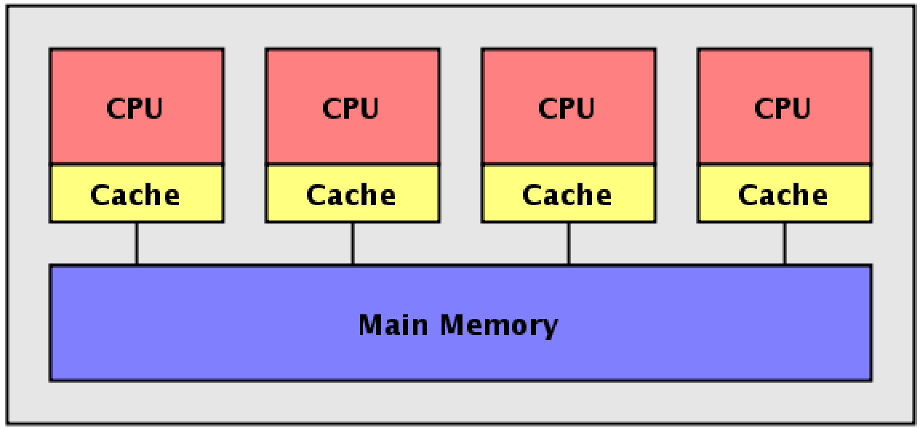
Shared Memory Programming and OpenMP

CS121 Parallel Computing

Fall 2021

Shared memory multiprocessor



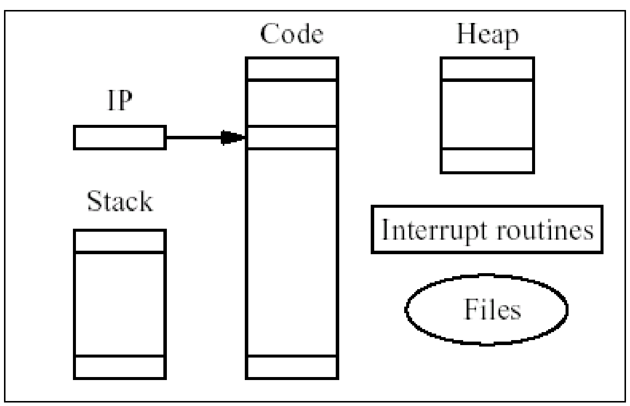
- Any memory location is accessible by any of the processors.
- A single address space exists.
  - Each memory location is given a unique address within a single range of addresses.
- Generally, more convenient than distributed memory programming.
  - But access to shared data needs to be controlled by the programmer, e.g. using critical sections.

Shared memory programming

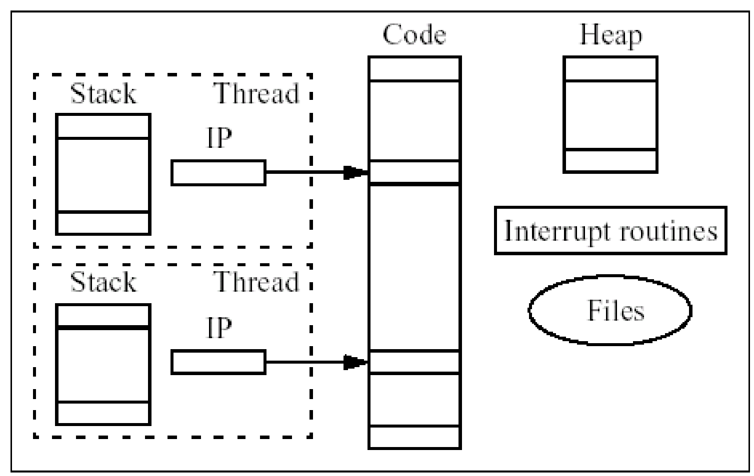
- Threads (e.g. Pthreads, Java)
  - The programmer decomposes the program into individual sequences of instructions (threads) that can execute in parallel and access shared data.
  - Very general, but hard to use because programmer must manage everything.
- Parallel programming language / library
  - A parallel language or library is used to create code that can be executed on a shared memory parallel architecture.
  - Requires new compiler, programmers to learn new language, etc.
- Compiler directives (e.g. OpenMP)
  - The programmer inserts compiler directives into a sequential program to specify parallelism and indicate shared data and the compiler translates into threads.
  - Still uses threads underneath, but system manages the threads.
  - Easy to program (though loses some flexibility). Requires less changes to compiler.
  - Most popular option.

Processes and threads

- Process (e.g. MPI)
  - Separate program with its own variables, memory, stack and instruction pointer.
  - Different programs can't access each other's memory.
- Thread (e.g. OpenMP)
  - Concurrent routine that shares the variables and memory space, but has its own stack and instruction pointer.



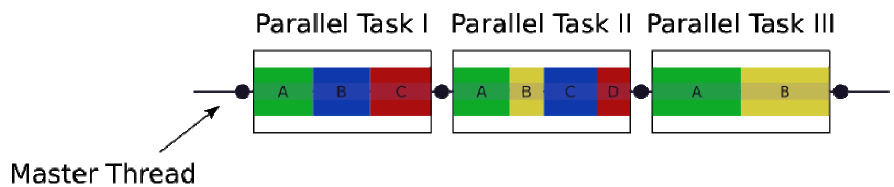
(a) Process

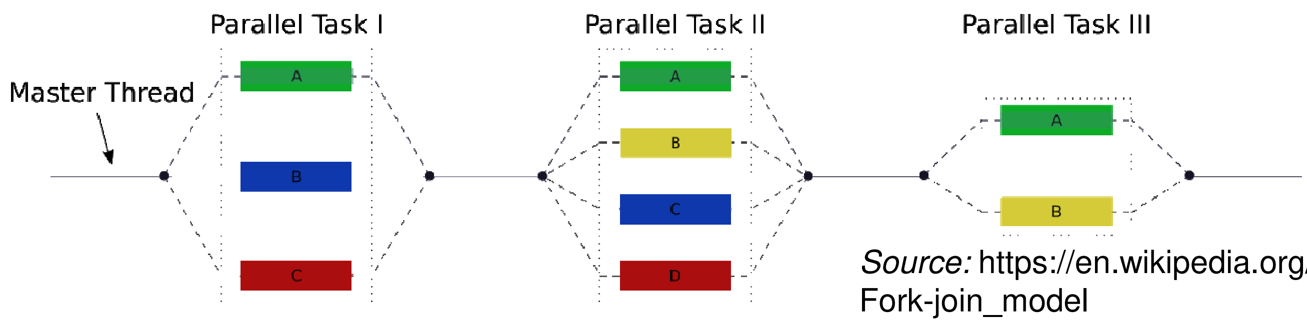


(b) Threads

Fork-join model

- A model for parallel computing using threads.
- Computation starts with master thread.
- If there is parallel work, master thread forks off slave threads.
  - Thread can be executed on same processor / core or a different one.
- When slave threads finish, they join (merge back into) master thread.

