Parallel Programming with OpenMP

CS240A, T. Yang, 2013
Modified from Demmel/Yelick's and Mary Hall's Slides

Introduction to OpenMP

- What is OpenMP?
  - Open specification for Multi-Processing
  - "Standard" API for defining multi-threaded shared-memory programs
  - openmp.org – Talks, examples, forums, etc.

- High-level API
  - Preprocessor (compiler) directives (~ 80%)
  - Library Calls (~ 19%)
  - Environment Variables (~ 1%)

A Programmer's View of OpenMP

- OpenMP is a portable, threaded, shared-memory programming *specification* with "light" syntax
  - Exact behavior depends on OpenMP *implementation*!
  - Requires compiler support (C or Fortran)

- OpenMP will:
  - Allow a programmer to separate a program into *serial regions* and *parallel regions,* rather than T concurrently-executing threads*.*
  - Hide stack management
  - Provide synchronization constructs

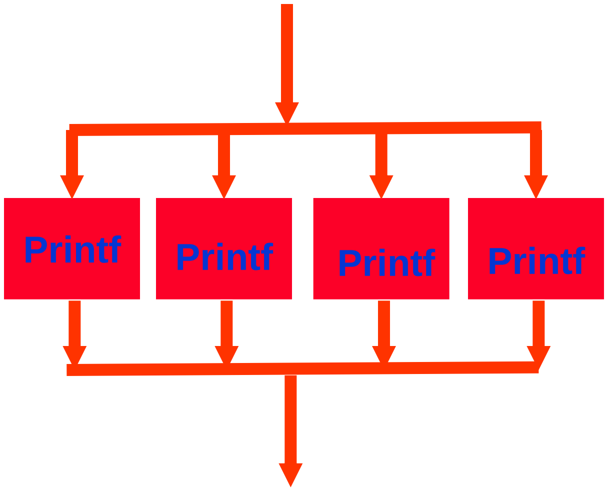
- OpenMP will not:
  - Parallelize automatically
  - Guarantee speedup
  - Provide freedom from data races

Motivation – OpenMP

```
int main() {

  // Do this part in parallel

  printf( "Hello, World!\n" );

  return 0;
}
```

Motivation – OpenMP

```
int main() {

  omp_set_num_threads(4);

  // Do this part in parallel
  #pragma omp parallel
  {
    printf( "Hello, World!\n" );
  }

  return 0;
}
```



OpenMP parallel region construct

- Block of code to be executed by multiple threads in parallel
- Each thread executes the **same code redundantly** **(SPMD)**
  - Work within work-sharing constructs is distributed among the threads in a team
- Example with C/C++ syntax

```
#pragma omp parallel [ clause [ clause ] ... ] new-line
        structured-block
```

- clause can include the following:

  private (list)

  shared (list)

OpenMP Data Parallel Construct: Parallel Loop

- All pragmas begin: #pragma
- Compiler calculates loop bounds for each thread directly from *serial* source (computation decomposition)
- Compiler also manages data partitioning
- Synchronization also automatic (barrier)

Serial Program:

```
void main()
{
   double Res[1000];

   for(int i=0;i<1000;i++) {
           do_huge_comp(Res[i]);
   }
}
```

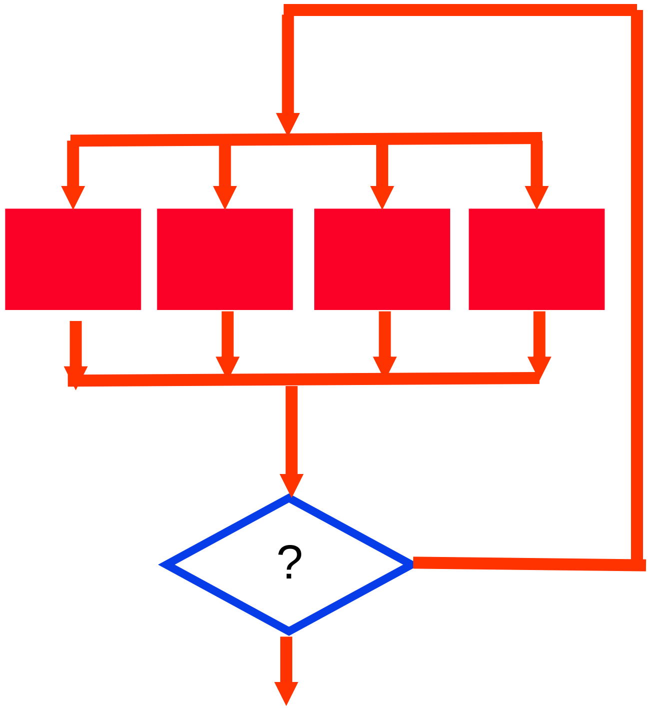
Parallel Program:

```
void main()
{
   double Res[1000];
#pragma omp parallel for
   for(int i=0;i<1000;i++) {
           do_huge_comp(Res[i]);
   }
}
```

Programming Model – Parallel Loops

- Requirement for parallel loops
  - No data dependencies (reads/write or write/write pairs) between iterations!

