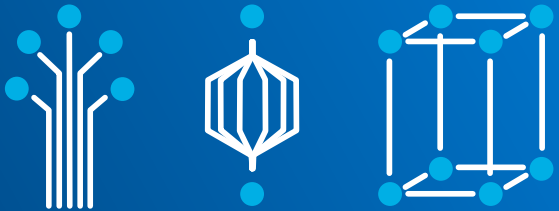
Fundamentals of Parallelism on Intel® Architecture

Week 3
Multithreading
with OpenMP

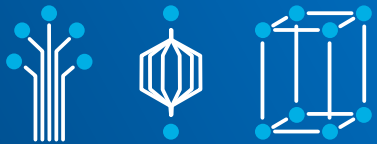


COLFAX RESEARCH

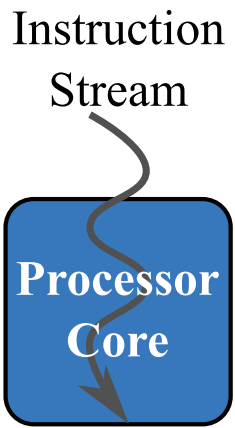
May 2017

intel

§1. Cores, Processes and Threads



Serial Processor, Serial Code

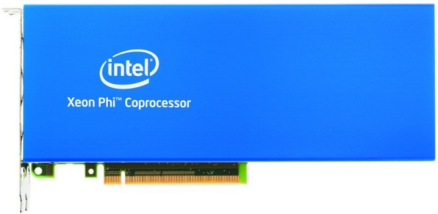


Computing Platforms

Intel Xeon Processor

Current: Broadwell
Upcoming: Skylake

Intel Xeon Phi Coprocessor, 1st generation



Knights Corner (KNC)

Intel Xeon Phi Processor, 2nd generation*

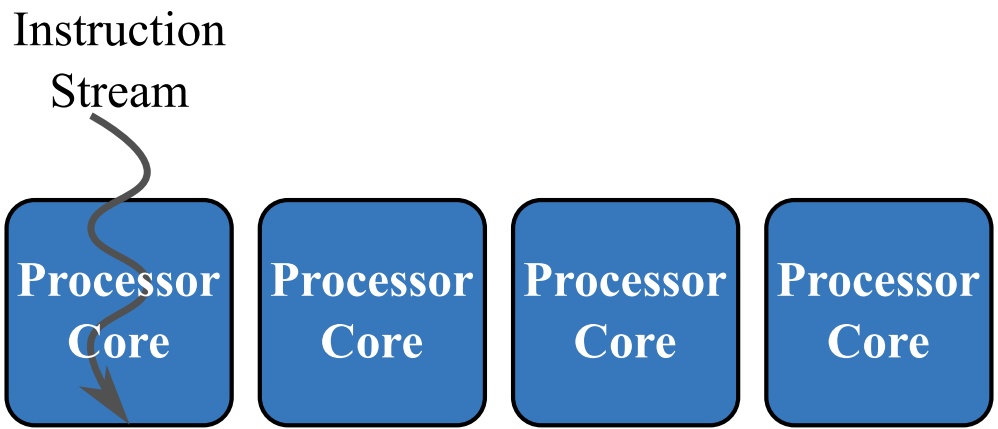
* socket and coprocessor versions

Knights Landing (KNL)

