Multicore Programming

From Threads to Transactional Memory

Yuan Lin	*Sun Microsystems*
Ali-Reza Adl-Tabatabai	*Intel*
Christos Kozyrakis	*Stanford University*
Bratin Saha	*Intel*

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Tutorial Motivation & Goals

- Motivation
  - All future processors will be multi-core chips
  - How do we write efficient code for >1 core

- Goals
  1. Introduction to multithreaded programming
     - The common practice in industry
     - Models, tools, and challenges
  2. Introduction to transactional memory
     - A research technology for easier parallel programming
     - Overview, use examples, and implementation

Presenters

- **Yuan Lin**, Sun Microsystems (Ph.D. UIUC)
  - Senior Staff Engineer, Scalable Systems Group
  - Compilers and tools for multithreaded applications

- **Ali-Reza Adl-Tabatabai**, Intel (Ph.D. CMU)
  - Principal Engineer, Programming Systems Lab
  - Compilers & runtimes for future Intel architectures

- **Christos Kozyrakis**, Stanford University (Ph.D. UC Berkeley)
  - Assistant Professor, Electrical Eng. & Computer Science
  - Architectures & programming models for transactional memory

- **Bratin Saha**, Intel (Ph.D. Yale)
  - Senior Staff Researcher, Programming Systems Lab
  - Design of highly scalable runtimes for multi-core processors

Agenda

- Multithreaded Programming

BREAK

- Transactional Memory (TM)
  - TM Introduction
  - TM Implementation Overview
  - Hardware TM Techniques
  - Software TM Techniques

Q&A

- Save your questions for the end of each topic
- Additional Q&A at the end of the tutorial

Extended bibliography attached at the end of the handout

Multithreaded Programming
Challenges, current practice, and languages/tools support

Yuan Lin
Systems Group
Sun Microsystems

Multi-core Architectures

- What?
  - A chip contains some number of "cores", each of which can run some number of strands (“hardware threads").
  - Different cores or chips may share caches at different levels. All caches are coherent.
  - All strands have access to the same shared memory.
- Why?
  - More and more difficult to get good ROI by improving single-core performance only.
    - Design complexity, power consumption, heat production, ...
  - Throughput is as important as speed.

Multi-core Architectures

- 2 strand/core, 1 core/chip
  - Intel Pentium 4 with Hyperthreading
- 1 strand/core, 2 cores/chip
  - Intel Dual Core Xeon, AMD Dual Core Opteron, Sun UltraSPARC IV
- 2 strand/core, 2 cores/chip
  - IBM Power 5
- 4 strand/core, 8 cores/chip
  - Sun UltraSPARC T1

Example: UltraSPARC T1

- Eight cores (individual execution pipelines) per chip.
- Four strands share a pipeline in each core.
- Different strands are scheduled on the pipeline in round-robin order.
- The slot of a stalled strand is given to the next strand.
- Four strands on a core share L1 cache, all strands share L2 cache.
- A single FPU is shared by all cores.
- OS sees the each strand as a processor. OS schedules LWPs on strands. HW schedules strands in the core.

Class of Applications

- Multi-process applications
  - e.g. Oracle database, SAP, PeopleSoft, ...
- Multi-threaded applications
  - e.g. Siebel CRM, Sybase engine, ...
- Single-threaded applications
  - Cannot be directly benefitted from multi-core architectures
  - Solution: make it multi-threaded or multi-process

Multithreaded Programming

- Are developers ready now?
  - Language developers
  - Compiler / tool developers
  - Library / runtime developers
  - OS / VM developers
  - Application developers
- What are the challenges?

Topics

- Multi-core Architectures
- Brief Overview of Pthreads, OpenMP and Java
- The Challenges

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- Brief Overview of Pthreads, OpenMP and Java
- The Challenges

Current Popular Parallel Programming Languages and APIs

- Shared Memory
  - Memory is “shared” unless declared “private”.
  - Accessing shared memory by direct read or write.
  - Examples: Pthreads, OpenMP, Java, C#
  - Closer to multi-core architectures than the rest two.
- Global Address Space
  - Memory is “private” unless declared “shared”.
  - Accessing shared memory by direct read or write.
  - Examples: UPC, Co-array Fortran
- Message Passing
  - No shared memory. Exchange data via messages.
  - Example: MPI

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POSIX Threads (Pthreads)

- IEEE POSIX 1003.1c-1995 standard:
  A standardized C language thread API
  - thread creation and termination
  - synchronization
  - scheduling
  - data management
  - process interaction
- Now incorporated into Single UNIX Specification, Version 3.
  - barriers, read/write locks, spin locks, etc.

Pthreads – a simple example

```
g = g + compute(1) + compute(2)
```

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```

```
main()
{
    pthread_t tid;
    void *status;
    int part;

    part = 1;
    pthread_create(&tid, NULL, work, (void *)part);

    part = 2;
    work((void *)part);

    pthread_join(tid, &status);
}
```

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```

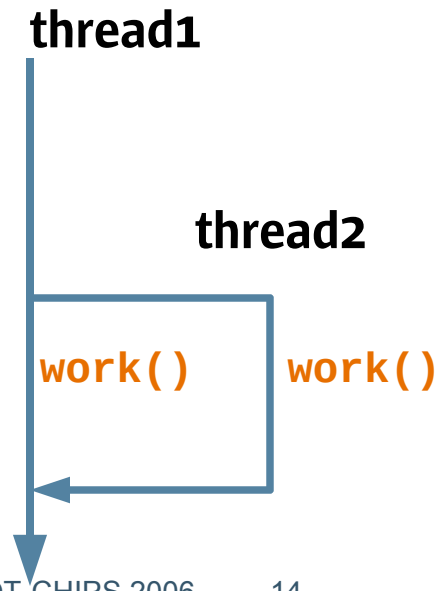

Pthreads – a simple example

```
g = g + compute(1) + compute(2)
```

```
void *work(void *arg)
{
    int result = compute((int)arg);
    pthread_mutex_lock(&lock);
    g += result;
    pthread_mutex_unlock(&lock);
    return NULL;
}

main()
{
    pthread_t tid;
    void *status;
    int part;

    part = 1;
    pthread_create(&tid, NULL, work, (void *)part);

    part = 2;
    work((void *)part);

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Pthreads – a simple example

- Understand Concurrency

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main()
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    pthread_t tid;
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    part = 1;
    pthread_create(&tid, NULL, work, (void *)part);

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}
```

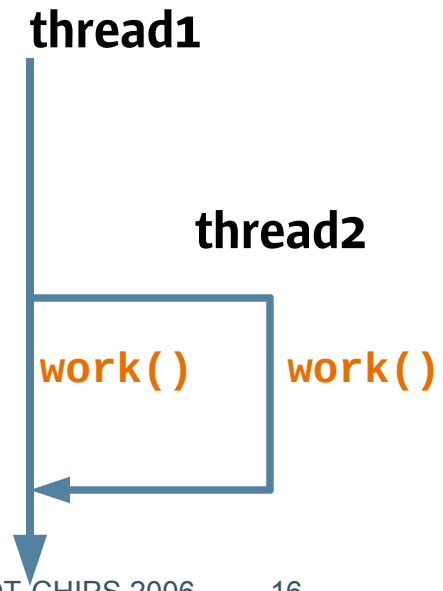

Pthreads – a simple example

- Understand Concurrency: what is the status of thread 2 when pthread_create() returns?
  - a) thread 2 has not started executing work().
  - b) thread 2 is executing work().
  - c) thread 2 has done work() and returned from work().

```
main()
{
    pthread_t tid;
    void *status;
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    part = 1;
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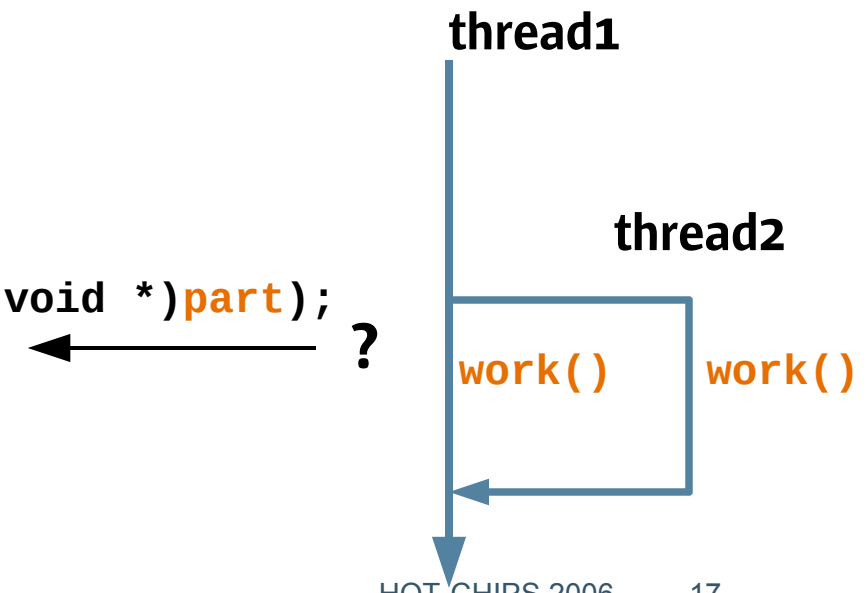

Pthreads – a simple example

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  - a) thread 2 has not started executing work().
  - b) thread 2 is executing work().
  - c) thread 2 has done work() and returned from work().

Could be any of the three!

```
main()
{
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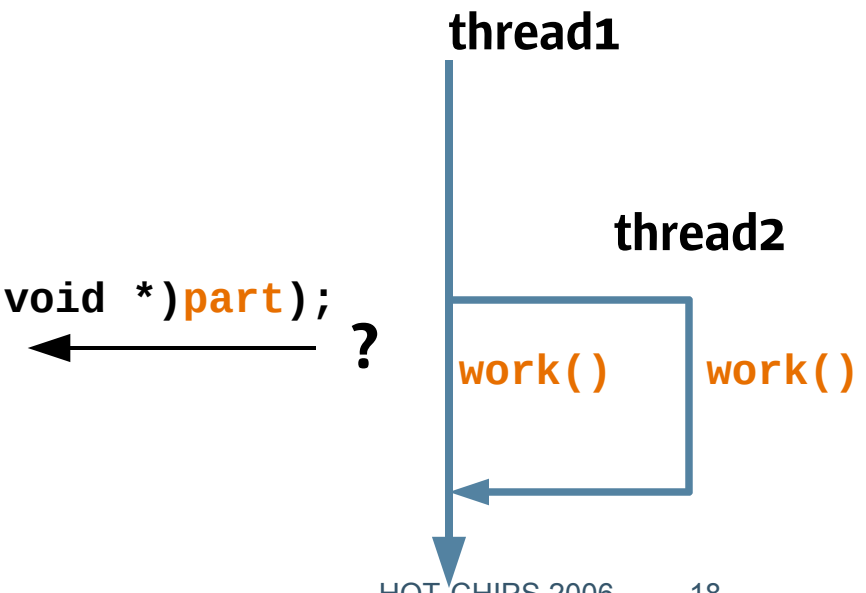


The Beauty of Pthreads

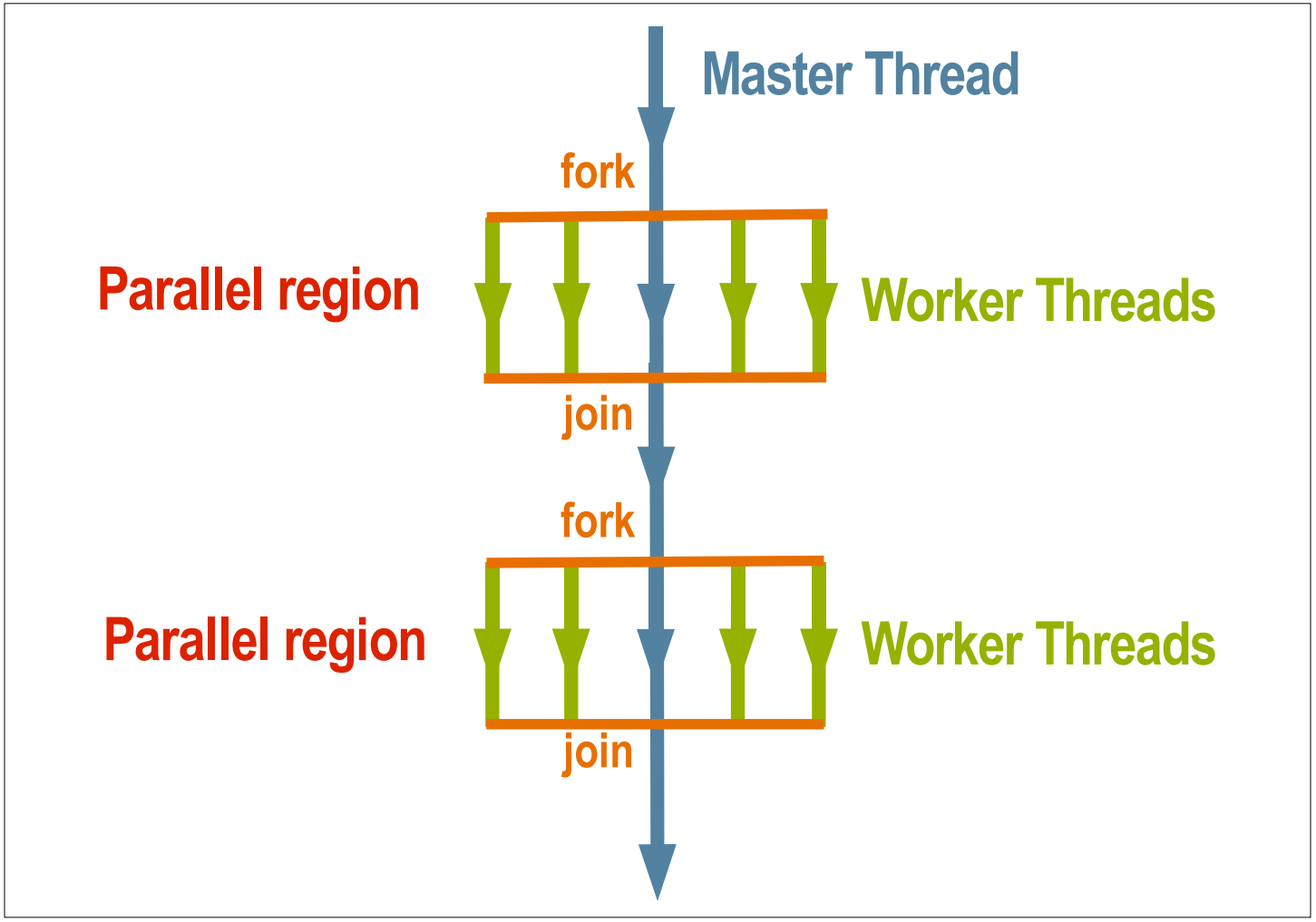
- Comprehensive Set of Functions and Specifications
  - Thread management
  - Synchronizations
  - Scheduling
  - Data management
  - Interaction with process, signals, ...

- Flexible
- Building block of higher level runtime

OpenMP

- An API specification for writing shared memory parallel programs in C, C++ and Fortran
- Consists of:
  - Compiler directives
  - Runtime routines
  - Environment variables
- Specification maintained by the OpenMP Architecture Review Board http://www.openmp.org
- Latest Specification: Version 2.5
- Language committee meetings for V3.0: since 9/2005

Thread Execution Model: fork and join



OpenMP – a simple example

```
g = g + compute(1) + compute(2)
```

```
for (int i=1; i<=2; i++) {
    int result;

    result = compute(i);
    g += result;
}
```

OpenMP – a simple example

```
g = g + compute(1) + compute(2)
```

```
#pragma omp parallel for reduction(+:g)
for (int i=1; i<=2; i++) {
    int result;

    result = compute(i);
    g += result;
}
```

The Beauty of OpenMP

- Possible to write a sequential program and its "functionally-equivalent" parallel version in the same code.

```
#pragma omp parallel for reduction(+:g)
for (int i=1; i<=2; i++) {
    int result;

    result = compute(i);
    g += result;
}
```

  - makes debugging easier
  - allows incremental parallelization

Java (J2SE)

- Basic threading support in the original spec
  - new Thread(), Object.wait, notify, notifyAll, synchronized
- Threading related updates for J2SE5
  - JSR-133: java memory model
  - JSR-166: java.util.concurrent package
    - Task scheduling framework
    - Concurrent collections
    - Atomic variables
    - Synchronizers (e.g. barriers, semaphores, latches, ...)
    - Locks
    - Timing

Java – a simple example

```
g = g + compute(1) + compute(2)
```

```
import java.util.concurrent.atomic.*;
public class A implement Runnable {
 private int g;
 private AtomicInteger id = new AtomicInteger(0);
 ...
 public void run() {
   int myid, myg;
   myid = id.incrementAndGet()
   myg = compute(myid);
   synchronized(this) {
     g += myg;
   }
 }
```

```
  public void go() {
     Thread t[];
     t = new Thread[2];
     id = 1;
     for (i=0; i<2; i++) {
       t[i] = new Thread(this);
       t[i].start();
     }
     for (i=0; i<2; i++) {
       try {
         t[i].join();
       }
       catch(InterruptedException iex){}
     }
   }
}
```

Java – a simple example

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    int myid, myg;
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    synchronized(this) {
      g += myg;
    }
  }
```

thread creation start, and join

```
  public void go() {
    Thread t[];
    t = new Thread[2];
    id = 1;
    for (i=0; i<2; i++) {
      t[i] = new Thread(this);
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    for (i=0; i<2; i++) {
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    }
  }
}
```

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   }
 }
```

atomic variables

```
  public void go() {
    Thread t[];
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    id = 1;
    for (i=0; i<2; i++) {
      t[i] = new Thread(this);
      t[i].start();
    }
    for (i=0; i<2; i++) {
      try {
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      }
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    }
  }
}
```

Java – a simple example

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 }
```

synchronized block

```
  public void go() {
     Thread t[];
     t = new Thread[2];
     id = 1;
     for (i=0; i<2; i++) {
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       t[i].start();
     }
     for (i=0; i<2; i++) {
       try {
         t[i].join();
       }
       catch(InterruptedException iex){}
     }
   }
}
```

The Beauty of Java

- A well studied and specified memory model.
- A set of easy to use, reliable, and performant concurrency utilities with many commonly used data structures.

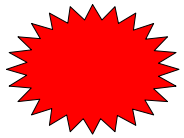
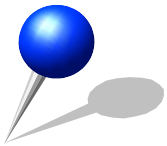
Topics

- Multi-core Architectures
- Brief Overview of Pthreads, OpenMP and Java
- The Challenges

Challenges in Multithreaded Programming

1. Finding and creating concurrent tasks
2. Mapping tasks to threads
3. Defining and implementing synchronization protocols
4. Dealing with race conditions
5. Dealing with deadlocks
6. Dealing with memory model
7. Composing parallel tasks
8. Achieving scalability
9. Achieving portable & predictable performance
10. Recovering from errors
11. Dealing with all single thread issues

For Each Challenge

- What is it? 
- How do programmers deal with it now?
- Any help from Pthreads, OpenMP or Java? **P/O/J**
- Any tools that can help now? 

Find and Create Concurrent Tasks

- Concurrency at Data Level
  - e.g. 6 crying babies waiting for diaper-change
- Concurrency at Function Level
  - e.g. changing diaper for a baby, complaining to the spouse, while playing sudoku in mind
- Granularity

Automatic Parallelization

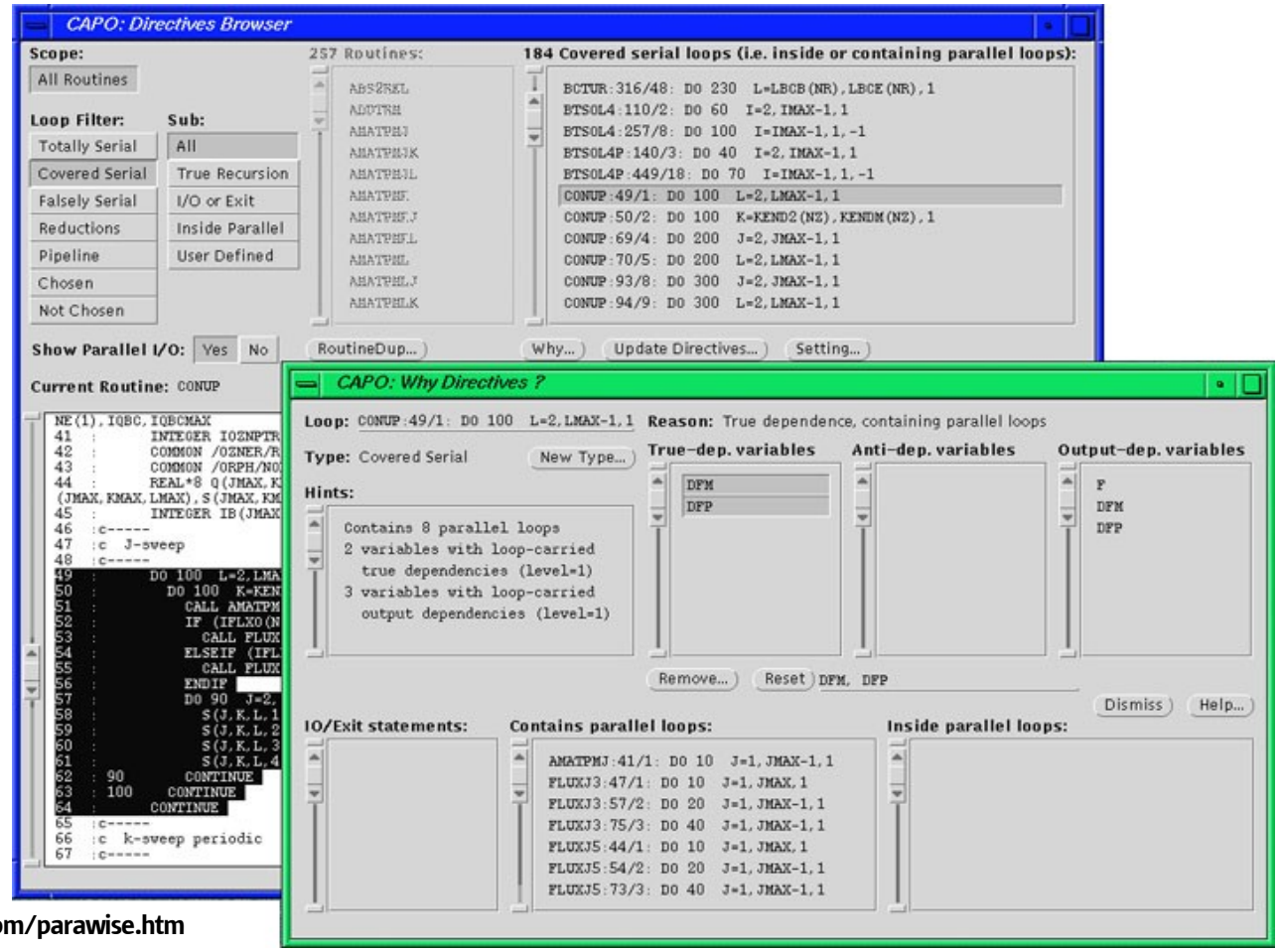
- Available in many compilers
  - SGI, Sun, Intel, IBM, ...

