CS 698L: OpenMP

Swarnendu Biswas

Semester 2019-2020-I

CSE, IIT Kanpur

Content influenced by many excellent references, see References slide for acknowledgements.

Material adapted from

- Several tutorials by Tim Mattson et al.
- P. Sadayappan, Ohio State, CS 5441
- Blaise Barney, OpenMP Tutorial, LLNL

What is OpenMP?

- OpenMP (Open Multi-Processing) is a popular shared-memory programming API
- OpenMP supports C/C++ and Fortran on a wide variety of architectures
- OpenMP is supported by popular C/C++ compilers, for e.g., LLVM/Clang, GNU GCC, Intel ICC, and IBM XLC

What is OpenMP?

- A directive based parallel programming model
  - OpenMP program is essentially a sequential program augmented with compiler directives to specify parallelism
  - Eases conversion of existing sequential programs
- Standardizes established SMP practice + vectorization and heterogeneous device programming

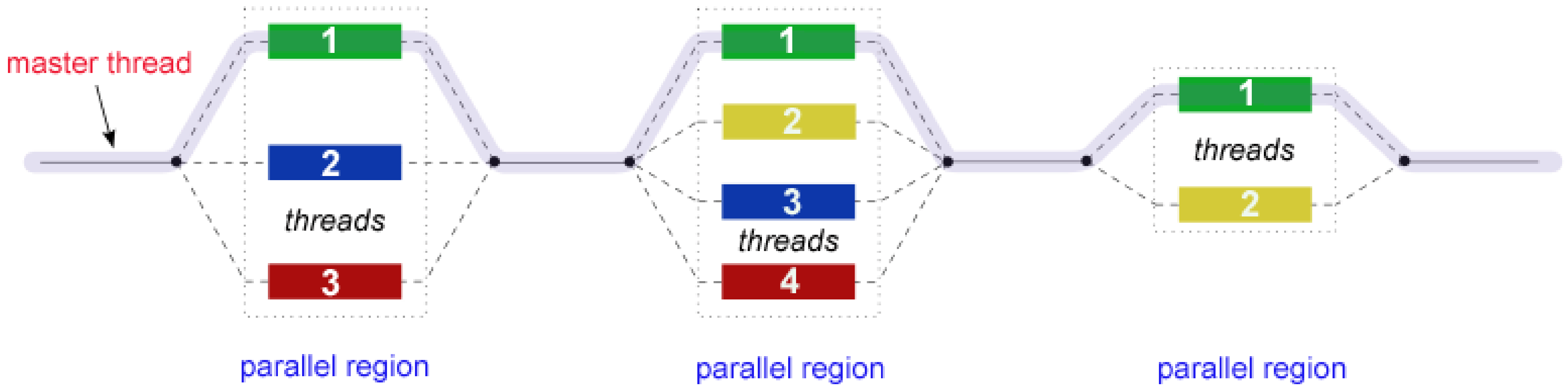
Key Concepts in OpenMP

- Parallel regions where parallel execution occurs via multiple concurrently executing threads
  - Each thread has its own program counter and executes one instruction at a time, similar to sequential program execution
- Shared and private data: shared variables are the means of communicating data between threads
- Synchronization: fundamental means of coordinating execution of concurrent threads
- Mechanism for **automated work distribution** across threads

Goals of OpenMP

- Standardization
  - Provide a standard among a variety of shared memory architectures/platforms
  - Jointly defined and endorsed by a group of major computer hardware and software vendors
- Ease of use
  - Provide capability to incrementally parallelize a serial program, unlike message-passing libraries which typically require an all or nothing approach
  - Provide the capability to implement both coarse-grain and fine-grain parallelism
- Portability
  - Most major platforms and compilers have OpenMP support

Fork-Join Model of Parallel Execution



Other Key Features

- Scope of data
  - Most data within a parallel region is shared by default
  - Programmers can control scope of access to data by different threads
- Nested parallelism
  - You can invoke a parallel region within another parallel region
- Dynamic threads and scheduling
  - The runtime can dynamically alter the number of parallel threads and also control the scheduling of work among threads

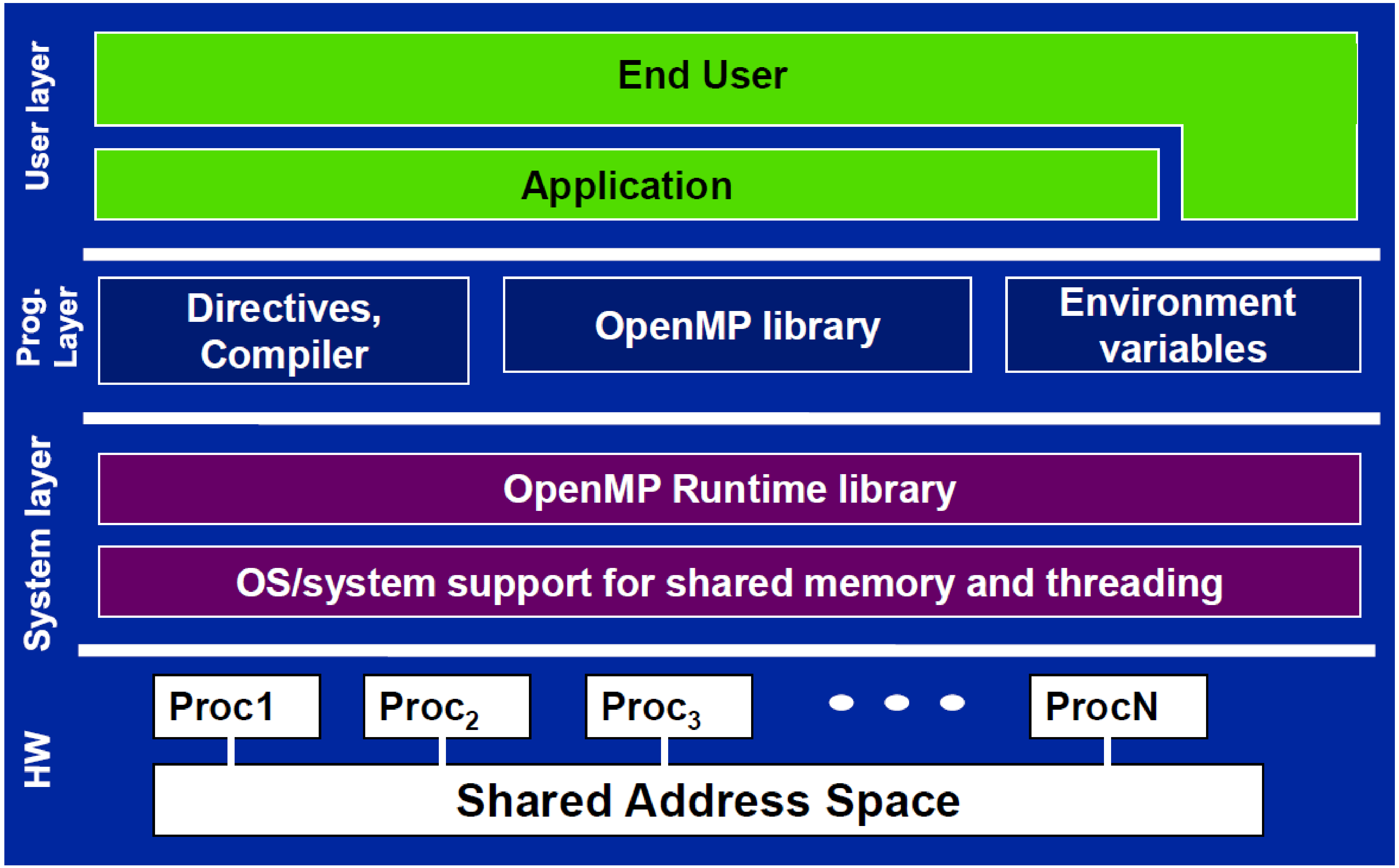
The OpenMP API

- Compiler directives
  - `#pragma omp parallel`
  - Comments, ignored unless instructed not to

- Runtime library routines
  - `int omp_get_num_threads(void);`

- Environment variables
  - `export OMP_NUM_THREADS=8`

OpenMP Solution Stack



General Code Structure

```
#include <omp.h>
…
int main() {
  …
  // serial code, master thread
  …
  // begin parallel section,
  // fork a team of threads
  #pragma omp parallel …
  {
    // parallel region executed by
    // all threads

    // other logic
    …
    // all parallel threads join
    // master thread
  }
  // resume serial code
  …
}
```

OpenMP Core Syntax

- Most common constructs in OpenMP are compiler directives
  - `#pragma omp directive [clause [clause]…] newline`
  - Example
    - `#pragma omp parallel num_threads(4)`
- Function prototypes and types in the file: `#include <omp.h>`
- Most OpenMP constructs apply to a **structured block**

Structured Block

- Structured block is a block of one or more statements surrounded by "{ }", with one point of entry at the top and one point of exit at the bottom
- It is okay to have an exit within the structured block
- Disallows code that branches into or out of the middle of the structured block

Format of Compiler Directives

- `#pragma omp`
  - Required for all OpenMP C/C++ directives
- `directive-name`
  - A valid OpenMP directive. Must appear after the pragma and before any clauses
  - Scope extends to the the structured block following a directive, does not span multiple routines or code files
- `[clause, ...]`
  - Optional. Clauses can be in any order, and repeated as necessary unless otherwise restricted
- `newline`
  - Required. Precedes the structured block which is enclosed by this directive.

Compiling an OpenMP Program

- Linux and GNU GCC
  - `g++ –fopenmp hello-world.cpp`
- Linux and Clang/LLVM
  - `clang++ -fopenmp hello-world.cpp`
- Can use the preprocessor macro `_OPENMP` to check for compiler support

Hello World with OpenMP!

```
#include <iostream>
#include <omp.h>

using namespace std;

int main() {
  cout << "This is serial code\n";
#pragma omp parallel
  {
    int num_threads = omp_get_num_threads();
    int tid = omp_get_thread_num();
    if (tid == 0) {
      cout << num_threads << "\n";
    }
    cout << "Hello World: " << tid << "\n";
  }

  cout << "This is serial code\n";
#pragma omp parallel num_threads(2)
  {
    int tid = omp_get_thread_num();
    cout << "Hello World: " << tid << "\n";
  }

  cout << "This is serial code\n";

  omp_set_num_threads(3);
#pragma omp parallel
  {
    int tid = omp_get_thread_num();
    cout << "Hello World: " << tid << "\n";
  }
}
```

Hello World with OpenMP!

- Each thread has a unique integer “id”; master thread has “id” 0, and other threads have “id” 1, 2, …
- OpenMP runtime function omp_get_thread_num() returns a thread’s unique “id”
- The function omp_get_num_threads() returns the total number of executing threads
- The function omp_set_num_threads(x) asks for “x” threads to execute in the next parallel region (must be set outside region)

Types of Parallelism with OpenMP

Coarse-grained

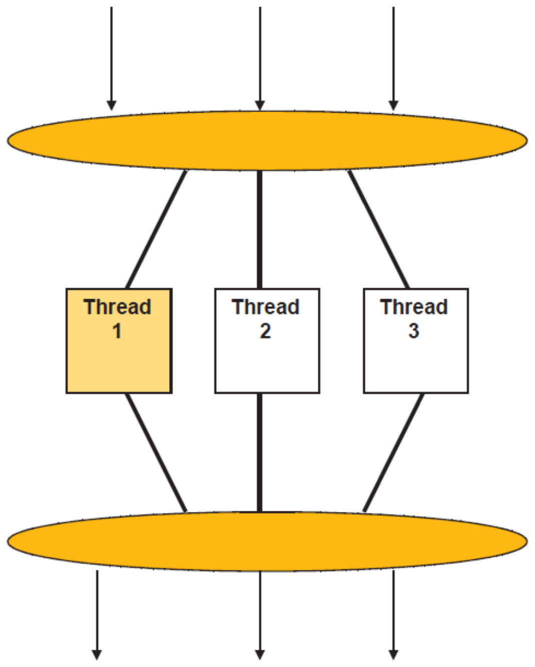
- Task parallelism
  - Split the work among threads that execute in parallel
  - Implicit join at the end of the segment, or explicit synchronization points

Fine-grained

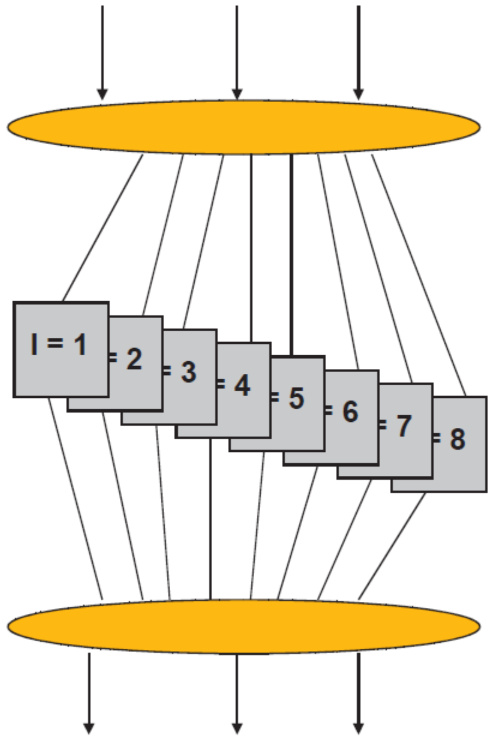
- Loop parallelism
  - Execute independent iterations of for-loops in parallel
  - Several choices in splitting the work

