

OpenMP II

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Open Source Economics Laboratory – BFI/UChicago

Including adapted teaching material from books, lectures and presentations by
B. Barney, B. Cumming, G. Hager, R. Rabenseifner, O. Schenk, G. Wellein

Roadmap – fast forward (3):

Day 3, Tuesday – July 23th

1. OpenMP session II (8.00-9.00 – hands on).
2. MPI session I (9.30-10.30 – hands on).
3. MPI session II (10.45-11.45 – hands on).
4. Exercise sheets (OpenMP & MPI) related to the day's topics (11.50-12.00).

Outline

- Work sharing constructs
 - Loops
 - Sections
 - Reductions (max, summation,...)

Components of OpenMP

Directives

Parallel regions

Work sharing

Synchronization

Data scope attributes :

- private
- firstprivate
- last private
- shared
- reduction

Orphaning

Runtime library routines

Number of threads

Thread ID

Dynamic thread adjustment

Nested Parallelism

Timers

API for locking

Environment variables

Number of threads

Scheduling type

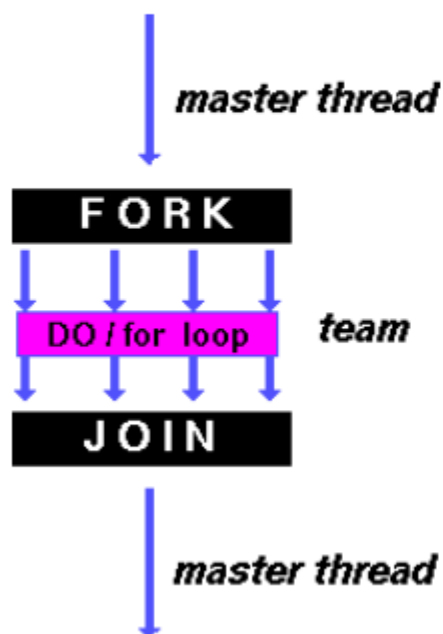
Dynamic thread adjustment

Nested Parallelism

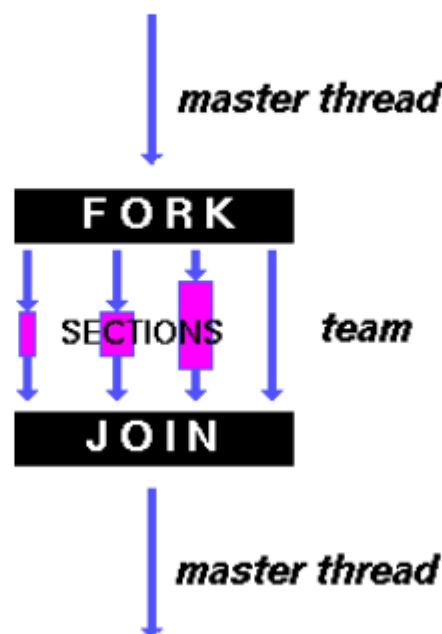
Worksharing constructs in OpenMP

See <https://computing.llnl.gov/tutorials/openMP/>

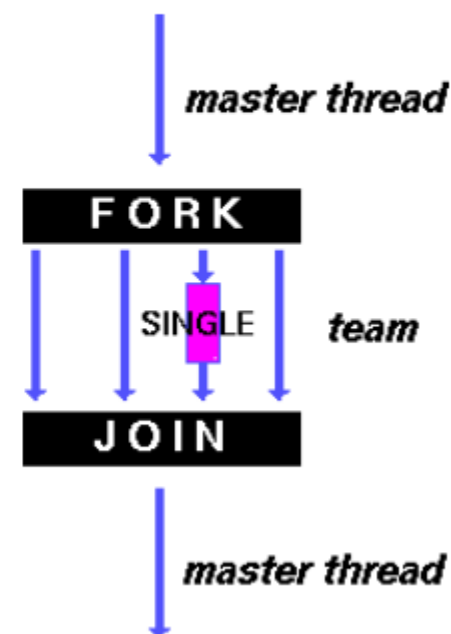
DO / for - shares iterations of a loop across the team. Represents a type of "data parallelism".



SECTIONS - breaks work into separate, discrete sections. Each section is executed by a thread. Can be used to implement a type of "functional parallelism".