- Preprocessor calculates loop bounds and divide iterations among parallel threads




```
#pragma omp parallel for

 for( i=0; i < 25; i++ )
 {

   printf("Foo");

 }
```

OpenMp: Parallel Loops with Reductions

- OpenMP supports reduce operation

```
sum = 0;
#pragma omp parallel for reduction(+:sum)
for (i=0; i < 100; i++)    {
sum += array[i];
}
```

- Reduce ops and init() values (C and C++):

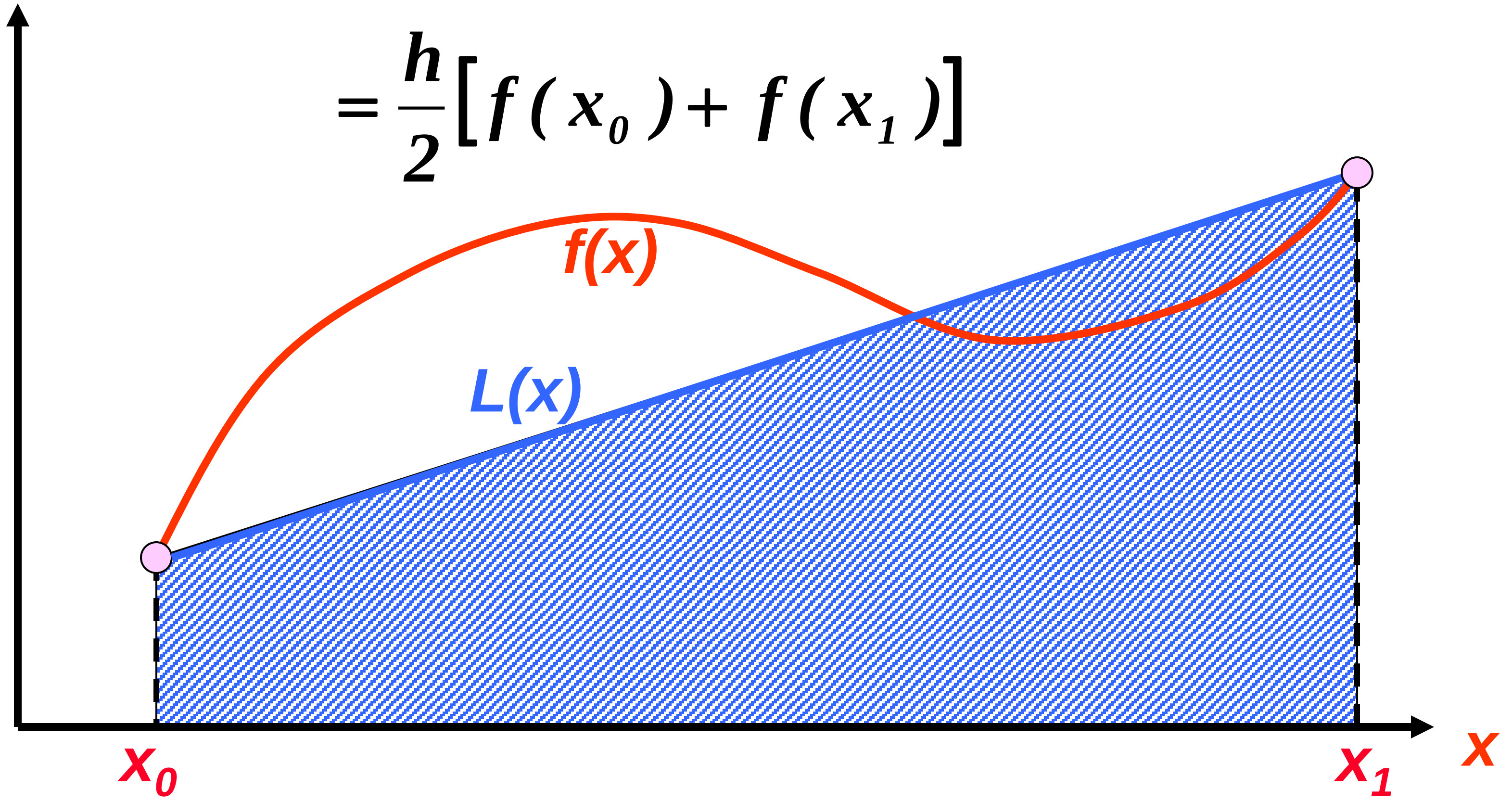
+	0	bitwise	&	~0	logical &	1
-	0	bitwise	|	0	logical |	0
*	1	bitwise	^	0		