Types of Parallelism with OpenMP

Task parallelism



Loop parallelism



The Essence of OpenMP

- **Create threads that execute in a shared address space**
  - The only way to create threads is with the `parallel` construct
  - Once created, all threads execute the code inside the construct
- **Split up the work between threads by one of two means**
  - SPMD (Single Program Multiple Data) – all threads execute the same code and you use the thread ID to assign work to a thread
  - Workshare constructs split up loops and tasks between threads
- **Manage data environment to avoid data access conflicts**
  - Synchronization so correct results are produced regardless of how threads are scheduled
  - Carefully manage which data can be private (local to each thread) and shared

OpenMP Constructs

- A construct consists of an executable directive and the associated loop, statement, or structured block

```
#pragma omp parallel
{
  // inside parallel construct
  subroutine ( );
}

void subroutine (void) {
  // outside parallel construct
}
```

OpenMP Regions

- A region consists of all code encountered during a specific instance of the execution of a given construct. Also includes implicit code introduced by the OpenMP implementation.

```
#pragma omp parallel
{
  // inside parallel region
  subroutine ( );
}

void subroutine (void) {
  // inside parallel region
}
```

Parallel Region Construct

- Block of code that will be executed by multiple threads
- `#pragma omp parallel [`*`clause`*` …]`
  `structured_block`

- Example of clauses
  - `private (list)`
  - `shared (list)`
  - `default (shared | none)`
  - `firstprivate (list)`
  - `reduction (operator: list)`
  - `num_threads (integer-expression)`
  - …

Parallel Region Construct

- When a thread reaches a `parallel` directive, it creates a team of threads and becomes the master of the team
  - By default OpenMP creates as many thread as many cores available in the system
- The master is a member of that team and has thread number 0 within that team
- The code is duplicated and all threads will execute that code
- There is an implied barrier at the end of a parallel section
- Only the master thread continues execution past this point

Threading in OpenMP

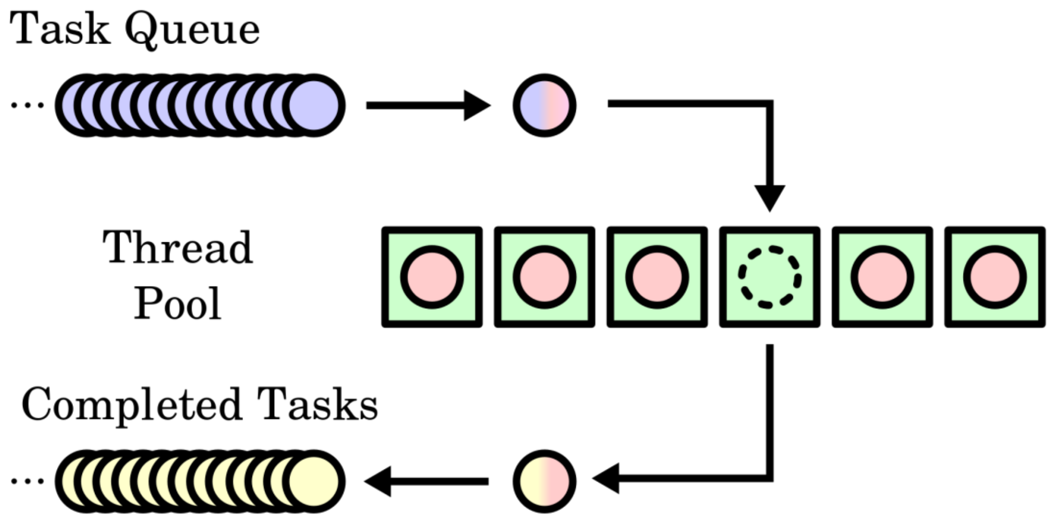
```
#pragma omp parallel
num_threads(4)
{
  foobar ();
}
```

- OpenMP implementations use a **thread pool** so full cost of threads creation and destruction is not incurred for reach parallel region
- Only three threads are created excluding the parent thread

```
void thunk () {
  foobar ();
}

pthread_t tid[4];

for (int i = 1; i < 4; ++i)
  pthread_create (&tid[i],0,thunk,
0);

for (int i = 1; i < 4; ++i)
  pthread_join (tid[i]);
```

Thread Pool

- Software design pattern
- Maintains a pool of threads waiting for work
- Advantageous when work is short-lived
  - Avoid the overhead of frequent thread creation and destruction
- Excess threads can degrade performance
  - Memory, context-switch, and other resource overhead



Specifying Number of Threads

- Desired number of threads can be specified in many ways
  - Setting environmental variable `OMP_NUM_THREADS`
  - Runtime OpenMP function `omp_set_num_threads(4)`
  - Clause in `#pragma` for parallel region

```
double A[1000];
#pragma omp parallel num_threads(4)
{
  int t_id = omp_get_thread_num();
  int nthrs = omp_get_num_threads();
  for (int i = t_id; i < 1000; i += nthrs) {
  A[i] = foo(i);
  }
}
```

Specifying Number of Threads

- Three ways
  - `OMP_NUM_THREADS`
  - `omp_set_num_threads(…)`
  - `#pragma omp parallel num_threads(…)`

- `OMP_NUM_THREADS` (if present) specifies initially the number of threads
- Calls to `omp_set_num_threads()` override the value of OMP_NUM_THREADS
- Presence of the `num_threads` clause overrides both other values

Distributing Work

- Threads can perform disjoint work division using their thread ids and knowledge of total # threads

```
double A[1000];
omp_set_num_threads(4);
#pragma omp parallel
{
  int t_id = omp_get_thread_num();
  for (int i = t_id; i < 1000; i += omp_get_num_threads()) {
    A[i]= foo(i);
  }
}
```

Cyclic distribution of work

Distributing Work

```
double A[1000];
omp_set_num_threads(4);
#pragma omp parallel
{
  int t_id = omp_get_thread_num();
  int num_thrs = omp_get_num_threads();
  int b_size = 1000 / num_thrs;
  for (int i = t_id*b_size; i < (t_id+1)*b_size; i += num_thrs) {
    A[i]= foo(i);
  }
}
```

Block distribution of work

Cyclic vs Block Distribution of Work

- Say I have a computation like

```
for (int i = 0; i < N; i++) {
  A[i] =  B[i] + C[i];
}
```

Would you prefer cyclic distribution or block distribution?

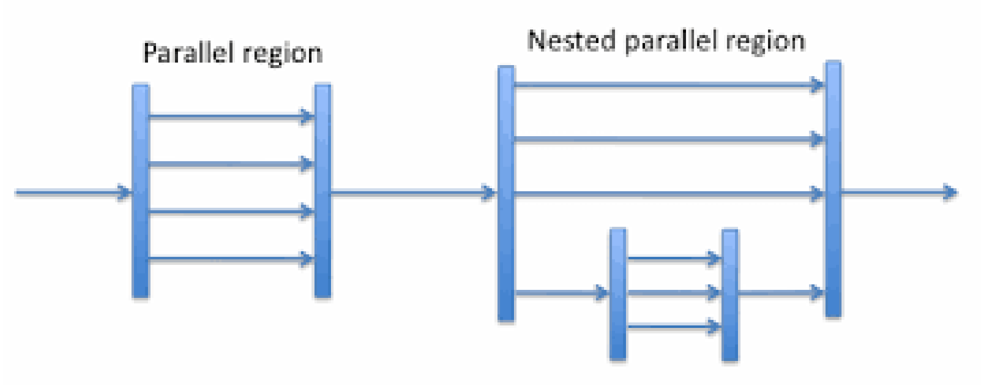
Other Subtle Issues about `parallel` Construct

- If a thread in a team executing a parallel region encounters another parallel directive, it creates a new team
- If execution of a thread terminates while inside a parallel region, execution of all threads in all teams terminates. The order of termination of threads is unspecified.

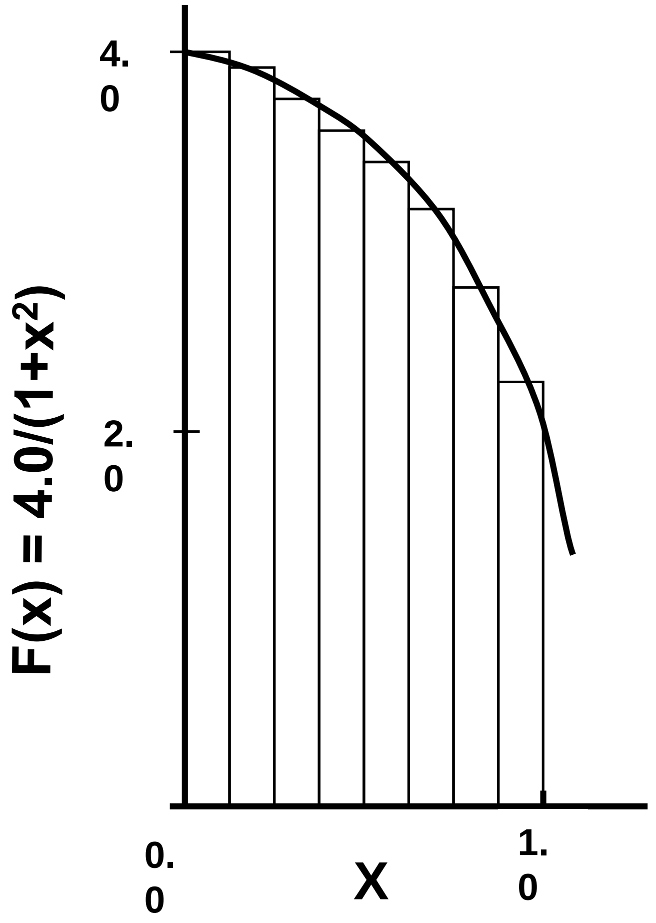
Nested Parallelism

- Allows to create parallel region within a parallel region itself
- Nested parallelism can help scale to large parallel computations
- Usually turned off by default
  - Can lead to oversubscription by creating lots of threads

- Set `OMP_NESTED` as `TRUE` or call `omp_set_nested()`



Recurring Example of Numerical Integration



- Mathematically

$$\int_0^1 \frac{4}{(1+x^2)}\,dx = \pi$$

- We can approximate the integral as the sum of the rectangles

$$\sum_{i=0}^{N} F(x_i)\Delta x \approx \pi$$

where each rectangle has width Δx and height $F(x_i)$ at the middle of interval *i*

Serial Pi Program

```
double seq_pi() {
  int i;
  double x, pi, sum = 0.0;
  double step = 1.0 / (double)NUM_STEPS;
  for (i = 0; i < NUM_STEPS; i++) {
    x = (i + 0.5) * step;
    sum += 4.0 / (1.0 + x * x);
  }
  pi = step * sum;
  return pi;
}
```

```
$ g++ -fopenmp compute-pi.cpp
$ ./a.out
3.14159
```

Computing Pi with OpenMP

```
double omp_pi_with_fs() {
  omp_set_num_threads(NUM_THRS);
  double sum[NUM_THRS] = {0.0};
  double pi = 0.0;
  double step = 1.0 / (double)NUM_STEPS;
  uint16_t num_thrs;

#pragma omp parallel
  {
    // Parallel region with worker threads
    uint16_t tid = omp_get_thread_num();
    uint16_t nthrds = omp_get_num_threads();
    if (tid == 0) {
      num_thrs = nthrds;
    }
    double x;
    for (int i = tid; i < NUM_STEPS; i += nthrds) {
      x = (i + 0.5) * step;
      sum[tid] += 4.0 / (1.0 + x * x);
    }
  } // end #pragma omp parallel
  for (int i = 0; i < num_thrs; i++) {
    pi += (sum[i] * step);
  }
  return pi;
}
```

Computing Pi with OpenMP

```
double omp_pi_with_fs() {
  omp_set_num_threads(NUM_THRS);
  double sum[NUM_THRS] = {0.0};
  double pi = 0
  double step =
  uint16_t num_

#pragma omp paral
  {
    // Parallel region with worker threads
    uint16_t tid = omp_get_thread_num();
    uint16_t nthrds = omp_get_num_threads();
```

```
    if (tid == 0) {
      num_thrs = nthrds;
    }

                              STEPS; i += nthrds) {

                              x * x);

  } // end #pragma omp parallel
  for (int i = 0; i < num_thrs; i++) {
    pi += (sum[i] * step);
  }
  return pi;
}
```

Great! This is a correct implementation, but…

Is there any problem with this code?

