CME 213

SPRING 2019

Eric Darve

OpenMP

- Standard multicore API for scientific computing
- Based on fork-join model: fork many threads, join and resume sequential thread
- Uses pragma:

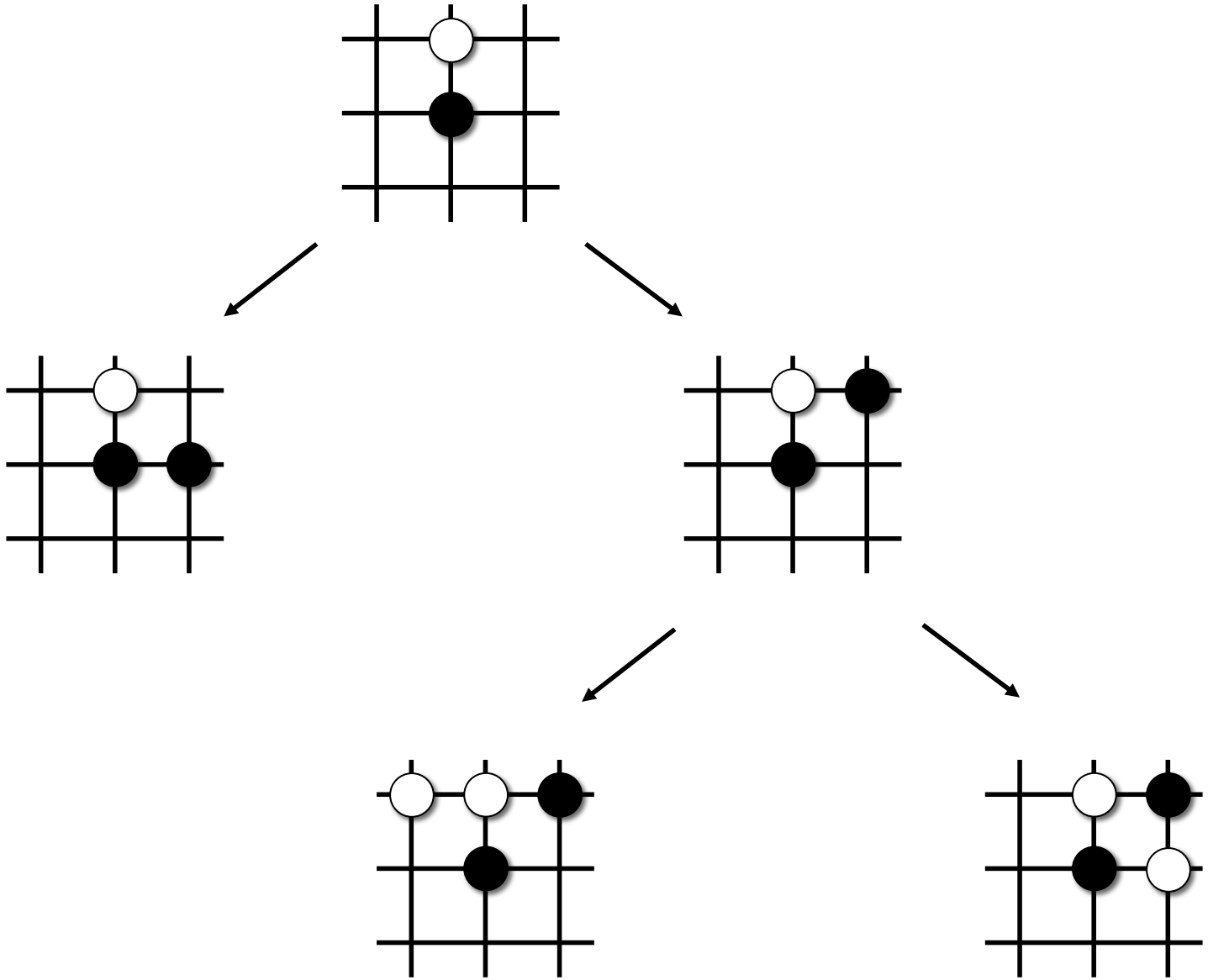
```
#pragma omp parallel
```

- Shared/private variables
- Parallel `for` loop:
  `scheduling(static, dynamic, guided)`
- Sections

Tasking constructs

Tasks

- Sections are convenient in static cases where we know ahead of time (at compilation) how many concurrent operations need to be executed.
- However, there are situations when we need to generate parallel work at run time.
- Example:
  - Parallel traversal of a tree.
  - Parallel traversal of a linked list.
- Tasks provide a more dynamic and flexible way to handle concurrent work.



tree.cc

- Assume we have a binary tree that we wish to traverse.
- We go through each node and execute some operations.
- Tree is not full, e.g., some of the child nodes may be missing.

