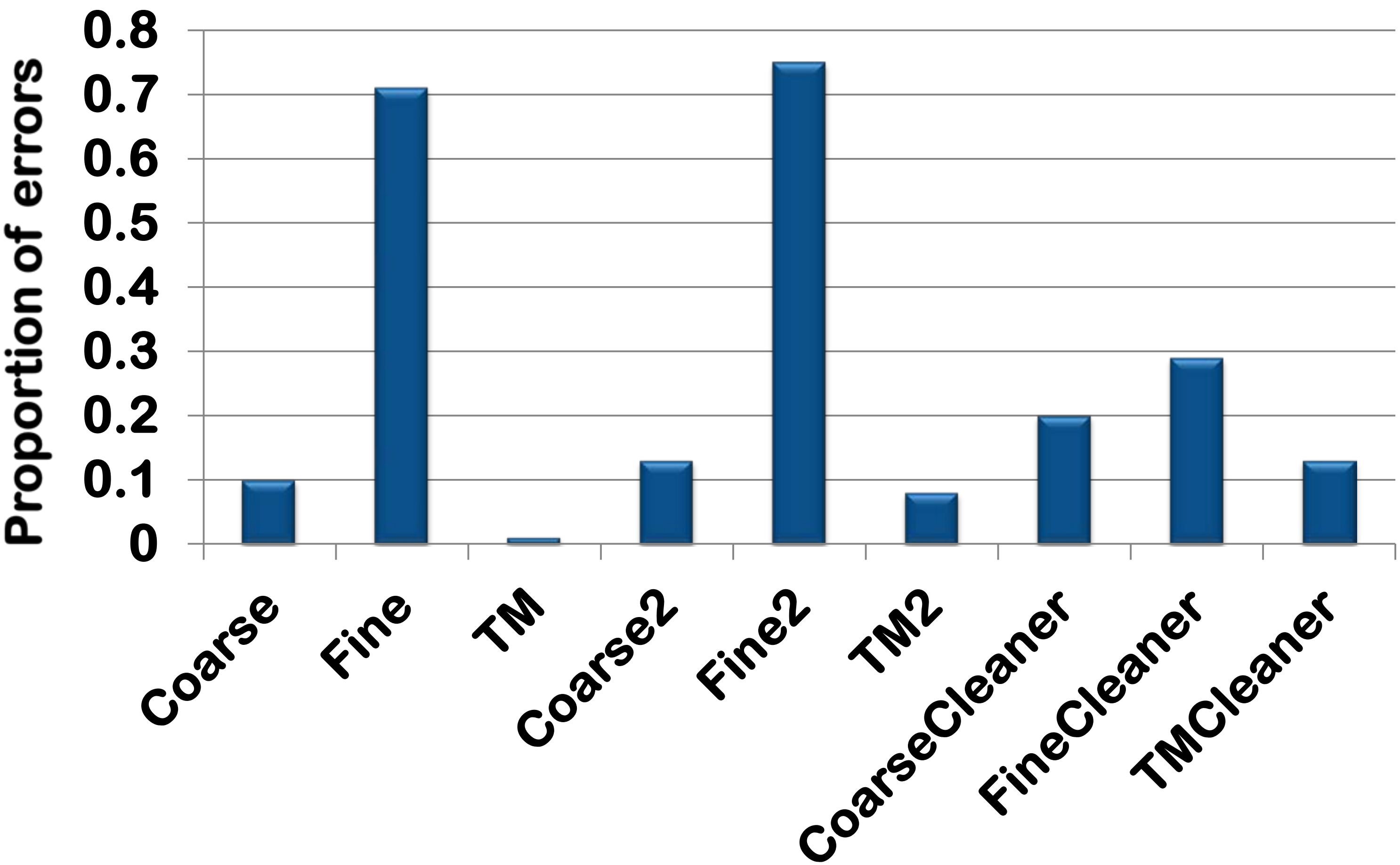


Overall Error Rates



Geometric Mean:
- **Coarse Locks: 27%**
- **Fine Locks: 62%**
- **TM: 10%**

Overall Error Rates: Year 2



Comments and conclusions

- TM problems
  - lack of documentation/tutorial
  - initial syntax of library-based TM
    - better in years 2/3 with different TM library
- Students found
  - TM harder than coarse-grained locking
  - TM easier than fine-grained locking and condition vars.
- Much fewer errors for TM than for locking

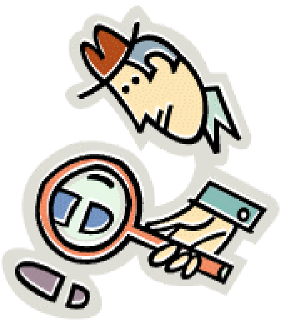
A Study of Transactional Memory vs. Locks in Practice

- “Explorative case study”
  - Broad scope
  - Less control, more realism
  - Lessons learned on a case-by-case basis
  - Programmed a desktop search engine

The Project: Parallel Desktop Search Engine

- 15 week project
- 12 subjects (Master's students)
  - Prior to project, same training for everyone (Parallel programming, locks / Pthreads, TM using Intel's STM compiler)
  - Randomly created 6 teams (2 students each)
    - 3 teams randomly assigned to use locks
    - 3 teams TM + Phreads
  - All using the same spec for indexing and search

- Collecting evidence
  - Code, svn, time records, weekly interviews, student diaries, notes, post-project questionnai observations



Code

- Average LOC about the same
- TM teams have fewer LOC with parallel constructs (2%-5% vs. 5%-11%)

	Locks Teams			TM Teams		
	L1	L2	L3	TM1	TM2	TM3
Total Lines of Code (excl. comments, blank lines)	**2014**	**2285**	**2182**	**1501**	**2131**	**3052**
	avg: 2160 stddev: 137			**avg: 2228 stddev: 780**		
LOC pthread*	157 8%	261 11%	120 5%	17 1%	23 1%	12 0%
LOC tm_*	0	0	0	36 2%	22 1%	139 5%
LOC with paral. constr. (pthread* + tm_*)	157 8%	261 11%	120 5%	53 4%	45 2%	151 5%
	avg: 179 stddev: 73			**avg: 83 stddev: 59**		

Code

- Locking programs more complex than TM
  - code inspections revealed thousands of locks
- TM teams combined transactions and locks
  - TM2: one lock to protect a large critical section containing I/O
  - TM3: two semaphores for producer-consumer synchronization
- All locks teams used condition variables, but none of the TM teams did
- Sync constructs rarely lexically nested

Code inspections with compiler experts at Intel

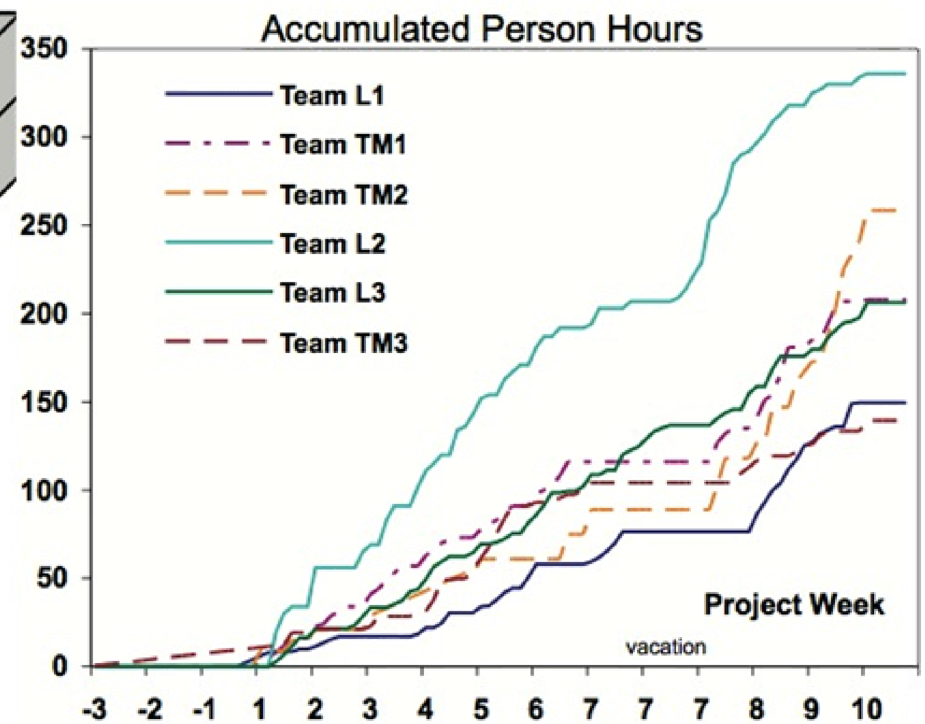
- Locks programs need fine-grained locking for scalability, but many locks complicate program understanding
  - L2: 1600 locks, L3: 80 locks, L1: 54 locks
  - L2 the only locking program to scale on indexing
- TM teams used locks and transactions to perform producer-consumer synchronization, perform I/O, and optimize access to immutable data
- Double-checked locking patterns in both locks and TM teams
  - Attempt to optimize performance
- Common mistake: unprotected reading of shared state. Exception: L1

Programming Effort

~14% difference in total programming effort in favor of TM

Total Effort (Person Hours)

	Reading	Search for Libraries	Design	Implementation	Additional Experiments	Testing	Debugging	Other	Total
Team L1	6	3	9	80	10	14	29	0	151
Team L3	24	1	17	72	7	52	16	19	208
Team L2	29	12	14	196	12	21	48	2	334
Team TM3	18	4	12	55	6	18	19	9	141
Team TM1	7	6	33	74	18	38	22	10	208
Team TM2	6	6	21	139	12	39	38	0	261
sum all	**90**	**32**	**106**	**616**	**65**	**182**	**172**	**40**	**1303**
	7%	2%	8%	47%	5%	14%	13%	3%	100%
sum L	**59**	**16**	**40**	**348**	**29**	**87**	**93**	**21**	**693**
	9%	2%	6%	50%	4%	13%	13%	3%	100%
sum TM	**31**	**16**	**66**	**268**	**36**	**95**	**79**	**19**	**610**
	5%	3%	11%	44%	6%	16%	13%	3%	100%
sum L - sumTM	$\boxed{28}$	0	-26	$\boxed{80}$	-7	-8	$\boxed{14}$	2	$\boxed{83}$



Less for TM

Increase for TM teams in last weeks: Refactoring transactions, performance problems, experiments

