Shared Memory Programming with OpenMP

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Outline - I

- Shared Memory Systems
  - Threaded Programming Model
  - Thread Communication
  - Synchronisation
    - Parallel Loops
    - Reductions
- OpenMP Fundamentals
  - Basic Concepts in OpenMP
  - History of OpenMP
  - Compiling and Running OpenMP Programs

Outline - II

- Parallel Regions
  - Parallel region directive
  - Some useful functions
  - Shared and Private variables
  - Reductions
- Work sharing
  - Parallel for/DO loops
  - Scheduling for loops
  - Single directive
  - Master directive
- Synchronisation

Shared Memory Systems

Shared Memory Systems

- Threaded programming is most often used on shared memory parallel computers.

- A shared memory computer consists of a number of processing units (CPUs) together with some memory.

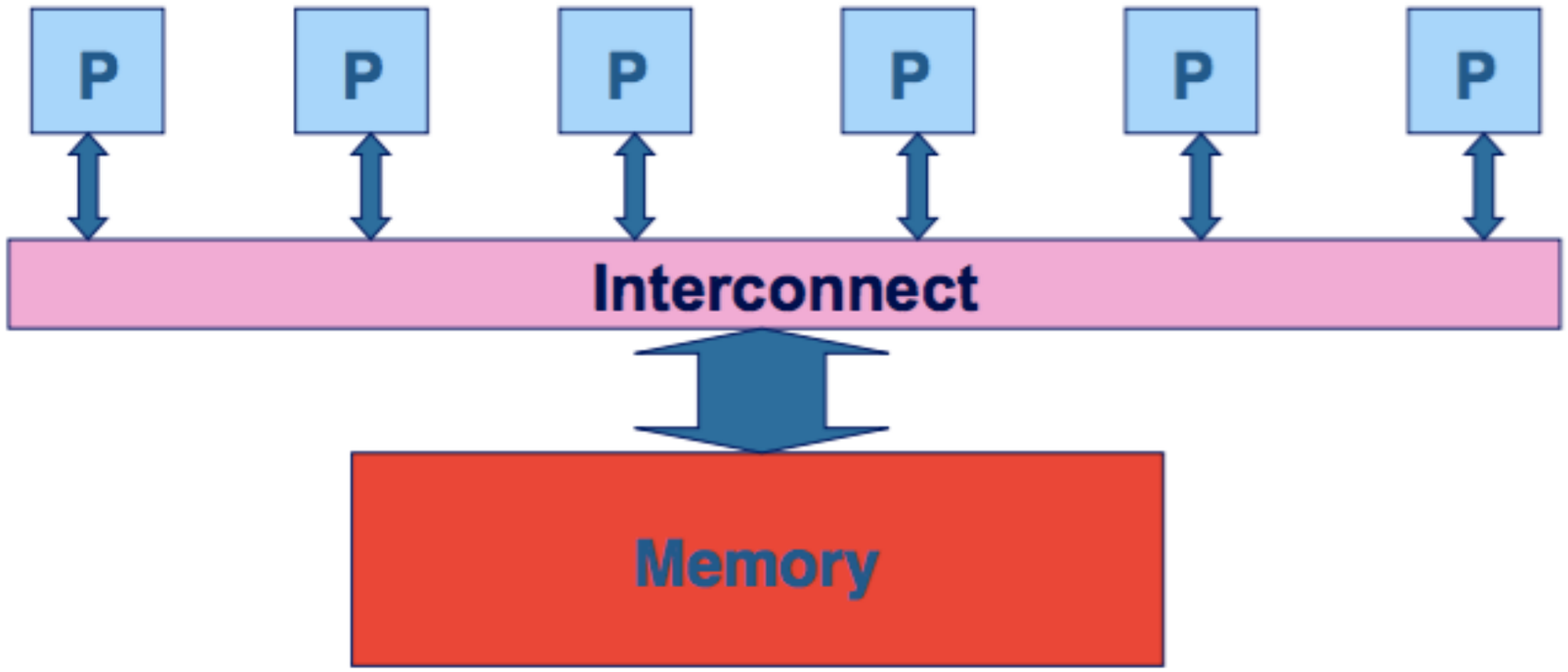
- Key feature of shared memory systems is *single address space* across the whole memory system.

  - every CPU can read or write all memory locations in the system

  - one logical memory space

  - all CPUs refer to a memory location using the same address

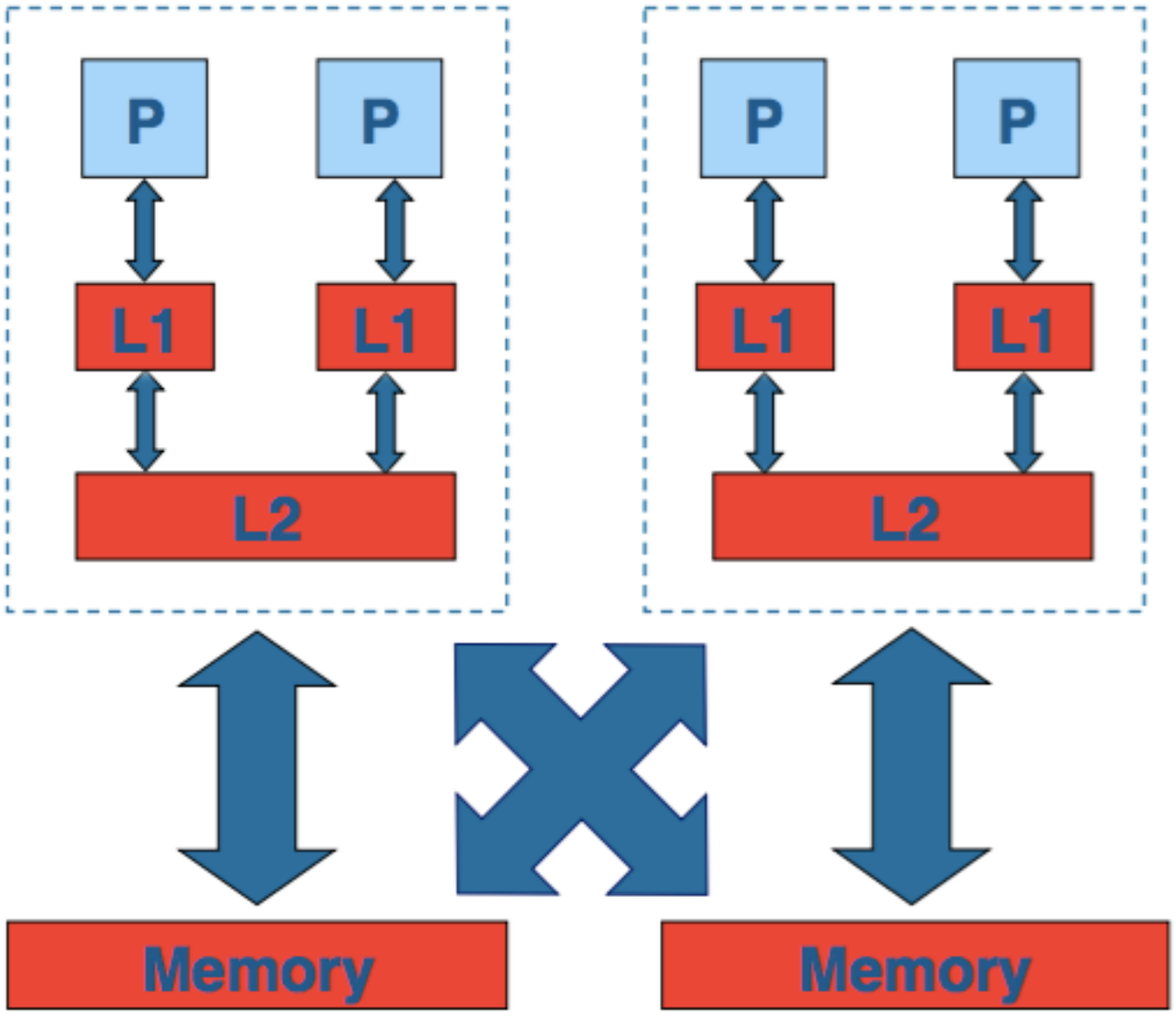
Conceptual Model



Real Hardware

- Real shared memory hardware is more complicated than this …
  - Memory may be split into multiple smaller units
  - There may be multiple levels of cache memory
    - some of these levels may be shared between subsets of processors
  - The interconnect may have a more complex topology
- … but a single space address is still supported
  - Hardware complexity can affect the performance of programs, but not their correctness.