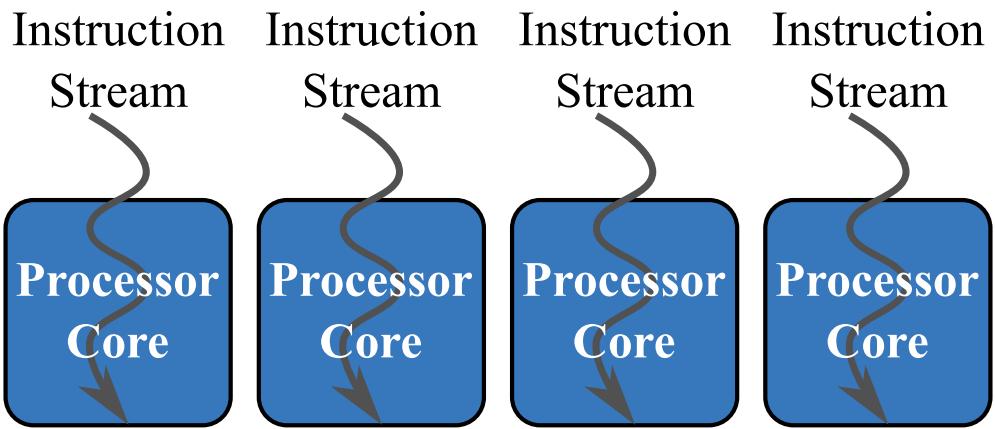
Multi-Core Architecture

Intel Many Integrated Core (MIC) Architecture

Parallel Processor, Serial Code

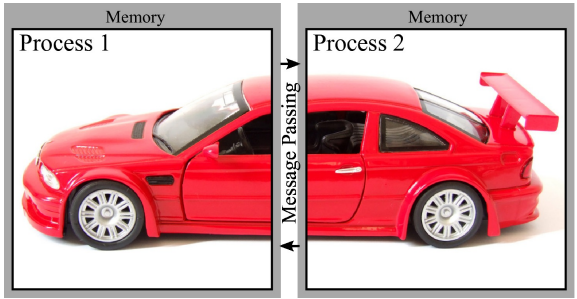


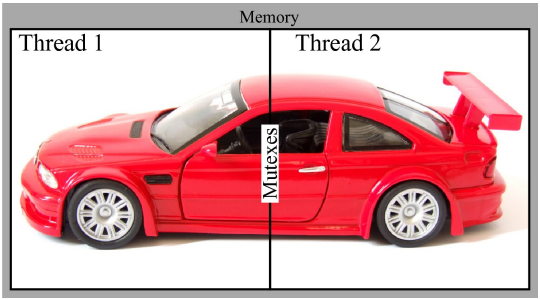
Parallel Processor, Parallel Code



Threads versus Processes

Option 1: Partitioning data set between threads/processes

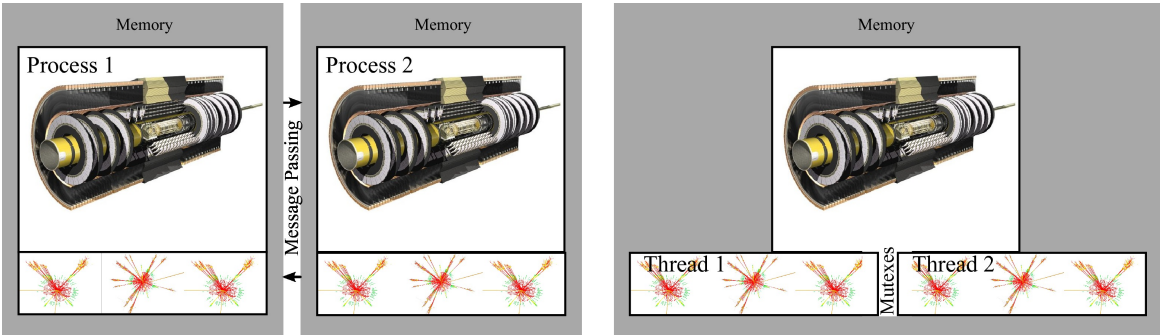




Examples: computational fluid dynamics (CFD), image processing.

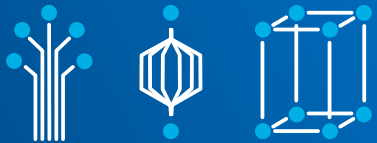
Threads versus Processes

Option 2: Sharing data set between threads/processes



Examples: particle transport simulation, machine learning (inference).

