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   - Parallel For Operator
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   - Loops: Scheduling
Parallel for

- Forks a team of threads to execute the following structured block.
- However, the structured block following the parallel for directive must be a for loop.
- Furthermore, with the parallel for directive the system parallelizes the for loop by dividing the iterations of the loop among the threads.
Good News/Bad News: threads divide up work themselves (Good), but you cannot control this (maybe Bad). Not useful when you need/want to avoid default data composition.
Legal forms for parallelizable for statements

\[
\begin{align*}
\text{for} & \quad \text{index} = \text{start} ; \quad \text{index} \geq \text{end} ; \quad \text{index} > \text{end} \\
& \quad \text{index++} \\
& \quad ++\text{index} \\
& \quad \text{index < end} \\
& \quad \text{index--} \\
& \quad \text{index <= end} \\
& \quad --\text{index} \\
& \quad \text{index} > \text{end} \\
& \quad \text{index} += \text{incr} \\
& \quad \text{index} -= \text{incr} \\
& \quad \text{index} = \text{index} + \text{incr} \\
& \quad \text{index} = \text{incr} + \text{index} \\
& \quad \text{index} = \text{index} - \text{incr}
\end{align*}
\]
Caveats

- The variable index must have integer or pointer type (e.g., it can’t be a float).

- The expressions start, end, and incr must have a compatible type. For example, if index is a pointer, then incr must have integer type.
Caveats

- The expressions start, end, and incr must not change during execution of the loop.

- During execution of the loop, the variable index can only be modified by the “increment expression” in the for statement.
Data dependencies

\[
\begin{align*}
\text{fibo}[0] &= \text{fibo}[1] = 1; \\
\text{for } (i = 2; i < n; i++) \\
&\quad \text{fibo}[i] = \text{fibo}[i - 1] + \text{fibo}[i - 2]; \\
\text{fibo}[0] &= \text{fibo}[1] = 1; \\
\# \text{pragma omp parallel for num_threads(2)} \\
\text{for } (i = 2; i < n; i++) \\
&\quad \text{fibo}[i] = \text{fibo}[i - 1] + \text{fibo}[i - 2];
\end{align*}
\]

\begin{align*}
1 &\quad 1 &\quad 2 &\quad 3 &\quad 5 &\quad 8 &\quad 13 &\quad 21 &\quad 34 &\quad 55 \\
&\quad 1 &\quad 1 &\quad 2 &\quad 3 &\quad 5 &\quad 8 &\quad 0 &\quad 0 &\quad 0 &\quad 0 \\
\end{align*}

this is correct

note 2 threads

but sometimes we get this
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>

int main(int argc, char* argv[]) {
    int thread_count, n, i;
    long long* fibo;

    if (argc != 3) Usage(argv[0]);
    thread_count = strtol(argv[1], NULL, 10);
    n = strtol(argv[2], NULL, 10);

    fibo = malloc(n*sizeof(long long));
    fibo[0] = fibo[1] = 1;
    # pragma omp parallel for num_threads(thread_count)
    for (i = 2; i < n; i++)
        fibo[i] = fibo[i-1] + fibo[i-2];

    printf("The first n Fibonacci numbers:\n");
    for (i = 0; i < n; i++)
        printf("%d\t%lld\n", i, fibo[i]);

    free(fibo);
    return 0;
} /* main */
Pacheco Data Dependencies example: local laptop had thread problems, but this did not happen on tuckoo (up to 10,000 threads, no problems)

```
[gidget:intro-par-pgming-pacheco/ipp-source/ch5] mthomas% gcc -fopenmp -o omp_fibo omp_fibo.c
[gidget:intro-par-pgming-pacheco/ipp-source/ch5] mthomas% ./omp_fibo 10 10
```

The first n Fibonacci numbers:

```
0 1
1 1
2 2
3 1
4 3
5 1
6 0
7 0
8 0
9 0
```

```
[gidget:intro-par-pgming-pacheco/ipp-source/ch5] mthomas% ./omp_fibo 10 10
```

The first n Fibonacci numbers:

```
0 1
1 1
2 2
3 1
4 3
5 4
6 7
7 0
8 0
9 0
```

```
[gidget:intro-par-pgming-pacheco/ipp-source/ch5] mthomas%
```
What went wrong?