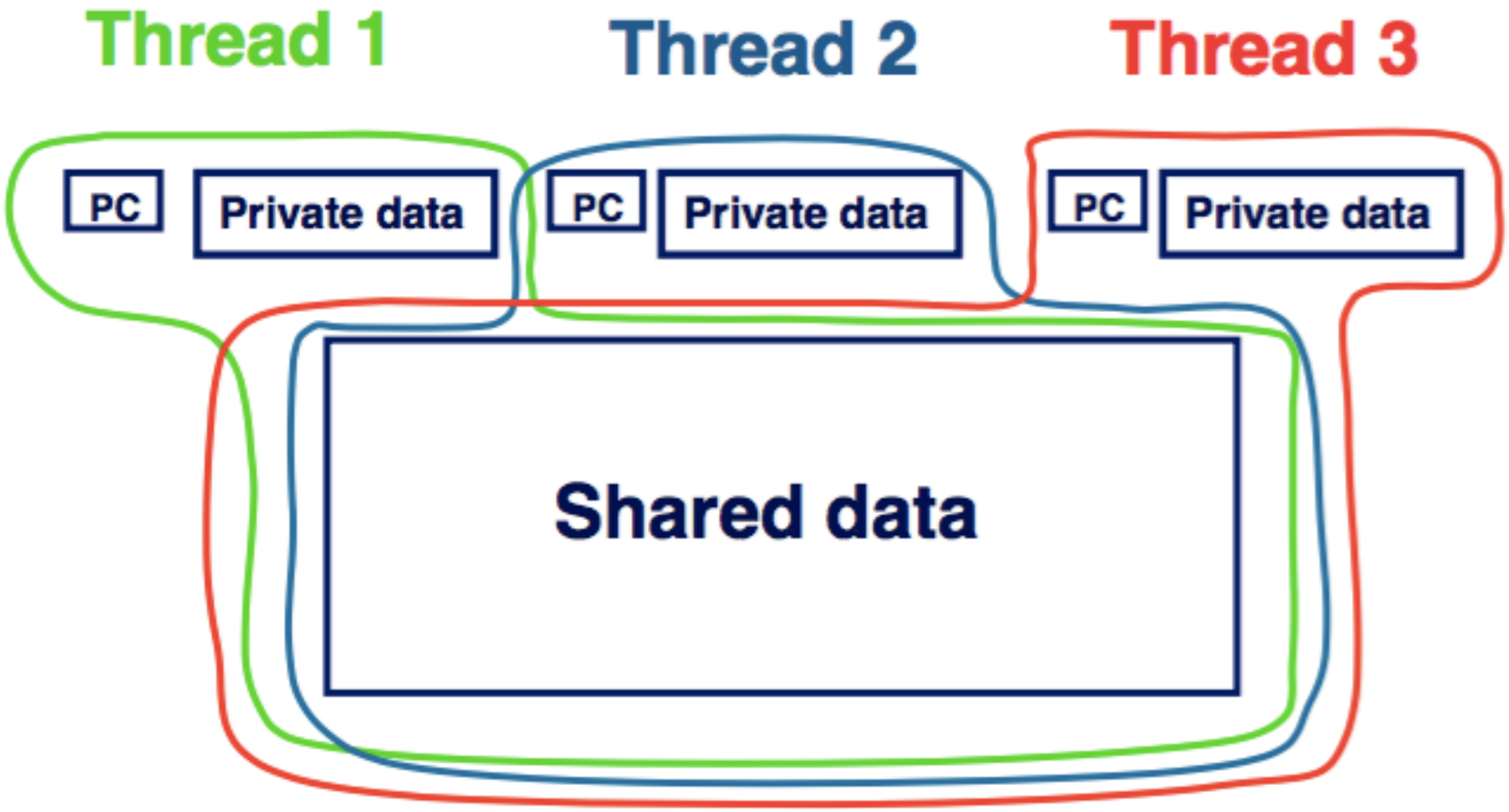
Real Hardware Example



Threaded Programming Model

- The programming model for shared memory is based on the notions of threads
    - threads are like processes, except that threads can share memory with each other (as well as having private memory)
- Shared data can be accessed by all threads
- Private data can only be accessed by the owning thread
- Different threads can follow different flows of control through the same program
    - each thread has its own program counter
- Usually run one thread per CPU/core
    - but could be more
    - can have hardware support for multiple threads per core

Threads (cont.)



Thread Communication

- In order to have useful parallel programs, threads must be able to exchange data with each other

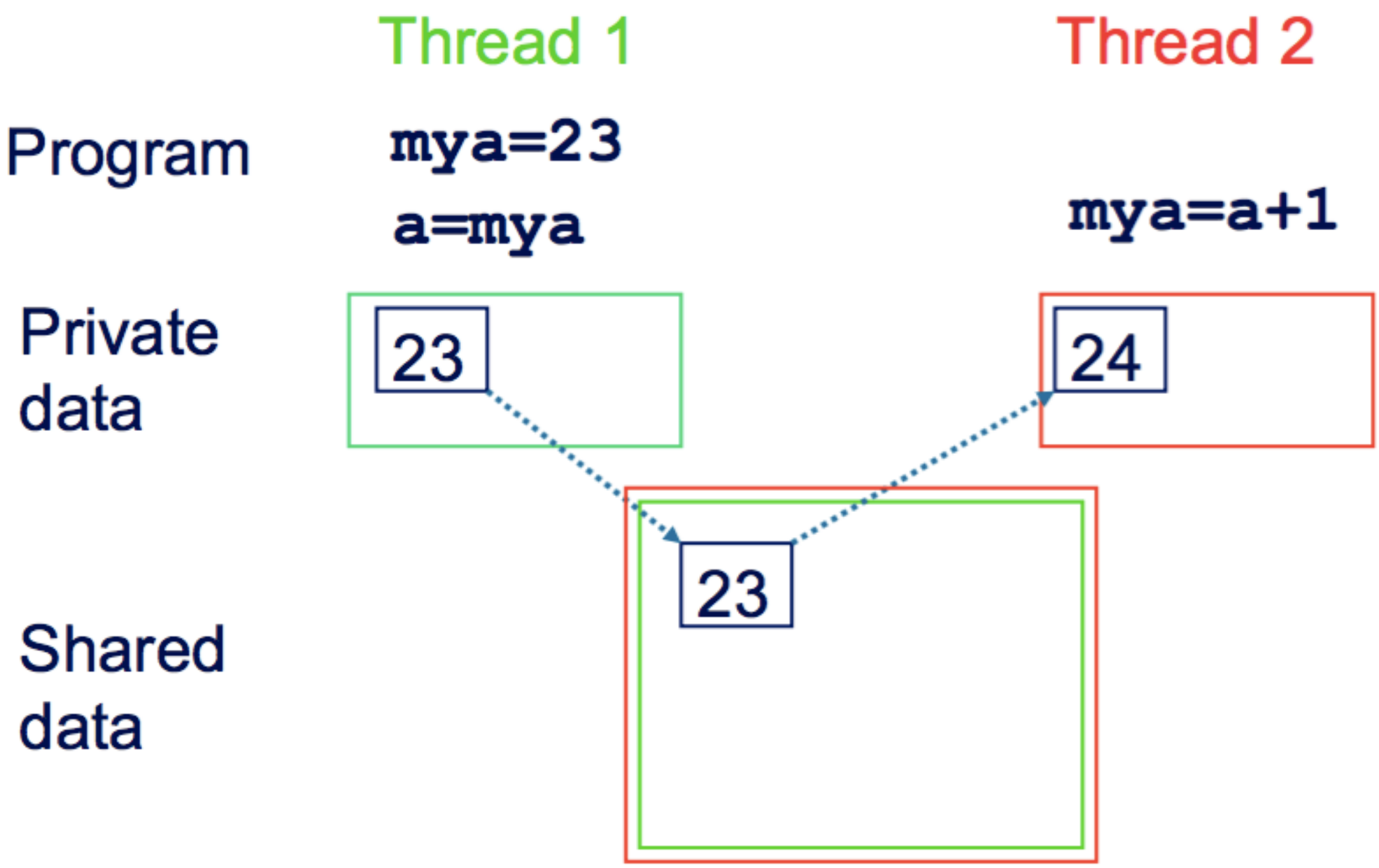
- Threads communicate with each via reading and writing shared data

  - thread 1 writes a value to a shared variable A

  - thread 2 can then read the value from A

- Note: there is no notion of messages in this model

Thread Communication



Synchronisation

- By default, threads execute **asynchronously**
- Each thread proceeds through program instructions independently of other threads
- This means we need to ensure that actions on shared variables occur in the correct order: e.g.
  - thread 1 must write variable A before thread 2 reads it
  - or
  - thread 1 must read variable A before thread 2 writes it
- Note that updates to shared variables (e.g. **`a = a + 1`**) are not atomic!
- If two threads try to do at the same time, one of the updates may get overwritten.