See `tree.cpp`

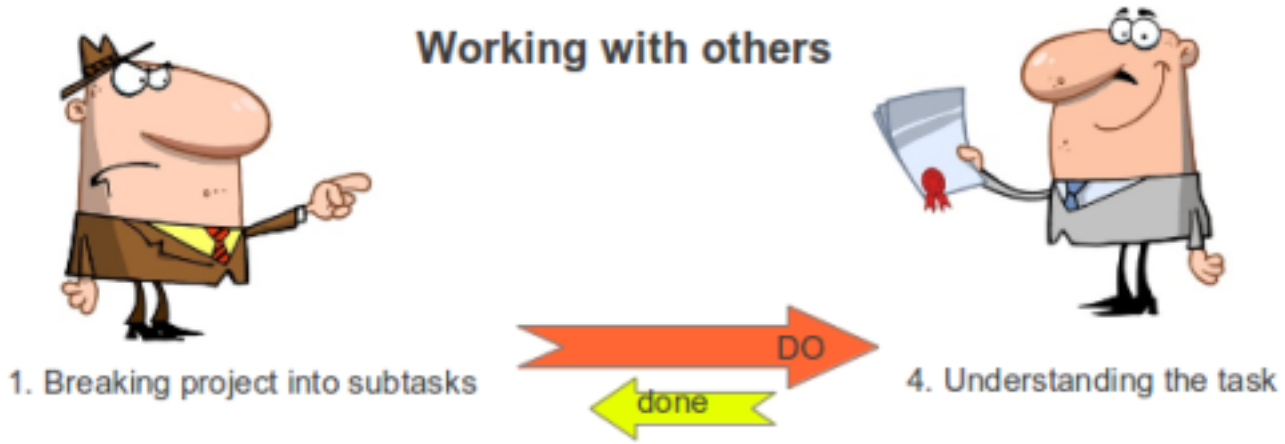
```
#pragma omp parallel
#pragma omp single
    // Only a single thread should execute this
    Traverse(root);


    void Traverse(struct Node *curr_node)
    {
        // Pre-order = visit then call Traverse()
        Visit(curr_node);

        if (curr_node->left)
    #pragma omp task
            Traverse(curr_node->left);

        if (curr_node->right)
    #pragma omp task
            Traverse(curr_node->right);
    }
```