SINGLE - serializes a section of code

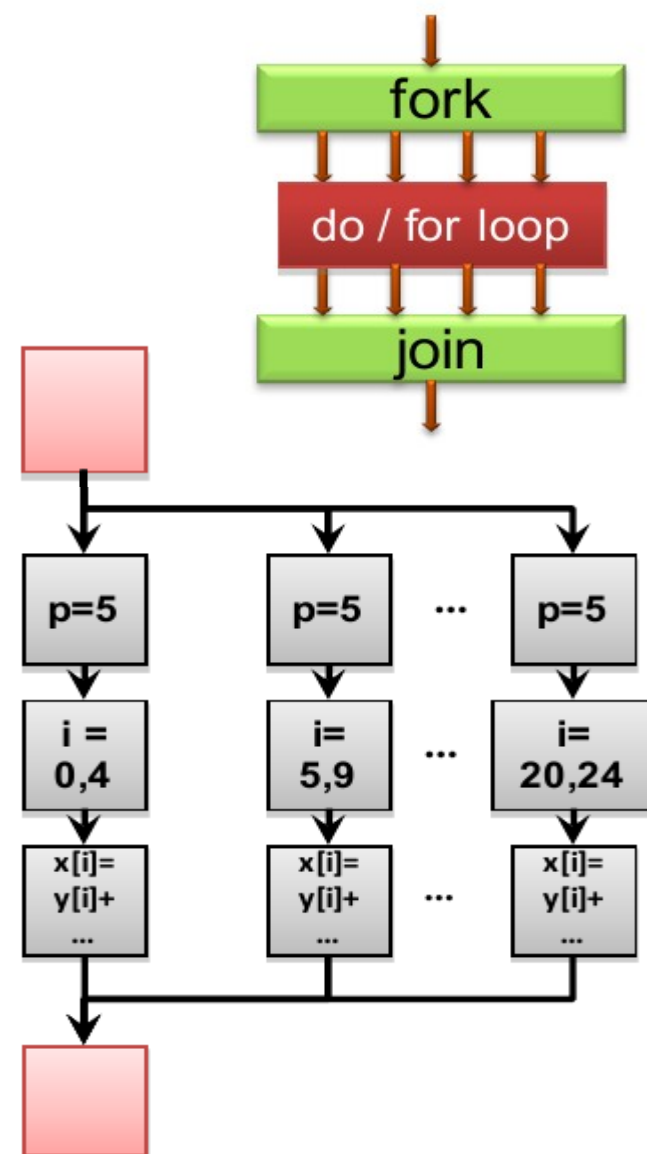


OpenMP worksharing “for/do loops”

See “A beginner's guide to supercomputing” – Sterling & Anderson

- *do/for* directive helps share iterations of a loop between a group of threads.
- If *nowait* is specified then the threads do not wait for synchronization at the end of a parallel loop.
- The *schedule* clause describes how iterations of a loop are divided among the threads in the team.

```
#pragma omp parallel private(p)
{
    p=5;
    #pragma omp for
        for (i=0; i<25; i++)
            x[i]=y[i]+p*(i+3);
    ...
} /* omp end parallel */
```



Format (Fortran/C/C++)

See <https://computing.llnl.gov/tutorials/openMP/>

| | |
|---------|--|
| Fortran | <pre>!\$OMP DO [clause ...] SCHEDULE (type [,chunk]) ORDERED PRIVATE (list) FIRSTPRIVATE (list) LASTPRIVATE (list) SHARED (list) REDUCTION (operator intrinsic : list) COLLAPSE (n) do_loop !\$OMP END DO [NOWAIT]</pre> |
| C/C++ | <pre>#pragma omp for [clause ...] newline schedule (type [,chunk]) ordered private (list) firstprivate (list) lastprivate (list) shared (list) reduction (operator: list) collapse (n) nowait for_loop</pre> |

Example: “do loops”

Serial code

```
double *x, *y, *z;
int n;
for(int i=0; i<n; ++i) {
    z[i] = x[i] + y[i];
}
```

C++

```
real(kind=8) :: x(:), y(:), z(:)
integer      :: i, n
do i=1,n
    z(i) = x(i) + y(i)
end do
```

Fortran

Parallel code

- compiler handles loop bounds for you.
- there is a compact single-line directive.
- **!\$OMP DO** (in Fortran)

```
double *x, *y, *z;
int n, i;
#pragma omp parallel
{
    #pragma omp for
    for(i=0; i<n; ++i) {
        z[i] = x[i] + y[i];
    }
}
```

C++

loop index
variable i is
private by
default

```
real(kind=8) :: x(:), y(:), z(:)
integer      :: i, n
!$omp parallel
!$omp do
do i=1,n
    z(i) = x(i) + y(i)
end do
!$omp end do
!$omp end parallel
```

