Source codes for OpenMP 5.0.0 Examples can be downloaded from github.

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The OpenMP Examples document has been updated with new features found in the OpenMP 5.0 Specification. The additional examples and updates are referenced in the Document Revision History of the Appendix, Section A.1 on page 388.

Text describing an example with a 5.0 feature specifically states that the feature support begins in the OpenMP 5.0 Specification. Also, an `omp_5.0` keyword has been added to metadata in the source code. These distinctions are presented to remind readers that a 5.0 compliant OpenMP implementation is necessary to use these features in codes.

Examples for most of the 5.0 features are included in this document, and incremental releases will become available as more feature examples and updates are submitted, and approved by the OpenMP Examples Subcommittee.

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Introduction

This collection of programming examples supplements the OpenMP API for Shared Memory Parallelization specifications, and is not part of the formal specifications. It assumes familiarity with the OpenMP specifications, and shares the typographical conventions used in that document.

The OpenMP API specification provides a model for parallel programming that is portable across shared memory architectures from different vendors. Compilers from numerous vendors support the OpenMP API.

The directives, library routines, and environment variables demonstrated in this document allow users to create and manage parallel programs while permitting portability. The directives extend the C, C++ and Fortran base languages with single program multiple data (SPMD) constructs, tasking constructs, device constructs, worksharing constructs, and synchronization constructs, and they provide support for sharing and privatizing data. The functionality to control the runtime environment is provided by library routines and environment variables. Compilers that support the OpenMP API often include a command line option to the compiler that activates and allows interpretation of all OpenMP directives.

The latest source codes for OpenMP Examples can be downloaded from the sources directory at https://github.com/OpenMP/Examples. The codes for this OpenMP 5.0.0 Examples document have the tag v5.0.0.

Complete information about the OpenMP API and a list of the compilers that support the OpenMP API can be found at the OpenMP.org web site

http://www.openmp.org
The following are examples of the OpenMP API directives, constructs, and routines.

A statement following a directive is compound only when necessary, and a non-compound statement is indented with respect to a directive preceding it.

Each example is labeled as `ename.seqno.ext`, where `ename` is the example name, `seqno` is the sequence number in a section, and `ext` is the source file extension to indicate the code type and source form. `ext` is one of the following:

- `c` – C code,
- `cpp` – C++ code,
- `f` – Fortran code in fixed form, and
- `f90` – Fortran code in free form.
Parallel Execution

A single thread, the *initial thread*, begins sequential execution of an OpenMP enabled program, as if the whole program is in an implicit parallel region consisting of an implicit task executed by the *initial thread*.

A *parallel* construct encloses code, forming a parallel region. An *initial thread* encountering a *parallel* region forks (creates) a team of threads at the beginning of the *parallel* region, and joins them (removes from execution) at the end of the region. The initial thread becomes the master thread of the team in a *parallel* region with a *thread* number equal to zero, the other threads are numbered from 1 to number of threads minus 1. A team may be comprised of just a single thread.

Each thread of a team is assigned an implicit task consisting of code within the parallel region. The task that creates a parallel region is suspended while the tasks of the team are executed. A thread is tied to its task; that is, only the thread assigned to the task can execute that task. After completion of the *parallel* region, the master thread resumes execution of the generating task.

Any task within a *parallel* region is allowed to encounter another *parallel* region to form a nested *parallel* region. The parallelism of a nested *parallel* region (whether it forks additional threads, or is executed serially by the encountering task) can be controlled by the OMP_NESTED environment variable or the *omp_set_nested()* API routine with arguments indicating true or false.

The number of threads of a *parallel* region can be set by the OMP_NUM_THREADS environment variable, the *omp_set_num_threads()* routine, or on the *parallel* directive with the num_threads clause. The routine overrides the environment variable, and the clause overrides all. Use the OMP_DYNAMIC or the *omp_set_dynamic()* function to specify that the OpenMP implementation dynamically adjust the number of threads for *parallel* regions. The default setting for dynamic adjustment is implementation defined. When dynamic adjustment is on and the number of threads is specified, the number of threads becomes an upper limit for the number of threads to be provided by the OpenMP runtime.
WORKSHARING CONSTRUCTS

A worksharing construct distributes the execution of the associated region among the members of the team that encounter it. There is an implied barrier at the end of the worksharing region (there is no barrier at the beginning). The worksharing constructs are:

- loop constructs: **for** and **do**
- **sections**
- **single**
- **workshare**

The **for** and **do** constructs (loop constructs) create a region consisting of a loop. A loop controlled by a loop construct is called an *associated* loop. Nested loops can form a single region when the **collapse** clause (with an integer argument) designates the number of *associated* loops to be executed in parallel, by forming a "single iteration space" for the specified number of nested loops. The **ordered** clause can also control multiple associated loops.

An associated loop must adhere to a "canonical form" (specified in the *Canonical Loop Form* of the OpenMP Specifications document) which allows the iteration count (of all associated loops) to be computed before the (outermost) loop is executed. Most common loops comply with the canonical form, including C++ iterators.

A **single** construct forms a region in which only one thread (any one of the team) executes the region. The other threads wait at the implied barrier at the end, unless the **nowait** clause is specified.

The **sections** construct forms a region that contains one or more structured blocks. Each block of a **sections** directive is constructed with a **section** construct, and executed once by one of the threads (any one) in the team. (If only one block is formed in the region, the **section** construct, which is used to separate blocks, is not required.) The other threads wait at the implied barrier at the end, unless the **nowait** clause is specified.

The **workshare** construct is a Fortran feature that consists of a region with a single structure block (section of code). Statements in the **workshare** region are divided into units of work, and executed (once) by threads of the team.

MASTER CONSTRUCT

The **master** construct is not a worksharing construct. The master region is executed only by the master thread. There is no implicit barrier (and flush) at the end of the **master** region; hence the other threads of the team continue execution beyond code statements beyond the **master** region.
1.1 A Simple Parallel Loop

The following example demonstrates how to parallelize a simple loop using the parallel loop construct. The loop iteration variable is private by default, so it is not necessary to specify it explicitly in a `private` clause.

```c
void simple(int n, float *a, float *b)
{
    int i;

    #pragma omp parallel for
    for (i=1; i<n; i++) /* i is private by default */
        b[i] = (a[i] + a[i-1]) / 2.0;
}
```

```fortran
SUBROUTINE SIMPLE(N, A, B)
    INTEGER I, N
    REAL B(N), A(N)

    !$OMP PARALLEL DO !I is private by default
    DO I=2,N
        B(I) = (A(I) + A(I-1)) / 2.0
    ENDDO
    !$OMP END PARALLEL DO
END SUBROUTINE SIMPLE
```
### 1.2 The parallel Construct

The `parallel` construct can be used in coarse-grain parallel programs. In the following example, each thread in the `parallel` region decides what part of the global array `x` to work on, based on the thread number:

```c
#include <omp.h>

void subdomain(float *x, int istart, int ipoints)
{
    int i;
    for (i = 0; i < ipoints; i++)
        x[istart+i] = 123.456;
}

void sub(float *x, int npoints)
{
    int iam, nt, ipoints, istart;
    #pragma omp parallel default(shared) private(iam,nt,ipoints,istart)
    {
        iam = omp_get_thread_num();
        nt = omp_get_num_threads();
        ipoints = npoints / nt;  /* size of partition */
        istart = iam * ipoints;  /* starting array index */
        if (iam == nt-1)  /* last thread may do more */
            ipoints = npoints - istart;
        subdomain(x, istart, ipoints);
    }

int main()
{
    float array[10000];
    sub(array, 10000);
    return 0;
}
```
SUBROUTINE SUBDOMAIN(X, ISTART, IPOINTS)
    INTEGER ISTART, IPOINTS
    REAL X(*)
    INTEGER I
    DO 100 I=1,IPOINTS
    X(ISTART+I) = 123.456
  100 CONTINUE
END SUBROUTINE SUBDOMAIN

SUBROUTINE SUB(X, NPOINTS)
    INCLUDE "omp_lib.h" ! or USE OMP_LIB
    REAL X(*)
    INTEGER NPOINTS
    INTEGER IAM, NT, IPOINTS, ISTART
    !$OMP PARALLEL DEFAULT(PRIVATE) SHARED(X,NPOINTS)
    IAM = OMP_GET_THREAD_NUM()
    NT = OMP_GET_NUM_THREADS()
    IPOINTS = NPOINTS/NT
    ISTART = IAM * IPOINTS
    IF (IAM .EQ. NT-1) THEN
        IPOINTS = NPOINTS - ISTART
    ENDIF
    CALL SUBDOMAIN(X,ISTART,IPOINTS)
    !$OMP END PARALLEL
END SUBROUTINE SUB

PROGRAM PAREXAMPLE
    REAL ARRAY(10000)
    CALL SUB(ARRAY, 10000)
END PROGRAM PAREXAMPLE
1.3 teams Construct on Host

Originally the `teams` construct was created for devices (such as GPUs) for independent executions of a structured block by teams within a league (on SMs). It was only available through offloading with the `target` construct, and the execution of a `teams` region could only be directed to host execution by various means such as `if` and `device` clauses, and the `OMP_TARGET_OFFLOAD` environment variable.

In OpenMP 5.0 the `teams` construct was extended to enable the host to execute a `teams` region (without an associated `target` construct), with anticipation of further affinity and threading controls in future OpenMP releases.

In the example below the `teams` construct is used to create two teams, one to execute single precision code, and the other to execute double precision code. Two teams are required, and the thread limit for each team is set to 1/2 of the number of available processors.

```
C / C++
```

**Example host_teams.1.c**

```
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <omp.h>
#define N 1000

int main(){
  int nteams_required=2, max_thrds, tm_id;
  float sp_x[N], sp_y[N], sp_a=0.0001e0;
  double dp_x[N], dp_y[N], dp_a=0.0001e0;

  // Create 2 teams, each team works in a different precision
  #pragma omp teams num_teams(nteams_required) \
            thread_limit(max_thrds) private(tm_id)
  {
    tm_id = omp_get_team_num();

    if( omp_get_num_teams() != 2 ) //if only getting 1, quit
      { printf("error: Insufficient teams on host, 2 required\n");
        exit(0);
      }

    if(tm_id == 0) // Do Single Precision Work (SAXPY) with this team
      {
        #pragma omp parallel
        {
          #pragma omp for //init
          for(int i=0; i<N; i++) {sp_x[i] = i*0.0001; sp_y[i]=i; }
```

---

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Example host_teams.1.f90

```c++
/*
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 */
```

```fortran
program main
  use omp_lib
  integer :: nteams_required=2, max_thrds, tm_id
  integer,parameter :: N=1000
  real :: sp_x(N), sp_y(N), sp_a=0.0001e0
  double precision :: dp_x(N), dp_y(N), dp_a=0.0001d0
  max_thrds = omp_get_num_procs()/nteams_required
  ! Create 2 teams, each team works in a different precision
  !$omp teams num_teams(nteams_required) thread_limit(max_thrds) private(tm_id)
  tm_id = omp_get_team_num()
  if( omp_get_num_teams() /= 2 ) then    ! if only getting 1, quit
```
stop "error: Insufficient teams on host, 2 required."
endif
if(tm_id == 0) then !! Do Single Precision Work (SAXPY) with this team
  !$omp parallel
  !$omp do !! init
do i = 1,Z
    sp_x(i) = i*0.0001e0
    sp_y(i) = i
  end do
  !$omp do simd simdlen(Z)
do i = 1,Z
    sp_x(i) = sp_a*sp_x(i) + sp_y(i)
  end do
  !$omp end parallel
endif
if(tm_id == 1) then !! Do Double Precision Work (DAXPY) with this team
  !$omp parallel
  !$omp do ?? init
do i = 1,Z
    dp_x(i) = i*0.0001d0
    dp_y(i) = i
  end do
  !$omp do simd simdlen(Z)
do i = 1,Z
    dp_x(i) = dp_a*dp_x(i) + dp_y(i)
  end do
  !$omp end parallel
endif
!$omp end teams
write(*,'("i=",i4," sp|dp= ", e15.7, d25.16 )') N, sp_x(N), dp_x(N)
write(*,'("i=",i4," sp|dp= ", e15.7, d25.16 )') N/2, sp_x(N/2), dp_x(N/2)
!! i=1000 sp|dp=  0.1000000E+04  0.1000000010000000D+04
!! i= 500 sp|dp=  0.5000000E+03  0.5000000050000000D+03
1.4 Controlling the Number of Threads on Multiple Nesting Levels

The following examples demonstrate how to use the `OMP_NUM_THREADS` environment variable to control the number of threads on multiple nesting levels:

---

C / C++

Example nthrs_nesting.1.c

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

int main (void)
{
    omp_set_nested(1);
    omp_set_dynamic(0);
    #pragma omp parallel
    {
        #pragma omp parallel
        {
            #pragma omp single
            {
                /* If OMP_NUM_THREADS=2,3 was set, the following should print:
                 * Inner: num_thds=3
                 * Inner: num_thds=3
                 */
                printf("Inner: num_thds=%d\n", omp_get_num_threads());
            }
        }
        #pragma omp barrier
        omp_set_nested(0);
        #pragma omp parallel
        {
            #pragma omp single
            {
                /* Even if OMP_NUM_THREADS=2,3 was set, the following should print, because nesting is disabled:
                 * Inner: num_thds=1
                 * Inner: num_thds=1
                 */
                printf("Inner: num_thds=%d\n", omp_get_num_threads());
            }
        }
    }
    #pragma omp barrier
    omp_set_nested(0);
    #pragma omp parallel
    {
        #pragma omp single
        {
            /* If nesting is not supported, the following should print:
             * Inner: num_thds=1
             */
            printf("Inner: num_thds=%d\n", omp_get_num_threads());
        }
    }
    #pragma omp barrier
    omp_set_nested(0);
    #pragma omp parallel
    {
        #pragma omp single
        {
            /* If OMP_NUM_THREADS=2,3 was set, the following should print:
             * Inner: num_thds=3
             * Inner: num_thds=3
             */
            printf("Inner: num_thds=%d\n", omp_get_num_threads());
        }
    }
}
```

---
S-38         }
S-39         }
S-40 #pragma omp barrier
S-41 #pragma omp single
S-42 {
S-43         /*
S-44             * If OMP_NUM_THREADS=2,3 was set, the following should print:
S-45             * Outer: num_thds=2
S-46             */
S-47             printf ("Outer: num_thds=%d\n", omp_get_num_threads());
S-48         }
S-49     }
S-50    return 0;
S-51 }

Example nthrs_nesting.1.f

S-1     program icv
S-2     use omp_lib
S-3     call omp_set_nested(.true.)
S-4     call omp_set_dynamic(.false.)
S-5     !$omp parallel
S-6     !$omp parallel
S-7     !$omp single
S-8     ! If OMP_NUM_THREADS=2,3 was set, the following should print:
S-9     ! Inner: num_thds= 3
S-10    ! Inner: num_thds= 3
S-11    ! If nesting is not supported, the following should print:
S-12    ! Inner: num_thds= 1
S-13    ! Inner: num_thds= 1
S-14    print *, "Inner: num_thds=", omp_get_num_threads()
S-15     !$omp end single
S-16     !$omp end parallel
S-17     !$omp barrier
S-18     call omp_set_nested(.false.)
S-19     !$omp parallel
S-20     !$omp single
S-21     ! Even if OMP_NUM_THREADS=2,3 was set, the following should print,
S-22     ! because nesting is disabled:
S-23     ! Inner: num_thds= 1
S-24     ! Inner: num_thds= 1
S-25     print *, "Inner: num_thds=", omp_get_num_threads()
S-26     !$omp end single
S-27     !$omp end parallel
S-28     !$omp barrier
!$omp single

! If OMP_NUM_THREADS=2,3 was set, the following should print:

! Outer: num_thds= 2

print *, "Outer: num_thds=", omp_get_num_threads()

!$omp end single

!$omp end parallel

end
1.5 Interaction Between the num_threads Clause and omp_set_dynamic

The following example demonstrates the num_threads clause and the effect of the omp_set_dynamic routine on it.

The call to the omp_set_dynamic routine with argument 0 in C/C++, or .FALSE. in Fortran, disables the dynamic adjustment of the number of threads in OpenMP implementations that support it. In this case, 10 threads are provided. Note that in case of an error the OpenMP implementation is free to abort the program or to supply any number of threads available.

