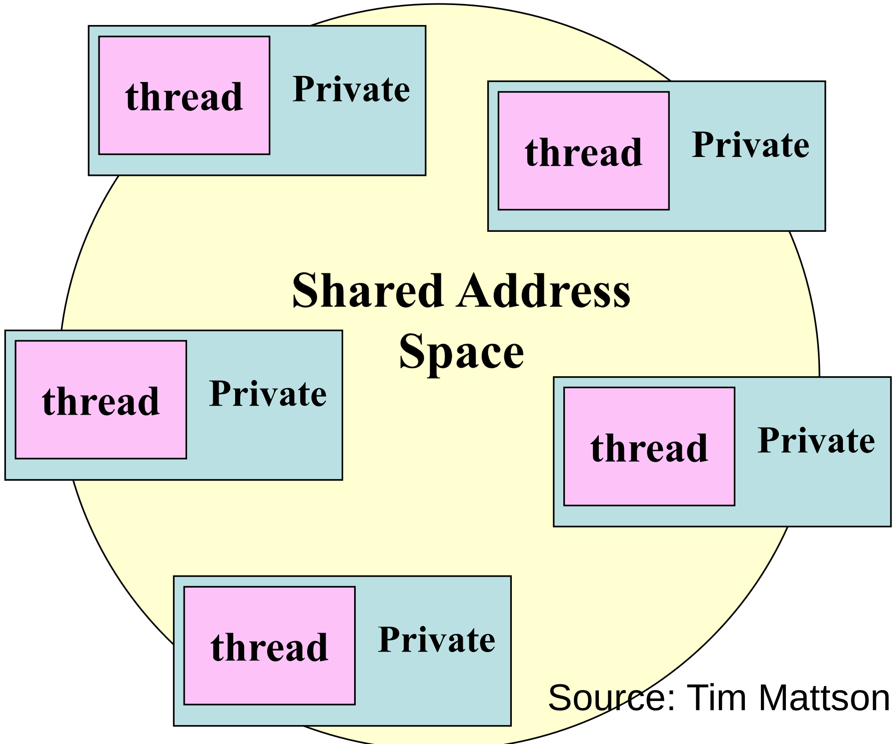
Parallel Programming with OpenMP

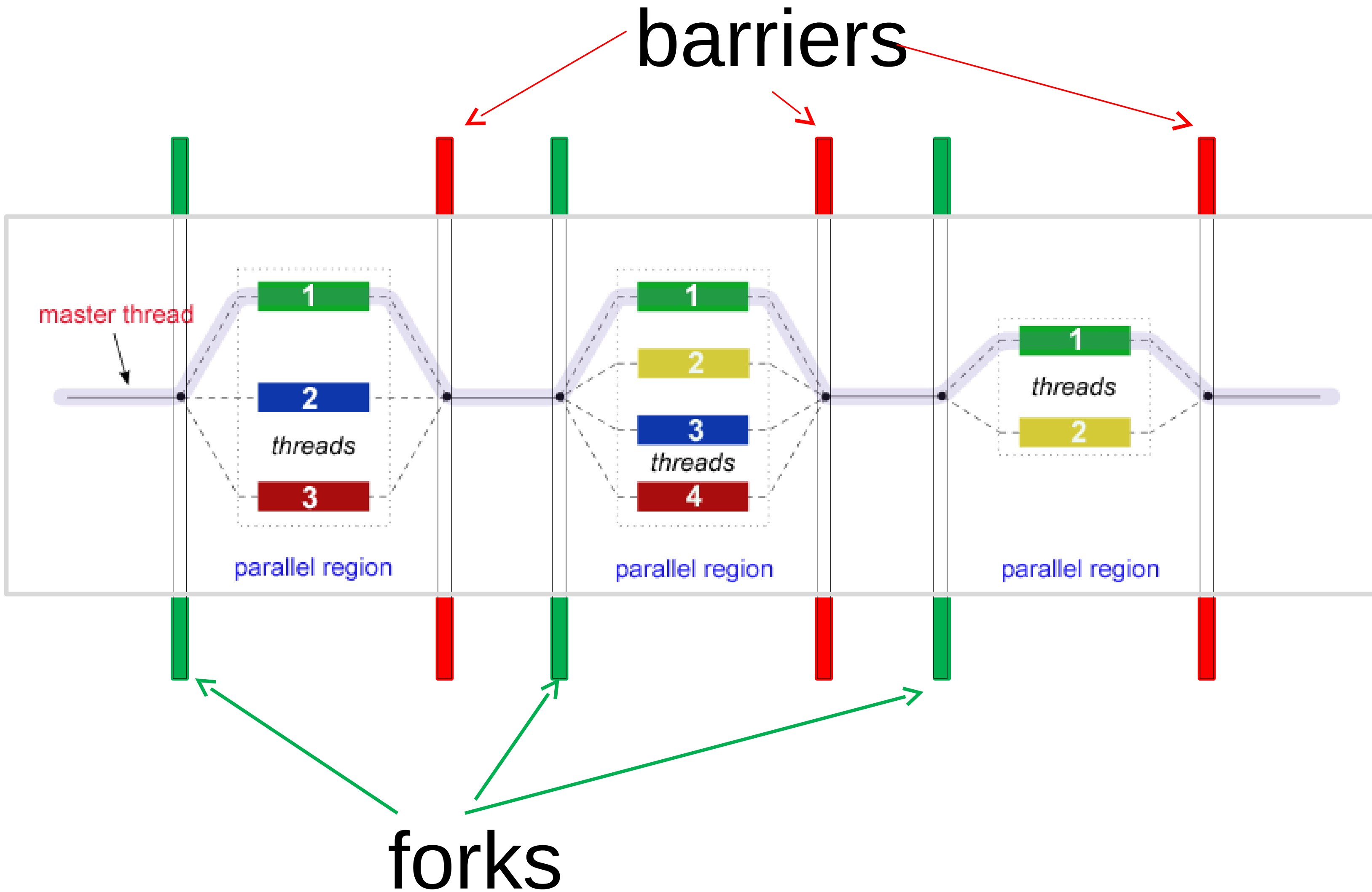
- OpenMP (Open Multi-Processing) is a popular shared-memory programming model
- Supported by popular production C (also Fortran) compilers: Clang, GNU Gcc, IBM xlc, Intel icc
- These slides borrow heavily from Tim Mattson's excellent OpenMP tutorial available at www.openmp.org, and from Jeffrey Jones (OSU CSE 5441)



Source: Tim Mattson

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
- Main concepts:
  - 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



https://computing.llnl.gov/tutorials/openMP/images/fork_join2.gif

OpenMP Core Syntax

- **Most of the constructs in OpenMP are compiler directives:**
  - **#pragma omp *construct* *[clause [clause]…]***
- **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: 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.**

Hello World in OpenMP

```
#include  <omp.h>
void main()
{
    #pragma omp parallel
    {
        int ID = 0;
        printf(“ hello(%d) ”, ID);
        printf(“ world(%d) \n”, ID);
    }
}
```

- An OpenMP program starts with one “master” thread executing “main” as a sequential program
- “#pragma omp parallel” indicates beginning of a parallel region
  - Parallel threads are created and join the master thread
  - All threads execute the code within the parallel region
  - At the end of parallel region, only master thread executes
  - Implicit “barrier” synchronization; all threads must arrive before master proceeds onwards

Hello World in OpenMP

```
#include  <omp.h>
void main()
{
   #pragma  omp  parallel
   {
      int ID = omp_get_thread_num();
      printf(" hello(%d) ", ID);
      printf(" world(%d) \n", ID);
   }
}
```

Sample Output:

hello(1) hello(0) world(1)

world(0)

hello (3) hello(2) world(3)

world(2)

- 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)

Work Distribution in Loops

- Basic mechanism: 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 work distribution

```
double   A[1000];

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

Block distribution of work

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();
   for (int i = t_id; i < 1000; i += omp_get_num_threads())
   {
      A[i] = foo(i);
   }
}
```

{
each thread will
execute the code
within the block
}

implicit barrier

OpenMP Data Environment

- Global variables (declared outside the scope of a parallel region) are **shared** among threads unless explicitly made private
- Automatic variables declared within parallel region scope are **private**
- Stack variables declared in functions called from within a parallel region are **private**

