Code Generation and Optimization for Transactional Memory Construct in an Unmanaged Language

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Motivation

- Existing Transactional Memory (TM) constructs focus on managed Language
- Efficient software transactional memory (STM) takes advantages of managed language features
  - Optimistic Versioning (direct update memory with backup)
  - Optimistic Read (invisible read)

- Challenges in Unmanaged Language (e.g. C)
  - Consistency
    - No type safety, first-class exception handling
  - Function call
    - No just-in-time compilation
  - Stack rollback
    - Stack alias
  - Conflict detection
    - Not object oriented

Contributions

- First to introduce comprehensive transactional memory construct to C programming language
  - Transaction, function called within transaction, transaction rollback, …
- First to support transactions in a production-quality optimizing C compiler
  - Code generation, optimization, indirect function calls, …
- Novel STM algorithm and API that supports optimizing compiler in an unmanaged environment
  - quiescent transaction, stack rollback, …

Outline

- TM Language Construct
- STM Runtime
- Code Generation and Optimization
- Experimental Results
- Related Work
- Conclusion

TM Language Constructs

- #pragma tm_atomic
```
{
    stmt1;
    stmt2;
}
```
- #pragma tm_atomic
```
{
    stmt 1;
    #pragma tm_atomic
    {
        stmt2;
        …
        tm_abort();
    }
}
```
- #pragma tm_function
```
int foo(int);

int bar(int);

#pragma tm_atomic
{
    foo(3);   // OK
    bar(10); // ERROR
}

foo(2) // OK
bar(1) // OK
```

Consistency Problem

Thread 1

```
#pragma tm_atomic
{
  if(tq->free) {

    for(temp1 = tq->free;
      temp1->next &&…,
      temp1 = temp1->next);

    task_struct[p_id].loc_free = tq->free;
    tq->free = temp1->next;
    temp1->next = NULL;

    …
  }
}
```

Thread 2

```
#pragma tm_atomic
{
  if(tq->free) {

    for(temp2 = tq->free;
      temp2->next &&…,
      temp2 = temp2->next);

    task_struct[p_id].loc_free = tq->free;
    tq->free = temp2->next;
    temp2->next = NULL;

    …
  }
}
```

Not NULL

shared free list

NULL

local free list

Memory Fault

NULL

- **Solution: timestamp based aggressive consistent checking**

Inconsistency Caused by Privatization

Thread 1

```
#pragma tm_atomic
{
  if(tq->free) {
    for(temp1 = tq->free;
      temp1->next &&…,
      temp1 = temp1->next);
    task_struct[p_id1].loc_free = tq->free;
    tq->free = temp1->next;
    temp1->next = NULL;
    …
  }
}

temp1 = task_struct[p_id1].loc_free;
/* process temp */
task_struct[p_id1].loc_free = temp1->next;
temp1->next = NULL;
```

Not NULL

NULL

Memory Fault

Thread 2

```
#pragma tm_atomic
{
  if(tq->free) {
    for(temp2 = tq->free;
      temp2->next &&…,
      temp2 = temp2->next);
    task_struct[p_id2].loc_free = tq->free;
    tq->free = temp2->next;
    temp2->next = NULL;
    …
  }
}

temp2 = task_struct[p_id2].loc_free;
/* process temp */
task_struct[p_id2].loc_free = temp2->next;
temp2->next = NULL;
```

NULL

- **Solution: Quiescent Transaction**

Quiescent Transaction

Thread 1

```
#pragma tm_atomic
{
  if(tq->free) {
    for(temp1 = tq->free;
      temp1->next &&…,
      temp1 = temp1->next);
    task_struct[p_id1].loc_free = tq->free;
    tq->free = temp1->next;
    temp1->next = NULL;
    …
  }
}

temp1 = task_struct[p_id1].loc_free;
/* process temp */
task_struct[p_id1].loc_free = temp1->next;
temp1->next = NULL;
```

Not NULL

Consistency Checking Fail

Thread 2

```
#pragma tm_atomic
  {
    if(tq->free) {
      for(temp2 = tq->free;
        temp2->next &&…,
        temp2 = temp2->next);
      task_struct[p_id2].loc_free = tq->free;
      tq->free = temp2->next;
      temp2->next = NULL;
      …
    }
  }

temp2 = task_struct[p_id2].loc_free;
/* process temp */
task_struct[p_id2].loc_free = temp2->next;
temp2->next = NULL;
```