Fortran

- let's attempt to parallelize the integral

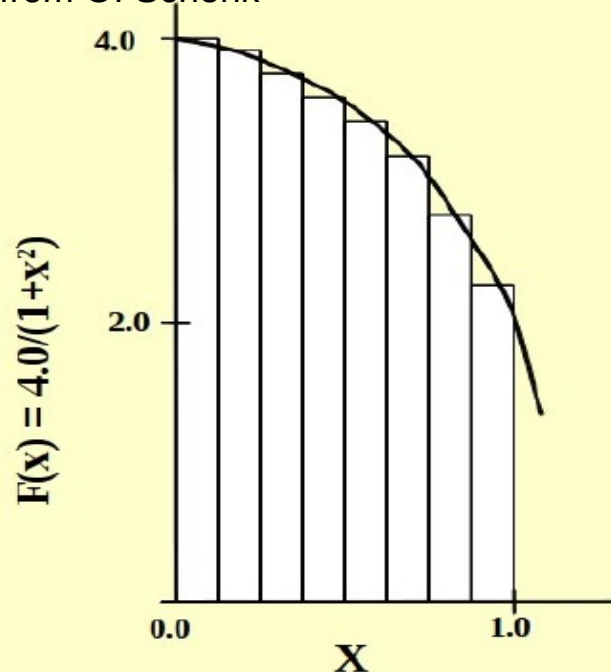
$$\pi = \int_0^1 dx \frac{4}{1+x^2}$$

by using techniques learnt so far (“**summation the hard way**”).

- [OSE2019/day3/code_day3/openmp/4.integration_pi.f90](#)
- [OSE2019/day3/code_day3/openmp/4a.integration_pi.cpp](#)

Computing Pi – the hard way

Fig. from O. Schenk



$$\int_0^1 \frac{4.0}{(1+x^2)} dx = \pi$$

$$\sum_{i=0}^N F(x_i) \Delta x \approx \pi$$

```

#define _USE_MATH_DEFINES

const int num_steps = 500000000;

int main( void ){
    int i;
    double sum = 0.0;
    double pi = 0.0;

    std::cout << "using " << omp_get_max_threads() << " OpenMP threads" << std::endl;

    const double w = 1.0/double(num_steps);

    double time = -omp_get_wtime();  time the program

    #pragma omp parallel firstprivate(sum)
    {
        #pragma omp for
        for (int i=0; i<num_steps; ++i)
        {
            double x = (i+0.5)*w;
            sum += 4.0/(1.0+x*x);
        }
        #pragma omp critical
        {
            pi = pi + w*sum;
        }
    }

    time += omp_get_wtime();

    std::cout << num_steps
    << " steps approximates pi as : "
    << pi
    << ", with relative error "
    << std::fabs(M_PI-pi)/M_PI
    << std::endl;
    std::cout << "the solution took " << time << " seconds" << std::endl;
}

```

firstprivate: private var that has been initialized before

get partial sums

each thread write to pi sequentially
each has their own copy of sum

Some clauses

SCHEDULE: Describes how iterations of the loop are divided among the threads in the team. The default schedule is implementation dependent

STATIC

Loop iterations are divided into pieces of size chunk and then statically assigned to threads. If chunk is not specified, the iterations are evenly (if possible) divided contiguously among the threads.

DYNAMIC

Loop iterations are divided into pieces of size chunk, and dynamically scheduled among the threads; when a thread finishes one chunk, it is dynamically assigned another. The default chunk size is 1.

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.

Example – default work sharing

See [OSE2019/day3/code_day3/openmp/openmp/4d.work.cpp](#)

```
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>
#include <iostream>
using namespace std;

int main()
{
    const int N = 100;
    int nthreads, threadid;
    int i;
    double a[N], b[N], c[N];

    //Initialize
    for (i = 0; i < N; i++){
        a[i] = 1.0*i;
        b[i] = 2.0*i;
    }

    #pragma omp parallel shared(a,b,c,nthreads) private(i,threadid)
    {
        threadid = omp_get_thread_num();
        if (threadid == 0) {
            nthreads = omp_get_num_threads();
            printf("Number of threads = %d\n", nthreads);
        }
        printf("My threadid = %d\n", threadid);

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

        } //join

    cout << "TEST c[99] = " << c[99] << endl;

    return 0;
}
```

