New Developments in OpenMP

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General Interest Seminar

OpenMP overview

OpenMP: An API for Writing Multithreaded Applications

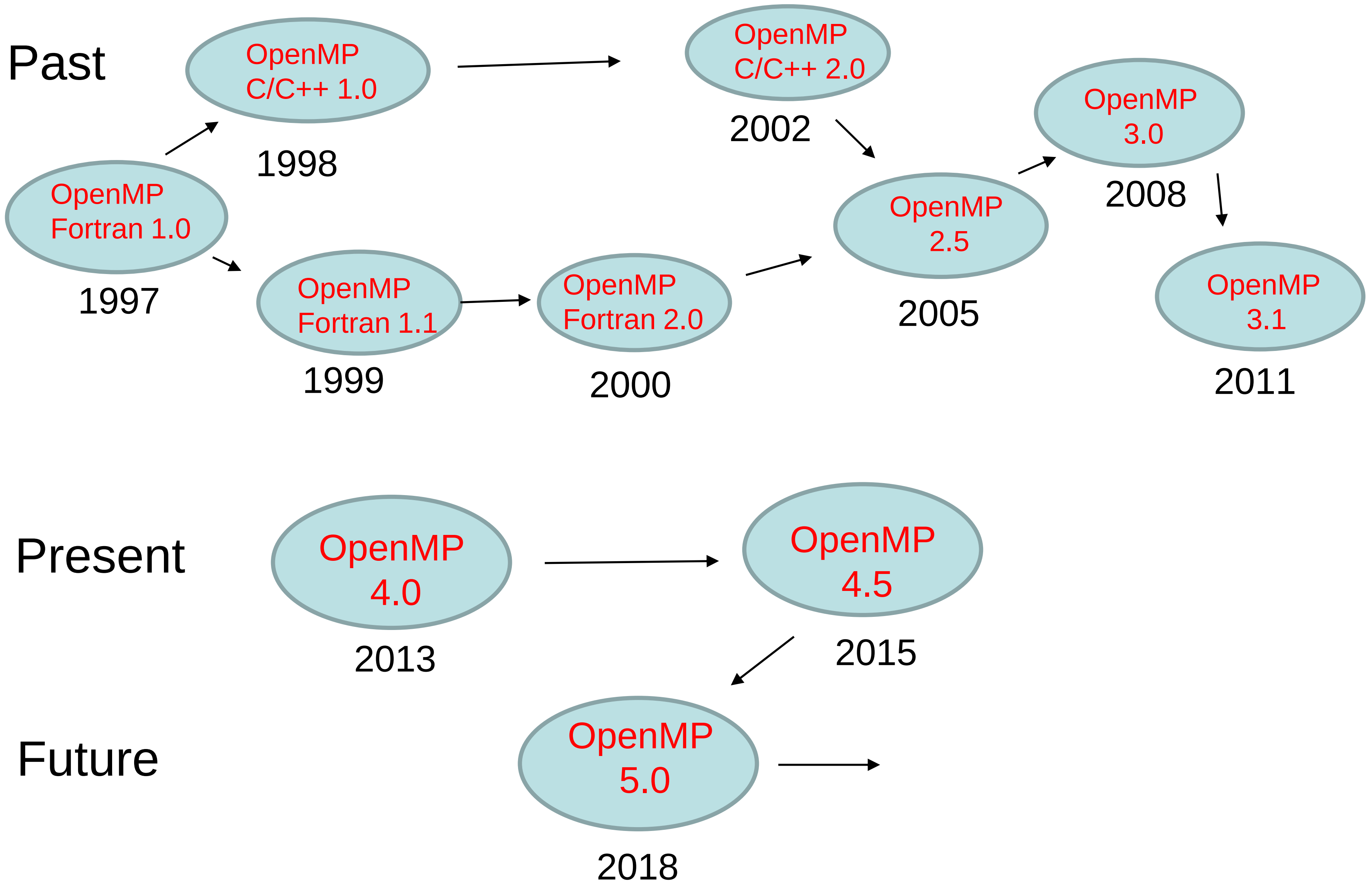
§ A set of compiler directives, library routines, and environment variables for parallel application programming

§ Greatly simplifies writing multi-threaded (MT) programs in Fortran, C and C++

§ Ease of Use: Provide capability to incrementally parallelize a serial program, unlike message-passing libraries which typically require an all or nothing approach

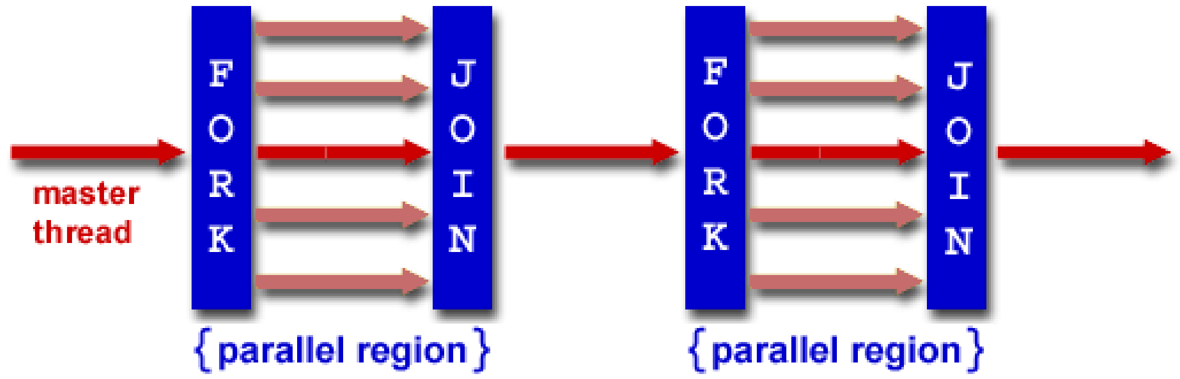
§ Standardizes established SMP practice + vectorization and heterogeneous device programming