Quiescent

TM Runtime Issues (Stack Rollback)

rollback a

Stack Crash

```
#pragma tm_atomic
{
   …
   foo()
   … // abort
}
```

```
foo() {
   int a;
   bar(&a)
   …
}
bar(int *p) {
   …
   *p ← …
   …
}
```

back a

- **Solution: Selective Stack Rollback**

Optimization Issues (Redundant Barrier)

```
#pragma tm_atomic
{
  a = b + 1;
  …; // may alias a or b
  a = b + 1;
}
```

```
desc = stmGetTxnDesc();
rec1 = IRComputeTxnRec(&b);
ver1 = IRRead(desc, rec1);
t = b;
IRCheckRead(desc, rec1, ver1);

desc = stmGetTxnDesc();
rec2 = IRComputeTxnRec(&a);
IRWrite(desc, rec2);
IRUndoLog(desc, &a);
a = t + 1;
```

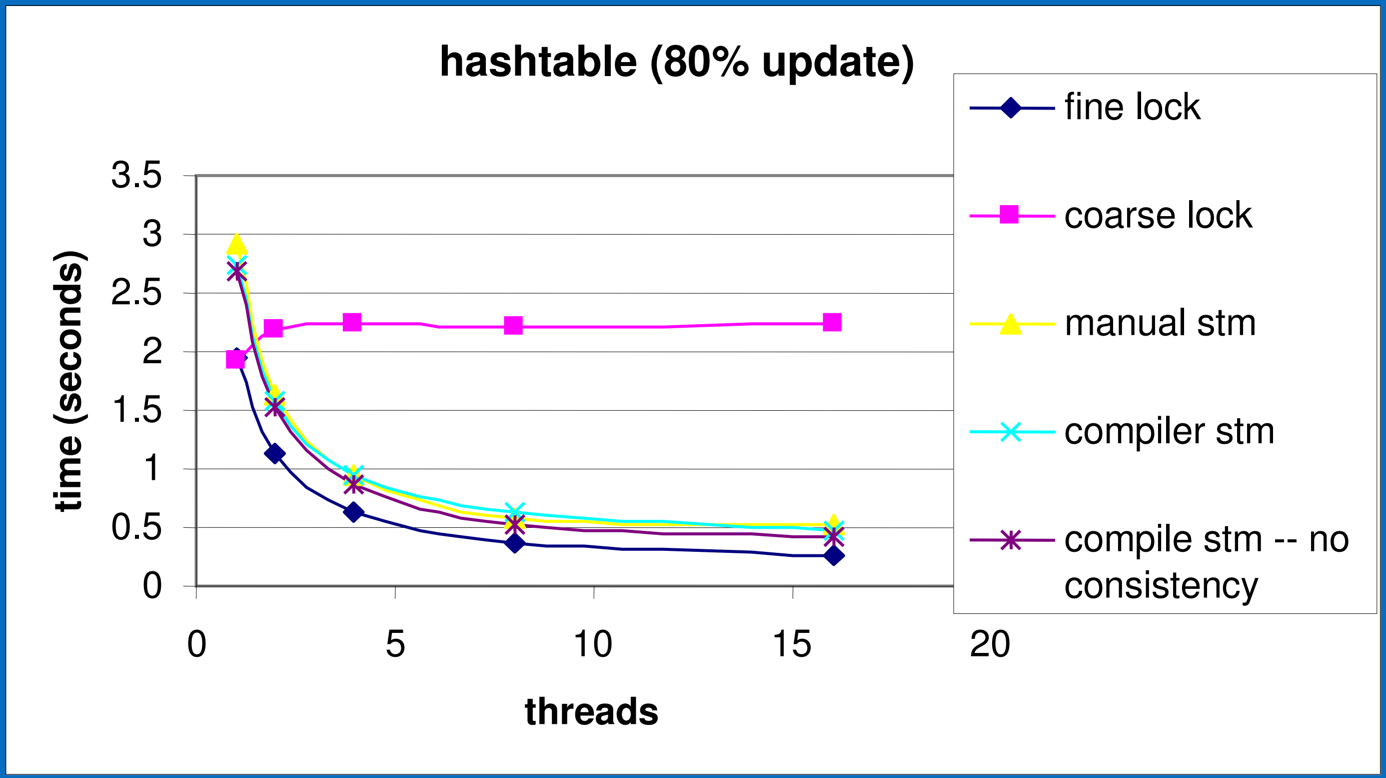
not redundant

```
desc = stmGetTxnDe
rec1 = IRComputeTxnRe
ver1 = IRRead(desc, rec1);
t = b;
IRCheckRead(desc, rec1, ver1);

desc = stmGetTxnDesc();
rec2 = IRComputeTxnRec(&a);
IRWrite(desc, rec2);
IRUndoLog(desc, &a);
a = t + 1;
```