Example: Trapezoid Rule for Integration

- Straight-line approximation

$$\int_a^b f(x)dx \approx \sum_{i=0}^{1} c_i f(x_i) = c_0 f(x_0) + c_1 f(x_1)$$

$$= \frac{h}{2}\left[f(x_0) + f(x_1)\right]$$



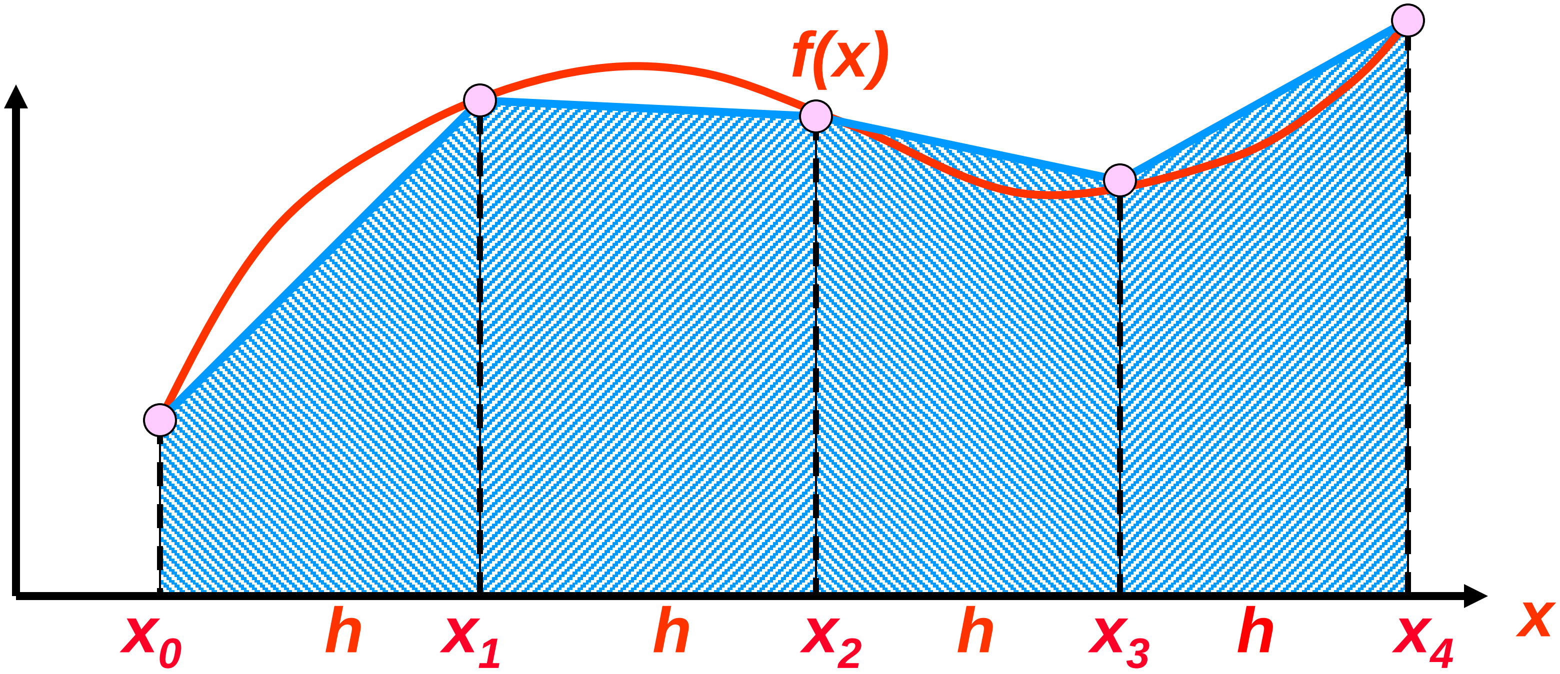
Composite Trapezoid Rule

$$\int_a^b f(x)dx = \int_{x_0}^{x_1} f(x)dx + \int_{x_1}^{x_2} f(x)dx + \cdots\cdots + \int_{x_{n-1}}^{x_n} f(x)dx$$

$$= \frac{h}{2}\left[f(x_0) + f(x_1)\right] + \frac{h}{2}\left[f(x_1) + f(x_2)\right] + \cdots + \frac{h}{2}\left[f(x_{n-1}) + f(x_n)\right]$$