Synchronisation Example

Program

CPU Registers

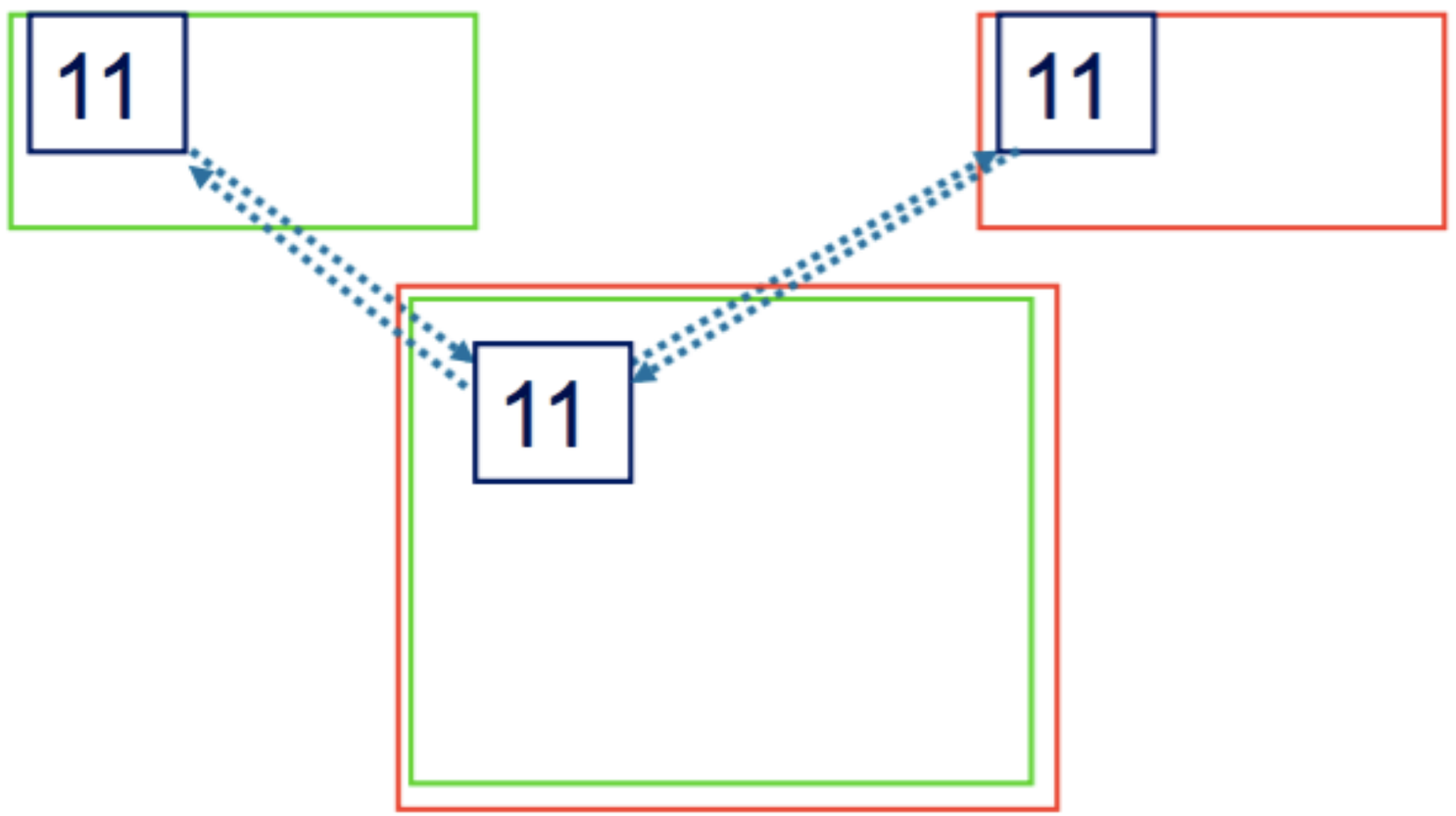
Memory

Thread 1

```
load a
add a 1
store a
```

Thread 2

```
load a
add a 1
store a
```



Parallel Loops

- Loops are the main source of parallelism in many applications

- If the iterations of a loop are independent (can be done any order) then we can share out the iterations between different threads

- e.g. if we have two threads and the loop

```
for (i=0; i<100; i++) {
    a[i] += b[i];
}
```

  - we could do iteration 0-49 on one thread and iterations 50-99 on the other.

```
for (i=0; i<100; i++)
    a[i] += b[i];
```

Parallelizable

```
for (j=0; j<100; j++)
    a[j] += 2;
```

Paralellizable

```
for (j=0; j<100; j++)
    a[j] = b[j] + b[j+1];
```

$a_0 = b_0 + b_1$ ①

$a_1 = b_1 + b_2$

$a_2 = b_2 + b_3$ ⑤

$a_{26} = b_{26} + b_{27}$ ③

$a_{99} = b_{99} + b_{100}$ ②

Parallelizable

```
for (k=0; k<100; k++)
    a[k+2] = a[k+1] + a[k];
```

① $a_2 = a_1 + a_0$

② $a_3 = a_2 + a_1$

③ $a_4 = a_3 + a_2$ ①

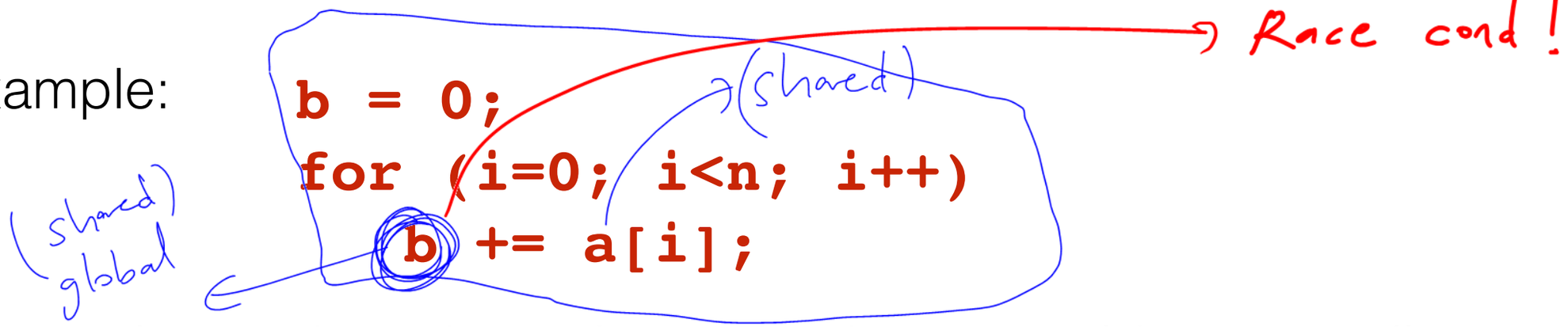
order matters ✓

loop is not independent, thus un-parallelizable!

Reductions

- A *reduction* produces a single value from associative operations such as addition, multiplication, max, min, and, or.

- For example:



- Allowing only one thread at a time to update **b** would remove all parallelism

- Instead, each thread can accumulate its own private copy, then these copies are reduced to give final result

- If the number of operations is much larger than the number of threads, most of the operations can proceed in parallel

OpenMP Fundamentals

What is OpenMP

- OpenMP is an API designed for programming shared memory parallel computers
- OpenMP uses the concepts of *threads*
- OpenMP is a set of extensions to C, C++ and Fortran
- The extensions consist of:
  - Compiler directives → MPI-Send, MPI-Recv, +, −, =
  - Runtime library routines → size -np 8 MPI-Comm-size, MPI-Comm-rank
  - Environment variables → nthreads → BASH

OMP NUM THREADS

Directives and Sentinels

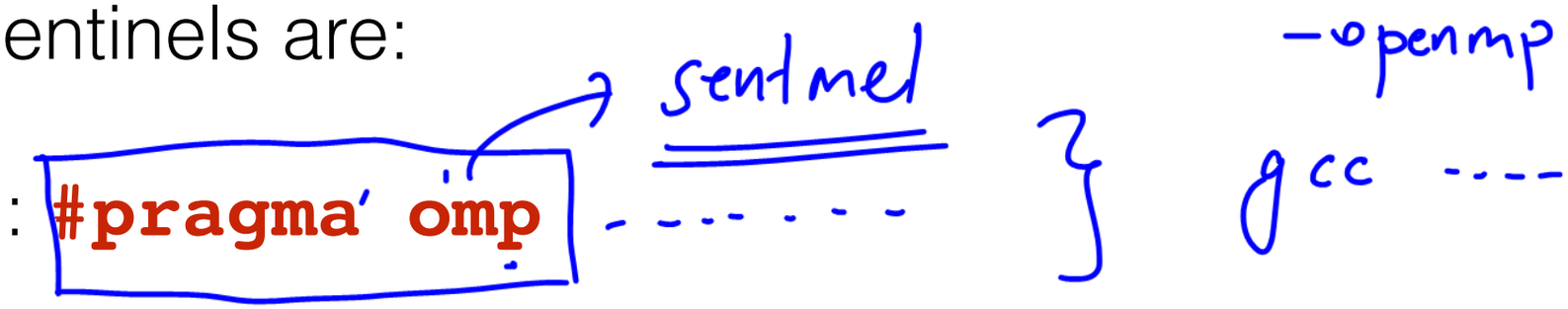
- A directive is a special line of source code with meaning only to certain compilers

- A directive is distinguished by a sentinel at the start of the line

- OpenMP sentinels are:

  - C / C++: `#pragma omp`

  - Fortran : `!$OMP`

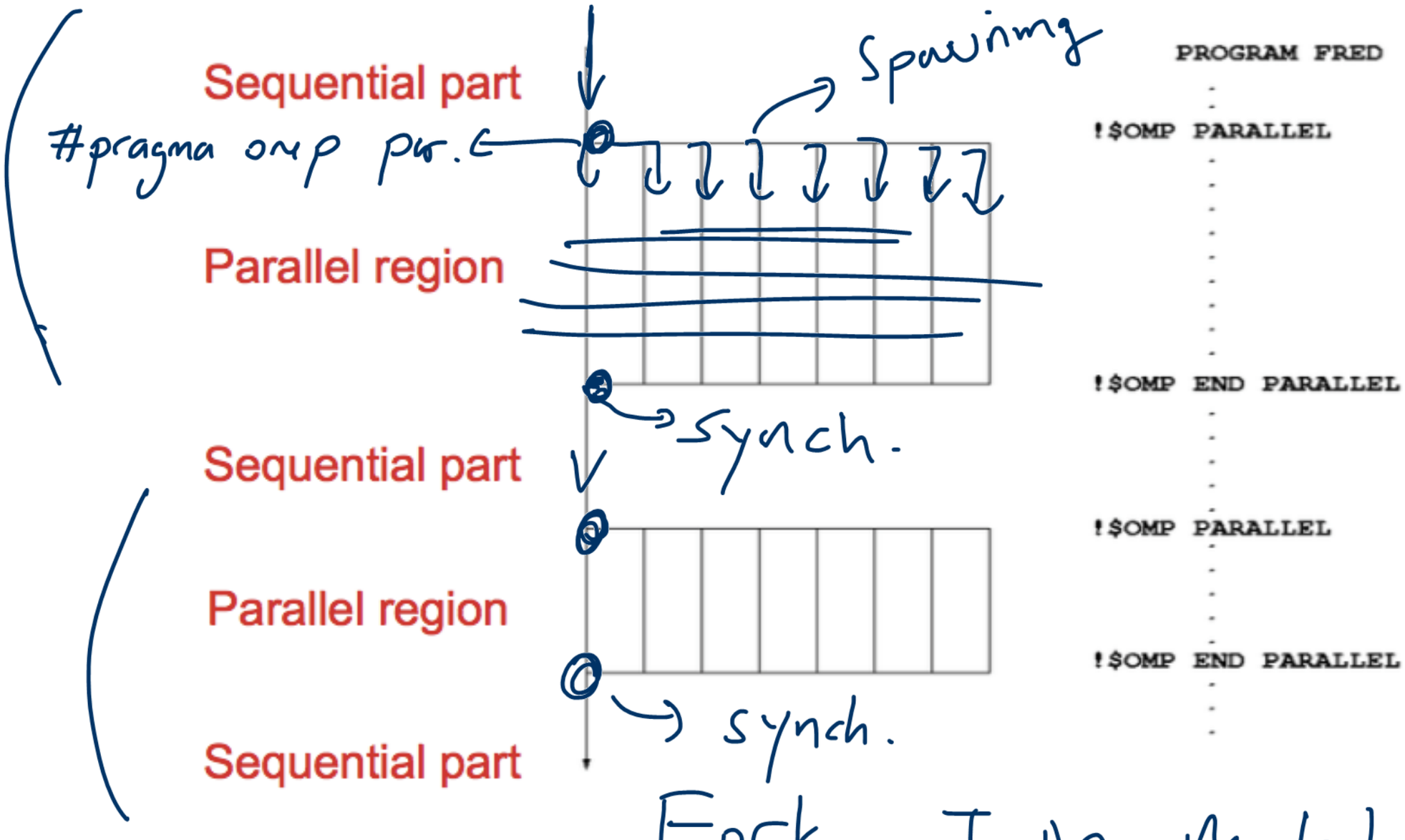


- This means that OpenMP directives are ignored if the code is compiled as regular sequential C/C++/Fortran

Parallel Region

- The *parallel region* is the basic parallel construct in OpenMP
- A parallel region defines a section of a program
- Program begins execution on a single thread (the master thread)
- When the first parallel region is encountered, master thread creates a team of threads (fork/join model)
- Every thread executes the statements which are inside the parallel region
- At the end of the parallel region, the master thread waits for the other threads to finish, and continues executing the next statements

Parallel Region




```
      PROGRAM FRED
      .
      .
!$OMP PARALLEL
      .
      .
      .
      .
      .
      .
      .
      .
      .
!$OMP END PARALLEL
      .
      .
      .
      .
      .
!$OMP PARALLEL
      .
      .
      .
      .
      .
!$OMP END PARALLEL
      .
      .
      .
```

Shared and Private Data

- Inside a parallel region, variables can either be *shared* or *private*

- All threads see the same copy of shared variables

- All threads can read or write shared variables

- Each thread has its own copy of private variables: these are invisible to other threads

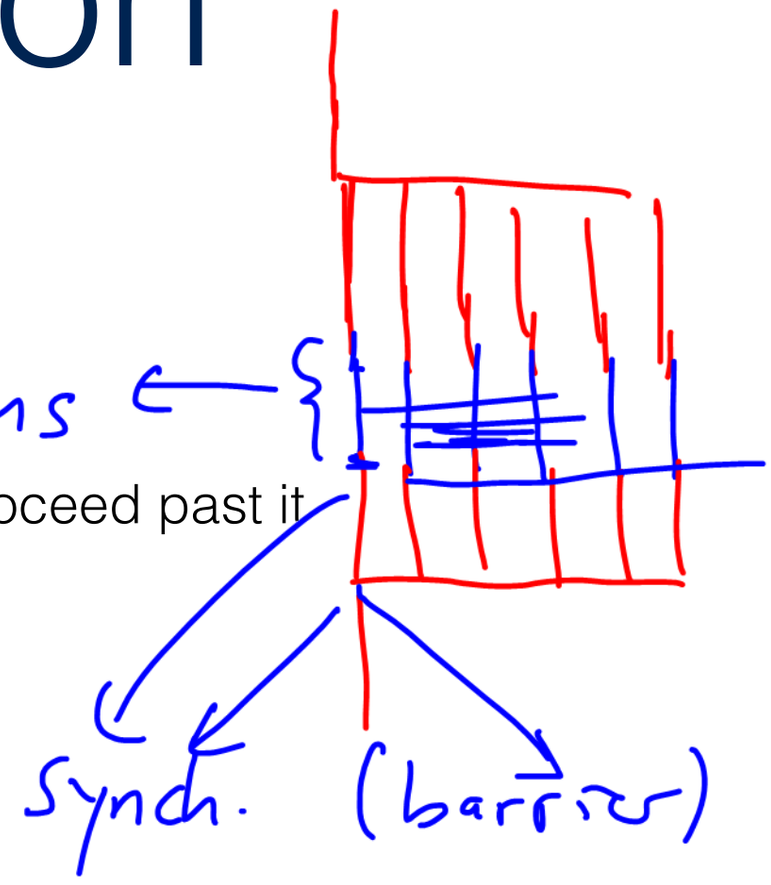
- A private variable can only be read or written by its own thread

Parallel Loops

- In a parallel region, all threads execute the same code
- OpenMP has also directives which indicate that work should be divided up between threads, not replicated
    - this is called *worksharing*
- Since loops are the main source of parallelism in many applications, OpenMP has an extensive support for parallelising loops
- There are a number of options to control which loop iterations are executed by which threads
- It is up to programmer to ensure that the iterations of a parallel loop are *independent*
- Only loops where the iteration count can be computed before the execution of the loop begins can be parallelised in this way

Synchronisation

- The main synchronisation concepts used in OpenMP are:
- Barrier
  - all threads must arrive at a barrier before any thread can proceed past it
  - e.g. delimiting phases of computation
- Critical regions
  - a section of code which only one thread at a time can enter
  - e.g. modification of shared variables
- Atomic update
  - an update to a variable which can be performed only by one thread at a time
  - e.g. modification of shared variables (special case)



(shared) count++; } only one single var can be updated!

Brief History of OpenMP

- Historical lack of standardisation in shared memory directives
  - each hardware vendor provided a different API
  - mainly directive based
    - almost all for Fortran
    - hard to write portable code
- OpenMP forum is set up by Digital, IBM, Intel, KAI and SGI. Now includes most major vendors (and some academic organisations)
- OpenMP Fortran standard released in October 1997, minor revision (1.1) in November 1999, Major revision (2.0) in November 2000
- OpenMP C/C++ standard released October 1998. Major revision (2.0) in March 2002

History (cont.)

- Combined OpenMP C/C++/Fortran standart (2.5) released in May 2005
    - no new features, but extensive rewriting and clarification
- Version 3.0 released in May 2008
    - new features, including tasks, better support for loop parallelism and nested parallelism
- Version 3.1 released in June 2011
    - corrections and some minor new features
    - most current compilers support this
- Version 4.0 released in July 2013
    - accelerator offloading, thread affinity, more task support
    - now appearing in implementations
- Version 4.5 released in November 2015
    - corrections and a few new features

www.openmp.org

Compiling and Running OpenMP Programs

- OpenMP is built-in to most of the compilers you are likely to use
- To compile OpenMP program you need to add a (compiler-specific) flag to your compile and link commands
    - **`-fopenmp`** for gcc/gfortran
    - **`-openmp`** for Intel compilers
- The number of threads which will be used is determined at runtime by **`OMP_NUM_THREADS`** environment variable
    - set this before you run the program
    - e.g. **`export OMP_NUM_THREADS=4`**
- Run in the same way you would a sequential program
    - type the name of the executable