```
#include <omp.h>
int main()
{
    omp_set_dynamic(0);
    #pragma omp parallel num_threads(10)
    {
        /* do work here */
    }
    return 0;
}
```

```
PROGRAM EXAMPLE
    INCLUDE "omp_lib.h"    ! or USE OMP_LIB
    CALL OMP_SET_DYNAMIC(.FALSE.)
    !$OMP PARALLEL NUM_THREADS(10)
    ! do work here
    !$OMP END PARALLEL
END PROGRAM EXAMPLE
```
The call to the `omp_set_dynamic` routine with a non-zero argument in C/C++, or `.TRUE.` in Fortran, allows the OpenMP implementation to choose any number of threads between 1 and 10.

---

### Example nthrs_dynamic.2.c

```c
#include <omp.h>

int main()
{
    omp_set_dynamic(1);
    #pragma omp parallel num_threads(10)
    {
        /* do work here */
    }
    return 0;
}
```

---

### Example nthrs_dynamic.2.f

```fortran
PROGRAM EXAMPLE
    INCLUDE "omp_lib.h" ! or USE OMP_LIB
    CALL OMP_SET_DYNAMIC(.TRUE.)
    !$OMP PARALLEL NUM_THREADS(10)
    ! do work here
    !$OMP END PARALLEL
END PROGRAM EXAMPLE
```

It is good practice to set the `dyn-var` ICV explicitly by calling the `omp_set_dynamic` routine, as its default setting is implementation defined.
1.6 Fortran Restrictions on the do Construct

If an end do directive follows a do-construct in which several DO statements share a DO termination statement, then a do directive can only be specified for the outermost of these DO statements. The following example contains correct usages of loop constructs:

Example fort_do.1.f

```fortran
SUBROUTINE WORK(I, J)
INTEGER I,J
END SUBROUTINE WORK

SUBROUTINE DO_GOOD()
INTEGER I, J
REAL A(1000)

DO 100 I = 1,10
 !$OMP DO
   DO 100 J = 1,10
   CALL WORK(I,J)
100 CONTINUE ! !$OMP ENDDO implied here

!$OMP DO
   DO 200 J = 1,10
   200 A(I) = I + 1
   !$OMP ENDDO

!$OMP DO
   DO 300 I = 1,10
   DO 300 J = 1,10
   CALL WORK(I,J)
300 CONTINUE
   !$OMP ENDDO
END SUBROUTINE DO_GOOD
```

The following example is non-conforming because the matching do directive for the end do does not precede the outermost loop:

Example fort_do.2.f

```fortran
SUBROUTINE WORK(I, J)
INTEGER I,J
END SUBROUTINE WORK

SUBROUTINE DO_WRONG
INTEGER I, J

DO 100 I = 1,10
 !$OMP DO
   DO 100 J = 1,10
   CALL WORK(I,J)
100 CONTINUE ! !$OMP ENDDO implied here

!$OMP DO
   DO 200 J = 1,10
   200 A(I) = I + 1
   !$OMP ENDDO

!$OMP DO
   DO 300 I = 1,10
   DO 300 J = 1,10
   CALL WORK(I,J)
300 CONTINUE
   !$OMP ENDDO
END SUBROUTINE DO_WRONG
```
DO 100 I = 1, 10
!
"OMP DO
DO 100 J = 1, 10
CALL WORK(I, J)
100 CONTINUE
!
"OMP ENDDO
END SUBROUTINE DO_WRONG
1.7 The `nowait` Clause

If there are multiple independent loops within a `parallel` region, you can use the `nowait` clause to avoid the implied barrier at the end of the loop construct, as follows:

```c++
#include <math.h>

void nowait_example(int n, int m, float *a, float *b, float *y, float *z)
{
    int i;
    #pragma omp parallel
    {
        #pragma omp for nowait
        for (i=1; i<n; i++)
            b[i] = (a[i] + a[i-1]) / 2.0;

        #pragma omp for nowait
        for (i=0; i<m; i++)
            y[i] = sqrt(z[i]);
    }
}
```

```fortran
SUBROUTINE NOWAIT_EXAMPLE(N, M, A, B, Y, Z)
    INTEGER N, M
    REAL A(*), B(*), Y(*), Z(*)
    INTEGER I

    !$OMP PARALLEL
    ...
    !$OMP END PARALLEL
```

Example nowait.1.c

```c++
#include <math.h>

void nowait_example(int n, int m, float *a, float *b, float *y, float *z)
{
    int i;
    #pragma omp parallel
    {
        #pragma omp for nowait
        for (i=1; i<n; i++)
            b[i] = (a[i] + a[i-1]) / 2.0;

        #pragma omp for nowait
        for (i=0; i<m; i++)
            y[i] = sqrt(z[i]);
    }
}
```

Example nowait.1.f

```fortran
SUBROUTINE NOWAIT_EXAMPLE(N, M, A, B, Y, Z)
    INTEGER N, M
    REAL A(*), B(*), Y(*), Z(*)
    INTEGER I

    !$OMP PARALLEL
    ...
    !$OMP END PARALLEL
```

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In the following example, static scheduling distributes the same logical iteration numbers to the threads that execute the three loop regions. This allows the `nowait` clause to be used, even though there is a data dependence between the loops. The dependence is satisfied as long the same thread executes the same logical iteration numbers in each loop.

Note that the iteration count of the loops must be the same. The example satisfies this requirement, since the iteration space of the first two loops is from 0 to \( n-1 \) (from 1 to \( N \) in the Fortran version), while the iteration space of the last loop is from 1 to \( n \) (2 to \( N+1 \) in the Fortran version).

---

**Example nowait.2.c**

```c
#include <math.h>
void nowait_example2(int n, float *a, float *b, float *c, float *y, float *z)
{
    int i;
    #pragma omp parallel
    {
        #pragma omp for schedule(static) nowait
        for (i=0; i<n; i++)
            c[i] = (a[i] + b[i]) / 2.0f;
        #pragma omp for schedule(static) nowait
        for (i=0; i<n; i++)
            z[i] = sqrtf(c[i]);
        #pragma omp for schedule(static) nowait
        for (i=1; i<=n; i++)
            y[i] = z[i-1] + a[i];
    }
}
```
SUBROUTINE NOWAIT_EXAMPLE2(N, A, B, C, Y, Z)

INTEGER N
REAL A(*), B(*), C(*), Y(*), Z(*)
INTEGER I

!$OMP PARALLEL
!$OMP DO SCHEDULE(STATIC)
DO I=1,N
    C(I) = (A(I) + B(I)) / 2.0
ENDDO
!$OMP END DO NOWAIT

!$OMP DO SCHEDULE(STATIC)
DO I=1,N
    Z(I) = SQRT(C(I))
ENDDO
!$OMP END DO NOWAIT

!$OMP DO SCHEDULE(STATIC)
DO I=2,N+1
    Y(I) = Z(I-1) + A(I)
ENDDO
!$OMP END DO NOWAIT
!$OMP END PARALLEL
END SUBROUTINE NOWAIT_EXAMPLE2
1.8 The collapse Clause

In the following example, the \( k \) and \( j \) loops are associated with the loop construct. So the iterations of the \( k \) and \( j \) loops are collapsed into one loop with a larger iteration space, and that loop is then divided among the threads in the current team. Since the \( i \) loop is not associated with the loop construct, it is not collapsed, and the \( i \) loop is executed sequentially in its entirety in every iteration of the collapsed \( k \) and \( j \) loop.

The variable \( j \) can be omitted from the \texttt{private} clause when the \texttt{collapse} clause is used since it is implicitly private. However, if the \texttt{collapse} clause is omitted then \( j \) will be shared if it is omitted from the \texttt{private} clause. In either case, \( k \) is implicitly private and could be omitted from the \texttt{private} clause.

```
Example collapse.1.c

S-1 void bar(float *a, int i, int j, int k);
S-2
S-3 int kl, ku, ks, jl, ju, js, il, iu, is;
S-4
S-5 void sub(float *a)
S-6 {
S-7     int i, j, k;
S-8
S-9 #pragma omp for collapse(2) private(i, k, j)
S-10     for (k=kl; k<=ku; k+=ks)
S-11         for (j=jl; j<=ju; j+=js)
S-12             for (i=il; i<=iu; i+=is)
S-13                 bar(a, i, j, k);
S-14 }
```
1

**Example collapse.1.f**

```fortran
subroutine sub(a)
  real a(*)
  integer kl, ku, ks, jl, ju, js, il, iu, is
  common /csub/ kl, ku, ks, jl, ju, js, il, iu, is
  integer i, j, k
  !$omp do collapse(2) private(i,j,k)
  do k = kl, ku, ks
    do j = jl, ju, js
      do i = il, iu, is
        call bar(a,i,j,k)
      enddo
    enddo
  enddo
  !$omp end do
end subroutine
```

In the next example, the \( k \) and \( j \) loops are associated with the loop construct. So the iterations of the \( k \) and \( j \) loops are collapsed into one loop with a larger iteration space, and that loop is then divided among the threads in the current team.

The sequential execution of the iterations in the \( k \) and \( j \) loops determines the order of the iterations in the collapsed iteration space. This implies that in the sequentially last iteration of the collapsed iteration space, \( k \) will have the value 2 and \( j \) will have the value 3. Since \textit{klast} and \textit{jlast} are \textit{lastprivate}, their values are assigned by the sequentially last iteration of the collapsed \( k \) and \( j \) loop. This example prints: 2 3.

**Example collapse.2.c**

```c
#include <stdio.h>
void test()
{
  int j, k, jlast, klast;
  #pragma omp parallel
  {
    #pragma omp for collapse(2) lastprivate(jlast, klast)
    for (k=1; k<=2; k++)
      for (j=1; j<=3; j++)
```

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The next example illustrates the interaction of the `collapse` and `ordered` clauses.

In the example, the loop construct has both a `collapse` clause and an `ordered` clause. The `collapse` clause causes the iterations of the \( k \) and \( j \) loops to be collapsed into one loop with a larger iteration space, and that loop is divided among the threads in the current team. An `ordered` clause is added to the loop construct, because an ordered region binds to the loop region arising from the loop construct.

According to Section 2.12.8 of the OpenMP 4.0 specification, a thread must not execute more than one ordered region that binds to the same loop region. So the `collapse` clause is required for the example to be conforming. With the `collapse` clause, the iterations of the \( k \) and \( j \) loops are collapsed into one loop, and therefore only one ordered region will bind to the collapsed \( k \) and \( j \) loop. Without the `collapse` clause, there would be two ordered regions that bind to each iteration of the \( k \) loop (one arising from the first iteration of the \( j \) loop, and the other arising from the second iteration of the \( j \) loop).
The code prints

0 1 1
0 1 2
0 2 1
1 2 2
1 3 1
1 3 2

--- C / C++ ---

Example collapse.3.c

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

void work(int a, int j, int k);

void sub()
{
    int j, k, a;
    #pragma omp parallel num_threads(2)
    {
        #pragma omp for collapse(2) ordered private(j,k) schedule(static,3)
        for (k=1; k<=3; k++)
            for (j=1; j<=2; j++)
                {
                    #pragma omp ordered
                    printf("%d %d %d\n", omp_get_thread_num(), k, j);
                    /* end ordered */
                    work(a,j,k);
                }
    }
}
```

--- C / C++ ---

Example collapse.3.f

```fortran
program test
include 'omp_lib.h'
!$omp parallel num_threads(2)
!$omp do collapse(2) ordered private(j,k) schedule(static,3)
    do k = 1,3
        do j = 1,2
            !$omp ordered
            print *, omp_get_thread_num(), k, j
            /* end ordered */
            call work(a,j,k)
        enddo
    enddo
```

--- Fortran ---

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1.9 **linear Clause in Loop Constructs**

The following example shows the use of the *linear* clause in a loop construct to allow the proper parallelization of a loop that contains an induction variable ($j$). At the end of the execution of the loop construct, the original variable $j$ is updated with the value $N/2$ from the last iteration of the loop.

```c
#include <stdio.h>
#define N 100
int main(void)
{
    float a[N], b[N/2];
    int i, j;
    for ( i = 0; i < N; i++ )
        a[i] = i + 1;
    j = 0;
    #pragma omp parallel
    #pragma omp for linear(j:1)
    for ( i = 0; i < N; i += 2 )
    {
        b[j] = a[i] * 2.0f;
        j++;
    }
    printf( "%d %f %f\n", j, b[0], b[j-1] );
    /* print out: 50 2.0 198.0 */
    return 0;
}
```

Example `linear_in_loop.1.c`
Example linear_in_loop.1.f90

```fortran
program linear_loop
  implicit none
  integer, parameter :: N = 100
  real :: a(N), b(N/2)
  integer :: i, j

  do i = 1, N
    a(i) = i
  end do
  
  j = 0
  !$omp parallel
  !$omp do linear(j:1)
  do i = 1, N, 2
    j = j + 1
    b(j) = a(i) * 2.0
  end do
  !$omp end parallel

  print *, j, b(1), b(j)
  ! print out: 50 2.0 198.0

end program
```

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1.10 **The parallel sections Construct**

In the following example routines \texttt{XAXIS}, \texttt{YAXIS}, and \texttt{ZAXIS} can be executed concurrently. The first \texttt{section} directive is optional. Note that all \texttt{section} directives need to appear in the \texttt{parallel sections} construct.

\begin{verbatim}
C / C++

Example psections.1.c
S-1 void XAXIS();
S-2 void YAXIS();
S-3 void ZAXIS();
S-4
S-5 void sect_example()
S-6 {
S-7     #pragma omp parallel sections
S-8     {
S-9         #pragma omp section
S-10        XAXIS();
S-11         
S-12         #pragma omp section
S-13        YAXIS();
S-14         
S-15         #pragma omp section
S-16        ZAXIS();
S-17     }
S-18 }

Example psections.1.f
S-1 SUBROUTINE SECT_EXAMPLE()
S-2 !$OMP PARALLEL SECTIONS
S-3 !$OMP SECTION
S-4   CALL XAXIS()
S-5 !$OMP SECTION
S-6   CALL YAXIS()
S-7
S-8 !$OMP SECTION
S-9   CALL ZAXIS()
S-10
S-11 !$OMP END PARALLEL SECTIONS
S-12 END SUBROUTINE SECT_EXAMPLE
\end{verbatim}
1.11 The firstprivate Clause and the sections Construct

In the following example of the sections construct the firstprivate clause is used to initialize the private copy of section_count of each thread. The problem is that the section constructs modify section_count, which breaks the independence of the section constructs. When different threads execute each section, both sections will print the value 1. When the same thread executes the two sections, one section will print the value 1 and the other will print the value 2. Since the order of execution of the two sections in this case is unspecified, it is unspecified which section prints which value.

```c
#include <omp.h>
#include <stdio.h>
#define NT 4
int main( ) {
    int section_count = 0;
    omp_set_dynamic(0);
    omp_set_num_threads(NT);
    #pragma omp parallel
    #pragma omp sections firstprivate( section_count )
    {
        #pragma omp section
        {
            section_count++;
            /* may print the number one or two */
            printf( "section_count %d\n", section_count );
        }
        #pragma omp section
        {
            section_count++;
            /* may print the number one or two */
            printf( "section_count %d\n", section_count );
        }
    }
    return 0;
}
```

Example fpriv_sections.1.c
```
Example fpriv_sections.1.f90

S-1  program section
S-2   use omp_lib
S-3   integer :: section_count = 0
S-4   integer, parameter :: NT = 4
S-5   call omp_set_dynamic(.false.)
S-6   call omp_set_num_threads(NT)
S-7   !$omp parallel
S-8   !$omp sections firstprivate ( section_count )
S-9   !$omp section
S-10  section_count = section_count + 1
S-11  ! may print the number one or two
S-12  print *, 'section_count', section_count
S-13  !$omp section
S-14  section_count = section_count + 1
S-15  ! may print the number one or two
S-16  print *, 'section_count', section_count
S-17  !$omp end sections
S-18  !$omp end parallel
S-19  end program section
```
The following example demonstrates the `single` construct. In the example, only one thread prints each of the progress messages. All other threads will skip the `single` region and stop at the barrier at the end of the `single` construct until all threads in the team have reached the barrier. If other threads can proceed without waiting for the thread executing the `single` region, a `nowait` clause can be specified, as is done in the third `single` construct in this example. The user must not make any assumptions as to which thread will execute a `single` region.

```c
#include <stdio.h>

void work1() {}
void work2() {}

void single_example()
{
    #pragma omp parallel
    {
        #pragma omp single
        printf("Beginning work1.\n");
        work1();
        #pragma omp single
        printf("Finishing work1.\n");
        work2();
        #pragma omp single nowait
        printf("Finished work1 and beginning work2.\n");
        work2();
    }
}
```

Example `single.1.c`
Example single.1.f

SUBROUTINE WORK1()
END SUBROUTINE WORK1

SUBROUTINE WORK2()
END SUBROUTINE WORK2

PROGRAM SINGLE EXAMPLE
!$OMP PARALLEL
!$OMP SINGLE
print *, "Beginning work1."
!$OMP END SINGLE
CALL WORK1()

!$OMP SINGLE
print *, "Finishing work1."
!$OMP END SINGLE

!$OMP SINGLE
print *, "Finished work1 and beginning work2."
!$OMP END SINGLE NOWAIT
CALL WORK2()

!$OMP END PARALLEL
END PROGRAM SINGLE EXAMPLE
1.13 The workshare Construct

The following are examples of the workshare construct.