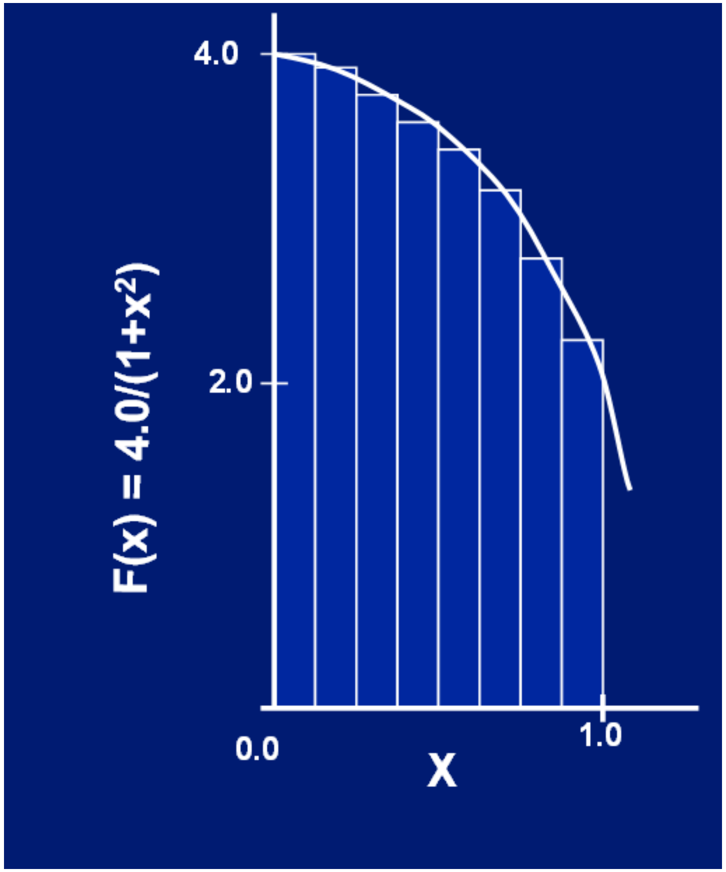
#pragma omp parallel private(x)

- each thread receives its own **uninitialized** variable x
- the variable x falls out-of-scope after the parallel region
- a global variable with the same name is unaffected **(3.0 and later)**

#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

Example: Numerical Integration



Mathematically:

$$\int_0^1 \frac{4.0}{(1+x2)}\, dx = \pi$$

Which can be approximated by:

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

where each rectangle has width Δx and height F(xi) at the middle of interval i.

https://software.intel.com/sites/default/files/m/d/4/1/d/8/1252a.gif

Sequential pi Program

```
int num_steps = 100000;
double step;

void main ()
{
int i;
double x, pi, sum = 0.0;

    step = 1.0/(double) num_steps;
    for (i = 0;  i < num_steps;  i++)
    {
        x = (i+0.5)*step;
        sum = sum + 4.0/(1.0+x*x);
    }
    pi = step * sum;
}
```

SPMD Programming

- **Single Program Multiple Data**
  - Each thread runs same program
  - Selection of data, or branching conditions, based on thread id
- in OpenMP implementation:
  - perform work division in parallel loops
  - query thread_id and num_threads
  - partition work among threads

Parallel Accumulation: Avoiding Race Conditions

```
sum = sum + 4.0/(1.0+x*x);

load_register 1, @sum
set_register  2, 4.0
set_register  3, 1.0
load_register 4, @x
multiply      5, 4, 4
add           4, 3, 5
divide        3, 2, 4
add           2, 1, 3
store         2, @sum
```

- High-level C statement translates into a sequence of low-level instructions
  - Accumulation into shared variable sum is not atomic: contributions can be lost if multiple threads execute the statements concurrently
  - Must use suitable synchronization to avoid race conditions