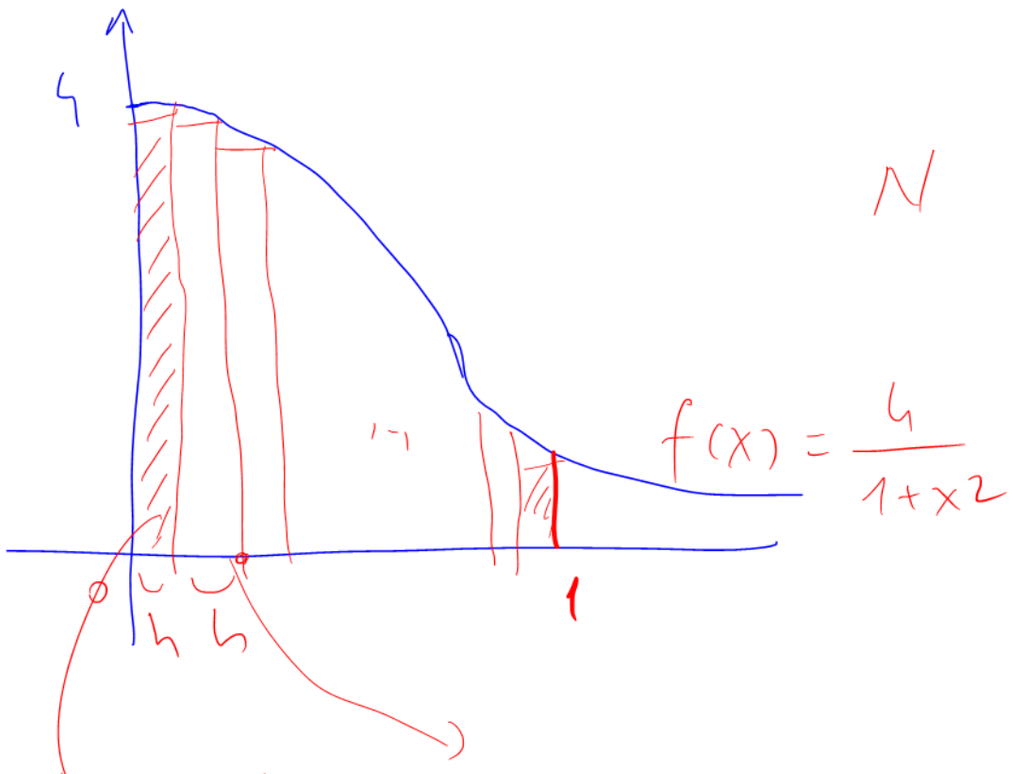
Exercise

- “Hello World” program
- Aim: to compile and run a trivial OpenMP program
- Vary the number of threads using the **OMP_NUM_THREADS** environment variable
- Run the code several times. Is the output always the same?

Exercise II.

PI Calculation with OpenMP

$$\int_0^1 \frac{4}{1+x^2}\,dx = 4\arctan x\Big|_0^1 = 4\left(\underbrace{\arctan 1}_{\frac{\pi}{4}} - \underbrace{\arctan 0}_{0}\right) = \pi$$



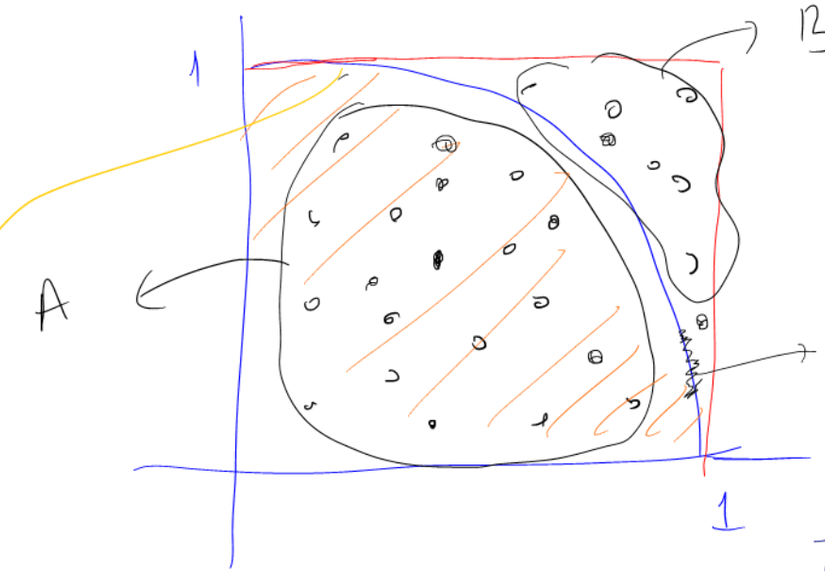
N steps

$$h = \frac{1-0}{N} = \frac{1}{N} \Rightarrow Nh = 1$$

$$h\cdot\frac{4}{1+h^2} + h\cdot\frac{4}{1+(2h)^2} + h\cdot\frac{4}{1+(3h)^2} + \cdots + h\cdot\frac{4}{1+(Nh)^2}$$

$$\approx \pi$$

Exercise: Monte - Carlo Simulation



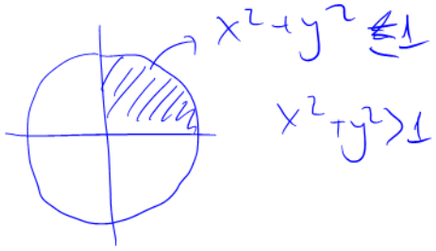
$x^2+y^2=1$

$\frac{\pi}{4}$

constant

$N = 100K$

$0 \le x \le 1$
$0 \le y \le 1$ } Random



$x^2+y^2=1$

if $x^2+y^2 \le 1$

$(x,y) \in A \rightarrow$ counter ++;

else

$(x,y) \notin A$

$\frac{A}{A+B} \rightarrow \pi/4 \approx \frac{\pi}{4}$

$N1 \rightarrow A1$

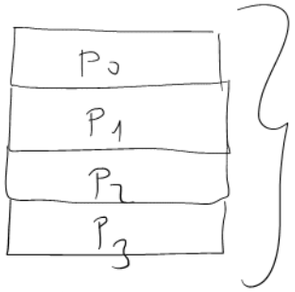
for $i = 1 : N$

$\frac{3,1415\,90\ldots}{4} \approx 0,79\ldots$

$\frac{A}{A+B} \rightarrow \frac{\pi}{4}$

$N1 = (A+B) \rightarrow 1$

$B = N - A$



1D Cartesian Topo.

Lyme top

$\varepsilon_0 = \|Ax_0 - b\|_2 \rightarrow$

$\varepsilon_i = \|Ax_i - b\|_2$

$\varepsilon_i \rightarrow 50$. 100

ε_i

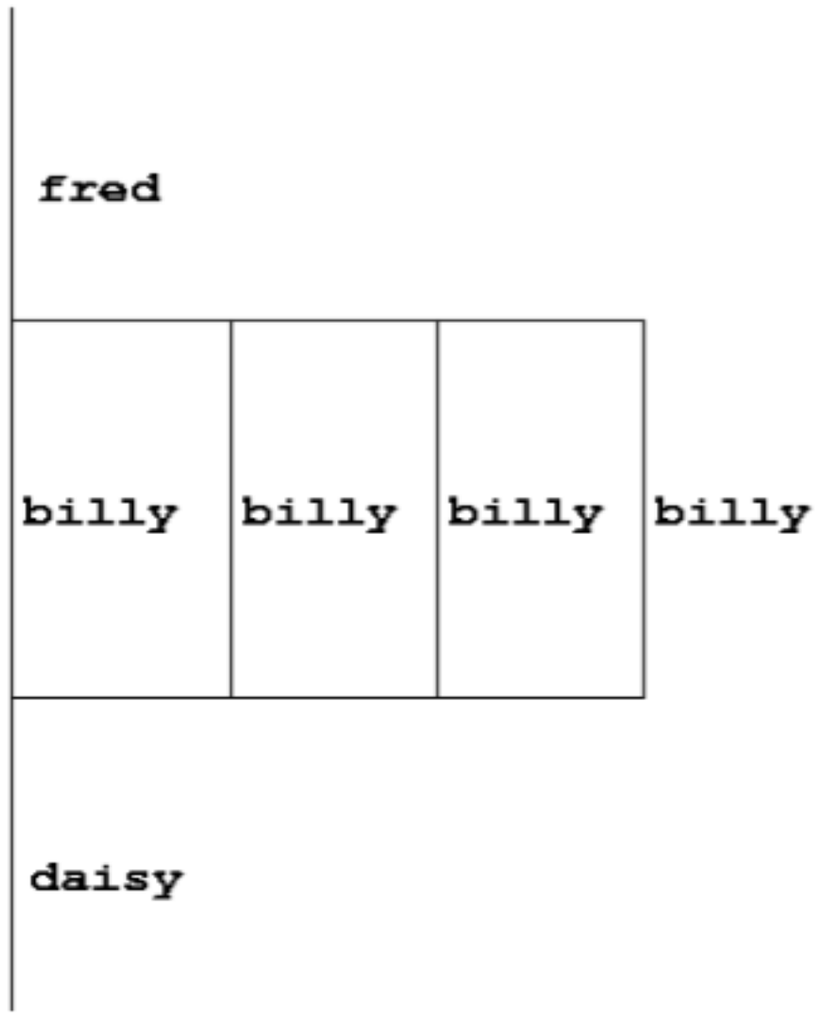
Parallel Regions

Parallel Region Directive

- Code within a parallel region is executed by all threads
- Syntax:
  - C/C++:
```
#pragma omp parallel
{
      block
}
```
  - Fortran:
```
!$OMP PARALLEL
      block
!$OMP END PARALLEL
```

Parallel Region Directive (cont.)

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



Useful Functions

- Often useful to find out number of threads being used
  - Fortran:

```
USE OMP_LIB
INTEGER FUNCTION OMP_GET_NUM_THREADS()
```

  - C/C++:

```
#include <omp.h>
int omp_get_num_threads(void);
```

  - Note: returns 1 if called outside parallel region!

Useful Functions (cont.)