Avoid False Sharing

- Array `sum[]` is a shared array, with each thread accessing exactly on element
- Cache line holding multiple elements of sum will be locally cached by each processor in its private L1 cache
- When a thread writes into into an index in `sum`, the entire cache line becomes “dirty” and causes invalidation of that line in all other processor’s caches
- Cache thrashing due to this “false sharing” causes performance degradation

Optimize the Pi Program: Avoid False Sharing

```
double omp_pi_without_fs1() {
  omp_set_num_threads(NUM_THRS);
  double sum[NUM_THRS][8];
  double pi = 0.0;
  double step = 1.0 / (double)NUM_STEPS;
  uint16_t num_thrs;
#pragma omp parallel
  {
    uint16_t tid = omp_get_thread_num();
    uint16_t nthrds = omp_get_num_threads();
    if (tid == 0) {
      num_thrs = nthrds;
    }
    double x;
    for (int i = tid; i < NUM_STEPS; i += nthrds) {
      x = (i + 0.5) * step;
      sum[tid][0] += 4.0 / (1.0 + x * x);
    }
  } // end #pragma omp parallel

  for (int i = 0; i < num_thrs; i++) {
    pi += (sum[i][0] * step);
  }
  return pi;
}
```

Optimize the Pi Program: Avoid False Sharing

```
double omp_pi_without_fs1() {
  omp_set_num_threads(NUM_THRS);
  double sum[NUM_THRS][8];
  double pi = 0.0;
  double step = 1.0 /
  uint16_t num_thrs;
#pragma omp parallel
  {
    uint16_t tid = omp_get_thread_num();
    uint16_t nthrds = omp_get_num_threads();
    if (tid == 0) {
      num_thrs = nthrds;
    }
```

```
    double x;
    for (int i = tid; i < NUM_STEPS; i += nthrds) {
      x = (i + 0.5) * step;
      sum[tid][0] += 4.0 / (1.0 + x * x);

                      lel

  for (int i = 0; i < num_thrs; i++) {
    pi += (sum[i][0] * step);
  }
  return pi;
}
```

How did we decide that PADDING has to be 8?

Optimize the Pi Program: Avoid False Sharing

```
double omp_pi_without_fs1() {
  omp_set_num_threads(NUM_THRS);
  double su
  double pi
  double st
  uint16_t
#pragma omp
  {
    uint16_t tid = omp_get_thread_num();
    uint16_t nthrds = omp_get_num_threads();
    if (tid == 0) {
      num_thrs = nthrds;
    }
```

```
      double x;
      for (int i = tid; i < NUM_STEPS; i += nthrds) {

                                                  * x);


                                                 {
      pi += (sum[i][0] * step);
    }
    return pi;
  }
```

How did we decide that PADDING has to be 8?

- Depends on the cache line size and the data type
- This is not portable, since it may not work across different cache configurations, architectures, and data types.

Optimize the Pi Program: Avoid False Sharing

```
double omp_pi_without_fs2() {
  omp_set_num_threads(NUM_THRS);
  double pi = 0.0;
  double step = 1.0 / (double)NUM_STEPS;
  uint16_t num_thrs;
#pragma omp parallel
  {
    uint16_t tid = omp_get_thread_num();
    uint16_t nthrds = omp_get_num_threads();
    if (tid == 0) {
      num_thrs = nthrds;
    }
    double x, sum;
    for (int i = tid; i < NUM_STEPS; i += nthrds) {
      x = (i + 0.5) * step;
      // Scalar variable sum is
      // thread-private, so no false sharing
      sum += 4.0 / (1.0 + x * x);
    }

    pi += (sum * step);
  } // end #pragma omp parallel

  return pi;
}
```

Optimize the Pi Program: Avoid False Sharing

```
double omp_pi_without_fs2() {
  omp_set_num_threads(NUM_THRS);
  double pi = 0.0;
  double step = 1.0 / (double)NUM_STEPS;
  uint16_t num_thrs;
#pragma omp parallel
  {
    uint16_t tid = omp_get_thread_num();
    uint16_t nthrds = omp_get_num_threads();
    if (tid == 0) {
      num_thrs = nthrds;
    }
```

```
    double x, sum;
    for (int i = tid; i < NUM_STEPS; i += nthrds) {
      x = (i + 0.5) * step;
      // Scalar variable sum is
                          so no false sharing
                          x * x);
    

    pi += (sum * step);
  } // end #pragma omp parallel

  return pi;
}
```

This program is now wrong! Why?

Synchronization Constructs

`critical` Construct

- Only one thread can enter critical section at a time; others are held at entry to critical section
- Prevents any race conditions in updating “res”

```
float res;
#pragma omp parallel
{
  float B;
  int id = omp_get_thread_num();
  int nthrds = omp_get_num_threads();
  for (int i = id; i < MAX; i += nthrds) {
    B = big_job(i);
#pragma omp critical
    consume (B, res);
  }
}
```

`critical` Construct

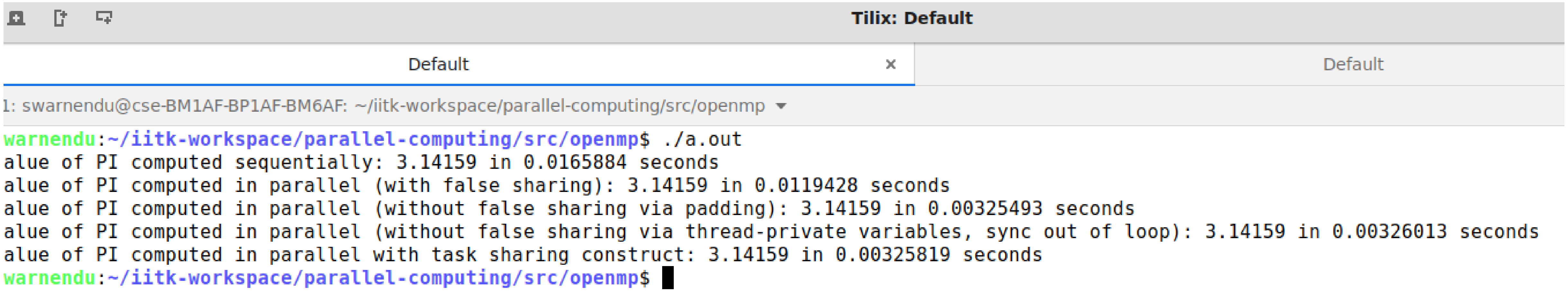
- Works by acquiring a lock
- If your code has multiple `critical` sections, they are all mutually exclusive
- You can avoid this by naming `critical` sections
  - `#pragma omp critical (optional_name)`

Correct Pi Program: Fix the Data Race

```
double omp_pi_without_fs2() {
  omp_set_num_threads(NUM_THRS);
  double pi = 0.0, step = 1.0 / (double)NUM_ST
EPS;
  uint16_t num_thrs;
#pragma omp parallel
  {
    uint16_t tid = omp_get_thread_num();
    uint16_t nthrds = omp_get_num_threads();
    if (tid == 0) {
      num_thrs = nthrds;
    }
    double x, sum;
    for (int i = tid; i < NUM_STEPS; i += nthrds) {
      x = (i + 0.5) * step;
      // Scalar variable sum is
      // thread-private, so no false sharing
      sum += 4.0 / (1.0 + x * x);
    }
#pragma omp critical // Mutual exclusion
    pi += (sum * step);
  } // end #pragma omp parallel

  return pi;
}
```

Evaluate the Pi Program Variants

- Sequential computation of pi
- Parallel computation with false sharing
- Parallel computation with padding
- Parallel computation with thread-local sum


Tilix: Default
Default
Default
1: swarnendu@cse-BM1AF-BP1AF-BM6AF: ~/iitk-workspace/parallel-computing/src/openmp

```
warnendu:~/iitk-workspace/parallel-computing/src/openmp$ ./a.out
alue of PI computed sequentially: 3.14159 in 0.0165884 seconds
alue of PI computed in parallel (with false sharing): 3.14159 in 0.0119428 seconds
alue of PI computed in parallel (without false sharing via padding): 3.14159 in 0.00325493 seconds
alue of PI computed in parallel (without false sharing via thread-private variables, sync out of loop): 3.14159 in 0.00326013 seconds
alue of PI computed in parallel with task sharing construct: 3.14159 in 0.00325819 seconds
warnendu:~/iitk-workspace/parallel-computing/src/openmp$
```

`atomic` Construct

- Atomic is an efficient critical section for simple reduction operations
- Applies only to the update of a memory location
- Uses hardware atomic instructions for implementation; much lower overhead than using critical section

```
float res;
#pragma omp parallel
{
  float B;
  int id = omp_get_thread_num();
  int nthrds = omp_get_num_threads();
  for (int i = id; i < MAX; i += nthrds) {
    B = big_job(i);
#pragma omp atomic
    res += B;
  }
}
```

`atomic` Construct

- Expression operation can be of type
  - x binop= expr
    - x is a scalar type
    - binop can be +, *, -, /, &, ^, |, <<, or >>
  - x++
  - ++x
  - x--
  - --x

```
float res;
#pragma omp parallel
{
  float B;
  int id = omp_get_thread_num();
  int nthrds = omp_get_num_threads();
  for (int i = id; i < MAX; i += nthrds) {
    B = big_job(i);
#pragma omp atomic
    res += B;
  }
}
```

`critical` vs `atomic`

`critical`

- Locks code segments
- Serializes all unnamed critical sections
- Less efficient than `atomic`
- More general

`atomic`

- Locks data variables
- Serializes operations on the same shared data
- Makes use of hardware instructions to provide atomicity
- Less general

Is `atomic` is always the way to go?

```
int sum = 0, m_val = 0;

#pragma omp parallel for
  for (int i = 0; i < N; i++) {
#pragma omp atomic
    sum += getVal();
  }

int getVal() {
  return ++m_val;
}
```

Barrier Synchronization

```
#pragma omp parallel private(id)
{
  int id=omp_get_thread_num();
  A[id] = big_calc1(id);

#pragma omp barrier

  B[id] = big_calc2(id);
}
```

explicit barrier

- Each thread waits until all threads arrive

Barrier Synchronization

```
#pragma omp parallel private(id)
{
  int id=omp_get_thread_num();
  A[id] = big_calc1(id);

#pragma omp barrier

#pragma omp for
  for (i=0;i<N;i++) {
    B[i]=big_calc2(i,A);
  }
```

explicit barrier

implicit barrier

```
#pragma omp for nowait
  for (i=0;i<N;i++) {
    C[i]=big_calc2(B, i);
  }

  A[id] = big_calc4(id);
}
```

no implicit barrier, nowait cancels barrier creation

Use of `nowait` clause

Can be useful if the two loops are independent

```
# pragma omp for nowait
for ( /* ... */ ) {
  // .. first loop ..
}

# pragma omp for
for ( /* ... */ ) {
  // .. second loop ..
}
```

```
# pragma omp for nowait
for (int i=0; i<N; i++ ) {
  a[i] = b[i] + c[i];
}

# pragma omp for
for (int i=0; i<N; i++) {
  d[i] = a[i] + b[i];
}
```

Clause `ordered`

- Specifies that iterations of the enclosed loop will be executed in the same order as if they were executed on a **serial** processor
- It must appear within the extent of `omp for` or `omp parallel for`
- **Should be used in two stages**

```
omp_set_num_threads(4);
#pragma omp parallel
{
#pragma omp for ordered
  for (int i=0; i<N; i++) {
    tmp = func1(i);
#pragma omp ordered
   cout << tmp << “\n”;
  }
}
```

Synchronization Constructs

High-level

- `critical`
- `atomic`
- `barrier`
- `ordered`

Low-level

- `locks`
- `flush`

Synchronization with Locks

- More flexible than critical sections (can use multiple locks)
- `critical` locks a code segment, while locks lock data
- More error-prone
  - For example, deadlock if a thread does not unset a lock after acquiring it

```
omp_lock_t lck;
omp_init_lock(&lck);
#pragma omp parallel
{
  do_many_things();
  omp_set_lock(&lck);
  // critical section
  omp_unset_lock(&lck);
  do_many_other_things ();
}
omp_destroy_lock(&lck);
```

Synchronization with Locks

- Nested locks can be acquired if it is available or owned by the same thread

- `omp_init_lock()`
- `omp_set_lock()`
- `omp_unset_lock()`
- `omp_test_lock()`
- `omp_destroy_lock()`

- `omp_init_nest_lock()`
- `omp_set_nest_lock()`
- `omp_unset_nest_lock()`
- `omp_test_nest_lock()`
- `omp_destroy_nest_lock()`

Synchronization Construct: `flush`

- `#pragma omp flush (list)`

- Identifies a point at which a thread is guaranteed to see a consistent view of memory with respect to the variables in "`list`"
  - Flush forces data to be updated in memory so other threads see the most recent value
- In the absence of a list, all shared objects are synchronized