Experiment Setup

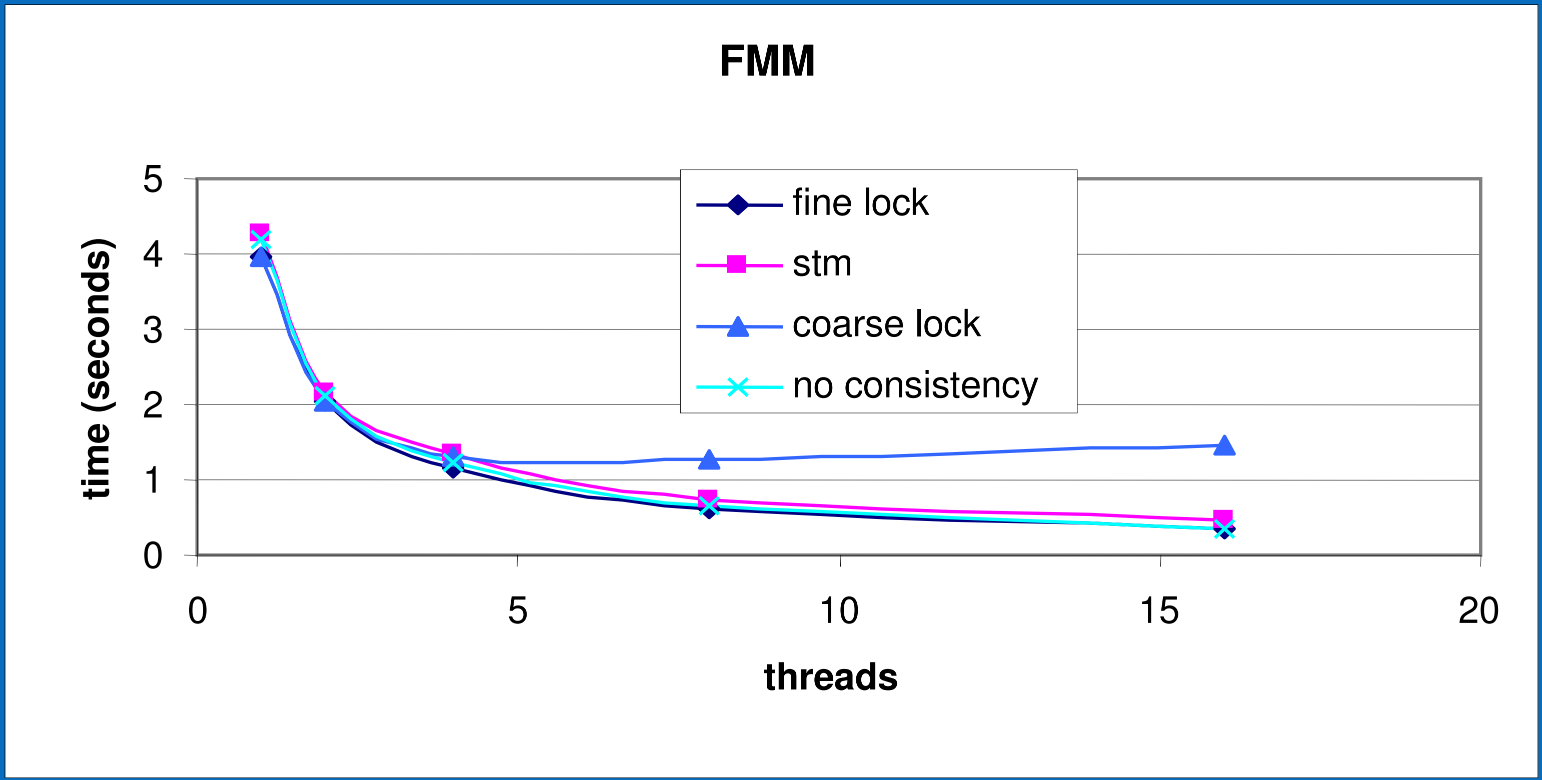
- Target System
  - 16-way IBM eServer xSeries 445, 2.2GHz Xeon
  - Linux 2.4.20, icc v9.0 (with STM), -O3
- Benchmarks
  - 3 synthetic concurrent data structure benchmarks
    - Hashtable, btree, avltree
  - 8 SPLASH-2 benchmarks
    - 4 SPLASH-2 benchmarks spend little time in critical sections
  - Fine-grained lock v. coarse-grained lock v. STM
    - Coarse-grain lock: replace all locks with a single global lock
    - STM:
      - Replace all lock sections with transactions
      - Put non-transactional conflicting accesses in transactions