- Also useful to find out number of the executing thread

  - Fortran:

```
USE OMP_LIB
INTEGER FUNCTION OMP_GET_THREAD_NUM()
```

  - C/C++:

```
#include <omp.h>
int omp_get_thread_num(void);
```

  - Note: Takes value between 0 and **`OMP_GET_NUM_THREADS() - 1`**

Clauses

- Specify additional information in the parallel region directive through *clauses*:
  - C/C++: **`#pragma omp parallel`** ***`[clauses]`***
  - Fortran: **`!$OMP PARALLEL`** ***`[clauses]`***
- Clauses are comma or space separated in Fortran, space separated in C/C++

Shared and Private Variables

- Inside a parallel region, variables can be either **shared** (all threads see same copy) or **private** (each thread has its own copy)

- **`shared`**, **`private`** and **`default`** are OpenMP clauses
  - C/C++:
    ```
    shared(list)
    private(list)
    default(shared|none)
    ```
  - Fortran:
    ```
    SHARED(list)
    PRIVATE(list)
    DEFAULT(SHARED|PRIVATE|NONE)
    ```

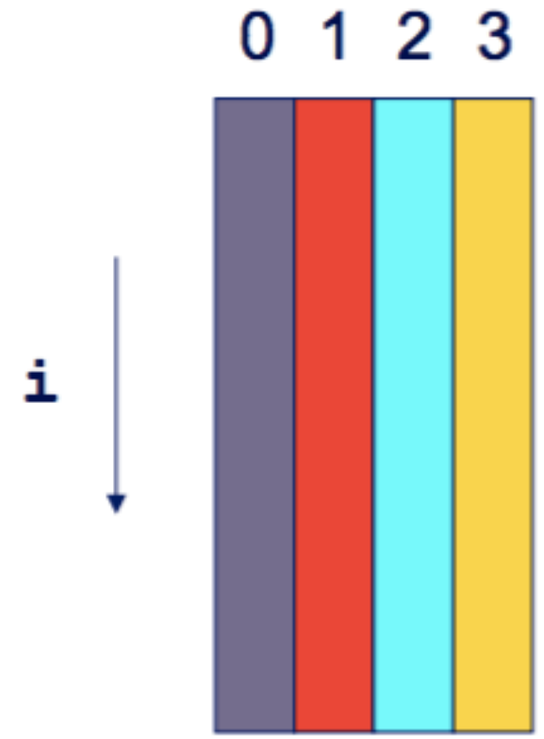
Shared and Private (cont.)

- On entry to a parallel region, private variables are uninitialised
- Variables declared inside the scope of the parallel region are automatically private
- After the parallel region ends, the original variable is unaffected by any changes to private copies
- Not specifying a **`DEFAULT`** clause is the same as specifying **`DEFAULT(SHARED)`**
  - Danger!
  - Always use **`DEFAULT(NONE)`**

Shared and Private (cont.)

- Example: each thread initializes its own column of a shared array

```
!$OMP PARALLEL  DEFAULT (NONE), PRIVATE (I, MYID),
!$OMP& SHARED(A,N)
   MYID = OMP_GET_THREAD_NUM() + 1
   DO I = 1, N
      A(I, MYID) = 1.0
   END DO
!$OMP END PARALLEL
```



Multi-line Directives

C/C++:

```
#pragma omp parallel default(none) \
private(i,myid) shared(a,n)
```

Fortran: fixed source form

```
!$OMP PARALLEL DEFAULT(NONE), PRIVATE(I,MYID),
!$OMP& SHARED(A,N)
```

Fortran: free source form

```
!$OMP PARALLEL DEFAULT(NONE), PRIVATE(I,MYID), &
!$OMP SHARED(A,N)
```

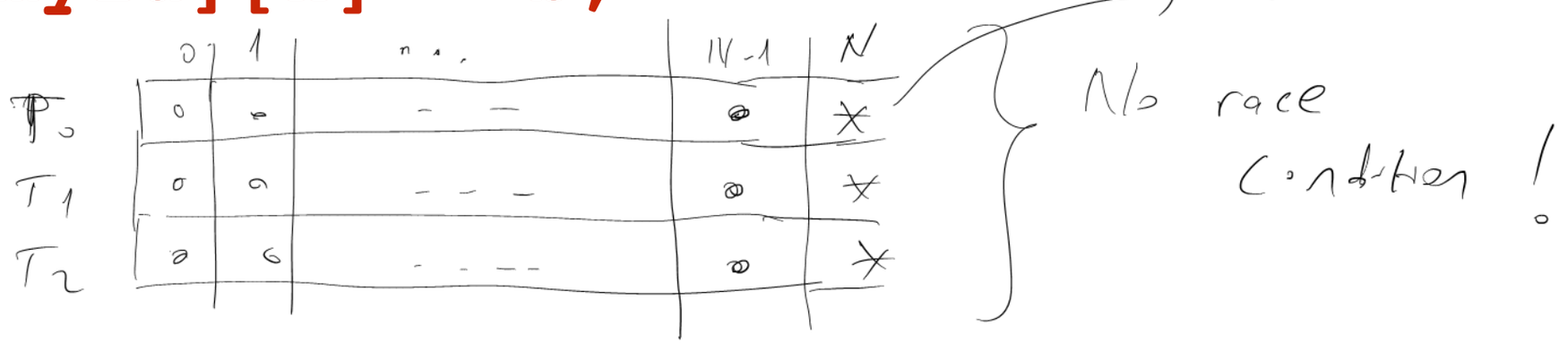
Initializing Private Variables

- Private variables are uninitialized at the start of the parallel region
- If we wish to initialize them, we use **`FIRSTPRIVATE`** clause:
  - C/C++: **`firstprivate(list)`**
  - Fortran: **`FIRSTPRIVATE(list)`**

Initializing Private Variables (cont.)

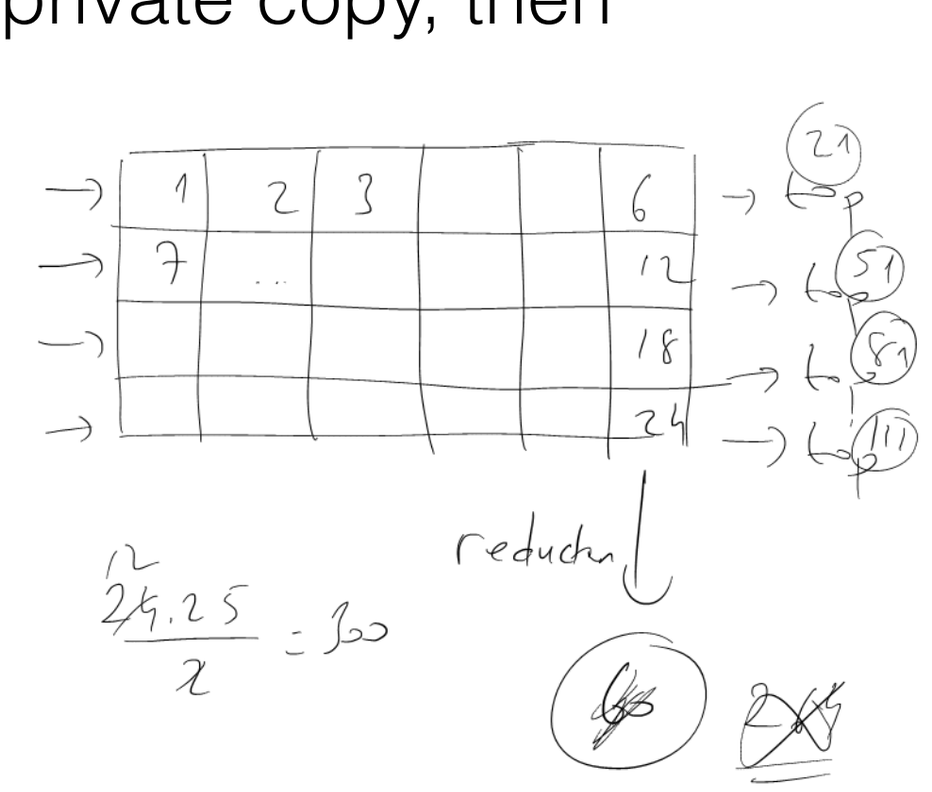
```
b = 23.0;
. . . . .
#pragma omp parallel firstprivate(b),
private(i, myid)
{
   myid = omp_get_thread_num();
   for (i=0; i<n; i++) {
      b += c[myid][i];
   }
      c[myid][n] = b;
}
```

Each thread sums its row up to b



Reductions

- A *reduction* produces a single value from associative operations such as addition, multiplication, max, min, and, or
- Would like each thread to reduce into a private copy, then reduce all these to give final result
- Use **`REDUCTION`** clause:
  - C/C++: **`reduction(op: list)`**
  - Fortran: **`REDUCTION(op: list)`**



- Can have reduction arrays in Fortran, but not in C/C++

Reductions (cont.)