```
> f90 -xautopar old-serial.f
```

- Long history
- Mostly loop based parallelization
- Limited adoption

Parallelization Assistance Tool

- ParaWise from Parallel Software Products, Inc.
  - > a semi-automatic parallelization tool for Fortran programs
  - > Long history
  - > Limited adoption



Screenshots from http://www.parallelsp.com/parawise.htm

Parallelization Assistance Tool

- A valuable tool may not need to be fancy.
- Dieter an Mey (RWTH, Aachen University) :
  - > “I consider the following a very valuable assistance tool: a tool that can find all the places in the source code where global variables are declared and all the places where the global variables are referenced, and show these places with a different color.”
  - > “I got the functionality from the Foresys tool from Simulog for Fortran and I found it quite useful. It would be nice to have such features in an IDE. ”

Find and Create Concurrent Tasks

P/O/J

- Pthread
  - No direct support.
- Java
  - No direct support.
  - The use of Executor/Thread Pools makes the concept of task explicit. (See details later.)

Find and Create Concurrent Tasks

P/O/J

- OpenMP
  - Use *worksharing* loops for basic data level parallelism

```
#pragma omp for
for (i=1; i<n; i++)
   work(data[i]);
```

  - Use *worksharing* sections for basic function level parallelism

```
#pragma omp sections
{
  #pragma omp section
  func1();
  #pragma omp section
  func2();
}
```

Tasks and Threads Mapping

- Threads vs Tasks
  - Thread: parallel execution engines provided by the OS
  - Tasks: concurrency unit in program logic
- A program can have tens of thousands of concurrent tasks.
  - e.g. players in a game server, components in a simulation system, requests in a web server
- The system can only supply hundreds of threads.
  - e.g. because of resource limitation
- There is overhead associated with creating and destroying threads.

Tasks and Threads Mapping

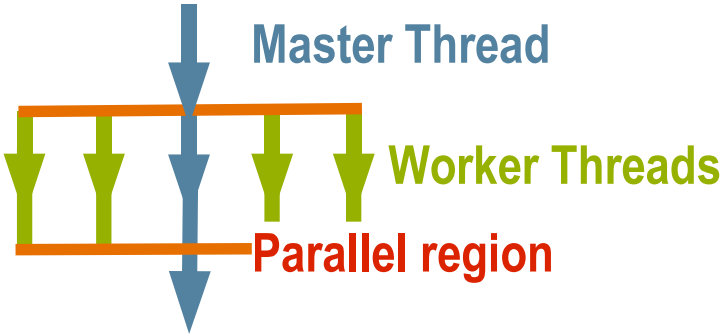
- Use well-designed data structures to hold task state.
- Deploy a task-to-thread model to deliver scalable and predictable performance.
  - master/slave
    - Master thread dispatches slave threads from a thread-pool to work on tasks. The threads in the pool are pre-allocated.
  - pipeline
    - Each thread performs a specific operation on a data item, and passes the data to the next thread in the pipeline.
  - task pool
    - Each thread execute a task from a pool and put new task generated to the pool.
  - ...

Tasks and Threads Mapping

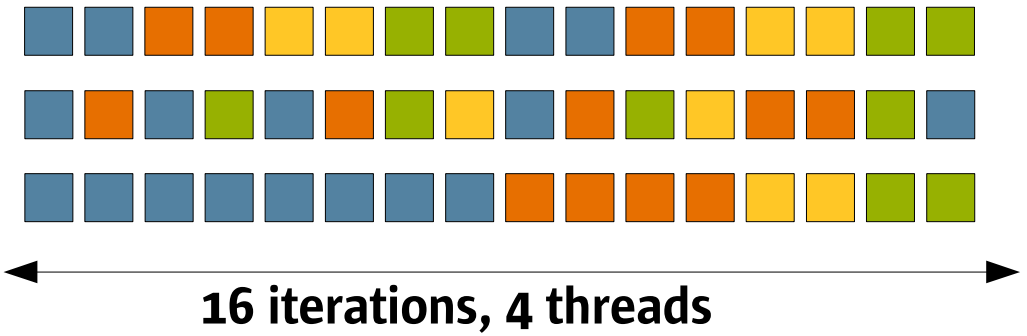
P/O/J

- Pthreads : No direct support

- OpenMP :
  - Basic master/slave model



  - Three loop scheduling methods
    - Static
    - Dynamic
    - Guided



Tasks and Threads Mapping

P/O/J

- Java
  - Thread pool utilities in J2SE5 provide pre-built thread mechanism to run tasks to a bounded number of threads.
  - To use thread pool,
    - instantiate an implementation of the ExecutorService interface and hand it a set of tasks, or
    - use configurable implementations: ThreadPoolExecutor and ScheduledThreadPoolExecutor
  - Use Callable and Future interfaces to get result from tasks.

```
class NetworkService {
   private final ServerSocket serverSocket;
   private final ExecutorService pool;

   public NetworkService(int port, int poolSize) throws IOException {
     serverSocket = new ServerSocket(port);
     pool = Executors.newFixedThreadPool(poolSize);
   }
   public void serve() {
     try {
       for (;;) {
         pool.execute(new Handler(serverSocket.accept()));
       }
     } catch (IOException ex) {
       pool.shutdown();
     }
   }
}
class Handler implements Runnable {
   private final Socket socket;
   Handler(Socket socket) { this.socket = socket; }
   public void run() {
     // read and service request
   }
}
```

http://java.sun.com/j2se/1.5.0/docs/api/java/util/concurrent/ExecutorService.html

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Thread pool

Task class

http://java.sun.com/j2se/1.5.0/docs/api/java/util/concurrent/ExecutorService.html

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```

Create thread pool

http://java.sun.com/j2se/1.5.0/docs/api/java/util/concurrent/ExecutorService.html

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   }
}
class Handler implements Runnable {
   private final Socket socket;
   Handler(Socket socket) { this.socket = socket; }
   public void run() {
     // read and service request
   }
}
```

Generate new tasks

http://java.sun.com/j2se/1.5.0/docs/api/java/util/concurrent/ExecutorService.html

```
class NetworkService {
   private final ServerSocket serverSocket;
   private final ExecutorService pool;

   public NetworkService(int port, int poolSize) throws IOException {
     serverSocket = new ServerSocket(port);
     pool = Executors.newFixedThreadPool(poolSize);
   }
   public void serve() {
     try {
       for (;;) {
         pool.execute(new Handler(serverSocket.accept()));
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     }
   }
}
class Handler implements Runnable {
   private final Socket socket;
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   public void run() {
     // read and service request
   }
}
```

Assign task to thread pool

http://java.sun.com/j2se/1.5.0/docs/api/java/util/concurrent/ExecutorService.html

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}
class Handler implements Runnable {
   private final Socket socket;
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   public void run() {
     // read and service request
   }
}
```

Shutdown thread pool

http://java.sun.com/j2se/1.5.0/docs/api/java/util/concurrent/ExecutorService.html

Defining and Implementing Synchronizations

- Understand the application logic and design the high-level synchronization scheme
  - e.g. traffic light
- Use the right synchronization primitives at the right place.
  - e.g. need to coordinate threads so they are executed in phases
    - use condition variables?
    - use barriers?
    - join threads and create new threads?

Defining and Implementing Synchronizations

P/O/J

- Pthreads:
  - Mutex locks, condition variables, semaphores, barriers, reader-writer locks
- OpenMP:
  - Locks, barriers, critical sections, ordered regions
- Java
  - Synchronized method/block, wait/notify
  - Condition variables, semaphores, barriers, countdown latch, exchanger, reader-writer locks

Race Conditions

- Race conditions occur when different threads access shared data without explicit synchronization.
- Race conditions can cause programs to behave in ways unexpected by the programmer.
- Bugs caused by race conditions are notoriously difficult to debug.

Race Conditions – An Example

Assume a = b = 0;

Thread 1:

```
a = a + 5;

lock (a_lock);
   b = b + 10;
unlock (a_lock);

barrier();
```

Thread 2:

```
lock (a_lock);
   b = b - 10;
unlock (a_lock);

a = a – 5;

barrier();
```

What's the value of 'a' and 'b' after the barrier?

Race Conditions – An Example

Thread 1:

```
a = a + 5;

lock (a_lock);
   b = b + 10;
unlock (a_lock);

barrier();
```

Assume a = b = 0;

Thread 2:

```
lock (a_lock);
   b = b - 10;
unlock (a_lock);

a = a – 5;

barrier();
```

We have a = 0 and b = 0.

Race Conditions – An Example

Assume a = b = 0;

Thread 1:

```
a = a + 5;

lock (a_lock);
   b = b + 10;
unlock (a_lock);

barrier();
```

Thread 2:

```
lock (a_lock);
   b = b - 10;
unlock (a_lock);

a = a – 5;

barrier();
```

'b' is 0.
'a' may be 0, 5, or -5.

Two Kinds of Race Conditions (1/2)

- Data Race
  - Concurrent accesses (at least one is a write) to shared memory are not protected by critical sections. Atomicity of the accesses is lost.

Thread 1

```
lock();
acnt1 = acnt1 + delta_x;
acnt2 = acnt2 – delta_x;
unlock();
```

Thread 2

```
lock();
acnt1 = acnt1 + delta_y;
acnt2 = acnt2 – delta_y;
unlock();
```

Two Kinds of Race Conditions (2/2)

- General Race
  - The order of accesses to shared memory is not enforced by synchronization.

Thread 1

```
put_job_in_queue(job)
post();
```

Thread 2

```
wait();
job = get_job_from_queue();
```

Data Race vs General Race

- A data race is also a general race.
- A data race can be fixed by using critical sections or adding synchronizations.
- A general race can be fixed by adding synchronizations to enforce ordering.
- Watch out for general races when the shared-memory accesses should occur in specific order.
- Watch out for data races in asynchronous programs.
- Tools are available to detect data races.

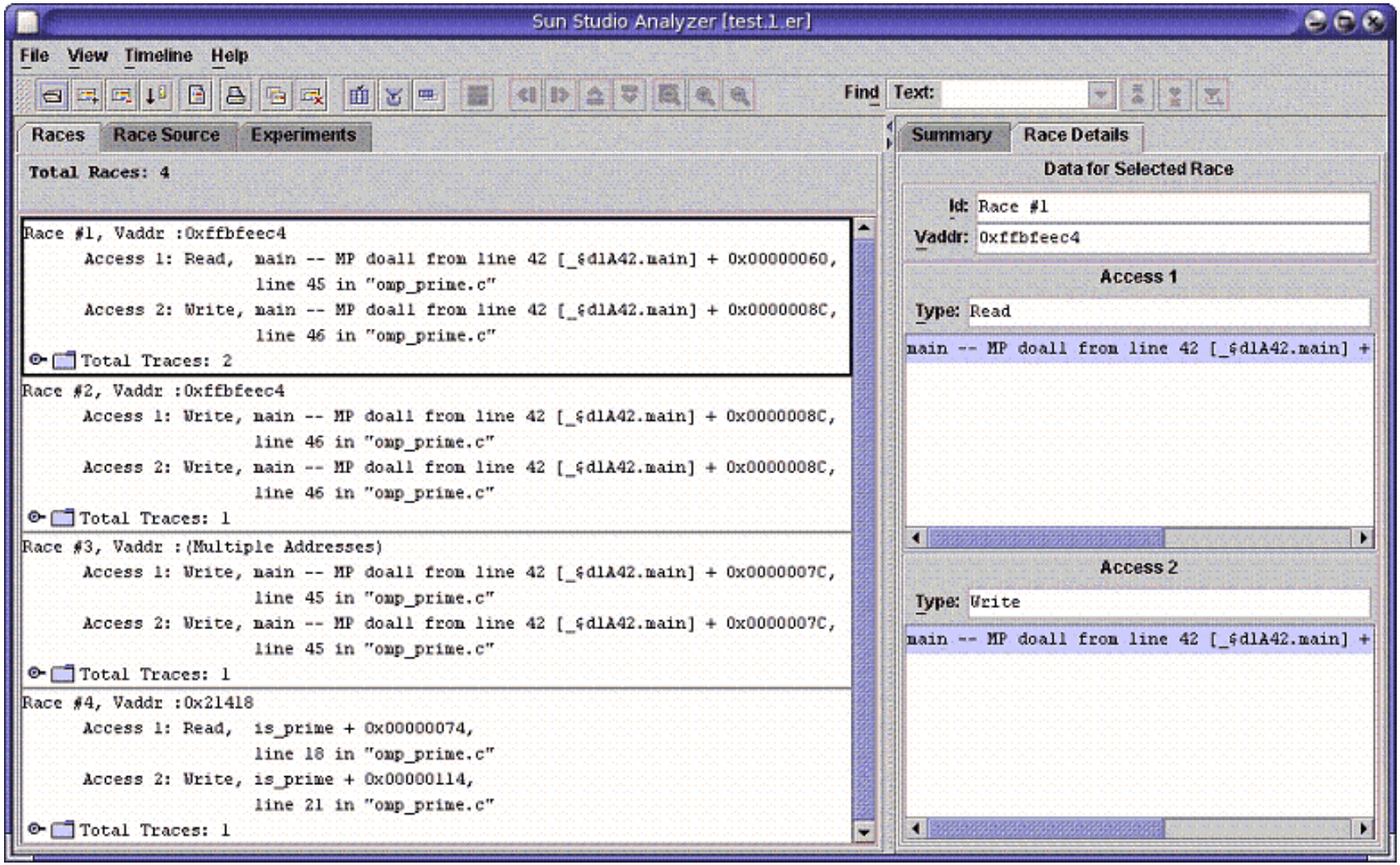
Data Race Detection Tools

- Static Detection
  - > + Can be fast and consume little memory.
  - > + Does not affect the behavior of program.
  - > + Is not affected by input data and scheduling
  - > + Can be used to check OS kernels and device drivers
  - > - False positives
- Example: LockLint from Sun Studio
  - > Reports data races and deadlocks due to inconsistent use of locking techniques.
  - > Originates from *WARLOCK*, which was designed to detect such errors in Solaris kernels and device drivers.

Data Race Detection Tools

- Runtime Detection
- Examples:
  - Helgrind from Valgrind
  - HP Visual Threads
  - Intel Thread Checker
  - Sun Data Race Detection Tool

Data Race Detection Tools



What to Do After a Data-race is Found?

- 1) Check whether it is a false positive.
  - A false positive is a reported data race that actually does not exist in the program.
  - No tool is perfect.
  - For example, the tool may not understand the synchronizations in your program.

What to Do After a Data-race is Found?

- 1) Check whether it is a false positive.
  - A false positive is a reported data race that actually does not exist in the program.
  - No tool is perfect.
  - For example, the tool may not understand the synchronizations in your program.
- 2) Check whether it is a benign race.
  - The programmer may put data race there in order to get better performance.
    - Yes? Are you sure? Check again!
  - Programs with intentional data races are very difficult to get right.
    - Are you relying on sequential consistency?

What to Do After a Data-race is Found?

- 3) Fix the bug, not the data race!

What to Do After a Data-race is Found?

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  - A data race could be a bug or caused by a bug.

What to Do After a Data-race is Found?

- 3) Fix the bug, not the data race!
  - A data race could be a bug or caused by a bug.

```
int pthread_create(pthread_t *thread,
                   const pthread_attr_t *attr,
                   void *(*start_routine)(void*),
                   void *arg);
```

What to Do After a Data-race is Found?

- 3) Fix the bug, not the data race!
  - A data race could be a bug or caused by a bug.

```
int pthread_create(pthread_t *thread,
                   const pthread_attr_t *attr,
                   void *(*start_routine)(void*),
                   void *arg);
```

```
void *work(void *arg)
{
     int myid = *(int *)arg;
     data[myid] = update(data[myid]);
     return NULL;
}

for (i=0; i<THREADS; i++)
     pthread_create(tids[i], NULL, work, &i);
```

What to Do After a Data-race is Found?

- 3) Fix the bug, not the data race!
  - A data race could be a bug or caused by a bug.