Hashtable



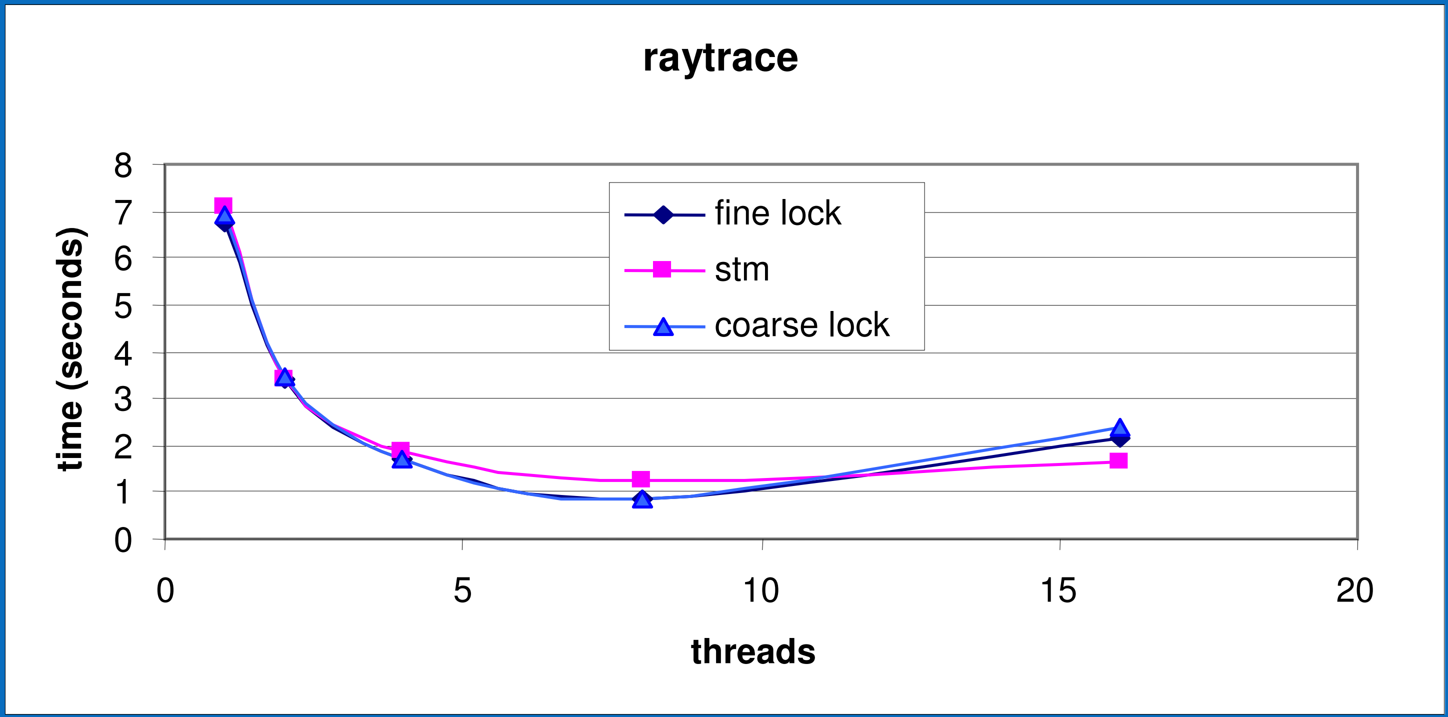
- STM scales similarly as fine grain lock
- Manual and compiler STM comparable performance