Task

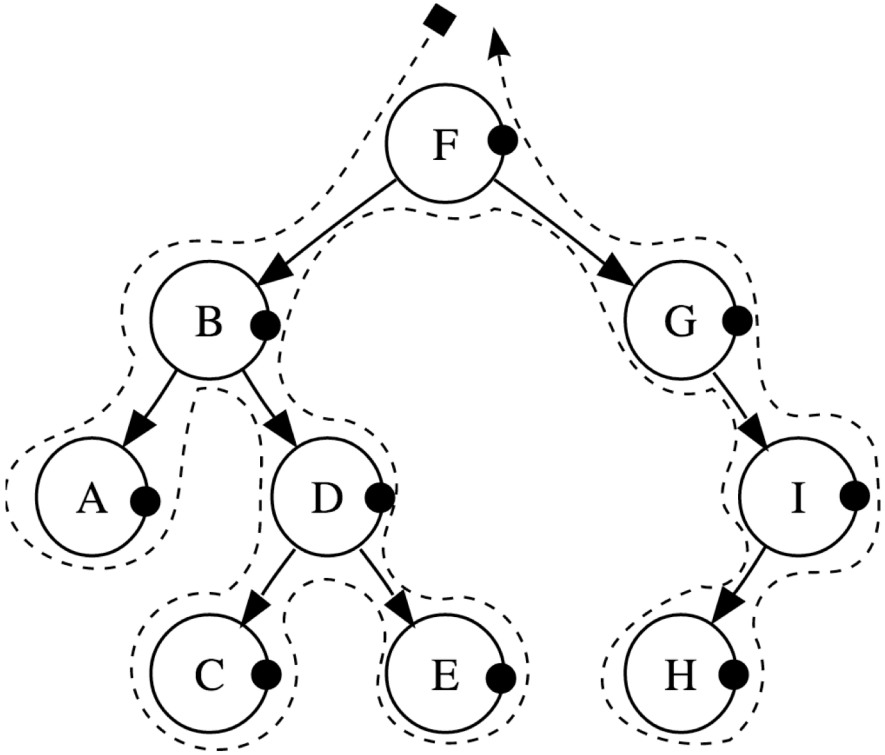


- When a thread encounters a task construct, a task is generated for the associated structured block.
- The encountering thread may immediately execute the task, or defer its execution. In the latter case, any thread in the team may be assigned the task.
- `task` should be called from within a parallel region for the different specified tasks to be executed in parallel.
- The tasks will be executed in no specified order because there are no synchronization directives.

Post-order traversal

Let us now assume that we want to traverse the tree using a post-order:

- Traverse the left subtree.
- Traverse the right subtree.
- Visit the root.



Post-order traversal

- Assume we cannot visit the root until the left and right subtrees have been visited.
- For example, we are counting some quantity associated with each tree node.
- In that case, a synchronization point is needed.
- The thread needs to wait until both subtrees have been visited.

tree_postorder.cpp

```
int PostOrderTraverse(struct Node *curr_node)
{
    int left = 0;
    int right = 0;
    if (curr_node->left)
#pragma omp task shared(left)
        left = PostOrderTraverse(curr_node->left);
    if (curr_node->right)
#pragma omp task shared(right)
        right = PostOrderTraverse(curr_node->right);
#pragma omp taskwait
    curr_node->data = left + right;
    Visit(curr_node);
    return 1 + left + right;
}
```

- Default attribute for task constructs is `firstprivate`.
- `firstprivate`: private but value is initialized with the value that the corresponding original item has when the construct is encountered.

Technical Explanation on taskwait

- OpenMP defines the concept of child task. A child task of a piece of code is a task generated by a directive
  `#pragma omp task`
  found in that piece of code.
- For example, in the previous code
  `PostOrderTraverse(curr_node->left)`
  and
  `PostOrderTraverse(curr_node->left)`
  are child tasks of the enclosing region.
- `taskwait` specifies a wait on the completion of the child tasks of the current task.
- Note that `taskwait` requires to wait for completion of the child tasks, but not completion of all descendant tasks (e.g., child tasks of child tasks).

Processing entries in a list

- This is another classical example cases of using tasks.
- We want to process entries in a list in parallel.
- A parallel for is not possible because there is no index we can use to iterate over the list entries.
- Tasks can be used for that purpose.

- See `list.cpp`

```
#pragma omp parallel
    {
#pragma omp single
        {
            Node *curr_node = head;
            while (curr_node)
            {
#pragma omp task
                {
                    Wait();
                    int tid = omp_get_thread_num();
                    Visit(curr_node);
                    printf("Task @%2d: node %p data %d\n",
                           tid, (void *)curr_node, curr_node->data);
                }
                curr_node = curr_node->next;
            }
        }
    }
```

curr_node is firstprivate by default

OpenMP
Master and Synchronization Constructs

Synchronization constructs

- Several constructs are available.
- We won't go into all the details.
- Check the reading material for more information.
- From most to least common.

Reduction

- Consider the code in `reduction.cpp`
- There is a race condition on `average`.
- The reduction clause does two things:
  - Prevent a race condition when updating **`average`**.
  - Improved efficiency: local reduction followed by a single final reduction across all thread values.

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

Technical definition

`reduction (op: list)`

- `op` can be: `{+, -, *, &, ^, |, &&, ||}`
- For each of the variables in `list`, a private copy is created for each thread.
- The private copies are initialized to the neutral element (zero) of the operation `op` and can be updated by the owning thread.
- At the end of the region, the local values of the reduction variables are combined according to the operator `op` and the result of the reduction is written into the original shared variable.