- OpenMP compilers don’t check for dependences among iterations in a loop that’s being parallelized with a parallel for directive.
- A loop in which the results of one or more iterations depend on other iterations cannot, in general, be correctly parallelized by OpenMP.
- Dependencies within the current loop is OK:
  
  ```
  #pragma omp parallel for numthreads (threadcount)
  x[i] = a + i * h
  y[i] = exp(x[i])
  ```
Estimating $\pi$

$$\pi = 4 \left[ 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \cdots \right] = 4 \sum_{k=0}^{\infty} \frac{(-1)^k}{2k+1}$$

```c
double factor = 1.0;
double sum = 0.0;
for (k = 0; k < n; k++) {
    sum += factor / (2 * k + 1);
    factor = -factor;
}
pi_approx = 4.0 * sum;
```
OpenMP solution #1

```c
double factor = 1.0;
double sum = 0.0;

#pragma omp parallel for num_threads(thread_count) 
  reduction(+:sum)
for (k = 0; k < n; k++) {
  sum += factor/(2*k+1);
  factor = -factor;
}
pi_approx = 4.0*sum;
```

loop dependency
Examine the series: for $\pi$:

Replace $(-1)^k$

```c++
double sum = 0.0;

#pragma omp parallel for num_threads(thread_count) \
default(none) reduction(+:sum) private(k, factor) \
shared(n)
for (k = 0; k < n; k++) {
    if (k % 2 == 0)
        factor = 1.0;
    else
        factor = -1.0;
    sum += factor/(2*k+1);
}
```
**Pacheco Data Dependencies example: omp_pi.c**

```c
int main(int argc, char* argv[]) {
    long long n, i;
    int thread_count;
    double factor;
    double sum = 0.0;

    if (argc != 3) Usage(argv[0]);
    thread_count = strtol(argv[1], NULL, 10);
    n = strtoll(argv[2], NULL, 10);
    if (thread_count < 1 || n < 1) Usage(argv[0]);

    # pragma omp parallel for num_threads(thread_count) 
    #     reduction(+: sum) private(factor)
    for (i = 0; i < n; i++) {
        factor = (i % 2 == 0) ? 1.0 : -1.0;
        sum += factor/(2*i+1);
        # ifdef DEBUG
        printf("Thread %d > i = %lld, my_sum = %.1f\n", my_rank, i, my_sum);
        # endif
    }
    sum = 4.0*sum;
    printf("With n = %lld terms and %d threads,\n", n, thread_count);
    printf(" Our estimate of pi = %.14f\n", sum);
    printf(" pi = %.14f\n", 4.0*atan(1.0));
    return 0;
} /* main */
```
Running omp_pi.c: could reproduce erroneous condition on OS Mountain Lion - not every time

With n = 100 terms and 10 threads,
Our estimate of pi = 3.13159290355855
pi = 3.14159265358979

With n = 1000 terms and 1 threads,
Our estimate of pi = 3.14059265383979
pi = 3.14159265358979

With n = 1000000 terms and 10 threads,
Our estimate of pi = 3.14159165358972
pi = 3.14159265358979

With n = 10000000 terms and 10 threads,
Our estimate of pi = 3.14159255358977
pi = 3.14159265358979
The default clause

- Lets the programmer specify the scope of each variable in a block.
  