```
int pthread_create(pthread_t *thread,
                   const pthread_attr_t *attr,
                   void *(*start_routine)(void*),
                   void *arg);
```

```
void *work(void *arg)
{
     int myid = *(int *)arg;
     data[myid] = update(data[myid]);
     return NULL;
}

for (i=0; i<THREADS; i++)
     pthread_create(tids[i], NULL, work, &i);
```

Data race reported

Bug!

What to Do After a Data-race is Found?

- 3) Fix the bug, not the data race!
  - A data race could be a bug or caused by a bug.
  - Most tools detect *certain* kind of data races only!

thread 1

```
acnt1 += x;

acnt2 -= x;
```

thread 2

```
acnt1 += y;

acnt2 -= y;
```

thread 3

```
print acnt1, acnt2
```

Data Race! Accounts are not balanced!
"account1 + account2" is not constant.

What to Do After a Data-race is Found?

- 3) Fix the bug, not the data race!
  - A data race could be a bug or caused by a bug.
  - Most tools detect *certain* kind of data races only!

thread 1

```
lock();
acnt1 += x;
unlock();
lock();
acnt2 -= x;
unlock();
```

thread 2

```
lock();
acnt1 += y;
unlock();
lock();
acnt2 -= y;
unlock();
```

thread 3

```
lock();
print acnt1, acnt2
unlock();
```

A wrong fix. No data race is reported.
But accounts are not balanced at certain stages!
"account1 + account2" is not constant.

What to Do After a Data-race is Found?

- 3) Fix the bug, not the data race!
  - A data race could be a bug or caused by a bug.
  - Most tools detect *certain* kind of data races only!

thread 1

```
lock();
acnt1 += x;


acnt2 -= x;
unlock();
```

thread 2

```
lock();
acnt1 += y;


acnt2 -= y;
unlock();
```

thread 3

```
lock();
print acnt1, acnt2
unlock();
```

A correct fix.

What to Do After a Data-race is Found?

- 3) Fix the bug, not the data race!
  - A data race could be a bug or caused by a bug.
  - Most tools detect *certain* kind of data races only!

- 4) Run the detection tool again after code change!
  - A tool may not be able to detect all data races by design.
  - The code change may introduce or reveal another data race.

Making Global Variables Private

- Pthreads: thread specific data
  - `pthread_key_create(), pthread_key_delete()`
  - `pthread_setspecific(), pthread_getspecific()`
- OpenMP: “threadprivate” directive

```
int total_for_this_thread;
#pragma omp threadprivate (total_for_this_thread)
```

- Java: java.lang.ThreadLocal class
  - private static ThreadLocal<int> totoal_for_this_thread;
- Thread Local Storage
  - Provided by compiler and runtime linker

```
__thread int total_for_this_thread;
```

Use MT-Safe Routines

- 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.
  - Example: malloc in libmtmalloc(3LIB).

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()

Deadlocks

- Two or more competing actions are waiting for the other to finish. None can finish.
- A common misunderstanding: a deadlock must involve mutex locks.
  - Deadlocks may be caused by mis-use of synchronizations or communications, such as barriers.
- Livelock
  - Two or more competing actions continually change their state in response to changes in the other actions. None will finish.

Necessary Conditions for a Deadlock

1. Mutual exclusion: a resource is exclusively owned by the process to which it is assigned.
2. Hold and wait: processes request new resources while holding some resources.
3. No preemption: only the process holding a resource can release it.
4. Circular wait: there is a circular chain of processes in which each process waits for a resource that the next process in the chain holds.

Deadlock: Prevention and Avoidance

- Prevention
  - Use protocols to ensure at least one of the four conditions does not hold.
  - Example: enforce lock hierarchy to ensure circular-wait never happens.
- Avoidance
  - Use global resource information to decide whether the current request can be satisfied or delayed.
  - Example: Banker's algorithm

Deadlock: Prevention and Avoidance

- It may be easy to apply the text book rules to deadlocks that involve obvious resources.
- In many applications, the four conditions are subtle, especially when the deadlock is caused by communication.
- Always examine the program logic!

Deadlocks: Example 1

thread 1:

```
Lock(a);
Lock(b);
```

thread 2:

```
Lock(b);
Lock(c);
```

thread 3:

```
Lock(c);
Lock(a);
```

The program may or may not deadlock in a particular run.

Deadlocks: Example 2

thread tid1:

```
pthread_join(tid2, NULL);
```

thread tid2:

```
pthread_join(tid1, NULL);
```

Deadlocks: Example 3

```
#pragma omp parallel num_threads(4)
{
    if (omp_thread_num()<3) {
        #pragma omp barrier
    }
    else {
        #pragma omp barrier
    }
}
```

Illegal OpenMP program!

Deadlocks: Example 4

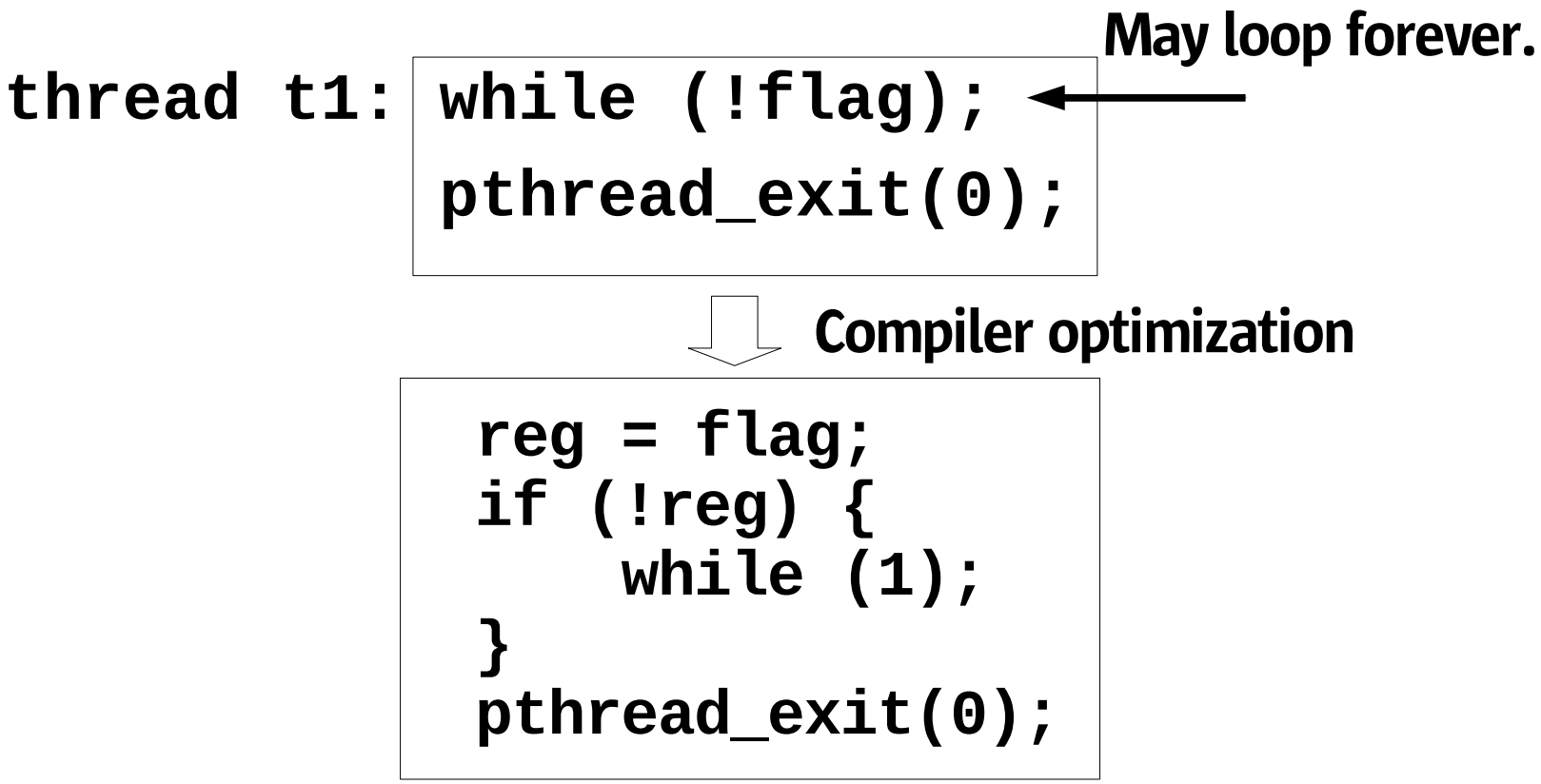
```
int flag = 0;

thread t1: while (!flag);
           pthread_exit(0);

thread t2: flag = 1;
           pthread_join(t1, NULL);
```

May loop forever.

Deadlocks: Example 4



Deadlocks

P/O/J

- Pthreads
  - Some error checking on locks, but not deadlocks.
    - If the mutex type is PTHREAD_MUTEX_ERRORCHECK and a thread attempts to relock a mutex that it has already locked, an error will be returned.
    - If the mutex type is PTHREAD_MUTEX_ERRORCHECK and a thread attempts to unlock a mutex that it has not locked or a mutex which is unlocked, an error will be returned.
- OpenMP
  - Makes one kind of deadlock illegal.
    - Barriers in a parallel region must be encountered by all threads in the team in the same order.

Deadlocks

P/O/J

- Java
  - Structured synchronized method/block makes the critical regions clearer than unstructured locks.
  - Locks associated with *synchronized* keyword are always released when the thread leaves (due to exception or not) the synchronized scope.
    - This automatic-releasing could be a bad thing for error recovery since it may leave the data in an inconsistent state that is not protected by locks.

Deadlock Detection Tools

- Static Checking
  - LockLint from Sun
- Runtime Checking
  - Thread Checker from Intel
  - OpenMP Runtime Error Detection from Sun

```
> setenv SUNW_MP_WARN TRUE
> a.out
WARNING (libmtsk): Threads at barrier from different directives.
   Thread at barrier from init.c:12.
   Thread at barrier from forbidden.c:17.
   Possible Reasons:
   Worksharing constructs not encountered by all threads in the
   team in the same order.
   Incorrect placement of barrier directives.
```

Memory Consistency Model

- The order in which memory operations will appear to be executed to a programmer.

- What affects the memory consistency?
  - Language
  - Compiler
  - Hardware

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

- Multi-threaded Versions

```
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;
}
```

Example: Lazy Initialization

- Multi-threaded Versions

```
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;
}
```

Example: Lazy Initialization

- Multi-threaded Versions

```
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

"Double-checked Locking"

```
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 *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.

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

Double-checked Locking

```
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. Alpha.

Memory Consistency Model

P/O/J

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

Memory Consistency Model

P/O/J

- 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

P/O/J

- 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

Memory Consistency Model

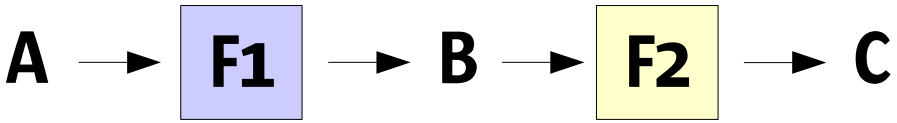
- Avoid writing codes that have deliberate data races. It is tricky and difficult to understand and debug.

Composing Parallel Tasks

- Modular design is common in software development.
- How to compose modules that are multi-threaded?
- Three models of composition
  - Sequential composition
  - Parallel composition
  - Nested composition

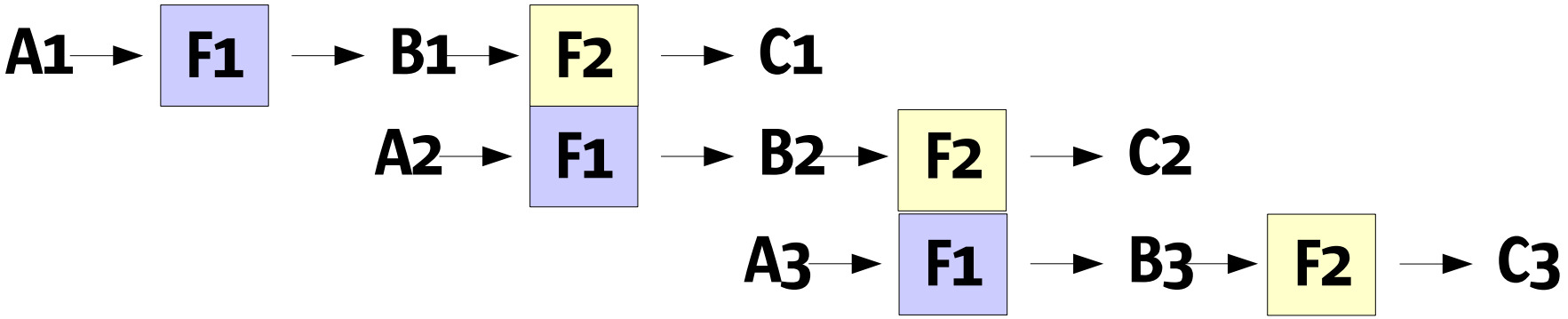
Composition: sequential vs parallel

- Sequential composition:



  - n threads for F1 and n threads for F2

- Parallel composition:



  - n1 threads for F1 and n2 threads for F2, n1+n2=n

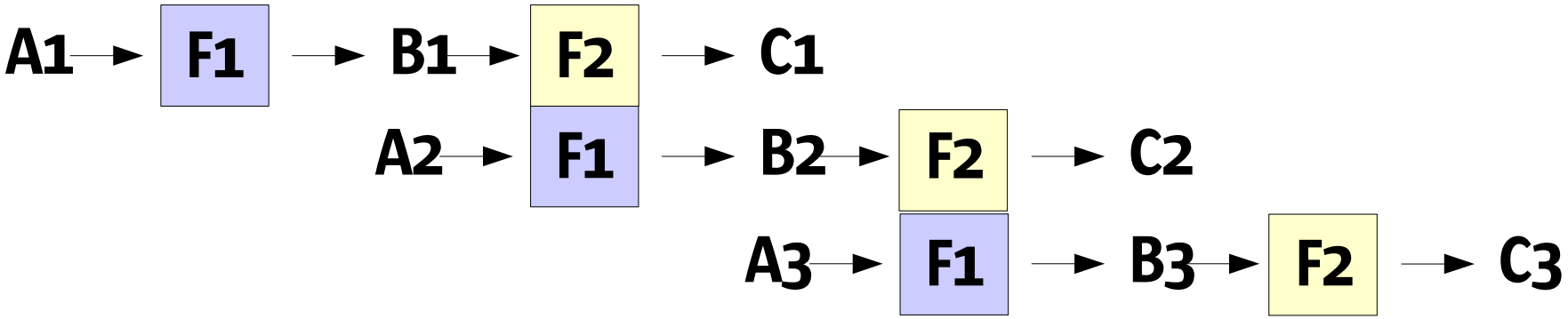
Composition: sequential vs parallel

- Sequential compositi

  - > n threads for F1 and

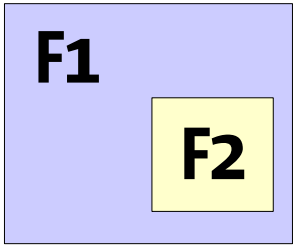
+ may improve resource utilization
  by overlapping F1 and F2
- may introduce extra communication,
  data migration, or thread migration

- Parallel composition:



  - > n1 threads for F1 and n2 threads for F2, n1+n2=n

Nested Composition



n1 thread for F1 and n2 threads for F2, n1*n2 = n

- Straight-forward approach: outer-module and inner module create their own threads.
  - Threads explosion.
- More complicated approach: outer-module and inner module get threads from the same thread pool.
  - Need a common threading frame work.
  - Implies API interface change or external global state
- Locks are not composable in general!
  - Dead locks

Composing Parallel Tasks

P/O/J

- Pthreads and Java: No direct support
- OpenMP:
  - Support nested composition of parallel tasks through nested parallel regions.

```
#omp parallel for
for (i=0; i<n; i++) {
      #omp parallel for
      for (j=0; j<m; j++) {
            ...
      }
}
```

  - Inflexible and possible low utilization of threads

Scalability

- Performance does not scale with the number of threads used.
- Common reason 1: system oversubscribed
  - e.g. 16 hardware threads, 32 software threads
- Common reason 2: not enough concurrency
  - Amdahl's law
- Common reason 3: lock contention
  - Frequent locking, unlocking activities
  - Long lock holding time

plockstat(1M)

- A utility in Solaris 10 that gathers and displays user-level locking statistics.
- Uses plockstat DTrace provider.
- Three types of lock events can be traced.
  - Contention events - probes for user level lock contention
  - Hold events - probes for lock acquiring, releasing etc.
  - Error events - error conditions.

plockstat(1M) - example

```
>plockstat ./a.out

Mutex block

Count     nsec Lock                         Caller
-------------------------------------------------------------------------------
  863  3822626 libc.so.1`libc_malloc_lock   a.out`_$p1A12.main+0x5c
  900  3423154 libc.so.1`libc_malloc_lock   a.out`_$p1A12.main+0x20
  340  2969890 a.out`mutex                  a.out`_$p1A12.main+0x30
15835  2894962 a.out`mutex                  a.out`_$p1A12.main+0x30
  415  2456968 libc.so.1`libc_malloc_lock   a.out`_$p1A12.main+0x20
  296  2208085 a.out`mutex                  a.out`_$p1A12.main+0x30
  441  2129956 libc.so.1`libc_malloc_lock   a.out`_$p1A12.main+0x5c
14032  2054952 a.out`mutex                  a.out`_$p1A12.main+0x30
    4    42900 libc.so.1`_uberdata          libc.so.1`_thr_exit_common+0xbc
    1    14800 libc.so.1`_uberdata          libmtsk.so.1`threads_fini+0x174
```

plockstat(1M) - example

```
>plockstat ./a.out

Mutex block

Count     nsec Lock                         Caller
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  863  3822626 libc.so.1`libc_malloc_lock   a.out`_$p1A12.main+0x5c
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    4    42900 libc.so.1`_uberdata          libc.so.1`_thr_exit_common+0xbc
    1    14800 libc.so.1`_uberdata          libmtsk.so.1`threads_fini+0x174
```

libc_malloc_lock

a.out`mutex

plockstat(1M) - example

(plockstat output cont.)

```
Mutex spin

Count     nsec Lock                         Caller
-------------------------------------------------------------------------------
 4225    13553 libc.so.1`libc_malloc_lock   a.out`_$p1A12.main+0x20
72525    13518 a.out`mutex                  a.out`_$p1A12.main+0x30
 1711    13399 a.out`mutex                  a.out`_$p1A12.main+0x30
    7    11600 libc.so.1`_uberdata          libc.so.1`_thr_exit_common+0xbc
 8111    10778 libc.so.1`libc_malloc_lock   a.out`_$p1A12.main+0x5c

Mutex unsuccessful spin

Count     nsec Lock                         Caller
-------------------------------------------------------------------------------
 1315    31766 libc.so.1`libc_malloc_lock   a.out`_$p1A12.main+0x20
  636    31008 a.out`mutex                  a.out`_$p1A12.main+0x30
29867    30875 a.out`mutex                  a.out`_$p1A12.main+0x30
   31    30590 libc.so.1`_uberdata          libc.so.1`_thr_exit_common+0xbc
 1304    29273 libc.so.1`libc_malloc_lock   a.out`_$p1A12.main+0x5c
    7    26320 libc.so.1`_uberdata          libmtsk.so.1`threads_fini+0x174
   19    24328 libc.so.1`_uberdata          libc.so.1`_thr_exit_common+0xbc
```

plockstat(1M) - example

(plockstat output cont.)

```
Mutex spin

Count     nsec Lock                         Caller
-------------------------------------------------------------------------------
 4225    13553 libc.so.1`libc_malloc_lock   a.out`_$p1A12.main+0x20
72525    13518 a.out`mutex                  a.out`_$p1A12.main+0x30
 1711    13399 a.out`mutex                  a.out`_$p1A12.main+0x30
    7    11600 libc.so.1`_uberdata          libc.so.1`_thr_exit_common+0xbc
 8111    10778 libc.so.1`libc_malloc_lock   a.out`_$p1A12.main+0x5c

Mutex unsuccessful spin

Count     nsec Lock                         Caller
-------------------------------------------------------------------------------
 1315    31766 libc.so.1`libc_malloc_lock   a.out`_$p1A12.main+0x20
  636    31008 a.out`mutex                  a.out`_$p1A12.main+0x30
29867    30875 a.out`mutex                  a.out`_$p1A12.main+0x30
   31    30590 libc.so.1`_uberdata          libc.so.1`_thr_exit_common+0xbc
 1304    29273 libc.so.1`libc_malloc_lock   a.out`_$p1A12.main+0x5c
    7    26320 libc.so.1`_uberdata          libmtsk.so.1`threads_fini+0x174
   19    24328 libc.so.1`_uberdata          libc.so.1`_thr_exit_common+0xbc
```

libc_malloc_lock

a.out`mutex

plockstat(1M) - example

- libc.so.1`libc_malloc_lock
  - Use libmtmalloc or libumem
- a.out`mutex
  - Resize the critical sections
    - scope
    - lock holding time
  - Replace critical sections with atomic operations

Atomic Operations

- atomic_ops
  - > atomic_ops package from HP
  - > atomic_ops(3c), available on Solaris 10

    atomic_add_16(), atomic_or_32(), atomic_add_32_nv(), ...
- OpenMP: “atomic” directive

  ```
  #pragma omp atomic
  a++;
  ```
- Java: atomic variable classes
  - > Nine flavors of atomic variables.