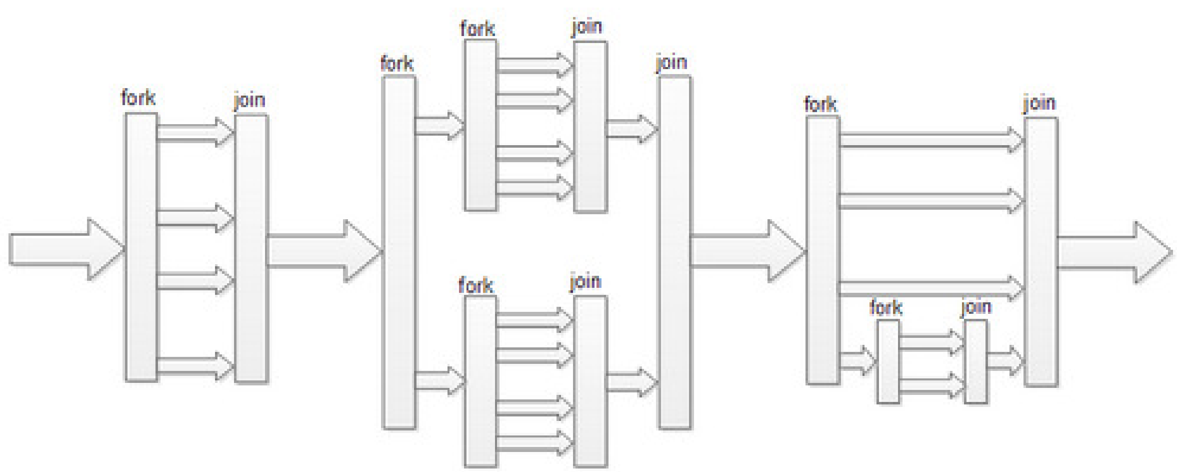




Source: https://en.wikipedia.org/wiki/Fork-join_model

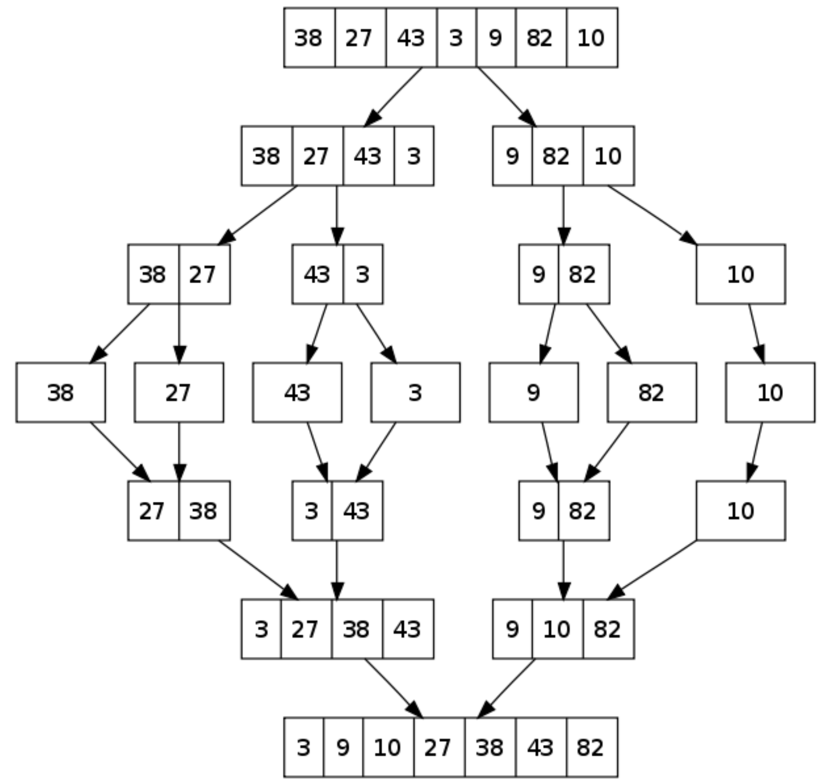
Fork-join model

- Spawned threads may recursively create further threads.
  - Slave threads join with the thread that spawned them.
  - Can also create detached threads, that don't do a join when they terminate.



Example

```
mergesort(A, lo, hi):
    if lo < hi:
        mid = ⌊(hi - lo) / 2⌋
         fork mergesort(A, lo, mid)
         mergesort(A, mid, hi)
         join
         merge(A, lo, mid, hi)
```



Source: https://en.wikipedia.org/wiki/Merge_sort

Statement execution order

- Single thread Execute statements in program order until blocked or end of time slice.
- Multi-threaded Instructions of different threads are interleaved in arbitrary order.
  - Correctness of program can't depend on particular interleaving order, or else race condition bug.
  - Ensuring no race conditions one of the primary challenges to shared memory programming.

Thread 1	Thread 2	Possible interleaving
Instruction 1.1	Instruction 2.1	Instruction 2.1
Instruction 1.2	Instruction 2.2	Instruction 1.1
Instruction 1.3	Instruction 2.3	Instruction 1.2
		Instruction 2.2
		Instruction 2.3
		Instruction 1.3

Race condition example

- Accessing shared data needs careful control because of interleaving of threads.
- Consider two threads which increment a shared counter x.
  - In sequential execution, x equals 2 at the end.
  - In parallel execution under given interleaving, x equals 1.

Thread 1	Thread 2	Possible interleaving
load x	load x	load x
compute x+1	compute x+1	compute x+1
store x	store x	load x
		store x
		compute x+1
		store x
		// x == 1

Thread safe routines

- A routine is thread safe if it can be called from multiple threads simultaneously and always produces correct results.
  - Standard I/O routines are thread safe.
    - Ex messages are printed without interleaving the characters.
  - Other system routines may not be thread safe, e.g. some random number generators
- Routines that access shared data may require special care to be made thread safe.
- If a routine is not thread safe, it must be executed by only one thread at a time in a "critical section".

Critical sections

- A block of code that can be executed by only one thread at a time.
  - Multiple changes can be made to data without interruption, so that data transitions from safe state to safe state.
  - Also called mutual exclusion.
  - Also appears in operating systems and programming languages, e.g. Java's `synchronized` statement.
- Helps avoid the race condition bugs we saw earlier.