  \texttt{default(none)}

- With this clause the compiler will require that we specify the scope of each variable we use in the block and that has been declared outside the block.
The default clause

double sum = 0.0;
#pragma omp parallel for num_threads(thread_count) \
  default(none) reduction(+:sum) private(k, factor) \
  shared(n)
for (k = 0; k < n; k++) {
  if (k % 2 == 0)
    factor = 1.0;
  else
    factor = -1.0;
  sum += factor/(2*k+1);
}
Bubble Sort: $\Theta(n^2)$

Loop carried dependence in outer loop - different threads sorting different data could result in wrong ordering.
Serial Odd-Even Transposition Sort

```
for (phase = 0; phase < n; phase++)
    if (phase % 2 == 0)
        for (i = 1; i < n; i += 2)
            if (a[i-1] > a[i]) Swap(&a[i-1], &a[i]);
    else
        for (i = 1; i < n-1; i += 2)
            if (a[i] > a[i+1]) Swap(&a[i], &a[i+1]);
```

See Pacheco, Chpt 3.7.
Odd-Even Transposition Sort: $\theta(n)$

### Serial Odd-Even Transposition Sort

<table>
<thead>
<tr>
<th>Phase</th>
<th>Subscript in Array</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0: 9 ← 7 ≥ 8 ← 6</td>
</tr>
<tr>
<td></td>
<td>1: 7 9 ← 6 8</td>
</tr>
<tr>
<td>1</td>
<td>2: 7 ← 6 9 ← 8</td>
</tr>
<tr>
<td></td>
<td>3: 6 7 ← 8 9</td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>
First OpenMP Odd-Even Sort

```c
for (phase = 0; phase < n; phase++) {
    if (phase % 2 == 0)
        #pragma omp parallel for num_threads(thread_count) \
            default(none) shared(a, n) private(i, tmp)
        for (i = 1; i < n; i += 2) {
            if (a[i-1] > a[i]) {
                tmp = a[i-1];
                a[i-1] = a[i];
                a[i] = tmp;
            }
        }
    else
        #pragma omp parallel for num_threads(thread_count) \
            default(none) shared(a, n) private(i, tmp)
        for (i = 1; i < n-1; i += 2) {
            if (a[i] > a[i+1]) {
                tmp = a[i+1];
                a[i+1] = a[i];
                a[i] = tmp;
            }
        }
}
```

Issues: implicit barrier after each phase completes; overhead associated with fork/join.
Second OpenMP Odd-Even Sort

```c
#pragma omp parallel num_threads(thread_count) \
    default(none) shared(a, n) private(i, tmp, phase)
for (phase = 0; phase < n; phase++) {
    if (phase % 2 == 0)
        # pragma omp for
        for (i = 1; i < n; i += 2) {
            if (a[i-1] > a[i]) {
                tmp = a[i-1];
                a[i-1] = a[i];
                a[i] = tmp;
            }
        }
    else
        # pragma omp for
        for (i = 1; i < n-1; i += 2) {
            if (a[i] > a[i+1]) {
                tmp = a[i+1];
                a[i+1] = a[i];
                a[i] = tmp;
            }
        }
```
Odd-even sort with two parallel for directives and two for directives.

(Times are in seconds.)

<table>
<thead>
<tr>
<th>thread_count</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two parallel for directives</td>
<td>0.770</td>
<td>0.453</td>
<td>0.358</td>
<td>0.305</td>
</tr>
<tr>
<td>Two for directives</td>
<td>0.732</td>
<td>0.376</td>
<td>0.294</td>
<td>0.239</td>
</tr>
</tbody>
</table>
OpenMP assigns/distributes work (block partitioning)

E.g., for $n$ iterations, then each thread gets $\frac{n}{\text{thread\_count}}$

Alternative approach: cyclic partitioning.

We want to parallelize this loop.

```
sum = 0.0;
for (i = 0; i <= n; i++)
    sum += f(i);
```

<table>
<thead>
<tr>
<th>Thread</th>
<th>Iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0, n/t, 2n/t, ...</td>
</tr>
<tr>
<td>1</td>
<td>1, n/t+1, 2n/t+1, ...</td>
</tr>
<tr>
<td>$\vdots$</td>
<td>$\vdots$</td>
</tr>
<tr>
<td>$t-1$</td>
<td>$t-1$, n/t+t-1, 2n/t+t-1, ...</td>
</tr>
</tbody>
</table>

Assignment of work using cyclic partitioning.
double f(int i) {
    int j, start = i*(i+1)/2, finish = start + i;
    double return_val = 0.0;

    for (j = start; j <= finish; j++) {
        return_val += sin(j);
    }
    return return_val;
} /* f */

Our definition of function f.
Results

- f(i) calls the sin function i times.
- Assume the time to execute f(2i) requires approximately twice as much time as the time to execute f(i).