OpenMP Brief History



OpenMP: Fork-Join Model

- OpenMP uses the fork-join model of parallel execution:



FORK: the master thread then creates a ***team*** of parallel threads
The statements in the program that are enclosed by the parallel region construct are then executed in parallel among the various team threads

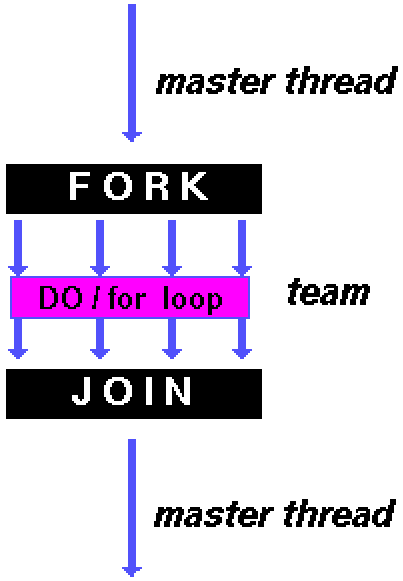
JOIN: When the team threads complete the statements in the parallel region construct, they synchronize and terminate, leaving only the master thread

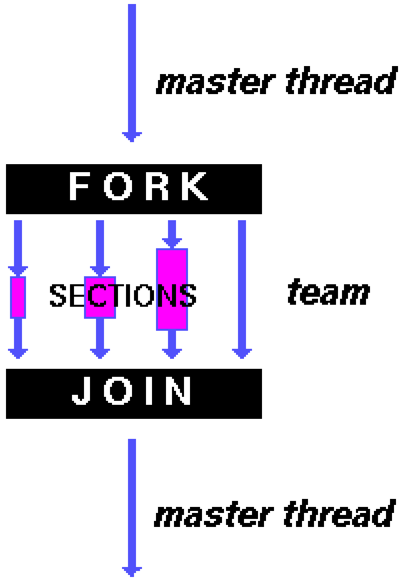
Types of Work-Sharing Constructs (Past):

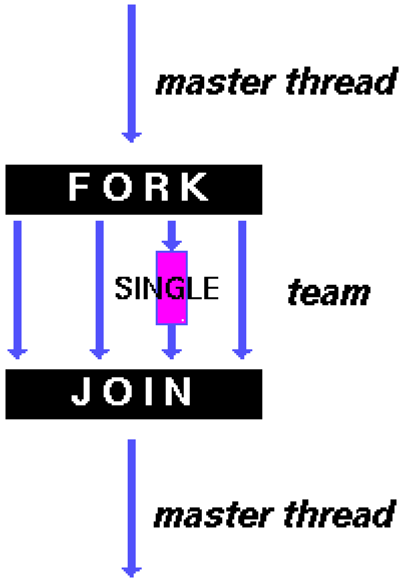
DO / for - shares iterations of a loop across the team. Represents a type of "data parallelism".

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







Loop Parallelism

Sequential code

```
for(i=0;I<N;i++)   { a[i] = a[i] + b[i];}
```

OpenMP parallel region

```
#pragma omp parallel
{
            int id, i, Nthrds, istart, iend;
            id = omp_get_thread_num();
            Nthrds = omp_get_num_threads();
            istart = id * N / Nthrds;
            iend = (id+1) * N / Nthrds;
            for(i=istart;I<iend;i++)   { a[i] = a[i] + b[i];}
}
```

OpenMP parallel region and a work-sharing for-construct

```
#pragma omp parallel
#pragma omp for schedule(static)
            for(i=0;I<N;i++)   { a[i] = a[i] + b[i];}
```

The OpenMP Common Core (Past)

OpenMP pragma, function, or clause	Concepts
#pragma omp parallel	Parallel region, teams of threads
int omp_get_thread_num() int omp_get_num_threads()	Number of threads, thread ID
double omp_get_wtime()	Walltime, speedup measure
#pragma omp barrier #pragma omp critica	Synchronization
#pragma omp for #pragma omp parallel for	Worksharing, parallel loops
reduction(op:list)	Reduction
schedule(dynamic [,chunk]) schedule (static [,chunk])	Loop schedules
private(list), firstprivate(list), shared(list)	Data environment
nowait	Disable implied barrier

Not all programs have simple loops OpenMP can parallelize

• Consider a program to traverse a linked list:

```
p=head;
while (p) {
        processwork(p);
        p = p->next;
}
```

• OpenMP can only parallelize loops in the basic standard form with loop counts known at runtime

Example: Fibonacci numbers

```
int fib (int n)
{
    int x,y;
    if (n < 2) return n;

    x = fib(n-1);
    y = fib (n-2);
    return (x+y);
}

int main()
{
    int NW = 1000;
    fib(NW);
}
```