Thread 1	**Thread 2**	**Possible interleaving**
load x	load x	load x
compute x+1	compute x+1	compute x+1
store x	store x	store x
		load x
		compute x+1
		store x
		// x == 2

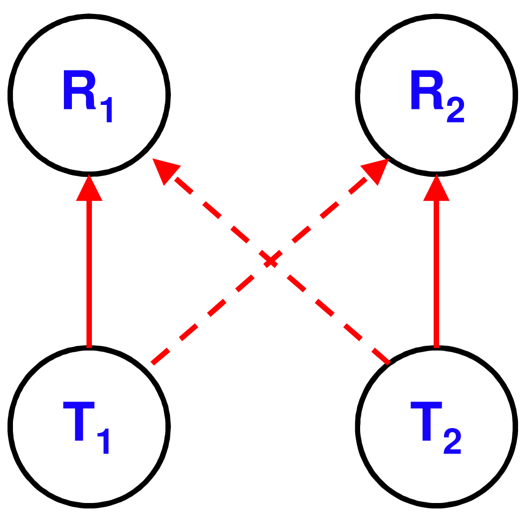
Locks

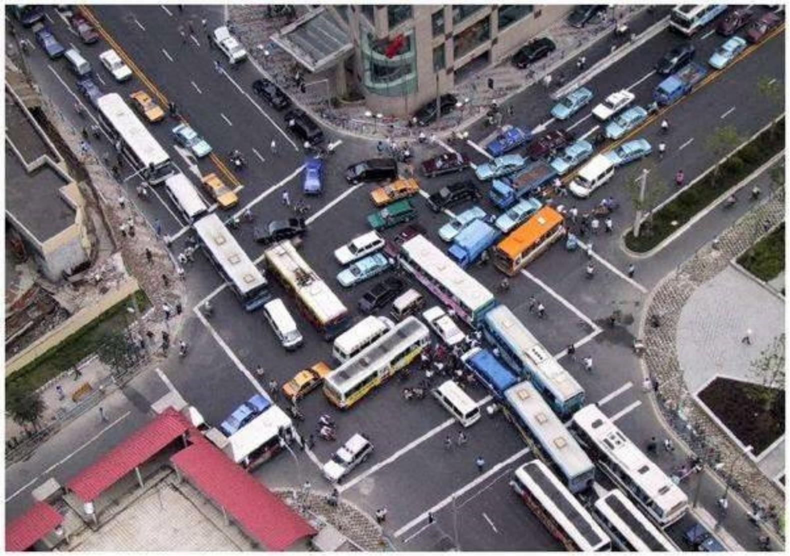
- A simple mechanism for ensuring mutual exclusion.
- A thread sets a lock before entering the critical section, and unsets it when it leaves.
- If a thread tries to set a lock and finds it locked, it blocks, i.e. waits for the lock to be unset.
  - So only the first thread to set the lock can execute the code in the critical section.
  - Other threads wait until the first thread finishes the critical section and unsets the lock, after which one of them can set the lock and perform the critical section.

```
set_lock(mutex);
critical section
...
unset_lock(mutex);
```

Deadlock

- A system state when all threads are stuck, i.e. can't take another step.
- Can occur when a thread T_1 waits for a resource held by T_2, while T_2 waits for a resource held by T_1.
- Can also have a waiting cycle of many threads.
- Can avoid deadlock by having all threads lock resources in same order.





Non-blocking locking

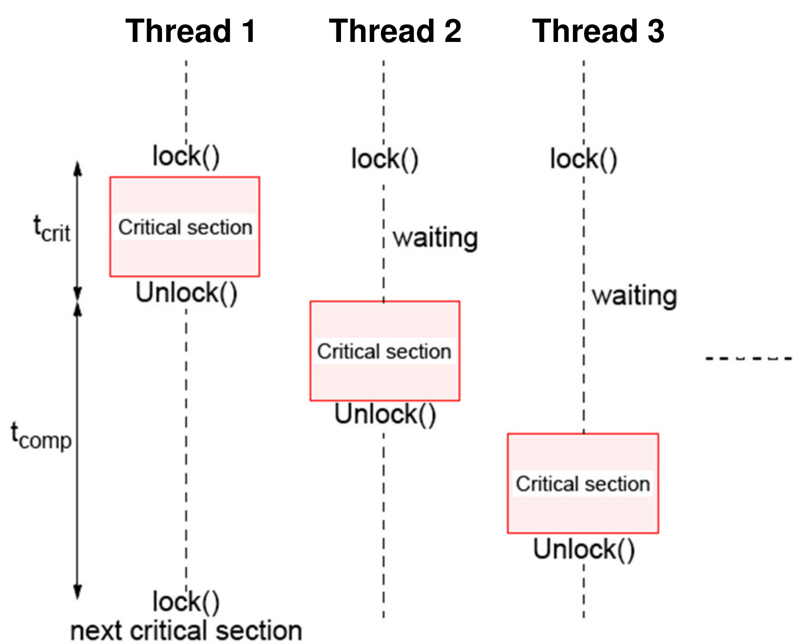
- Attempt to lock without blocking.

```
flag = test_lock(mutex);
if (!flag) {
    critical section
    unset_lock(mutex);
} else …
```

- If lock currently unset, it will set it and return success.
- If lock currently set, it will return failure without blocking.
- Can avoid deadlock.
  - Threads can use `test_lock` to access resource.
- Can avoid waiting time associated with blocking.
  - Thread can do other work and `test_lock` again later.

Critical sections and performance

- Critical sections lead to serialization of code.
  - If multiple threads want access to a critical section and reach it at the same time, the threads must be executed sequentially.
  - Then the execution time becomes almost that of a single processor.
- For performance, avoid critical sections when possible, and minimize their size.



When $t_{comp} < pt_{crit}$, less than p processor will be active

Condition variables

- Often, a critical section needs to be executed only when a specific condition is met.
- Can use a condition variable.
  - Thread gets the lock for a critical section, then calls the condition variable to wait for condition to become true.
  - Waiting thread goes to sleep and releases lock, atomically.
  - If there are several waiters, they get put in a queue.
  - On a `signal_all`, one of the waking threads reacquires lock.
- More efficient than continually testing a lock to see when condition met.
- `wait(cond, lock)`
  - Atomically release `lock` and go to sleep. Upon waking, try to reacquire `lock`.
- `signal(cond)`
  - Wake up one sleeping thread waiting on `cond`.
- `signal_all(cond)`
  - Wake up all sleeping threads waiting on `cond`.