Exercise

Open the file

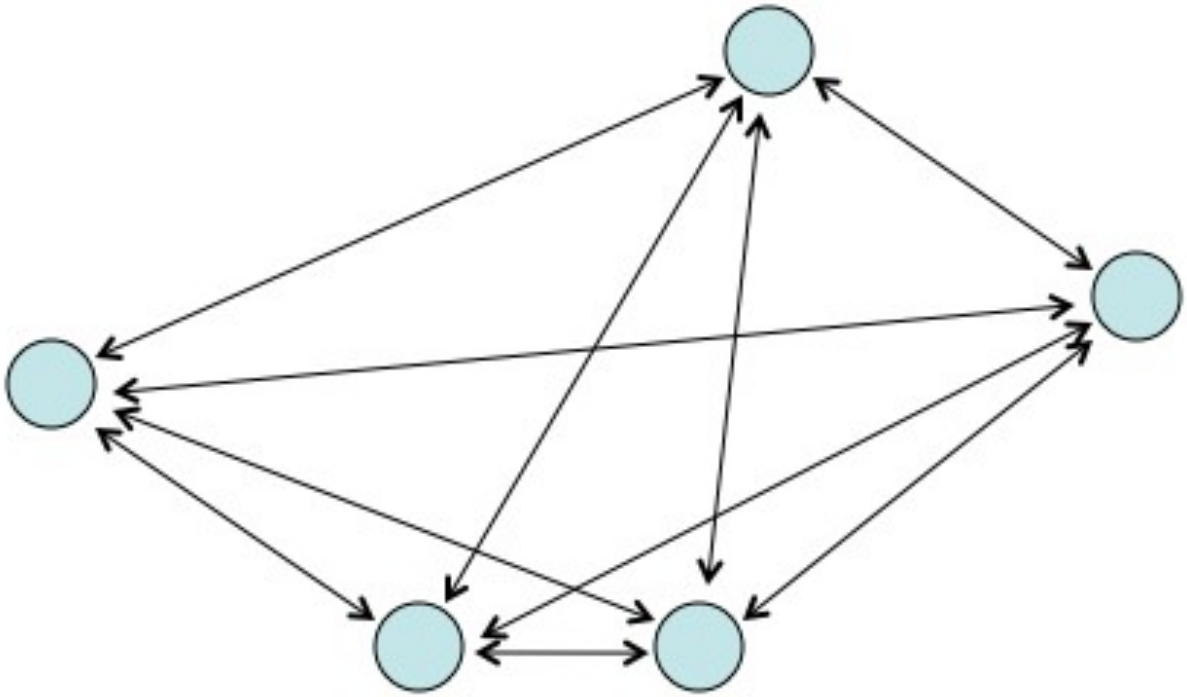
`entropy.cpp`

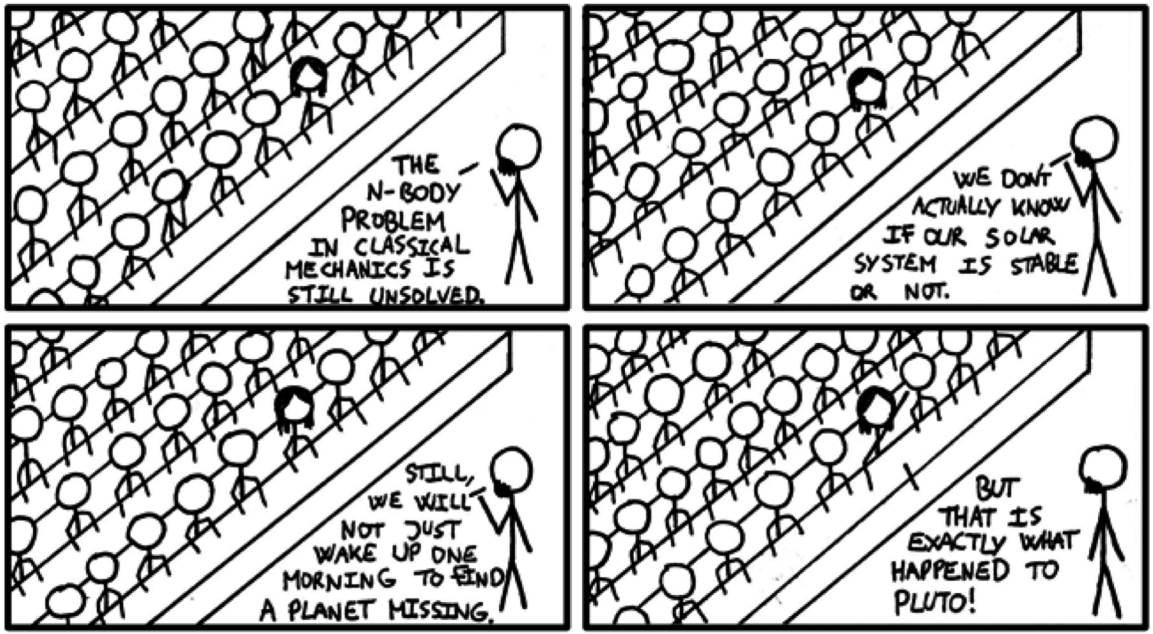
Atomic

- This is a situation similar to the previous case.
- However, this is generalized to any kind of updates of a shared variable.
- When all threads try to read and write to a shared variable, a race condition ensues.
- Atomic guarantees the correctness of the final result.

- See `atomic.cpp`

- Atomic: atomic exclusion, but only applies to the update of a memory location, e.g., the force in our example.




THE N-BODY PROBLEM IN CLASSICAL MECHANICS IS STILL UNSOLVED.
WE DON'T ACTUALLY KNOW IF OUR SOLAR SYSTEM IS STABLE OR NOT.
STILL, WE WILL NOT JUST WAKE UP ONE MORNING TO FIND A PLANET MISSING.
BUT THAT IS EXACTLY WHAT HAPPENED TO PLUTO!

```
#pragma omp parallel for
    for (int i = 0; i < n; ++i)
        for (int j = i + 1; j < n; ++j)
        {
            const float x_ = x[i] - x[j];
            const float f_ = force(x_);
#pragma omp atomic
            f[i] += f_;
#pragma omp atomic
            f[j] -= f_;
        }
```

Critical

Piece of code executed by only one thread at a time.

`critical.cpp`

Similar to mutex.

```
    set<int> m;
#pragma omp parallel
    {