Programming Effort

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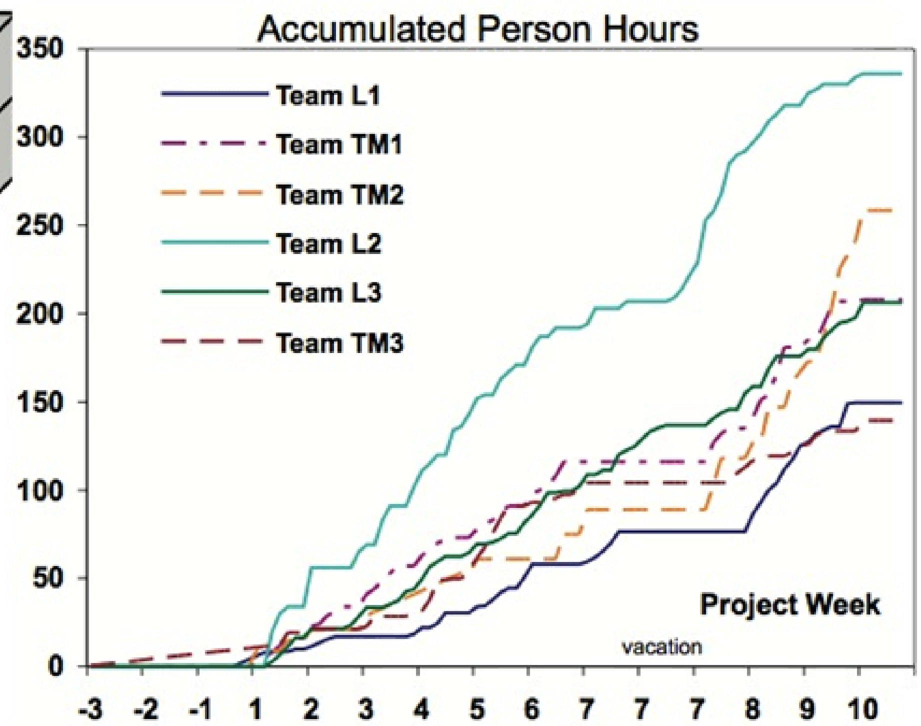
	5%	3%	11%	44%	6%	16%	13%	3%	100%
sum L - sumTM	*28*	*0*	*-26*	*80*	*-7*	*-8*	*4*	*2*	*83*



Debugging segfaults

- Locks teams: 55 hours (59%) of debugging time
- TM teams: 23 hours (29%) of debugging time

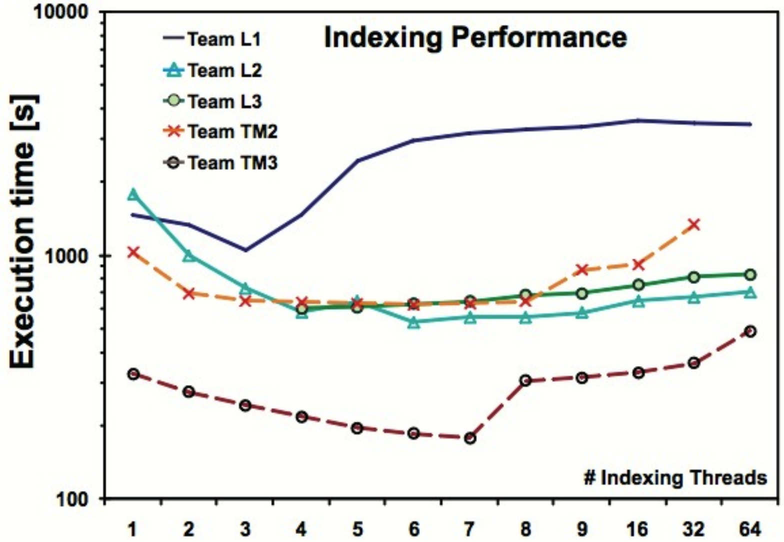
→ Influenced by LOC containing parallel constructs

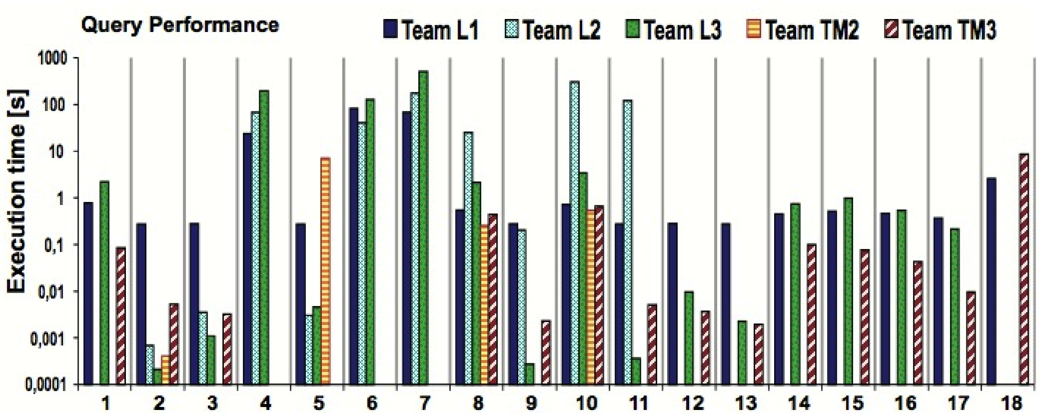
Parallelization Progress

- TM allowed teams to think more sequentially
  – spent 50% less time as the locks teams on writing parallel code
  – Hours spent on sequential code versus parallel code
  – Time lag between the first day of work on sequential code and the first day of work on parallel code
    – (L1 :1 day, L2: 13 days, L3: 19 days) vs. (TM3, 19 days, TM2: 23 days, TM1: 29 days)
  – Yet TM3 had first working parallel version, even though they subjectively believed they advanced slowly

- By project deadline
  – L1 had performance problems, skipped performance tests
  – L2 did not finish performance tests
  – L3 discovered a new concurrency bug (winner for locks)
  – TM1 fails on benchmark
  – TM2 reasonable performance
  – TM3 excellent (winner for TM)

Performance





Query type

1	one frequent word	6	frequent text passage (3 words)	11	wildcard rare (*word)	16	exclusion (1 frequent word)
2	one rare word	7	rare text passage (3 words)	12	AND frequent (2 words)	17	exclusion (1 rare word)
3	one random word	8	wildcard frequent (word*)	13	AND rare (2 words)	18	AND four characters with wildcards
4	frequent text passage (2 words)	9	wildcard rare (word*)	14	AND frequent (3 words)		
5	rare text passage (2 words)	10	wildcard frequent (*word)	15	AND rare (3 words)		

- TM3 outperforms on indexing performance and most teams on query performance

→ Counterexample that TM performance need not be bad in practice

Performance

Is TM Fast Enough?

- Many different STMs with different goals (and different guarantees)
  - TL2: baseline state-of-the-art
  - TinySTM: added safety guarantees (opacity)
  - NOrec: generalized support of many features
  - InvalSTM: contention-heavy programs
  - SkySTM: scalable to upwards of 250 threads

- How to choose?
  - Use adaptive algorithm (Wang et al., HiPEAC'12)
  - ***Change TM without changing client code***

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's Power 8 (2014)

- HTM will only improve existing STM performance

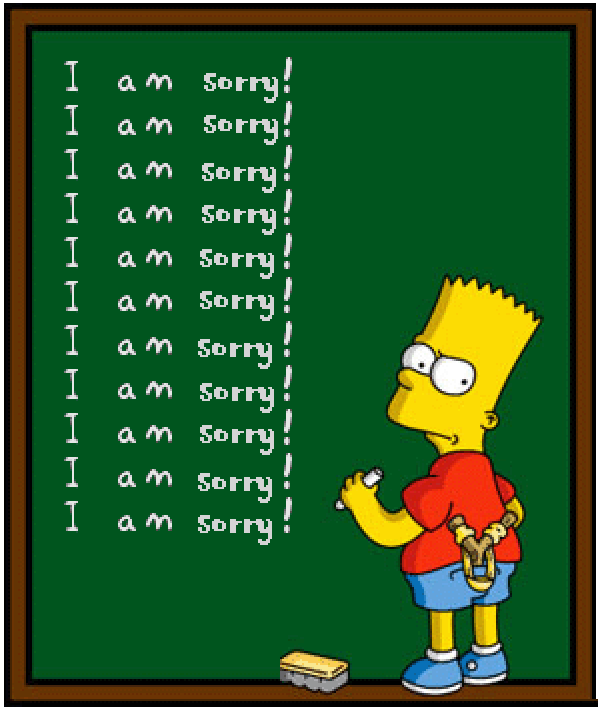
Commercial/OS Compilers

- Sun Studio (for Rock)
- Intel STM
- IBM AlphaWorks STM (for BG)
- GNU 4.7, 4.8, 4.9
- IBM xlC z/OS v1R13 compiler

Intel 12.2 and GNU 4.7 support

- Both based on Draft C++ TM spec
- Intel is based on V1.0, but has many extensions
- GNU is based on V1.1
  - See slide on Draft 1.1 addition for differences
- Both use a form of Intel TM ABI V1.1 2006/05/06
  - GNU does not implement all of the ABI (mostly missing the Intel TM extensions)

How to rollback an irrevocable action



Real-World STM Application

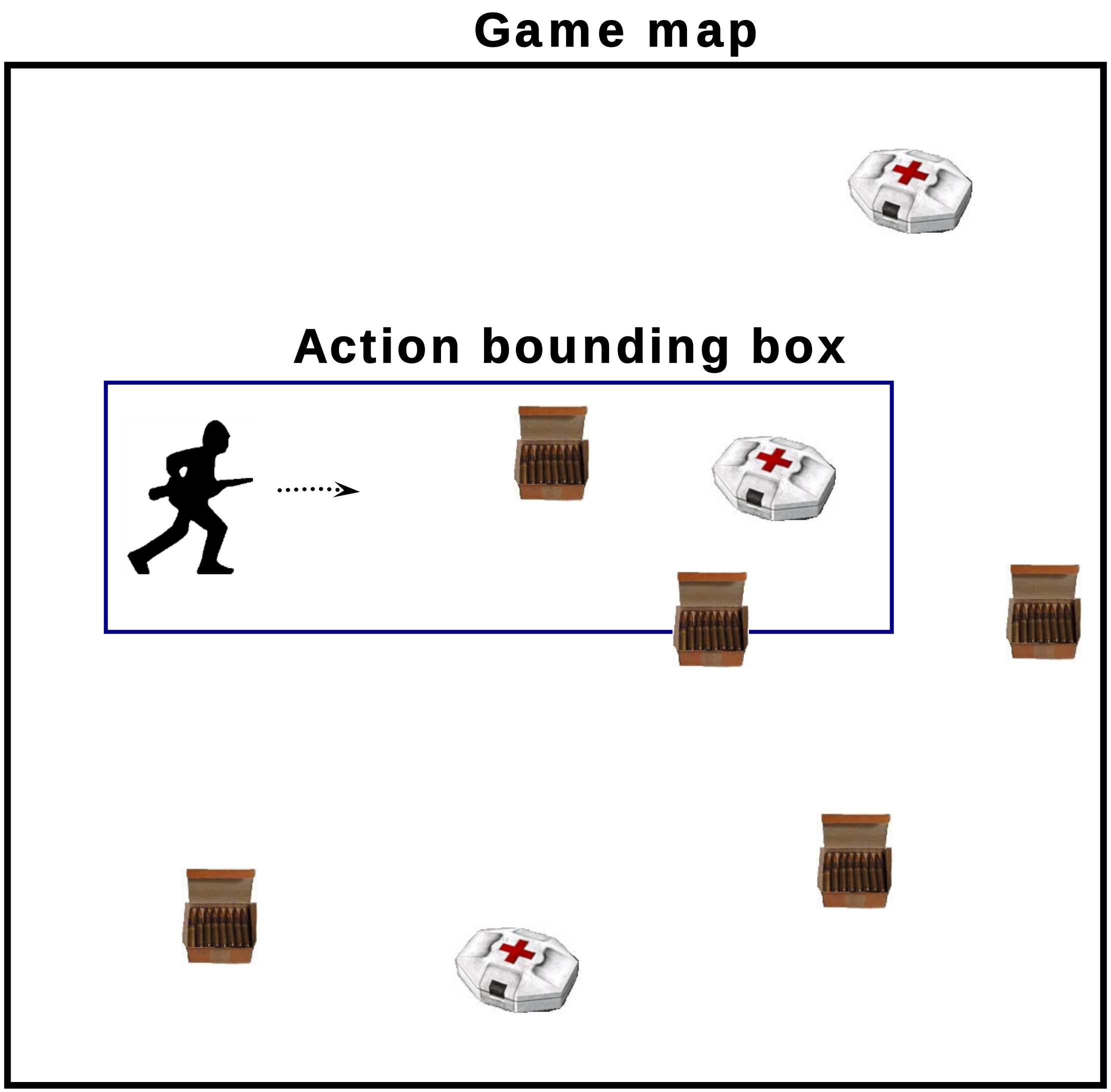
- Transactional Memory Support for Scalable and Transparent Parallelization of Multiplayer Games
  - Daniel Lupei, Bogdan Simion, Don Pinto, Mihai Burcea, Matthew Misler, William Krick, Cristiana Amza
  - application: SynQuake, simulates Quake battles
  - used software-only TM (STM)
  - presented at EuroSys 2010