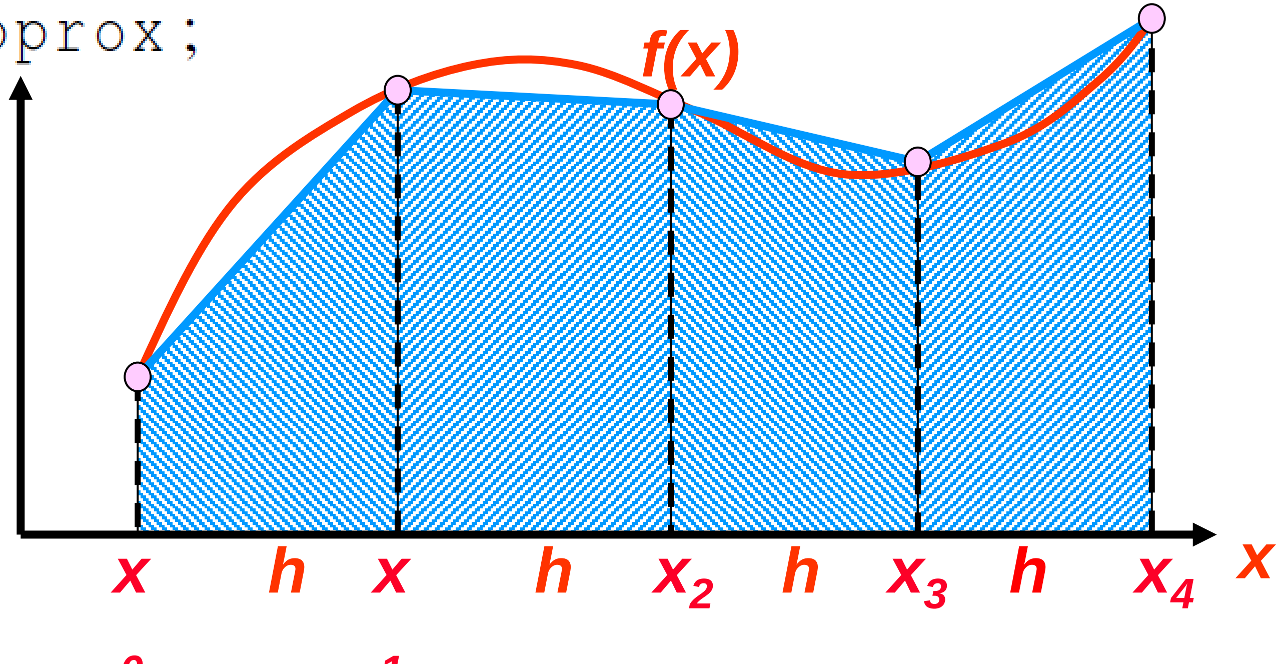
$$= \frac{h}{2}\left[f(x_0) + 2f(x_1) + \cdots + 2f(x_i) + \cdots + 2f(x_{n-1}) + f(x_n)\right]$$