In the following example, workshare spreads work across the threads executing the parallel region, and there is a barrier after the last statement. Implementations must enforce Fortran execution rules inside of the workshare block.

Example workshare.1.f

```fortran
SUBROUTINE WSHARE1(AA, BB, CC, DD, EE, FF, N)
INTEGER N
REAL AA(N,N), BB(N,N), CC(N,N), DD(N,N), EE(N,N), FF(N,N)

!$OMP PARALLEL
!$OMP WORKSHARE
AA = BB
CC = DD
EE = FF
!$OMP END WORKSHARE
!$OMP END PARALLEL
END SUBROUTINE WSHARE1
```

In the following example, the barrier at the end of the first workshare region is eliminated with a nowait clause. Threads doing CC = DD immediately begin work on EE = FF when they are done with CC = DD.

Example workshare.2.f

```fortran
SUBROUTINE WSHARE2(AA, BB, CC, DD, EE, FF, N)
INTEGER N
REAL AA(N,N), BB(N,N), CC(N,N)
REAL DD(N,N), EE(N,N), FF(N,N)

!$OMP PARALLEL
!$OMP WORKSHARE
AA = BB
CC = DD
EE = FF
!$OMP END WORKSHARE NOWAIT
!$OMP WORKSHARE
EE = FF
!$OMP END WORKSHARE
!$OMP END PARALLEL
END SUBROUTINE WSHARE2
```
The following example shows the use of an `atomic` directive inside a `workshare` construct. The computation of `SUM(AA)` is workshared, but the update to `R` is atomic.

**Example workshare.3.f**

```fortran
SUBROUTINE WSHARE3(AA, BB, CC, DD, N)
  INTEGER N
  REAL AA(N,N), BB(N,N), CC(N,N), DD(N,N)
  REAL R
  R=0
  !$OMP PARALLEL
  !$OMP WORKSHARE
  AA = BB
  !$OMP ATOMIC UPDATE
  R = R + SUM(AA)
  CC = DD
  !$OMP END WORKSHARE
  !$OMP END PARALLEL
END SUBROUTINE WSHARE3
```

Fortran `WHERE` and `FORALL` statements are compound statements, made up of a control part and a statement part. When `workshare` is applied to one of these compound statements, both the control and the statement parts are workshared. The following example shows the use of a `WHERE` statement in a `workshare` construct.

Each task gets worked on in order by the threads:

**Example workshare.4.f**

```fortran
SUBROUTINE WSHARE4(AA, BB, CC, DD, EE, FF, GG, HH, N)
  INTEGER N
  REAL AA(N,N), BB(N,N), CC(N,N)
  REAL DD(N,N), EE(N,N), FF(N,N)
  REAL GG(N,N), HH(N,N)
  AA = BB
  CC = DD
  WHERE (EE .ne. 0) FF = 1 / EE then
  GG = HH
```

CHAPTER 1. PARALLEL EXECUTION
In the following example, an assignment to a shared scalar variable is performed by one thread in a `workshare` while all other threads in the team wait.

*Example workshare.5.f*

```fortran
SUBROUTINE WSHARE5(AA, BB, CC, DD, N)
    INTEGER N
    REAL AA(N,N), BB(N,N), CC(N,N), DD(N,N)
    INTEGER SHR
    !$OMP PARALLEL SHARED(SHR)
    !$OMP WORKSHARE
    AA = BB
    SHR = 1
    CC = DD * SHR
    !$OMP END WORKSHARE
    !$OMP END PARALLEL
END SUBROUTINE WSHARE5
```

The following example contains an assignment to a private scalar variable, which is performed by one thread in a `workshare` while all other threads wait. It is non-conforming because the private scalar variable is undefined after the assignment statement.

*Example workshare.6.f*

```fortran
SUBROUTINE WSHARE6_WRONG(AA, BB, CC, DD, N)
    INTEGER N
    REAL AA(N,N), BB(N,N), CC(N,N), DD(N,N)
    INTEGER PRI
    !$OMP PARALLEL PRIVATE(PRI)
    !$OMP WORKSHARE
    AA = BB
    PRI = 1
    CC = DD * PRI
    !$OMP END WORKSHARE
    !$OMP END PARALLEL
END SUBROUTINE WSHARE6_WRONG
```
Fortran execution rules must be enforced inside a **workshare** construct. In the following example, the same result is produced in the following program fragment regardless of whether the code is executed sequentially or inside an OpenMP program with multiple threads:

*Example workshare.7.f*

```fortran
SUBROUTINE WSHARE7(AA, BB, CC, N)
    INTEGER N
    REAL AA(N), BB(N), CC(N)
    !$OMP PARALLEL
    !$OMP WORKSHARE
    AA(1:50) = BB(11:60)
    CC(11:20) = AA(1:10)
    !$OMP END WORKSHARE
    !$OMP END PARALLEL
END SUBROUTINE WSHARE7
```

---

**CHAPTER 1. PARALLEL EXECUTION**
The following example demonstrates the master construct. In the example, the master keeps track of how many iterations have been executed and prints out a progress report. The other threads skip the master region without waiting.

```c
#include <stdio.h>
extern float average(float, float, float);

void master_example( float* x, float* xold, int n, float tol )
{
    int c, i, toobig;
    float error, y;
    c = 0;
    #pragma omp parallel
    {
        do{
            #pragma omp for private(i)
            for( i = 1; i < n-1; ++i ){
                xold[i] = x[i];
            }
            #pragma omp single
            {
                toobig = 0;
            }
            #pragma omp for private(i,y,error) reduction(+:toobig)
            for( i = 1; i < n-1; ++i ){
                y = x[i];
                x[i] = average( xold[i-1], x[i], xold[i+1] );
                error = y - x[i];
                if( error > tol || error < -tol ) ++toobig;
            }
            #pragma omp master
            {
                ++c;
                printf( "iteration %d, toobig=%d\n", c, toobig );
            }
        }while( toobig > 0 );
    }
}
```

Example master.1.c
Example master.1.f

S-1 SUBROUTINE MASTER_EXAMPLE( X, XOLD, N, TOL )
S-2 REAL X(*), XOLD(*), TOL
S-3 INTEGER N
S-4 INTEGER C, I, TOOBIG
S-5 REAL ERROR, Y, AVERAGE
S-6 EXTERNAL AVERAGE
S-7 C = 0
S-8 TOOBIG = 1
S-9 !$OMP PARALLEL
S-10 DO WHILE( TOOBIG > 0 )
S-11 !$OMP DO PRIVATE(I)
S-12 DO I = 2, N-1
S-13 XOLD(I) = X(I)
S-14 ENDDO
S-15 !$OMP SINGLE
S-16 TOOBIG = 0
S-17 !$OMP END SINGLE
S-18 !$OMP DO PRIVATE(I,Y,ERROR), REDUCTION(+:TOOBIG)
S-19 DO I = 2, N-1
S-20 Y = X(I)
S-21 X(I) = AVERAGE( XOLD(I-1), X(I), XOLD(I+1) )
S-22 ERROR = Y-X(I)
S-23 IF( ERROR > TOL .OR. ERROR < -TOL ) TOOBIG = TOOBIG+1
S-24 ENDDO
S-25 !$OMP MASTER
S-26 C = C + 1
S-27 PRINT *, 'Iteration ', C, 'TOOBIG=', TOOBIG
S-28 !$OMP END MASTER
S-29 ENDDO
S-30 !$OMP END PARALLEL
S-31 END SUBROUTINE MASTER_EXAMPLE
## 1.15 The loop Construct

The following example illustrates the use of the OpenMP 5.0 `loop` construct for the execution of a loop. The `loop` construct asserts to the compiler that the iterations of the loop are free of data dependencies and may be executed concurrently. It allows the compiler to use heuristics to select the parallelization scheme and compiler-level optimizations for the concurrency.

---

### Example loop.1.c

```c
#include <stdio.h>
#define N 100
int main()
{
    float x[N], y[N];
    float a = 2.0;
    for(int i=0;i<N;i++){ x[i]=i; y[i]=0;} // initialize

    #pragma omp parallel
    {
        #pragma omp loop
        for(int i = 0; i < N; ++i) y[i] = a*x[i] + y[i];
    }

    if(y[N-1] != (N-1)*2.0) printf("Error: 2*(N-1) != y[N-1]=%f",y[N-1]);
}
```
The following example shows a parallel random access iterator loop.

Example pra_iterator.1.cpp

```cpp
#include <vector>

void iterator_example()
{
    std::vector<int> vec(23);
    std::vector<int>::iterator it;
    #pragma omp parallel for default(none) shared(vec)
    for (it = vec.begin(); it < vec.end(); it++)
    {
        // do work with *it //
    }
}
```

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Some programs rely on a fixed, prespecified number of threads to execute correctly. Because the default setting for the dynamic adjustment of the number of threads is implementation defined, such programs can choose to turn off the dynamic threads capability and set the number of threads explicitly to ensure portability. The following example shows how to do this using `omp_set_dynamic`, and `omp_set_num_threads`.

In this example, the program executes correctly only if it is executed by 16 threads. If the implementation is not capable of supporting 16 threads, the behavior of this example is implementation defined. Note that the number of threads executing a `parallel` region remains constant during the region, regardless of the dynamic threads setting. The dynamic threads mechanism determines the number of threads to use at the start of the `parallel` region and keeps it constant for the duration of the region.

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

void do_by_16(float *x, int iam, int ipoints) {}

void dynthreads(float *x, int npoints)
{
    int iam, ipoints;
    omp_set_dynamic(0);
    omp_set_num_threads(16);
    #pragma omp parallel shared(x, npoints) private(iam, ipoints)
    {
        if (omp_get_num_threads() != 16)
            abort();
        iam = omp_get_thread_num();
        ipoints = npoints/16;
        do_by_16(x, iam, ipoints);
    }
}
```
Fortran

Example set_dynamic_nthrs.1.f

SUBROUTINE DO_BY_16(X, IAM, IPOINTS)
    REAL X(*)
    INTEGER IAM, IPOINTS
END SUBROUTINE DO_BY_16

SUBROUTINE DYNTHREADS(X, NPOINTS)

    INCLUDE "omp_lib.h" ! or USE OMP_LIB

    INTEGER NPOINTS
    REAL X(NPOINTS)
    INTEGER IAM, IPOINTS

    CALL OMP_SET_DYNAMIC(.FALSE.)
    CALL OMP_SET_NUM_THREADS(16)

    !$OMP PARALLEL SHARED(X,NPOINTS) PRIVATE(IAM, IPOINTS)

    IF (OMP_GET_NUM_THREADS() .NE. 16) THEN
        STOP
    ENDIF

    IAM = OMP_GET_THREAD_NUM()
    IPOINTS = NPOINTS/16
    CALL DO_BY_16(X,IAM,IPOINTS)

    !$OMP END PARALLEL

END SUBROUTINE DYNTHREADS

END
1.18 The `omp_get_num_threads` Routine

In the following example, the `omp_get_num_threads` call returns 1 in the sequential part of the code, so `np` will always be equal to 1. To determine the number of threads that will be deployed for the `parallel` region, the call should be inside the `parallel` region.

```
#include <omp.h>

void work(int i);

void incorrect() {
  int np, i;
  np = omp_get_num_threads(); /* misplaced */
  #pragma omp parallel for schedule(static)
  for (i=0; i < np; i++)
    work(i);
}
```

```
SUBROUTINE WORK(I)
  INTEGER I
  I = I + 1
END SUBROUTINE WORK

SUBROUTINE INCORRECT()
  INCLUDE "omp_lib.h" ! or USE OMP_LIB
  INTEGER I, NP
  NP = OMP_GET_NUM_THREADS() ! misplaced: will return 1
  !$OMP PARALLEL DO SCHEDULE(STATIC)
  DO I = 0, NP-1
    CALL WORK(I)
  ENDDO
  !$OMP END PARALLEL DO
END SUBROUTINE INCORRECT
```
The following example shows how to rewrite this program without including a query for the number of threads:

```c
#include <omp.h>

void work(int i);

void correct()
{
    int i;

    #pragma omp parallel private(i)
    {
        i = omp_get_thread_num();
        work(i);
    }
}
```

```fortran
SUBROUTINE WORK(I)
    INTEGER I
    I = I + 1
END SUBROUTINE WORK

SUBROUTINE CORRECT()
    INCLUDE "omp_lib.h" ! or USE OMP_LIB
    INTEGER I

    !$OMP PARALLEL PRIVATE(I)
    I = OMP_GET_THREAD_NUM()
    CALL WORK(I)
    !$OMP END PARALLEL

END SUBROUTINE CORRECT
```
OpenMP Affinity

OpenMP Affinity consists of a proc_bind policy (thread affinity policy) and a specification of places ("location units" or processors that may be cores, hardware threads, sockets, etc.). OpenMP Affinity enables users to bind computations on specific places. The placement will hold for the duration of the parallel region. However, the runtime is free to migrate the OpenMP threads to different cores (hardware threads, sockets, etc.) prescribed within a given place, if two or more cores (hardware threads, sockets, etc.) have been assigned to a given place.

Often the binding can be managed without resorting to explicitly setting places. Without the specification of places in the OMP_PLACES variable, the OpenMP runtime will distribute and bind threads using the entire range of processors for the OpenMP program, according to the OMP_PROC_BIND environment variable or the proc_bind clause. When places are specified, the OMP runtime binds threads to the places according to a default distribution policy, or those specified in the OMP_PROC_BIND environment variable or the proc_bind clause.

In the OpenMP Specifications document a processor refers to an execution unit that is enabled for an OpenMP thread to use. A processor is a core when there is no SMT (Simultaneous Multi-Threading) support or SMT is disabled. When SMT is enabled, a processor is a hardware thread (HW-thread). (This is the usual case; but actually, the execution unit is implementation defined.) Processor numbers are numbered sequentially from 0 to the number of cores less one (without SMT), or 0 to the number HW-threads less one (with SMT). OpenMP places use the processor number to designate binding locations (unless an "abstract name" is used.)

The processors available to a process may be a subset of the system’s processors. This restriction may be the result of a wrapper process controlling the execution (such as numactl on Linux systems), compiler options, library-specific environment variables, or default kernel settings. For instance, the execution of multiple MPI processes, launched on a single compute node, will each have a subset of processors as determined by the MPI launcher or set by MPI affinity environment variables for the MPI library.

Threads of a team are positioned onto places in a compact manner, a scattered distribution, or onto the master’s place, by setting the OMP_PROC_BIND environment variable or the proc_bind
clause to close, spread, or master, respectively. When OMP_PROC_BIND is set to FALSE no 
binding is enforced; and when the value is TRUE, the binding is implementation defined to a set of 
places in the OMP_PLACES variable or to places defined by the implementation if the 
OMP_PLACES variable is not set.

The OMP_PLACES variable can also be set to an abstract name (threads, cores, sockets) to specify 
that a place is either a single hardware thread, a core, or a socket, respectively. This description of 
the OMP_PLACES is most useful when the number of threads is equal to the number of hardware 
thread, cores or sockets. It can also be used with a close or spread distribution policy when the 
equality doesn’t hold.
2.1 The proc_bind Clause

The following examples demonstrate how to use the proc_bind clause to control the thread binding for a team of threads in a parallel region. The machine architecture is depicted in the figure below. It consists of two sockets, each equipped with a quad-core processor and configured to execute two hardware threads simultaneously on each core. These examples assume a contiguous core numbering starting from 0, such that the hardware threads 0,1 form the first physical core.

The following equivalent place list declarations consist of eight places (which we designate as p0 to p7):

OMP_PLACES="{0,1},{2,3},{4,5},{6,7},{8,9},{10,11},{12,13},{14,15}"

or

OMP_PLACES="{0:2}:8:2"

2.1.1 Spread Affinity Policy

The following example shows the result of the spread affinity policy on the partition list when the number of threads is less than or equal to the number of places in the parent’s place partition, for the machine architecture depicted above. Note that the threads are bound to the first place of each subpartition.

Example affinity.1.c