Portable & Predictable Performance

- Use the same program on different platforms and achieve consistent performance.
- Ideal: performance is determined only by the algorithm used.
- What affects performance?
  - > Algorithm
  - > Compiler
  - > Runtime (VM)
  - > OS
  - > HW

Performance Analysis Tools

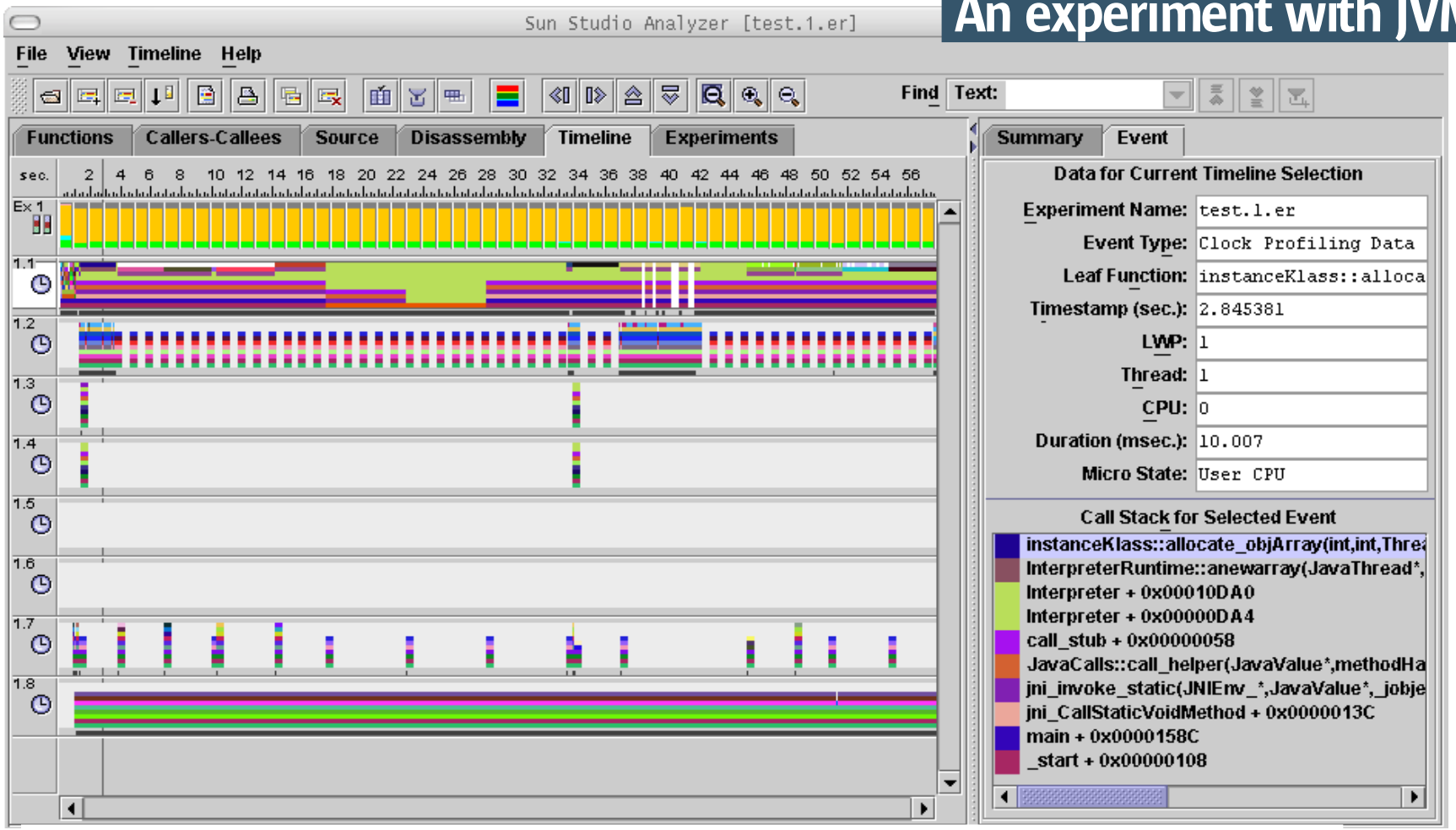
- Sun Studio Performance Analyzer
- Intel Vtune and Thread Profiler
- Quest Software JProbe
- Borland Optimizeit
- ...
- OS level tools: dtrace, mpstat, lockstat, ...

Sun Studio Performance Analyzer

- General purpose application level profiler
- Post-mortem analysis
- MT aware
- Supports dynamic libraries
- Clock profiling
- Hardware counter profiling
- Support for OpenMP

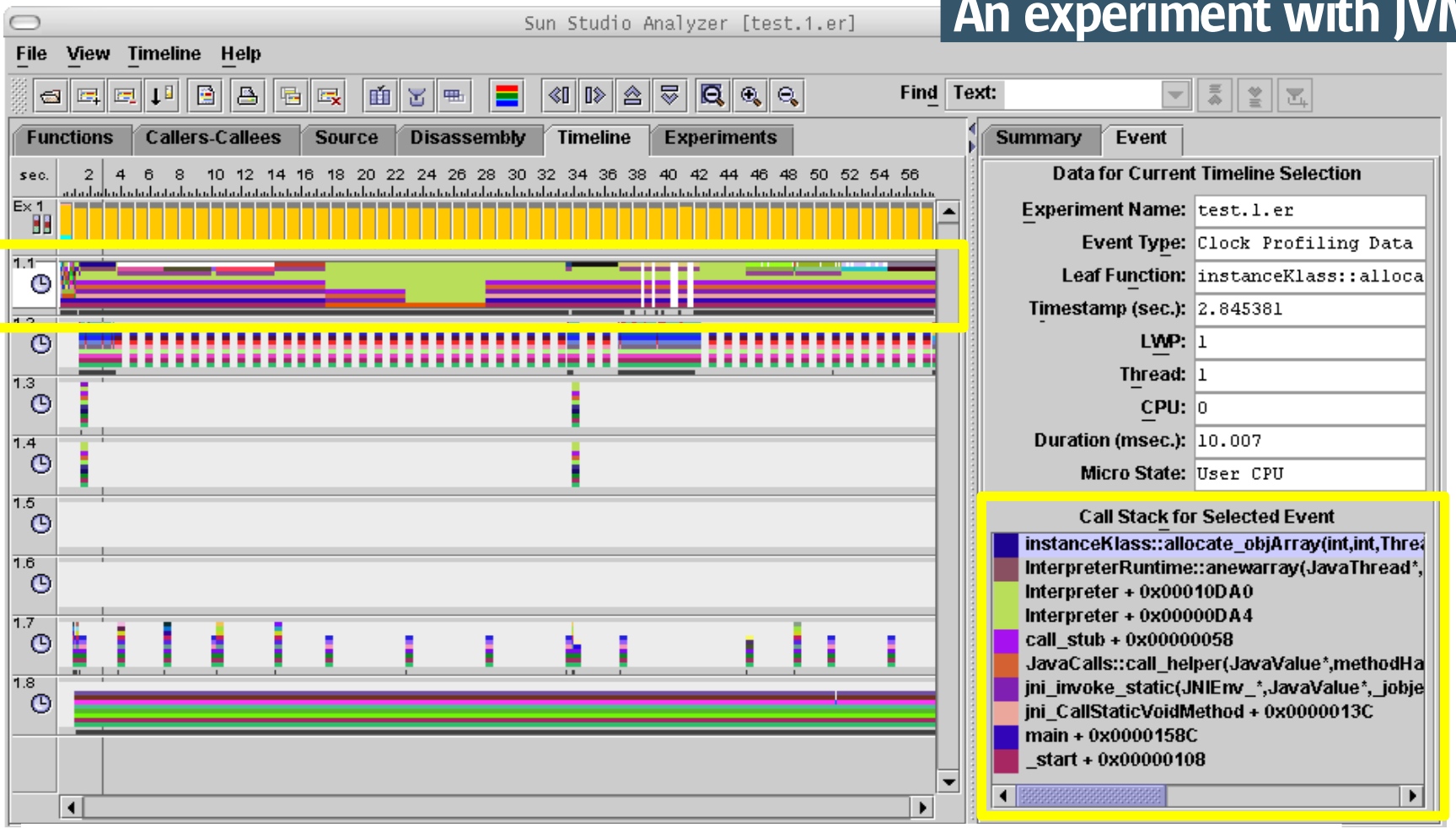
Sun Studio Performance Analyzer

An experiment with JVM



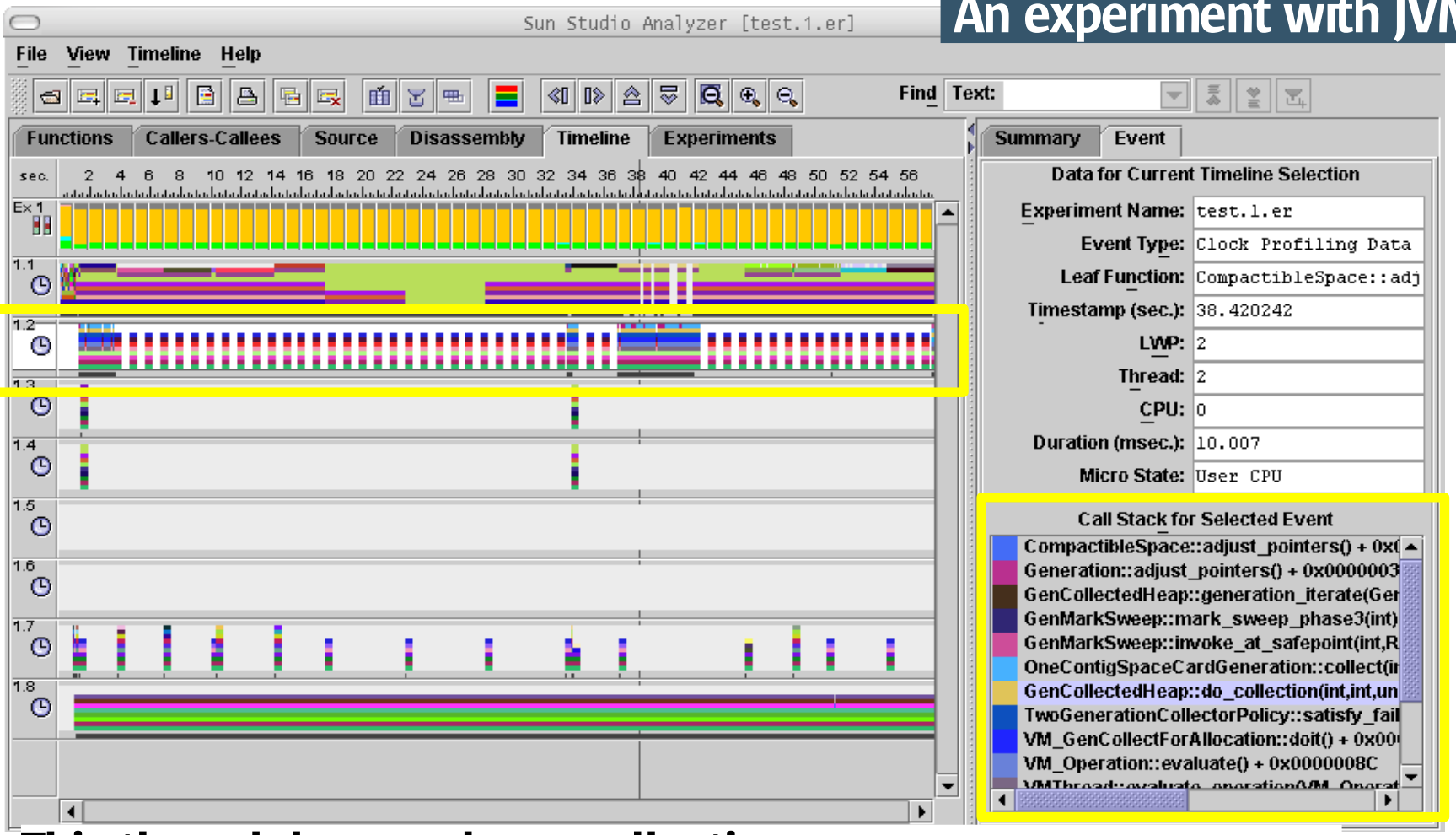
Single threaded Java application. JVM is multi-threaded.

Sun Studio Performance Analyzer



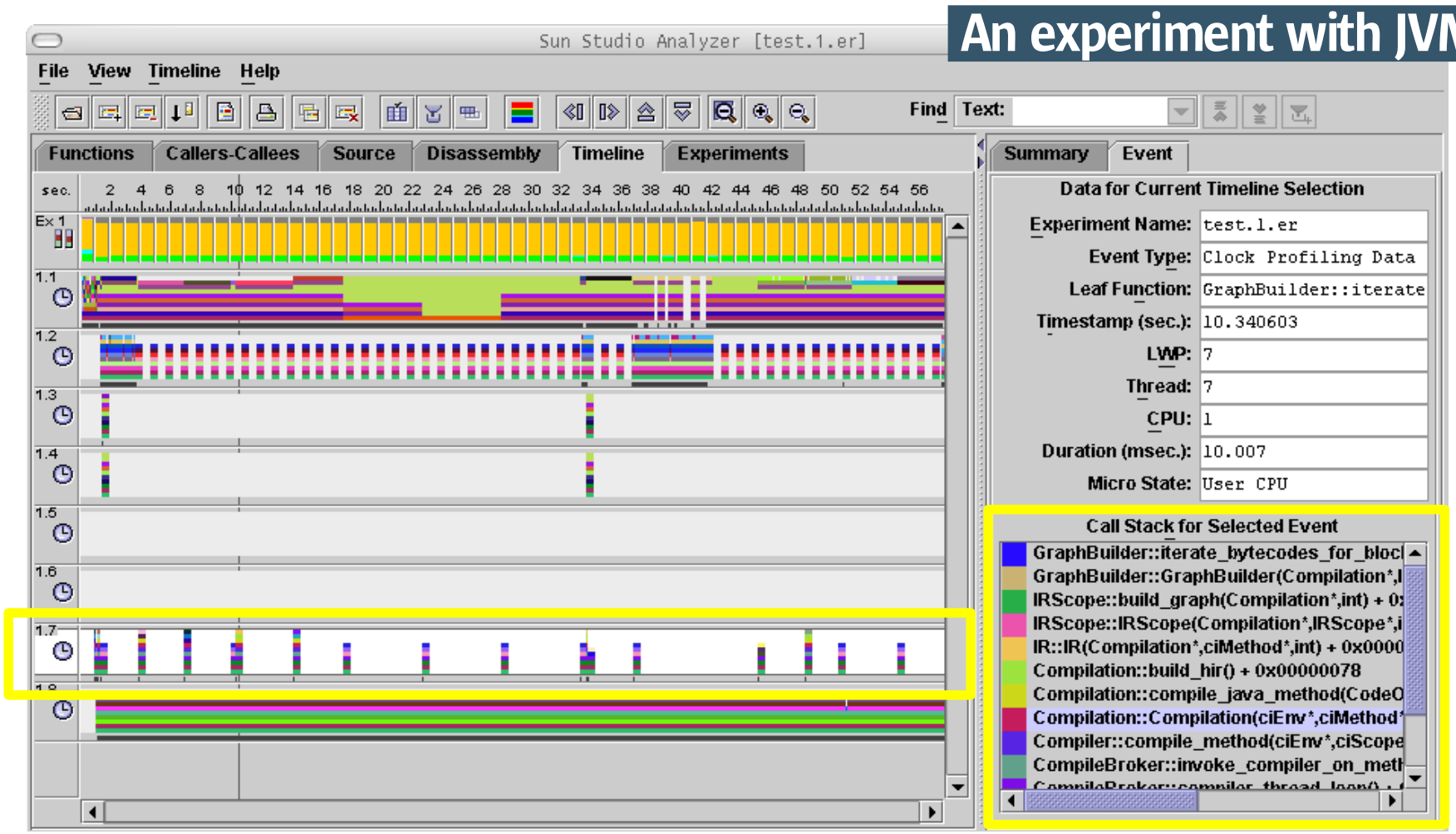
This thread executes user application.

Sun Studio Performance Analyzer



This thread does garbage collection.

Sun Studio Performance Analyzer

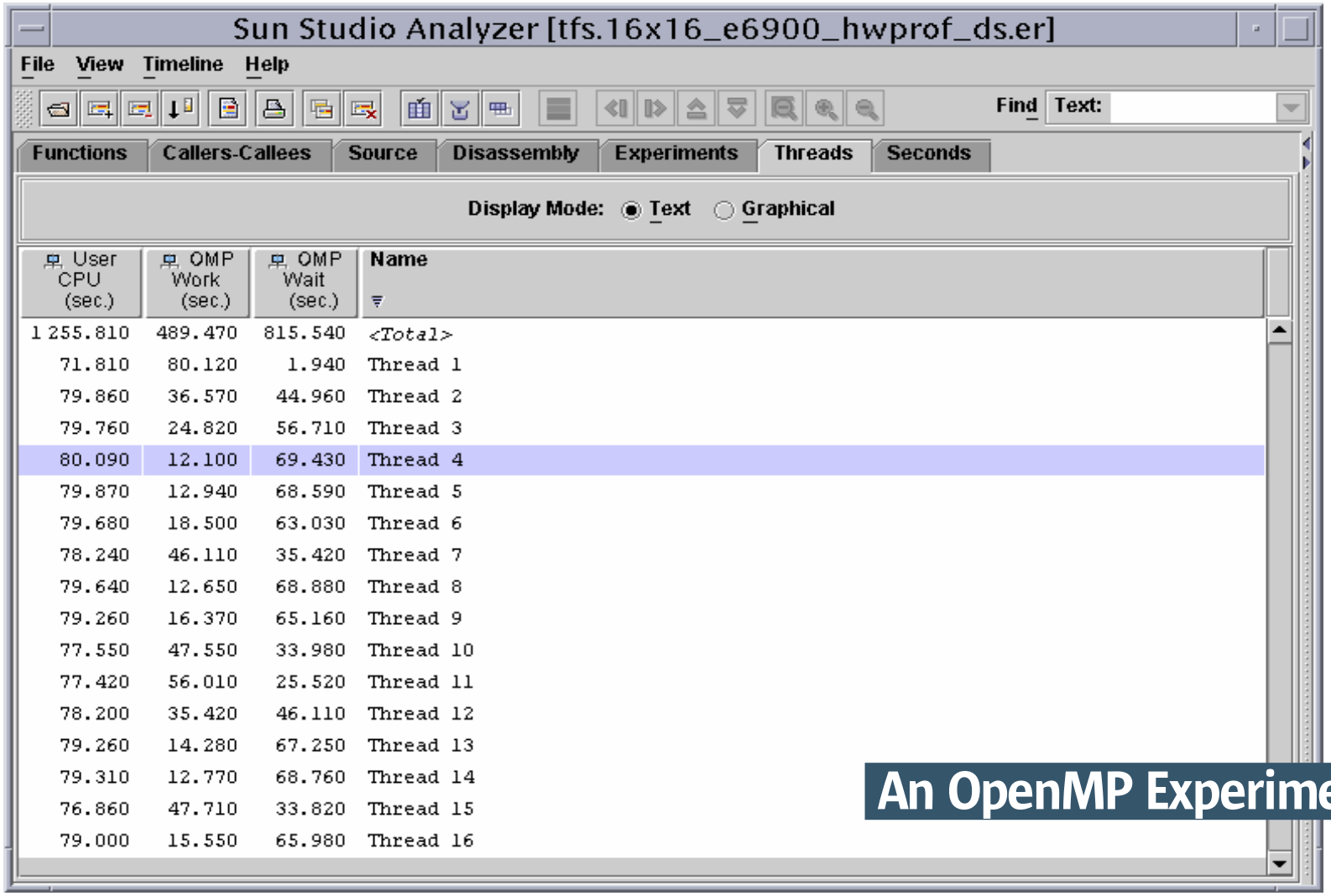


This thread does JIT compilation.