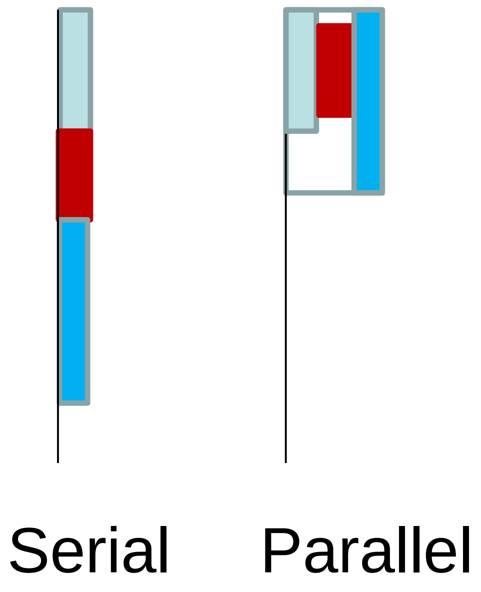
- Fn = Fn-1 + Fn-2
- Inefficient O(n2) recursive implementation!

What are tasks?

- Tasks are independent units of work

- Tasks are composed of:
  - code to execute
  - data to compute with

- Threads are assigned to perform the work of each task.
  - The thread that encounters the task construct may execute the task immediately.
  - The threads may defer execution until later



Task constructs in OpenMP

- The task construct was added to support irregular programs:
  - While loops or loops whose iteration limits are not known at compiler time.
  - Recursive algorithms
  - divide and conquer problems.

- The task construct has expanded over the years with new features to support irregular problems with tasks in each new release of OpenMP

#pragma omp task

- Creates a new task, Task added to task queue
- Available thread picks next task from queue to execute

#pragma omp taskwait

- Acts like barrier
- Waits until all child tasks have finished

OpenMP 4.x

- OpenMP has been significantly modernized since the OpenMP 4.0 (July 2013) and OpenMP 4.5 (Nov 2015) specification releases.
- Major additions include: SIMD, task dependencies, task groups, thread affinity, user defined reductions, taskloop, doacross.
- Target device support was first introduced in OpenMP 4.0 and was the focus for enhancement for OpenMP 4.5.

Task Groups   Task Dependencies   Taskloop   Task Priority

Thread Affinity   SIMD   Target Device Support

Doacross   Fortran 2003 Support

OpenMP 4.0 Major Additions

- Task dependences and task groups
- SIMD constructs
- Device constructs
- Thread affinity control
- User-defined reductions
- Initial support for Fortran 2003
- Support for array sections (including in C and C++)
- Sequentially consistent atomics
- Display of initial OpenMP internal control variables

OpenMP 4.5 Focused on Device Support

- Unstructured data mapping
- Asynchronous execution
- Scalar variables are firstprivate by default
- Improvements for C/C++ array sections
- Device runtime routines: allocation, copy, etc.
- Clauses to support device pointers
- Ability to map structure elements
- New combined constructs
- New way to map global variables (link)

OpenMP 4.5 Other New Features

- Many clarifications and minor enhancements
  - SIMD extensions
  - Addition of schedule modifiers: simd, monotonic, nonmonotonic
  - Clarifications of thread affinity policies
  - Support for if clause on combined/composite constructs
  - Reductions for C/C++ arrays
  - Runtime routines to support affinity
- Support for doacross loops
- Divide loop into tasks with taskloop construct
- Task priorities

OpenMP Programming Model

- Directive-based programming model:

  - Multi-level parallelism supported (cpus, threads, SIMD)
  - Task-based is the modern approach to parallelism
  - High-level access to parallelism

- Hybrid MPI/OpenMP
  - Running on devices such as CPUs and GPUs.

The task construct (OpenMP 4.5)

#pragma omp task *[clause[[,]clause]...]*
        structured-block

Generates an explicit task

where *clause* is one of the following:

Task consists of
  Code to execute
  Data environment

if(*[* **task :***]scalar-expression***)**
untied
default(shared | none)
private(*list***)**
firstprivate(*list***)**
shared(*list***)**
final(scalar-expression)
mergeable
depend(*dependence-type* **:** *list***)**
priority(*priority-value***)**

#pragma omp taskgroup

#pragma omp taskloop

#pragma omp taskyield

Parallel Fibonacci

```
int fib (int n)
{
    int x,y;
    if (n < 2) return n;

#pragma omp task shared(x)
    x = fib(n-1);
#pragma omp task shared(y)
    y = fib (n-2);
#pragma omp taskwait
    return (x+y);
}

int main()
{ int NW = 1000;
    #pragma omp parallel
    {
        #pragma omp master
            fib(NW);
    }
}
```

- Binary tree of tasks
- Traversed using a recursive function
- A task cannot complete until all tasks below it in the tree are complete (enforced with taskwait)
- **x,y** are local, and so by default they are private to current task
  – must be shared on child tasks so they don't create their own firstprivate copies at this level!