```c
void work();
int main()
{
    #pragma omp parallel proc_bind(spread) num_threads(4)
```
It is unspecified on which place the master thread is initially started. If the master thread is initially started on p0, the following placement of threads will be applied in the parallel region:

- thread 0 executes on p0 with the place partition p0,p1
- thread 1 executes on p2 with the place partition p2,p3
- thread 2 executes on p4 with the place partition p4,p5
- thread 3 executes on p6 with the place partition p6,p7

If the master thread would initially be started on p2, the placement of threads and distribution of the place partition would be as follows:

- thread 0 executes on p2 with the place partition p2,p3
- thread 1 executes on p4 with the place partition p4,p5
- thread 2 executes on p6 with the place partition p6,p7
- thread 3 executes on p0 with the place partition p0,p1

The following example illustrates the spread thread affinity policy when the number of threads is greater than the number of places in the parent’s place partition.

Let $T$ be the number of threads in the team, and $P$ be the number of places in the parent’s place partition. The first $T/P$ threads of the team (including the master thread) execute on the parent’s place. The next $T/P$ threads execute on the next place in the place partition, and so on, with wrap around.
Example affinity.2.c

```c
1
S-1 void work();
S-2 void foo()
S-3 {
S-4   #pragma omp parallel num_threads(16) proc_bind(spread)
S-5   {
S-6     work();
S-7   }
S-8 }
```

Example affinity.2.f90

```fortran
2
S-1 subroutine foo
S-2 !$omp parallel num_threads(16) proc_bind(spread)
S-3   call work()
S-4 !$omp end parallel
S-5 end subroutine
```

It is unspecified on which place the master thread is initially started. If the master thread is initially started on p0, the following placement of threads will be applied in the parallel region:

- threads 0,1 execute on p0 with the place partition p0
- threads 2,3 execute on p1 with the place partition p1
- threads 4,5 execute on p2 with the place partition p2
- threads 6,7 execute on p3 with the place partition p3
- threads 8,9 execute on p4 with the place partition p4
- threads 10,11 execute on p5 with the place partition p5
- threads 12,13 execute on p6 with the place partition p6
- threads 14,15 execute on p7 with the place partition p7

If the master thread would initially be started on p2, the placement of threads and distribution of the place partition would be as follows:

- threads 0,1 execute on p2 with the place partition p2
- threads 2,3 execute on p3 with the place partition p3
- threads 4,5 execute on p4 with the place partition p4
- threads 6,7 execute on p5 with the place partition p5
- threads 8,9 execute on p6 with the place partition p6
- threads 10,11 execute on p7 with the place partition p7
- threads 12,13 execute on p0 with the place partition p0
- threads 14,15 execute on p1 with the place partition p1
2.1.2 Close Affinity Policy

The following example shows the result of the close affinity policy on the partition list when the number of threads is less than or equal to the number of places in parent’s place partition, for the machine architecture depicted above. The place partition is not changed by the close policy.

```
Example affinity.3.c
void work();
int main()
{
    #pragma omp parallel proc_bind(close) num_threads(4)
    {
        work();
    }
    return 0;
}
```

```
Example affinity.3.f
PROGRAM EXAMPLE
!$OMP PARALLEL PROC_BIND(CLOSE) NUM_THREADS(4)
CALL WORK()
!$OMP END PARALLEL
END PROGRAM EXAMPLE
```

It is unspecified on which place the master thread is initially started. If the master thread is initially started on p0, the following placement of threads will be applied in the parallel region:

- thread 0 executes on p0 with the place partition p0-p7
- thread 1 executes on p1 with the place partition p0-p7
- thread 2 executes on p2 with the place partition p0-p7
- thread 3 executes on p3 with the place partition p0-p7

If the master thread would initially be started on p2, the placement of threads and distribution of the place partition would be as follows:

- thread 0 executes on p2 with the place partition p0-p7
- thread 1 executes on p3 with the place partition p0-p7
- thread 2 executes on p4 with the place partition p0-p7
- thread 3 executes on p5 with the place partition p0-p7
The following example illustrates the `close` thread affinity policy when the number of threads is
greater than the number of places in the parent’s place partition.

Let \( T \) be the number of threads in the team, and \( P \) be the number of places in the parent’s place
partition. The first \( T/P \) threads of the team (including the master thread) execute on the parent’s
place. The next \( T/P \) threads execute on the next place in the place partition, and so on, with wrap
around. The place partition is not changed by the `close` policy.

```c
Example affinity.4.c

void work();
void foo()
{
  #pragma omp parallel num_threads(16) proc_bind(close)
  {
    work();
  }
}
```

```fortran
Example affinity.4.f90

subroutine foo
!$omp parallel num_threads(16) proc_bind(close)
call work()
!$omp end parallel
end subroutine
```

It is unspecified on which place the master thread is initially started. If the master thread is initially
running on p0, the following placement of threads will be applied in the parallel region:

- threads 0,1 execute on p0 with the place partition p0-p7
- threads 2,3 execute on p1 with the place partition p0-p7
- threads 4,5 execute on p2 with the place partition p0-p7
- threads 6,7 execute on p3 with the place partition p0-p7
- threads 8,9 execute on p4 with the place partition p0-p7
- threads 10,11 execute on p5 with the place partition p0-p7
- threads 12,13 execute on p6 with the place partition p0-p7
- threads 14,15 execute on p7 with the place partition p0-p7

If the master thread would initially be started on p2, the placement of threads and distribution of the
place partition would be as follows:

- threads 0,1 execute on p2 with the place partition p0-p7
• threads 2,3 execute on p3 with the place partition p0-p7
• threads 4,5 execute on p4 with the place partition p0-p7
• threads 6,7 execute on p5 with the place partition p0-p7
• threads 8,9 execute on p6 with the place partition p0-p7
• threads 10,11 execute on p7 with the place partition p0-p7
• threads 12,13 execute on p0 with the place partition p0-p7
• threads 14,15 execute on p1 with the place partition p0-p7

2.1.3 Master Affinity Policy

The following example shows the result of the master affinity policy on the partition list for the machine architecture depicted above. The place partition is not changed by the master policy.

```
Example affinity.5.c

void work();
int main()
{
    #pragma omp parallel proc_bind(master) num_threads(4)
    {
        work();
    }
    return 0;
}
```

Example affinity.5.f

```
PROGRAM EXAMPLE
!$OMP PARALLEL PROC_BIND(MASTER) NUM_THREADS(4)
CALL WORK()
!$OMP END PARALLEL
END PROGRAM EXAMPLE
```

It is unspecified on which place the master thread is initially started. If the master thread is initially running on p0, the following placement of threads will be applied in the parallel region:

• threads 0-3 execute on p0 with the place partition p0-p7

If the master thread would initially be started on p2, the placement of threads and distribution of the place partition would be as follows:

• threads 0-3 execute on p2 with the place partition p0-p7
2.2 Task Affinity

The next example illustrates the use of the `affinity` clause with a `task` construct. The variables in the `affinity` clause provide a hint to the runtime that the task should execute "close" to the physical storage location of the variables. For example, on a two-socket platform with a local memory component close to each processor socket, the runtime will attempt to schedule the task execution on the socket where the storage is located.

Because the C/C++ code employs a pointer, an array section is used in the `affinity` clause. Fortran code can use an array reference to specify the storage, as shown here.

Note, in the second task of the C/C++ code the $B$ pointer is declared shared. Otherwise, by default, it would be firstprivate since it is a local variable, and would probably be saved for the second task before being assigned a storage address by the first task. Also, one might think it reasonable to use the `affinity` clause `affinity(B[:N])` on the second `task` construct. However, the storage behind $B$ is created in the first task, and the array section reference may not be valid when the second task is generated. The use of the $A$ array is sufficient for this case, because one would expect the storage for $A$ and $B$ would be physically "close" (as provided by the hint in the first task).

```
C / C++
Example affinity.6.c
```

```
S-1
S-2  double * alloc_init_B(double *A, int N);
S-3  void     compute_on_B(double *B, int N);
S-4
S-5  void task_affinity(double *A, int N)
S-6  {
S-7     double * B;
S-8     #pragma omp task depend(out:B) shared(B) affinity(A[0:N])
S-9       {
S-10       B = alloc_init_B(A,N);
S-11       }
S-12
S-13     #pragma omp task depend( in:B) shared(B) affinity(A[0:N])
S-14     {
S-15     compute_on_B(B,N);
S-16     }
S-17
S-18     #pragma omp taskwait
S-19   }
S-20
```

```
C / C++
```
Example affinity.6.f90

subroutine task_affinity(A, N)
  !$omp task depend(out:B) shared(B) affinity(A)
  call alloc_init_B(B,A)
  !$omp end task
  !$omp task depend(in:B) shared(B) affinity(A)
  call compute_on_B(B)
  !$omp end task
  !$omp taskwait
end subroutine

2.3 Affinity Display

The following examples illustrate ways to display thread affinity. Automatic display of affinity can be invoked by setting the `OMP_DISPLAY_AFFINITY` environment variable to `TRUE`. The format of the output can be customized by setting the `OMP_AFFINITY_FORMAT` environment variable to an appropriate string. Also, there are API calls for the user to display thread affinity at selected locations within code.

For the first example the environment variable `OMP_DISPLAY_AFFINITY` has been set to `TRUE`, and execution occurs on an 8-core system with `OMP_NUM_THREADS` set to 8.

The affinity for the master thread is reported through a call to the API `omp_display_affinity()` routine. For default affinity settings the report shows that the master thread can execute on any of the cores. In the following parallel region the affinity for each of the team threads is reported automatically since the `OMP_DISPLAY_AFFINITY` environment variable has been set to `TRUE`. 
These two reports are often useful (as in hybrid codes using both MPI and OpenMP) to observe the affinity (for an MPI task) before the parallel region, and during an OpenMP parallel region. Note: the next parallel region uses the same number of threads as in the previous parallel region and affinities are not changed, so affinity is NOT reported.

In the last parallel region, the thread affinities are reported because the thread affinity has changed.

Example affinity_display.1.c

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

int main(void){ //MAX threads = 8, single socket system
    omp_display_affinity(NULL); //API call-- Displays Affinity of Master Thread
    // API CALL OUTPUT (default format):
    //team_num= 0, nesting_level= 0, thread_num= 0, thread_affinity= 0,1,2,3,4,5,6,7
    // OMP_DISPLAY_AFFINITY=TRUE, OMP_NUM_THREADS=8
    #pragma omp parallel num_threads(omp_get_num_procs())
    {
        if(omp_get_thread_num()==0)
        printf("1st Parallel Region -- Affinity Reported \n");
        // DISPLAY OUTPUT (default format) has been sorted:
        // team_num= 0, nesting_level= 1, thread_num= 0, thread_affinity= 0
        // team_num= 0, nesting_level= 1, thread_num= 1, thread_affinity= 1
        // ...
        // team_num= 0, nesting_level= 1, thread_num= 7, thread_affinity= 7
        // doing work here
    }
    #pragma omp parallel num_threads(omp_get_num_procs() )
    {
        if(omp_get_thread_num()==0)
        printf("%s\n","Same Affinity as in Previous Parallel Region",
                " -- no Affinity Reported\n");
        // NO AFFINITY OUTPUT:
        //(output in 1st parallel region only for OMP_DISPLAY_AFFINITY=TRUE)
        // doing more work here
    }
```
// Report Affinity for 1/2 number of threads
#pragma omp parallel num_threads( omp_get_num_procs()/2 )
{
  if(omp_get_thread_num()==0)
    printf("Report Affinity for using 1/2 of max threads.\n");

  // DISPLAY OUTPUT (default format) has been sorted:
  // team_num= 0, nesting_level= 0, thread_num= 0, thread_affinity= 0,1
  // team_num= 0, nesting_level= 1, thread_num= 1, thread_affinity= 2,3
  // team_num= 0, nesting_level= 1, thread_num= 2, thread_affinity= 4,5
  // team_num= 0, nesting_level= 1, thread_num= 3, thread_affinity= 6,7

  // do work
}
return 0;

---------

Example affinity_display.f90

program affinity_display ! MAX threads = 8, single socket system
  use omp_lib
  implicit none
  character(len=0) :: null
  call omp_display_affinity(null) !API call- Displays Affinity of Master Thread

  ! API CALL OUTPUT (default format):
  ! team_num= 0, nesting_level= 0, thread_num= 0, thread_affinity= 0,1,2,3,4,5,6,7

  ! OMP_DISPLAY_AFFINITY=TRUE, OMP_NUM_THREADS=8

  !$omp parallel num_threads(omp_get_num_procs())

  if(omp_get_thread_num()==0) then
    print*, "1st Parallel Region -- Affinity Reported"
  endif

  ! DISPLAY OUTPUT (default format) has been sorted:
  ! team_num= 0, nesting_level= 1, thread_num= 0, thread_affinity= 0
  ! team_num= 0, nesting_level= 1, thread_num= 1, thread_affinity= 1
  ! ...
! team_num= 0, nesting_level= 1, thread_num= 7, thread_affinity= 7

! doing work here

 !$omp end parallel

 !$omp parallel num_threads( omp_get_num_procs() )

 if(omp_get_thread_num()==0) then
  print*, "Same Affinity in Parallel Region -- no Affinity Reported"
 endif

! NO AFFINITY OUTPUT:
!(output in 1st parallel region only for OMP_DISPLAY_AFFINITY=TRUE)

! doing more work here

 !$omp end parallel

 ! Report Affinity for 1/2 number of threads

 !$omp parallel num_threads( omp_get_num_procs()/2 )

 if(omp_get_thread_num()==0) then
  print*, "Different Affinity in Parallel Region -- Affinity Reported"
 endif

 ! DISPLAY OUTPUT (default format) has been sorted:
! team_num= 0, nesting_level= 1, thread_num= 0, thread_affinity= 0,1
! team_num= 0, nesting_level= 1, thread_num= 1, thread_affinity= 2,3
! team_num= 0, nesting_level= 1, thread_num= 2, thread_affinity= 4,5
! team_num= 0, nesting_level= 1, thread_num= 3, thread_affinity= 6,7

! do work

 !$omp end parallel

end program

In the following example 2 threads are forked, and each executes on a socket. Next, a nested parallel region runs half of the available threads on each socket.

These OpenMP environment variables have been set:

- OMP_PROC_BIND="TRUE"
- OMP_NUM_THREADS="2,4"
- OMP_PLACES="[0,2,4,6],[1,3,5,7]"
• `OMP_AFFINITY_FORMAT="nest_level= %L, parent_thrd_num= %a, thrd_num= %n, thrd_affinity= %A"`

where the numbers correspond to core ids for the system. Note, `OMP_DISPLAY_AFFINITY` is not set and is `FALSE` by default. This example shows how to use API routines to perform affinity display operations.