Multiplayer games

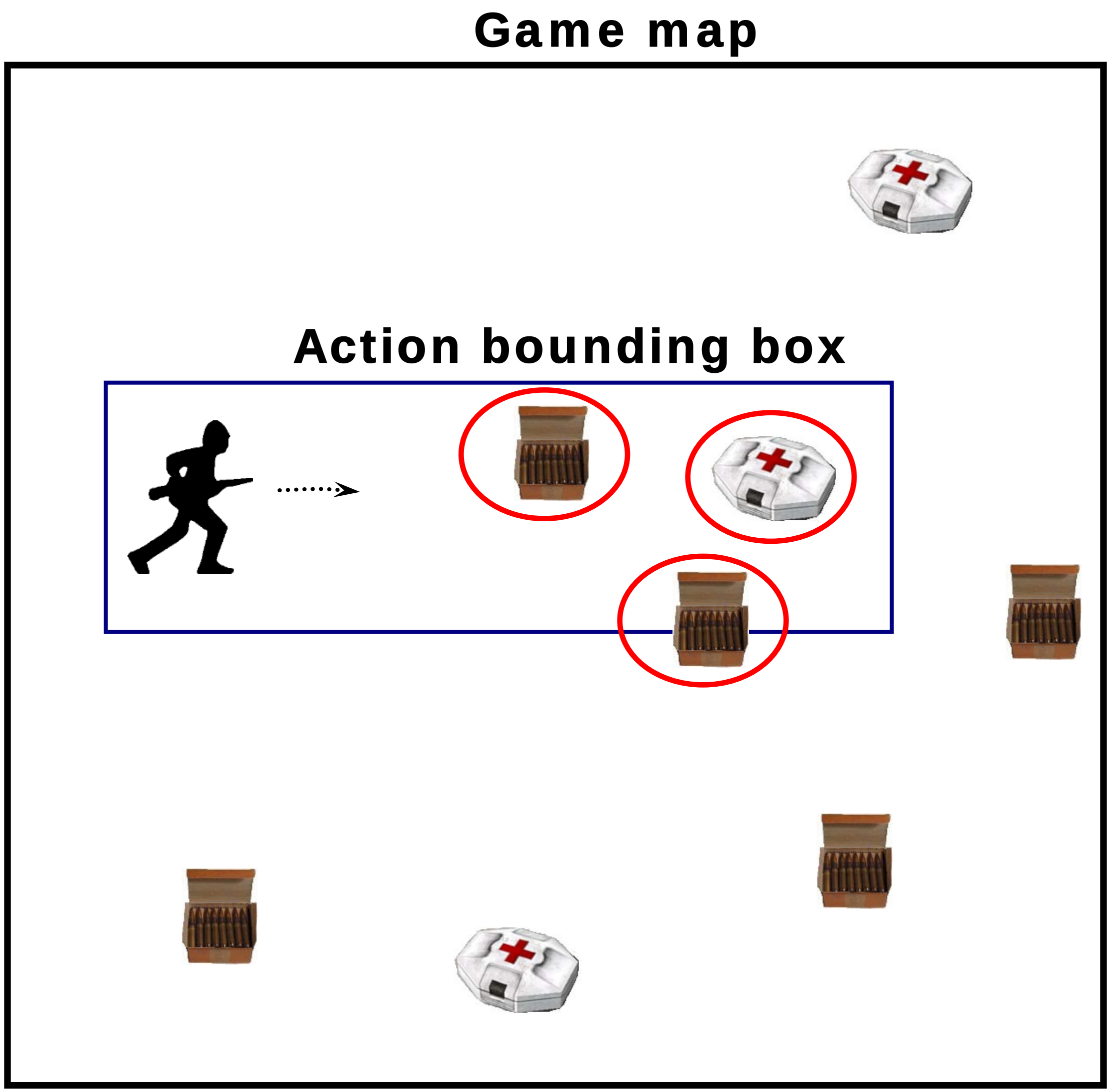
- More than 100k concurrent players

Game server is the bottleneck

Game interactions

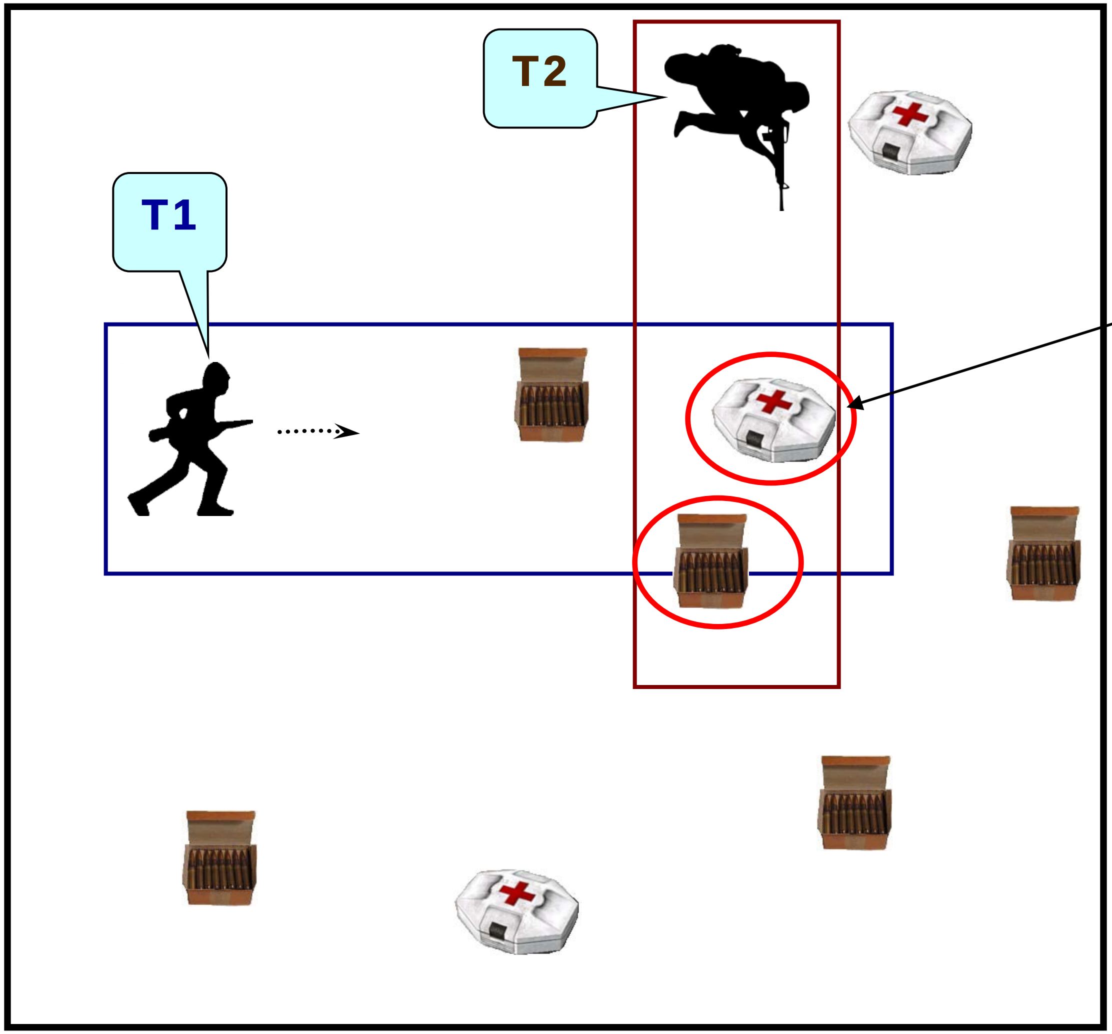


Collision detection



Conflicting player actions

Game map

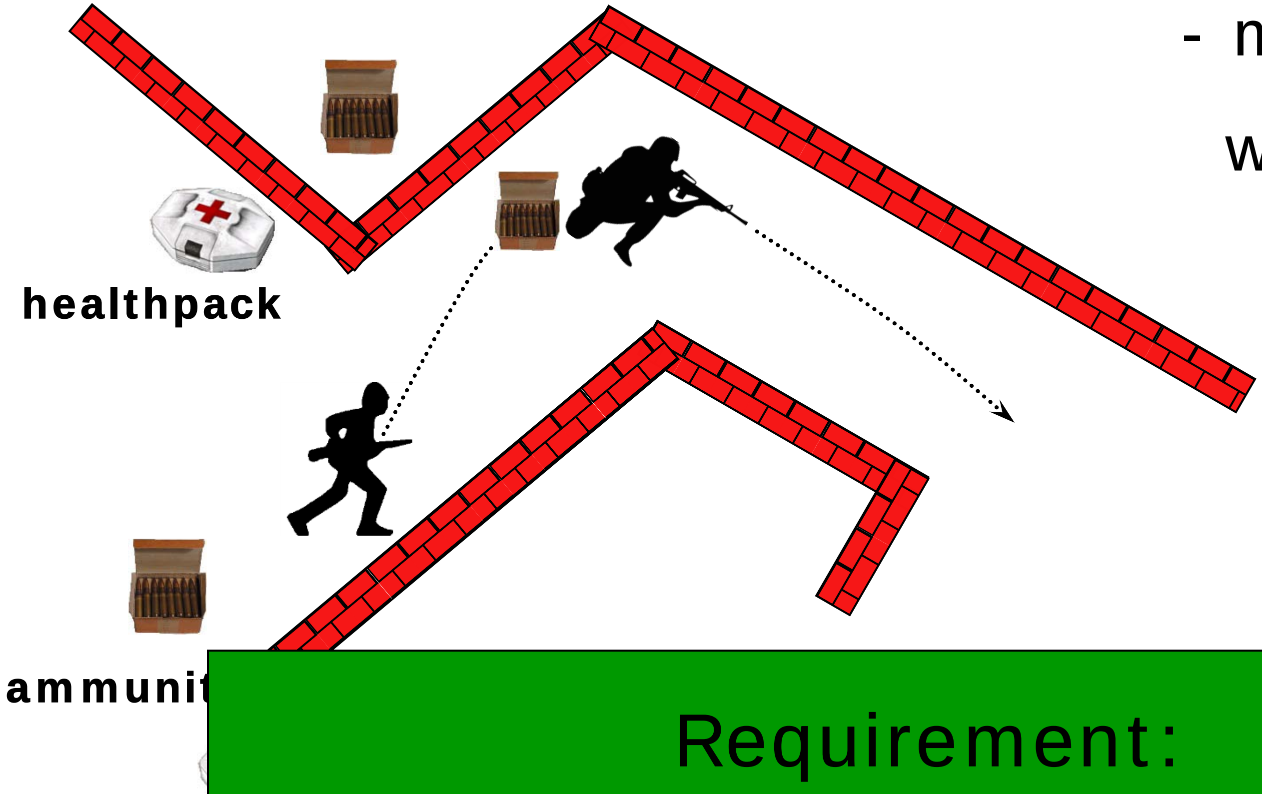


Need for synchronization

Player actions

Compound action:

- move, charge weapon and shoot



Requirement:
consistency and atomicity
of whole game action

Conservative locking

GAME ACTION

Lock 1, Lock 2, Lock3

Subaction 1

Subaction 2

Subaction 3

Unlock 1,2,3

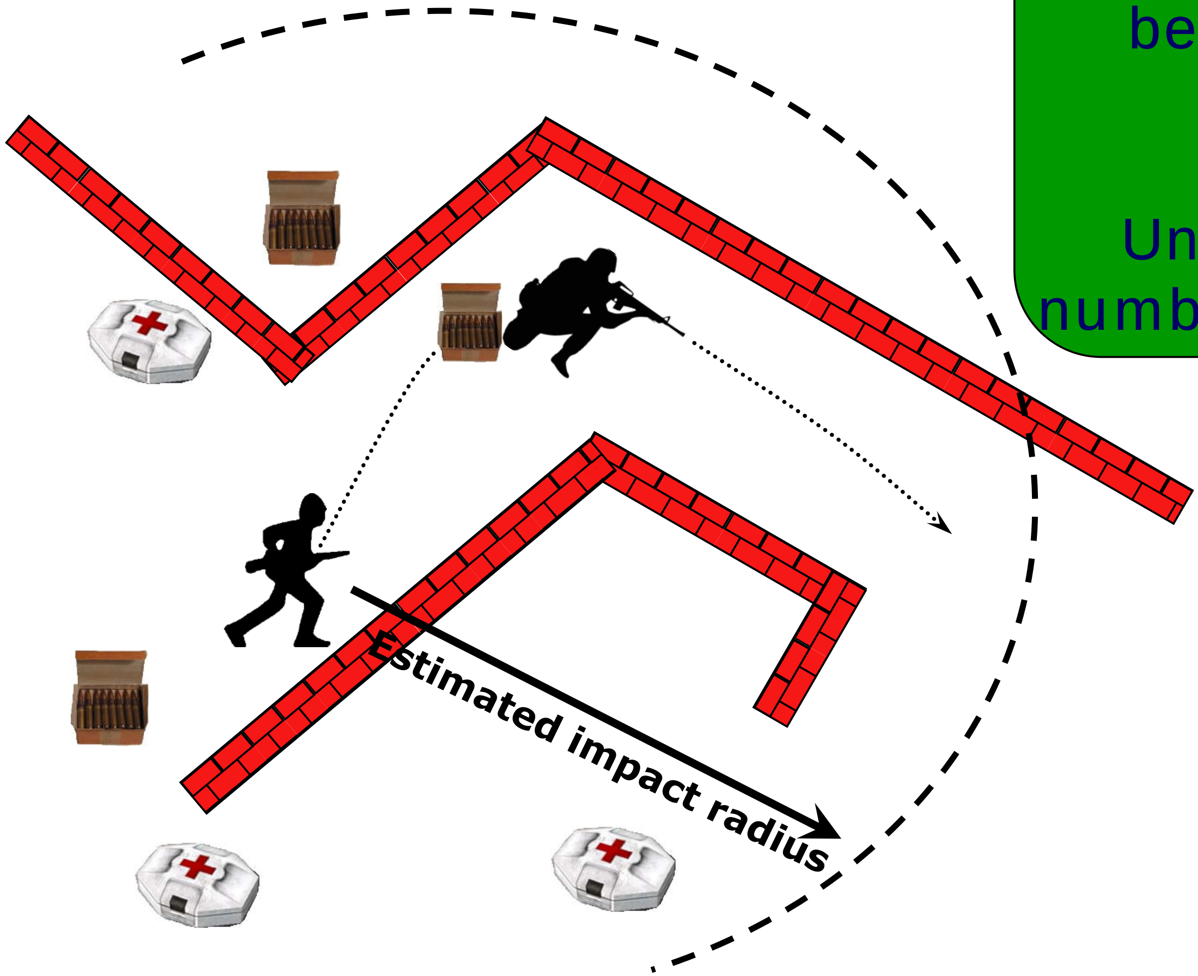
Conservatively acquire all locks at beginning of action

Problem 1:
Unnecessarily long conflict duration

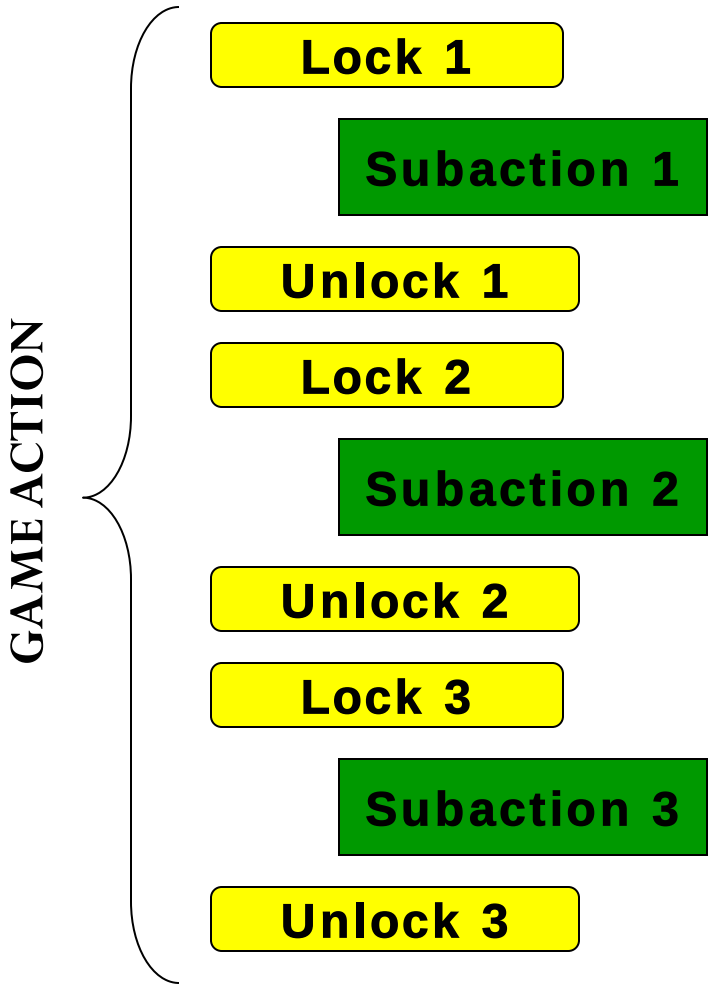
Conservative locking

Conservative estimate of impact range at beginning of action