        const int id = omp_get_thread_num();
        const int n_threads = omp_get_num_threads();
        for (int i(id); i < n; i += n_threads)
        {
            // A different way to write a parallel for loop
            bool is_prime = LongCalculation(i);
#pragma omp critical
            if (is_prime)
                Consume(i, m); /* Save this prime */
        }
    }
```

Single

`#pragma omp single`

- Definition: structured block is executed by only one thread.
- See example using tasks.

`single.cpp`

```
#pragma omp parallel
    {
        BigCalculationOne();
#pragma omp single
        {
            ApplyBoundaryConditions();
        }
        BigCalculationTwo();
    }
```

Ordered

```
#pragma omp for ordered schedule(dynamic)
    for (unsigned n = 0; n < size; ++n)
    {
        files[n].Compress();

#pragma omp ordered
        Send(files[n]);
    }
```

Mandelbrot fractal set

- Iteration:

$$z_{n+1} = z_n^2 + c$$

- Start iteration from 0.
- Complex number *c* is in the Mandelbrot set *M* if the sequence z_n remains bounded.
- For example, *c* = 1 gives

  `0  1  2  5  26 …`

  and diverges. Not in *M*.
- *c* = -1 gives

  `0  -1  0  -1  0  -1 …`

  and remains bounded. *c* is in *M*.