For each of the two first-level threads the `OMP_PLACES` variable specifies a place with all the core-ids of the socket ({0,2,4,6} for one thread and {1,3,5,7} for the other). (As is sometimes the case in 2-socket systems, one socket may consist of the even id numbers, while the other may have the odd id numbers.) The affinities are printed according to the `OMP_AFFINITY_FORMAT` format: providing the parallel nesting level (%L), the ancestor thread number (%a), the thread number (%n) and the thread affinity (%A). In the nested parallel region within the `socket_work` routine the affinities for the threads on each socket are printed according to this format.

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

void socket_work(int socket_num, int n_thrds);

int main(void)
{
    int n_sockets, socket_num, n_thrds_on_socket;

    omp_set_nested(1); // or env var= OMP_NESTED=true
    omp_set_max_active_levels(2); // or env var= OMP_MAX_ACTIVE_LEVELS=2

    n_sockets = omp_get_num_places();
    n_thrds_on_socket = omp_get_place_num_procs(0);

    // OMP_NUM_THREADS=2,4
    // OMP_PLACES="{0,2,4,6},{1,3,5,7}" #2 sockets; even/odd proc-ids
    // OMP_AFFINITY_FORMAT=
    // "nest_level= %L, parent_thrd_num= %a, thrd_num= %n, thrd_affinity= %A"

    #pragma omp parallel num_threads(n_sockets) private(socket_num)
    {
        socket_num = omp_get_place_num();

        if(socket_num==0)
            printf(" LEVEL 1 AFFINITIES 1 thread/socket, %d sockets:\n\n", n_sockets);

        omp_display_affinity(NULL); // not needed if OMP_DISPLAY_AFFINITY=TRUE
    }
```

---

**C / C++**

**Example affinity_display.2.c**

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

void socket_work(int socket_num, int n_thrds);

int main(void)
{
    int n_sockets, socket_num, n_thrds_on_socket;

    omp_set_nested(1); // or env var= OMP_NESTED=true
    omp_set_max_active_levels(2); // or env var= OMP_MAX_ACTIVE_LEVELS=2

    n_sockets = omp_get_num_places();
    n_thrds_on_socket = omp_get_place_num_procs(0);

    // OMP_NUM_THREADS=2,4
    // OMP_PLACES="{0,2,4,6},{1,3,5,7}" #2 sockets; even/odd proc-ids
    // OMP_AFFINITY_FORMAT=
    // "nest_level= %L, parent_thrd_num= %a, thrd_num= %n, thrd_affinity= %A"

    #pragma omp parallel num_threads(n_sockets) private(socket_num)
    {
        socket_num = omp_get_place_num();

        if(socket_num==0)
            printf(" LEVEL 1 AFFINITIES 1 thread/socket, %d sockets:\n\n", n_sockets);

        omp_display_affinity(NULL); // not needed if OMP_DISPLAY_AFFINITY=TRUE
    }
```
socket_work(socket_num, n_thrds_on_socket);
}

return 0;
}

void socket_work(int socket_num, int n_thrds)
{
    #pragma omp parallel num_threads(n_thrds)
    {
        if(omp_get_thread_num()==0)
            printf(" LEVEL 2 AFFINITIES, %d threads on socket %d\n",n_thrds, socket_num);

        omp_display_affinity(NULL); // not needed if OMP_DISPLAY_AFFINITY=TRUE

        // OUTPUT:
        // LEVEL 2 AFFINITIES, 4 threads on socket 0
        // nest_level= 2, parent_thrd_num= 0, thrd_num= 0, thrd_affinity= 0
        // nest_level= 2, parent_thrd_num= 0, thrd_num= 1, thrd_affinity= 2
        // nest_level= 2, parent_thrd_num= 0, thrd_num= 2, thrd_affinity= 4
        // nest_level= 2, parent_thrd_num= 0, thrd_num= 3, thrd_affinity= 6

        // LEVEL 2 AFFINITIES, 4 threads on socket 1
        // nest_level= 2, parent_thrd_num= 1, thrd_num= 0, thrd_affinity= 1
        // nest_level= 2, parent_thrd_num= 1, thrd_num= 1, thrd_affinity= 3
        // nest_level= 2, parent_thrd_num= 1, thrd_num= 2, thrd_affinity= 5
        // nest_level= 2, parent_thrd_num= 1, thrd_num= 3, thrd_affinity= 7

        // ... Do Some work on Socket
    }
}
Example affinity_display.2.f90

program affinity_display

    use omp_lib
    implicit none
    character(len=0) :: null
    integer :: n_sockets, socket_num, n_thrds_on_socket;

    call omp_set_nested(.true.) ! or env var= OMP_NESTED=true
    call omp_set_max_active_levels(2) ! or env var= OMP_MAX_ACTIVE_LEVELS=2

    n_sockets = omp_get_num_places()
    n_thrds_on_socket = omp_get_place_num_procs(0)

    ! OMP_NUM_THREADS=2,4
    ! OMP_PLACES="{0,2,4,6},{1,3,5,7}" #2 sockets; even/odd proc-ids
    ! OMP_AFFINITY_FORMAT="nest_level= %L, parent_thrd_num= %a, thrd_num= %n, thrd_affinity= %A"

    !$omp parallel num_threads(n_sockets) private(socket_num)
    socket_num = omp_get_place_num()
    if(socket_num==0) then
        write(*,'("LEVEL 1 AFFINITIES 1 thread/socket ",i0," sockets")')n_sockets
    endif
    call omp_display_affinity(null) !not needed if OMP_DISPLAY_AFFINITY=TRUE

    ! OUTPUT:
    !  LEVEL 1 AFFINITIES 1 thread/socket, 2 sockets:
    !    nest_level= 1, parent_thrd_num= 0, thrd_num= 0, thrd_affinity= 0,2,4,6
    !    nest_level= 1, parent_thrd_num= 0, thrd_num= 1, thrd_affinity= 1,3,5,7

    call socket_work(socket_num, n_thrds_on_socket)

    !$omp end parallel
end program

subroutine socket_work(socket_num, n_thrds)
    implicit none
    integer :: socket_num, n_thrds
    character(len=0) :: null
The next example illustrates more details about affinity formatting. First, the
`omp_get_affininity_format()` API routine is used to obtain the default format. The code
checks to make sure the storage provides enough space to hold the format. Next, the
`omp_set_affinity_format()` API routine sets a user-defined format:

```
host=%20H
thrd_num=%0.4n binds_to=%A.
```

The host, thread number and affinity fields are specified by `%20H`, `%0.4n` and `%A: `H`, `n` and `A` are
single character "short names" for the host, thread_num and thread_affinity data to be printed, with
format sizes of 20, 4, and "size as needed". The period (.) indicates that the field is displayed
right-justified (default is left-justified) and the "0" indicates that any unused space is to be prefixed
with zeros (e.g. instead of "1", "0001" is displayed for the field size of 4).

Within the parallel region the affinity for each thread is captured by

`omp_capture_affinity()` into a buffer array with elements indexed by the thread number
(`thrd_num`). After the parallel region, the thread affinities are printed in thread-number order.

If the storage area in buffer is inadequate for holding the affinity data, the stored affinity data is
truncated. The maximum value for the number of characters (`nchars`) returned by
omp_capture_affinity is captured by the reduction(max:max_req_store) clause
and the if(nchars >= max_req_store) max_req_store=nchars statement. It is used to report possible
truncation (if max_req_store > buffer_store).

Example affinity_display.3.c

```c
#include <stdio.h>
#include <stdlib.h> // also null is in <stddef.h>
#include <stddef.h>
#include <string.h>
#include <omp.h>

#define FORMAT_STORE 80
#define BUFFER_STORE 80

int main(void){
    int i, n, thrd_num, max_req_store;
    size_t nchars;

    char default_format[FORMAT_STORE];
    char my_format[] = "host=%20H thrd_num=%0.4n binds_to=%A";
    char **buffer;

    // CODE SEGMENT 1 AFFINITY FORMAT
    // Get and Display Default Affinity Format
    nchars = omp_get_affinity_format(default_format,(size_t)FORMAT_STORE);
    printf("Default Affinity Format is: %s\n",default_format);
    if(nchars >= FORMAT_STORE){
        printf("Caution: Reported Format is truncated. Increase\n");
        printf(" FORMAT_STORE to %d.\n", nchars+1);
    }
    // Set Affinity Format
    omp_set_affinity_format(my_format);
    printf("Affinity Format set to: %s\n",my_format);

    // CODE SEGMENT 2 CAPTURE AFFINITY
    // Set up buffer for affinity of n threads
```

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n = omp_get_num_procs();
buffer = (char **)malloc( sizeof(char *) * n );
for(i=0;i<n;i++){ buffer[i]=(char *)malloc( sizeof(char) * BUFFER_STORE); }

// Capture Affinity using Affinity Format set above.
// Use max reduction to check size of buffer areas
max_req_store = 0;
#pragma omp parallel private(thrd_num,nchars) reduction(max:max_req_store)
{
    if(omp_get_num_threads()>n) exit(1); //safety: don’t exceed # of buffers
    thrd_num=omp_get_thread_num();
nchars=omp_capture_affinity(buffer[thrd_num],(size_t)BUFFER_STORE,NULL);
    if(nchars > max_req_store) max_req_store=nchars;
}

// ...
for(i=0;i<n;i++)
    printf("thrd_num= %d, affinity: %s\n", i,buffer[i]);

// For 4 threads with OMP_PLACES='{0,1},{2,3},{4,5},{6,7}'
// Format host=%20H thrd_num=%0.4n binds_to=%A

// affinity: host=hpc.cn567            thrd_num=0000 binds_to=0,1
// affinity: host=hpc.cn567            thrd_num=0001 binds_to=2,3
// affinity: host=hpc.cn567            thrd_num=0002 binds_to=4,5
// affinity: host=hpc.cn567            thrd_num=0003 binds_to=6,7

if(max_req_store>=BUFFER_STORE){
    printf("Caution: Affinity string truncated. Increase\n");
    printf("BUFFER_STORE to %d\n",max_req_store+1);
}

for(i=0;i<n;i++) free(buffer[i]);
free (buffer);
return 0;
program affinity_display
  use omp_lib
  implicit none
  integer, parameter :: FORMAT_STORE=80
  integer, parameter :: BUFFER_STORE=80

  integer :: i, n, thrd_num, nchars, max_req_store
  character(FORMAT_STORE) :: default_format
  character(*), parameter :: my_format = &
    "host=%20H thrd_num=%0.4n binds_to=%A"
  character(:), allocatable :: buffer(:)
  character(len=0) :: null

  ! CODE SEGMENT 1 AFFINITY FORMAT
  ! Get and Display Default Affinity Format
  nchars = omp_get_affinity_format(default_format)
  print*,"Default Affinity Format: ", trim(default_format)
  if( nchars > FORMAT_STORE) then
    print*,"Caution: Reported Format is truncated. Increase"
    print*," FORMAT_STORE to ", nchars
  endif

  ! Set Affinity Format
  call omp_set_affinity_format(my_format)
  print*,"Affinity Format set to: ", my_format

  ! CODE SEGMENT 2 CAPTURE AFFINITY
  ! Set up buffer for affinity of n threads
  n = omp_get_num_procs()
  allocate( character(len=BUFFER_STORE):buffer(0:n-1) )

  ! Capture Affinity using Affinity Format set above.
  ! Use max reduction to check size of buffer areas
  max_req_store = 0
  !$omp parallel private(thrd_num,nchars) reduction(max:max_req_store)
if(omp_get_num_threads()>n) stop "ERROR: increase buffer lines"

thrd_num=omp_get_thread_num()
nchars=omp_capture_affinity(buffer(thrd_num),null)
if(nchars>max_req_store) max_req_store=nchars
!...
!
!$omp end parallel

do i = 0, n-1
   print*, "thrd_num= ",i,"    affinity:", trim(buffer(i))
end do
!
!
!
if(max_req_store > BUFFER_STORE) then
   print*, "Caution: Affinity string truncated. Increase"
   print*, "BUFFER_STORE to ",max_req_store
endif

deallocate(buffer)
end program

---

2.4 Affinity Query Functions

In the example below a team of threads is generated on each socket of the system, using nested parallelism. Several query functions are used to gather information to support the creation of the teams and to obtain socket and thread numbers.

For proper execution of the code, the user must create a place partition, such that each place is a listing of the core numbers for a socket. For example, in a 2 socket system with 8 cores in each socket, and sequential numbering in the socket for the core numbers, the OMP_PLACES variable would be set to "[0:8],[8:8]", using the place syntax {lower_bound:length:stride}, and the default stride of 1.
The code determines the number of sockets \((n_{\text{sockets}})\) using the \texttt{omp_get_num_places()} query function. In this example each place is constructed with a list of each socket’s core numbers, hence the number of places is equal to the number of sockets.

The outer parallel region forms a team of threads, and each thread executes on a socket (place) because the \texttt{proc_bind} clause uses \texttt{spread} in the outer \texttt{parallel} construct. Next, in the \texttt{socket_init} function, an inner parallel region creates a team of threads equal to the number of elements (core numbers) from the place of the parent thread. Because the outer \texttt{parallel} construct uses a \texttt{spread} affinity policy, each of its threads inherits a subpartition of the original partition. Hence, the \texttt{omp_get_place_num_procs} query function returns the number of elements (here procs = cores) in the subpartition of the thread. After each parent thread creates its nested parallel region on the section, the socket number and thread number are reported.

Note: Portable tools like hwloc (Portable HardWare LOCality package), which support many common operating systems, can be used to determine the configuration of a system. On some systems there are utilities, files or user guides that provide configuration information. For instance, the socket number and proc_id’s for a socket can be found in the \texttt{/proc/cpuinfo} text file on Linux systems.

---

\texttt{C / C++}

\textit{Example affinity_query.1.c}

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

void socket_init(int socket_num)
{
    int n_procs;
    n_procs = omp_get_place_num_procs(socket_num);
    #pragma omp parallel num_threads(n_procs) proc_bind(close)
    {
        printf("Reporting in from socket num, thread num: %d %d\n",
                socket_num,omp_get_thread_num());
    }
}

int main()
{
    int n_sockets, socket_num;
    omp_set_nested(1); // or export OMP_NESTED=true
    omp_set_max_active_levels(2); // or export OMP_MAX_ACTIVE_LEVELS=2
    n_sockets = omp_get_num_places();
    #pragma omp parallel num_threads(n_sockets) private(socket_num) \ proc_bind(spread)
```
subroutine socket_init(socket_num)
  use omp_lib
  integer :: socket_num, n_procs
  n_procs = omp_get_place_num_procs(socket_num)
  !$omp parallel num_threads(n_procs) proc_bind(close)
  print*,"Reporting in from socket num, thread num: ", &
  socket_num,omp_get_thread_num()
  !$omp end parallel
end subroutine

program numa_teams
  use omp_lib
  integer :: n_sockets, socket_num
  call omp_set_nested(.true.) ! or export OMP_NESTED=true
  call omp_set_max_active_levels(2) ! or export OMP_MAX_ACTIVE_LEVELS=2
  n_sockets = omp_get_num_places()
  !$omp parallel num_threads(n_sockets) private(socket_num) &
  !$omp proc_bind(spread)
  socket_num = omp_get_place_num()
  call socket_init(socket_num)
end program
CHAPTER 3

Tasking

Tasking constructs provide units of work to a thread for execution. Worksharing constructs do this, too (e.g. for, do, sections, and singles constructs); but the work units are tightly controlled by an iteration limit and limited scheduling, or a limited number of sections or single regions. Worksharing was designed with "data parallel" computing in mind. Tasking was designed for "task parallel" computing and often involves non-locality or irregularity in memory access.

The task construct can be used to execute work chunks: in a while loop; while traversing nodes in a list; at nodes in a tree graph; or in a normal loop (with a taskloop construct). Unlike the statically scheduled loop iterations of worksharing, a task is often enqueued, and then dequeued for execution by any of the threads of the team within a parallel region. The generation of tasks can be from a single generating thread (creating sibling tasks), or from multiple generators in a recursive graph tree traversals. A taskloop construct bundles iterations of an associated loop into tasks, and provides similar controls found in the task construct.

Sibling tasks are synchronized by the taskwait construct, and tasks and their descendant tasks can be synchronized by containing them in a taskgroup region. Ordered execution is accomplished by specifying dependences with a depend clause. Also, priorities can be specified as hints to the scheduler through a priority clause.

Various clauses can be used to manage and optimize task generation, as well as reduce the overhead of execution and to relinquish control of threads for work balance and forward progress.

Once a thread starts executing a task, it is the designated thread for executing the task to completion, even though it may leave the execution at a scheduling point and return later. The thread is tied to the task. Scheduling points can be introduced with the taskyield construct. With an untied clause any other thread is allowed to continue the task. An if clause with a true expression allows the generating thread to immediately execute the task as an undeferred task. By including the data environment of the generating task into the generated task with the mergeable and final clauses, task generation overhead can be reduced.

A complete list of the tasking constructs and details of their clauses can be found in the Tasking Constructs chapter of the OpenMP Specifications, in the OpenMP Application Programming Interface section.
3.1 The task and taskwait Constructs

The following example shows how to traverse a tree-like structure using explicit tasks. Note that the `traverse` function should be called from within a parallel region for the different specified tasks to be executed in parallel. Also note that the tasks will be executed in no specified order because there are no synchronization directives. Thus, assuming that the traversal will be done in post order, as in the sequential code, is wrong.