§2. Creating Threads



Threading Frameworks

Framework	Functionality
C++11 Threads	Asynchronous functions; only C++
POSIX Threads	Fork/join; C/C++/Fortran; Linux
Cilk Plus	Async tasks, loops, reducers, load balance; C/C++
TBB	Trees of tasks, complex patterns; only C++
OpenMP	Tasks, loops, reduction, load balancing, affinity, nesting, C/C++/Fortran (+SIMD, offload)

"Hello World" OpenMP Program

```
1  #include <omp.h>
2  #include <cstdio>
3
4  int main(){
5    // This code is executed by 1 thread
6    const int nt=omp_get_max_threads();
7    printf("OpenMP with %d threads\n", nt);
8
9  #pragma omp parallel
10   { // This code is executed in parallel
11     // by multiple threads
12     printf("Hello World from thread %d\n",
13                       omp_get_thread_num());
14   }
15 }
```

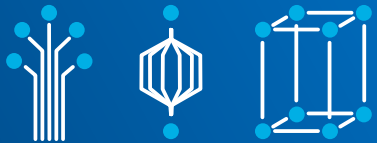
- OpenMP = “Open Multi-Processing” = computing-oriented framework for shared-memory programming
- Threads – streams of instructions that share memory address space
- Distribute threads across CPU cores for parallel speedup

Compiling the "Hello World" OpenMP Program

```
vega@lyra% icpc -qopenmp hello_omp.cc
vega@lyra% export OMP_NUM_THREADS=5
vega@lyra% ./a.out
OpenMP with 5 threads
Hello World from thread 0
Hello World from thread 3
Hello World from thread 1
Hello World from thread 2
Hello World from thread 4
```

`OMP_NUM_THREADS` controls number of OpenMP threads (default: logical CPU count)

§3. Variable Sharing



Control of Variable Sharing

Method 1: using clauses in pragma omp parallel (C, C++, Fortran):

```
1 int A, B; // Variables declared at the beginning of a function
2 #pragma omp parallel private(A) shared(B)
3   {
4     // Each thread has its own copy of A, but B is shared
5   }
```

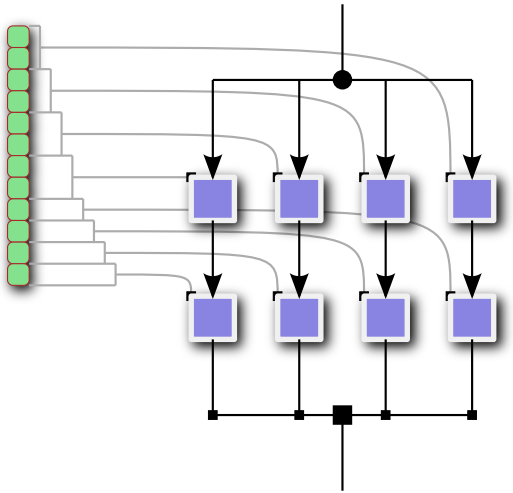
Method 2: using scoping (only C and C++):

```
1 int B; // Variable declared outside of parallel scope - shared by default
2 #pragma omp parallel
3   {
4     int A; // Variable declared inside the parallel scope - always private
5     // Each thread has its own copy of A, but B is shared
6   }
```


§4. Parallel Loops

Loop-Centric Parallelism: For-Loops in OpenMP

- Simultaneously launch multiple threads
- Scheduler assigns loop iterations to threads
- Each thread processes one iteration at a time



Parallelizing a `for`-loop.