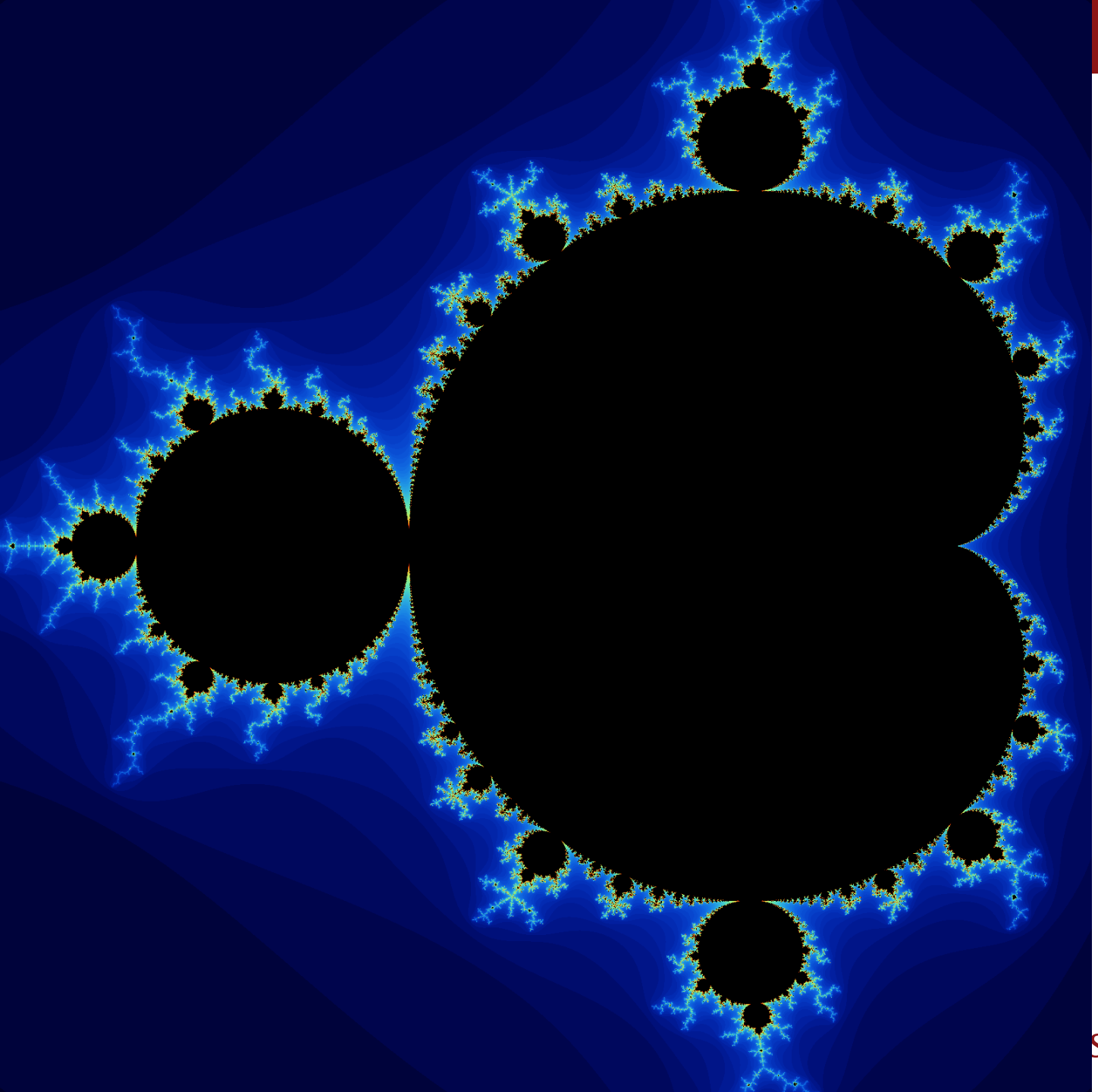
Number of iterations

We calculate the number of iterations until z_n becomes greater than 2:

```
unsigned iter = 0;
complex z(0);
while (abs(z) <= 2.0 && iter < iter_max)
{
    z = z * z + c;
    iter++;
}
return (iter == iter_max) ? 0 : iter;
```

This is based on

$$c \in M \quad \Leftrightarrow \quad \limsup_{n \to \infty} |z_n| \leq 2$$



Color based on `iter`

OMP code for Mandelbrot

```
#pragma omp parallel for ordered schedule(dynamic)
    for (int k = 0; k < size; ++k)
    {
        const int i = k % width;
        const int j = k / width;
        complex c = begin + complex(i * span.real() / (width - 1.0),
                                    j * span.imag() / (height - 1.0));
        unsigned n = MandelbrotCalculate(c);
        colors[k] = (int)n;
#pragma omp ordered
        {
            PrintCharacter(i, j, n, width);
        }
    }
```

ASCII output

Other constructs

- There are several other constructs that can be useful in special cases.

- Short list:
  1. Master
  2. Barrier
  3. Locks
  4. Flush
  5. double omp_get_wtime(void);
  6. and many others…