FMM



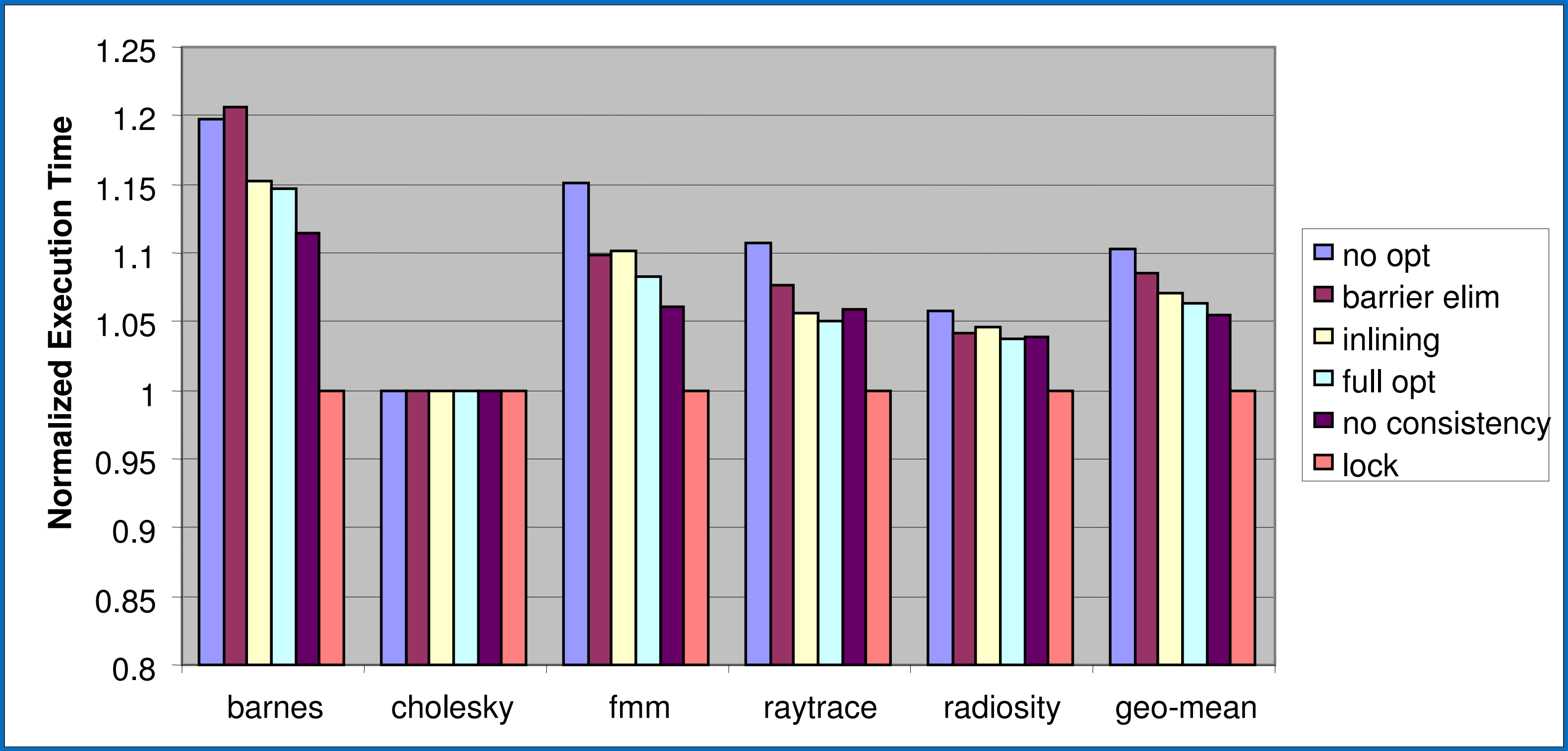
- STM is much better than coarse-grain lock

Splash 2



- STM can be more scalable than locks

Optimization Benefits



- The overhead is within 15%, with average only 6.4%

Related Work

- Transactional Memory
  - [Herlihy, ISCA93]
  - [Ananian, HPCA05], [Rajwar, ISCA05], [Moore, HPCA06], [Hammond, ASPLOS04], [McDonald, ISCA06], [Saha, MICRO 06]
- Software Transactional Memory
  - [Shavit, PODC95], [Herlihy, PODC03], [Harris, ASPLOS04]
- Prior work on TM constructs in managed languages
  - [Adl-Tabatabai, PLDI06], [Harris, PLDI06], [Carlstrom, PLDI06], [Ringengerg, ICFP05]
- Efficient STM
  - [Saha, PPoPP06]
- Time-stamp based approach
  - [Dice, DISC06], [Riegel, DISC06]