$$h = \frac{b-a}{n}$$



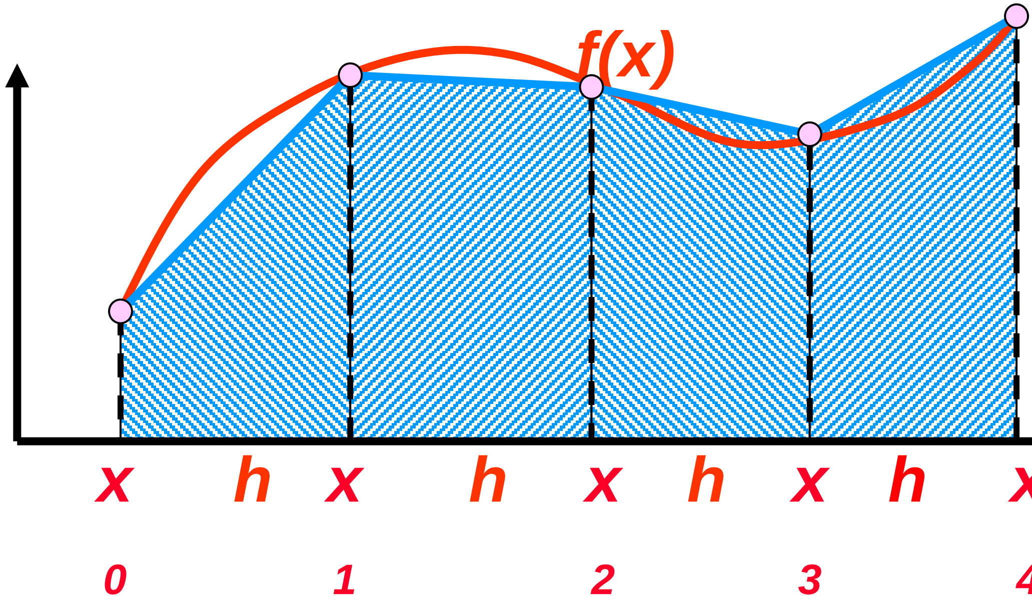
Serial algorithm for composite trapezoid rule

```
/* Input:  a, b, n */
h = (b-a)/n;
approx = (f(a) + f(b))/2.0;
for (i = 1; i <= n-1; i++) {
    x_i = a + i*h;
    approx += f(x_i);
}
approx = h*approx;
```



From Serial Code to Parallel Code

```
h = (b-a)/n;
approx = (f(a) + f(b))/2.0;
for (i = 1; i <= n-1; i++)
   approx += f(a + i*h);
approx = h*approx;
```

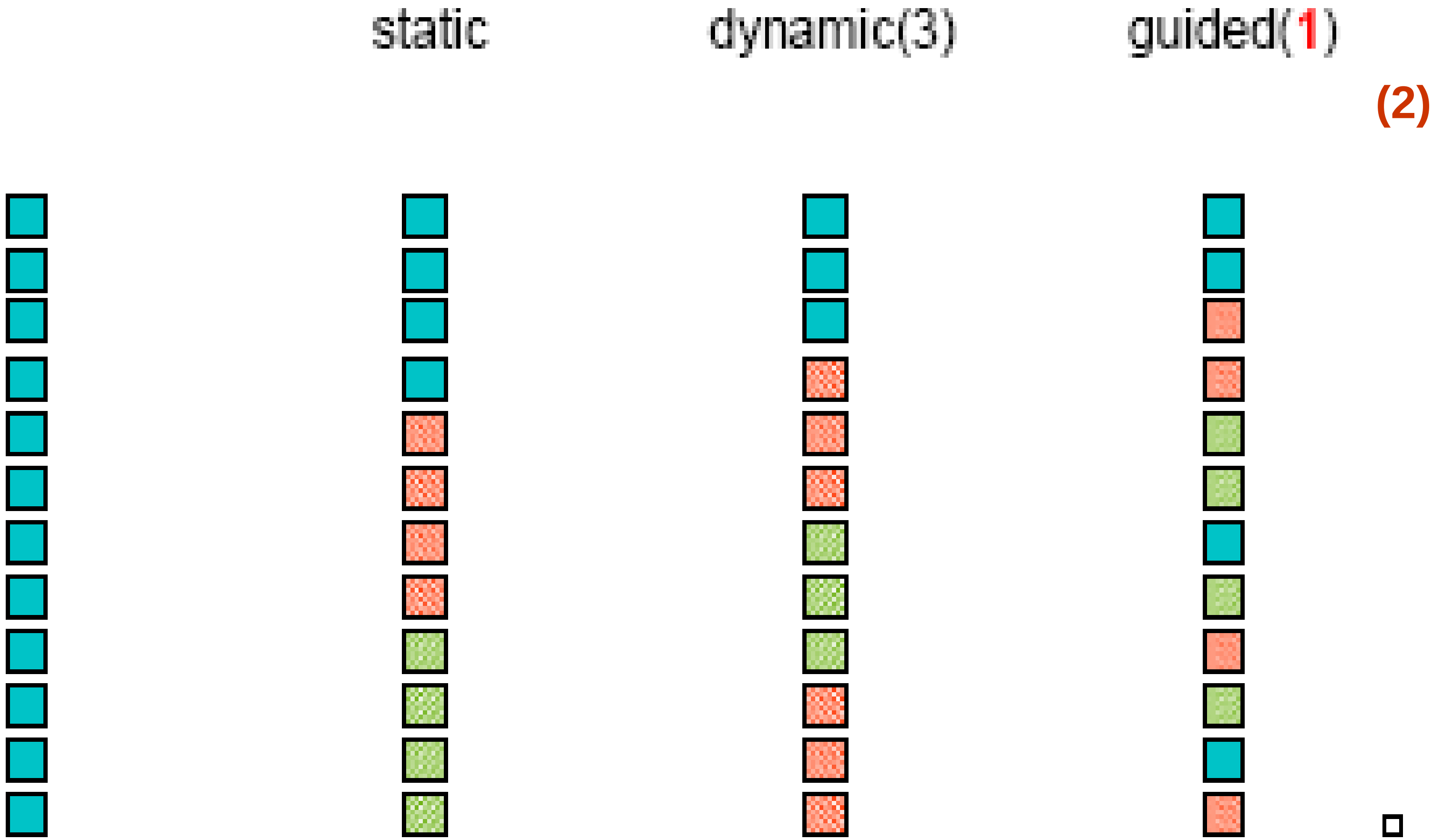



```
   h = (b-a)/n;
   approx = (f(a) + f(b))/2.0;
#  pragma omp parallel for num_threads(thread_count) \
      reduction(+: approx)
   for (i = 1; i <= n-1; i++)
      approx += f(a + i*h);
   approx = h*approx;
```