```c
struct node {
    struct node *left;
    struct node *right;
};

extern void process(struct node *);

void traverse( struct node *p ) {
    if (p->left)
        #pragma omp task // p is firstprivate by default
        traverse(p->left);
    if (p->right)
        #pragma omp task // p is firstprivate by default
        traverse(p->right);
    process(p);
}
```

```fortran
RECURSIVE SUBROUTINE traverse ( P )
    TYPE Node
    TYPE(Node), POINTER :: left, right
END TYPE Node

    TYPE(Node) :: P

    IF (associated(P%left)) THEN
        !$OMP TASK ! P is firstprivate by default
        CALL traverse(P%left)
        !$OMP END TASK
    ENDF
```
In the next example, we force a postorder traversal of the tree by adding a `taskwait` directive. Now, we can safely assume that the left and right sons have been executed before we process the current node.

```c
struct node {
  struct node *left;
  struct node *right;
};
extern void process(struct node *);
void postorder_traverse( struct node *p ) {
  if (p->left)
    #pragma omp task // p is firstprivate by default
    postorder_traverse(p->left);
  if (p->right)
    #pragma omp task // p is firstprivate by default
    postorder_traverse(p->right);
  #pragma omp taskwait
  process(p);
}
```
Example tasking.2.f90

```fortran
RECURSIVE SUBROUTINE traverse ( P )
  TYPE Node
    TYPE(Node), POINTER :: left, right
  END TYPE Node
  TYPE(Node) :: P
  IF (associated(P%left)) THEN
    !$OMP TASK ! P is firstprivate by default
    CALL traverse(P%left)
  !$OMP END TASK
  ENDIF
  IF (associated(P%right)) THEN
    !$OMP TASK ! P is firstprivate by default
    CALL traverse(P%right)
  !$OMP END TASK
  ENDIF
  !$OMP TASKWAIT
  CALL process ( P )
END SUBROUTINE
```

The following example demonstrates how to use the task construct to process elements of a linked list in parallel. The thread executing the single region generates all of the explicit tasks, which are then executed by the threads in the current team. The pointer p is firstprivate by default on the task construct so it is not necessary to specify it in a firstprivate clause.

Example tasking.3.c

```c
typedef struct node node;
struct node {
  int data;
  node * next;
};
void process(node * p)
{
  /* do work here */
}
void increment_list_items(node * head)
{
  #pragma omp parallel
  {
```
```c
#pragma omp single
{
    node * p = head;
    while (p) {
        #pragma omp task
        // p is firstprivate by default
        process(p);
        p = p->next;
    }
}
```

---

**Example tasking.3.f90**

```fortran
MODULE LIST

    TYPE NODE
    INTEGER :: PAYLOAD
    TYPE (NODE), POINTER :: NEXT
END TYPE NODE

CONTAINS

    SUBROUTINE PROCESS(p)
        TYPE (NODE), POINTER :: P
        ! do work here
    END SUBROUTINE

    SUBROUTINE INCREMENT_LIST_ITEMS (HEAD)

        TYPE (NODE), POINTER :: HEAD
        TYPE (NODE), POINTER :: P
        !$OMP PARALLEL PRIVATE(P)
        !$OMP SINGLE
        P => HEAD
        DO
            !$OMP TASK
            ! P is firstprivate by default
            CALL PROCESS(P)
            !$OMP END TASK
            P => P%NEXT
            IF ( .NOT. ASSOCIATED (P) ) EXIT
        END DO
        !$OMP END SINGLE
    END SUBROUTINE

```

---

**CHAPTER 3. TASKING**

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The `fib()` function should be called from within a parallel region for the different specified tasks to be executed in parallel. Also, only one thread of the parallel region should call `fib()` unless multiple concurrent Fibonacci computations are desired.

Example tasking.4.c

```c
int fib(int n) {
    int i, j;
    if (n<2)
        return n;
    else {
        #pragma omp task shared(i)
        i=fib(n-1);
        #pragma omp task shared(j)
        j=fib(n-2);
        #pragma omp taskwait
        return i+j;
    }
}
```

Example tasking.4.f

```fortran
RECURSIVE INTEGER FUNCTION fib(n) RESULT(res)
INTEGER n, i, j
IF ( n .LT. 2) THEN
    res = n
ELSE
    !$OMP TASK SHARED(i)
    i = fib( n-1 )
    !$OMP END TASK
    !$OMP TASK SHARED(j)
    j = fib( n-2 )
    !$OMP END TASK
    !$OMP TASKWAIT
    res = i+j
END IF
END FUNCTION
```
Note: There are more efficient algorithms for computing Fibonacci numbers. This classic recursion algorithm is for illustrative purposes.

The following example demonstrates a way to generate a large number of tasks with one thread and execute them with the threads in the team. While generating these tasks, the implementation may reach its limit on unassigned tasks. If it does, the implementation is allowed to cause the thread executing the task generating loop to suspend its task at the task scheduling point in the `task` directive, and start executing unassigned tasks. Once the number of unassigned tasks is sufficiently low, the thread may resume execution of the task generating loop.

### Example tasking.5.c

```c
#define LARGE_NUMBER 10000000
double item[LARGE_NUMBER];
extern void process(double);

int main() {
    #pragma omp parallel
    {
        #pragma omp single
        {
            int i;
            for (i=0; i<LARGE_NUMBER; i++)
                #pragma omp task // i is firstprivate, item is shared
                process(item[i]);
        }
    }
}
```
The following example is the same as the previous one, except that the tasks are generated in an untied task. While generating the tasks, the implementation may reach its limit on unassigned tasks. If it does, the implementation is allowed to cause the thread executing the task generating loop to suspend its task at the task scheduling point in the task directive, and start executing unassigned tasks. If that thread begins execution of a task that takes a long time to complete, the other threads may complete all the other tasks before it is finished.

In this case, since the loop is in an untied task, any other thread is eligible to resume the task generating loop. In the previous examples, the other threads would be forced to idle until the generating thread finishes its long task, since the task generating loop was in a tied task.
Example tasking.6.f

```fortran
real*8 item(10000000)
!$omp parallel
!$omp single
!$omp task untied
! loop iteration variable i is private
  do i=1,10000000
    !$omp task ! i is firstprivate, item is shared
      call process(item(i))
  end do
!$omp end task
end do
!$omp end task
!$omp end single
!$omp end parallel
end
```

The following two examples demonstrate how the scheduling rules illustrated in Section 2.11.3 of the OpenMP 4.0 specification affect the usage of `threadprivate` variables in tasks. A `threadprivate` variable can be modified by another task that is executed by the same thread. Thus, the value of a `threadprivate` variable cannot be assumed to be unchanged across a task scheduling point. In untied tasks, task scheduling points may be added in any place by the implementation.

A task switch may occur at a task scheduling point. A single thread may execute both of the task regions that modify `tp`. The parts of these task regions in which `tp` is modified may be executed in any order so the resulting value of `var` can be either 1 or 2.
Example tasking.7.c

```c
int tp;
#pragma omp threadprivate(tp)
int var;
void work()
{
#pragma omp task
{
    /* do work here */
#pragma omp task
{
        tp = 1;
    /* do work here */
#pragma omp task
{
    /* no modification of tp */
    var = tp;  // value of tp can be 1 or 2
    }  // end task
    }  // end task
    tp = 2;
}  // end task
}
```
In this example, scheduling constraints prohibit a thread in the team from executing a new task that modifies `tp` while another such task region tied to the same thread is suspended. Therefore, the value written will persist across the task scheduling point.

```
Example tasking.8.c

```
The following two examples demonstrate how the scheduling rules illustrated in Section 2.11.3 of
the OpenMP 4.0 specification affect the usage of locks and critical sections in tasks. If a lock is
held across a task scheduling point, no attempt should be made to acquire the same lock in any code
that may be interleaved. Otherwise, a deadlock is possible.

In the example below, suppose the thread executing task 1 defers task 2. When it encounters the
task scheduling point at task 3, it could suspend task 1 and begin task 2 which will result in a
deadlock when it tries to enter critical region 1.
In the following example, lock is held across a task scheduling point. However, according to the scheduling restrictions, the executing thread can't begin executing one of the non-descendant tasks that also acquires lock before the task region is complete. Therefore, no deadlock is possible.
Example tasking.10.c

```c
#include <omp.h>

void work() {
    omp_lock_t lock;
    omp_init_lock(&lock);
    #pragma omp parallel
    {
        int i;
        #pragma omp for
        for (i = 0; i < 100; i++) {
            #pragma omp task
            {
                // lock is shared by default in the task
                omp_set_lock(&lock);
                // Capture data for the following task
                #pragma omp task
                // Task Scheduling Point 1
                { /* do work here */ }
                omp_unset_lock(&lock);
            }
        }
    }
    omp_destroy_lock(&lock);
}
```

Example tasking.10.f90

```fortran
module example
    include 'omp_lib.h'
    integer (kind=omp_lock_kind) lock
    integer i
contains
    subroutine work
        call omp_init_lock(lock)
        !$omp parallel
        !$omp do
        do i=1,100
        !$omp task
        ! Outer task
        call omp_set_lock(lock) ! lock is shared by
        ! default in the task
```
The following examples illustrate the use of the `mergeable` clause in the `task` construct. In this first example, the `task` construct has been annotated with the `mergeable` clause. The addition of this clause allows the implementation to reuse the data environment (including the ICVs) of the parent task for the task inside `foo` if the task is included or undeferred. Thus, the result of the execution may differ depending on whether the task is merged or not. Therefore the `mergeable` clause needs to be used with caution. In this example, the use of the `mergeable` clause is safe. As `x` is a shared variable the outcome does not depend on whether or not the task is merged (that is, the task will always increment the same variable and will always compute the same value for `x`).

```
#include <stdio.h>

void foo ( )
{
    int x = 2;
    #pragma omp task shared(x) mergeable
    {
        x++;
    }
    #pragma omp taskwait
    printf("%d\n",x);  // prints 3
}
```
Example tasking.11.f90

subroutine foo()
    integer :: x
    x = 2
    !$omp task shared(x) mergeable
    x = x + 1
    !$omp end task
    !$omp taskwait
    print *, x ! prints 3
end subroutine

This second example shows an incorrect use of the `mergeable` clause. In this example, the created task will access different instances of the variable `x` if the task is not merged, as `x` is `firstprivate`, but it will access the same variable `x` if the task is merged. As a result, the behavior of the program is unspecified and it can print two different values for `x` depending on the decisions taken by the implementation.

Example tasking.12.c

#include <stdio.h>
void foo ( )
{
    int x = 2;
    #pragma omp task mergeable
    {
        x++;
    }
    #pragma omp taskwait
    printf("%d\n",x); // prints 2 or 3
The following example shows the use of the `final` clause and the `omp_in_final` API call in a recursive binary search program. To reduce overhead, once a certain depth of recursion is reached the program uses the `final` clause to create only included tasks, which allow additional optimizations.

The use of the `omp_in_final` API call allows programmers to optimize their code by specifying which parts of the program are not necessary when a task can create only included tasks (that is, the code is inside a `final` task). In this example, the use of a different state variable is not necessary so once the program reaches the part of the computation that is finalized and copying from the parent state to the new state is eliminated. The allocation of `new_state` in the stack could also be avoided but it would make this example less clear. The `final` clause is most effective when used in conjunction with the `mergeable` clause since all tasks created in a `final` task region are included tasks that can be merged if the `mergeable` clause is present.

```c
#include <string.h>
#include <omp.h>
#define LIMIT 3 /* arbitrary limit on recursion depth */

void check_solution(char *);

void bin_search (int pos, int n, char *state)
{
    if ( pos == n ) {
        check_solution(state);
        return;
    }
    #pragma omp task final( pos > LIMIT ) mergeable
    {
        char new_state[n];
        if (!omp_in_final() ) {
            memcpy(new_state, state, pos);
```

### Example tasking.12.f90

```fortran
subroutine foo()
    integer :: x
    x = 2
    !$omp task mergeable
    x = x + 1
    !$omp end task
    !$omp taskwait
    print *, x ! prints 2 or 3
end subroutine
```

### Example tasking.13.c

```c
#include <string.h>
#include <omp.h>
#define LIMIT 3 /* arbitrary limit on recursion depth */

void check_solution(char *);

void bin_search (int pos, int n, char *state)
{
    if ( pos == n ) {
        check_solution(state);
        return;
    }
    #pragma omp task final( pos > LIMIT ) mergeable
    {
        char new_state[n];
        if (!omp_in_final() ) {
            memcpy(new_state, state, pos);
```
```c
state = new_state;
}
state[pos] = 0;
bin_search(pos+1, n, state);
}
#pragma omp task final( pos > LIMIT ) mergeable
{
    char new_state[n];
    if (! omp_in_final() ) {
        memcpy(new_state, state, pos);
        state = new_state;
    }
    state[pos] = 1;
    bin_search(pos+1, n, state);
}
#pragma omp taskwait
```
The following example illustrates the difference between the `if` and the `final` clauses. The `if` clause has a local effect. In the first nest of tasks, the one that has the `if` clause will be undeferred but the task nested inside that task will not be affected by the `if` clause and will be created as usual. Alternatively, the `final` clause affects all `task` constructs in the `final` task region but not the `final` task itself. In the second nest of tasks, the nested tasks will be created as included tasks. Note also that the conditions for the `if` and `final` clauses are usually the opposite.

```c
void bar(void);

void foo ()
{
    int i;
    #pragma omp task if(0) // This task is undeferred
    {
        #pragma omp task // This task is a regular task
        for (i = 0; i < 3; i++) {
            #pragma omp task // This task is a regular task
            bar();
        }
    }
    #pragma omp task final(1) // This task is a regular task
    {
        #pragma omp task // This task is included
        for (i = 0; i < 3; i++) {
            #pragma omp task // This task is also included
            bar();
        }
    }
}
```

The Fortran code is as follows:

```fortran
!$omp end task
!$omp taskwait
end subroutine
```

**Example tasking.14.c**
Example tasking.14.f90

subroutine foo()
  integer i

  !$omp task if(.FALSE.) ! This task is undeferred
  !$omp task ! This task is a regular task
  do i = 1, 3
    !$omp task ! This task is a regular task
    call bar()
    !$omp end task
  enddo

  !$omp end task
  !$omp end task
  !$omp task final(.TRUE.) ! This task is a regular task
  !$omp task ! This task is included
  do i = 1, 3
    !$omp task ! This task is also included
    call bar()
    !$omp end task
  enddo

  !$omp end task
  !$omp end task
end subroutine
3.2 Task Priority

In this example we compute arrays in a matrix through a `compute_array` routine. Each task has a priority value equal to the value of the loop variable \( i \) at the moment of its creation. A higher priority on a task means that a task is a candidate to run sooner.

The creation of tasks occurs in ascending order (according to the iteration space of the loop) but a hint, by means of the `priority` clause, is provided to reverse the execution order.