Problem 2:
Unnecessarily high number of locked objects



Fine-grained locking?



Not possible !

Problem:
- No atomicity for whole action

Fine-grained locking?

GAME ACTION

Lock 1

Subaction 1

Lock 2

Subaction 2

Lock 3

Subaction 3

Unlock 1, 2, 3

Not possible !

Problem:

- Deadlocks
- Inconsistent view

STM

- Alternative parallelization paradigm
  - Implement game actions as transactions
  - Track accesses to shared and private data
  - Conflict detection and resolution
- Automatic *consistency and atomicity*
  - Transaction commits if no conflict
  - Transaction rolls back if conflict occurs

STM - Synchronization

GAME ACTION

BEGIN Transaction

Subaction 1

Subaction 2

Subaction 3

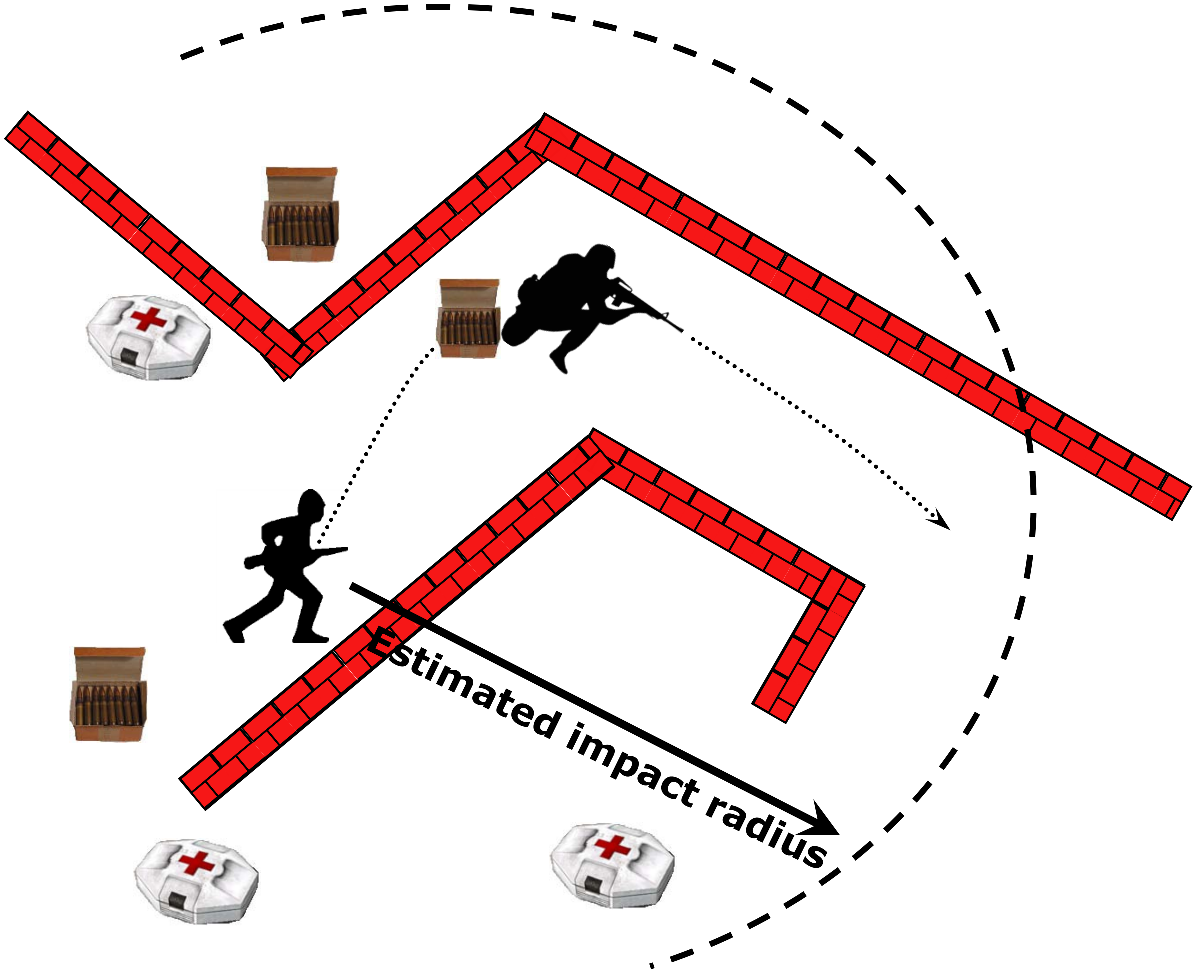
COMMIT Transaction

Problems solved:

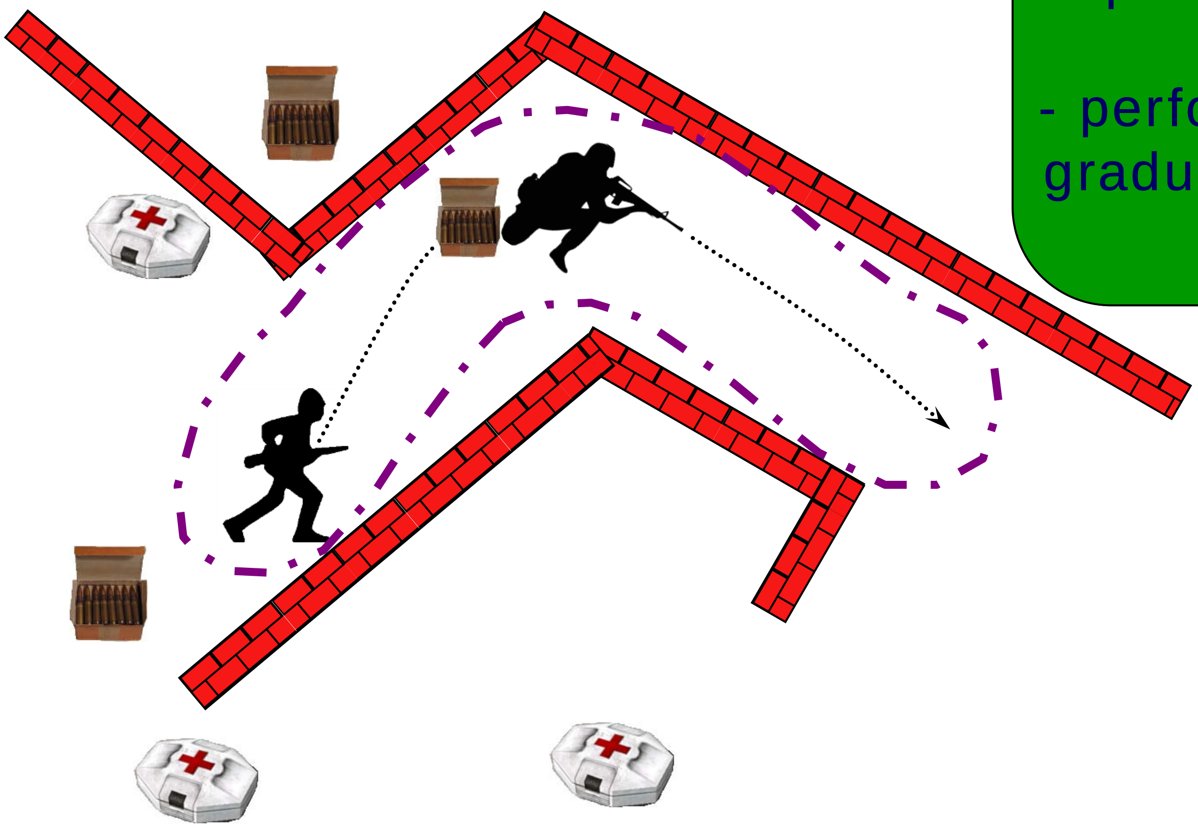
- Deadlocks
- Atomicity

Handled automatically

STM - Synchronization



STM - Synchronization



Collision detection optimized:

- split action into subactions

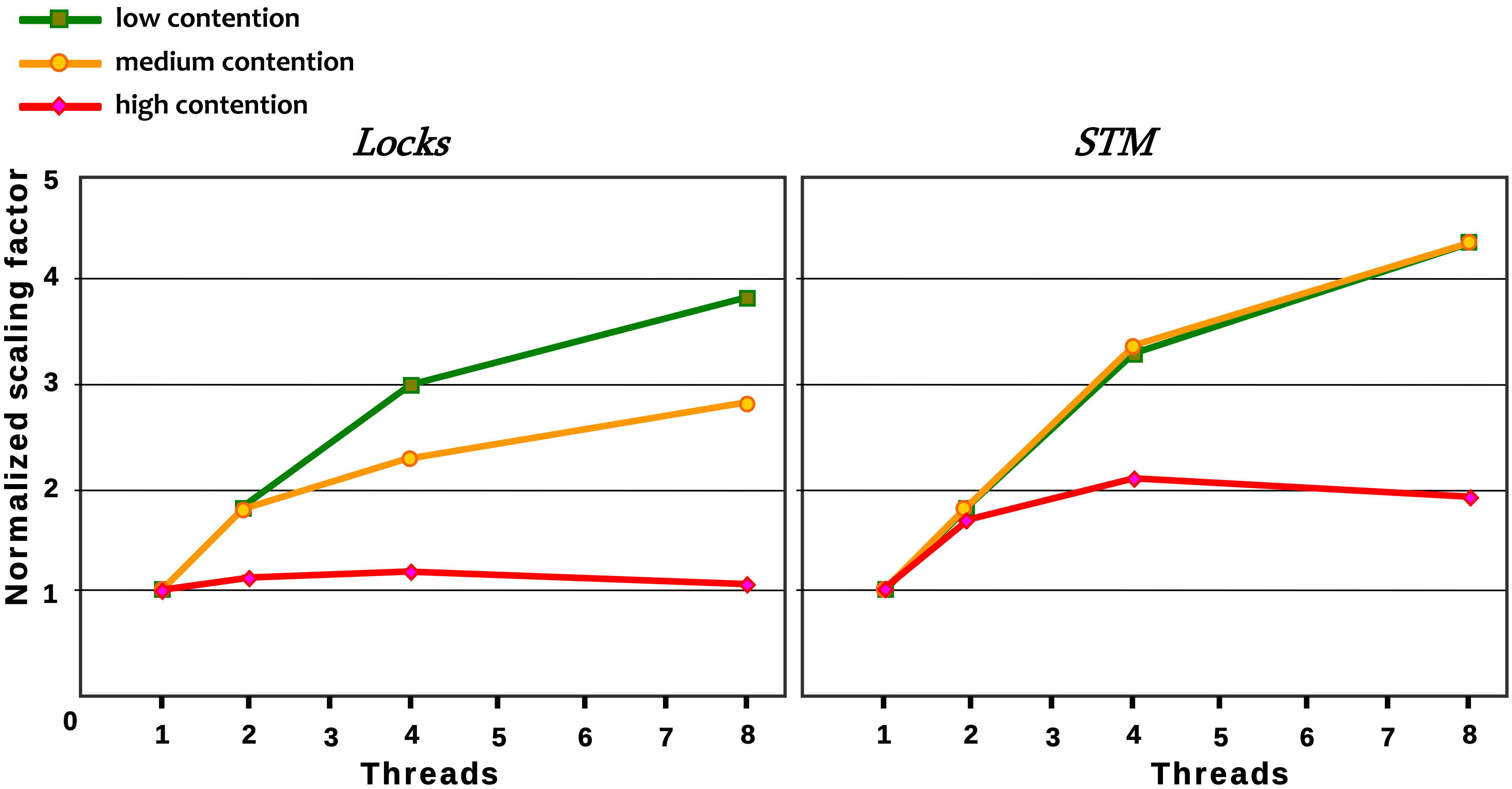
- perform collision detection gradually for each subaction

Experimental Results

- Test scenarios:
  - 1 – 8 quests, short/long range actions
- Performance comparison
  - Locks vs. STM scaling and performance
  - Influence of load balancing on scaling