Programming Model – Loop Scheduling

- schedule clause determines how loop iterations are divided among the thread team
  - **`static([chunk])`** divides iterations statically between threads
    - Each thread receives [chunk] iterations, rounding as necessary to account for all iterations
    - Default **`[chunk]`** is **`ceil( # iterations / # threads )`**
  - **`dynamic([chunk])`** allocates **`[chunk]`** iterations per thread, allocating an additional **`[chunk]`** iterations when a thread finishes
    - Forms a logical work queue, consisting of all loop iterations
    - Default **`[chunk]`** is 1
  - **`guided([chunk])`** allocates dynamically, but **`[chunk]`** is exponentially reduced with each allocation

Loop scheduling options



Impact of Scheduling Decision

- Load balance
  - Same work in each iteration?
  - Processors working at same speed?
- Scheduling overhead
  - Static decisions are cheap because they require no run-time coordination
  - Dynamic decisions have overhead that is impacted by complexity and frequency of decisions
- Data locality
  - Particularly within cache lines for small chunk sizes
  - Also impacts data reuse on same processor

More loop scheduling attributes

- RUNTIME The scheduling decision is deferred until runtime by the environment variable OMP_SCHEDULE. It is illegal to specify a chunk size for this clause.
- AUTO The scheduling decision is delegated to the compiler and/or runtime system.
- **NO WAIT / nowait**: If specified, then threads do not synchronize at the end of the parallel loop.
- **ORDERED**: Specifies that the iterations of the loop must be executed as they would be in a serial program.
- **COLLAPSE**: Specifies how many loops in a nested loop should be collapsed into one large iteration space and divided according to the schedule clause (collapsed order corresponds to original sequential order).

OpenMP environment variables

OMP_NUM_THREADS

- sets the number of threads to use during execution
- when dynamic adjustment of the number of threads is enabled, the value of this environment variable is the maximum number of threads to use
- For example,

  setenv OMP_NUM_THREADS 16 **[csh, tcsh]**

  export OMP_NUM_THREADS=16 **[sh, ksh, bash]**

OMP_SCHEDULE

- applies only to do/for and parallel do/for directives that have the schedule type RUNTIME
- sets schedule type and chunk size for all such loops
- For example,

  setenv OMP_SCHEDULE GUIDED,4 **[csh, tcsh]**

  export OMP_SCHEDULE= GUIDED,4 **[sh, ksh, bash]**

Programming Model – Data Sharing

- Parallel programs often employ two types of data
  - Shared data, visible to all threads, similarly named
  - Private data, visible to a single thread (often stack-allocated)
- PThreads:
  - Global-scoped variables are shared
  - Stack-allocated variables are private
- OpenMP:
  - **`shared`** variables are shared
  - **`private`** variables are private

```
// shared, globals
int bigdata[1024];

void* foo(void* bar) {
  // private, stack
  int tid;
  int tid;
  #pragma omp parallel \
  /* Calculation goes
  shared ( bigdata ) \
     here */
  private ( tid )
} {
    /* Calc. here */
  }
}
```

Programming Model - Synchronization

- OpenMP Synchronization
  - OpenMP Critical Sections
    - Named or unnamed
    - No *explicit* locks / mutexes

```
#pragma omp critical
{
  /* Critical code here */
}
```

  - Barrier directives

```
#pragma omp barrier
```

  - Explicit Lock functions
    - When all else fails – may require flush directive

```
omp_set_lock( lock l );
/* Code goes here */
omp_unset_lock( lock l );
```