Conclusion

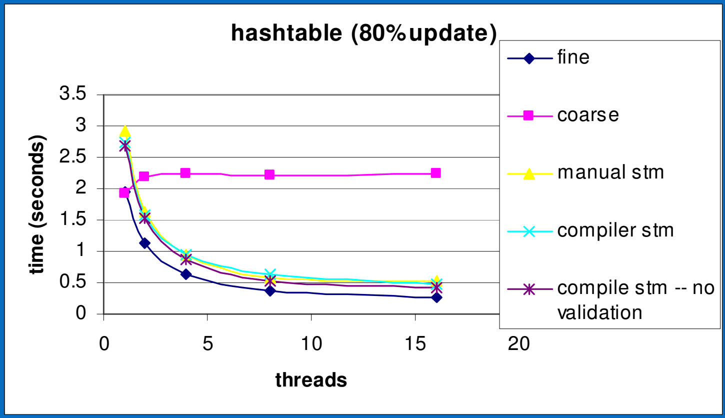
- We solve the key STM compiler problems for unmanaged languages
  - Aggressive consistency checking
  - Static function cloning
  - Selective stack rollback
  - Cache-line based conflict detection
- We developed a highly optimized STM compiler
  - Efficient register rollback
  - Barrier elimination
  - Barrier inlining
- We evaluated our STM compiler with well-known parallel benchmarks
  - The optimized STM compiler can achieve most of the hand-coded benefits
  - There are opportunities for future performance tuning and enhancement

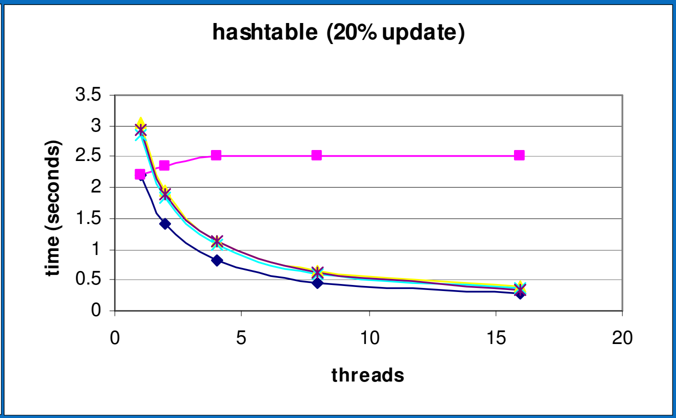
Questions ?

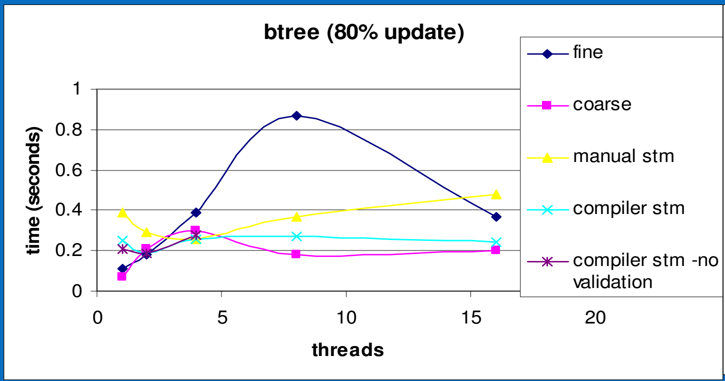
STM Runtime API

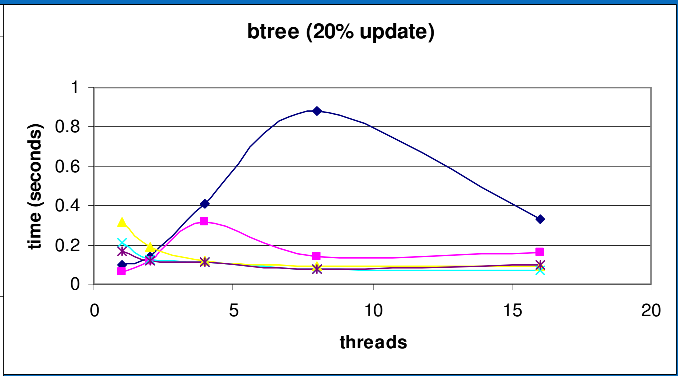
*TxnDesc**	*stmGetTxnDesc();*
uint32	*stmStart(TxnDesc*, TxnMemento*);*
uint32	*stmStartNested(TxnDesc*, TxnMemento*);*
void	*stmCommit(TxnDesc*);*
void	*stmCommitNested(TxnDesc*);*
void	*stmUserAbort(TxnDesc*);*
void	*stmAbort(TxnDesc*);*
uint32	*stmValidate(TxnDesc*);*
*uint32**	*stmComputeTxnRec(uint32* addr);*
uint32	*stmRead(TxnDesc*, uint32* txnRec);*
void	*stmCheckRead(TxnDesc*, uint32* txnRec, uint32 version);*
void	*stmWrite(TxnDesc*,uint32* txnRec);*
Void	*stmUndoLog(TxnDesc*, uint32* addr,*uint32 size);