Linked lists with tasks

```
#pragma omp parallel
{
    #pragma omp single
    {
        p=head;
        while (p) {
            #pragma omp task firstprivate(p)
                    processwork(p);
            p = p->next;
        }
    }
}
```

Creates a task with its own copy of “p” initialized to the value of “p” when the task is defined

taskloop Example: saxpy Operation

```
for (i = 0; i<SIZE; i+=1)
   { A[i]=A[i]*B[i]*S;
}
```

blocking

```
for (i = 0; i<SIZE; i+=TS) {
   UB = SIZE < (i+TS) ? SIZE : i+TS;
   for (ii=i; ii<UB; ii++) {
      A[ii]=A[ii]*B[ii]*S;
   }
}
```

```
for (i = 0; i<SIZE; i+=TS) {
   UB = SIZE < (i+TS) ? SIZE : i+TS;
   #pragma omp task private(ii) \
      firstprivate(i,UB) shared(S,A,B)
   for (ii=i; ii<UB; ii++) {
      A[ii]=A[ii]*B[ii]*S;
   }
}
```

taskloop

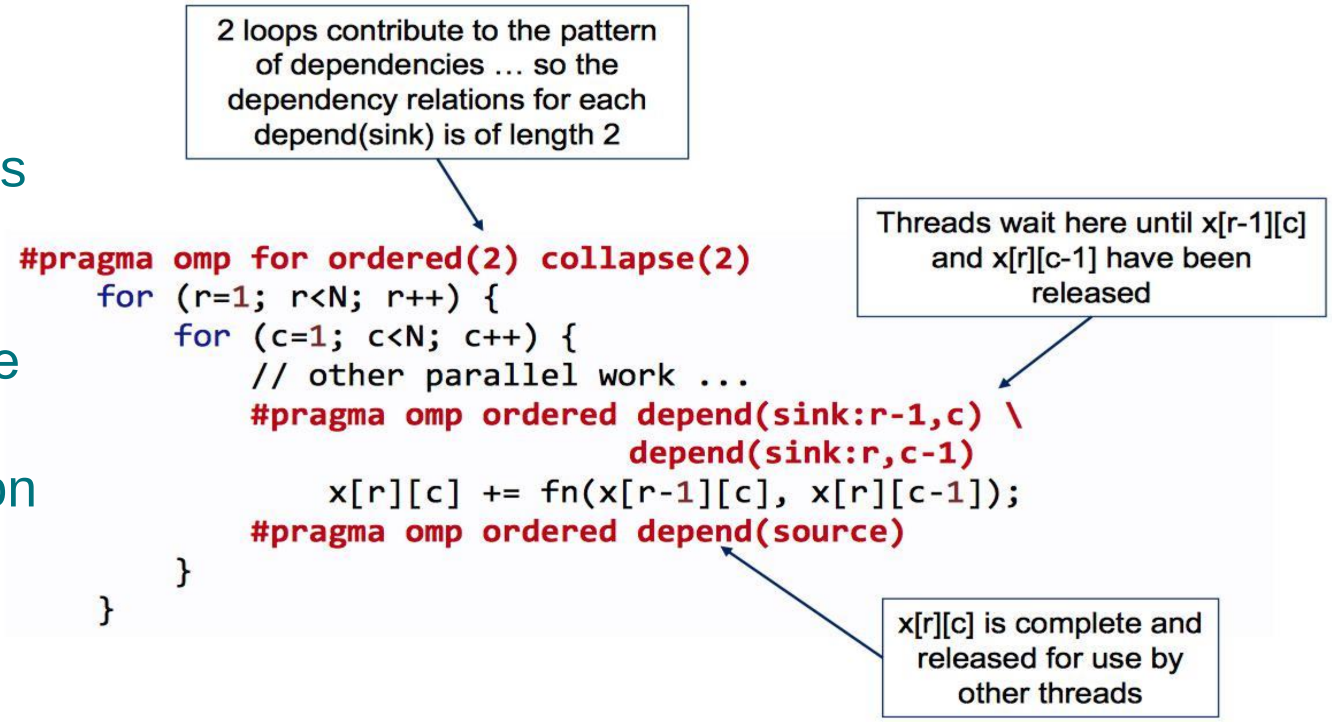
```
#pragma omp taskloop grainsize(TS)
for (i = 0; i<SIZE; i+=1) {
   A[i]=A[i]*B[i]*S;
}
```

- Manual transformation is cumbersome and error prone
- Applying blocking techniques for large loops can be tricky
- `taskloop`: improved programmability

Parallelizing doacross Loop

- Help with cross-iteration dependencies

- Use “ordered” clause to ensure structured blocks are executed on lexical order



2 loops contribute to the pattern of dependencies … so the dependency relations for each depend(sink) is of length 2

```
#pragma omp for ordered(2) collapse(2)
    for (r=1; r<N; r++) {
        for (c=1; c<N; c++) {
            // other parallel work ...
            #pragma omp ordered depend(sink:r-1,c) \
                                depend(sink:r,c-1)
                x[r][c] += fn(x[r-1][c], x[r][c-1]);
            #pragma omp ordered depend(source)
        }
    }
```

Threads wait here until x[r-1][c] and x[r][c-1] have been released

x[r][c] is complete and released for use by other threads

Vectorization?

Vectorization is an on-node, in-core way of exploiting data level parallelism in programs by applying the same operation to multiple data items in parallel.

```
DO I= 1, N
   Z(I) = X(I) + Y(I)
ENDDO
```

• Requires transforming a program so that a single instruction can launch many operations on different data

• Applies most commonly to array operations in loops

SIMD loop construct in OpenMP

- SIMD=single instruction applies the same operation to multiple data concurrently

- vectorization = processing multiple elements of an array at the same time.