Producer-consumer example

- Producer threads add items to a queue, consumer threads remove them.
  - If queue empty, consumers wait. If queue full, producers wait.
- Instead of continuously locking the queue and checking if it's full / empty, go to sleep until signaled.
- Accesses to queue still need to be protected using `lock`.
- Producers and consumers signal each other using condition variables `not_full`, `not_empty`.
- Use `while` loop around `wait` because there may be multiple producers, consumers.
  - E.g. producer's `signal_all` can wake several consumers, one of which consumes the queue item. So the other consumers should check again whether items == 0.

```
Producer() {
   set(lock)
   while (items == N)
      wait(not_full, lock);
   /* access shared resource */
   items++;
   signal_all(not_empty);
   release(lock);
}
```

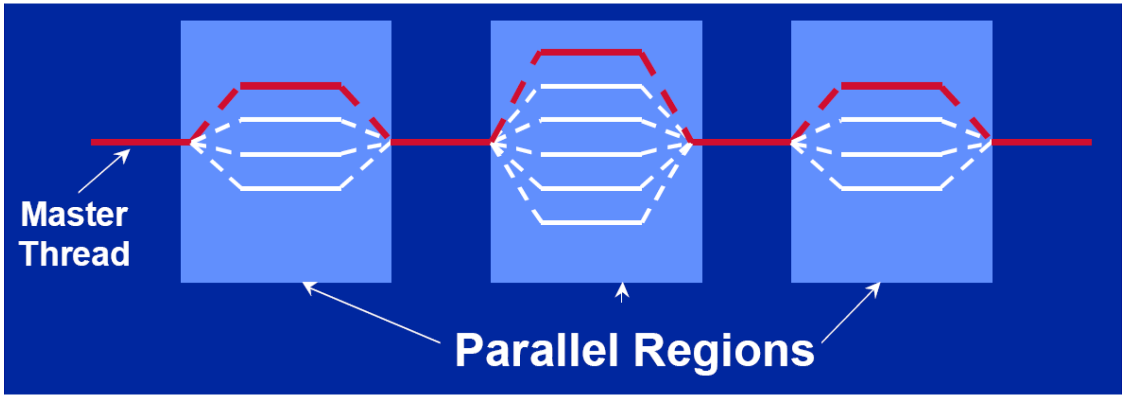
```
Consumer() {
   set(lock)
   while (items == 0)
      wait(not_empty, lock);
   /* access shared resource */
   items--;
   signal_all(not_full);
   release(lock);
}
```

OpenMP

- OpenMP is a standard for shared memory programming adopted by many hardware vendors.
- Can be used with different languages, e.g. C, C++ and Fortran.
- Compiler directives are used to specify parallelism and to indicate shared data.
- An OpenMP compatible compiler produces parallel program using the directives. A noncompatible compiler produces correct sequential program using same code.
  - Several OpenMP compilers available, e.g. Intel C compiler.
- Can be used to add parallelism incrementally to a sequential program, e.g. by parallelizing for loops.
- Underneath, OpenMP still uses threads.
  - OpenMP gives a more convenient, succinct way to manage threads.
  - But it lacks some of the expressiveness of explicit threading.

OpenMP

- OpenMP is based on threads, and uses the "fork-join" model.
  - Initially, a single master thread exists.
  - Parallel regions (sections of code) can be executed by a team of threads.
  - Compiler takes care of creating and coordinating threads.
- Available for C / C++ and Fortran. Documentation at http://openmp.org/wp/openmp-specifications/



Parallel regions

- The `parallel` directive forks a team of threads, each of which executes the following region, enclosed in {...}.

```
#pragma omp parallel
structured-block // { ... code ... }
```

- Threads do a join at end of parallel region, and execution resumes with the single master thread.
- Number of threads can be set by
  - `num_threads` clause after the parallel directive.
  - `omp_set_num_threads()` library routine previously called.
  - Environment variable `OMP_NUM_THREADS`.
  - Recommendation is one thread per processor / core.
- Threads can do the work in the region in parallel.
  - Can do different things based on thread ID.
  - Can share work using `for`, `sections`, `task`, etc. directives.
- Parallel regions can be nested.

Parallel regions

- Example

```
#pragma omp parallel private(iam, np)
{
    np = omp_get_num_threads();
    iam = omp_get_thread_num();
    printf("Hello from thread %d out of %d\n",
            iam, np);
}
```

  - All threads in parallel region run this code.
  - `iam` and `np` are private variables (i.e. instance of variable for each thread).
  - `omp_get_num_threads()` returns the number of threads n in the team used for the parallel region.
  - `omp_get_thread_num()` returns thread number (identity) in range 0 to n-1 with master thread 0.
  - Messages printed in arbitrary order.

Work sharing

- Share some work inside a parallel region among threads.
- For example, `for` construct inside a parallel region partitions iterations of the loop among the threads.

```
#pragma omp for
for(i=0; i<n; i++)
    {do_stuff(i);}
```

  - The way in which iterations are assigned to threads can be specified by an additional `schedule` clause.
- For this and other worksharing constructs:
  - Does not start a new team of threads - that is done by an enclosing `parallel` construct.
  - Implicit barrier at the end of the construct unless a `nowait` clause is included. I.e. each thread will wait at end of construct for all other threads to finish.

Schedule clause

- Used for assigning iterations of parallel `for` to threads.
- `schedule(static[,chunk])`
  - Each thread gets a chunk of iterations of size “chunk” – by default chunks approximately equal.
  - Chunks assigned in round robin order.
- `schedule(dynamic[,chunk])`
  - Each time a thread finishes its iterations, grabs “chunks” more iterations, until all have been executed – default is 1.
  - Dynamic scheduling has some overhead, but can result in better load balancing if iterations not all equal sized.
- `schedule(guided[,chunk])`
  - Each thread dynamically grabs iterations where the size starts large and shrinks down to “chunk”.
  - Dynamic load balancing with less overhead.
- `schedule(runtime)`
  - Schedule type and chunk size taken from the OMP_SCHEDULE environment variable.

Combined `parallel for`

- If a `parallel` directive is followed by a single `for` directive, they can be combined.

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

- Several restrictions on structure of `for` loop.
  - Number of iterations `n` must not change.
  - Loop increment must be fixed.
  - Must not exit loop prematurely (with `break`, `goto`, `throw`).
  - Purpose of restrictions is so amount of work in loop can be determined at start.