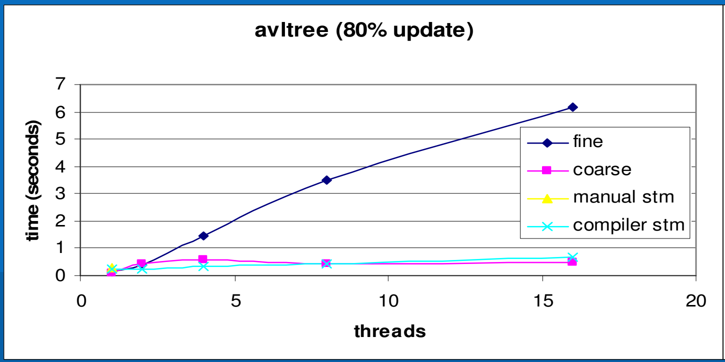
Data Structures

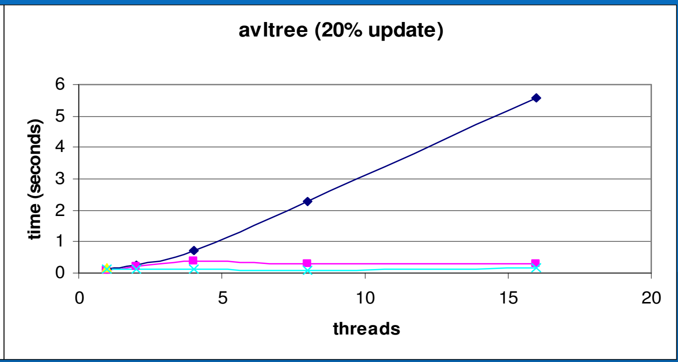












Example 1

- #pragma tm_atomic
- {
-     t = head;
-     Head = t->next;
- }

- … = *t;
-

- #pragma tm_atomic
- {
-     s = head;
-     *s = …;
- }

Example 2

- #pragma tm_atomic
- {
-     t = head;
-     head = t->next;
- }

- … = *t;

- #pragma tm_atomic
- {
-     s = head;
-     *s = …;
-     head = s->next;
- }

Example 3

- #pragma tm_atomic
- {
-     t = head;
-     head = t->next;
- }

- *t = …;

- #pragma tm_atomic
- {
-     s = head;
-     … = *s;
-     head = s->next;
- }

Optimization Issues (Register Checkpointing)

- Source Code

```
#pragma tm_atomic
{
   t1 = 0;
   t2 = t1 + t2;
   …
}
t1 = t3;
t3 = 1;
```

- Checkpointing Code

```
t2_bkup = t2;
while(setjmp(…)) {
  t2 = t2_bkup;
}
stmStart(…)
   t1 = 0;
   t2 = t1 + t2;
   …
stmCommit(…);
t1 = t3;
t3 = 1;
```

- Optimized Code

```
t2_backup = t2;
t1 = 0;
while(setjmp(…)) {
  t2 = t2_bkup;
}
stmStart(…);
  t2 = t1 + t2;
  t1 = t3;
  t3 = 1;
  …
stmCommit(…);
```

can not recover

Abort

- **Checkpointing all the live-in local data does not work with compiler optimizations across transaction boundary**

TimeStamp based Consistency Checking

Global Timestamp 0

Thread 1

```
#pragma tm_atomic
{
  if(tq->free) {

    for(temp1 = tq->free;
      temp1->next &&…,
      temp1 = temp1->next);

    task_struct[p_id].loc_free = tq->free;
    tq->free = temp1->next;
    temp1->next = NULL;

    …
  }
}
```

Version 0

Version 1

Local Timestamp 0

Thread 2

```
#pragma tm_atomic
{
  if(tq->free) {

    for(temp2 = tq->free;
      temp2->next &&…,
      temp2 = temp2->next);

    task_struct[p_id].loc_free = tq->free;
    tq->free = temp2->next;
    temp2->next = NULL;

    …
  }
}
```

Version 1

Local Timestamp 0

Checkpointing Approach

normal entry

```
t2_bkup = t2
t3_bkup = t3
```

retry entry

```
t2 = t2_bkup
t3 = t3_bkup
```

```
#pragma tm_atomic
{
  t1 = 0
  t2 = t1 + t2;
  …
}
t1 = t3;
t3 = 1;
```

Optimization

normal entry

```
t2_bkup = t2
t3_bkup = t3
t1 = 0
```

retry entry

```
t2 = t2_bkup
t3 = t3_bkup
t1 = 0
```

```
#pragma tm_atomic
{
  t2 = t1 + t2;
  t1 = t3;
  t3 = 1;
  …
}
```