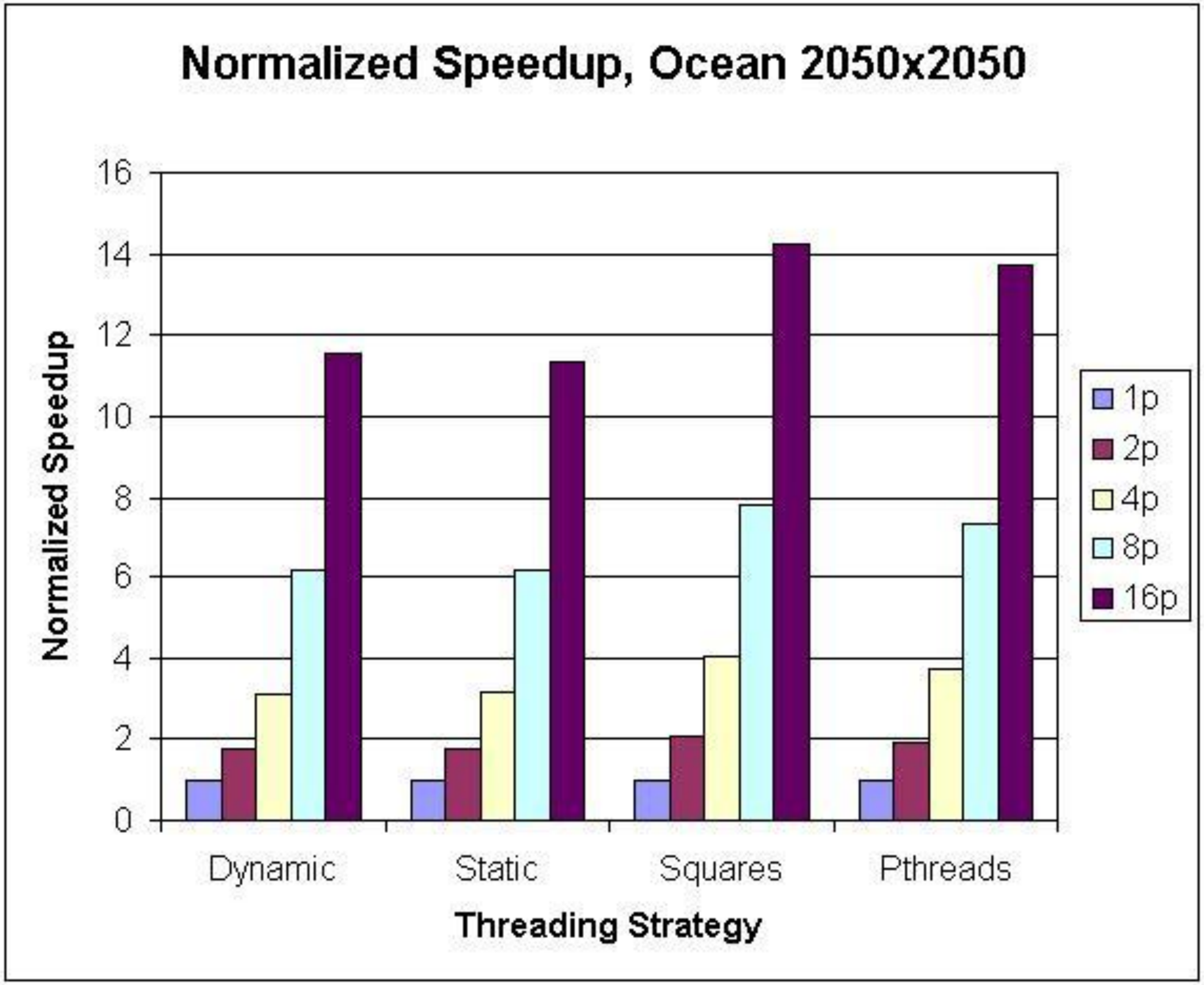
  - Single-thread regions *within* parallel regions
    - `master, single` directives

```
#pragma omp single
{
  /* Only executed once */
}
```