Synchronization Construct: `flush`

- If `list` contains a pointer, the pointer is flushed, not the object referred to by the pointer
- It is recommended not to use flushes, excepting certain cases where you want to implement say your own spin lock
- Flushes are expensive, since they require compilers to generate memory fences

Clause `master`

```
#pragma omp parallel
{
  do_many_things();
#pragma omp master
  {
    reset_boundaries();
  }
  do_many_other_things();
}
```

multiple threads of control

only master thread executes this region, other threads just skip it, no barrier is implied

multiple threads of control

Clause `single`

```
#pragma omp parallel
{
  do_many_things();
#pragma omp single
  {
    reset_boundaries();
  }

  do_many_other_things();
}
```

multiple threads of control

a single thread executes this region, may not be the master thread

implicit barrier, all other threads wait; can remove with nowait clause

multiple threads of control

Simplify Control Flow: Use `single`

```
double omp_pi_without_fs2() {
  omp_set_num_threads(NUM_THRS);
  double pi = 0.0, step = 1.0 / (double)NUM_ST
EPS;
  uint16_t num_thrs;
#pragma omp parallel
  {
    uint16_t tid = omp_get_thread_num();
    uint16_t nthrds = omp_get_num_threads();

#pragma omp single
      num_thrs = nthrds;
```

```
    double x, sum;
    for (int i = tid; i < NUM_STEPS; i += nthrds) {
      x = (i + 0.5) * step;
      // Scalar variable sum is
      // thread-private, so no false sharing
      sum += 4.0 / (1.0 + x * x);
    }
#pragma omp critical // Mutual exclusion
    pi += (sum * step);
  }
  return pi;
}
```

Reductions in OpenMP

- Reductions are common patterns
  - True dependence that cannot be removed
- OpenMP provides special support via `reduction` clause
  - OpenMP compiler automatically creates local variables for each thread, and divides work to form partial reductions, and code to combine the partial reductions
- Predefined set of **associative** operators can be used with reduction clause,
  - For e.g., +, *, -, min, max

```
double sum = 0.0;

omp_set_num_threads(N);
#pragma omp parallel
  double my_sum = 0.0;
  my_sum = func(omp_get_thread_num());
#pragma omp critical
  sum += my_sum;
```

Reductions in OpenMP

- Reductions clause specifies an operator and a list of reduction variables (must be **shared** variables)
- OpenMP compiler creates a local copy for each reduction variable, initialized to operator's identity (e.g., 0 for +; 1 for *)
- After work-shared loop completes, contents of local variables are combined with the "entry" value of the shared variable
- Final result is placed in shared variable

```
double sum = 0.0;

omp_set_num_threads(N);
#pragma omp parallel reduction(+ : sum)
  sum += func(omp_get_thread_num());
```

Reduction Operators and Initial Values

C/C++ only

Operator	Initial value
+	0
*	1
-	0
Min	Largest positive number
Max	Smallest negative number

Operator	Initial value
&	~0
|	0
^	0
&&	1
||	0

Computing Pi with OpenMP

```
double omp_pi_with_fs() {
  omp_set_num_threads(NUM_THRS);
  double sum[NUM_THRS] = {0.0};
  double pi = 0.0;
  double step = 1.0 / (double)NUM_STEPS;
  uint16_t num_thrs;

#pragma omp parallel
  {
    // Parallel region with worker threads
    uint16_t tid = omp_get_thread_num();
    uint16_t nthrds = omp_get_num_threads();
```

```
#pragma omp single
    num_thrs = nthrds;
    double x;
    for (int i = tid; i < NUM_STEPS; i += nthrds) {
      x = (i + 0.5) * step;
      sum[tid] += 4.0 / (1.0 + x * x);
    }
  } // end #pragma omp parallel

#pragma omp parallel for reduction(+ : pi)
  for (int i = 0; i < num_thrs; i++) {
    pi += (sum[i] * step);
  }
  return pi;
}
```

Data Sharing

Understanding Scope of Shared Data

- As with any shared-memory programming model, it is important to identify shared data
  - Multiple child threads may read and update the shared data
  - Need to coordinate communication among the team by proper initialization and assignment to variables

- Scope of a variable refers to the set of threads that can access the thread in a `parallel` block

Data Scope

- Variables (declared outside the scope of a parallel region) are **shared** among threads unless explicitly made private
- A variable in a parallel region can be either shared or private
  - Variables **declared** within parallel region scope are **private**
  - Stack variables declared in functions called from within a parallel region are private

Implicit Rules

```
int n = 10, a = 7;

#pragma omp parallel
{
  …
  int b = a + n;
  b++;
  …
}
```

- n and a are shared variables
- b is a private variable

Data Sharing: `shared` Clause

- `shared (list)`
  - Shared by all threads, all threads access the same storage area for shared variables
- `#pragma omp parallel shared(x)`

- Responsibility for synchronizing accesses is on the programmer

Data Sharing: `private` Clause

- `private (list)`
  - A new object is declared for each thread in the team
  - Variables declared private should be assumed to be uninitialized for each thread

- `#pragma omp parallel private(x)`
  - Each thread receives its own **uninitialized** variable x
  - Variable x falls out-of-scope after the parallel region
  - A global variable with the same name is unaffected (v3.0 and later)

Understanding the `private` clause

```
int p = 0;

#pragma omp parallel private(p)
{
  // value of p is undefined
  p = omp_get_thread_num();
  // value of p is defined
  …
}
// value of p is undefined
```

Clause `firstprivate`

- `firstprivate (list)`
  - Variables in `list` are private, and are initialized according to the value of their original objects **prior** to entry into the parallel construct

- `#pragma omp parallel firstprivate(x)`
  - x must be a global-scope variable
  - Each thread receives a **by-value copy** of x
  - The local x's fall out-of-scope after the parallel region
  - The base global variable with the same name is unaffected

Clause `firstprivate`

```
incr = 0;
#pragma omp parallel firstprivate(incr)
  {
    ...
    for (i = 0; i <= MAX; i++) {
      if ((i%2)==0) incr++;
    }
  }
```

Each thread gets its own copy of incr with an initial value of 0

Clause `lastprivate`

- `lastprivate (list)`
  - Variables in `list` are private, the values from the **last (sequential)** iteration or section is copied back to the original objects

```
void sq2(int n, double *lastterm) {
  double x; int i;
#pragma omp parallel for lastprivate(x)
  for (i = 0; i < n; i++) {
    x = a[i]*a[i] + b[i]*b[i];
    b[i] = sqrt(x);
  }
  *lastterm = x;
}
```

"x" has the value it held for the "last sequential" iteration, i.e., for i=(n-1)

Clause `default`

- `default (shared | none)`
  - Specify a default scope for all variables in the lexical extent of any parallel region

```
int a, b, c, n;


#pragma omp parallel for
default(shared), private(a, b)
for (int i = 0; i < n; i++) {
  // a and b are private variables
  // c and n are shared variables
}
```

Clause `default`

```
int n = 10;
std::vector<int> vector(n);
int a = 10;

#pragma omp parallel for default(none) shared(n, vector)
for (int i = 0; i < n; i++) {
  vector[i] = i*a;
}
```

Is this snippet correct?

Data Sharing Example

```
A = 1,B = 1, C = 1
#pragma omp parallel private(B) firstprivate(C)
```

- What can we say about the scope of A, B, and C, and their values?

Data Sharing Example

```
A = 1,B = 1, C = 1
#pragma omp parallel private(B) firstprivate(C)
```

- What can we say about the scope of A, B, and C, and their values?

- Inside the parallel region
    - “A” is shared by all threads; equals 1
    - “B” and “C” are local to each thread.
        - B’s initial value is undefined
        - C’s initial value equals 1
- Following the parallel region
    - B and C revert to their original values of 1
    - A is either 1 or the value it was set to inside the parallel region

Data Sharing Example

```
double A[10];
int main() {
  int index[10];
#pragma omp parallel
  work(index);
  printf(“%d\n”, index[0]);;
}

void work(int *index) {
  double temp[10];
  static int count;
  ...
}
```

A, index and count are shared by all threads

temp is local to each thread

Threadprivate Variables

- A threadprivate variable provides one instance of a variable for each thread
- The variable refers to a unique storage block in each thread
- Enables persistent private variables, not limited in lifetime to one parallel region

```
int a, b;
# pragma omp threadprivate (a, b)
// a and b are thread-private
```

`private` vs `threadprivate`

`private`

- Local to a parallel region
- Mostly allocated on the stack
- Value is assumed to be undefined on entry and exit from a parallel region

`threadprivate`

- Persists across parallel regions
- Mostly allocated on the heap on thread-local storage
- Value is undefined on entry to the first parallel region

Clause `copyin`

- Used to initialize threadprivate data upon entry to a parallel region
- Specifies that the master thread's value of a threadprivate variable should be copied to the corresponding variables in the other threads

```
int a, b;
…
# pragma omp threadprivate (a, b)
  // .. code ..
# pragma omp parallel copyin (a, b)
{
  // a and b copied from master thread
}
```

Summary of Data Sharing Rules

- Variables are shared by default
- Variables declared within parallel blocks and subroutines called from within a parallel region are private (reside on a stack private to each thread), unless scoped otherwise
- Default scoping rule can be changed with `default` clause

- Recommended
  - Always use the `default(none)` clause
  - Declare private variables in the `parallel` region

Runtime Routines and Environment Variables

Runtime Library Routines

- `omp_set_num_threads()`
- `omp_get_num_threads()`
- `omp_get_thread_num()`
- `omp_get_max_threads()`
- `omp_in_parallel()`
- `omp_set_dynamic()`
- `omp_get_dynamic()`
- `omp_num_procs()`
- …

Environment Variables

- Set the default number of threads to use
    - `OMP_NUM_THREADS int_literal`
- Control the size of child threads' stack
    - `OMP_STACKSIZE`
- Hint to runtime how to treat idle threads
    - `OMP_WAIT_POLICY`
    - `ACTIVE` keep threads alive at barriers/locks
    - `PASSIVE` try to release processor at barriers/locks
- Process binding is enabled if this variable is true, the runtime will not move threads around between processors
    - `OMP_PROC_BIND true | false`
- `...`

Worksharing Construct

Worksharing Construct

- Loop structure in parallel region is same as sequential code
- No explicit thread-id based work division; instead system automatically divides loop iterations among threads
- User can control work division: block, cyclic, block-cyclic, etc., via "schedule" clause in `pragma`

```
float res;
#pragma omp parallel
{
#pragma omp for
  for (int i = 0; i < MAX; i++) {
    B = big_job(i);
  }
}
```

Worksharing Construct

```
#pragma omp parallel
{
#pragma omp for
  for (int i=0; i<N; i++) {
    func1(i);
  }
}
```

If the team consists of only one thread then the worksharing region is not executed in parallel.

Variable i is made “private” to each thread by default. You could also do this explicitly with a “private(i)” clause.

Worksharing Construct

```
for(i=0;i< N;i++) {
  a[i] = a[i] + b[i];
}
```

sequential code

work sharing construct

```
#pragma omp parallel
#pragma omp for
for(i=0;i<N;i++) {
  a[i] = a[i] + b[i];
}
```

OpenMP parallel region

```
#pragma omp parallel
{
  int id, i, Nthrds, istart, iend;
  id = omp_get_thread_num();
  Nthrds = omp_get_num_threads();
  istart = id * N / Nthrds;
  iend = (id+1) * N / Nthrds;
  if (id == Nthrds-1) iend = N;
  for(i=istart;i<iend;i++) {
    a[i] = a[i] + b[i];
  }
}
```

Combined Worksharing Construct

```
float res;
#pragma omp parallel
{
#pragma omp for
  for (int i = 0; i < MAX; i++) {
    B = big_job(i);
#pragma omp critical
    consume (B, res);
  }
}
```

```
float res;
#pragma omp parallel for
for (int i = 0; i < MAX; i++) {
  B = big_job(i);
#pragma omp critical
  consume (B, res);
}
```

Often a parallel region has a single work-shared loop

Limitations on the Loop Structure

- Loops need to be in the canonical form
  - Cannot use `while` or `do-while`
- Loop variable must have integer or pointer type
- Cannot use a loop where the trip count cannot be determined

- `for (index = start; index < end; index++)`
- `for (index = start; index >= end; index = index - incr)`

Take Care with the Worksharing Construct

OpenMP compiler will not check for dependences

Take Care when Sharing Data

```
#pragma omp parallel for
{
  for(i=0; i<n; i++) {
    tmp = 2.0*a[i];
    a[i] = tmp;
    b[i] = c[i]/tmp;
  }
}
```

```
#pragma omp parallel for
private(tmp)
{
  for(i=0; i<n; i++) {
    tmp = 2.0*a[i];
    a[i] = tmp;
    b[i] = c[i]/tmp;
  }
}
```

Take Care when Sharing Data

```
int i = 0, n = 10, a = 7;

#pragma omp parallel for
  for (i = 0; i< n; i++) {
    int b = a + i;
  }
```