Function Clone

- Source Code

```
#pragma tm_function
void foo(…) {
…
}
```

- STM Code

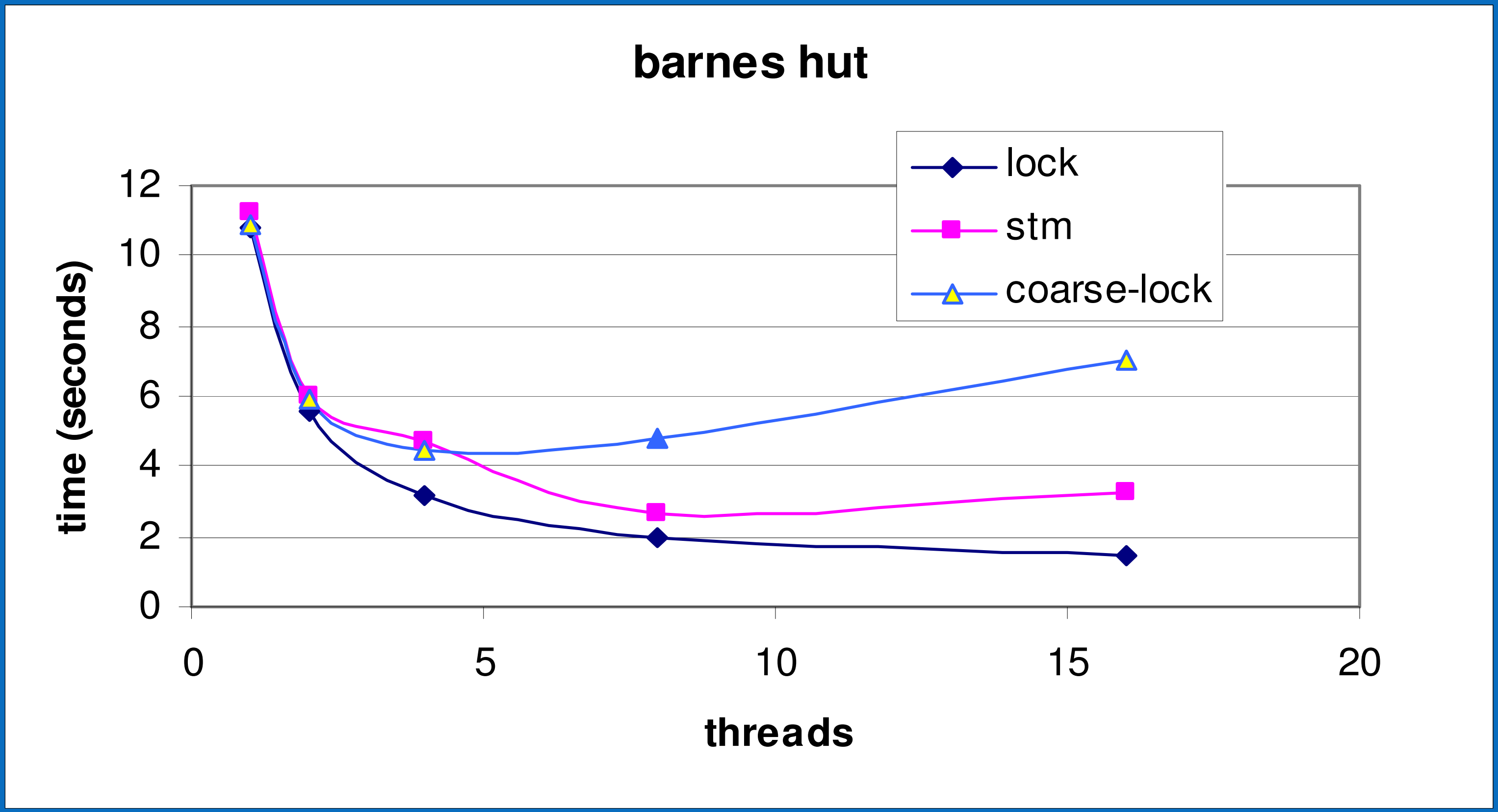
```
<foo-4>:
&foo_tm

<foo>: // normal version
no-op maker
… // normal code

<foo_tm>: // transactional version
… // code for transaction
```

Point to transactional version

Unique Marker

```
#pragma tm_atomic
{
   foo();
   (*fp)();
}
```

```
foo_tm();
 if(*fp == “no-op marker”)
       (**(fp-4))();  // call foo_tm
 else
       handle non-TM binary
```



- STM is much better than coarse-grain lock (fine lock ???)