- n = 10,000
  - one thread
  - run-time = 3.67 seconds.
Results

- **n = 10,000**
  - two threads
  - default assignment
  - run-time = 2.76 seconds
  - speedup = 1.33

- **n = 10,000**
  - two threads
  - cyclic assignment
  - run-time = 1.84 seconds
  - speedup = 1.99
Scheduling: OpenMP assignment of threads.

The Schedule Clause

- Default schedule:

  ```c
  sum = 0.0;
  #pragma omp parallel for num_threads(thread_count) \ 
  reduction(+:sum)
  for (i = 0; i <= n; i++)
  sum += f(i);
  ```

- Cyclic schedule:

  ```c
  sum = 0.0;
  #pragma omp parallel for num_threads(thread_count) \ 
  reduction(+:sum) schedule(static,1)
  for (i = 0; i <= n; i++)
  sum += f(i);
  ```
double funtst(int); /* Thread function */
/*-----------------------------------------------*/
int main(int argc, char* argv[]) {
    int thread_count = strtol(argv[1], NULL, 10);
    int i, n;
    double sum;
    sum = 0.0;
    n=100000;
    # pragma omp parallel for num_threads(thread_count) \
        reduction(+:sum) schedule(static,1)
    for( i=0; i <=n; i++) {
        sum += funtst(i);
    }
    printf("N=%d, sum=%f\n",n,sum);
    return 0;
} /* main */

/*-----------------------------------------------
* Function: Hello
* Purpose: Thread function that prints message
*/
double funtst(int i) {
    int j, start=i*(i+1)/2, finish=start+i;
    for(j=start; j<=finish; j++) {
        ret_val += sin(j);
    }
    return ret_val;
} /* funtst */
OpenMP: Parallel for Directive
Loops: Scheduling

results

==== WITHOUT SCHEDULING ====================
[gidget] mthomas% date ; ./omp_myt 1 ; date
Tue Nov 6 15:46:51 PST 2012
N=100000, sum=-0.284234
Tue Nov 6 15:50:18 PST 2012
[gidget] mthomas% date ; ./omp_myt 2 ; date
Tue Nov 6 15:51:08 PST 2012
N=100000, sum=-1.027596
Tue Nov 6 15:52:53 PST 2012
[gidget] mthomas% date ; ./omp_myt 8 ; date
Tue Nov 6 15:46:12 PST 2012
N=100000, sum=-1.931278
Tue Nov 6 15:46:40 PST 2012
[gidget] mthomas% date ; ./omp_myt 16 ; date
Tue Nov 6 15:42:40 PST 2012
N=100000, sum=7.887650
Tue Nov 6 15:43:12 PST 2012
[gidget] mthomas% date ; ./omp_myt 32 ; date
Tue Nov 6 15:43:56 PST 2012
N=100000, sum=22.965623
Tue Nov 6 15:44:27 PST 2012

==== WITH SCHEDULING ====================
[gidget] mthomas% date ; ./omp_myt_sch 1 ; date
Tue Nov 6 15:33:20 PST 2012
N=100000, sum=-0.284234
Tue Nov 6 15:37:05 PST 2012
[gidget] mthomas% date ; ./omp_myt_sch 2 ; date
Tue Nov 6 15:42:24 PST 2012
N=100000, sum=-0.284234
Tue Nov 6 15:44:51 PST 2012
[gidget] mthomas% date ; ./omp_myt_sch 8 ; date
Tue Nov 6 15:32:43 PST 2012
N=100000, sum=-0.284234
Tue Nov 6 15:33:12 PST 2012
[gidget] mthomas% date ; ./omp_myt_sch 16 ; date
Tue Nov 6 15:32:43 PST 2012
N=100000, sum=-0.284234
Tue Nov 6 15:32:34 PST 2012
[gidget] mthomas% date ; ./omp_myt_sch 32 ; date
Tue Nov 6 15:31:11 PST 2012
N=100000, sum=-0.284234
Tue Nov 6 15:31:40 PST 2012
**schedule (type, chunksize)**