Different ways to parallelize for

```
// sequential

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

```
// create parallel region
// then do worksharing

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

```
// create parallel region and do
//worksharing together

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

```
// manual parallelization

#pragma omp parallel {
     int id, i, Nthreads, start, end;
     id = omp_get_thread_num();
     Nthreads = omp_get_num_threads();
     start = id * N / Nthreads;
     end = (id + 1) * N / Nthreads;
     for (i = start; i < end; i++) {
          a[i] = a[i] + b[i];
     }
}
```

```
// threads do redundant work

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

Other work sharing constructs

- Sections construct
  - Each thread assigned some sections of work.
  - Threads can be assigned 0, or multiple sections of work.
  - There's an implicit barrier at end of sections block, i.e. threads wait for each other to finish all sections before executing code after section.
  - Can turn off barrier using `nowait`.

```
#pragma omp parallel {
    #pragma omp sections {
        #pragma omp section
        { // do stuff }
        #pragma omp section
         { // do stuff }
        ...
    }
}
```

Other work sharing constructs

- Single construct
  - Structured block is executed by one thread of parallel region only (not necessarily master thread).
  - Barrier implied unless use `nowait`.
  - For doing tasks that should only be done by one thread when inside a parallel region.
- Master construct
  - Structured block is executed by master thread only. No implicit barrier at end.

```
#pragma omp parallel {
    #pragma omp single {
    // do stuff
    }
}
```

```
#pragma omp parallel {
    #pragma omp master {
    // do stuff
    }
}
```

Data environment

- OpenMP has a shared memory programming model.
  - Some variables are shared and accessible by all threads.
  - Other threads are private, and each thread has its own copy.
- Most variables are shared by default.
  - Global and static variables are shared.
  - Variables declared in master thread shared by default.
- Some variables parallel blocks private by default.
  - Loop index of `for` / `parallel for` construct.
  - Stack variables (e.g. function argument or local variable) created during execution of a `parallel` region.
  - Automatic variables in functions called in `parallel` region.

Data environment

- Variable status can be changed in `parallel` regions and worksharing constructs, except `shared` which only applies to `parallel` regions.
  - `shared(variable-list)`
  - `private(variable-list)`
- Can also add `default(private)` or `default(shared)` clause to make shared variables private or shared by default.

```
1 int x = 5;
2 #pragma omp parallel private(x) {
3   int p = omp_get_thread_num();
4    x = p;
5   printf(“private x is %d\n",x);
6 }
7 printf(“shared x is %d\n",x);
```

- At line 1, x is shared.
- At line 3, each thread has a private copy of x, but x’s value is uninitialized.
- At line 5, every thread prints a different x.
- At line 7, master thread prints x is 5.

Data environment

- When entering parallel region, set the initial values of private variables to be its value outside region using `firstprivate(variable-list)`
- When exiting `parallel for`, set the values of private variables outside the region to be their values in the final iteration of the `for` loop using `lastprivate(variable-list)`

```
int tmp = 2;
#pragma omp parallel for firstprivate(tmp) lastprivate(tmp)
for (int i = 0; i < 10; i++)
// each thread has a private tmp initialized to 2
    tmp++;
}
// prints a value for tmp != 2; the value depends on which
// thread performed the last iteration of the for loop, and
// how many iterations that loop performed
printf("%d\n", tmp);
```

Data environment

- Reduction combines values from threads.
  - `reduction(op : variable-list)`
    - Variables in the list must be shared in the enclosing `parallel` region.
    - Each thread initially makes a local copy of each list variable and updates it.
    - Local copies are reduced into a single global copy at the end of the construct.
    - More efficient than using a critical section.

```
#pragma omp parallel for reduction (+ : x)
for (i=0; i<n; i++) {
    x = x + a[i]; }
```

```
#pragma omp parallel for
for (i=0; i<n; i++) {
    #pragma omp critical
    {x = x + a[i];}}
```

Synchronization constructs

- OpenMP has critical sections and locks to protect accesses.
- Critical sections

  `#pragma omp critical [name] structured-block`
  - Only one thread can execute associated structured block at a time.
  - Name can be used to identify the critical section. Critical sections with no name default to the same.
- Locks

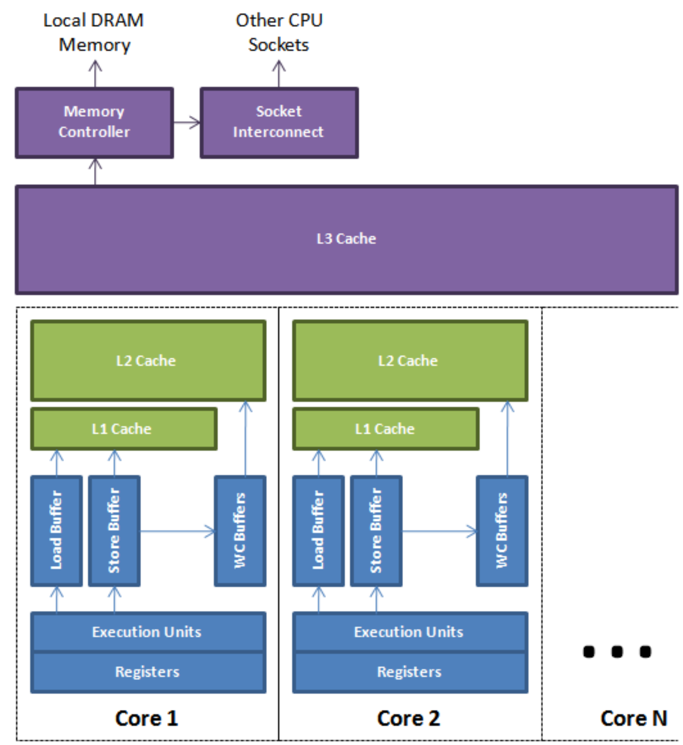
  `omp_init_lock(arg), omp_set_lock(arg), omp_unset_lock(arg), omp_test_lock(arg), omp_destroy_lock(arg)`
  - `arg` is a memory location.
- Critical sections protect sections of code, but locks protect data.
  - Ex Consider a hash function insert routine.
    - A critical section around the routine allows only one thread to insert at a time, even when different threads want to insert to different locations.
    - We only want to prevent concurrent inserts to same table entry. So associate one lock with each table entry.
- Barriers

  `#pragma omp barrier`

  All threads must reach the barrier before any can proceed.

Synchronization constructs

- Atomic operations `#pragma omp atomic expression-statement`
  - Only one thread can execute the associated `expression-statement` at a time.
  - Only works for simple statements such as `x++`, max, test&set, etc.
  - Done in hardware; more efficient than locks or critical sections.
- Flushing values
  - `#pragma omp flush [(var)]`
  - Writes listed variables from buffer to cache or memory to ensure all processors observe latest variable values.