Performance Tools: A Challenge

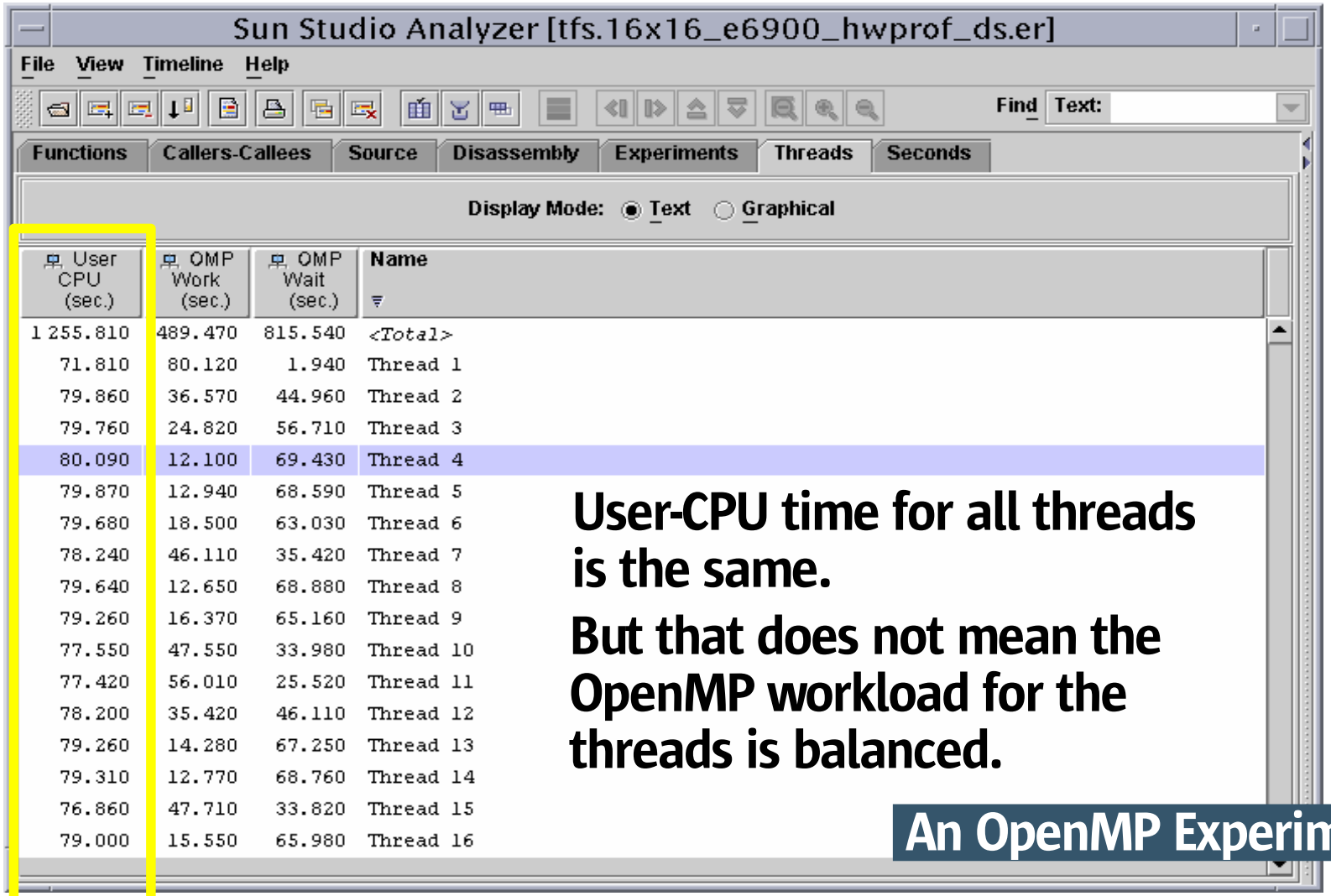
- Be aware of the threading model and provide relevant information.
  - Identify tasks, in addition to threads
  - Provide state information at different abstraction levels
  - Goals
    - Identify serial bottlenecks
    - Help resolve load imbalances

Sun Studio Performance Analyzer



An OpenMP Experiment

Sun Studio Performance Analyzer

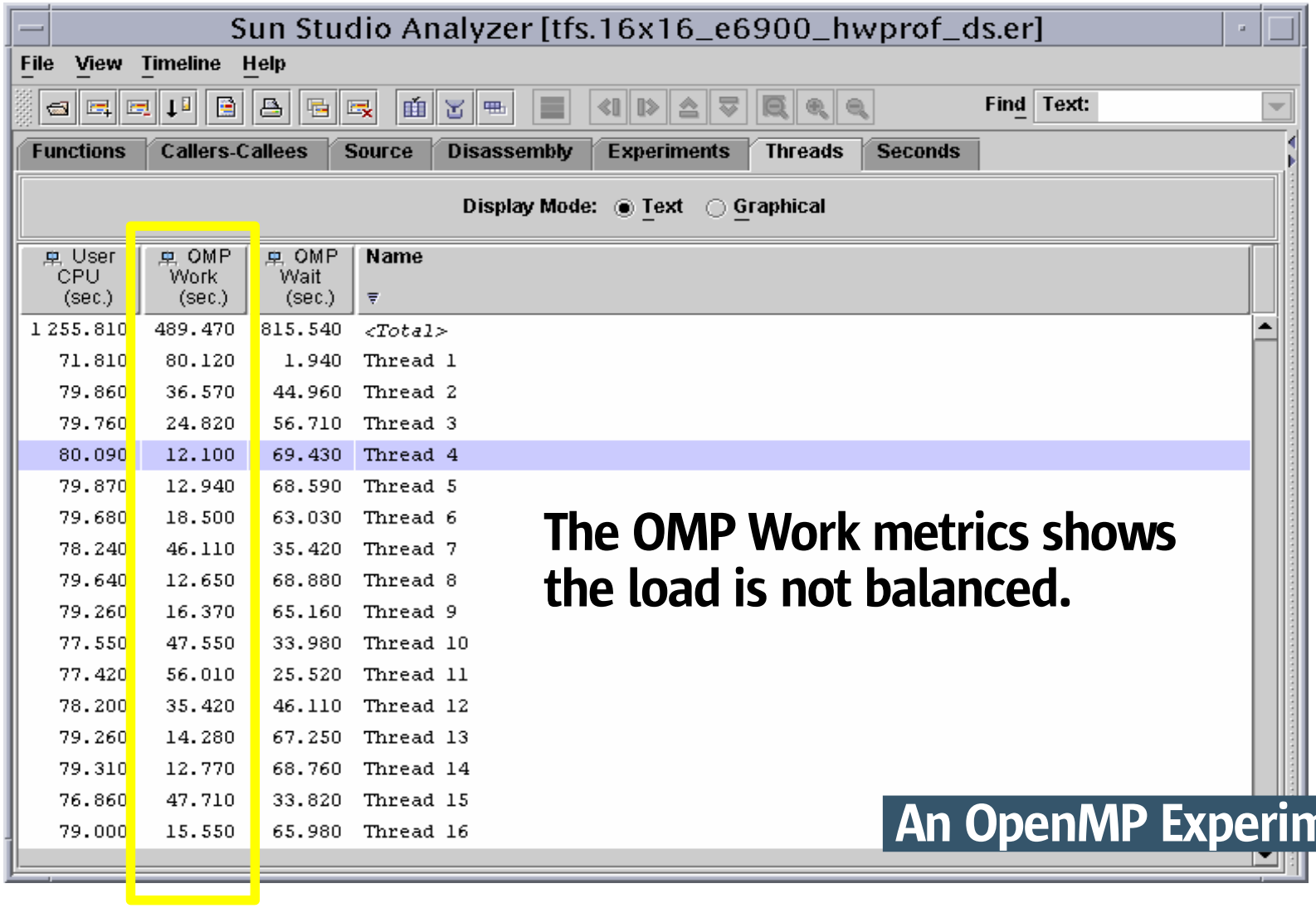


User-CPU time for all threads is the same.

But that does not mean the OpenMP workload for the threads is balanced.

An OpenMP Experiment

Sun Studio Performance Analyzer

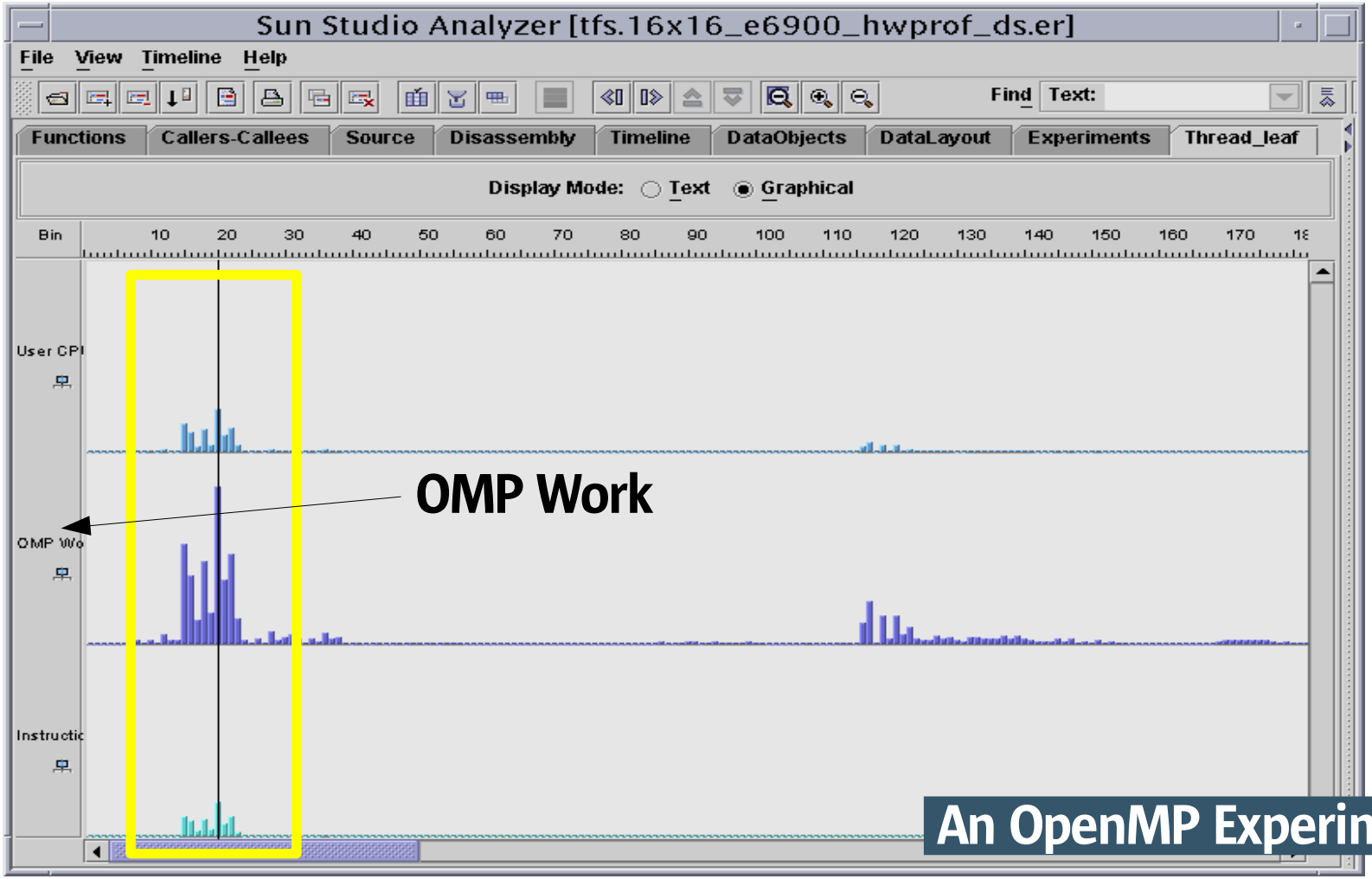


User CPU (sec.)	OMP Work (sec.)	OMP Wait (sec.)	Name
1 255.810	489.470	815.540	*<Total>*
71.810	80.120	1.940	Thread 1
79.860	36.570	44.960	Thread 2
79.760	24.820	56.710	Thread 3
80.090	12.100	69.430	Thread 4
79.870	12.940	68.590	Thread 5
79.680	18.500	63.030	Thread 6
78.240	46.110	35.420	Thread 7
79.640	12.650	68.880	Thread 8
79.260	16.370	65.160	Thread 9
77.550	47.550	33.980	Thread 10
77.420	56.010	25.520	Thread 11
78.200	35.420	46.110	Thread 12
79.260	14.280	67.250	Thread 13
79.310	12.770	68.760	Thread 14
76.860	47.710	33.820	Thread 15
79.000	15.550	65.980	Thread 16

The OMP Work metrics shows the load is not balanced.

An OpenMP Experiment

Sun Studio Performance Analyzer



Error Recovery

- Catch the errors and restore the application to a stable state.
- Error recovery becomes more difficult in mt applications because it may be an asynchronous problem!
  - Notify other threads
    - Who? How? When?
  - Update global structures
    - Deadlocks or infinite loops in recovering process!
- A common approach: use check points

All Single Thread Issues

- “50% chance a bug has nothing to do with multi-threading. It is just 200x difficult to debug in a multi-thread program”.
- Referencing un-initialized memory
- Out-of-bound array accesses
- Dereferencing a stale pointer
- ...
- Tools: Lint, Purify, Valgrind, dbx rtc, ...

MT- capable debuggers

- Basic Features
  - Examing the thread states
  - Examing thread specific data
  - Setting breakpoints for a specific thread
  - Control the execution of the threads
- Advanced Features
  - Integrated with deadlock/data race detection tools
  - Examing synchronization status
  - Be aware of threading model
- Tools
  - Dbx from Sun, TotalView from Etnus, GDB, ...

dbx – Examine Status

- Print a list of all known threads
  - `(dbx) threads`

```
o t@1 a l@1 ?() breakpoint in work()
*>t@2 a l@2 work() breakpoint in  work()
  t@3 a l@3 work() running in _thr_setup()
```

- Switch the viewing context to another thread
  - `(dbx) thread t@3`

dbx – Set Breakpoints

- A break point can be set specifically to a particular thread.
  - **`(dbx) stop at 430 -thread t@2`**

- Breaking is synchronous - “stop the world”
  - When any thread stops, all other threads *sympathetically* stop.

dbx - Control Execution

- Keep the given thread from ever running
  - **(dbx) thread -suspend t@2**
- Resume a thread
  - **(dbx) thread -resume t@2**
- Single step a thread
  - **(dbx) step t@2**
  - **(dbx) next t@2**

Summary

- Multi-core architecture provides a new thread-rich environment.
- Challenges in multi-threaded programming need to be addressed at all levels.
  - languages
  - compilers and tools
  - libraries and utilities
  - VM and OS
  - programming practice

To Learn More ...

- Pthread
  - "Programming with POSIX Threads", David Butenhof
- OpenMP
  - www.openmp.org
- Java
  - "Java Concurrency in Practice", Brian Goetz et al
  - JSR-133
    - http://www.cs.umd.edu/~pugh/java/memoryModel/
  - JSR-166
    - http://gee.cs.oswego.edu/dl/concurrency-interest/index.html

To Learn More ...

- "Developing and Tuning Applications on UltraSPARC T1 Chip Multithreading Systems", Denis Sheahan
  - http://www.sun.com/blueprints/1205/819-5144.html
- Dtrace
  - http://www.sun.com/bigadmin/content/dtrace/
- Threading Methodolgy: Principles and Practices
  - http://www.intel.com/cd/software/products/asmo-na/eng/threading/219349.htm
- Using the Sun Studio Data-Race Detection Tool
  - http://developers.sun.com/prodtech/cc/downloads/drdt/using.html

Thank you!

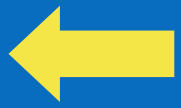
yuan.lin@sun.com

Agenda

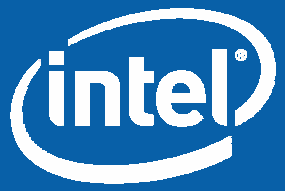
Multithreaded Programming

Transactional Memory (TM)

- TM Introduction
- TM Implementation Overview
- Hardware TM Techniques
- Software TM Techniques



Q&A



Transactional Memory Introduction

Ali-Reza Adl-Tabatabai
Programming Systems Lab
Intel Corporation

Transactional memory definition

Memory transaction: A sequence of memory operations that either execute completely (commit) or have no effect (abort)

An "all or nothing" sequence of operations

- On commit, all memory operations appear to take effect as a unit (all at once)
- On abort, none of the stores appear to take effect

Transactions run in isolation

- Effects of stores are not visible until transaction commits
- No concurrent conflicting accesses by other transactions

Similar to database ACID properties

Transactional memory language construct

The basic atomic construct:

```
lock(L); x++; unlock(L);     →    atomic {x++;}
```

Declarative – user simply specifies, system implements "under the hood"

Basic atomic construct universally proposed

- HPCS languages (Fortress, X10, Chapel) provide atomic in lieu of locks
- Research extensions to languages – Java, C#, Atomos, CaML, Haskell, …

Lots of recent research activity

- Transactional memory language constructs
- Compiling & optimizing atomic
- Hardware & software implementations of transactional memory

Example: Java 1.4 HashMap

Fundamental data structure

- Map: Key → Value

```
public Object get(Object key)  {
    int idx = hash(key);                    // Compute hash
    HashEntry e = buckets[idx];             // to find bucket
    while (e != null)  {                    // Find element in bucket
        if (equals(key, e.key))
          return e.value;
        e = e.next;
      }
    return null;
  }
```

Not thread safe: don't pay lock overhead if you don't need it

Synchronized HashMap

Java 1.4 solution: Synchronized layer

- Convert any map to thread-safe variant
- Explicit locking – user specifies concurrency

```
public Object get(Object key)
    {
      synchronized (mutex) // mutex guards all accesses to map m
        {
          return m.get(key);
        }
    }
```

Coarse-grain synchronized HashMap:

- Thread-safe, easy to program
- Limits concurrency → poor scalability
  - E.g., 2 threads can't access disjoint hashtable elements

Transactional HashMap

Transactional layer via an 'atomic' construct

- Ensure all operations are atomic
- Implicit atomic directive – system discovers concurrency

```
public Object get(Object key)
    {
      atomic                          // System guarantees atomicity
        {
          return m.get(key);
        }
    }
```

Transactional HashMap:

- Thread-safe, easy to program
- Good scalability

Transactions: Scalability

Concurrent read operations

- Basic locks do not permit multiple readers
  - Reader-writer locks
- Transactions automatically allow multiple concurrent readers

Concurrent access to disjoint data

- Programmers have to manually perform fine-grain locking
  - Difficult and error prone
  - Not modular
- Transactions automatically provide fine-grain locking

ConcurrentHashMap

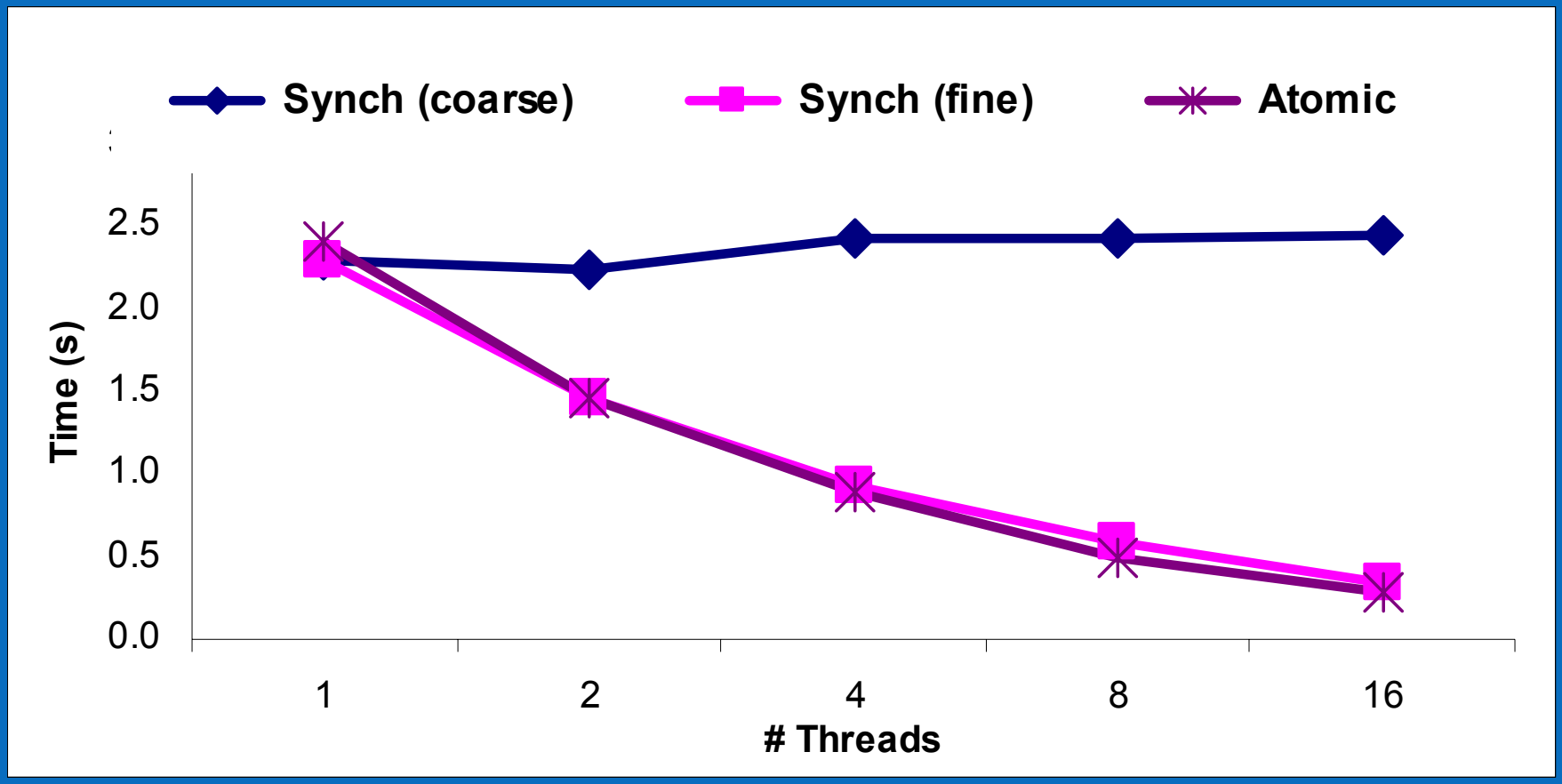
Java 5 solution: Complete redesign

```
public Object get(Object key) {
  int hash = hash(key);
  // Try first without locking...
  Entry[] tab = table;
  int index = hash & (tab.length - 1);
  Entry first = tab[index];
  Entry e;

  for (e = first; e != null; e = e.next) {
    if (e.hash == hash && eq(key, e.key)) {
      Object value = e.value;
      if (value != null)
        return value;
      else
        break;
    }
  }
  …
  …
  // Recheck under synch if key not there or interference
  Segment seg = segments[hash & SEGMENT_MASK];
  synchronized(seg) {
    tab = table;
    index = hash & (tab.length - 1);
    Entry newFirst = tab[index];
    if (e != null || first != newFirst) {
      for (e = newFirst; e != null; e = e.next) {
        if (e.hash == hash && eq(key, e.key))
          return e.value;
      }
    }
    return null;
  }
}
```

Fine-grain locking & concurrent reads: complicated & error prone

HashMap performance



Transactions scales as well as fine-grained locks

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

Example: A bank application

Bank accounts with names and balances

- HashMap is natural fit as building block

```
class Bank {
  ConcurrentHashMap accounts;
  …
  void deposit(String name, int amount) {
    int balance = accounts.get(name);          // Get the current balance
    balance = balance + amount;                // Increment it
    accounts.put(name, balance);               // Set the new balance
  }
  …
}
```

Not thread-safe – Even with ConcurrentHashMap

Thread safety

Suppose Fred has $100

T0: deposit("Fred", 10)

- bal = acc.get("Fred") <- 100
- bal = bal + 10
- acc.put("Fred", bal) -> 110

T1: deposit("Fred", 20)

- bal = acc.get("Fred") <- 100
- bal = bal + 20
- acc.put("Fred", bal) -> 120

Fred has $120. $10 lost.