Value in original variable is saved

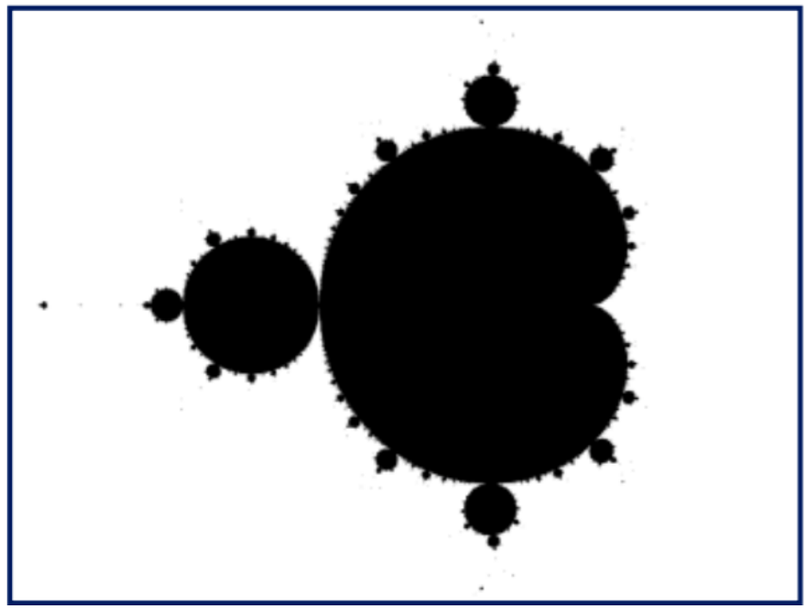
Each thread gets a private copy of **b**, initialized to 0

```
B = 10
!$OMP PARALLEL REDUCTION (+:B),
!$OMP& PRIVATE(I, MYID)
   MYID = OMP_GET_THREAD_NUM() + 1
   DO I = 1, N
      B = B + C[I][MYID]
   END DO
!$OMP END PARALLEL
   A = B
```

All accesses inside the parallel region are to the private copies

At the end of the parallel region, all the private copies are added into the original variable

Exercise



- Area of the Mandelbrot set
- Aim: introduction to using parallel regions
- Estimate the area of the Mandelbrot set by Monte Carlo sampling
  - Generate a grid of complex numbers in a box surrounding the set
  - Test each number to see if it is in the set or not
  - Ratio of points inside a total number of points gives an estimate of the area
  - Testing of points is independent - parallels with a parallel region

Worksharing

Worksharing Directives

- Directives which appear inside a parallel region and indicate how work should be shared out between threads are
  - Parallel DO/for loops
  - Single directive
  - Master directive

Parallel DO/for Loops

- Loops are the most common source of parallelism in most codes. Therefore, parallel loop directives are vey important!

- A parallel DO/for loop divides up the iterations of the loop between threads

- The loop directive appears inside a parallel region and indicates that the work should be shared out between threads, instead of replication

- There is a synchronisation point at the end of the loop: all threads must finish their iterations before any thread can proceed

Parallel DO/for Loops (cont.)

Syntax:

Fortran: **!$OMP DO *[clauses]***
DO loop
!$OMP END DO

C/C++: **#pragma omp for *[clauses]***
for loop

Restrictions in C/C++

- Because the for loop in C is a general while loop, there are restrictions on the form it can take

- It has two determinable trip count - it must be of the form
  - **`for (var = a; var`** *logical-op* **`b;`** *incr-exp*`)`
  - where *logical-op* is one of <, <=, >, >=
  - and *incr-exp* is **`var = var +/- incr`** or semantic
  - equivalent such as **`var++`**
  - also can not modify **`var`** within the loop body

Parallel Loops (Example)

```
!$OMP PARALLEL
!$OMP DO
  DO i=1,n
    b(i)=(a(i)-a(i-1))*0.5
  END DO
!$OMP END DO
!$OMP END PARALLEL
```

```
#pragma omp parallel
{
  #pragma omp for
  for (int i=1, i<=n, i++) {
    b(i)=(a(i)-a(i-1))*0.5;
  }
}
```

Parallel DO/for Directive

- This construct is common that there is shorthand form which combines parallel region and DO/for loops

- C/C++: **#pragma omg parallel for *[clauses]***

  for loop

- Fortran: **!$OMP PARALLEL DO *[clauses]***

  do loop

  !$OMP END PARALLEL DO

Clauses

- DO/for directive can take PRIVATE, FIRSTPRIVATE and REDUCTION clauses which refer to the scope of the loop

- Note that the parallel loop variable is PRIVATE by default
    - loop indices are private by default in Fortran, but not in C

- PARALLEL DO/for directive can take all clauses available for PARALLEL directive

- PARALLEL DO/for is not the same as DO/for or the same as PARALLEL

Parallel DO/for Loops (cont.)

- With no additional clauses, the DO/for directive will partition the iterations as equally as possible between the threads
- However this is implementation dependent, and there is still some ambiguity
    - e.g. 7 iterations, 3 threads. Could partition as 3+3+1 or 3+2+2

SCHEDULE Clause

- The SCHEDULE clause gives a variety of options for specifying which loop iteration are executed by which thread
- Syntax:
    - C/C++: **`schedule(kind[, chunksize])`**
    - Fortran: **`SCHEDULE(kind[, chunksize])`**
    - where kind is one of
        - **`STATIC, DYNAMIC, GUIDED, AUTO or RUNTIME`**
    - and chunksize is an integer expression with positive value
- e.g. **`!$OMP DO SCHEDULE(DYNAMIC, 4)`**

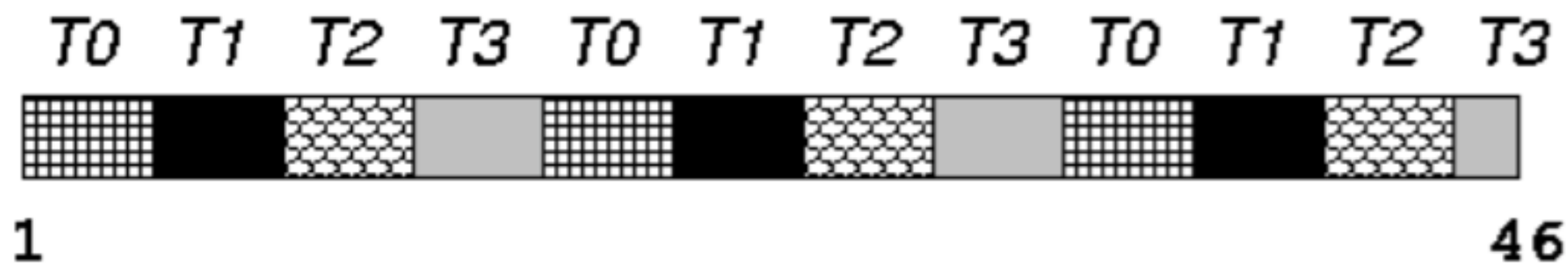
STATIC Schedule

- With no *chunksize* specified, the iteration space is divided into (approximately) equal chunks, and one chunk is assigned to each thread in order (**block** schedule)

- If *chunksize* is specified, the iteration space is divided into chunks, each of *chunksize* iterations, and the chunks are assigned cyclically to each thread in order (**block cyclic** schedule)

STATIC Schedule

SCHEDULE(STATIC)



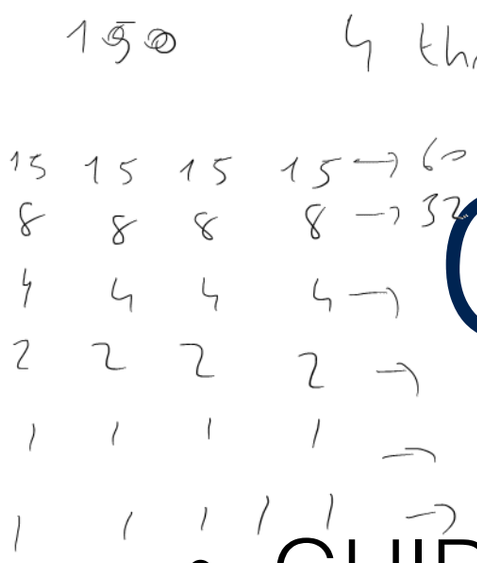
SCHEDULE(STATIC,4)

DYNAMIC Schedule

- DYNAMIC schedule divides the iteration space up into chunks of size *chunksize,* and assigns them to threads on a first-come-first-served basis

- i.e. as a thread finish a chunk, it is assigned the next chunk in the list

- When no *chunksize* is specified, it defaults to 1



GUIDED Schedule

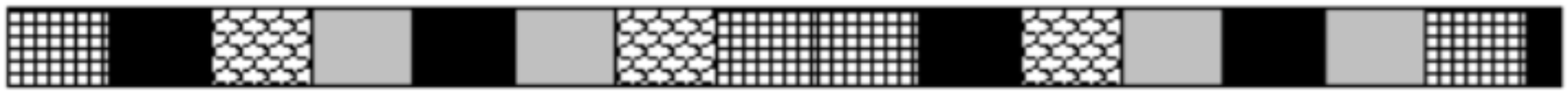
- GUIDED schedule is similar to DYNAMIC, but the chunk starts off large and gets smaller exponentially

- The size of the next chunk is proportional to the number of remaining iteration divided by the number of threads

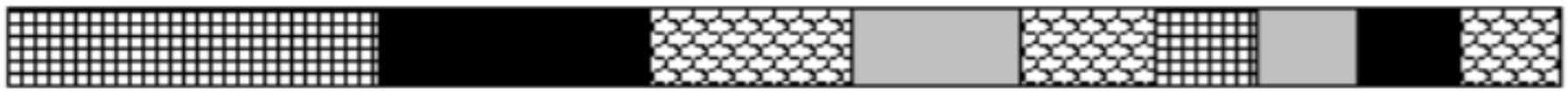
- The *chunksize* specifies the minimum size of the chunks

- When no *chunksize* is specified, it defaults to 1

DYNAMIC and GUIDED Schedules



1 **SCHEDULE(DYNAMIC,3)** 46



1 **SCHEDULE(GUIDED,3)** 46

AUTO Schedule

- Lets the runtime have full of freedom to choose its own assignment of iterations to threads

- If the parallel loop is executed many times, the runtime can evolve a good schedule which has good load balance and low overheads

Choosing a Schedule

- STATIC best for load balanced loops - least overhead
- STATIC, n good for loops with mild or smooth load imbalance, but can induce overheads
- DYNAMIC useful if iterations have widely varying loads, but ruins data locality
- GUIDED often less expensive than DYNAMIC, but beware of loops where the first iterations are the most expensive
- AUTO may be useful if the loop is executed many times over

SINGLE Directive

- Indicates that a block of code is to be executed by a **single thread only**

- The first thread to reach the SINGLE directive will execute the block

- There is a **synchronisation** point at the end of the block: all other threads wait until block has been executed

SINGLE Directive (cont.)