- OpenMP can enable vectorization of both serial as well as parallelized loops

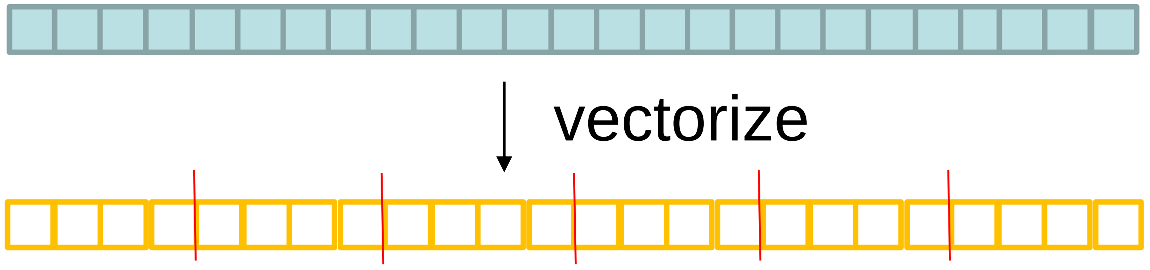
- OpenMP uses SIMD constructs.

```
#progma omp simd [clause [ [,] clause], …]
  for-loops
```

Example

```
void sprod(float *a, float *b, int n)
{
   float sum=0.0;

   #pragma omp simd reduction(+:sum)
      for (int k=0; k<n; k++)
         sum += a[k] * b[k];
      return sum;
}
```



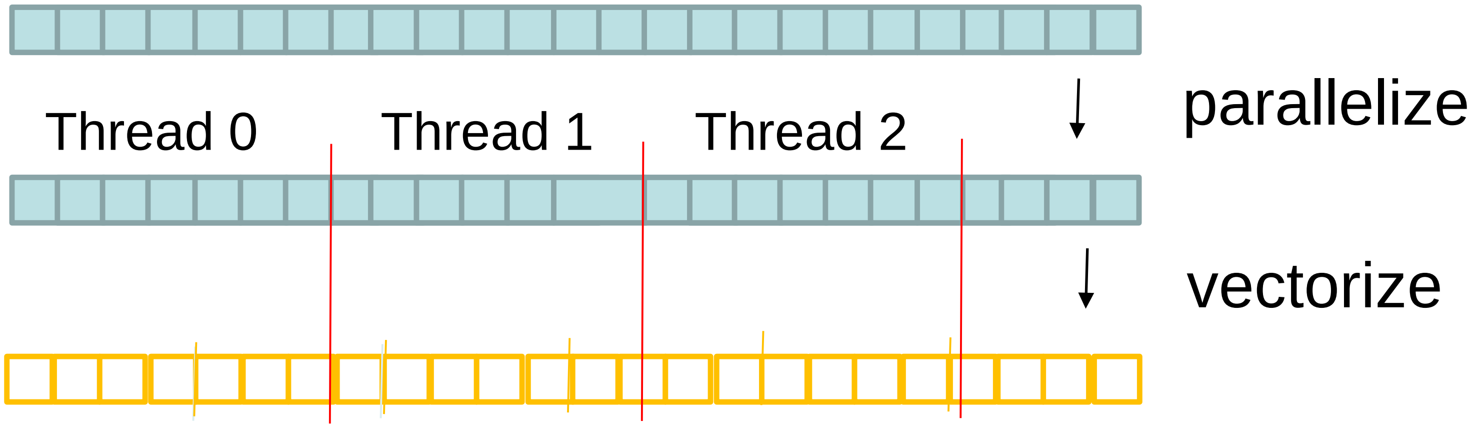
- Vectorize a loop nest is to cut loop into chunks that fit a SIMD vector register
- No parallelization of the loop body

SIMD Worksharing Construct

```
#progma omp for simd [clause [ [,] clause], …]
      for-loops
```

```
void sprod(float *a, float *b, int n){
   float sum=0.0;
#pragma omp for simd reduction(+:sum)
      for (int k=0; k<n; k++)
        sum += a[k] * b[k];
      return sum;
}
```

- Distribute a loop's iteration across a thread team
- Subdivide loop chunks to fit a SIMD vector register



Example: loops

```
#include <stdio.h>
#define N 10000
int main()
{
    long long d1=0;
    double a[N], b[N], c[N], d2=0.0;

    for (int i=0;i<N;i++)
        d1+=i*(N+1-i);

    for (int i=0; i<N;i++) {
            a[i]=i;
            b[i]=N+1-i;
    }

   for (int i=0; i<N; i++)
        d2+=a[i]*b[i];

   printf("result1 = %ld\nresult2 = %.2lf\n", d1, d2);
}
```

OpenMP SIMD Loop Example

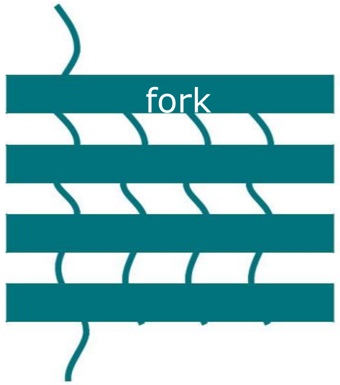
```
#include <stdio.h>
#include <omp.h>

#define N 10000
int main()
{
   long long d1=0;
   double a[N], b[N], c[N], d2=0.0;
   #pragma omp simd reduction(+:d1)
   for (int i=0;i<N;i++)
      d1+=i*(N+1-i);
   #pragma omp simd
      for (int i=0; i<N;i++) {
         a[i]=i;
         b[i]=N+1-i;
   }
   #pragma omp parallel for simd reduction(+:d2)
      for (int i=0; i<N; i++)
         d2+=a[i]*b[i];
   printf("result1 = %ld\nresult2 = %.2lf\n", d1, d2);
}
```