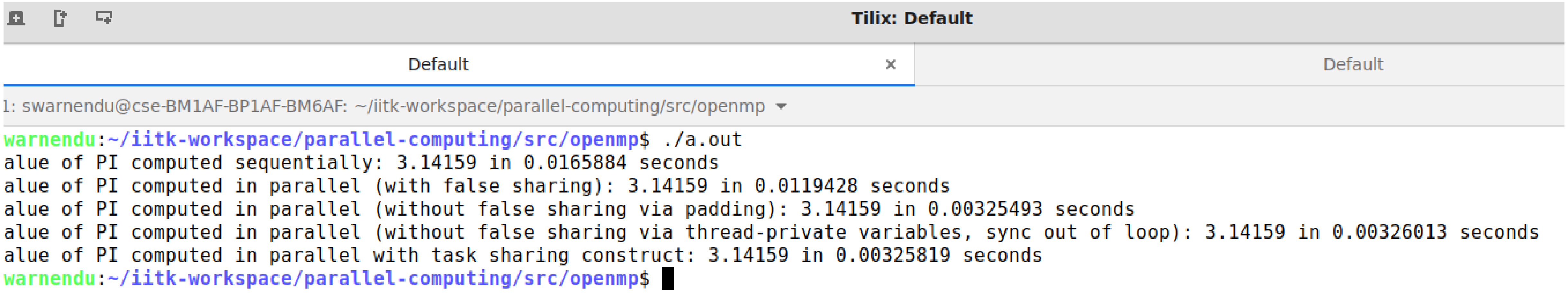
- n and a are shared variables
- b is a private variable
- A loop iteration variable is private by default
    - So i is private

Our Refined Pi Implementation

```
double omp_pi() {
  double x, pi, sum = 0.0;
  double step = 1.0 / (double)NUM_STEPS;

#pragma omp parallel for private(x) reduction(+ : sum) num_threads(NUM_THRS)
  for (int i = 0; i < NUM_STEPS; i++) {
    x = (i + 0.5) * step;
    sum += 4.0 / (1.0 + x * x);
  }
  pi = step * sum;
  return pi;
}
```

Evaluate the Pi Program Variants

- Sequential computation of pi
- Parallel computation with false sharing
- Parallel computation with padding
- Parallel computation with thread-local sum
- Worksharing construct



Tilix: Default

Default

Default

1: swarnendu@cse-BM1AF-BP1AF-BM6AF: ~/iitk-workspace/parallel-computing/src/openmp

```
warnendu:~/iitk-workspace/parallel-computing/src/openmp$ ./a.out
alue of PI computed sequentially: 3.14159 in 0.0165884 seconds
alue of PI computed in parallel (with false sharing): 3.14159 in 0.0119428 seconds
alue of PI computed in parallel (without false sharing via padding): 3.14159 in 0.00325493 seconds
alue of PI computed in parallel (without false sharing via thread-private variables, sync out of loop): 3.14159 in 0.00326013 seconds
alue of PI computed in parallel with task sharing construct: 3.14159 in 0.00325819 seconds
warnendu:~/iitk-workspace/parallel-computing/src/openmp$ 
```

Finer Control on Work Distribution

- The `schedule` clause determines how loop iterators are mapped onto threads
  - Most implementations use block partitioning

- `#pragma omp parallel for schedule [, <chunksize>]`

- Good assignment of iterations to threads can have a significant impact on performance

Finer Control on Work Distribution

- `#pragma omp parallel for schedule(static[,chunk])`
  - Fixed-sized chunks (or as equal as possible) assigned (alternating) to num_threads
  - Typical default is: chunk = iterations/num_threads
  - Set chunk = 1 for cyclic distribution
- `#pragma omp parallel for schedule(dynamic[,chunk] )`
  - Run-time scheduling (has overhead)
  - Each thread grabs “chunk” iterations off queue until all iterations have been scheduled, default is 1
  - Good load-balancing for uneven workloads

Finer Control on Work Distribution

- `schedule(static)`
  - OpenMP guarantees that if you have two separate loops with the same number of iterations and execute them with the same number of threads using static scheduling, then each thread will receive exactly the same iteration range(s) in both parallel regions
  - Beneficial for NUMA systems: if you touch some memory in the first loop, it will reside on the NUMA node where the executing thread was. Then in the second loop the same thread could access the same memory location faster since it will reside on the same NUMA node.

https://stackoverflow.com/questions/10850155/whats-the-difference-between-static-and-dynamic-schedule-in-openmp

Finer Control on Work Distribution

- `#pragma omp parallel for schedule(guided[,chunk])`
  - Threads dynamically grab blocks of iterations
  - Chunk size starts relatively large, to get all threads busy with good amortization of overhead
  - Subsequently, chunk size is reduced to "`chunk`" to produce good workload balance
  - By default, initial size is iterations/num_threads

Example of `guided` Schedule with Two Threads

Thread	Chunk	Chunk Size	Remaining Iterations
0	1-5000	5000	5000
1	5001-7500	2500	2500
1	7501-8750	1250	1250
1	8751-9375	625	625
0	9376-9688	313	312
1	9689-9844	156	156
0	9845-9922	78	78
1	9923-9961	39	39
0	9962-9981	20	19
1	9982-9991	10	9
0	9992-9996	5	4
0	9997-9998	2	2
0	9999	1	1
1	10000	1	0

Finer Control on Work Distribution

- `#pragma omp parallel for schedule(runtime)`
  - Decision deferred till run-time
  - Schedule and chunk size taken from `OMP_SCHEDULE` environment variable or from runtime library routines
    - $ export OMP_SCHEDULE="static,1"

- `#pragma omp parallel for schedule(auto)`
  - Schedule is left to the compiler runtime to choose (need not be any of the above)
  - Any possible mapping of iterations to threads in the team can be chosen

Understanding the `schedule` clause

Schedule clause	When to use?
`static`	Predetermined and predictable by the programmer; low overhead at run-time, scheduling is done at compile-time
`dynamic`	Unpredictable, highly variable work per iteration; greater overhead at run-time, more complex scheduling logic
`guided`	Special case of dynamic to reduce scheduling overhead
`auto`	When the runtime can learn from previous executions of the same loop

Nested Loops

- For perfectly nested rectangular loops we can parallelize multiple loops in the nest with the collapse clause

```
#pragma omp parallel for collapse(2)
  for (int i = 0; i < N; i++) {
    for (int j = 0; j < M; j++) {
    }
  }
```

j is implicitly private with the collapse clause

- Will form a single loop of length NxM and then parallelize that
- Useful when there are more than N threads

Nested Loops

- `collapse` works with square loops, not with triangular loops

```
int i, j;
#pragma omp parallel for num_threads(2)
collapse(2) private(j)
  for (i = 0; i < 4; i++)
    for (j = 0; j <= i; j++)
      cout << i << j <<
omp_get_thread_num()) << "\n";
```

Does not compile on GCC 7.4

```
int i, j;
#pragma omp parallel for num_threads(2)
collapse(2) private(j)
  for (i = 0; i < 4; i++)
    for (j = 0; j < 100; j++)
      cout << i << j <<
omp_get_thread_num()) << "\n";
```

Data Sharing with Work Sharing

What is going to happen?

```
#include <omp.h>

int main() {
  int i, j=5;
  double x=1.0, y=42.0;
#pragma omp parallel for default(none)
reduction(*:x)
  for (i=0;i<N;i++) {
    for (j=0;j<3;j++)
      x += foobar(i, j, y);
  }
  printf(“ x is %f\n”,(float)x);
}
```

```
#include <omp.h>

int main() {
  int i, j=5;
  double x=1.0, y=42.0;
#pragma omp parallel for default(none)
reduction(*:x) shared(y) collapse(2)
  for (i=0;i<N;i++) {
    for (j=0;j<3;j++)
      x += foobar(i, j, y);
  }
  printf(“ x is %f\n”,(float)x);
}
```

OpenMP Sections

- Noniterative worksharing construct
- Worksharing for function-level parallelism; complementary to "`omp for`" loops
- The `sections` construct gives a different structured block to each thread

```
#pragma omp parallel
{
  …
#pragma omp sections
  {
#pragma omp section
    x_calculation();
#pragma omp section
    y_calculation();
#pragma omp section
    z_calculation();
  } // implicit barrier
…
}
```

Explicit Tasks

Explicit Task Constructs in OpenMP

- Not all programs have simple loops OpenMP can parallelize
- OpenMP can only parallelize loops in a basic standard form with loop counts known at runtime

- Consider a program to traverse a linked list

```
p=head;
while (p) {
  dowork(p);
  p = p->next;
}
```

One Potential Solution

1

```
while (p != NULL) {
  p = p->next;
  count++;
}
```

2

```
p = head;
for (i=0; i<count; i++) {
  parr[i] = p;
  p = p->next;
}
```

3

```
#pragma omp parallel
{
  #pragma omp for schedule(static,1)
  for(i=0; i<count; i++)
    dowork(parr[i]);
}
```

One Potential Solution

1

```
while (p != NULL) {
  p = p->next;
  count++;
}
```

2

```
p = head;
for (i=0; i<count; i++) {
  parr[i] = p;
  p = p->next;
}
```

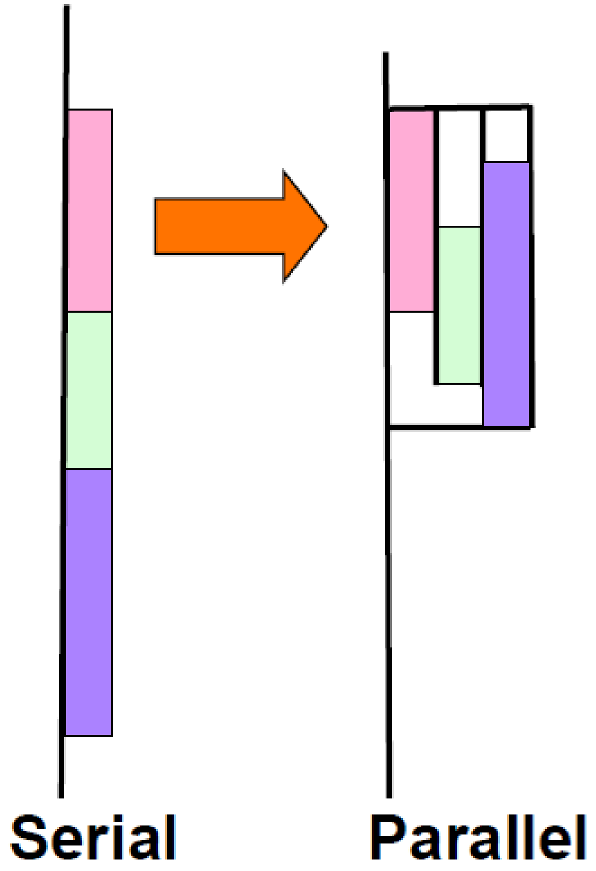
3

```
#pragma omp parallel
{
                    dule(static,1)
                    )
```

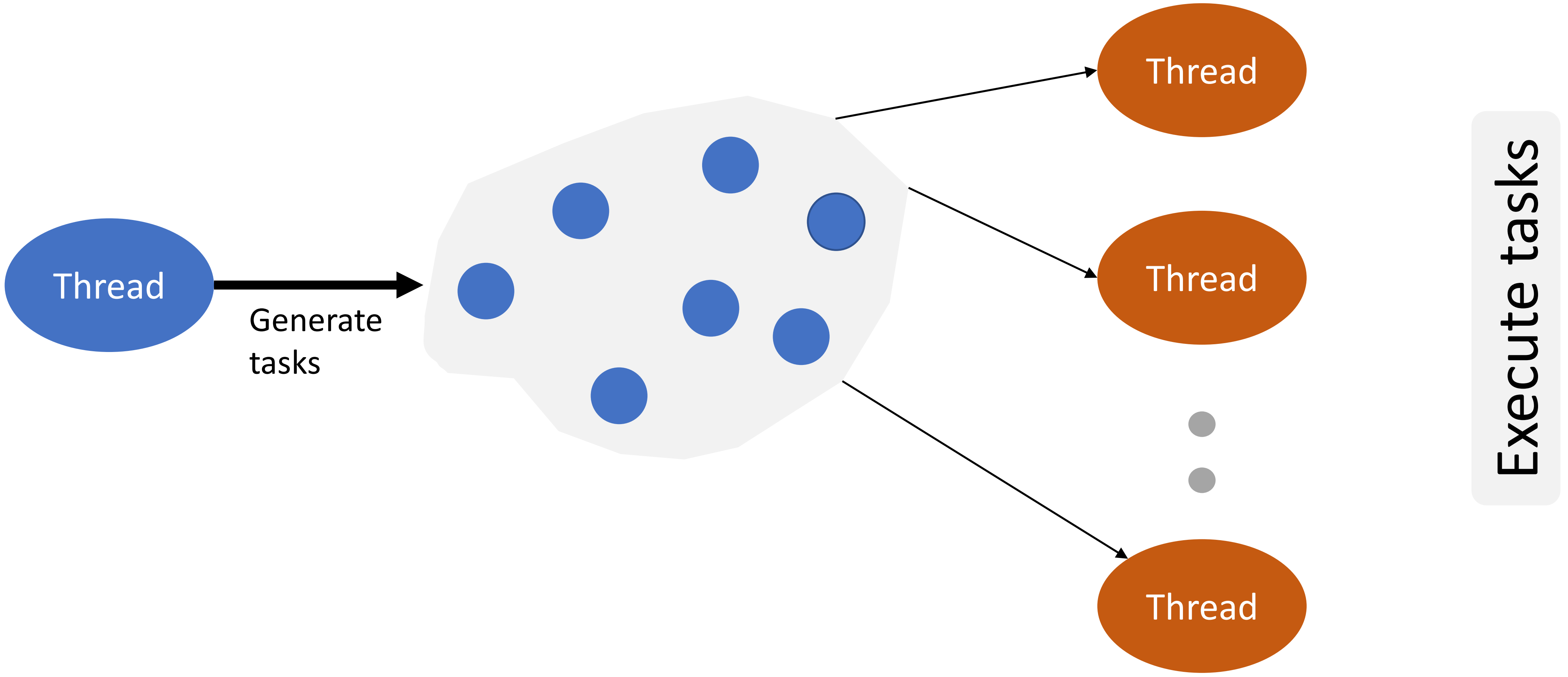
This works, but is inelegant (had to use a vector or array as an intermediate) and is inefficient (requires multiple passes over the data)