Scalability

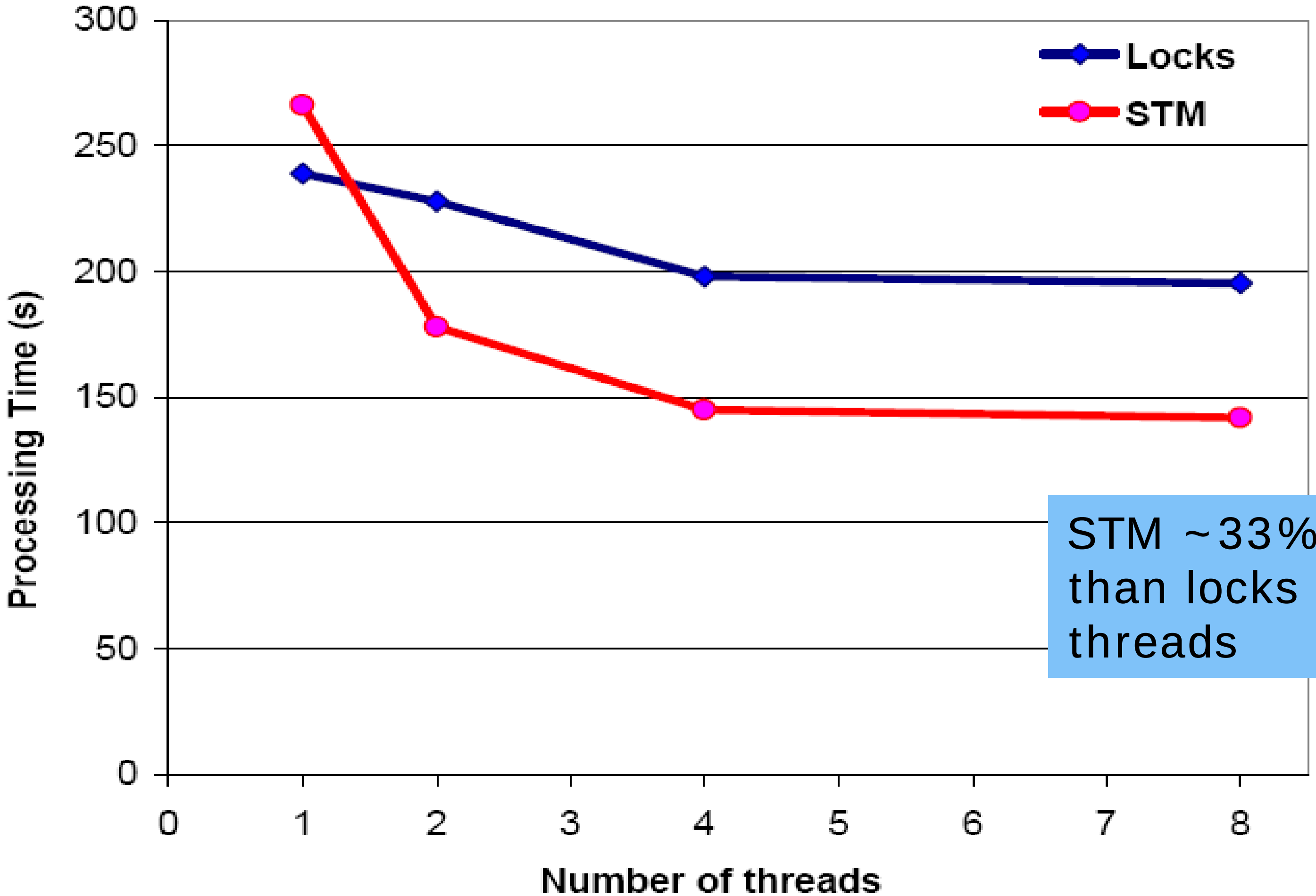
8 core machine



STM scales better in all 3 contention scenarios

Processing Times

Medium contention



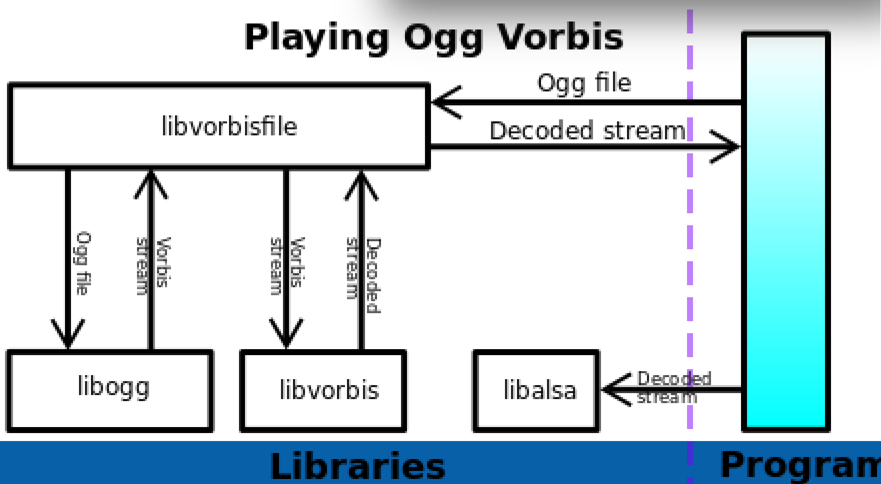
STM ~33% faster than locks for 4-8 threads

Transactional memory benefits

- As easy to use as coarse-grain locks

- Scale as well as fine-grain locks

- Composition:
  - Safe & scalable composition of software modules
  - Locks don't compose



Conclusions

- TM naturally aligns with generic programming
- Many problems are well-suited for TM
- Early studies show TM to be easy to program and less buggy than locks
- Software-only TM can outperform locks

Agenda

- STM, HTM, HybridTM
- Birth of a specification
- Design Goals
- Motivation for SG5 in C++ Standard
  - Use cases
  - Usability
  - Performance
- **Language Constructs**
  - Transactions, atomic and synchronized
  - Race-free semantics
  - Unsafe statements
  - Exception handling
- SG5 Progress

2014: SG5 TM Language in a nutshell

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

Transaction statement

- 2 forms

```
atomic_noexcept {x++;}
atomic_commit   {x++;}
atomic_cancel   {x++;}
```

atomic

```
synchronized    {x++;}
```

synchronized

Atomic & relaxed transactions

```
atomic_cancel {
  x++;
  if (cond)
    throw 1;
}
```

Appear to execute atomically

Can be cancelled

Unsafe statements prohibited

```
synchronized {
  x++;
  print(x);
}
```

Cannot be cancelled

No other restrictions on content

All transactions appear to execute in serial order

Racy programs have undefined behavior

I/O Without Transactions

```
void foo()
{
  cout << "Hello Concurrent Programming World!" << endl;
}
```

```
// Thread 1
foo();
```

```
// Thread 2
foo();
```

```
Hello Concurrent Programming World!
```

```
Hello Hello Concurrent Concurrent Programming
Programming World! World!
```

...***Hello Concurrent Programming Hell World!***...
(and other fun [and appropriate] variations)

I/O With Transactions

```
void foo()
{
  cout << "Hello Concurrent Programming World!" << endl;
}
```

```
// Thread 1
atomic_noexcept
{
   foo();
}
```

```
// Thread 2
atomic_noexcept
{
   foo();
}
```

```
Hello Hello ... Hello
```

Three Hello's?
There are only two calls?

I/O and Irrevocable Actions: Take Two

```
void foo()
{
  cout << "Hello Concurrent Programming World!" << endl;
}
```

```
// Thread 1
synchronized
{
   foo();
}
```

```
// Thread 2
synchronized
{
   foo();
}
```

```
Hello Concurrent Programming World!
Hello Concurrent Programming World!

(only possible answer)
```

Communication via synchronization (Important, but may not be in TS)

```
synhronized {
    lock (L)
     sendMessage();
    unlock (L)


    lock (L)
     receiveReply();
    unlock (L)
}
```

Will deadlock for **transaction_atomic**

```
lock (L)
 receiveMessage();
 sendReply();
unlock (L)
```

Nested ***non-transactional*** synchronization violates atomicity (isolation)

Function Call Safety

- 3 features for safety of functions calls

1. transaction_safe attribute
2. transaction_unsafe attribute
3. Concept of implicitly declared safe function

- Different combinations offer different degrees of ability to call functions from within atomic transactions

Incorrect Program

```
atomic_noexcept {
    p = new Foo();
    f(p);
}
```

data race

```
if (p != NULL)
t = p->x;      //S
```

Racy program → undefined behavior

Practically, p **might** be NULL in S

Unsafe statements

Operations for which system can't guarantee atomicity

- Access to volatile objects
- Asm statements
- Calls to functions that execute unsafe code

Functions that break atomicity must not be declared safe

- Synchronization: operations on locks and C++0x atomics
- Certain I/O functions

Implicit safety declarations

Non-virtual functions can be implicitly declared safe

```
void foo()  {x++;}

atomic_noexcept {
  foo();
}
```

Safe statements

Call to foo() is safe after the definition

Help with template functions

Implicit safety & template functions

```
template <class Op>
void t(int& x, Op f) { f(x++);}
```

Safe

```
void (*p1) (int) transaction_safe;
atomic_noexcept { t(v, p1);}
```

Unsafe

```
void (*p2) (int);
t(v, p2);
```

Enables reuse of template libraries

What happens on an exception?

```
atomic_cancel {
  x++;
  if (cond)
    throw 1;
}
```

When integer escapes the transaction

- Should the effects of x++ be committed?
- Or should they be rolled back?

Active debate in community

Both sides are right

Some programs behave surprisingly under commit-on-escape

Others under rollback-on-escape

Observations:

- Exceptions that can unexpectedly escape a transaction are potentially dangerous
- No single behavior appropriate for all cases
  - Only the programmer can determine what's appropriate

Our approach

Support both semantics & let programmer decide

New syntax for

- Exception specifications on transaction statements
- Throwing exceptions that roll back a transaction
  - Allowed on atomic_cancel only

Exception specification

Specify whether an exception is allowed to propagate outside of scope

```
atomic_noexcept                {…}//not allowed
atomic_commit                  {…}//allowed
atomic_cancel                  {…}//allowed
```

Terminate if contract violated

No default is not allowed, you must think about exceptions

```
atomic                         {…}//compile failure
```

Commit-on-exception

Standard syntax for exception throw

```
atomic_noecept {
  try {
      throw 1;
  } catch ( int & e) {
       …; //exception caught here
  }
}
```

Easy to specify that any exception may commit

```
atomic_commit {
  exception_throwing_fun();
}
```

Rollback-on-exception

Syntax for exception throw

```
try {
   atomic_cancel{
   try { ...
      throw 1;
   } catch (int& e) {
      assert(0); //never reached!
   }
} catch (int &e) {
   cout <<“Caught e!” << endl;
}
```

Exception must be enums or integrals

Restrict exceptions to enum / integral?

```
try
{
   atomic_cancel
   {
      ...
      throw TxException(txState);
   }
}
catch (TxException &e)
{
   cout << e.state(); // CRASH!
}
```

Accessing state that no longer exists.

Summary

TM adoption requires common interfaces

TS for SG5 specification

- Opens path for standard language extensions & semantics
- Establishes a reference point to move forward

We need programmers' feedback

http://groups.google.com/group/tm-languages

Agenda

- STM, HTM, HybridTM
- Birth of a specification
- Design Goals
- Motivation for SG5 in C++ Standard
  - Use cases
  - Usability
  - Performance
- Language Constructs
  - Transactions, atomic and relaxed
  - Race-free semantics
  - Unsafe statements
  - Attributes
  - Transaction expressions and try blocks
  - Cancel
  - Exception handling
- **SG5 Progress**

TM TS progress timeline 2008-2014

- 2008: every other week discussions by Intel, Sun, IBM started in July, later joined by HP, Redhat, academia, research
- 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, show use-cases, performance data
- 2013: Presented to Evolution as a proposed C++ Technical Specification
- 2014 Feb NWIP APPROVED: http://wiki.edg.com/twiki/bin/view/Wg21issaquah/FormalMotions :
  - Move to direct the Convener to request a New Work item for a Technical Specification for C++ Transactional Memory based on N3919 as an indication of its content.
- 3 Month NWIP Balloting: 21 out of 22 US companies approved,Nvidia abstained. But US will approve it.
- 2014: June ISO countries balloting now.
- Need 5 ISO countries to actively participate

TM TS 2014: Drive for PDTS

- 2014: June: a paper N3999
  - Core Second review, Library Evolution Second review, Library First Review
  - Changed from Safe-by-default to more static checking, fixes based on feedback
- 2014: Sept 15: Core wording third review telecon
- 2014: Oct 6: Library wording second review telecon
- 2014: Nov : on Monday in Rapperswil, have a motion to create a TM TS working paper with Nxxxx (or a possible intra-meeting updated version Nxxxx++) as its initial content
- 2014:Nov: Friday/Saturday: a paper Nyyyy for the post-Urbana-Champaign mailing that implements that motion (has the technical content of Nxxxx with tweaks but no major changes, and put into the structure of a TS); adopt that as a TM TS working paper and Vote to start the PDTS Ballot
- 3-6 Month PDTS Ballot: Principle Comment Stage, review all comments

TM TS 2015: Drive for DTS

- May 2015 meeting:
  - If we Address all comments from PDTS
  - Then vote to start a DTS ballot
- 3-6 month Ballot complete November 2015.