Parallel pi Program

```
#include     <omp.h>
int      num_steps = 100000;
double        step;
#define      NUM_THREADS        2

void main ()
{
int      i,  nthreads;
double        pi = 0.0,  sum[NUM_THREADS];

    step = 1.0/(double) num_steps;
    omp_set_num_threads(NUM_THREADS);
```

```
    #pragma omp parallel
    {
    int i, id,nt;
    double   x;

        id = omp_get_thread_num();
        nt = omp_get_num_threads();
        if (id == 0) nthreads = nt;

        sum[ id ] = 0.0;
        for ( i = id; i < num_steps;  i += nt)
        {                                          ^ partition method
            x = (i+0.5)*step;
            sum[id] += 4.0/(1.0+x*x);
        }
    }  <-  implicit barrier
this loop is serial  ->
    for( i = 0; i < nthreads; i++)
    {
        pi += sum[i] * step;
    }
}
```

Avoiding False Sharing in Cache

```
sum[id]  +=  4.0/(1.0+x*x);

sum[id]   =   sum[id]  + 4.0/(1.0+x*x);
```

- 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 element 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

Block vs. Cyclic Work Distribution

```
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())
   {
       sum[id]  +=  4.0/(1.0+x*x);
   }
}
```

```
double A[1000];

omp_set_num_threads(4);
#pragma omp parallel
{
   int t_id     = omp_get_thread_num();
   int b_size = 1000 / omp_get_num_threads();
   for (int i = (t_id-1) * b_size; i < t_id * b_size; i ++)
   {
       sum[id]  +=  4.0/(1.0+x*x);
   }
}
```

- Block/cyclic work distribution will not impact performance here
- But if statement in loop were like: “A[i] += B[i]*C[i]”, block distribution would be preferable

Synchronization: Critical Sections

```
float res;
#pragma omp parallel
{
float      B;
int   i, id, nthrds;

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

- 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”

Synchronization: Atomic

```
float res;
#pragma omp parallel
{
float      B;
int   i, id, nthrds;

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

- Atomic: very efficient critical section for simple accumulation operations (x binop= expr; or x++, x--, etc.)
- Used hardware atomic instructions for implementation; much lower overhead than using critical section

Parallel pi: No False Sharing

```
int      num_steps = 100000;
double        step;
#define       NUM_THREADS         2

void main ()
{
int      i,  nthreads;
double        pi = 0.0;

    step = 1.0/(double) num_steps;
    omp_set_num_threads(NUM_THREADS);
```

no array, no false sharing ->

```
    #pragma omp parallel
    {
    int i, id,nthrds;
    double    x, sum;

        id        = omp_get_thread_num();
        nthrds = omp_get_num_threads();
        if (id == 0) nthreads = nthrds;

        sum  = 0.0;
        for ( i = id; i < num_steps;  i += nthrds)
        {
            x = (i+0.5)*step;
            sum += 4.0/(1.0+x*x);
        }
        #pragma  omp  atomic
        {
            pi  +=  sum * step;
        }
    }
}
```

<- sum is now local

^ each thread adds its partial sum one thread at a time

Loop worksharing constructs
A motivating example

Sequential code

```
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];}
}
```

OpenMP parallel region and a worksharing for construct

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

OpenMP Combined Work-Sharing Construct

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

➡

```
#pragma omp parallel for
for( 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
- Combined construct for such cases: just add the work-sharing “for” clause to the parallel region pragma

Loop worksharing constructs:
The schedule clause

- The schedule clause affects how loop iterations are mapped onto threads
  - schedule(static [,chunk])
    - Deal-out blocks of iterations of size "chunk" to each thread.
  - schedule(dynamic[,chunk])
    - Each thread grabs "chunk" iterations off a queue until all iterations have been handled.

Schedule Clause	When To Use
STATIC	**Pre-determined and predictable by the programmer**
DYNAMIC	**Unpredictable, highly variable work per iteration**

Least work at runtime : scheduling done at compile-time

Most work at runtime : complex scheduling logic used at run-time

loop work-sharing constructs:
The schedule clause

Schedule Clause	When To Use
STATIC	**Pre-determined and predictable by the programmer**
DYNAMIC	**Unpredictable, highly variable work per iteration**
GUIDED	**Special case of dynamic to reduce scheduling overhead**
AUTO	**When the runtime can "learn" from previous executions of the same loop**

Least work at runtime : scheduling done at compile-time

Most work at runtime : complex scheduling logic used at run-time

OpenMP Reductions