Example of loop work sharing

/code_day3/openmp\$./4d.work-static.exec

```
My threadid = 2
My threadid = 1
My threadid = 3
Number of threads = 4
My threadid = 0
TEST c[99] = 297
```

Example – default work sharing

See [OSE2019/day3/code_day3/openmp/4e.work-print.cpp](#)

Print out the thread ID and the index.
Use default scheduling.

```
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>
#include <iostream>
using namespace std;

int main()
{
    const int N = 20;
    int nthreads, threadid;
    int i;
    double a[N], b[N], c[N];

    //Initialize
    for (i = 0; i < N; i++){
        a[i] = 1.0*i;
        b[i] = 2.0*i;
    }

    #pragma omp parallel shared(a,b,c,nthreads) private(i,threadid)
    {
        threadid = omp_get_thread_num();
        if (threadid == 0) {
            nthreads = omp_get_num_threads();
            printf("Number of threads = %d\n", nthreads);
        }
        printf("My threadid = %d\n", threadid);

        #pragma omp for
        for (i = 0; i < N; i++){
            c[i] = a[i] + b[i];
            printf("Thread id = %d working on index %d\n", threadid, i);
        }

        } //join

    cout << "TEST c[19] = " << c[19] << endl;

    return 0;
}
```

./4e.work-static-print.exec

```
Number of threads = 4
My threadid = 0
Thread id = 0 working on index 0
Thread id = 0 working on index 1
Thread id = 0 working on index 2
Thread id = 0 working on index 3
Thread id = 0 working on index 4
My threadid = 2
Thread id = 2 working on index 10
Thread id = 2 working on index 11
Thread id = 2 working on index 12
Thread id = 2 working on index 13
Thread id = 2 working on index 14
My threadid = 3
Thread id = 3 working on index 15
Thread id = 3 working on index 16
Thread id = 3 working on index 17
Thread id = 3 working on index 18
Thread id = 3 working on index 19
My threadid = 1
Thread id = 1 working on index 5
Thread id = 1 working on index 6
Thread id = 1 working on index 7
Thread id = 1 working on index 8
Thread id = 1 working on index 9
TEST c[19] = 57
```

Example – static work sharing

See [OSE2019/day3/code_day3/openmp/openmp/4f.work-static.cpp](#)

Print out the thread id and the index.
Use static scheduling.

```
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>
#include <iostream>
using namespace std;

int main()
{
    const int N = 20;
    int nthreads, threadid;
    int i;
    double a[N], b[N], c[N];
```

```
//Initialize
for (i = 0; i < N; i++){
    a[i] = 1.0*i;
    b[i] = 2.0*i;
}
```

```
int chunk = 3; → chunk size
```

```
#pragma omp parallel shared(a,b,c,nthreads) private(i,threadid)
{
    threadid = omp_get_thread_num();
    if (threadid == 0) {
        nthreads = omp_get_num_threads();
        printf("Number of threads = %d\n", nthreads);
    }
    printf("My threadid = %d\n", threadid);
```

```
#pragma omp for schedule(static,chunk) → each thread work on a chunk w/ a particular chunk size
for (i = 0; i < N; i++){
    c[i] = a[i] + b[i];
    printf("Thread id = %d working on index %d\n", threadid,i);
}

} //join
```

```
cout << "TEST c[19] = " << c[19] << endl;
```

```
return 0;
}
```

```
Number of threads = 4
My threadid = 0
Thread id = 0 working on index 0
Thread id = 0 working on index 1
Thread id = 0 working on index 2
Thread id = 0 working on index 12
Thread id = 0 working on index 13
Thread id = 0 working on index 14
My threadid = 2
Thread id = 2 working on index 6
Thread id = 2 working on index 7
Thread id = 2 working on index 8
Thread id = 2 working on index 18
Thread id = 2 working on index 19
My threadid = 1
Thread id = 1 working on index 3
Thread id = 1 working on index 4
Thread id = 1 working on index 5
Thread id = 1 working on index 15
Thread id = 1 working on index 16
Thread id = 1 working on index 17
My threadid = 3
Thread id = 3 working on index 9
Thread id = 3 working on index 10
Thread id = 3 working on index 11
TEST c[19] = 57
```

tasks spread unevenly. Some threads are idle while others are working. Will slow down the code.