Current Status

- EWG Approved to start a NP for a TS 16/6/1/0/0
- LEWG Approved 8/3/2/0/0
- Continue telecon every other week to create a first TS Working Draft for Rapperswil
- Continue working on enhancements for further TS

Enable 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

Summary

TM adoption requires common high-level interfaces

- SG5 Opens path for standard language extensions & semantics

  -proposed draft TS specification for 2015

  –hardware is here and now

  - would you want C++ 2017, or 2022 that has no TM support?

We need feedback, all are welcome to join:

https://groups.google.com/forum/?hl=en&fromgroups=#!forum/c-tm-language-

My blogs and email address

- ISOCPP.org Director, VP http://isocpp.org/wiki/faq/wg21#michael-wong
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 Feature Request Page http://www.ibm.com/developerworks/rfe/?PROD_ID=700
Chair of WG21 SG5 Transactional MemoryM: https://groups.google.com/a/isocpp.org/forum/?hl=en&fromgroups#!forum/tm

Research challenges

- **Performance**
  - Compiler optimizations
  - Right mix of hardware & software components
  - Dealing with contention
- **Semantics**
  - Strong atomicity
  - Nested parallelism
  - Integration with locks
- **Debugging & performance analysis tools**
  - Good diagnostics
- **System integration**
  - I/O
  - Transactional OS
  - Distributed transactions

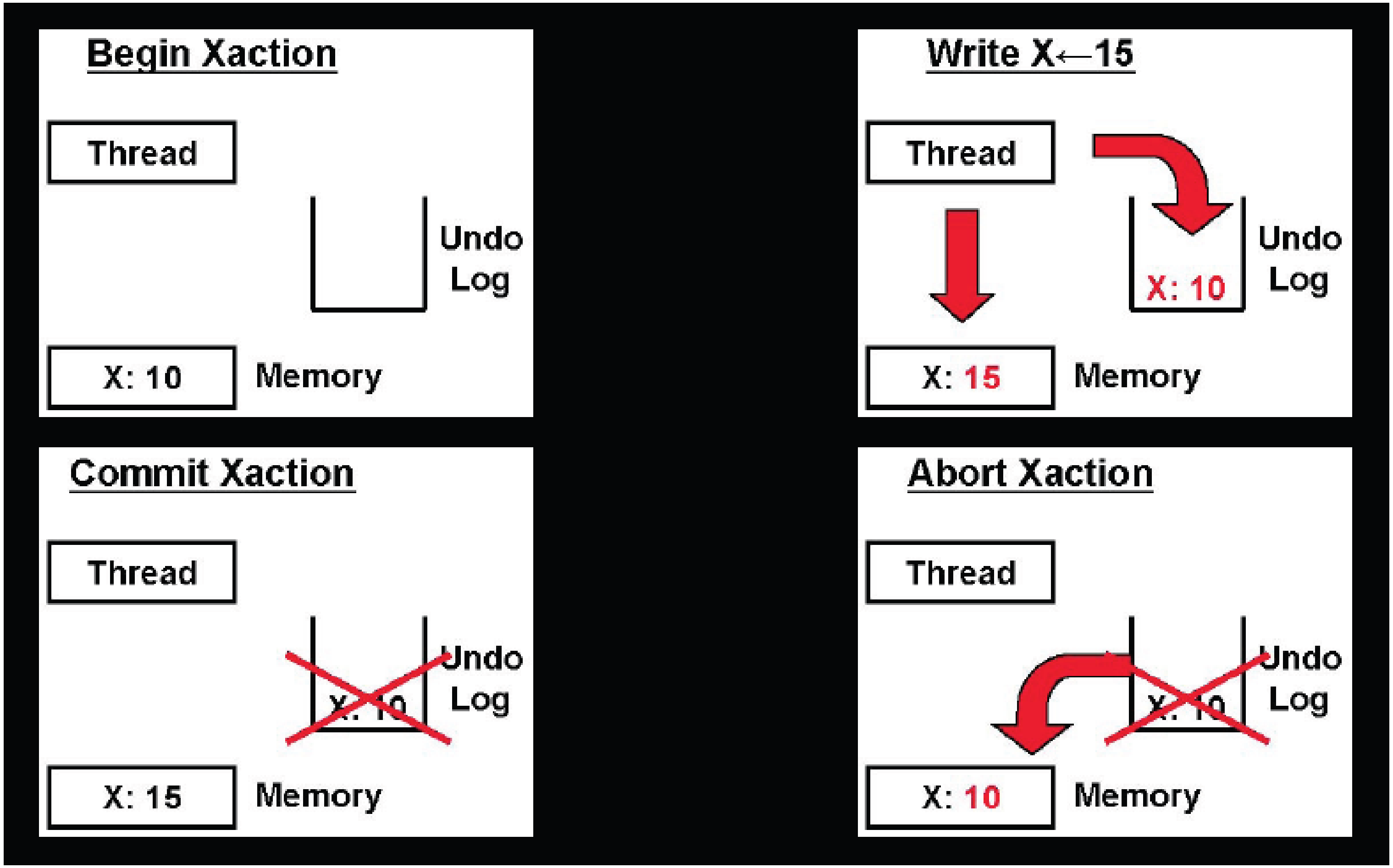
Implementation requirements

- **TM implementation must provide atomicity and isolation**
  - Without sacrificing concurrency
- **Basic implementation requirements**
  - Data versioning
  - Conflict detection & resolution
- **Implementation options**
  - Hardware transactional memory (HTM)
  - Software transactional memory (STM)
  - Hybrid transactional memory

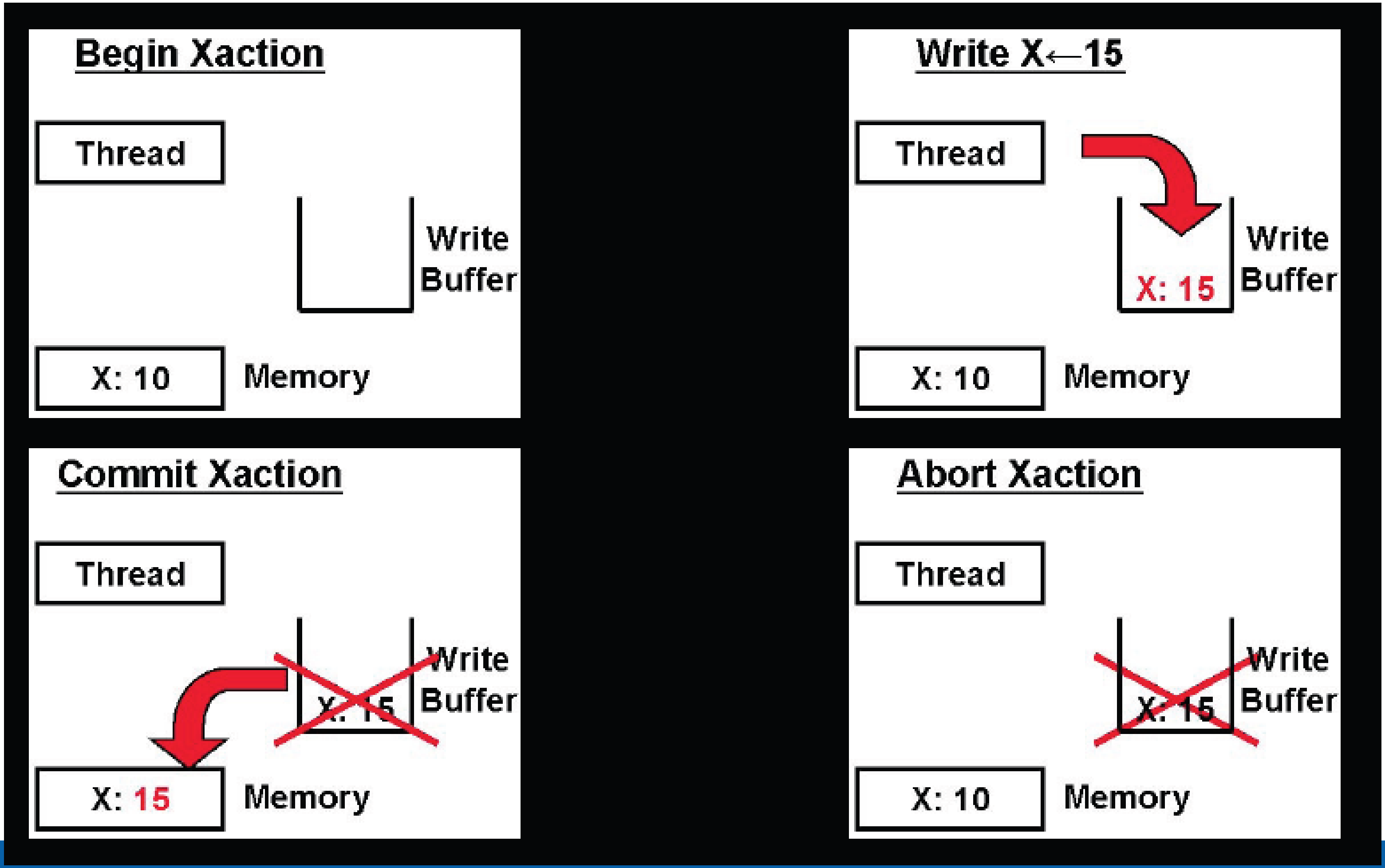
Data Versioning

- **Manage uncommited(new) and commited(old) versions of data for concurrent transactions**
- **1. Eager (undo-log based)**
  - Update memory location directly; maintain undo info in a log
  - +Faster commit, direct reads (SW)
  - –Slower aborts, no fault tolerance, weak atomicity (SW)
- **2.Lazy (write-buffer based)**
  - Buffer writes until commit; update memory location on commit
  - +Faster abort, fault tolerance, strong atomicity (SW)
  - –Slower commits, indirect reads (SW)