Traditional solution: Locks

```
class Bank {
  ConcurrentHashMap accounts;
  …
  void deposit(String name, int amount) {
    synchronized(accounts) {
      int balance = accounts.get(name);          // Get the current balance
      balance = balance + amount;                // Increment it
      accounts.put(name, balance);               // Set the new balance
    }
  }
  …
}
```

Thread-safe – but no scaling

- ConcurrentHashMap does not help
- Performance requires redesign from scratch & fine-grain locking

Transactional solution

```
class Bank {
  HashMap accounts;
  …
  void deposit(String name, int amount) {
    atomic {
      int balance = accounts.get(name);          // Get the current balance
      balance = balance + amount;                // Increment it
      accounts.put(name, balance);               // Set the new balance
    }
  }
  …
}
```

Thread-safe – and it scales!

Safe composition + performance

Transactional memory benefits

As easy to use as coarse-grain locks

Scale as well as fine-grain locks

Safe and scalable composition

Failure atomicity:

- Automatic recovery on errors

Traditional exception handling

```
class Bank {
  Accounts accounts;
  …
  void transfer(String name1, String name2, int amount) {
    synchronized(accounts) {
      try {
        accounts.put(name1, accounts.get(name1)-amount);
        accounts.put(name2, accounts.get(name2)+amount);
      }
      catch (Exception1) {..}
      catch (Exception2) {..}
    }
    …
 }
```

Manually catch all exceptions and determine what needs to be undone

Side effects may be visible to other threads before they are undone

Failure recovery using transactions

```
class Bank {
  Accounts accounts;
  …
  void transfer(String name1, String name2, int amount) {
    atomic {
        accounts.put(name1, accounts.get(name1)-amount);
        accounts.put(name2, accounts.get(name2)+amount);
    }
  }
  …
}
```

System rolls back updates on an exception

Partial updates not visible to other threads

Challenges in parallel programming

Finding independent tasks

Mapping tasks to threads

Defining & implementing synchronization protocol

Race conditions

Deadlock avoidance

Memory model

Composing parallel tasks

Scalability

Portable & predictable performance

Recovering from errors

... Single thread issues

→ Transactions address a lot of parallel programming problems

Challenges in parallel programming

Finding independent tasks

Mapping tasks to threads

Defining & implementing synchronization protocol

Race conditions

Deadlock avoidance

Memory model

Composing parallel tasks

Scalability

Portable & predictable performance

Recovering from errors

... Single thread issues

→ But not a silver bullet

Summary

Transactions provide many benefits over locks

- Automatic fine-grain concurrency
- Automatic read concurrency
- Deadlock avoidance
- Eliminates locking protocols
- Automatic failure recovery

→ Safe & scalable composition of thread-safe software modules

Challenge: How to implement transactions efficiently?

Agenda

- Multithreaded Programming
- Transactional Memory (TM)
  - TM Introduction
  - TM Implementation Overview
  - Hardware TM Techniques
  - Software TM Techniques
- Q&A

Transactional Memory Implementation Overview

Christos Kozyrakis

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TM 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

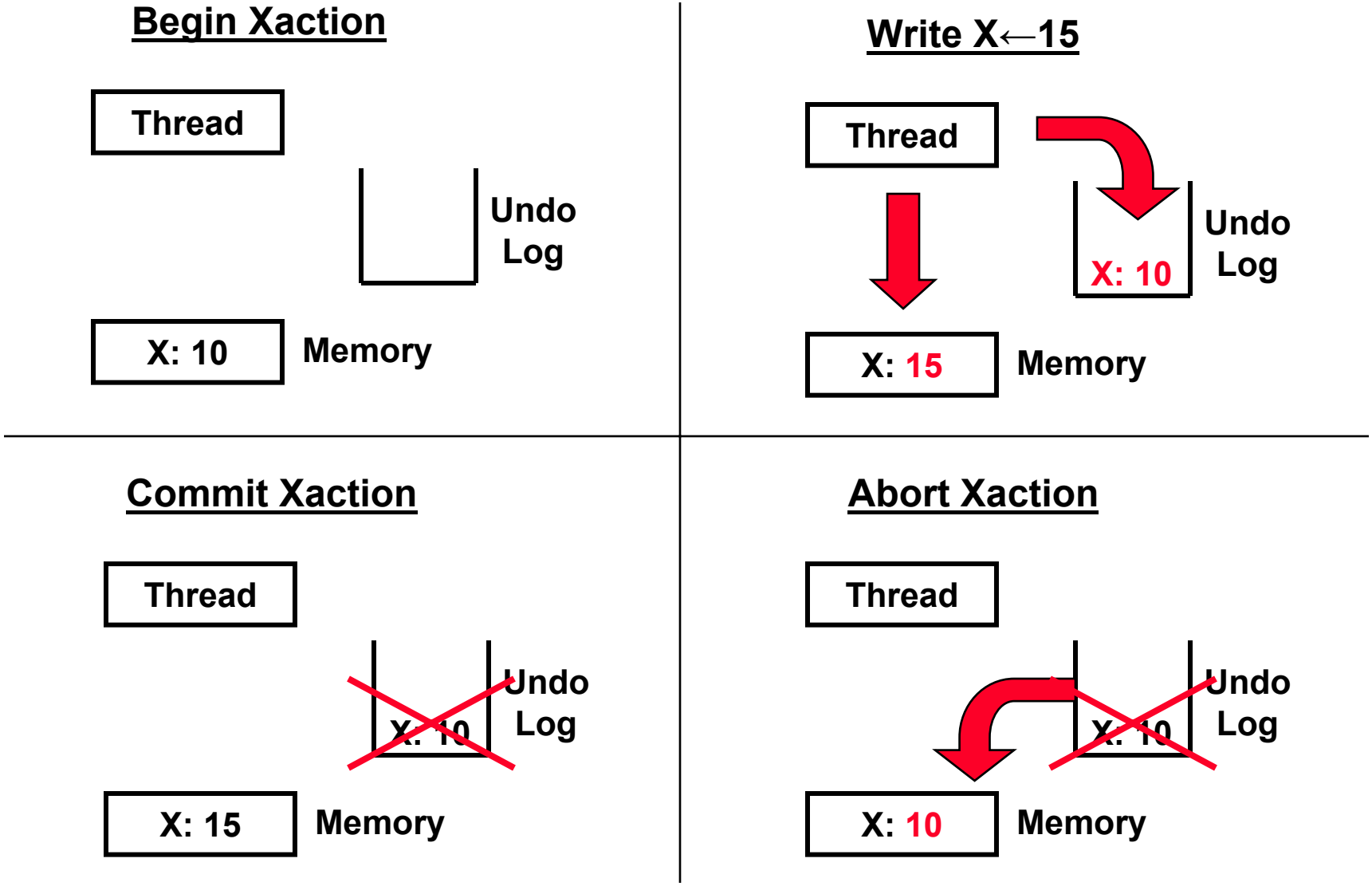
Data Versioning

- Manage uncommited (new) and commited (old) versions of data for concurrent transactions

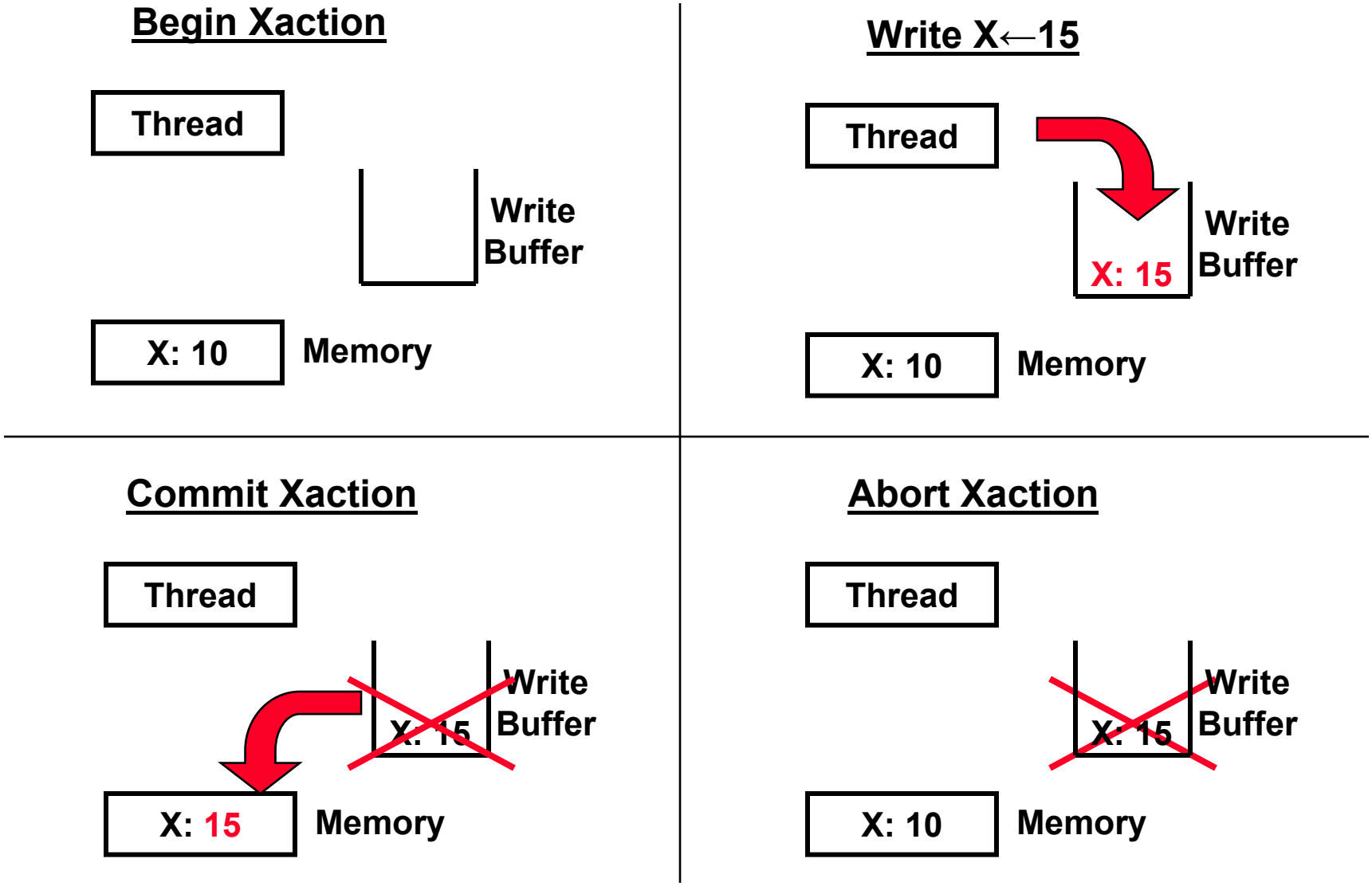
1. Eager or undo-log based
   - Update memory location directly; maintain undo info in a log
   + Faster commit, direct reads (SW)
   – Slower aborts, no fault tolerance, weak atomicity (SW)

2. Lazy or 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 Versioning Illustration



Lazy Versioning Illustration



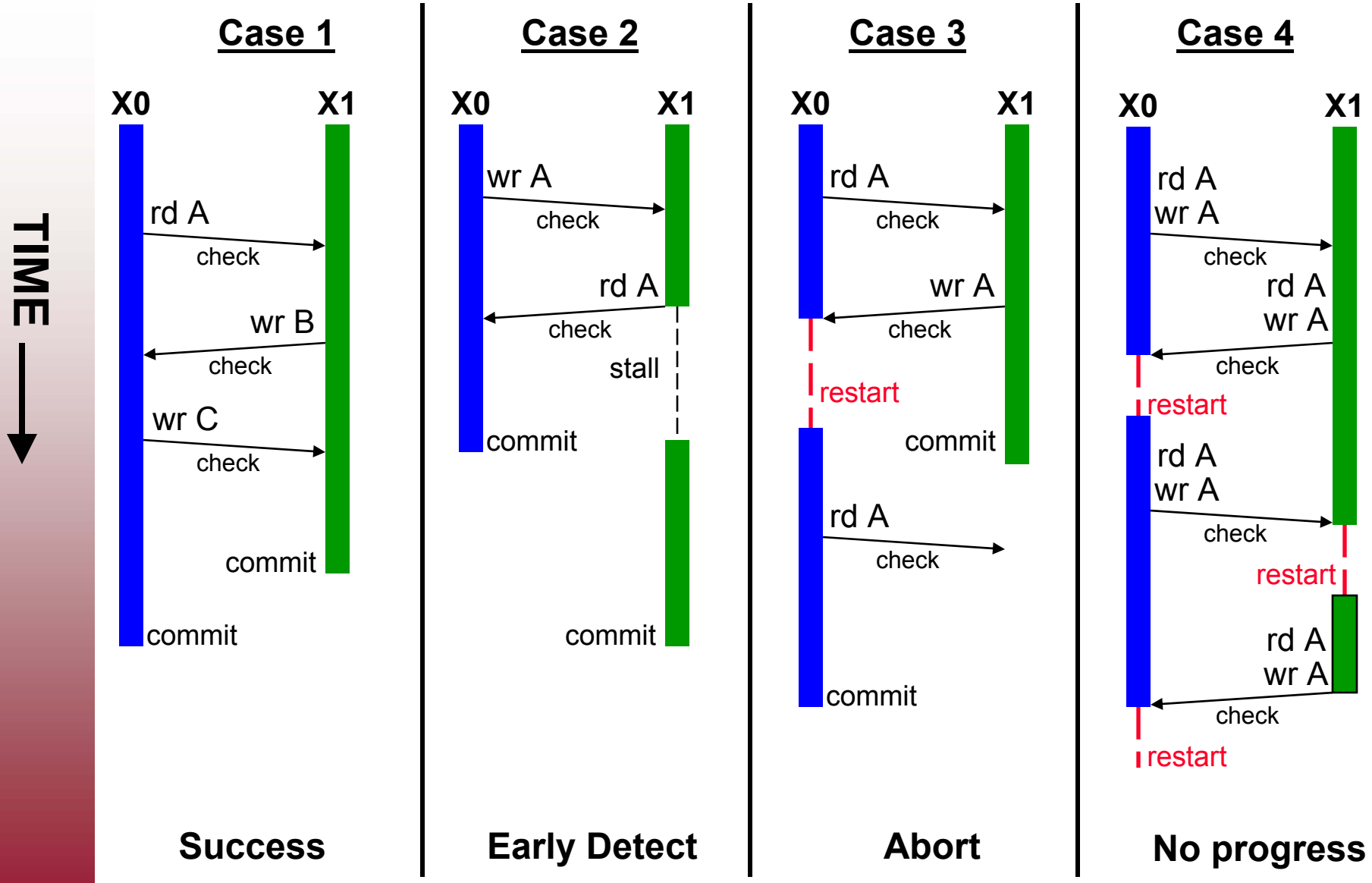
Conflict Detection

- Detect and handle conflicts between transaction
  - Read-Write and (often) Write-Write conflicts
  - For detection, a transactions tracks its read-set and write-set

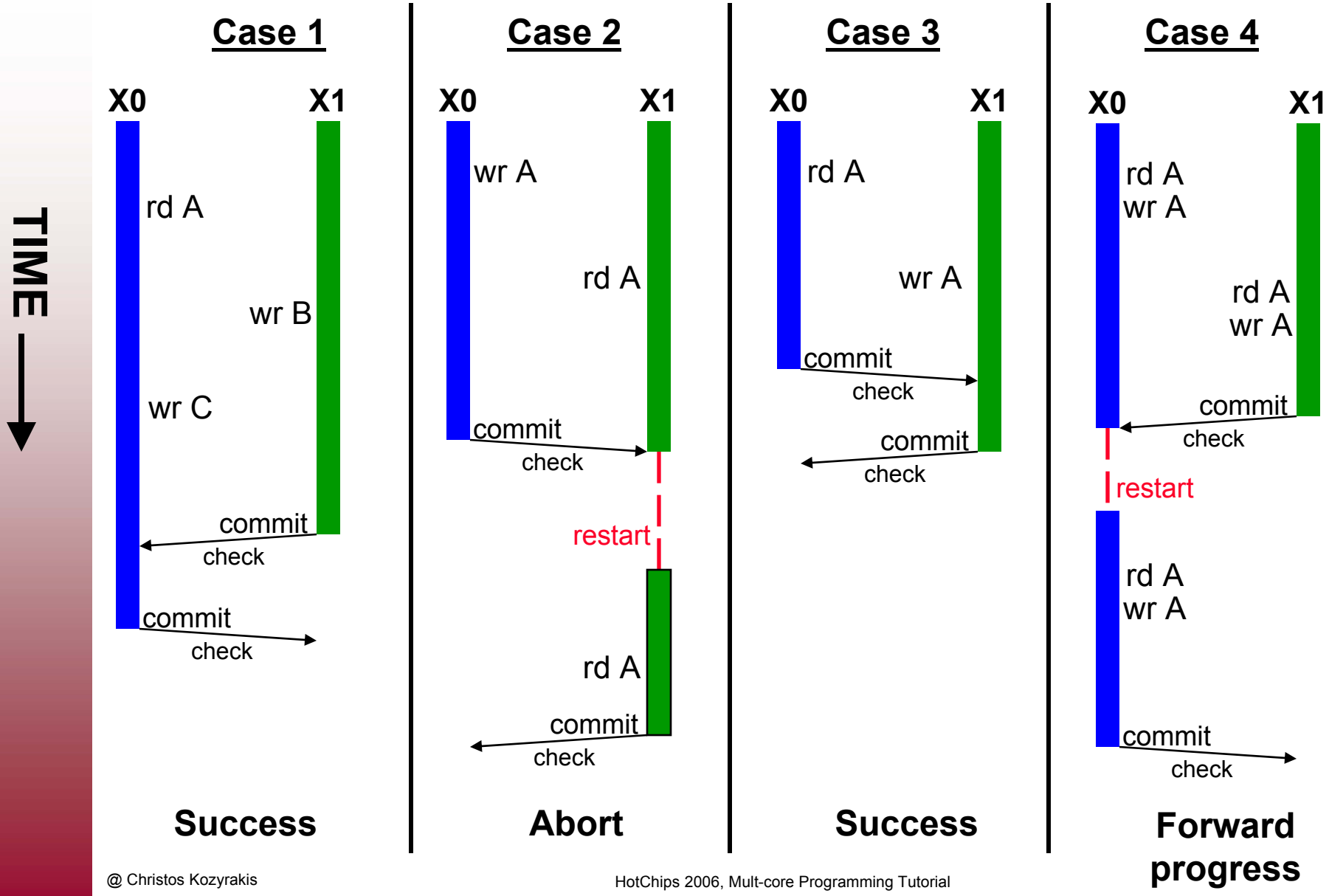
1. Eager or encounter or pessimistic
   - Check for conflicts during loads or stores
     - HW: check through coherence lookups
     - SW: checks through locks and/or version numbers
   - Use contention manager to decide to stall or abort
2. Lazy or commit or optimistic
   - Detect conflicts when a transaction 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/or version numbers

- Can use separate mechanism for loads & stores (SW)

Pessimistic Detection Illustration



Optimistic Detection Illustration



Conflict Detection Tradeoffs

1. Eager or encounter or pessimistic
   - \+ Detect conflicts early
     - Lower abort penalty, turn some aborts to stalls
   - – No forward progress guarantees, more aborts in some cases
   - – Locking issues (SW), fine-grain communication (HW)

2. Lazy or commit or optimistic
   - \+ Forward progress guarantees
   - \+ Potentially less conflicts, no locking (SW), bulk communication (HW)
   - – Detects conflicts late

Implementation Space

Conflict Detection	Version Management: Eager	Version Management: Lazy
Pessimistic	HW: UW LogTM SW: Intel McRT, MS-STM	HW: MIT LTM, Intel VTM SW: MS-OSTM
Optimistic	HW: -- SW: --	HW: Stanford TCC SW: Sun TL/2