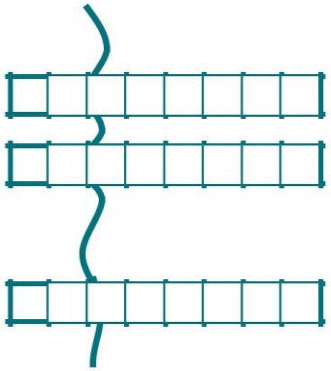
Existing Parallel Loop Constructs

- Existing parallel loop constructs are tightly bound to execution model:

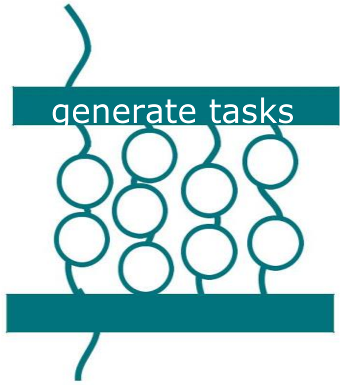
```
#pragma omp for
for (i=0; i<N;++i) {…}
```



```
#pragma omp simd
for (i=0; i<N;++i) {…}
```



```
#pragma omp taskloop
for (i=0; i<N;++i) {…}
```



OpenMP for Accelerators: host/device Model

- **Host-centric: the execution of an OpenMP program starts on the *host device* and it may offload *target regions* to *target devices***

  - In principle, a target region also begins as a single thread of execution: when a target construct is encountered, the target region is executed by the implicit device thread and the encountering thread/task [on the host] waits at the construct until the execution of the region completes

  - If a target device is not present, or not supported, or not available, the target region is executed by the host device

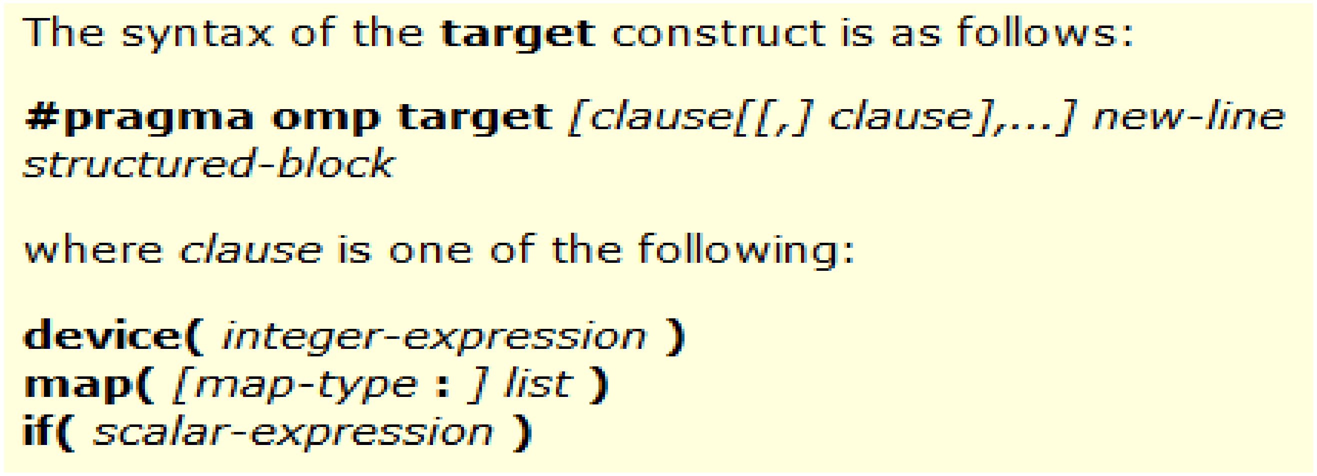
  - If a construct creates a *data environment*, the data environment is created at the time the construct is encountered

- **When an OpenMP program begins, each device has an initial *device data environment***

- **Directives accepting data-mapping attribute clauses determine how an *original* variable is mapped to a *corresponding* variable in a device data environment**
  - original: the variable on the host
  - corresponding: the variable on the device
  - the corresponding variable in the device data environment may share storage with the original variable

Device Target constructs

- **Creates a device data environment for the extent of the region**
  - when a target data construct is encountered, a new device data environment is created, and the encountering task executes the target data region
  - when an if clause is present and the if-expression evaluates to false, the device is the host



The syntax of the **target** construct is as follows:

#pragma omp target *[clause[[,] clause],...] new-line*
structured-block

where *clause* is one of the following:

device(*integer-expression* **)**
map(*[map-type* **:** *] list* **)**
if(*scalar-expression* **)**

More Directives and Functions for Devices

omp target data: Creates a device data environment and execute the construct on the same device. The target construct specifies that the region is executed by a device and the encountering task waits for the device to complete the target region

omp target update: Makes the corresponding list items in the device data environment consistent with their original list items

omp distribute: distributes a loop over the teams in the league

omp declare target: marks function(s) that can be called on the device

omp teams: Creates a league of thread teams where the master thread of each team executes the region, associated with num_teams and num_threads clause

omp get team num()
omp get team size()
omp get num devices()
omp_get_default_device()