Synchronization constructs

- Ordered statements are used in `for` and `parallel for` constructs to cause the subsequent structured block to be executed in strict loop order.
  - Code outside the ordered block can still execute in parallel.
- Should usually use static schedule with small chunk size.

```
#pragma omp parallel for ordered
   schedule(static, 1)
for (i = 0; i < n; i += 1)
     // do stuff in interleaved order
     // s, t are increased / decreased in
     // order 0, 1, 2, ...
     #pragma omp ordered {
          s += i;
          t -= i;
     }
```

Static schedule with default chunk size

tid	List of iterations	Timeline
0	0,1,2	==o==o==o
1	3,4,5	==.......o==o==o
2	6,7,8	==..............o==o==o

Static schedule with chunk size 1

tid	List of iterations	Timeline
0	0,3,6	==o==o==o
1	1,4,7	==.o==o==o
2	2,5,8	==..o==o==o

Runtime execution

- Runtime environment routines
  - Number of threads
    `omp_set_num_threads(), omp_get_num_threads(), omp_get_thread_num()`
  - Number of processors
    `omp_num_procs(),`
  - Currently in active region?
    `omp_in_parallel()`
  - Allows number of threads in parallel regions to be adjusted dynamically
    `omp_set_dynamic(int), omp_get_dynamic()`

OpenMP example

- Mandelbrot Set

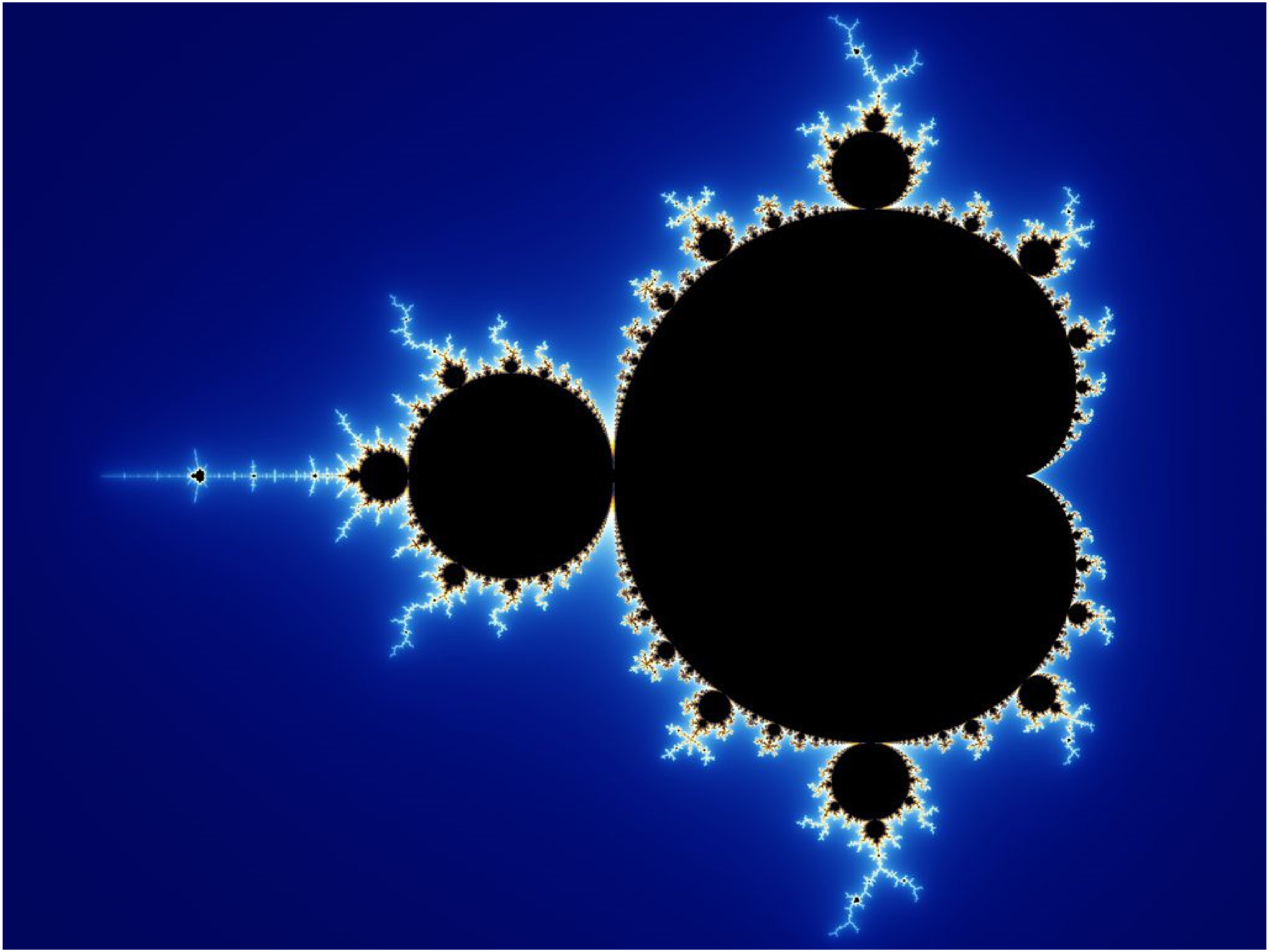
Set of points in a complex plane that are quasi-stable (will increase and decrease, but not exceed some limit) when computed by iterating the function