```c
void compute_array (float *node, int M);
```

```c
void compute_matrix (float *array, int N, int M) {
    int i;
    #pragma omp parallel private(i)
    #pragma omp single
    { 
        for (i=0; i<N; i++) {
            #pragma omp task priority(i)
            compute_array(&array[i*M], M);
        }
    }
}
```

```fortran
subroutine compute_matrix(matrix, M, N)
    implicit none
    integer :: M, N
    real :: matrix(M, N)
    integer :: i
    interface
        subroutine compute_array(node, M)
            implicit none
            integer :: M
            real :: node(M)
        end subroutine
    end interface
    !$omp parallel private(i)
    !$omp single
    do i=1,N
        !$omp task priority(i)
    end do
```

Example task_priority.1.c

Example task_priority.1.f90
call compute_array(matrix(:, i), M)

enddo

!$omp end single

!$omp end parallel

end subroutine compute_matrix
3.3 Task Dependences

3.3.1 Flow Dependence

This example shows a simple flow dependence using a `depend` clause on the `task` construct.

```
#include <stdio.h>

int main() {
    int x = 1;
    #pragma omp parallel
    #pragma omp single
    {
        #pragma omp task shared(x) depend(out: x)
        x = 2;
        #pragma omp task shared(x) depend(in: x)
        printf("x = %d\n", x);
    }
    return 0;
}
```

Example task_dep.1.c

```
program example
    integer :: x
    x = 1
    !$omp parallel
    !$omp single
    !$omp task shared(x) depend(out: x)
    x = 2
    !$omp end task
    !$omp task shared(x) depend(in: x)
    print*, "x = ", x
    !$omp end task
    !$omp end single
    !$omp end parallel
end program
```

Example task_dep.1.f90

The program will always print "x = 2", because the `depend` clauses enforce the ordering of the tasks. If the `depend` clauses had been omitted, then the tasks could execute in any order and the program and the program would have a race condition.
3.3.2 Anti-dependence

This example shows an anti-dependence using the depend clause on the task construct.

```
#include <stdio.h>

int main()
{
    int x = 1;
    #pragma omp parallel
    #pragma omp single
    {
        #pragma omp task shared(x) depend(in: x)
        printf("x = %d\n", x);
        #pragma omp task shared(x) depend(out: x)
        x = 2;
    }
    return 0;
}
```

```
program example
   integer :: x
   x = 1
   !$omp parallel
   !$omp single
   !$omp task shared(x) depend(in: x)
   print*, "x = ", x
   !$omp end task
   !$omp task shared(x) depend(out: x)
   x = 2
   !$omp end task
   !$omp end single
   !$omp end parallel
end program
```

The program will always print "x = 1", because the depend clauses enforce the ordering of the tasks. If the depend clauses had been omitted, then the tasks could execute in any order and the program would have a race condition.
3.3.3 Output Dependence

This example shows an output dependence using the `depend` clause on the `task` construct.

```c
#include <stdio.h>

int main() {
    int x;
    #pragma omp parallel
    #pragma omp single
    {
        #pragma omp task shared(x) depend(out: x)
        x = 1;
        #pragma omp task shared(x) depend(out: x)
        x = 2;
        #pragma omp taskwait
        printf("x = %d\n", x);
    }
    return 0;
}
```

The program will always print "x = 2", because the `depend` clauses enforce the ordering of the tasks. If the `depend` clauses had been omitted, then the tasks could execute in any order and the program would have a race condition.
3.3.4 Concurrent Execution with Dependences

In this example we show potentially concurrent execution of tasks using multiple flow dependences expressed using the `depend` clause on the `task` construct.

---

**Example task_dep.4.c**

```c
#include <stdio.h>

int main() {
    int x = 1;
    #pragma omp parallel
    #pragma omp single
    {
        #pragma omp task shared(x) depend(out: x)
        x = 2;
        #pragma omp task shared(x) depend(in: x)
        printf("x + 1 = %d. ", x+1);
        #pragma omp task shared(x) depend(in: x)
        printf("x + 2 = %d\n", x+2);
    }
    return 0;
}
```

---

**Example task_dep.4.f90**

```fortran
program example
    integer :: x
    x = 1
    !$omp parallel
    !$omp single
    !$omp task shared(x) depend(out: x)
    x = 2
    !$omp end task
    !$omp task shared(x) depend(in: x)
    print*, "x + 1 = ", x+1, " ."
    !$omp end task
    !$omp task shared(x) depend(in: x)
    print*, "x + 2 = ", x+2, " ."
```

---
The last two tasks are dependent on the first task. However there is no dependence between the last two tasks, which may execute in any order (or concurrently if more than one thread is available). Thus, the possible outputs are "x + 1 = 3. x + 2 = 4." and "x + 2 = 4. x + 1 = 3.". If the depend clauses had been omitted, then all of the tasks could execute in any order and the program would have a race condition.

6 3.3.5 Matrix multiplication

This example shows a task-based blocked matrix multiplication. Matrices are of NxN elements, and the multiplication is implemented using blocks of BSxBS elements.

Example task_dep.5.c

```c
// Assume BS divides N perfectly
void matmul_depend(int N, int BS, float A[N][N], float B[N][N], float C[N][N] )
{
    int i, j, k, ii, jj, kk;
    for (i = 0; i < N; i+=BS) {
        for (j = 0; j < N; j+=BS) {
            for (k = 0; k < N; k+=BS) {
                // Note 1: i, j, k, A, B, C are firstprivate by default
                // Note 2: A, B and C are just pointers
                #pragma omp task private(ii, jj, kk) \
                depend ( in: A[i:BS][k:BS], B[k:BS][j:BS] ) \
                depend ( inout: C[i:BS][j:BS] ) \
                for (ii = i; ii < i+BS; ii++ )
                for (jj = j; jj < j+BS; jj++ )
                for (kk = k; kk < k+BS; kk++ )
            }
        }
    }
}
```
Example task_dep.5.f90

! Assume BS divides N perfectly

subroutine matmul_depend (N, BS, A, B, C)
  implicit none
  integer :: N, BS, BM
  real, dimension(N, N) :: A, B, C
  integer :: i, j, k, ii, jj, kk
  BM = BS - 1
  do i = 1, N, BS
    do j = 1, N, BS
      do k = 1, N, BS
        !$omp task shared(A,B,C) private(ii,jj,kk) &
        !$omp depend ( in: A(i:i+BM, k:k+BM), B(k:k+BM, j:j+BM) ) &
        !$omp depend ( inout: C(i:i+BM, j:j+BM) )
        do ii = i, i+BM
          do jj = j, j+BM
            do kk = k, k+BM
              C(jj,ii) = C(jj,ii) + A(kk,ii) * B(jj,kk)
            end do
          end do
        end do
      end do
    end do
  end do
  !$omp end task
end subroutine

3.3.6 taskwait with Dependences

In this subsection three examples illustrate how the depend clause can be applied to a taskwait construct to make the generating task wait for specific child tasks to complete. This is an OpenMP 5.0 feature. In the same manner that dependences can order executions among child tasks with depend clauses on task constructs, the generating task can be scheduled to wait on child tasks at a taskwait before it can proceed.

Note: Since the depend clause on a taskwait construct relaxes the default synchronization behavior (waiting for all children to finish), it is important to realize that child tasks that are not predecessor tasks, as determined by the depend clause of the taskwait construct, may be running concurrently while the generating task is executing after the taskwait.
In the first example the generating task waits at the `taskwait` construct for the completion of the first child task because a dependence on the first task is produced by \( x \) with an `in` dependence type within the `depend` clause of the `taskwait` construct. Immediately after the first `taskwait` construct it is safe to access the \( x \) variable by the generating task, as shown in the print statement. There is no completion restraint on the second child task. Hence, immediately after the first `taskwait` it is unsafe to access the \( y \) variable since the second child task may still be executing. The second `taskwait` ensures that the second child task has completed; hence it is safe to access the \( y \) variable in the following print statement.

```
#include<stdio.h>

void foo()
{
    int x = 0, y = 2;

    #pragma omp task depend(inout: x) shared(x)
    x++; // 1st child task

    #pragma omp task shared(y)
    y--; // 2nd child task

    #pragma omp taskwait depend(in: x) // 1st taskwait
    printf("x=%d\n",x);

    // Second task may not be finished.
    // Accessing y here will create a race condition.

    #pragma omp taskwait // 2nd taskwait
    printf("y=%d\n",y);
}

int main()
{
    #pragma omp parallel
    #pragma omp single
    foo();

    return 0;
}
```

---

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Example task_dep.6.f90

```fortran
subroutine foo()
    implicit none
    integer :: x, y
    x = 0
    y = 2
    !$omp task depend(inout: x) shared(x)
    x = x + 1 !! 1st child task
    !$omp end task
    !$omp task shared(y)
    y = y - 1 !! 2nd child task
    !$omp end task
    !$omp taskwait depend(in: x) !! 1st taskwait
    print*, "x=", x
    !! Second task may not be finished.
    !! Accessing y here will create a race condition.
    !$omp taskwait !! 2nd taskwait
    print*, "y=", y
end subroutine foo
```

```fortran
program p
    implicit none
    !$omp parallel
    !$omp single
    call foo()
    !$omp end single
    !$omp end parallel
end program p
```

In this example the first two tasks are serialized, because a dependence on the first child is produced by x with the **in** dependence type in the **depend** clause of the second task. However, the generating task at the first **taskwait** waits only on the first child task to complete, because a
dependence on only the first child task is produced by \( x \) with an \texttt{in} dependence type within the \texttt{depend} clause of the \texttt{taskwait} construct. The second \texttt{taskwait} (without a \texttt{depend} clause) is included to guarantee completion of the second task before \( y \) is accessed. (While unnecessary, the \texttt{depend(inout: y)} clause on the 2nd child task is included to illustrate how the child task dependences can be completely annotated in a data-flow model.)

\begin{verbatim}
C / C++

Example task_dep.7.c

#include<stdio.h>

void foo()
{
  int x = 0, y = 2;

  #pragma omp task depend(inout: x) shared(x)
  x++; // 1st child task

  #pragma omp task depend(in: x) depend(inout: y) shared(x, y)
  y -= x; // 2nd child task

  #pragma omp taskwait depend(in: x) // 1st taskwait
  printf("x=%d\n",x);

  // Second task may not be finished.
  // Accessing y here would create a race condition.

  #pragma omp taskwait // 2nd taskwait
  printf("y=%d\n",y);
}

int main()
{
  #pragma omp parallel
  #pragma omp single
  foo();

  return 0;
}
\end{verbatim}

C / C++
Example task_dep.7.f90

subroutine foo()
  implicit none
  integer :: x, y

  x = 0
  y = 2

  !$omp task depend(inout: x) shared(x)
  x = x + 1 !! 1st child task
  !$omp end task

  !$omp task depend(in: x) depend(inout: y) shared(x, y)
  y = y - x !! 2nd child task
  !$omp end task

  !$omp taskwait depend(in: x) !! 1st taskwait
  print*, "x=", x

  !! Second task may not be finished.
  !! Accessing y here would create a race condition.

  !$omp taskwait !! 2nd taskwait
  print*, "y=", y

end subroutine foo

program p
  implicit none
  !$omp parallel
  !$omp single
  call foo()
  !$omp end single
  !$omp end parallel
end program p

This example is similar to the previous one, except the generating task is directed to also wait for completion of the second task.
The depend clause of the taskwait construct now includes an in dependence type for y. Hence the generating task must now wait on completion of any child task having y with an out (here inout) dependence type in its depend clause. So, the depend clause of the taskwait construct now constrains the second task to complete at the taskwait, too. (This change makes the second taskwait of the previous example unnecessary— it has been removed in this example.)

Note: While a taskwait construct ensures that all child tasks have completed; a depend clause on a taskwait construct only waits for specific child tasks (prescribed by the dependence type and list items in the taskwait’s depend clause). This and the previous example illustrate the need to carefully determine the dependence type of variables in the taskwait depend clause when selecting child tasks that the generating task must wait on, so that its execution after the taskwait does not produce race conditions on variables accessed by non-completed child tasks.

```
#include<stdio.h>

void foo()
{
    int x = 0, y = 2;

    #pragma omp task depend(inout: x) shared(x) x++;
    // 1st child task

    #pragma omp task depend(in: x) depend(inout: y) shared(x, y) y -= x;
    // 2st child task

    #pragma omp taskwait depend(in: x,y)

    printf("x=%d\n",x);
    printf("y=%d\n",y);
}

int main()
{
    #pragma omp parallel
    #pragma omp single
    foo();

    return 0;
}
```
subroutine foo()
  implicit none
  integer :: x, y
  x = 0
  y = 2
  !$omp task depend(inout: x) shared(x)
  x = x + 1 ! 1st child task
  !$omp end task
  !$omp task depend(in: x) depend(inout: y) shared(x, y)
  y = y - x ! 2nd child task
  !$omp end task
  !$omp taskwait depend(in: x, y)
  print*, "x=", x
  print*, "y=", y
end subroutine foo

program p
  implicit none
  !$omp parallel
  !$omp single
  call foo()
  !$omp end single
  !$omp end parallel
end program p
3.3.7 Mutually Exclusive Execution with Dependences

In this example we show a series of tasks, including mutually exclusive tasks, expressing dependences using the `depend` clause on the `task` construct.

The program will always print 6. Tasks T1, T2 and T3 will be scheduled first, in any order. Task T4 will be scheduled after tasks T1 and T2 are completed. T5 will be scheduled after tasks T1 and T3 are completed. Due to the `mutexinoutset` dependence type on `c`, T4 and T5 may be scheduled in any order with respect to each other, but not at the same time. Tasks T6 will be scheduled after both T4 and T5 are completed.

---

**Example task_dep.9.c**

```c
#include <stdio.h>

int main()
{
    int a, b, c, d;
    #pragma omp parallel
    #pragma omp single
    {
        #pragma omp task depend(out: c)
        c = 1; /* Task T1 */
        #pragma omp task depend(out: a)
        a = 2; /* Task T2 */
        #pragma omp task depend(out: b)
        b = 3; /* Task T3 */
        #pragma omp task depend(in: a) depend(mutexinoutset: c)
        c += a; /* Task T4 */
        #pragma omp task depend(in: b) depend(mutexinoutset: c)
        c += b; /* Task T5 */
        #pragma omp task depend(in: c)
        d = c; /* Task T6 */
    }
    printf("%d\n", d);
    return 0;
}
```

---

Example task_dep.9.f90

```fortran
program example
  integer :: a, b, c, d
  !$omp parallel
  !$omp single
    !$omp task depend(out: c)
    c = 1      ! Task T1
    !$omp end task
    !$omp task depend(out: a)
    a = 2      ! Task T2
    !$omp end task
    !$omp task depend(out: b)
    b = 3      ! Task T3
    !$omp end task
    !$omp task depend(in: a) depend(mutexinoutset: c)
    c = c + a  ! Task T4
    !$omp end task
    !$omp task depend(in: b) depend(mutexinoutset: c)
    c = c + b  ! Task T5
    !$omp end task
    !$omp task depend(in: c)
    d = c      ! Task T6
    !$omp end task
  !$omp end single
  !$omp end parallel
  print *, d
end program
```

The following example demonstrates a situation where the `mutexinoutset` dependence type is advantageous. If `shortTaskB` completes before `longTaskA`, the runtime can take advantage of this by scheduling `longTaskBC` before `shortTaskAC`.

Example task_dep.10.c

```c
void foo (void)
{
  int a, b, c;
  c = 0;
  #pragma omp parallel
  #pragma omp single
  {
    #pragma omp task depend(out: a)
    a = longTaskA();
  }
```
Example task_dep.10.f90

```fortran
subroutine foo
  integer :: a, b, c
  c = 0
  !$omp parallel
  !$omp single
  !$omp task depend(out: a)
    a = longTaskA()
  !$omp end task
  !$omp task depend(out: b)
    b = shortTaskB()
  !$omp end task
  !$omp task depend(in: a) depend(mutexinoutset: c)
    c = shortTaskAC(a,c)
  !$omp end task
  !$omp task depend(in: b) depend(mutexinoutset: c)
    c = longTaskBC(b,c)
  !$omp end task
  !$omp end single
  !$omp end parallel
end subroutine foo
```

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3.3.8 Multidependences Using Iterators

The following example uses an iterator to define a dynamic number of dependences.

In the `single` construct of a parallel region a loop generates n tasks and each task has an `out` dependence specified through an element of the v array. This is followed by a single task that defines an `in` dependence on each element of the array. This is accomplished by using the `iterator` modifier in the `depend` clause, supporting a dynamic number of dependences (n here).

The task for the `print_all_elements` function is not executed until all dependences prescribed (or registered) by the iterator are fulfilled; that is, after all the tasks generated by the loop have completed.

Note, one cannot simply use an array section in the `depend` clause of the second task construct because this would violate the `depend` clause restriction:

"List items used in `depend` clauses of the same task or sibling tasks must indicate identical storage locations or disjoint storage locations".

In this case each of the loop tasks use a single disjoint (different storage) element in their `depend` clause; however, the array-section storage area prescribed in the commented directive is neither identical nor disjoint to the storage prescribed by the elements of the loop tasks. The iterator overcomes this restriction by effectively creating n disjoint storage areas.