```
double avg = 0.0;
double A[SIZE];
#pragma omp parallel for
for (int i = 0; i < SIZE; i++;)
{
  avg += A[i];
 }
avg = avg / SIZE;
```

- Reductions commonly occur in codes (as in pi example)
- 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, e.g., +, *, -, min, max

OpenMP Reductions

```
double avg = 0.0;
double A[SIZE];
#pragma  omp  parallel  for reduction(+ : avg)

for (int i = 0; i < SIZE; i++;)
{
  avg += A[i];
 }
avg = avg / SIZE;
```

- 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

Parallel pi: Using Reduction

```
int     num_steps = 100000;
double       step;
                              manage number of threads

void main ()
{
int     i;
double       x, pi, sum = 0.0;

    step = 1.0/(double) num_steps;
                              manage number of threads

                              parallelize, and reduce into sum
    for (i = 0;  i < num_steps;  i++)
    {
        x = (i+0.5)*step;
        sum = sum + 4.0/(1.0+x*x);
    }
    pi = step * sum;
}
```

```
int     num_steps = 100000;
double       step;
#define      NUM_THREADS        2

void main ()
{
int     i;
double       x, pi, sum = 0.0;

    step = 1.0/(double) num_steps;
    omp_set_num_threads(NUM_THREADS);

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

OpenMP: Reduction operands/initial-values

- Many different associative operands can be used with reduction:
- Initial values are the ones that make sense mathematically.

Operator	Initial value
+	0
*	1
-	0
min	Largest pos. number
max	Most neg. number

C/C++ only	
Operator	**Initial value**
&	~0
|	0
^	0
&&	1
||	0

Fortran Only	
Operator	**Initial value**
.AND.	.true.
.OR.	.false.
.NEQV.	.false.
.IEOR.	0
.IOR.	0
.IAND.	All bits on
.EQV.	.true.

Synchronization: Barrier

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

    #pragma omp for
    for(i=0;i<N;i++)
    {
        C[i]=big_calc3(i,A);
    }

    #pragma omp for nowait
    for(i=0;i<N;i++)
    {
        B[i]=big_calc2(C, i);
    }
    A[id] = big_calc4(id);
}
```

explicit barrier

implicit barrier at end of parallel region

no barrier!
nowait cancels barrier creation

Synchronization: Master and Single

multiple threads of control

only **master thread** executes this region

multiple threads of control

```
#pragma omp parallel
{
    do_many_things();

    #pragma omp master
    {
        reset_boundaries();
    }

    do_many_other_things();
}
```

multiple threads of control

a single thread is chosen to execute this region

implicit barrier

multiple threads of control

```
#pragma omp parallel
{
    do_many_things();

    #pragma omp single
    {
        reset_boundaries();
    }

    do_many_other_things();
}
```

Synchronization: Locks

```
omp_lock_t   lck;
omp_init_lock(&lck);

#pragma omp parallel
{
    do_many_things();
    omp_set_lock(&lck);
        {code requiring mutual exclusion}
    omp_unset_lock(&lck);
    do_many_other_things ();
}
omp_destroy_lock(&lck);
```

multiple threads of control

wait here for your turn …

multiple threads of control

- Alternate way to critical sections of achieving mutual exclusion
- More flexible than critical sections (can use multiple locks)
- More error-prone – for example, deadlock if a thread does not unset a lock after acquiring it

OpenMP Sections

```
#pragma omp parallel
{
    . . .

    #pragma omp sections
    {
    #pragma omp section
        X_calculation();
    #pragma omp section
        y_calculation();
    #pragma omp section
        z_calculation();
    }
    . . .