Example

```
#pragma omp target data device(0) map(alloc:tmp[:N]) map(to:input[:N)) map(from:res)
{
    #pragma omp target device(0)
    #pragma omp parallel for
    for (i=0; i<N; i++)
      tmp[i] = some_computation(input[i], i);

    update_input_array_on_the_host(input);

    #pragma omp target update device(0) to(input[:N])

    #pragma omp target device(0)
    #pragma omp parallel for reduction(+:res)
    for (i=0; i<N; i++)
      res += final_computation(input[i], tmp[i], i)
}
```

OpenMP 5.0 updates: https://www.openmp.org

OPENMP 5.0 IS A MAJOR LEAP FORWARD

Full Support for Accelerators and New Tool APIs

- **Full support for accelerator devices**. OpenMP now has full support for accelerator devices, including mechanisms to require unified shared memory between the host system and coprocessor devices, the ability to use device-specific function implementations, better control of implicit data mappings, and the ability to override device offload at runtime. In addition, it supports reverse offload, implicit function generation, and the ability to copy object-oriented data structures easily.

- **Improved debugging and performance analysis.** Two new tool interfaces enable the development of third party tools to support intuitive debugging and deep performance analysis.

OpenMP 5.0 updates

- **Support for the latest versions of C, C++, and Fortran.** OpenMP now supports important features of Fortran 2008, C11, and C++17.

- **Support for a fully descriptive loop construct.** The loop construct lets the compiler optimize a loop while not forcing any specific implementation. This construct allows the compiler more freedom to choose a good implementation for a specific target than do other OpenMP directives.

- **Multilevel memory systems.** Memory allocation mechanisms are available that place data in different kinds of memories, such as high-bandwidth memory. New OpenMP features also make it easier to deal with the NUMA-ness of modern HPC systems.

- **Enhanced portability.** The declare variant directive and a new meta-directive allow programmers to improve performance portability by adapting OpenMP pragmas and user code at compile time.

OpenMP 5.0: Some Main Features

Detachable Tasks

Task Reductions

Memory Allocators

Tools APIs: OMPD,OMPT

C++14 and C++17 support

Dependence Objects

Unified Shared Memory

loop Construct

Fortran 2008 support

Collapse non-rect. Loops

Multi-level Parallelism

Task-to-data Affinity

Data Serialization for Offload

Parallel Scan

Meta-directives

Display Affinity

“Reverse Offloading”

User Defined Function Variants

Improved Task Dependences

Task Reductions

- Task reductions extend traditional reductions to arbitrary task graphs
- Extend the existing task and taskgroup constructs
- Also work with the taskloop construct

```
int res = 0;
node_t* node = NULL;
...
#pragma omp parallel
{
   #pragma omp single
   {
      #pragma omp taskgroup task_reduction(+: res)
      {
        while (node) {
           #pragma omp task in_reduction(+: res) \
                            firstprivate(node)
           {
              res += node->value;
           }
           node = node->next;
        }
      }
   }
}
```

Memory Allocators

Allocator name	Storage selection intent
omp_default_mem_alloc	use default storage
omp_large_cap_mem_alloc	use storage with large capacity
omp_const_mem_alloc	use storage optimized for read-only variables
omp_high_bw_mem_alloc	use storage with high bandwidth
omp_low_lat_mem_alloc	use storage with low latency
omp_cgroup_mem_alloc	use storage close to all threads in the contention group of the thread requesting the allocation
omp_pteam_mem_alloc	use storage that is close to all threads in the same parallel region of the thread requesting the allocation
omp_thread_local_mem_alloc	use storage that is close to the thread requesting the allocation

Example: Using Memory Allocators

```
void allocator_example(omp_allocator_t *my_allocator) {
    int a[M], b[N], c;
    #pragma omp allocate(a) allocator(omp_high_bw_mem_alloc)
    #pragma omp allocate(b) // controlled by OMP_ALLOCATOR and/or omp_set_default_allocator
    double *p = (double *) ompmalloc(N*M*sizeof(*p));alloc(N*M*sizeof(*p), my_allocator);

    #pragma omp parallel private(a) allocate(my_allocator:a)
    {
        some_parallel_code();
    }

    #pragma omp target firstprivate(c) allocate(omp_const_mem_alloc:c)  // on target; must be compile-time expr
    {
         #pragma omp parallel private(a) allocate(omp_high_bw_mem_alloc:a)
          {
              some_other_parallel_code();
           }
    }

    omp_free(p);
```

Requires Unified Shared Memory

- Single address space over CPU and GPU memories
- Data migrated between CPU and GPU memories transparently to the application - no need to explicitly copy data

```
// No data directive needed.
#pragma omp requires unified_shared_memory
for (k=0; k < NTIMES; k++)
{
    #pragma omp target teams distribute parallel for
        for (j=0; j<ARRAY_SIZE; j++) {
            a[j] = b[j] + scalar * c[j];
        }
}
```