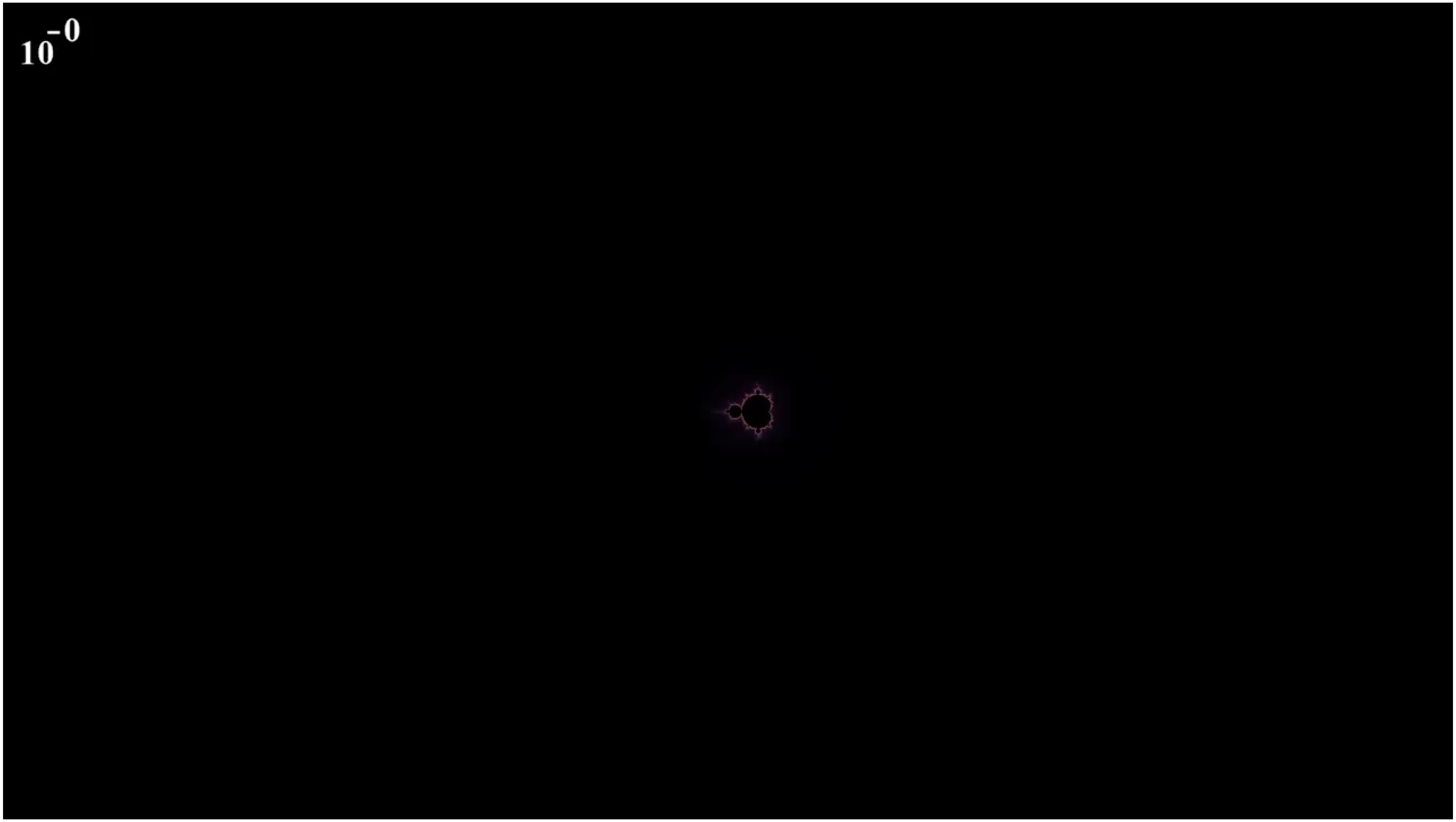
$$z_{k+1} = z_k^2 + c$$

where z_{k+1} is the $(k + 1)$th iteration of the complex number $z = a + bi$ and c is a complex number giving position of point in the complex plane. The initial value for z is zero.

Iterations continued until magnitude of z is greater than 2 or number of iterations reaches arbitrary limit. Magnitude of z is the length of the vector given by

$$z_{\text{length}} = \sqrt{a^2 + b^2}$$

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Sequential routine

$z_{k+1} = z_k^2 + c$

$z^2 = (a + bi)*(a + bi)$
$= a^2 – b^2 + 2abi$

count gives colour (or intensity) to be displayed

It's known z will diverge if $|z| \geq 2$.

```
structure complex {
    float real;
    float imag;
};

int calpixel(complex c) {
    int count, max;
    complex z;
    float temp, lengthsq;
    max = 256;
    z.real = 0; z.imag = 0;
    count = 0; /* number of iterations */
    do {
        temp = z.real * z.real - z.imag * z.imag + c.real;
        z.imag = 2 * z.real * z.imag + c.imag;
        z.real = temp;
        lengthsq = z.real * z.real + z.imag * z.imag;
        count++;
    } while ((lengthsq < 4.0) && (count < max));
    return count;
}
```