[This is just a subset of proposed implementations]

- No convergence yet
- Decision will depend on
  - Application characteristics
  - Importance of fault tolerance & strong atomicity
  - Success of contention managers, implementation complexity
- May have different approaches for HW, SW, and hybrid

Conflict Detection Granularity

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

Advanced Implementation Issues

- Atomicity with respect to non-transactional code
  - Weak atomicity: non-commited transaction state is visible
  - Strong atomicity: non-committed transaction state not visible
- Nested transactions
  - Common approach: subsume within outermost transaction
  - Recent: nested version management & conflict detection
- Support for PL & OS design
  - Conditional synchronization, exception handling, …
  - Key mechanisms: 2-phase commit, commit/abort handlers, open nesting

See paper by McDonald et.al at ISCA'06

HTM: Hardware Transactional Memory Implementations

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Why Hardware Support for TM

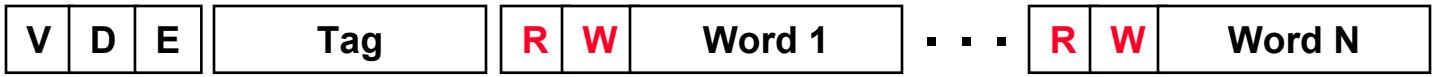
- Performance
  - Software TM starts with a 40% to 2x overhead handicap
- Features
  - Works for all binaries and libraries wo/ need to recompile
  - Forward progress guarantees
  - Strong atomicity
  - Word-level conflict detection
- How much HW support is needed?
  - This is the topic of ongoing research
  - All proposed HTMs are essentially hybrid
    - Add flexibility by switching to software on occasion

HTM Implementation Mechanisms

- Data versioning in caches
  - Cache the write-buffer or the undo-log
  - Zero overhead for both loads and stores
  - Works with private, shared, and multi-level caches
- Conflict detection through cache coherence protocol
  - Coherence lookups detect conflicts between transactions
  - Works with snooping & directory coherence
- Notes
  - HTM support similar to that for thread-level speculation (TLS)
    - Some HTMs support both TM and TLS
  - Virtualization of hardware resources discussed later

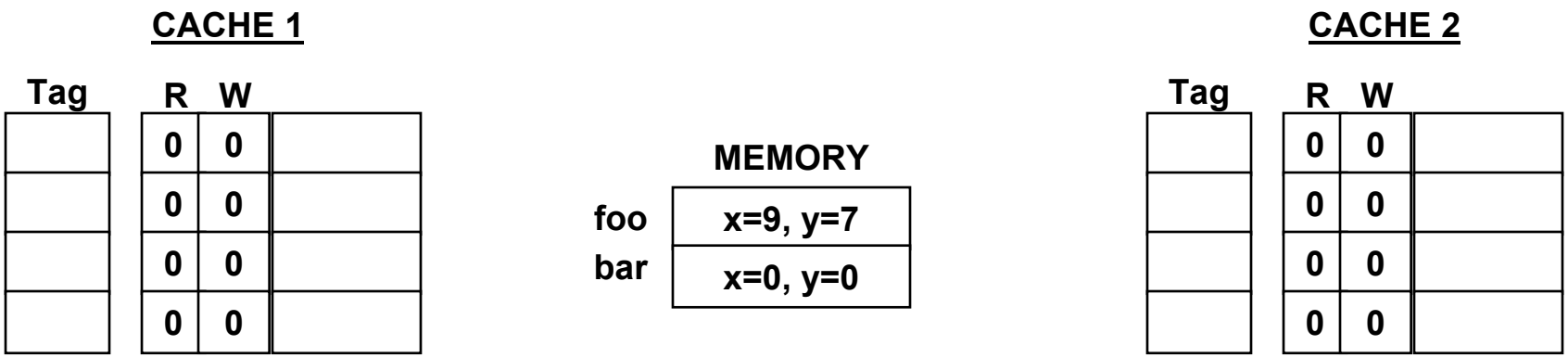
HTM Design

- Cache lines annotated to track read-set & write set
  - R bit: indicates data read by transaction; set on loads
  - W bit: indicates data written by transaction; set on stores
    - R/W bits can be at word or cache-line granularity
  - R/W bits gang-cleared on transaction commit or abort
  - For eager versioning, need a 2nd cache write for undo log



- Coherence requests check R/W bits to detect conflicts
  - E.g. shared request to W-word is a read-write conflict
  - E.g. exclusive request to W-word is a write-write conflict
  - E.g. exclusive request to R-word is a write-read conflict

HTM Example

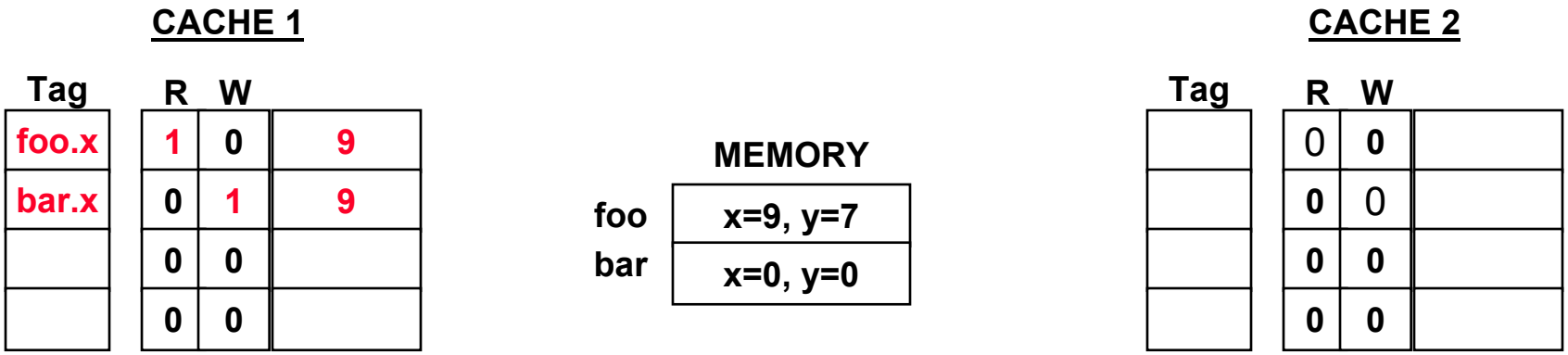



```
T1 atomic {
     bar.x = foo.x;
     bar.y = foo.y;
   }
```

```
T2  atomic {
      t1 = bar.x;
      t2 = bar.y;
    }
```

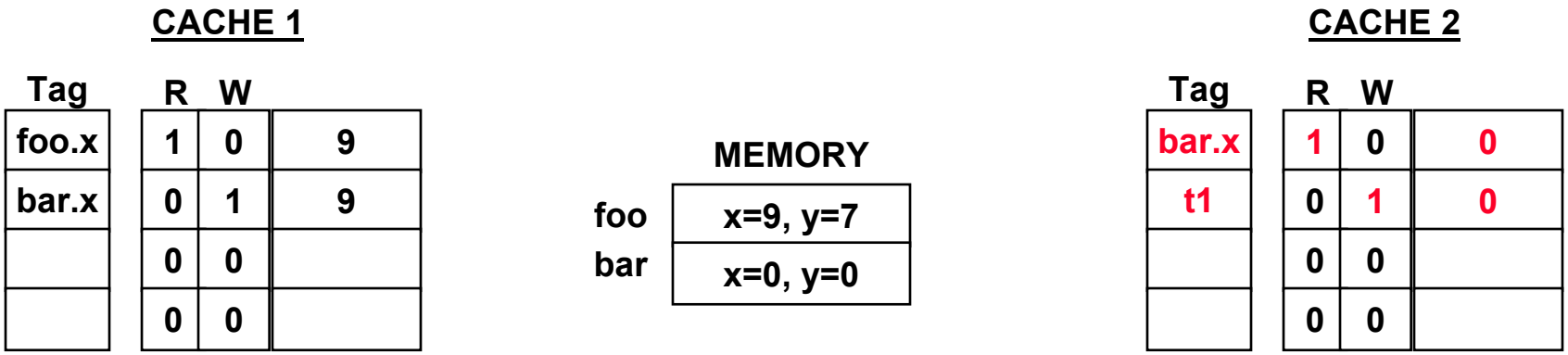
- T1 copies **foo** into **bar**
- T2 should read [0, 0] or should read [9,7]
- Assume HTM system with lazy versioning & optimistic detection

HTM Example (1)



- Both transactions make progress independently

HTM Example (2)

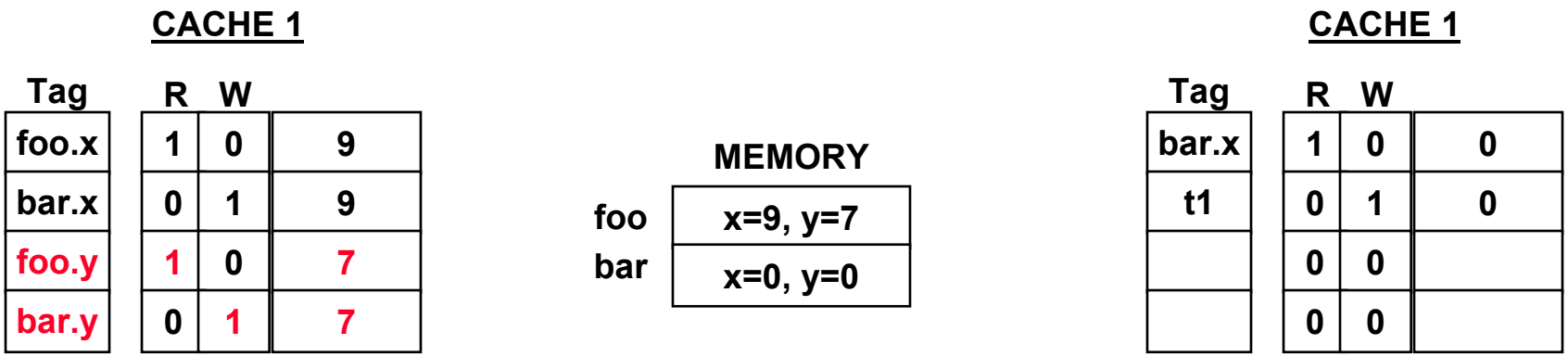



```
T1 atomic {
     bar.x = foo.x;
     bar.y = foo.y;
   }
```

```
T2  atomic {
      t1 = bar.x;
      t2 = bar.y;
    }
```

- Both transactions make progress independently

HTM Example (3)

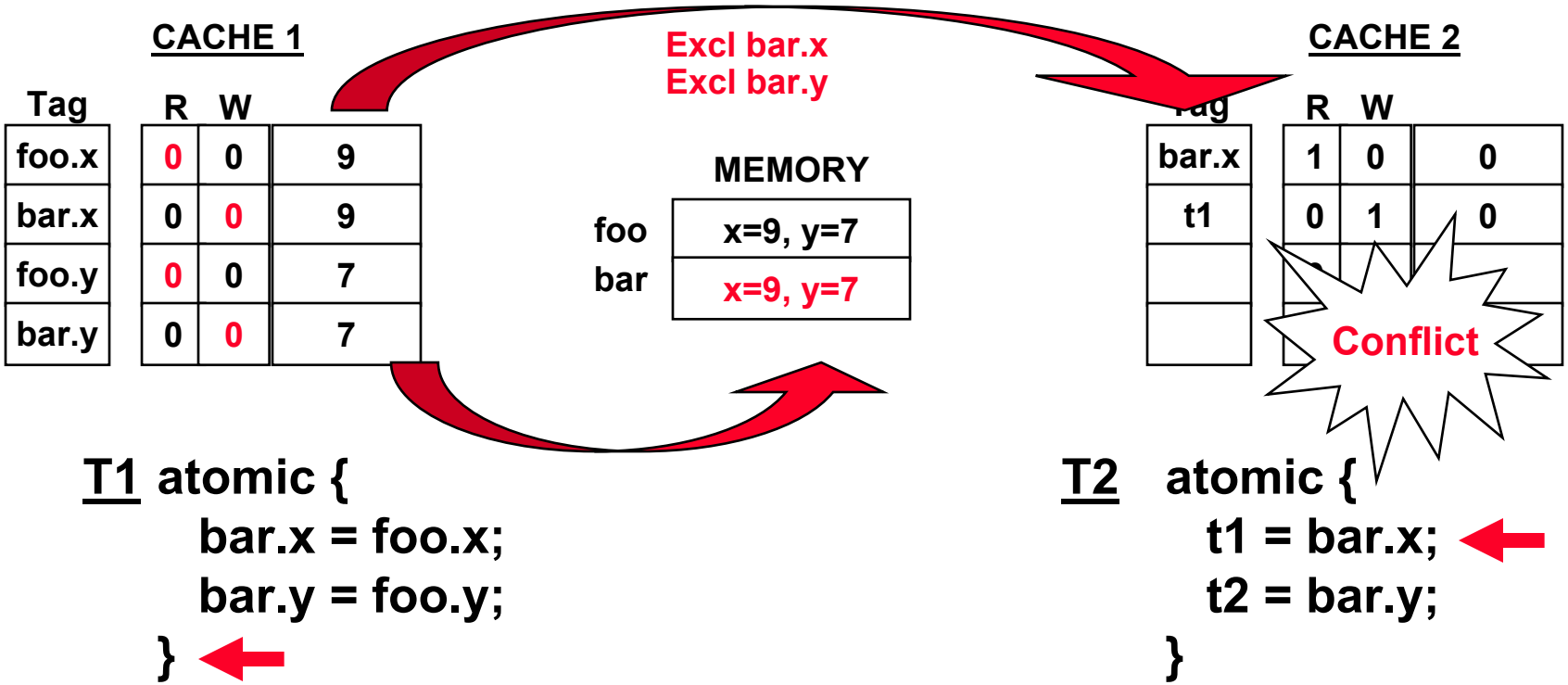



```
T1 atomic {
     bar.x = foo.x;
     bar.y = foo.y;
   }
```

```
T2  atomic {
      t1 = bar.x;
      t2 = bar.y;
    }
```

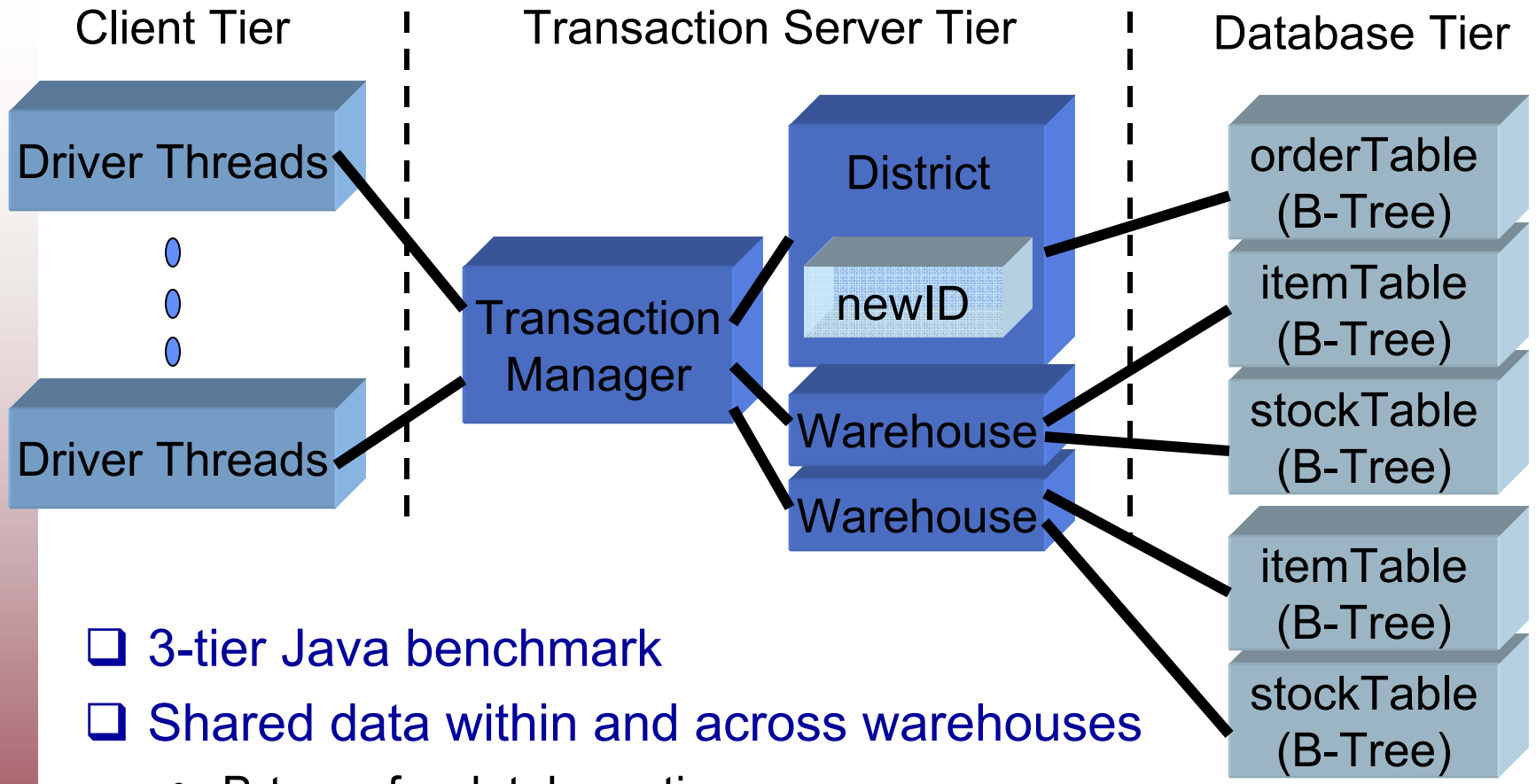
- Transaction T1 is now ready to commit

HTM Example (3)



- T1 updates shared memory
  - R/W bits are cleared
  - This is a logical update, data may stay in caches as dirty
- Exclusive request for bar.x reveals conflict with T2
  - T2 is aborted & restarted; all R/W cache lines are invalidated
  - When it reexecutes, it will read [9,7] without a conflict

Performance Example: SpecJBB2000



- 3-tier Java benchmark
- Shared data within and across warehouses
  - B-trees for database tier
- Can we parallelize the actions within a warehouse?
  - Orders, payments, delivery updates, etc

Sequential Code for NewOrder

```
TransactionManager::go() {
      // 1. initialize a new order transaction
      newOrderTx.init();
      // 2. create unique order ID
      orderId = district.nextOrderId(); // newID++
      order = createOrder(orderId);
      // 3. retrieve items and stocks from warehouse
      warehouse = order.getSupplyWarehouse();
      item = warehouse.retrieveItem();   // B-tree search
      stock = warehouse.retrieveStock(); // B-tree search
      // 4. calculate cost and update node in stockTable
      process(item, stock);
      // 5. record the order for delivery
      district.addOrder(order); // B-tree update
      // 6. print the result of the process
      newOrderTx.display();
}
```

- Non-trivial code with complex data-structures
  - Fine-grain locking ➔ difficult to get right
  - Coarse-grain locking ➔ no concurrency

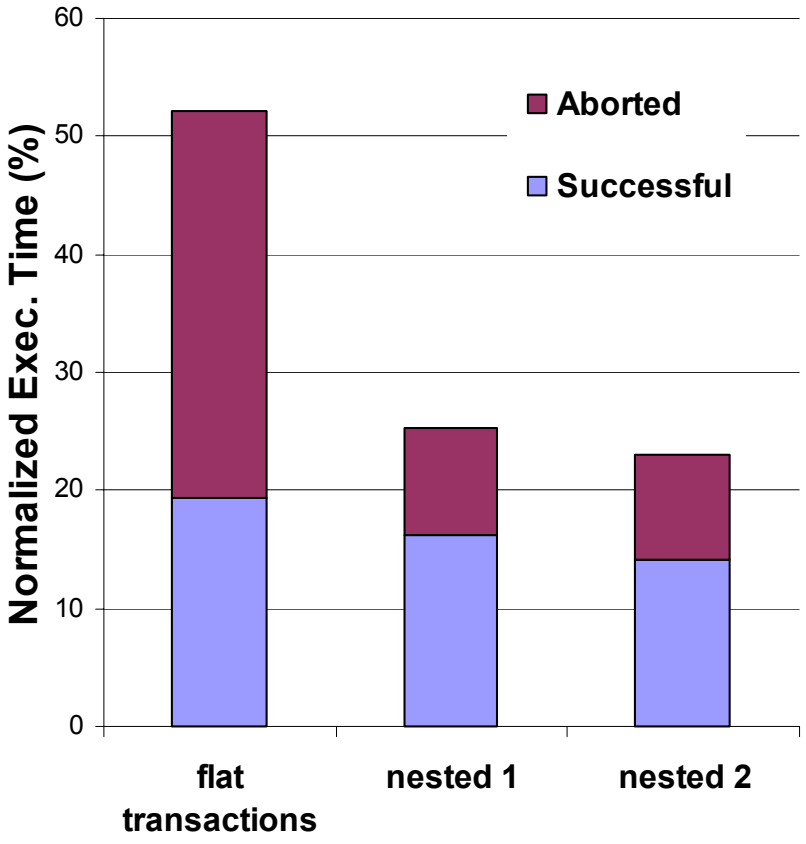
Transactional Code for NewOrder

```
TransactionManager::go() {
    atomic { // begin transaction
       // 1. initialize a new order transaction
       // 2. create a new order with unique order ID
       // 3. retrieve items and stocks from warehouse
       // 4. calculate cost and update warehouse
       // 5. record the order for delivery
       // 6. print the result of the process
    } // commit transaction
}
```