Loop-Centric Parallelism: For-Loops in OpenMP

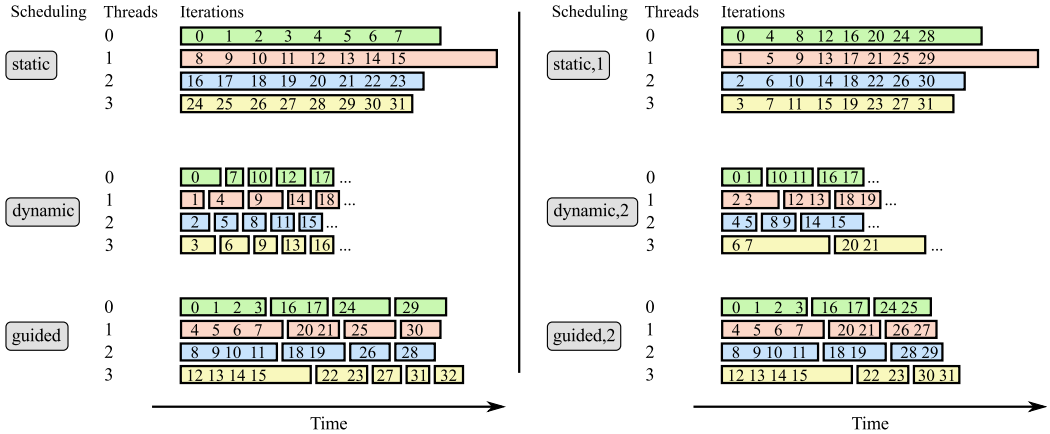
The OpenMP library will distribute the iterations of the loop following the `#pragma omp parallel for` across threads.

```
1 #pragma omp parallel for
2 for (int i = 0; i < n; i++) {
3   printf("Iteration %d is processed by thread %d\n",
4          i, omp_get_thread_num());
5   // ... iterations will be distributed across available threads...
6 }
```


Loop-Centric Parallelism: For-Loops in OpenMP

```
1  #pragma omp parallel
2  {
3    // Code placed here will be executed by all threads.
4
5    // Alternative way to specify private variables:
6    // declare them in the scope of pragma omp parallel
7    int private_number=0;
8
9  #pragma omp for
10   for (int i = 0; i < n; i++) {
11     // ... iterations will be distributed across available threads...
12   }
13   // ... code placed here will be executed by all threads
14 }
```


Loop Scheduling Modes in OpenMP



§5. Example: Stencil Code

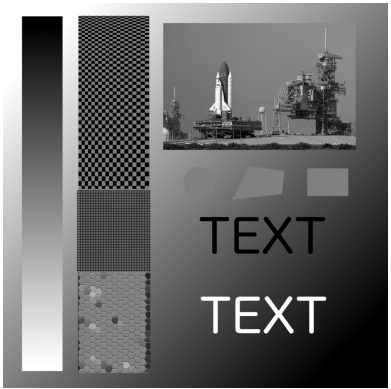
Stencil Operators

- Linear systems of equations
- Partial differential equations

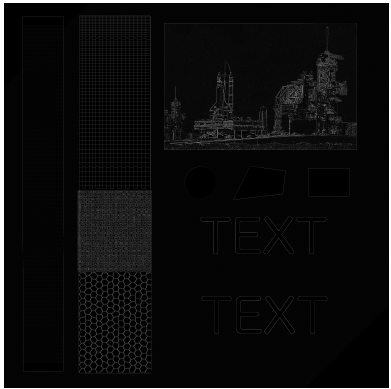
$$
\begin{aligned}
Q_{x,y} = \; & c_{00}P_{\mathrm{x-1,y-1}} + c_{01}P_{\mathrm{x,y-1}} + c_{02}P_{\mathrm{x+1,y-1}} + \\
& c_{10}P_{\mathrm{x-1,y}} + c_{11}P_{\mathrm{x,y}} + c_{12}P_{\mathrm{x+1,y}} + \\
& c_{20}P_{\mathrm{x-1,y+1}} + c_{21}P_{\mathrm{x,y+1}} + c_{22}P_{\mathrm{x+1,y+1}}
\end{aligned}
$$

Fluid dynamics, heat transfer, image processing (convolution matrix), cellular automata.