}
```

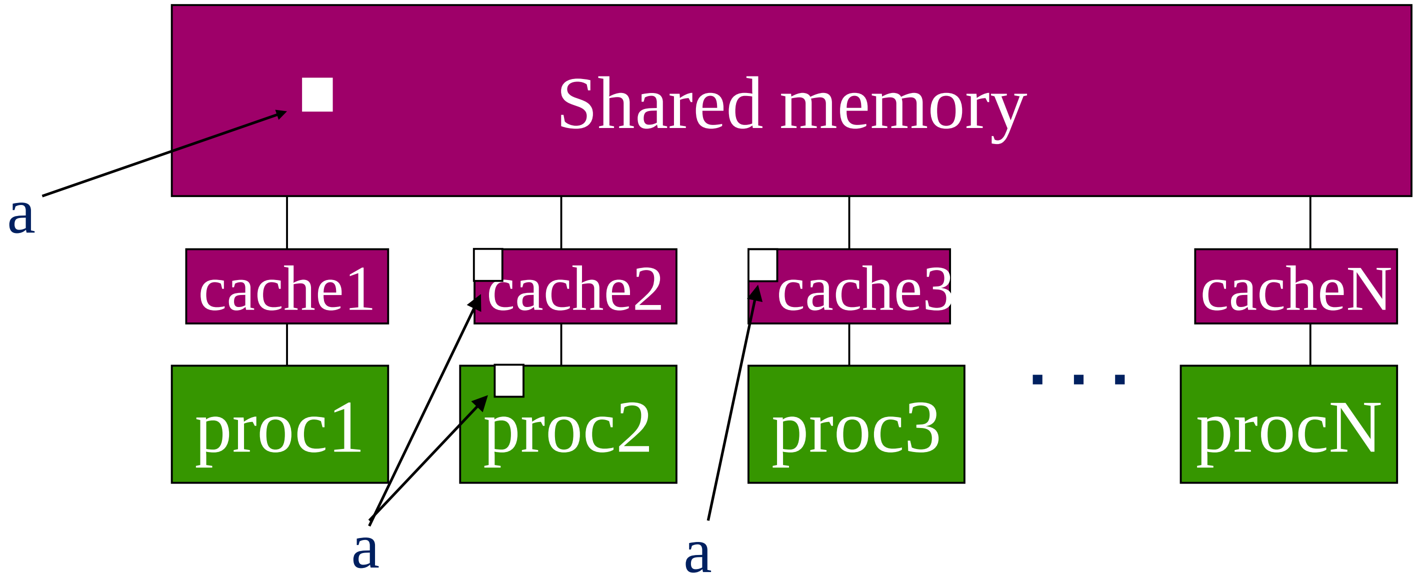
multiple threads of control
each section assigned to a different thread

by default:
extra threads are idled

- Work-sharing for functional parallelism; complementary to “omp for” for loops

OpenMP memory model

- OpenMP supports a shared memory model
- All threads share an address space, but it can get complicated:



- Multiple copies of data may be present in memory, various levels of cache, or in registers

OpenMP and relaxed consistency

- OpenMP supports a **relaxed-consistency** shared memory model
  - Threads can maintain a **temporary view** of shared memory that is not consistent with that of 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**

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

Flush and synchronization

- A flush operation is implied by OpenMP synchronizations, e.g.,
  - at entry/exit of parallel regions
  - at implicit and explicit barriers
  - at entry/exit of critical regions

  ….