Example – dynamic work sharing

See [OSE2019/day3/code_day3/openmp/4g.work-dynamic.cpp](#)

Print out the thread id and the index.
Use dynamic scheduling.

```
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>
#include <iostream>
using namespace std;

int main()
{
    const int N = 20;
    int nthreads, threadid;
    int i;
    double a[N], b[N], c[N];

    //Initialize
    for (i = 0; i < N; i++){
        a[i] = 1.0*i;
        b[i] = 2.0*i;
    }

    int chunk = 3;

#pragma omp parallel shared(a,b,c,nthreads) private(i,threadid)
    {
        threadid = omp_get_thread_num();
        // if (threadid == 0) {
        //     nthreads = omp_get_num_threads();
        //     printf("Number of threads = %d\n", nthreads);
        // }
        // printf("My threadid = %d\n", threadid);

#pragma omp for schedule(dynamic,chunk)
        for (i = 0; i < N; i++){
            c[i] = a[i] + b[i];
            printf("Thread id = %d working on index %d\n", threadid,i);
        }

        //join

    }

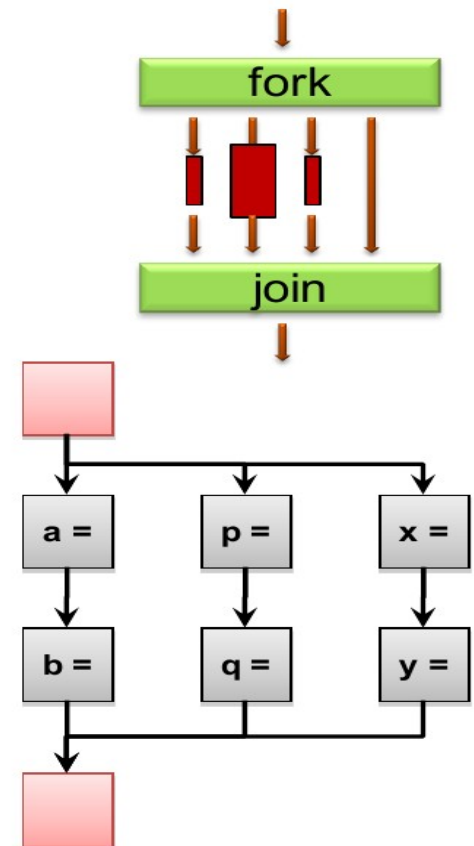
    cout << "TEST c[19] = " << c[19] << endl;
```

```
Thread id = 0 working on index 0
Thread id = 0 working on index 1
Thread id = 0 working on index 2
Thread id = 1 working on index 9
Thread id = 1 working on index 10
Thread id = 1 working on index 11
Thread id = 1 working on index 15
Thread id = 1 working on index 16
Thread id = 1 working on index 17
Thread id = 1 working on index 18
Thread id = 1 working on index 19
Thread id = 3 working on index 3
Thread id = 3 working on index 4
Thread id = 3 working on index 5
Thread id = 0 working on index 12
Thread id = 0 working on index 13
Thread id = 0 working on index 14
Thread id = 2 working on index 6
Thread id = 2 working on index 7
Thread id = 2 working on index 8
TEST c[19] = 57
```

OpenMP worksharing “sections”

- **sections** directive is a non iterative work sharing construct.
- Independent section of code are nested within a **sections** directive.
- It specifies enclosed **section** of codes between different threads.
- Code enclosed within a **section** directive is executed by a thread within the pool of threads.

```
#pragma omp parallel private(p)
{
#pragma omp sections
{{ a=...;
   b=...; }
#pragma omp section
{ p=...;
  q=...; }
#pragma omp section
{ x=...;
  y=...; }
} /* omp end sections */
} /* omp end parallel */
```



Fortran/C/C++ “sections”

| | |
|---------|---|
| Fortran | <pre> !\$OMP SECTIONS [clause ...] PRIVATE (list) FIRSTPRIVATE (list) LASTPRIVATE (list) REDUCTION (operator intrinsic : list) !\$OMP SECTION block !\$OMP SECTION block !\$OMP END SECTIONS [NOWAIT] </pre> |
| C/C++ | <pre> #pragma omp sections [clause ...] newline private (list) firstprivate (list) lastprivate (list) reduction (operator: list) nowait { #pragma omp section newline structured_block #pragma omp section newline structured_block } </pre> |

Example on “sections”