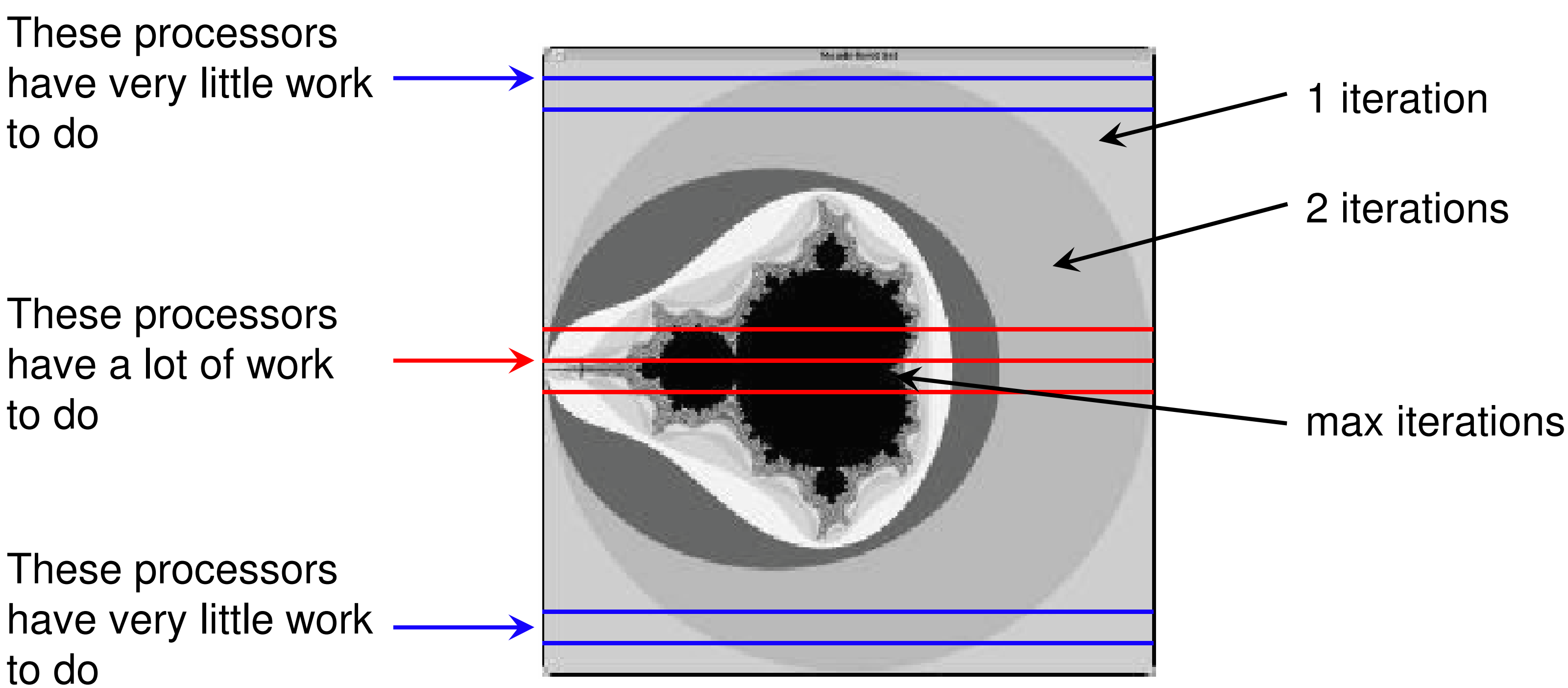
Parallelization of Mandelbrot

- Calculations for each pixel are independent.
  - Sometimes called an embarrassingly parallel computation.
- Static assignment
  - Divide the image into groups of pixels by row and assign each group to a separate thread.
  - By default, group (chunk) size is approximately equal.

```
#pragma omp parallel for private(j) schedule (static)
for (i = 0; i < n; i++)
    for (j = 0; j < n; j++)
        colour[i][j] = calpixel(i,j);
```

  - Not efficient as different pixels require different numbers of iterations and the computation time of different strips will vary considerably.

Static schedule



- This is a load balancing problem. Processors for top and bottom rows mostly idle, while processors for middle rows have lots of computation.

Parallelization of Mandelbrot

- Cyclic assignment

```
#pragma omp parallel for private(j) schedule (static, 1)
for (i = 0; i < n; i++)
    for (j = 0; j < n; j++)
        colour[i][j] = calpixel(i,j);
```

  - Iterations are assigned in a round robin manner.
  - Each thread receives a mixed set of tasks, some with a lot, some with little computation.

- Dynamic assignment

```
#pragma omp parallel for private(j) schedule (dynamic, 1)
for (i = 0; i < n; i++)
    for (j = 0; j < n; j++)
        colour[i][j] = calpixel(i,j);
```

  - When a thread has finished the current row, it receives a new row to compute.
  - Can also use guided.

PGAS languages

- Partitioned Global Address Space is another model for thread based shared memory parallelism.
- Includes a number of languages, e.g. Unified Parallel C (UPC), Coarray Fortran (CAF), Global Arrays, etc.
  - These are based on loop parallelism, like OpenMP.
- Also asynchronous PGAS languages, e.g. X10 and Chapel.
  - Parent threads explicitly spawn and synch with child threads.
- So far not very widely used, and still requires tuning for good performance.

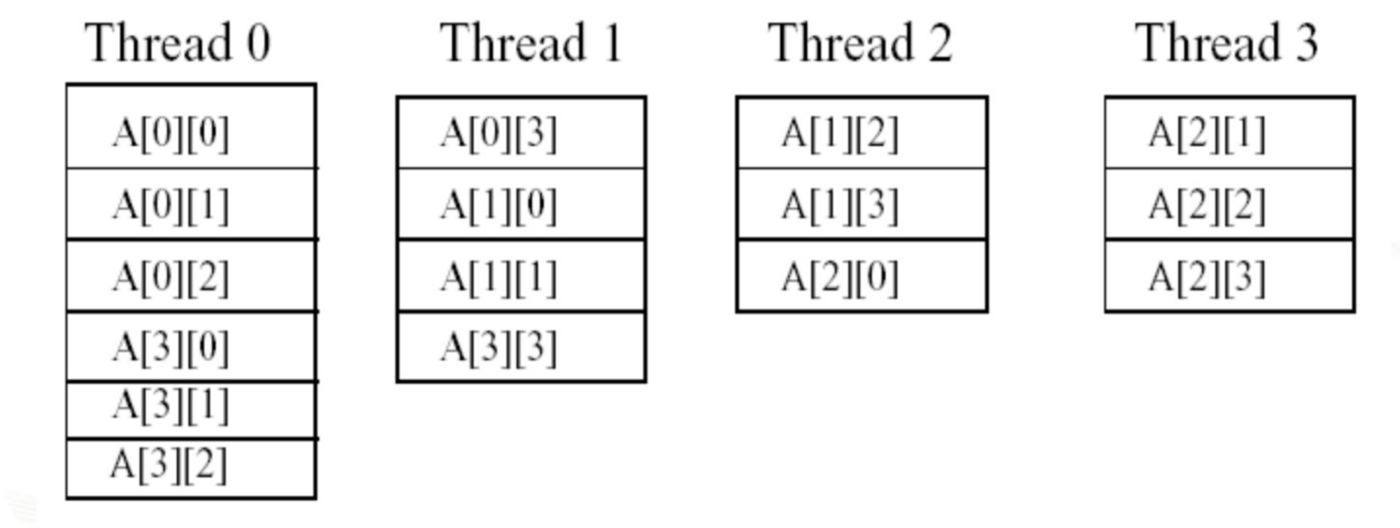
PGAS memory model

- A global address space accessible to all threads.
- However, address space is divided into partitions, and each thread has an affinity to one partition.
  - This partition is the local memory of a processor. The other partitions are local memories at other processors.
  - Thread also has private data only it can access.
- The convenience of OpenMP, but a more precise performance model because it captures data locality.
- Supports pointers to shared and private data, and static and dynamic memory allocation.

PGAS arrays

- Arrays can be partitioned across threads to increase local memory accesses and performance.
- Ex Assume THREADS = 4. In UPC A array is distributed as follows among the threads' memories.
  - Allocate in blocks of 3, row major order, round robin through threads.

```
shared [3] int A[4][THREADS]
```



UPC constructs

- For loops are parallelized with `upc_forall(init; test; update; affinity)`
  - `Affinity controls which threads execute which iterations.`

```
shared double x[N], y[N], z[N];
int main() {
    int i;
    upc_forall(i=0; i < N; ++i; i)
        z[i] = x[i] + y[i];
}
```

- Expressions for barrier synchronization and locks.
- Synchronize memory between threads using fences and strict / relaxed memory models.

Other methods for shared memory

- MPI 2 and 3 support one sided communication, allowing processes to directly read or write data from each other without passing messages.
- Can also combine MPI and OpenMP.
  - Use MPI between different nodes, and OpenMP within each node.
  - OpenMP can improve load balancing and reduce number of small messages, both weaknesses of MPI.
  - Must use MPI library that supports threads.