Edge Detection



$$\begin{bmatrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{bmatrix} \rightarrow$$

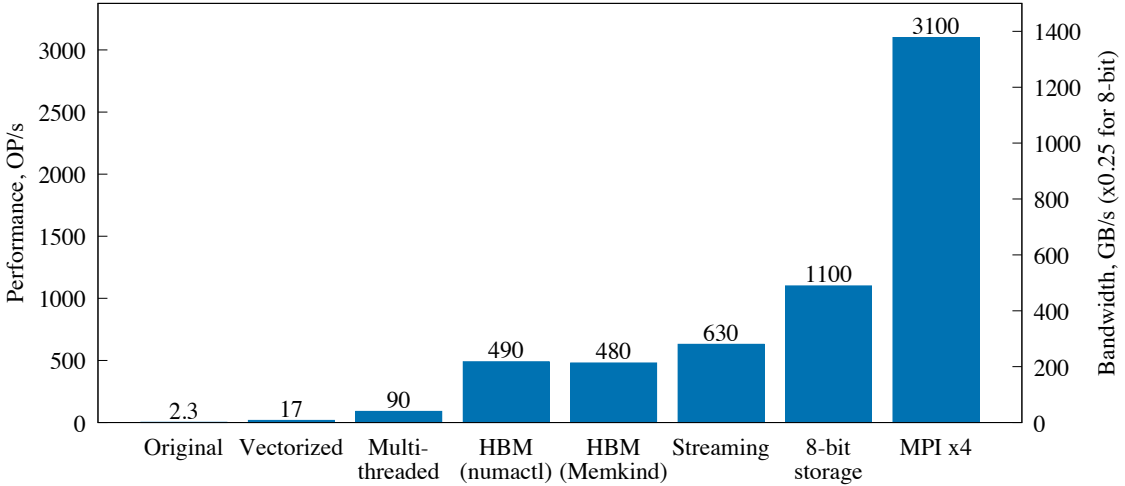


Multithreading

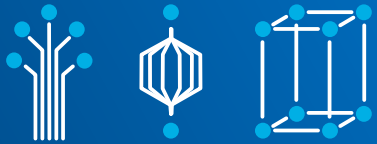
```
user@vega% icpc -c -qopenmp -xMIC-AVX512 stencil.cc
```

```
1 #pragma omp parallel for
2 for (int i = 1; i < height-1; i++)
3 #pragma omp simd
4  for (int j = 1; j < width-1; j++)
5   out[i*width + j] =
6   -in[(i-1)*width + j-1] -   in[(i-1)*width + j] - in[(i-1)*width + j+1]
7   -in[(i  )*width + j-1] + 8*in[(i  )*width + j] - in[(i  )*width + j+1]
8   -in[(i+1)*width + j-1] -   in[(i+1)*width + j] - in[(i+1)*width + j+1];
```

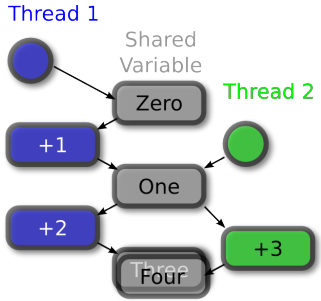

Performance



§6. Data Races and Mutexes



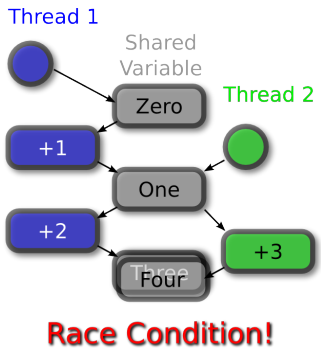
Race Conditions and Unpredictable Program Behavior