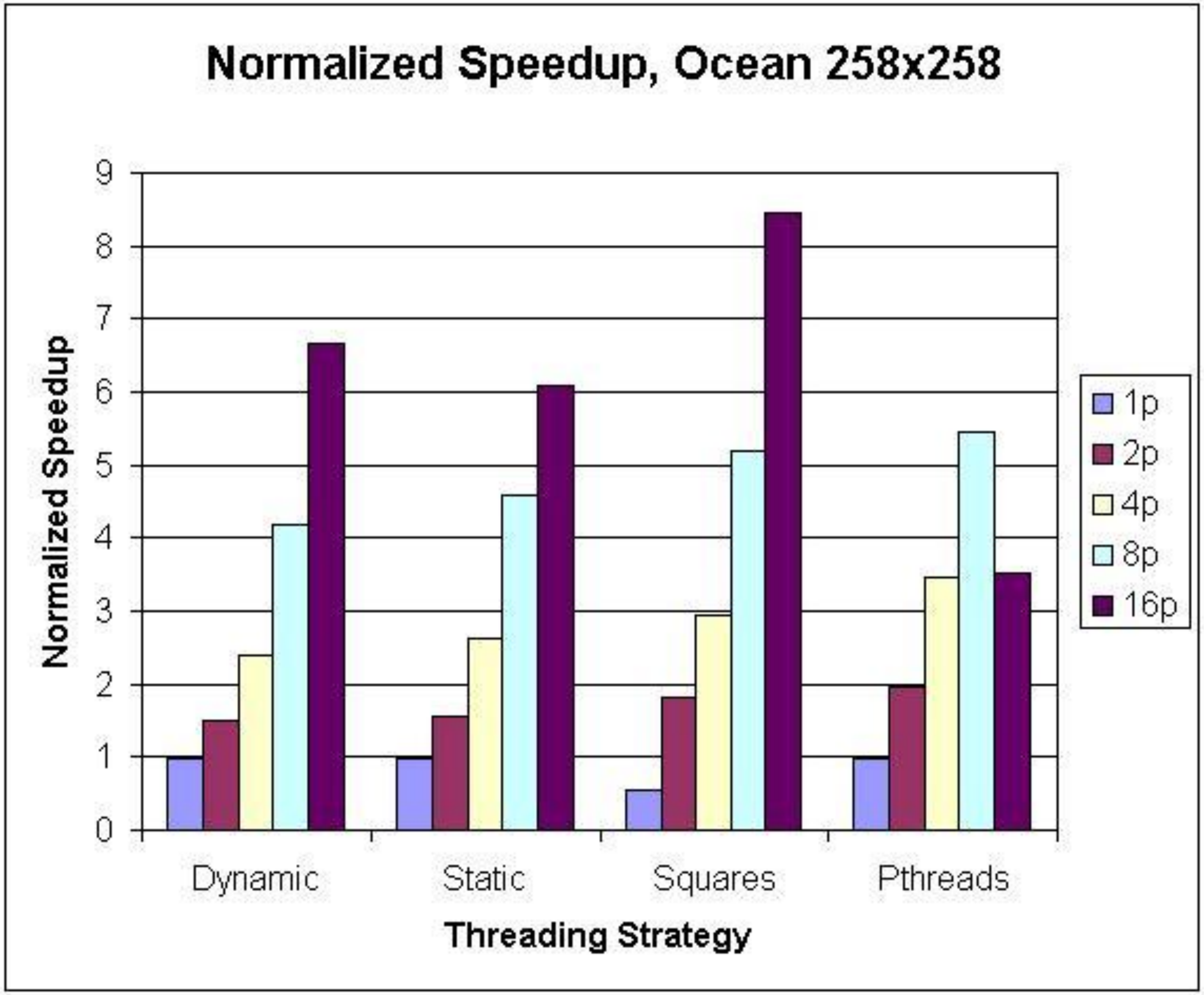
Microbenchmark: Grid Relaxation (Stencil)

```
for( t=0; t < t_steps; t++) {
  #pragma omp parallel for \
   shared(grid,x_dim,y_dim) private(x,y)

  for( x=0; x < x_dim; x++) {
    for( y=0; y < y_dim; y++) {
      grid[x][y] = /* avg of neighbors */
    }
  }
   // Implicit Barrier Synchronization

  temp_grid = grid;
  grid = other_grid;
  other_grid = temp_grid;
}
```

Microbenchmark: Ocean



Microbenchmark: Ocean



OpenMP Summary

- OpenMP is a compiler-based technique to create concurrent code from (mostly) serial code
- OpenMP can enable (easy) parallelization of loop-based code
  - Lightweight syntactic language extensions

- OpenMP performs comparably to manually-coded threading
  - Scalable
  - Portable

- Not a silver bullet for all applications

More Information

- openmp.org
  - OpenMP official site
- www.llnl.gov/computing/tutorials/openMP/
  - A handy OpenMP tutorial
- www.nersc.gov/nusers/help/tutorials/openmp/
  - Another OpenMP tutorial and reference