Eager Update



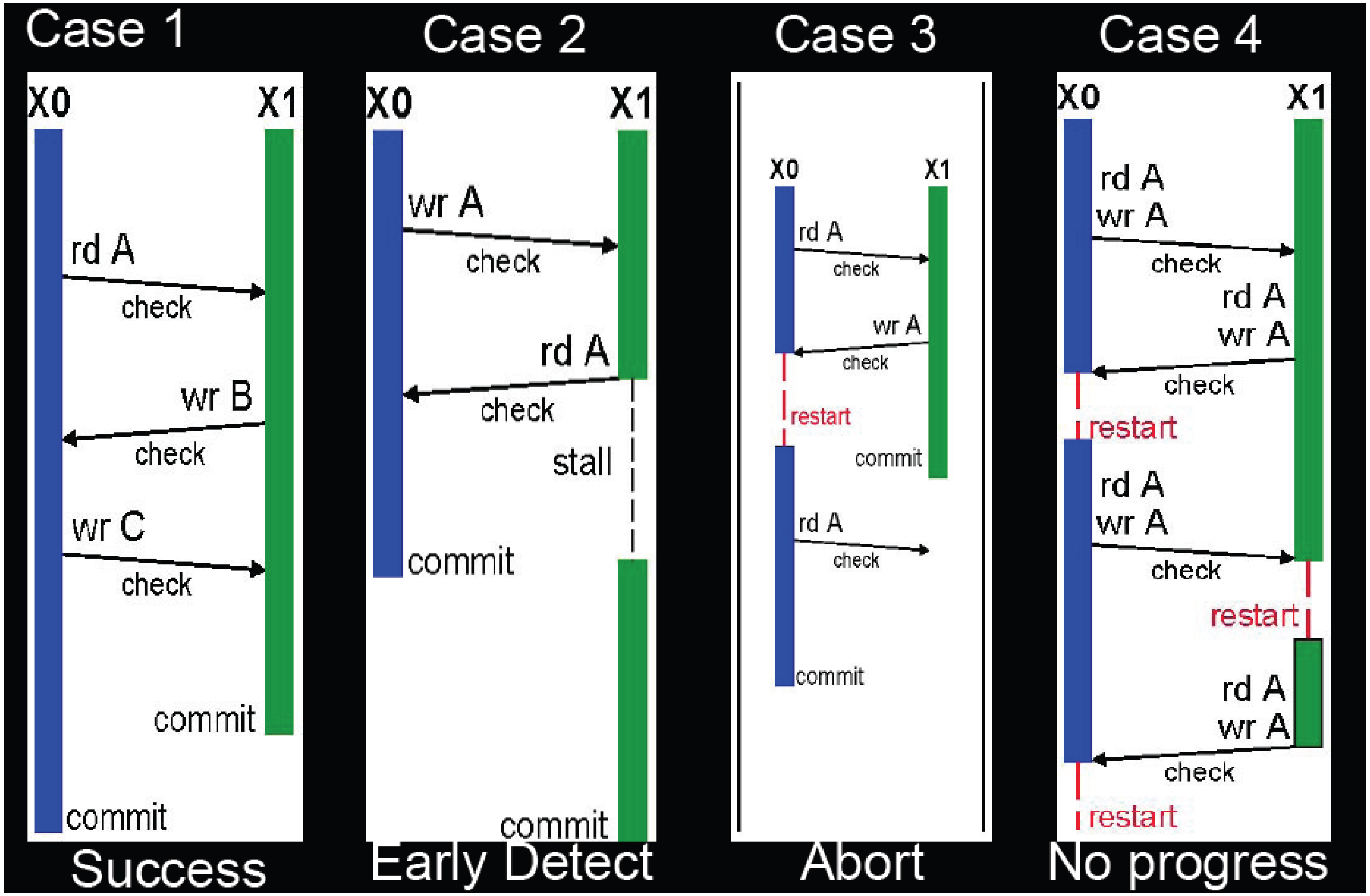
Lazy Update


Begin Xaction
Thread
Write
Buffer
X: 10
Memory
Write X←15
Thread
X: 15
Write
Buffer
X: 10
Memory
Commit Xaction
Thread
X: 15
Write
Buffer
X: 15
Memory
Abort Xaction
Thread
X: 15
Write
Buffer
X: 10
Memory

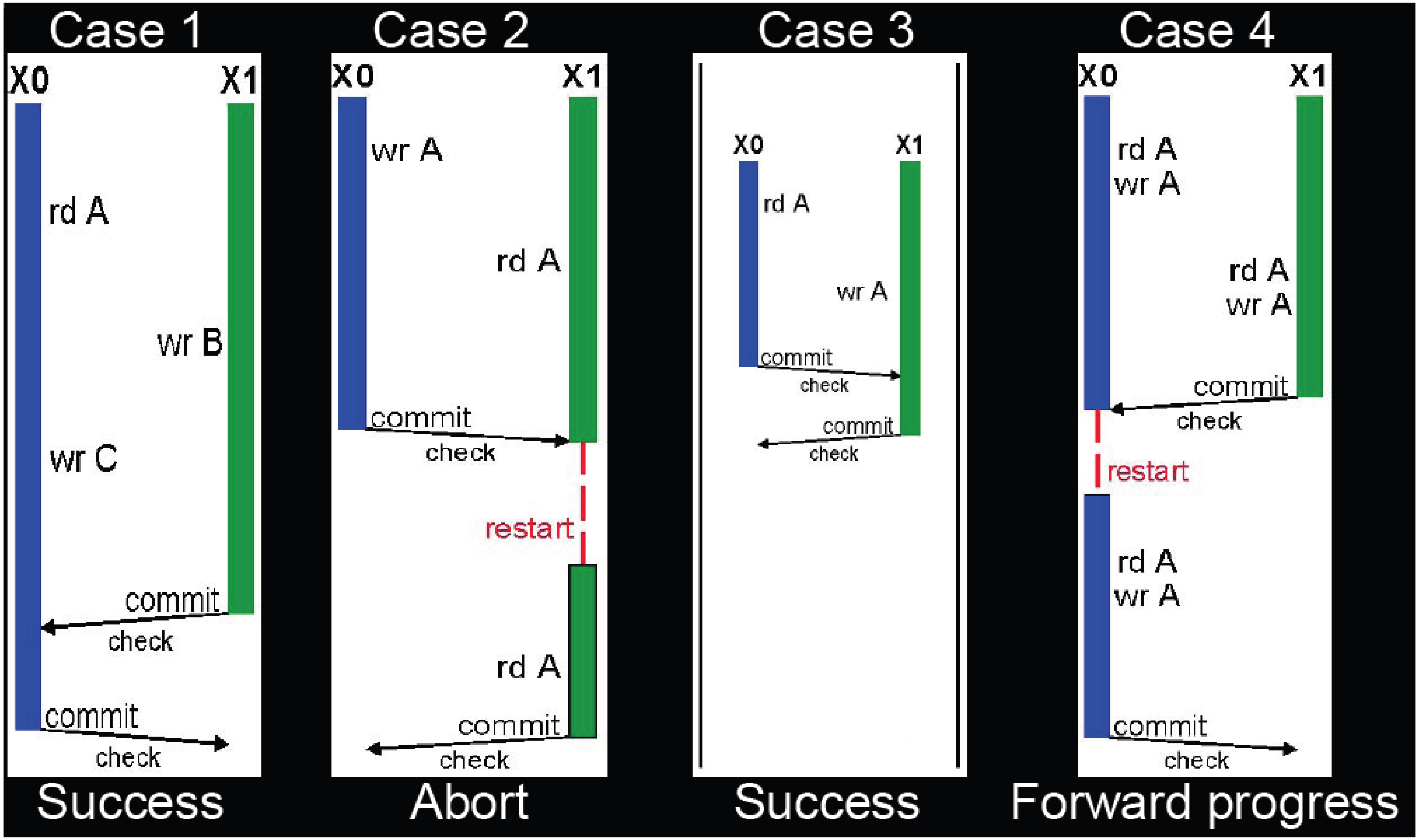
Conflict Detection

- **Detect and handle conflicts between transaction**
  - Read-Write and (often) Write-Write conflicts
  - For detection, a transactions tracks its read-set and write-set
- **1.Pessimistic detection**
  - Check for conflicts during loads or stores
    - HW: check through coherence lookups
    - SW: checks through locks and/or version numbers
  - Use contention manager to decide to stall or abort
    - Various priority policies to handle common case fast
- **2.Optimistic detection**
  - Detect conflicts when a transaction attempts to commit
    - HW: write-set of committing transaction compared to read-set of others
      - Committing transaction succeeds; others may abort
    - SW: validate write-set and read-set using locks and version numbers
- **Can use separate mechanism for loads & stores (SW)**

Pessimistic Detection



Optimistic Detection



Conflict Detection Tradeoff

- **1.Pessimistic conflict detection (aka encounter or eager)**
  - +Detect conflicts early
    - Undo less work, turn some aborts to stalls
  - –No forward progress guarantees, more aborts in some cases
  - –Locking issues (SW), fine-grain communication (HW)
- **2.Optimistic conflict detection (akacommit or lazy)**
  - +Forward progress guarantees
  - +Potentially less conflicts, no locking (SW), bulk communication (HW)
  - –Detects conflicts late

Conflict Detection Granularity

- **Object granularity (SW / hybrid)**
  - +Reduced overhead (time/space)
  - +Close to programmer's reasoning
  - –False sharing on large objects (e.g. arrays, PODs, non-polymorphic non-PODs)
    - Unnecessary aborts
- **Word granularity**
  - +Minimize false sharing
  - –Increased overhead (time/space) (e.g. polymorphic non-PODs)
- **Cache line granularity**
  - +Compromise between object & word
  - +Works for both HW/SW
- **Mix & match -> best of both words**
  - Word-level for arrays, PODs, non-polymorphic non-PODs, object-level for polymorphic non-PODs

Atomicity to Non-Transactional Code

- Can non-transactional code read non-committed updates?
  - Yes -> weak isolation (atomicity)
  - No -> strong isolation (atomicity)
- Strong atomicity is generally preferred
  - Otherwise there can be consistency and correctness issues
  - Difficult to provide in SW with eager version management
    - But static or dynamic analysis may be able to help…

Flat Nesting

- **Flat nesting**
  - **Merged atomicity and isolation**
    - **Inner does not commits until outer commits**
    - **Inner aborts causes outer to abort**
  - **Bad programming abstraction for languages using composition**

```
int x=1;
_transaction {
   x=2;
   _transaction
{
      x=3;
      abort;
   }
}
```

Closed Nesting

- **Closed nesting**
  - **Independent rollback and restart**
    - **Read-set and write-set tracked independently from parent**
    - **On inner conflict, abort inner transaction but not outer**
    - **On inner commit, merge with parent's read-set and write-set**
  - **Uses: reduce cost of conflict, allow alternate execution paths**

```
int x=1;
_transaction {
   x=2;
   _transaction
{
      x=3;
      abort;
   }
}
```

Open Nesting

- Independent atomicity and isolation for nested transactions
  - On inner commit, shared memory is updated immediately
  - Independent rollback similar to closed nesting
- – Uses: system and runtime code, reduce frequency of conflicts
  - But, may be too tricky for end programmers

```
int x=1;
_transaction {
   x=2;
   _transaction {
   x=3;
    }

_transaction_cancel;
}
```

Summary

- **Multicore: an inflection point in mainstream SW development**
- **Navigating inflection requires new language abstractions**
  - Safety
  - Scalability & performance
  - Modularity
- **Transactional memory enables safe & scalable composition of software modules**
  - Automatic fine-grained & read concurrency
  - Avoids deadlock, eliminates locking protocols
  - Automatic failure recovery
  - Avoids lost wakeups, allows composition of alternatives
- **TM in a non-managed environment**
  - Indirect calls
  - Aliased pointers
  - Exceptions
  - Unsafe types
- **Many open research challenges**