Syntax:

Fortran

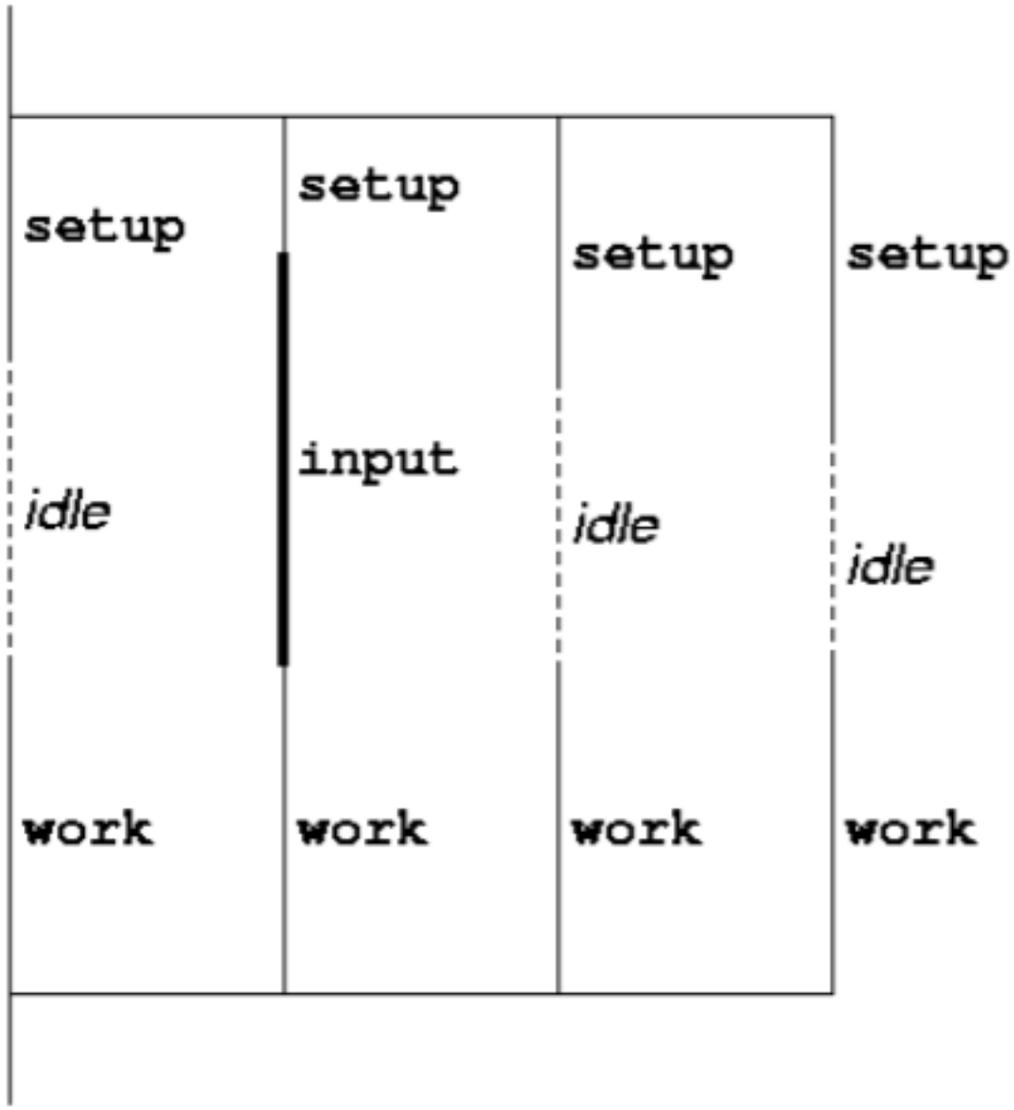
```
!$OMP SINGLE [clauses]
   block
!$OMP END SINGLE
```

C/C++:

```
#pragma omp single [clauses]
   structured block
```

SINGLE Directive (cont.)

```
#pragma omp parallel
{
  setup(x);
  #pragma omp single
  {
    input(y);
  }
  work(x,y);
}
```



SINGLE Directive (cont.)

- SINGLE directive can take PRIVATE and FIRSTPRIVATE clauses

- Directive must contain a structured block: can not branch into or out of it

MASTER Directive

- Indicates that a block of code should be executed by the **master thread** (thread 0) **only**

- There is **no synchronisation** at the end of the block: other threads skip the block and continue executing

MASTER Directive (cont.)

Syntax:

Fortran
```
!$OMP MASTER
    block
!$OMP END MASTER
```

C/C++:
```
#pragma omp master
    structured block
```

Synchronisation

Why is It Required?

- Need to synchronise actions on shared variables
- Need to ensure correct ordering of reads and writes
- Need to protect updates to shared variables (not atomic by default)

BARRIER Directive

- No thread can proceed reached a barrier until all the other threads have arrived

- Note that there is an implicit barrier at the end of DO/for, SECTIONS and SINGLE directives

- Syntax:

    - C/C++: **`#pragma omp barrier`**

    - Fortran: **`!$OMP BARRIER`**

- Either all threads or none must encounter the barrier: otherwise DEADLOCK!

BARRIER Directive (cont.)

Example:

```
!$OMP PARALLEL PRIVATE(I,MYID,NEIGHB)
   myid = omp_get_thread_num()
   neighb = myid - 1
   if (myid.eq.0) neighb = omp_get_num_threads()-1
   ...
   a(myid) = a(myid)*3.5
!$OMP BARRIER
   b(myid) = a(neighb) + c
   ...
!$OMP END PARALLEL
```

- Barrier required to force synchronisation on **a**

Critical Sections

- A critical section is a block of code which can be executed by only one thread at a time

- Can be used to protect updates to shared variables

- The CRITICAL directive allows critical sections to be named

- If one thread is in a critical section with a given name, no other thread may be in a critical section with the same name (though they can be in critical sections with other names)

Critical Directive

Fortran
```
!$OMP CRITICAL [(name)]
   block
!$OMP END CRITICAL [(name)]
```

C/C++:
```
#pragma omp critical [(name)]
   structured block
```

- In Fortran, the names on the directive pair must match
- If the name is omitted, a null name is assumed (all unnamed critical sections effectively have the same null name)

Critical Directive (cont.)

Example: Pushing and popping a task stack

```
!$OMP PARALLEL SHARED(STACK),PRIVATE(INEXT,INEW)
      ...
!$OMP CRITICAL (STACKPROT)
      inext = getnext(stack)
!$OMP END CRITICAL (STACKPROT)
      call work(inext,inew)
!$OMP CRITICAL (STACKPROT)
      if (inew .gt. 0) call putnew(inew,stack)
!$OMP END CRITICAL (STACKPROT)
      ...
!$OMP END PARALLEL
```

Atomic Directive

- Used to protect a single update to a shared variable.
- Applies only to a single statement.
- Syntax:

Fortran: **!$OMP ATOMIC**

statement

where *statement* must have one of these forms:

x = x op expr, *x = expr op x*, *x = intr (x, expr)* or

x = intr (expr, x)

op is one of +, *, -, /, **.and.**, **.or.**, **.eqv.**, or **.neqv.**

intr is one of **MAX**, **MIN**, **IAND**, **IOR** or **IEOR**

Atomic Directive (cont.)

C/C++: **`#pragma omp atomic`**

statement

where *statement* must have one of the forms:

x binop = *expr*, *x*++, ++*x*, *x*−−, or −−*x*

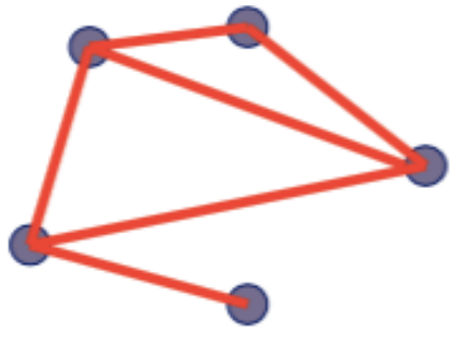
and *binop* is one of **+**, *****, **−**, **/**, **&**, **^**, **<<**, or **>>**

- Note that the evaluation of *expr* is not atomic.
- May be more efficient than using CRITICAL directives, e.g. if different array elements can be protected separately.
- No interaction with CRITICAL directives

Atomic Directive (cont.)

Example (compute degree of each vertex in a graph):

```
#pragma omp parallel for
      for (j=0; j<nedges; j++){
#pragma omp atomic
         degree[edge[j].vertex1]++;
#pragma omp atomic
         degree[edge[j].vertex2]++;
      }
```



QUESTIONS
or
COMMENTS!