  (but not at entry to worksharing regions)

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:

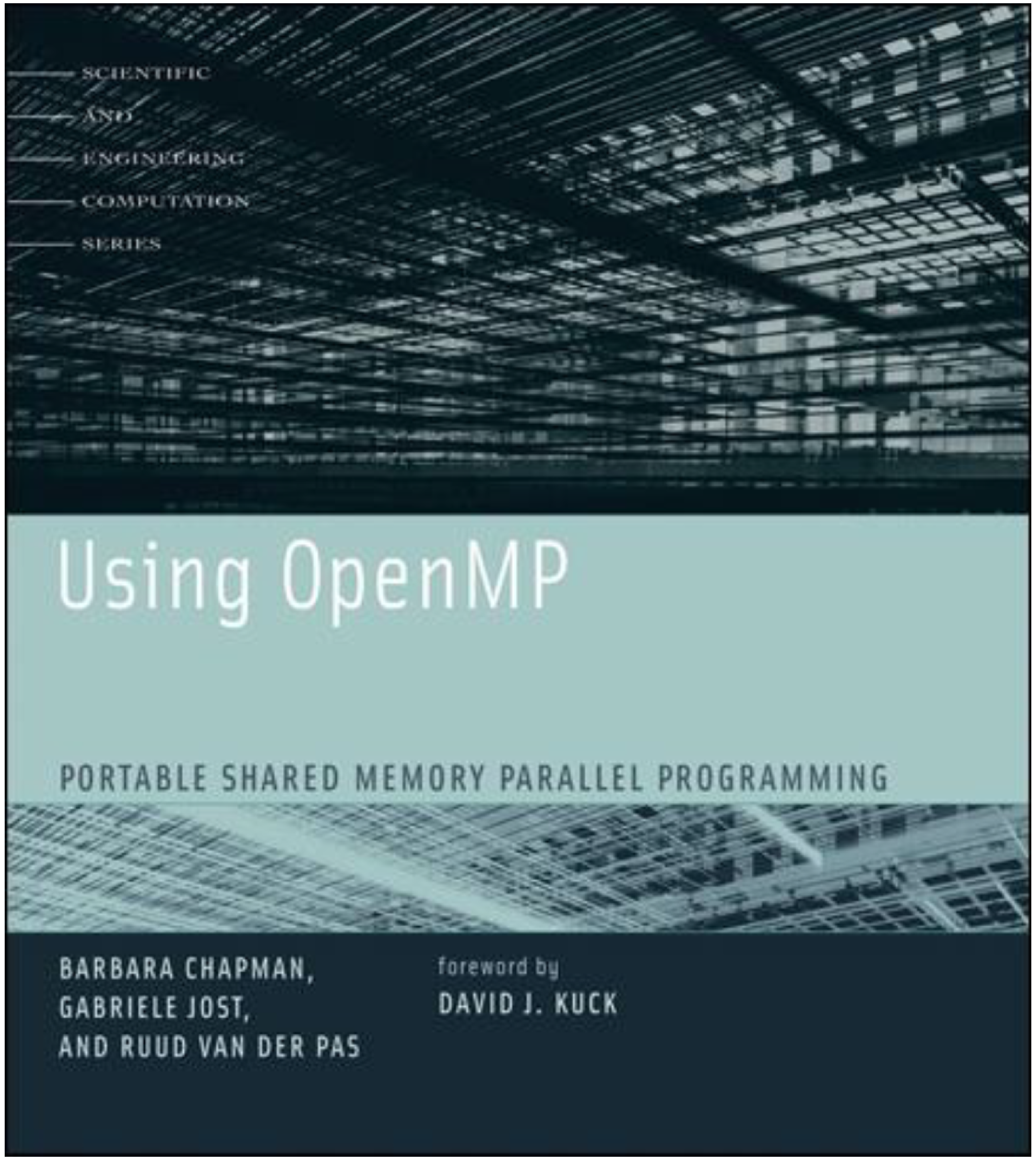
- the writing threads follow the writes with a construct that implies a flush.
- the reading threads precede the reads with a construct that implies a flush.

This is a rare event … or putting this another way, you should avoid writing code that depends on ordering reads/writes around flushes.

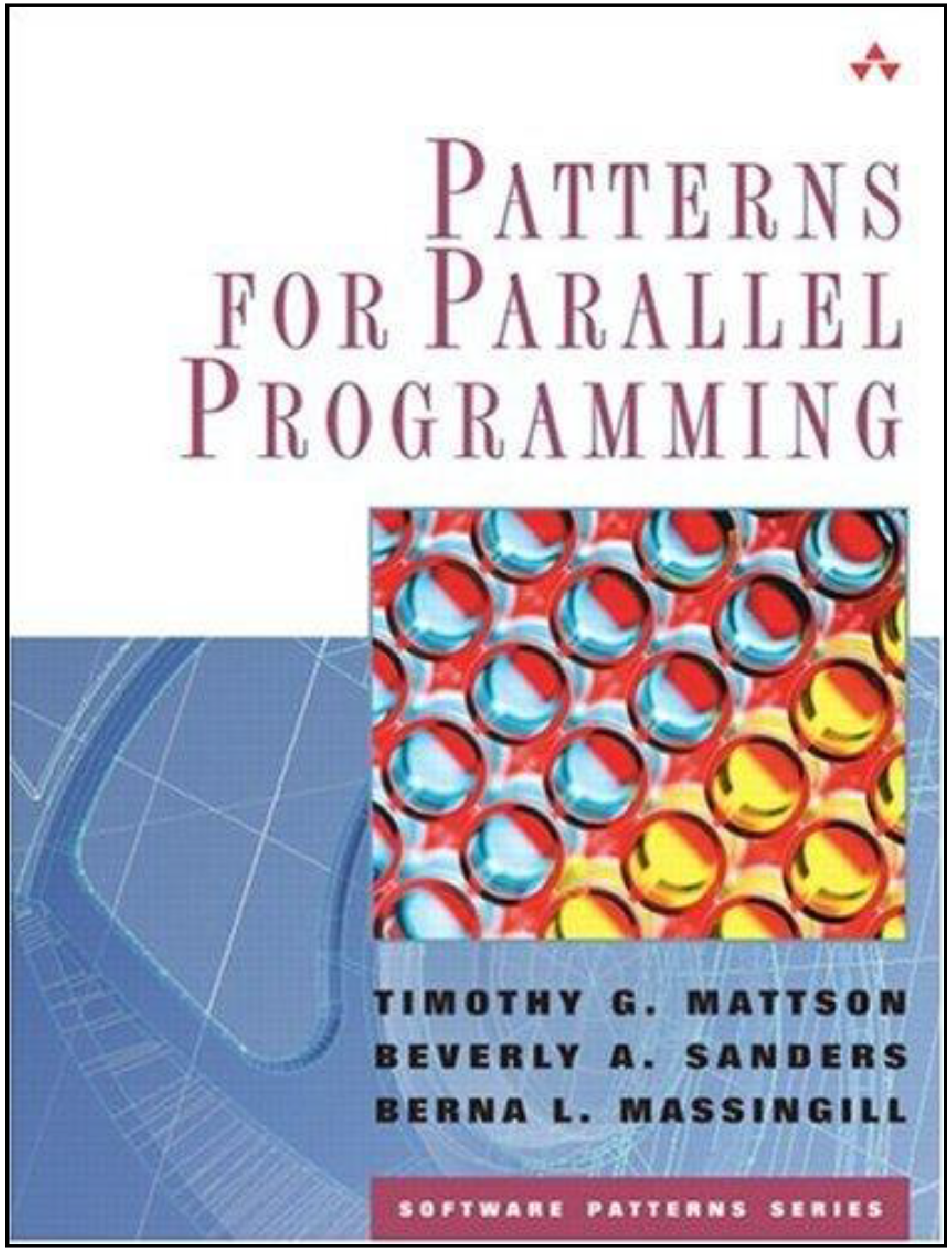
The OpenMP Common Core: Most OpenMP programs only use these 19 items

OpenMP pragma, function, or clause	Concepts
#pragma omp parallel	Parallel region, teams of threads, structured block, interleaved execution across threads
int omp_get_thread_num() int omp_get_num_threads()	Create threads with a parallel region and split up the work using the number of threads and thread ID
double omp_get_wtime()	Speedup and Amdahl's law. False Sharing and other performance issues
setenv OMP_NUM_THREADS N	Internal control variables. Setting the default number of threads with an environment variable
#pragma omp barrier #pragma omp critical	Synchronization and race conditions. Revisit interleaved execution.
#pragma omp for #pragma omp parallel for	Worksharing, parallel loops, loop carried dependencies
reduction(op:list)	Reductions of values across a team of threads
schedule(dynamic [,chunk]) schedule (static [,chunk])	Loop schedules, loop overheads and load balance
private(list), firstprivate(list), shared(list)	Data environment
nowait	Disabling implied barriers on workshare constructs, the high cost of barriers, and the flush concept (but not the flush directive)
#pragma omp single	Workshare with a single thread
#pragma omp task #pragma omp taskwait	Tasks including the data environment for tasks.

Books about OpenMP



- A book about OpenMP by a team of authors at the forefront of OpenMP's evolution.



- A book about how to "think parallel" with examples in OpenMP, MPI and java