Tasks in OpenMP

- Explicit tasks were introduced in OpenMP 3.0
- Tasks are independent units of work
- Tasks are composed of
  - code to execute
  - data to compute with
  - control variables
- Threads are assigned to perform the work of each task
- The runtime system decides when tasks are executed
  - Tasks may be deferred
  - Tasks may be executed immediately

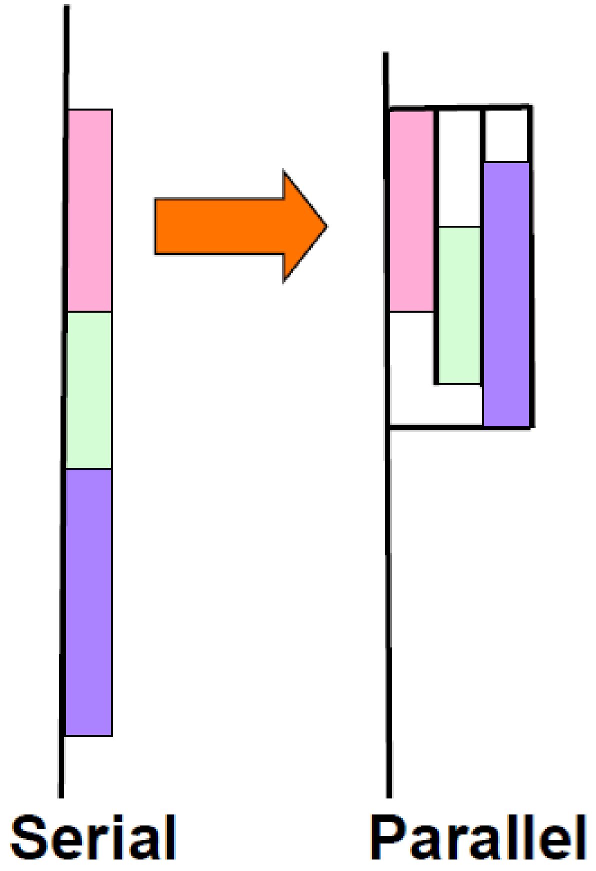


The Tasking Concept in OpenMP



Tasks in OpenMP

- The task construct includes a structured block of code
- Inside a parallel region, a thread encountering a task construct will package up the code block and its data for execution
- Tasks can be nested: i.e. a task may itself generate tasks



Task Directive

```
#pragma omp parallel
{
  #pragma omp master
  {
    #pragma omp task
      fred();
    #pragma omp task
      daisy();
    #pragma omp task
      billy();
  }
}
```

Task 0 packages data

Tasks executed by some thread in some order

All tasks complete before this barrier ends

Task Completion

- You can use a barrier
- `#pragma omp taskwait`
  - Wait for child tasks to complete

Example of Tasks

```
#pragma omp parallel
{
#pragma omp single
  {
    cout << “A ”;
#pragma omp task
    cout << “race “;
#pragma omp task
    cout << “car “;
    cout << “is fun to watch!”;
  }
}
```

```
#pragma omp parallel
{
#pragma omp single
  {
    cout << “A ”;
#pragma omp task
    cout << “race “;
#pragma omp task
    cout << “car “;
#pragma omp taskwait
    cout << “is fun to watch!”;
  }
}
```

SIMD Programming

SPMD Programming

- Single Program Multiple Data
    - Each thread runs same program
    - Selection of data, or branching conditions, based on thread id
        - General and common parallel programming paradigm
- In OpenMP implementations
    - Perform work division in parallel loops
    - Query `thread_id` and `num_threads`
    - Partition work among threads

How about SIMD support?

- Support in older versions of OpenMP required vendor-specific extensions
  - Programming models (e.g., Intel Cilk Plus)
  - Compiler pragmas (e.g., `#pragma vector`)
  - Low-level constructs or intrinsics (e.g., `_mm_add_pd()`)

```
#pragma omp parallel for
#pragma vector always
#pragma ivdep
for (int i = 0; i < N; i++) {
  a[i] = b[i] + 10;
}
```

`simd` Construct

- `#pragma omp simd …`
  - Can be applied to a loop to indicate that the loop can be transformed to a SIMD loop
  - Use SIMD instructions
  - Partition loop into chunks that fit a SIMD vector register
  - Does not parallelize the loop body

- `#pragma omp declare simd`
  - Applied to a function to enable creation of one or more versions to allow for SIMD processing

`simd` Worksharing Construct

- `#pragma omp for simd …`

- Parallelize and vectorize a loop nest
    - Distribute a loop’s iteration space across a thread team
    - Subdivide loop chunks to fit a SIMD vector register

SIMD Function Vectorization

- Declare one or more functions to be compiled for calls from a SIMD-parallel loop

```
#pragma omp declare simd …
function-definition-or-declaration
```

```
#pragma omp declare simd
float min(float a, float b) {
  return a < b ? a : b;
}
```

```
// Vector version
vec8 min_v(vec8 a, vec8 b) {
  return a < b ? a : b;
}
```

OpenMP Memory Model

Correctness of Shared-memory Programs

"To write correct and efficient shared memory programs, programmers need a precise notion of how memory behaves with respect to read and write operations from multiple processors"

S. Adve and K. Gharachorloo. Shared Memory Consistency Models: A Tutorials. WRL Research Report, 1995.

Busy-Wait Paradigm

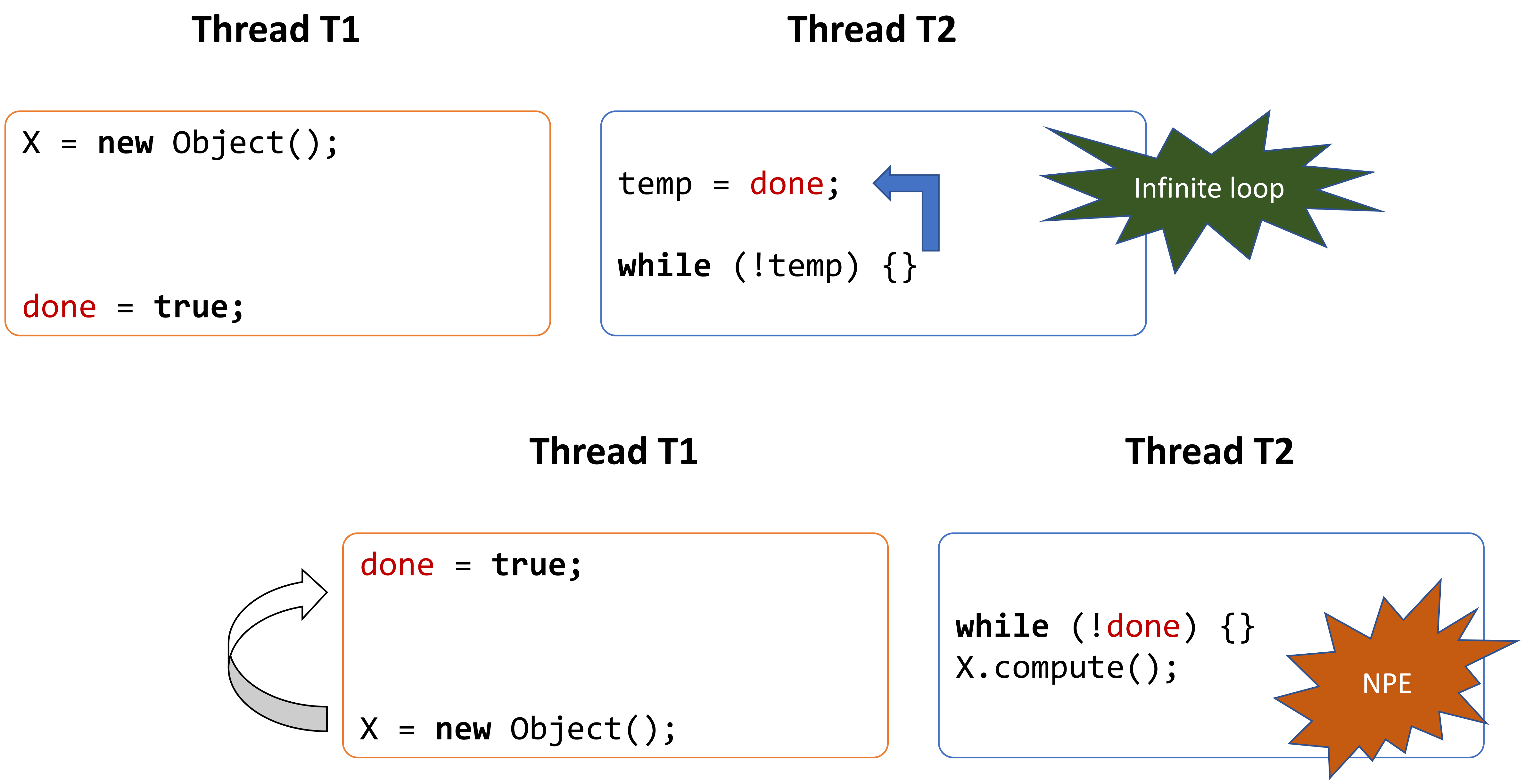
```
Object X = null;
boolean done= false;
```

Thread T1

```
X = new Object();
done = true;
```

Thread T2

```
while (!done) {}
if (X != null)
  X.compute();
```



Thread T1

```
X = new Object();



done = true;
```

Thread T2

```
temp = done;

while (!temp) {}
```

Thread T1

```
done = true;



X = new Object();
```

Thread T2

```
while (!done) {}
X.compute();
```

What Value Can a Read Return?

```
X = 0
done = 0
```

Core C1

```
S1: store X, 10
S2: store done, 1
```

Core C2

```
L1: load r1, done
B1: if (r1 != 1) goto L1
L2: load r2, X
```

Reordering of Accesses by Hardware

Different addresses!

- Store-store
- Load-load
- Load-store
- Store-load

Reordering of Accesses by Hardware

Different addresses!

Store-store

Correct in a single-threaded context

Non-trivial in a multithreaded context

Store-load

What values can a load return?

Return the “last” write

Uniprocessor: program order

Multiprocessor: ?

Memory Consistency Model

Set of rules that govern how systems process memory operation requests from multiple processors

- Determines the order in which memory operations appear to execute

Specifies the allowed behaviors of multithreaded programs executing with shared memory

- Both at the hardware-level and at the programming-language-level
- There can be multiple correct behaviors

Importance of Memory Consistency Models

- Determines what optimizations are correct
- Contract between the programmer and the hardware
- Influences ease of programming and program performance
- Impacts program portability

Dekker’s Algorithm

```
flag1 = 0
flag2 = 0
```

Core C1

```
S1: store flag1, 1
L1: load r1, flag2
```

Core C2

```
S2: store flag2, 1
L2: load r2, flag1
```

Can both r1 and r2 be set to zero?

Sequential Consistency

A multiprocessor system is sequentially consistent if the result of any execution is the same as if the operations of all processors were executed in **some sequential order**, and the operations of each individual processor appear in **the order specified by the program**.