- Whole NewOrder as one atomic transaction
  - 2 lines of code changed
- Also tried nested transactional versions
  - To reduce frequency & cost of violations

HTM Performance

- Simulated 8-way CMP with TM support
  - Stanford's TCC architecture
  - Lazy versioning and optimistic conflict detection
- Speedup over sequential
  - Flat transactions: 1.9x
    - Code similar to coarse-grain locks
    - Frequent aborted transactions due to dependencies
  - Nested transactions: 3.9x to 4.2x
    - Reduced abort cost OR
    - Reduced abort frequency
- See paper in [WTW'06] for details
  - http://tcc.stanford.edu



HTM Virtualization (1)

- Hardware TM resources are limited
  - What if cache overflows? ➔ Space virtualization
  - What if time quanta expires? ➔ Time virtualization
  - HTM + interrupts, paging, thread migrations, …

- HTM virtualization approaches
  1. Dual TM implementation [Intel@PPoPP'06]
     - Start transaction in HTM; switch to STM on overflow
     - Carefully handle interactions between HTM & STM transactions
     - Typically requires 2 versions of the code
  2. Hybrid TM [Sun@ASPLOS'06]
     - HTM design is optional
     - Hash-based techniques to detect interaction between HTM & STM

HTM Virtualization Approaches (cont)

3. Virtualized TM [Intel@ISCA'05]
   - Map write-buffer/undo-log and read-/write-set to virtual memory
     - They become unbounded; they can be at any physical location
   - Caches capture working set of write-buffer/undo-log
     - Hardware and firmware handle misses, relocation, etc

4. eXtended TM [Stanford@ASPLOS'06]
   - Use OS virtualization capabilities (virtual memory)
     - On overflow, use page-based TM ➔ no HW/firmware needed
     - Overflow either all transaction state or just a part of it
   - Works well when most transactions are small
     - See common case study at HPCA'06
   - Smart interrupt handling
     - Wait for commit Vs. abort transaction Vs. virtualize transaction

Coarse-grain or Bulk HTM Support

- Concept
  - Track read and write addresses using signatures
    - Bloom filters implemented in hardware
  - Process sets of addresses at once using signature operations
    - To manage versioning and to detect conflicts
  - Adds 2Kbits per signature, 300 bits compressed

- Tradeoffs
  - \+ Conceptually simpler design
    - Decoupled from cache design and coherence protocol
  - – Inexact operations can lead to false conflicts
    - May lead to degradation
    - Depends on application behavior and signature mechanism

- See paper by Ceze et.al at ISCA'06

Transactional Coherence

- Key observation
  - Coherence & consistency only needed at transaction boundaries
- Transactional Coherence
  - Eliminate MESI coherence protocol
  - Coherence based on R/W bits
  - All coherence communication at commit points
- Bulk coherence creates hybrid between shared-memory and message passing
- See TCC papers at [ISCA'04], [ASPLOS'04], & [PACT'05]

```
foo() {
  work1();
  atomic {
     a.x = b.x;
     a.y = b.y;
  }
  work2();
}
```

Hardware TM Summary

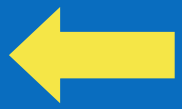
- High performance + compatibility with binary code,…
- Common characteristics
  - Data versioning in caches
  - Conflict detection through the coherence protocol
- Active research area; current research topics
  - Support for PL and OS development (see paper [ISCA'06])
    - Two-phase commit, transactional handlers, nested transactions
  - Development and comparison of various implementations
  - Hybrid TM systems
  - Scalability issues

Agenda

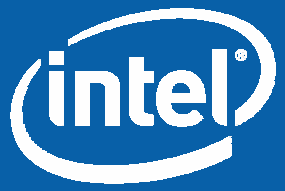
Multithreaded Programming

Transactional Memory (TM)

- TM Introduction
- TM Implementation Overview
- Hardware TM Techniques
- Software TM Techniques



Q&A



Software Transactional Memory

Bratin Saha
Programming Systems Lab
Intel Corporation

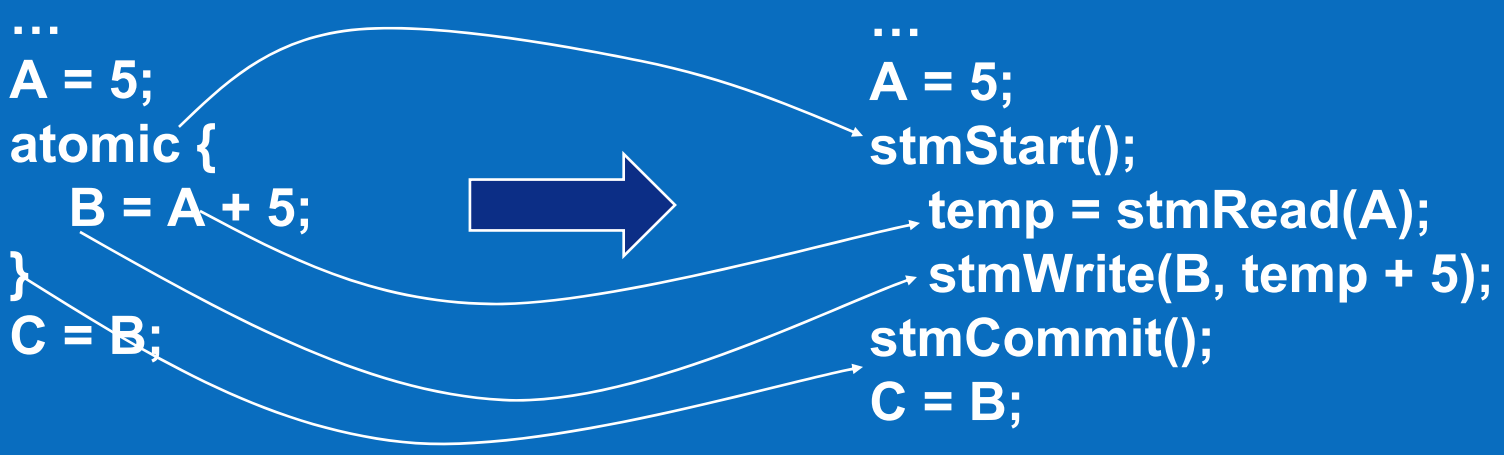
Outline

→Software Transactional Memory
- Translating a language construct
- Runtime support
- Compiler support

→ Hybrid Transactional Memory

→ Open issues & conclusions

Compiling Atomic



Transactional memory accessed via STM read & write functions

- Compiler inserts appropriate calls
- Code generation, control flow, optimizations in later slides

STM tracks accesses & detects data conflicts

Runtime Data Structures

Per-thread

- Transaction Descriptor
  - Read set, write set, & log
  - For validation, commit, & rollback
- Transaction Memento
  - Checkpoint of transaction descriptor
  - For nesting & partial rollback

Per-data

- Transaction Record (TxR)
  - Pointer-sized field guarding shared data
  - Track transactional state of data
    - Shared: Read-only access by multiple readers
    - Exclusive: write-only access by single owner

Mapping Data to Transaction Records

Every data item has an associated transaction record

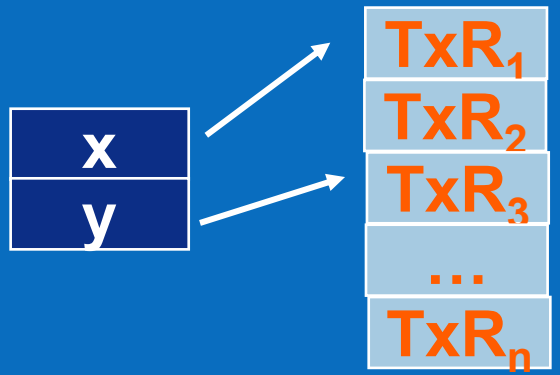
Object granularity (Java/C#)

```
class Foo {
   int x;
   int y;
}
```

TxR embedded in object

Cache line or word granularity (C/C++)

```
struct Foo {
   int x;
   int y;
}
```



Address-based hash into global TxR table

Implementing Atomicity: Example

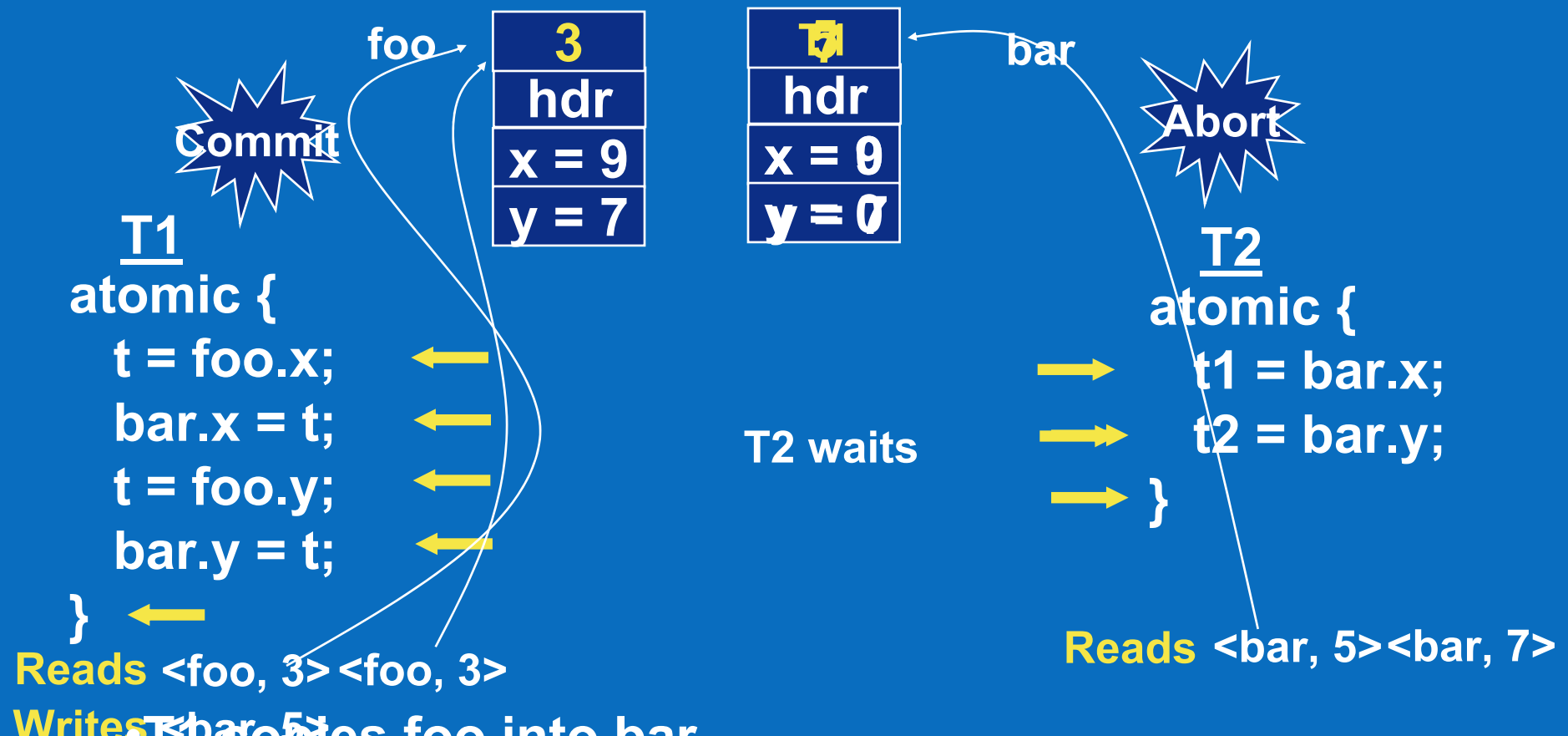
We will show one way to implement atomicity in a STM

Uses two phase locking for writes

Uses optimisitic concurrency for reads

Illustrates how transaction records are used

Example



- T1 copies foo into bar
- T2 should read [0, 0] or should read [9,7]

Ensuring Atomicity: Options

Memory Ops → Mode ↓	Reads	Writes
Pessimistic Concurrency	Read lock on TxR (reader-writer lock or reader list)	
Optimistic Concurrency	Use versioning on TxR	

Ensuring Atomicity: Options

Memory Ops → Mode ↓	Reads	Writes
Pessimistic Concurrency	- Caching effects - Lock operations	
Optimistic Concurrency	+ Caching effects + Avoids lock operations	

See Saha et al. PPoPP '06 paper for quantitative results

Ensuring Atomicity: Options

Memory Ops → Mode ↓	Reads	Writes
Pessimistic Concurrency		Write lock on TxR
Optimistic Concurrency		Buffer writes & acquire locks at commit

Ensuring Atomicity: Options

Memory Ops → Mode ↓	Reads	Writes
Pessimistic Concurrency		+ In place updates + Fast commits + Fast reads
Optimistic Concurrency		- Slow commits - Reads have to search for latest value

See Saha et al. PPoPP '06 paper for quantitative results

Java Virtual Machine Support

On-demand cloning of methods called inside transactions

JIT compiler automatically inserts read/write barriers

- Maps barriers to first class opcodes in intermediate representation
- Good compiler representation → greater optimization opportunities
- Determine conflict detection granularity on per-type basis

Garbage collection support

- Enumeration of references in STM data structures
- Filtering to remove redundant log entries
- Mappings are valid across moving GC

Representing Read/Write Barriers

Coarse-grain barriers hide redundant locking/logging

```
atomic {
        a.x = t1
        a.y = t2
        if(a.z == 0) {
                a.x = 0
                a.z = t3
        }
}
```

```
…
stmWr(&a.x, t1)
stmWr(&a.y, t2)
if(stmRd(&a.z) != 0) {
        stmWr(&a.x, 0);
        stmWr(&a.z, t3)
}
```

An STM IR for Optimization

Redundancies exposed:

```
atomic {
        a.x = t1
        a.y = t2
        if(a.z == 0) {
                a.x = 0
                a.z = t3
        }
}
```

```
txnOpenForWrite(a)
txnLogObjectInt(&a.x, a)
a.x = t1
txnOpenForWrite(a)
txnLogObjectInt(&a.y, a)
a.y = t2
txnOpenForRead(a)
if(a.z != 0) {
        txnOpenForWrite(a)
        txnLogObjectInt(&a.x, a)
        a.x = 0
        txnOpenForWrite(a)
        txnLogObjectInt(&a.z, a)
        a.z = t3
}
```

Optimized Code

Fewer & cheaper STM operations

```
atomic {
        a.x = t1
        a.y = t2
        if(a.z == 0) {
                a.x = 0
                a.z = t3
        }
}
```

```
txnOpenForWrite(a)
txnLogObjectInt(&a.x, a)
a.x = t1
txnLogObjectInt(&a.y, a)
a.y = t2
if(a.z != 0) {
        a.x = 0
        txnLogObjectInt(&a.z, a)
        a.y = t3
}
```

Compiler Optimizations for Transactions

Standard optimizations

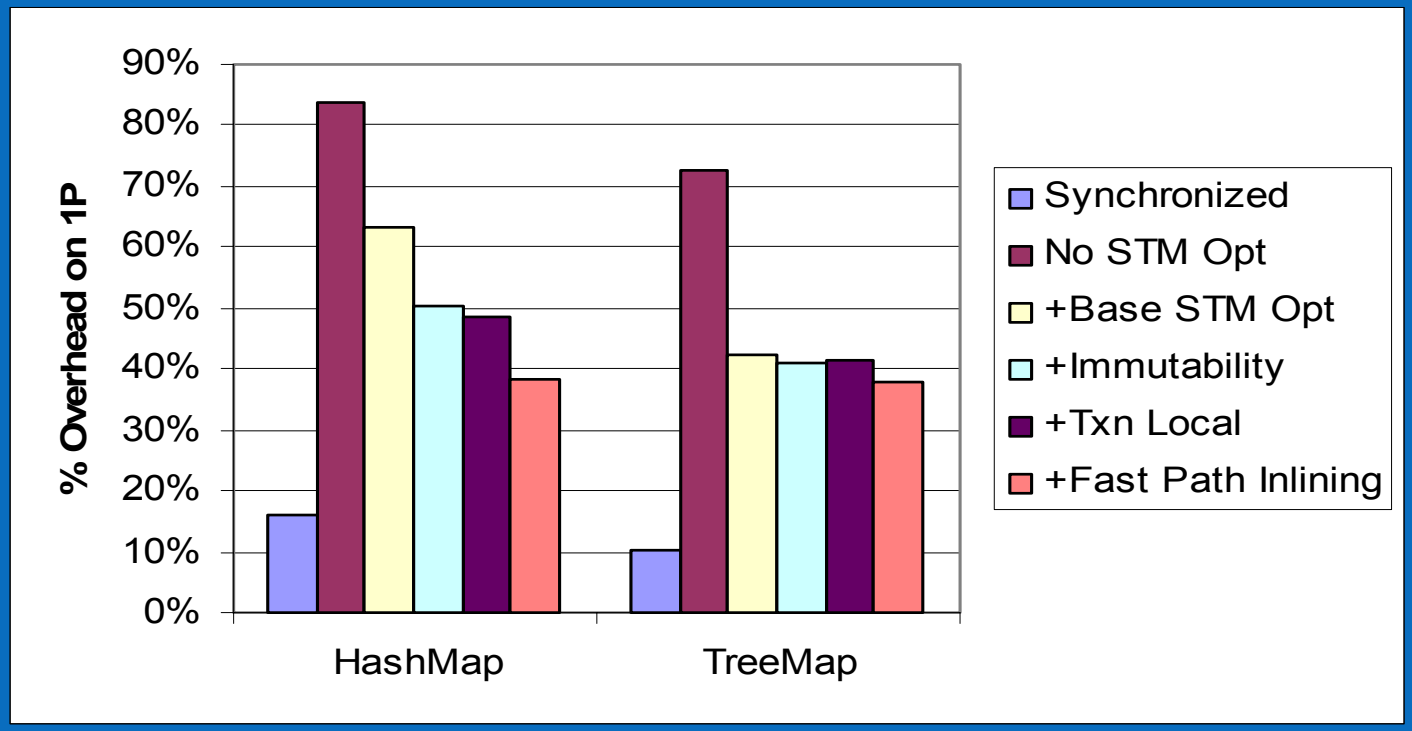
- CSE, Dead-code-elimination, …
- Careful IR representation exposes opportunities and enables optimizations with almost no modifications
- Subtle in presence of nesting

STM-specific optimizations

- Immutable field / class detection & barrier removal (vtable/String)
- Transaction-local object detection & barrier removal
- Partial inlining of STM fast paths to eliminate call overhead

Effect of Compiler Optimizations

1P overheads over thread-unsafe baseline



Prior STMs typically incur ~2x on 1P

With compiler optimizations:

- < 40% over no concurrency control
- < 30% over synchronization

Hybrid TM: Combining HTM with STM

General approach:

- Try transaction using HTM first
- Fall back on STM if HTM aborts
- Atomic blocks multiversioned for HTM & STM execution

Accelerates simple transaction

- Small
- Flat transactions

STM-STM conflicts detected by the STM machinery

HTM-HTM conflicts detected by the HTM machinery

HTM-STM conflicts requires additional code in the HTM code path

Hybrid TM: Basic Mechanism

```
HTMReadBarrier(addr)
   check transaction record for addr is not locked by a SW transaction
   if (transaction record free)
       read the address
   else
      abort

HTMWriteBarrier(addr)
   check transaction record for addr is not locked by a SW transaction
   if (transaction record is free)
       perform the write
       increment version number to indicate HTM modification
   else
       abort
```

HTM check ensures no concurrent SW TM modification

Research challenges

Performance
- Right mix of HW & SW components
- Good diagnostics & contention management

Semantics
- I/O & communication
- Nested parallelism

Debugging & performance analysis tools

System integration

Conclusions

Multi-core architectures: an inflection point in mainstream SW development

Navigating inflection requires new parallel programming abstractions

Transactions are a better synchronization abstraction than locks

- Software engineering and performance benefits

Lots of research on implementation and semantics issues

- Great progress, but there are still open problems