- **Type can be:**
  - **static:** the iterations can be assigned to the threads before the loop is executed.
  - **dynamic or guided:** the iterations are assigned to the threads while the loop is executing.
  - **auto:** the compiler and/or the run-time system determine the schedule.
  - **runtime:** the schedule is determined at run-time.

- The **chunksize** is a positive integer.
chunks assigned in round-robin fashion.

**The Static Schedule Type**

twelve iterations, 0, 1, \ldots, 11, and three threads

\begin{verbatim}
schedule(static,1)
\end{verbatim}

Thread 0: 0, 3, 6, 9
Thread 1: 1, 4, 7, 10
Thread 2: 2, 5, 8, 11
The Static Schedule Type

twelve iterations, 0, 1, \ldots, 11, and three threads

\texttt{schedule(static,2)}

Thread 0 : 0, 1, 6, 7
Thread 1 : 2, 3, 8, 9
Thread 2 : 4, 5, 10, 11
The Static Schedule Type

twelve iterations, 0, 1, \ldots, 11, and three threads

\begin{verbatim}
schedule(static, 4)
\end{verbatim}

Thread 0 : 0, 1, 2, 3
Thread 1 : 4, 5, 6, 7
Thread 2 : 8, 9, 10, 11
The Dynamic Schedule Type

- The iterations are also broken up into chunks of chunksize consecutive iterations.
- Each thread executes a chunk, and when a thread finishes a chunk, it requests another one from the run-time system.
- This continues until all the iterations are completed.
- The chunksize can be omitted. When it is omitted, a chunksize of 1 is used.
The Guided Schedule Type

- Each thread also executes a chunk, and when a thread finishes a chunk, it requests another one.
- However, in a guided schedule, as chunks are completed the size of the new chunks decreases.
- If no `chunksize` is specified, the size of the chunks decreases down to 1.
- If `chunksize` is specified, it decreases down to `chunksize`, with the exception that the very last chunk can be smaller than `chunksize`.
Assignment of trapezoidal rule iterations 1–9999 using a guided schedule with two threads.

<table>
<thead>
<tr>
<th>Thread</th>
<th>Chunk</th>
<th>Size of Chunk</th>
<th>Remaining Iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1 – 5000</td>
<td>5000</td>
<td>4999</td>
</tr>
<tr>
<td>1</td>
<td>5001 – 7500</td>
<td>2500</td>
<td>2499</td>
</tr>
<tr>
<td>1</td>
<td>7501 – 8750</td>
<td>1250</td>
<td>1249</td>
</tr>
<tr>
<td>1</td>
<td>8751 – 9375</td>
<td>625</td>
<td>624</td>
</tr>
<tr>
<td>0</td>
<td>9376 – 9687</td>
<td>312</td>
<td>312</td>
</tr>
<tr>
<td>1</td>
<td>9688 – 9843</td>
<td>156</td>
<td>156</td>
</tr>
<tr>
<td>0</td>
<td>9844 – 9921</td>
<td>78</td>
<td>78</td>
</tr>
<tr>
<td>1</td>
<td>9922 – 9960</td>
<td>39</td>
<td>39</td>
</tr>
<tr>
<td>1</td>
<td>9961 – 9980</td>
<td>20</td>
<td>19</td>
</tr>
<tr>
<td>1</td>
<td>9981 – 9990</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>1</td>
<td>9991 – 9995</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>0</td>
<td>9996 – 9997</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>9998 – 9998</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>9999 – 9999</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
The Runtime Schedule Type

- The system uses the environment variable `OMP_SCHEDULE` to determine at runtime how to schedule the loop.
- The `OMP_SCHEDULE` environment variable can take on any of the values that can be used for a static, dynamic, or guided schedule.