Leslie Lamport

Interleavings with SC

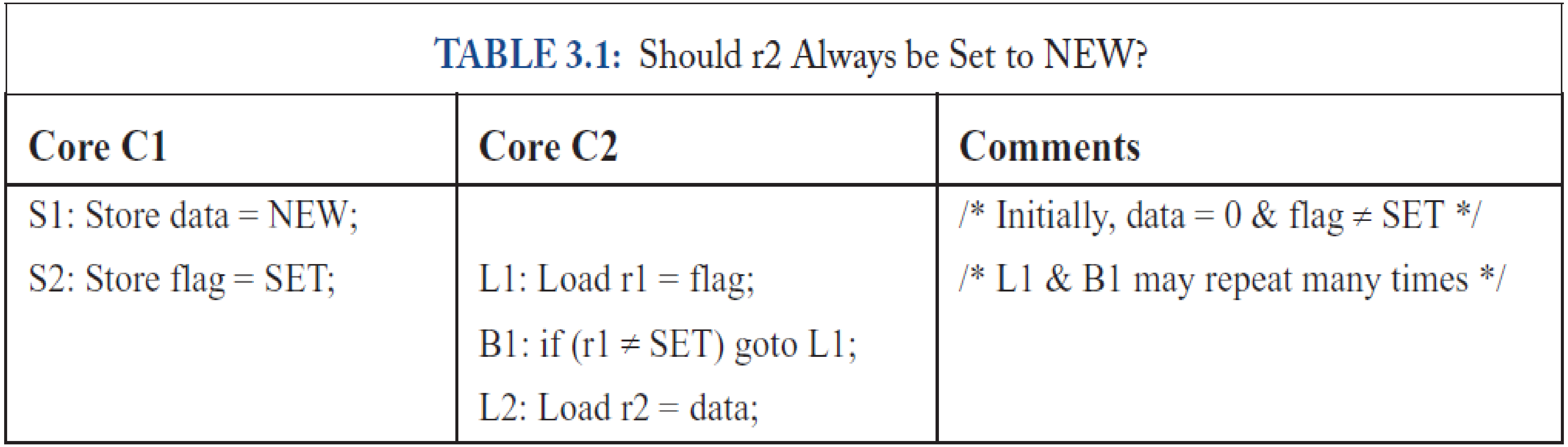
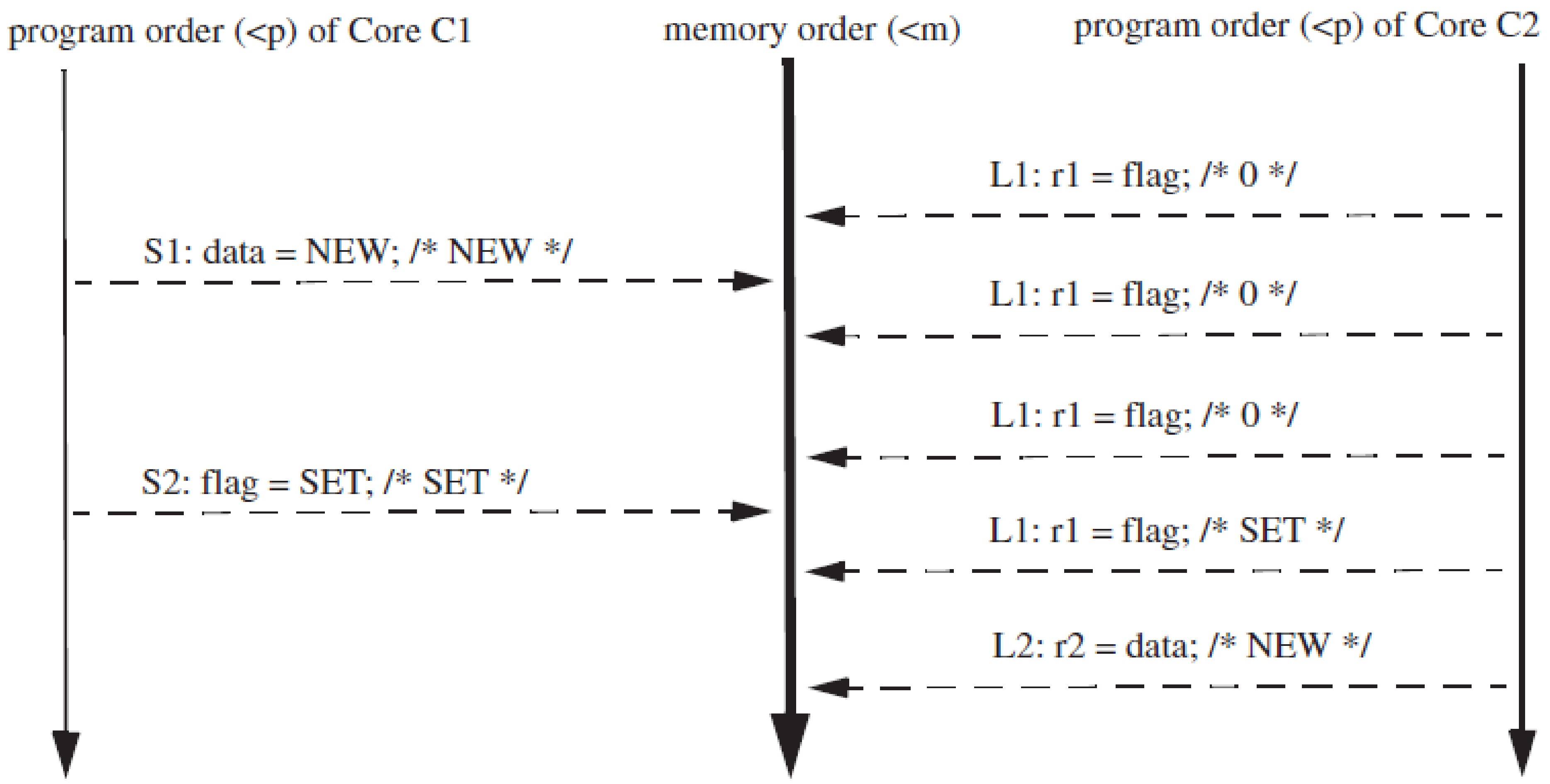


TABLE 3.1: Should r2 Always be Set to NEW?

Core C1	Core C2	Comments
S1: Store data = NEW;		/* Initially, data = 0 & flag ≠ SET */
S2: Store flag = SET;	L1: Load r1 = flag;	/* L1 & B1 may repeat many times */
	B1: if (r1 ≠ SET) goto L1;	
	L2: Load r2 = data;	

Interleavings with SC



SC Formalism

Every load gets its value from the last store before it (in global memory order) to the same address

SC Rules

Suppose we have two addresses a and b

- a == b or a!= b

Constraints

- if $L(a) <_p L(b) \Rightarrow L(a) <_m L(b)$
- If $L(a) <_p S(b) \Rightarrow L(a) <_m S(b)$
- If $S(a) <_p S(b) \Rightarrow S(a) <_m S(b)$
- If $S(a) <_p L(b) \Rightarrow S(a) <_m L(b)$

End-to-end SC

Simple memory model that can be implemented both in hardware and in languages

Performance can take a hit

- Naive hardware
- Maintain program order - expensive for a write

Existing Memory Consistency Models

Hardware	Programming Languages
• Sequential Consistency (SC)	• Java
• Total Store Order (TSO)	• C++ and OpenMP
• Partial Store Order (PSO)	• …
• Weak Ordering (WO)	
• …	

Cache Coherence

Single writer multiple readers (SWMR)

Memory updates are passed correctly, cached copies always contain the most recent data

Virtually a synonym for SC, but for a single memory location

Alternate definition based on relaxed ordering

- A write is **eventually** made visible to all processors
- Writes to the **same** location appear to be seen in the same order by all processors (serialization)
  - SC - *all*

Memory Consistency vs Cache Coherence

Memory Consistency	**Cache Coherence**
• **Defines** shared memory behavior	• **Does not define** shared memory behavior
• Related to **all** shared-memory locations	• Specific to a **single** shared-memory location
• Policy on **when** new value is propagated to other cores	• **Propagate** new value to other cached copies • Invalidation-based or update-based
• Memory consistency implementations can use cache coherence as a "black box"	

Total Store Order

Allows reordering stores to loads

Can read own write early, not other's writes

Conjecture: widely-used x86 memory model is equivalent to TSO

TSO Rules

a == b or a != b

- If $L(a) <_p L(b) \Rightarrow L(a) <_m L(b)$
- If $L(a) <_p S(b) \Rightarrow L(a) <_m S(b)$
- If $S(a) <_p S(b) \Rightarrow S(a) <_m S(b)$
- ~~If $S(a) <_p L(b) \Rightarrow S(a) <_m L(b)$~~ /* Enables FIFO Write Buffer */

Every load gets its value from the last store before it to the same address

Support for FENCE Operations in TSO

If $L(a) <_p$ FENCE $\Rightarrow L(a) <_m$ FENCE

If $S(a) <_p$ FENCE $\Rightarrow S(a) <_m$ FENCE

If FENCE $<_p$ FENCE $\Rightarrow$ FENCE $<_m$ FENCE

If FENCE $<_p L(a) \Rightarrow$ FENCE $<_m L(a)$

If FENCE $<_p S(a) \Rightarrow$ FENCE $<_m S(a)$

If $S(a) <_p$ FENCE $\Rightarrow S(a) <_m$ FENCE

If FENCE $<_p L(a) \Rightarrow$ FENCE $<_m L(a)$

Possible Outcomes with TSO

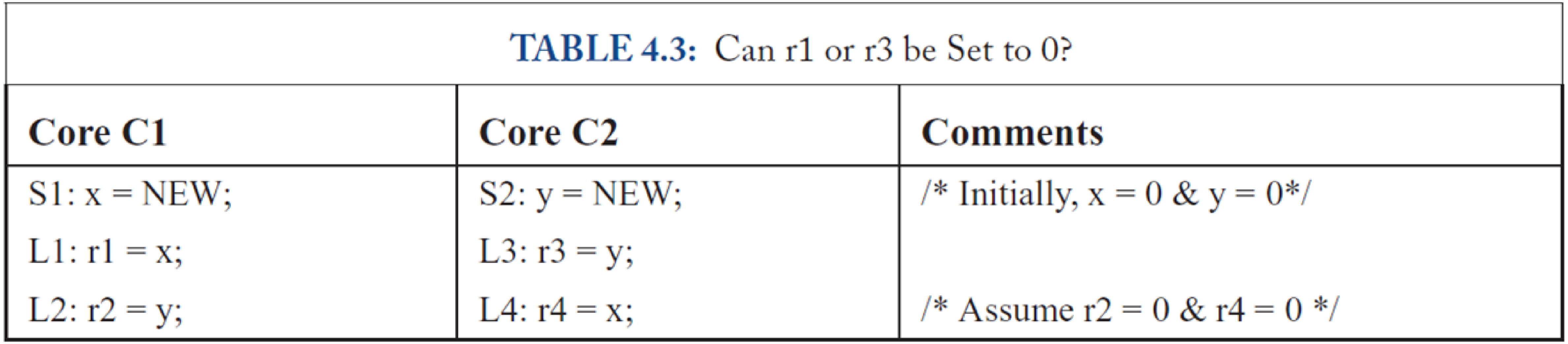
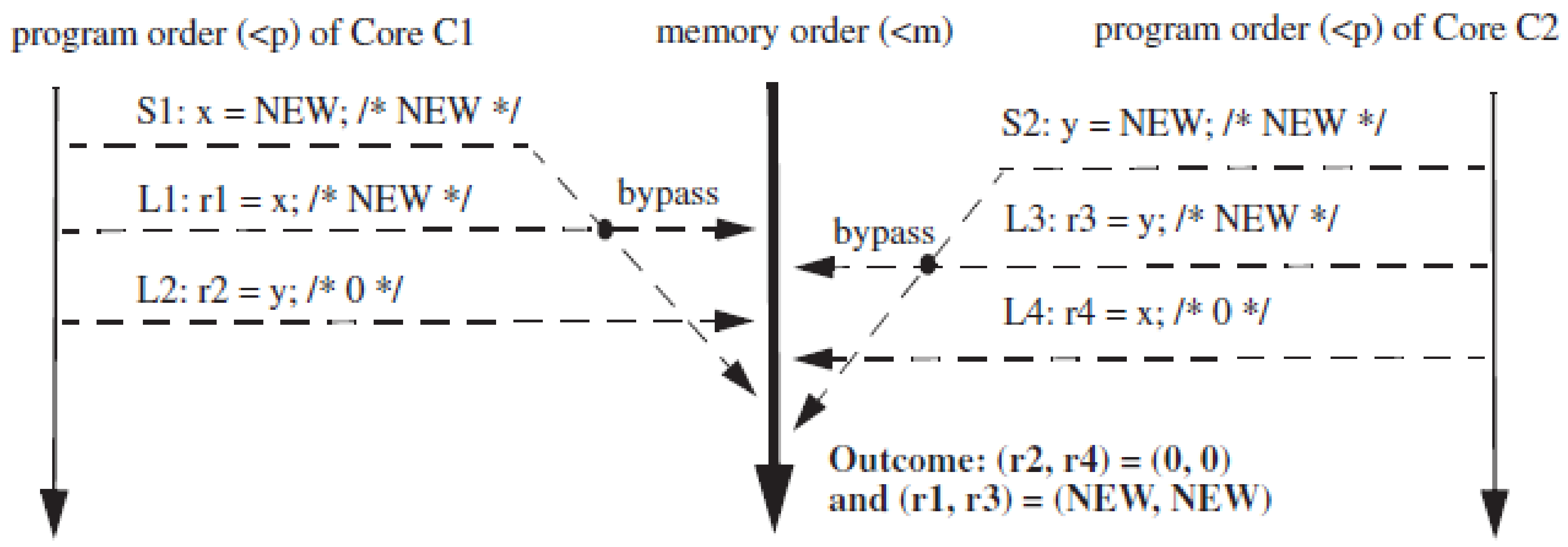


TABLE 4.3: Can r1 or r3 be Set to 0?