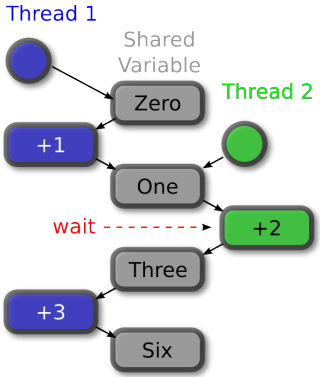



```
1  int total = 0;
2  #pragma omp parallel for
3  for (int i = 0; i < n; i++) {
4    // Race condition
5    total = total + i;
6   }
```

- Occurs when 2 or more threads access the same memory address, and at least one of these accesses is for writing

Mutexes





- Mutual exclusion conditions (mutexes) protect data races by serializing code.

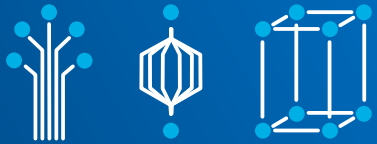
Mutexes in OpenMP

```
1  #pragma omp parallel
2    {
3      // parallel code
4  #pragma omp critical
5      {
6        // protected code
7        // multiple lines
8        // many variables
9      }
10   }
```

```
1  #pragma omp parallel
2    {
3      // parallel code
4  #pragma omp atomic
5        // protected code
6        // one line
7        // specific operations
8        // on scalars
9        total += i;
10   }
```

Good parallel codes minimize the use of mutexes.

§7. Parallel Reduction

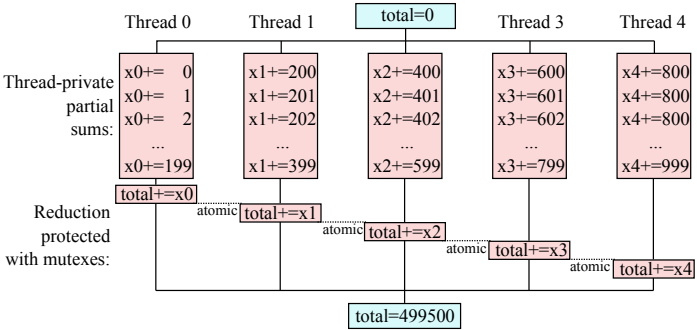


Built-in reduction

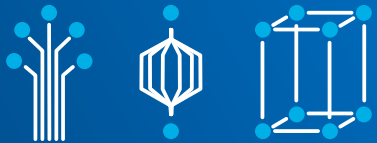
```
1 int total = 0;
2 #pragma omp parallel for reduction(+: total)
3 for (int i = 0; i < n; i++) {
4   total += i
```


Reduction with Thread-Private Storage

```
1  int total = 0;
2  #pragma omp parallel
3  {
4    int total_thr = 0;
5  #pragma omp for
6    for (int i=0; i<n; i++)
7      total_thr += i;
8
9  #pragma omp atomic
10   total += total_thr;
11
12 }
```



§8. Example: Numerical Integration



Midpoint Rectangle Method

$$I(a,b) = \int_0^a f(x)\mathrm{d}x \approx \sum_{i=0}^{n-1} f\left(x_{\mathrm{i}+\frac{1}{2}}\right)\Delta x,$$

where

$$\Delta x = \frac{a}{n}, \qquad x_{\mathrm{i}+\frac{1}{2}} = \left(i+\frac{1}{2}\right)\Delta x.$$

Serial Implementation

```
1 const double dx = a/(double)n;
2 double integral = 0.0;
3
4 for (int i = 0; i < n; i++) {
5   const double xip12 = dx*((double)i + 0.5);
6   const double dI = BlackBoxFunction(xip12)*dx;
7
8   integral += dI;
9 }
```


Unprotected Race Condition

```
1 const double dx = a/(double)n;
2 double integral = 0.0;
3 #pragma omp parallel for
4 for (int i = 0; i < n; i++) {
5   const double xip12 = dx*((double)i + 0.5);
6   const double dI = BlackBoxFunction(xip12)*dx;
7
8   integral += dI;
9 }
```