OpenMP Compilers and Tools

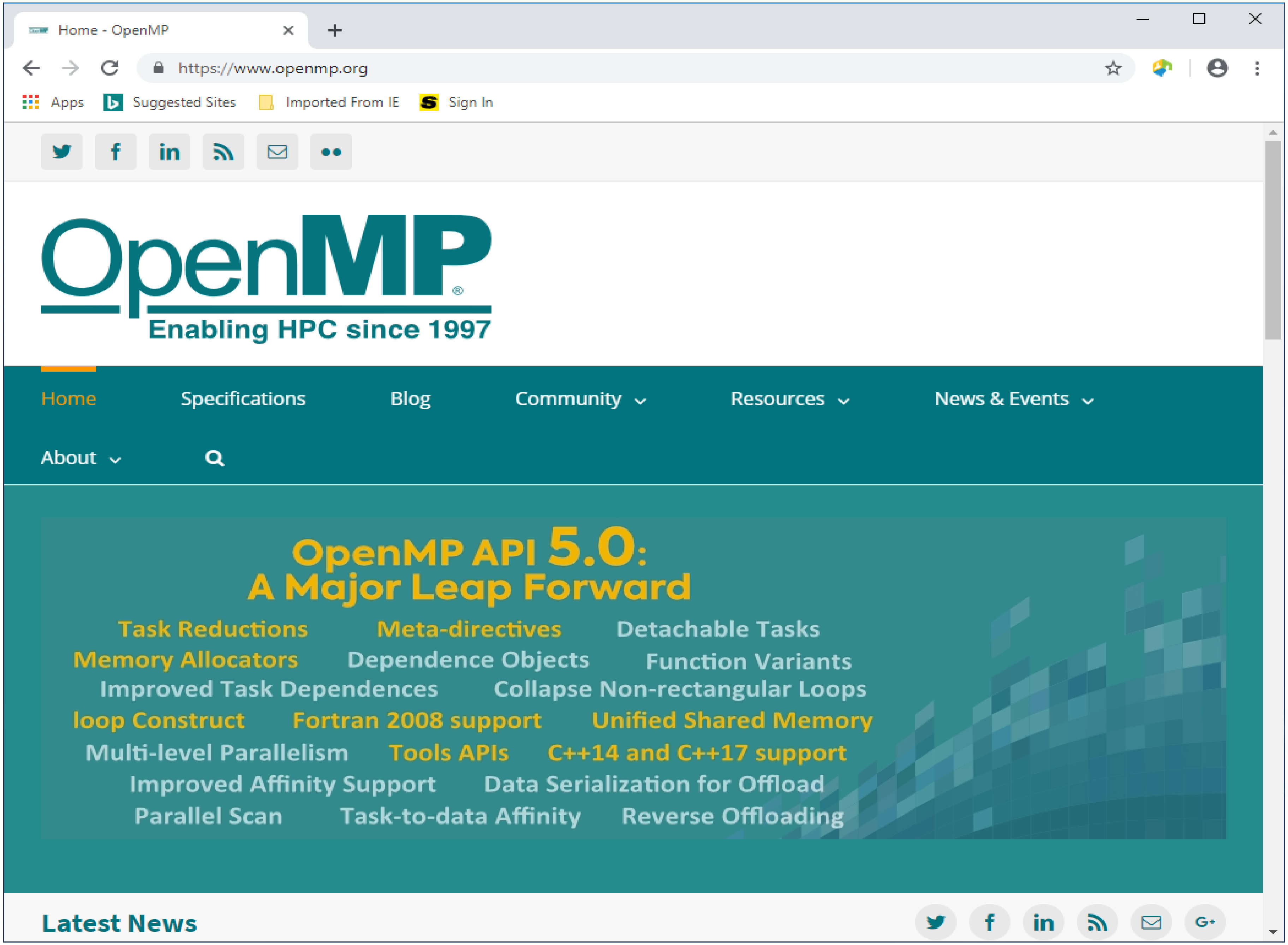
Vendor	Compiler/Language	Information
GNU	GCC C/C++/Frotran	Free and open source From GCC 6.1, OpenMP 4.5 is fully supported for C and C++. Compile with -fopenmp to enable OpenMP.
Intel	C/C++/Frotran	OpenMP 4.5 C/C++/Fortran supported in version 17.0, 18.0, and 19.0 compilers Compile with -qopenmp on Linux

https://www.openmp.org/resources/openmp-compilers-tools/

OpenMP 5.0:

GNU/GCC 9, 2019, only partial support will be ready.

Intel: upcoming versions



OpenMP API 5.0:
A Major Leap Forward

Task Reductions Meta-directives Detachable Tasks
Memory Allocators Dependence Objects Function Variants
Improved Task Dependences Collapse Non-rectangular Loops
loop Construct Fortran 2008 support Unified Shared Memory
Multi-level Parallelism Tools APIs C++14 and C++17 support
Improved Affinity Support Data Serialization for Offload
Parallel Scan Task-to-data Affinity Reverse Offloading

Latest News

Resources

OpenMP specifications for C/C++ and Fortran, http://www.openmp.org/

https://www2.cisl.ucar.edu/sites/default/files/MultiCore8_HelenHe.pdf

https://www.openmp.org/wp-content/uploads/OpenMP4.0.0.Examples.pdf

https://www.openmp.org/wp-content/uploads/openmp-examples-4.5.0.pdf

https://ukopenmpusers.co.uk/wp-content/uploads/uk-openmp-users-2018-OpenMP45Tutorial_new.pdf