Core C1	**Core C2**	**Comments**
S1: x = NEW;	S2: y = NEW;	/* Initially, x = 0 & y = 0*/
L1: r1 = x;	L3: r3 = y;	
L2: r2 = y;	L4: r4 = x;	/* Assume r2 = 0 & r4 = 0 */

Possible Outcomes with TSO



Partial Store Order (PSO)

- Allows reordering of store to loads and stores to stores
- Writes to **different** locations from the same processor can be pipelined or overlapped and are allowed to reach memory or other cached copies out of program order

- Can read own write early, not other’s writes

Opportunities to Reorder Memory Operations

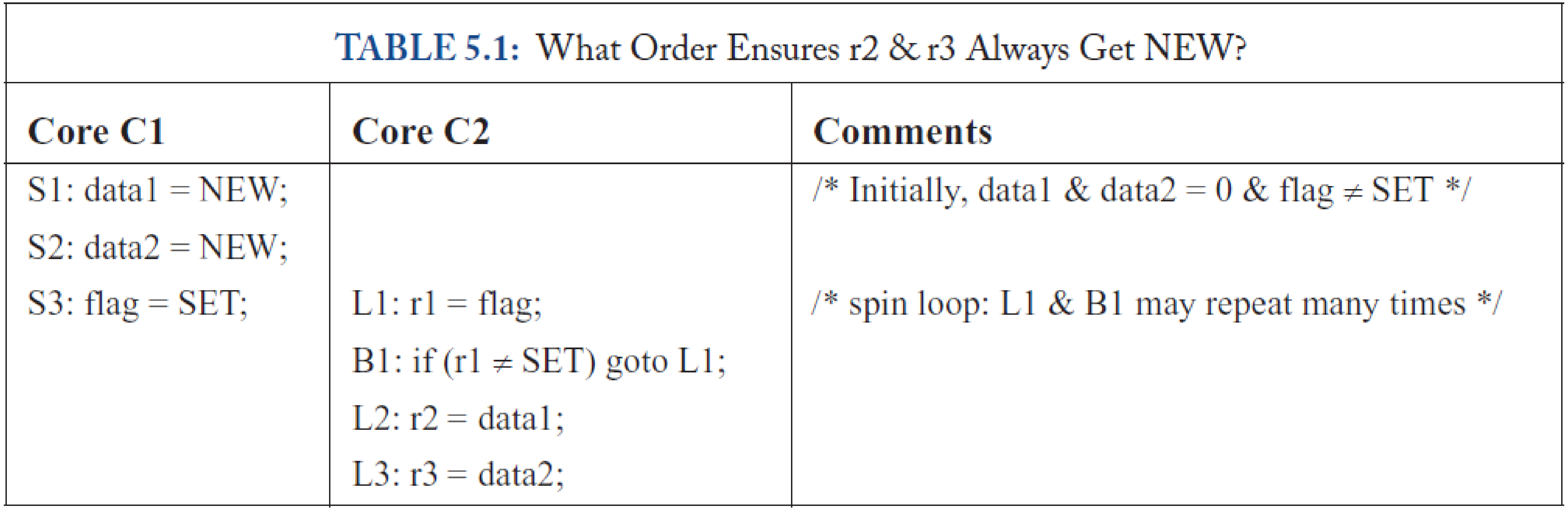


TABLE 5.1: What Order Ensures r2 & r3 Always Get NEW?

Core C1	Core C2	Comments
S1: data1 = NEW;		/* Initially, data1 & data2 = 0 & flag ≠ SET */
S2: data2 = NEW;		
S3: flag = SET;	L1: r1 = flag;	/* spin loop: L1 & B1 may repeat many times */
	B1: if (r1 ≠ SET) goto L1;	
	L2: r2 = data1;	
	L3: r3 = data2;	

Reorder Operations Within a Synchronization Block

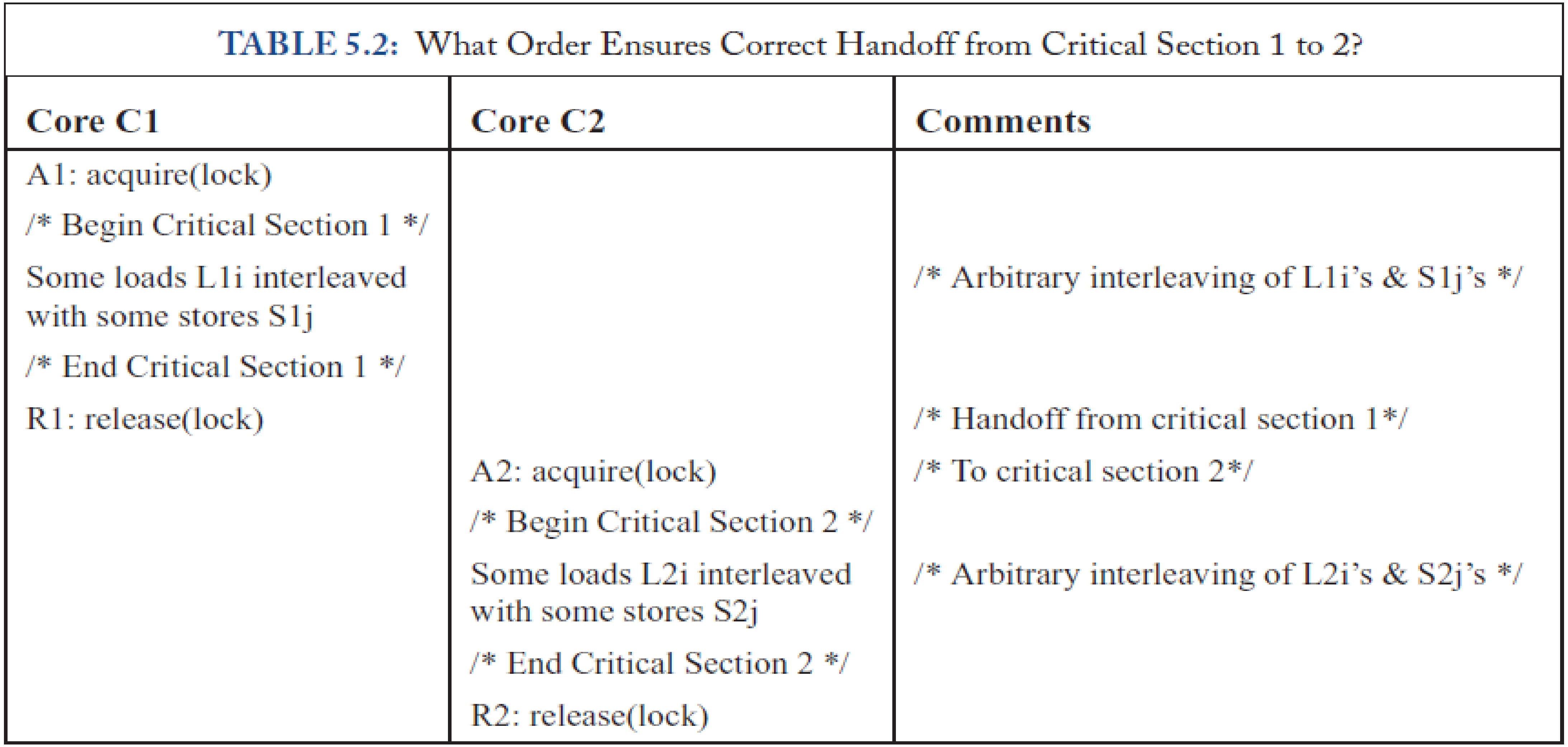


TABLE 5.2: What Order Ensures Correct Handoff from Critical Section 1 to 2?

Core C1	Core C2	Comments
A1: acquire(lock)		
/* Begin Critical Section 1 */		
Some loads L1i interleaved with some stores S1j		/* Arbitrary interleaving of L1i's & S1j's */
/* End Critical Section 1 */		
R1: release(lock)		/* Handoff from critical section 1*/
	A2: acquire(lock)	/* To critical section 2*/
	/* Begin Critical Section 2 */	
	Some loads L2i interleaved with some stores S2j	/* Arbitrary interleaving of L2i's & S2j's */
	/* End Critical Section 2 */	
	R2: release(lock)	

Optimization Opportunities

Non-FIFO coalescing write buffer

Support non-blocking reads

- Hide latency of reads
- Use lockup-free caches and speculative execution

Simpler support for speculation

- Need not compare addresses of loads to coherence requests
- For SC, need support to check whether the speculation is correct

Desirable Properties of a Memory Model

Hard to satisfy all three properties

- Programmability
- Performance
- Portability

Think of SC

Pros
- Intuitive
- Serializability of instructions

Cons
- No atomicity of regions
- Inhibits compiler transformations
- Almost all recent architectures violate SC

Relaxed Consistency Memory Model

- OpenMP supports a relaxed consistency shared memory model
  - Closely related to the weak ordering model
- Threads can maintain a temporary view of shared memory that is not consistent with other threads
- These temporary views are made consistent only at certain points in the program
- The operation that enforces consistency is called the flush operation

Semantics of the `flush` Operation

- A flush is a sequence point at which a thread is guaranteed to see a consistent view of memory
  - All previous read/writes by this thread have completed and are visible to other threads
  - No subsequent read/writes by this thread have occurred
- A flush operation is analogous to a fence in other shared memory APIs

Potential Benefits with Relaxed Consistency

- Relaxed memory model allows flexibility to OpenMP implementations
- Write to A
  - May complete immediately
  - May complete after the execution marked "…"

```
A = 1


…

…


#pragma omp flush(A)
```

Flush and Synchronization

- A flush operation is implied by OpenMP synchronizations
    - at entry/exit of parallel, critical, and ordered regions
    - at implicit and explicit barriers
    - at entry/exit of parallel worksharing regions
    - during lock APIs
    - ….

Flush and Synchronization

- This means if you are mixing reads and writes of a variable across multiple threads, you cannot assume the reading threads see the results of the writes unless:
  - The writing threads follow the writes with a construct that implies a flush.
  - The reading threads precede the reads with a construct that implies a flush

Reordering Example

```
1. a = …;
2. b = …;
3. c = …;

4. #pragma omp flush(c)
5. #pragma omp flush(a, b)

6. …= a…b…;
7. …c…;
```

- 1 and 2 may not be moved after 5
- 4 and 5 maybe interchanged at will
- 6 may not be moved before 5

OpenMP Example

```
#pragma omp parallel sections
{
  // Producer
#pragma omp section
  {
    // produce data
    flag = 1;
  }
  // Consumer
#pragma omp section
  {
    while (flag == 0 ) {}
    // consume data
  }
}
```

```
#pragma omp parallel sections
{
#pragma omp section
  {
    // produce data
#pragma omp flush
#pragma omp write
    flag = 1;
#pragma omp flush(flag)
  }
#pragma omp section
  {
    while (1) {
#pragma omp flush(flag)
#pragma omp atomic read
      flag_read = flag
      if (flag_read) break;
    }
#pragma omp flush
    // consume data
  }
}
```

OpenMP Optimizing Compiler

- Can reorder operations freely inside a parallel region
    - No guarantees about the ordering of operations during a parallel region excepting around flush operations
    - Parallel region contains implicit flushes
    - Cannot move operations outside of the parallel region or around synchronization operations
    - Presence of flush operations make the OpenMP memory model a variant of weak ordering

More Rules

- If the intersection of the flush-sets of two flushes performed by two different threads is non-empty, then the two flushes must be completed as if in some sequential order, seen by all threads
- If the intersection of the flush-sets of two flushes performed by one thread is non-empty, then the two flushes must appear to be completed in that thread's program order
- If the intersection of the flush-sets of two flushes is empty, then the threads can observe these flushes in any order

References

- Tim Mattson et al. The OpenMP Common Core: A hands on exploration, SC 2018.
- Tim Mattson and Larry Meadows. A “Hands-on” Introduction to OpenMP. SC 2008.
- Ruud van der Pas. OpenMP Tasking Explained. SC 2013.
- Peter Pacheco. An Introduction to Parallel Programming.
- Blaise Barney. OpenMP. https://computing.llnl.gov/tutorials/openMP/