See [OSE2019/day3/code_day3/openmp/5a.vec_add_sections.cpp](#)

```
#include <iostream>
#include <omp.h>
#define N 1

using namespace std;

int main ()
{
    int i;
    float a[N], b[N], c[N], d[N];

    /* Some initializations */
    for (i=0; i < N; i++) {
        a[i] = i * 1.5;
        b[i] = i + 22.35;
    }

    #pragma omp parallel shared(a,b,c,d) private(i)
    {
        #pragma omp sections nowait
        {
            #pragma omp section
            for (i=0; i < N; i++)
            {
                c[i] = a[i] + b[i];
                cout << "Section 1: hello from thread " << omp_get_thread_num() << " of " << omp_get_num_threads() << " index " << i << endl;
            }

            #pragma omp section
            for (i=0; i < N; i++)
            {
                d[i] = a[i] * b[i];
                cout << "Section 2: hello from thread " << omp_get_thread_num() << " of " << omp_get_num_threads() << " index " << i << endl;
            }

            #pragma omp section
            {
                cout << "Section 3: hello from thread " << omp_get_thread_num() << " of " << omp_get_num_threads() << endl;
                cout << "This section 3 does nothing " << endl;
            }

        } /* end of sections */
    } /* end of parallel region */
}
```

3 sections

>export OMP_NUM_THREADS = 2
./5.vec_add_sections.f90

>export OMP_NUM_THREADS = 3
>export OMP_NUM_THREADS = 4

→ what do we observe?

Sections run in parallel

Reductions

→ e.g. summation the “easy way”

The **REDUCTION** clause performs a reduction on the variables that appear in the list.

→ **reduction(op:list)**

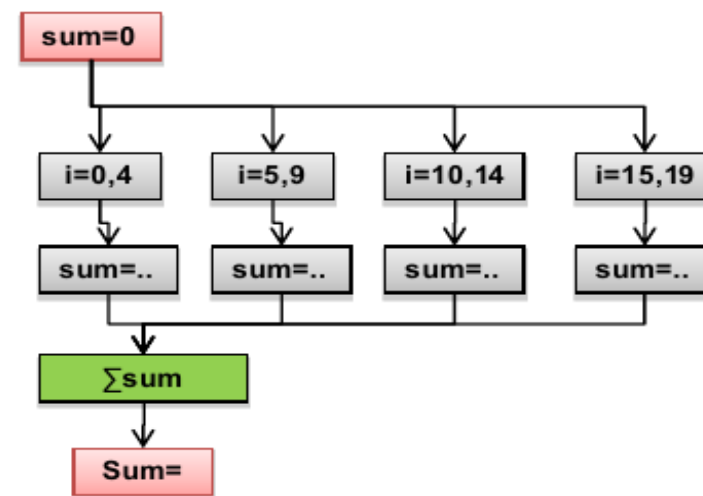
e.g. **reduction(+:pi),**
reduction(max:Maxval)

A **private copy** for each list variable is created for each thread.

At the end of the reduction, the reduction variable is applied to all private copies of the shared variable, and the final result is written to the global shared variable.

```
#pragma omp parallel for \
    default(shared) private(i) \
    schedule(static,chunk) \
    reduction(+:result)
```

```
for (i=0; i < n; i++)
    result += (a[i] * b[i]);
```



Example: Reduction

> OSE2019/day3/code_day3/openmp/6a.integration_pi_reduction.cpp
(play with OMP_NUM_THREADS & timing)

```
#include <iostream>
#include <cmath>

#include <omp.h>

#define _USE_MATH_DEFINES

const int num_steps = 500000000;

int main( void ){
    int i;
    double sum = 0.0;
    double pi = 0.0;

    std::cout << "using " << omp_get_max_threads() << " OpenMP threads" << std::endl;

    const double w = 1.0/double(num_steps);

    double time = -omp_get_wtime();

    #pragma omp parallel for reduction(+:sum)
    for(int i=0; i<num_steps; ++i) {
        double x = (i+0.5)*w;
        sum += 4.0/(1.0+x*x);
    }

    pi = sum*w;

    time += omp_get_wtime();

    std::cout << num_steps
              << " steps approximates pi as : "
              << pi
              << ", with relative error "
              << std::fabs(M_PI-pi)/M_PI
              << std::endl;
    std::cout << "the solution took " << time << " seconds" << std::endl;
}
```

Reduction

- ↳
1. hide away private sums
 2. hide away critical regions
 3. hide away summation of partial sums.

Same steps as the
example of pi integration
w/ critical regions.

Questions?

1. Advice – RTFM

<https://en.wikipedia.org/wiki/RTFM>

2. Advice – <http://imgtfy.com/>

<http://imgtfy.com/?q=open+mp>