Excessive Use of Mutexes

```
1 const double dx = a/(double)n;
2 double integral = 0.0;
3 #pragma omp parallel for
4 for (int i = 0; i < n; i++) {
5   const double xip12 = dx*((double)i + 0.5);
6   const double dI = BlackBoxFunction(xip12)*dx;
7 #pragma omp atomic
8   integral += dI;
9 }
```

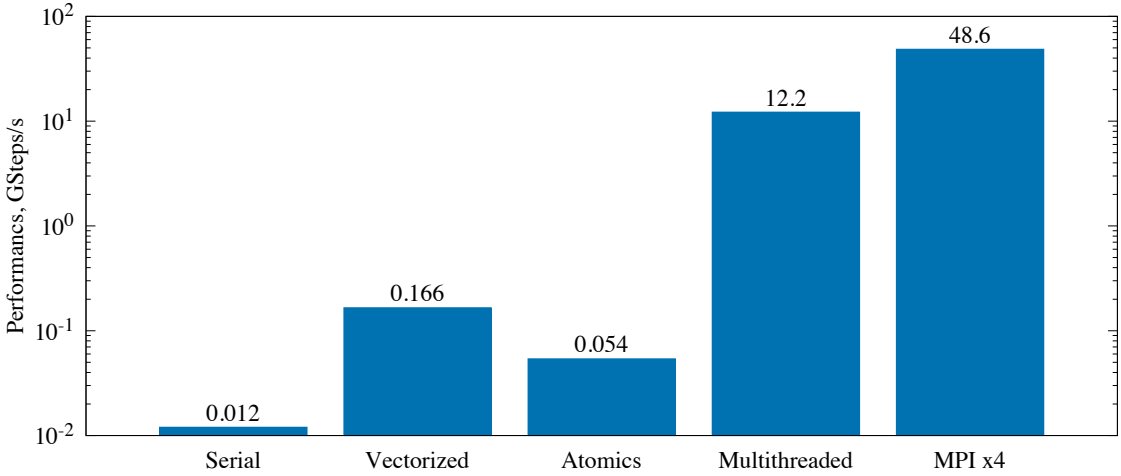

Built-in reduction

```
1 const double dx = a/(double)n;
2 double integral = 0.0;
3 #pragma omp parallel for reduction(+: integral)
4 for (int i = 0; i < n; i++) {
5   const double xip12 = dx*((double)i + 0.5);
6   const double dI = BlackBoxFunction(xip12)*dx;
7
8   integral += dI;
9 }
```

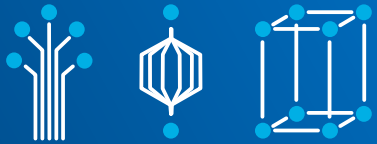

Reduction with Thread-Private Storage

```
1  const double dx = a/(double)n;
2  double integral = 0.0;
3  #pragma omp parallel
4  {
5    double integral_th = 0.0;
6  #pragma omp for
7  for (int i = 0; i < n; i++) {
8      const double xip12 = dx*((double)i + 0.5);
9      const double dI = BlackBoxFunction(xip12)*dx;
10     integral_th += dI;
11   }
12 #pragma omp atomic
13   integral += integral_th;
14 }
```


Performance



§9. Learn more



OpenMP Concepts and Constructs

`#pragma omp parallel` – create threads

`#pragma omp for` – process loop with threads

`#pragma omp task/taskyield` – asynchronous tasks

`#pragma omp critical/atomic` – mutexes

`#pragma omp barrier/taskwait` – synchronization points

`#pragma omp sections/single` – blocks of code for individual threads

`#pragma omp flush` – enforce memory consistency

`#pragma omp ordered` – partial loop serialization

`OMP_*` – environment variables, `omp_*()` – functions

Click construct names for links to the OpenMP reference from the LLNL