```c
#include<stdio.h>

void set_an_element(int *p, int val) {
    *p = val;
}

void print_all_elements(int *v, int n) {
    int i;
    for (i = 0; i < n; ++i) {
        printf("%d, ", v[i]);
    }
    printf("\n");
}

void parallel_computation(int n) {
    int v[n];
    #pragma omp parallel
    #pragma omp single
    {
        int i;
    }
```
for (i = 0; i < n; ++i)
    #pragma omp task depend(out: v[i])
    set_an_element(&v[i], i);

#pragma omp task depend(iterator(it = 0:n), in: v[it])
    // #pragma omp task depend(in: v[0:n]) Violates Array section restriction.
print_all_elements(v, n);

Example task_dep.11.f90

subroutine set_an_element(e, val)
  implicit none
  integer :: e, val
  e = val
end subroutine

subroutine print_all_elements(v, n)
  implicit none
  integer :: n, v(n)
  print *, v
end subroutine

subroutine parallel_computation(n)
  implicit none
  integer :: n
  integer :: i, v(n)
  do i=1, n
      !$omp task depend(out: v(i))
      all set_an_element(v(i), i)
  !$omp end task
  enddo
  !$omp task depend(iterator(it = 1:n), in: v(it))

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!!$omp task depend(in: v(1:n)) Violates Array section restriction.
call print_all_elements(v, n)
!!$omp end task
!!$omp end single
!!$omp end parallel
end subroutine
3.4 The taskgroup Construct

In this example, tasks are grouped and synchronized using the taskgroup construct.

Initially, one task (the task executing the start_background_work() call) is created in the parallel region, and later a parallel tree traversal is started (the task executing the root of the recursive compute_tree() calls). While synchronizing tasks at the end of each tree traversal, using the taskgroup construct ensures that the formerly started background task does not participate in the synchronization, and is left free to execute in parallel. This is opposed to the behavior of the taskwait construct, which would include the background tasks in the synchronization.

---

Example taskgroup.1.c

```c
extern void start_background_work(void);
extern void check_step(void);
extern void print_results(void);
struct tree_node
{
    struct tree_node *left;
    struct tree_node *right;
};
typedef struct tree_node* tree_type;
extern void init_tree(tree_type);
define max_steps 100
void compute_something(tree_type tree)
{
    // some computation
}
void compute_tree(tree_type tree)
{
    if (tree->left)
    {
        #pragma omp task
        compute_tree(tree->left);
    }
    if (tree->right)
    {
        #pragma omp task
        compute_tree(tree->right);
    }
    #pragma omp task
    compute_something(tree);
}
int main()
{
```

---

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int i;
tree_type tree;
init_tree(tree);
#pragma omp parallel
#pragma omp single
{
    #pragma omp task
    start_background_work();
    for (i = 0; i < max_steps; i++)
    {
        #pragma omp taskgroup
        {
            #pragma omp task
            compute_tree(tree);
        } // wait on tree traversal in this step
        check_step();
    }
} // only now is background work required to be complete
print_results();
return 0;

Example taskgroup.1.f90

module tree_type_mod
    integer, parameter :: max_steps=100
    type tree_type
        type(tree_type), pointer :: left, right
    end type
contains
    subroutine compute_something(tree)
        type(tree_type), pointer :: tree
    ! some computation
    end subroutine
recursive subroutine compute_tree(tree)
    type(tree_type), pointer :: tree
    if (associated(tree%left)) then
        !$omp task
        call compute_tree(tree%left)
        !$omp end task
    endif
    if (associated(tree%right)) then
        !$omp task
        call compute_tree(tree%right)
        !$omp end task
end subroutine
endif

!$omp task
    call compute_something(tree)
!$omp end task
end subroutine

end module

program main

use tree_type_mod

type(tree_type), pointer :: tree

call init_tree(tree);
!
!$omp parallel
!$omp single
!$omp task
    call start_background_work()
!$omp end task
!$omp end single
!$omp end parallel

!$omp taskgroup
!$omp task
    call compute_tree(tree)
!$omp end task
!$omp end taskgroup ! wait on tree traversal in this step
!$omp taskgroup ! only now is background work required to be complete
    call check_step()
!$omp end taskgroup

enddo

end program
3.5 The taskyield Construct

The following example illustrates the use of the taskyield directive. The tasks in the example compute something useful and then do some computation that must be done in a critical region. By using taskyield when a task cannot get access to the critical region the implementation can suspend the current task and schedule some other task that can do something useful.

---

### Example taskyield.1.c

```c
#include <omp.h>  

void something_useful ( void );
void something_critical ( void );

void foo ( omp_lock_t * lock, int n )
{
  int i;
  for ( i = 0; i < n; i++ )
    #pragma omp task
    {
      something_useful();
      while ( !omp_test_lock(lock) ) {
        #pragma omp taskyield
      }
      something_critical();
      omp_unset_lock(lock);
    }
}
```

---

### Example taskyield.1.f90

```fortran
subroutine foo ( lock, n )  
  use omp_lib
  integer (kind=omp_lock_kind) :: lock
  integer n
  integer i

  do i = 1, n
    !$omp task
    call something_useful()
    do while ( .not. omp_test_lock(lock) )
      !$omp taskyield
    end do
  end do
```

---

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call something_critical()
call omp_unset_lock(lock)
 !$omp end task
end do
end subroutine

---

Fortran
3.6 The taskloop Construct

The following example illustrates how to execute a long running task concurrently with tasks created with a taskloop directive for a loop having unbalanced amounts of work for its iterations.

The grainsize clause specifies that each task is to execute at least 500 iterations of the loop.

The nogroup clause removes the implicit taskgroup of the taskloop construct; the explicit taskgroup construct in the example ensures that the function is not exited before the long-running task and the loops have finished execution.

```
void long_running_task(void);
void loop_body(int i, int j);
void parallel_work(void) {
    int i, j;
    #pragma omp taskgroup
    {
        #pragma omp task
        long_running_task(); // can execute concurrently
        #pragma omp taskloop private(j) grainsize(500) nogroup
        for (i = 0; i < 10000; i++) { // can execute concurrently
            for (j = 0; j < i; j++) {
                loop_body(i, j);
            }
        }
    }
}
```

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Because a **taskloop** construct encloses a loop, it is often incorrectly perceived as a worksharing construct (when it is directly nested in a **parallel** region).

While a worksharing construct distributes the loop iterations across all threads in a team, the entire loop of a **taskloop** construct is executed by every thread of the team.

In the example below the first taskloop occurs closely nested within a **parallel** region and the entire loop is executed by each of the $T$ threads; hence the reduction sum is executed $T \times N$ times.

The loop of the second taskloop is within a **single** region and is executed by a single thread so that only $N$ reduction sums occur. (The other $N-1$ threads of the **parallel** region will participate in executing the tasks. This is the common use case for the **taskloop** construct.)

In the example, the code thus prints $x_1 = 16384 \ (T \times N)$ and $x_2 = 1024 \ (N)$. 
Example taskloop.2.c

```c
#include <stdio.h>

#define T 16
#define N 1024

void parallel_work() {
    int x1 = 0, x2 = 0;

    #pragma omp parallel shared(x1,x2) num_threads(T)
    {
        #pragma omp taskloop
        for (int i = 0; i < N; ++i) {
            #pragma omp atomic
            x1++; // executed T*N times
        }

        #pragma omp single
        #pragma omp taskloop
        for (int i = 0; i < N; ++i) {
            #pragma omp atomic
            x2++; // executed N times
        }
    }

    printf("x1 = %d, x2 = %d\n", x1, x2);
}
```

Example taskloop.2.f90

```fortran
subroutine parallel_work
    implicit none

    integer :: x1, x2
    integer :: i
    integer, parameter :: T = 16
    integer, parameter :: N = 1024

    x1 = 0
    x2 = 0

    !$omp parallel shared(x1,x2) num_threads(T)
    !$omp taskloop
    do i = 1,N
        !$omp atomic
```
x1 = x1 + 1 ! executed T*N times
end do
!$omp end taskloop

!$omp single
!$omp taskloop
do i = 1,N
!$omp atomic
x2 = x2 + 1 ! executed N times
!$omp end atomic
end do
!$omp end taskloop
!$omp end single
!$omp end parallel

write (*,'(A,I0,A,I0)') 'x1 = ', x1, ', x2 = ',x2
end subroutine
3.7 The parallel master taskloop Construct

In the OpenMP 5.0 Specification several combined constructs containing the taskloop construct were added.

Just as the for and do constructs have been combined with the parallel construct for convenience, so too, the combined parallel master taskloop and parallel master taskloop simd constructs have been created for convenience.

In the following example the first taskloop construct is enclosed by the usual parallel and master constructs to form a team of threads, and a single task generator (master thread) for the taskloop construct.

The same OpenMP operations for the first taskloop are accomplished by the second taskloop with the parallel master taskloop combined construct. The third taskloop uses the combined parallel master taskloop simd construct to accomplish the same behavior as closely nested parallel master, and taskloop simd constructs.

As with any combined construct the clauses of the components may be used with appropriate restrictions. The combination of the parallel master construct with the taskloop or taskloop simd construct produces no additional restrictions.

---

Example parallel_master_taskloop.1.c

```c
#include <stdio.h>

#define N 100

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

    for(int i=0; i<N; i++) { b[i]=i; c[i]=i; } //init

    #pragma omp parallel
    #pragma omp master
    #pragma omp taskloop     // taskloop 1
    for(i=0; i<N; i++) { a[i] = b[i] + c[i]; }

    #pragma omp parallel master taskloop     // taskloop 2
    for(i=0; i<N; i++) { b[i] = a[i] + c[i]; }

    #pragma omp parallel master taskloop simd // taskloop 3
    for(i=0; i<N; i++) { c[i] = a[i] + b[i]; }

```

---

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Example parallel_master_taskloop.1.f90

program main

integer, parameter :: N=100
integer :: i, a(N), b(N), c(N)

do i=1,N !! initialize
    b(i) = i
    c(i) = i
enddo

!$omp parallel
!$omp master
!$omp taskloop !! taskloop 1
do i=1,N
    a(i) = b(i) + c(i)
enddo
!$omp end taskloop
!$omp end master
!$omp end parallel

!$omp parallel master taskloop !! taskloop 2
do i=1,N
    b(i) = a(i) + c(i)
enddo
!$omp end parallel master taskloop

!$omp parallel master taskloop simd !! taskloop 3
do i=1,N
    c(i) = a(i) + b(i)
enddo
!$omp end parallel master taskloop simd

print*, c(1), c(N) !! 5 and 500

end program
CHAPTER 4

Devices

The target construct consists of a target directive and an execution region. The target region is executed on the default device or the device specified in the device clause.

In OpenMP version 4.0, by default, all variables within the lexical scope of the construct are copied to and from the device, unless the device is the host, or the data exists on the device from a previously executed data-type construct that has created space on the device and possibly copied host data to the device storage.

The constructs that explicitly create storage, transfer data, and free storage on the device are categorized as structured and unstructured. The target data construct is structured. It creates a data region around target constructs, and is convenient for providing persistent data throughout multiple target regions. The target enter data and target exit data constructs are unstructured, because they can occur anywhere and do not support a "structure" (a region) for enclosing target constructs, as does the target data construct.

The map clause is used on target constructs and the data-type constructs to map host data. It specifies the device storage and data movement to and from the device, and controls on the storage duration.

There is an important change in the OpenMP 4.5 specification that alters the data model for scalar variables and C/C++ pointer variables. The default behavior for scalar variables and C/C++ pointer variables in an 4.5 compliant code is firstprivate. Example codes that have been updated to reflect this new behavior are annotated with a description that describes changes required for correct execution. Often it is a simple matter of mapping the variable as tofrom to obtain the intended 4.0 behavior.

In OpenMP version 4.5 the mechanism for target execution is specified as occurring through a target task. When the target construct is encountered a new target task is generated. The target task completes after the target region has executed and all data transfers have finished.

This new specification does not affect the execution of pre-4.5 code; it is a necessary element for asynchronous execution of the target region when using the new nowait clause introduced in OpenMP 4.5.
4.1 target Construct

4.1.1 target Construct on parallel Construct

This following example shows how the target construct offloads a code region to a target device.

The variables p, v1, v2, and N are implicitly mapped to the target device.

Example target.1.c

```c
extern void init(float*, float*, int);
extern void output(float*, int);
void vec_mult(int N)
{
  int i;
  float p[N], v1[N], v2[N];
  init(v1, v2, N);
  #pragma omp target
  #pragma omp parallel for private(i)
  for (i=0; i<N; i++)
    p[i] = v1[i] * v2[i];
  output(p, N);
}
```

Example target.1.f90

```fortran
subroutine vec_mult(N)
  integer :: i,N
  real :: p(N), v1(N), v2(N)
  call init(v1, v2, N)
  !$omp target
  !$omp parallel do
  do i=1,N
    p(i) = v1(i) * v2(i)
  end do
  !$omp end target
  call output(p, N)
end subroutine
```
This following example shows how the target construct offloads a code region to a target device. The variables \( p, v1 \) and \( v2 \) are explicitly mapped to the target device using the map clause. The variable \( N \) is implicitly mapped to the target device.

---

### Example target.2.c

```c
extern void init(float*, float*, int);
extern void output(float*, int);

void vec_mult(int N)
{
    int i;
    float p[N], v1[N], v2[N];
    init(v1, v2, N);
    #pragma omp target map(v1, v2, p)
    #pragma omp parallel for
    for (i=0; i<N; i++)
        p[i] = v1[i] * v2[i];
    output(p, N);
}
```

---

### Example target.2.f90

```fortran
subroutine vec_mult(N)
    integer :: i,N
    real :: p(N), v1(N), v2(N)
    call init(v1, v2, N)
    !$omp target map(v1,v2,p)
    !$omp parallel do
    do i=1,N
        p(i) = v1(i) * v2(i)
    end do
    !$omp end target
    call output(p, N)
end subroutine
```

---

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4.1.3 map Clause with to/from map-types

The following example shows how the target construct offloads a code region to a target device.

In the map clause, the to and from map-types define the mapping between the original (host) data and the target (device) data. The to map-type specifies that the data will only be read on the device, and the from map-type specifies that the data will only be written to on the device. By specifying a guaranteed access on the device, data transfers can be reduced for the target region.

The to map-type indicates that at the start of the target region the variables $v1$ and $v2$ are initialized with the values of the corresponding variables on the host device, and at the end of the target region the variables $v1$ and $v2$ are not assigned to their corresponding variables on the host device.

The from map-type indicates that at the start of the target region the variable $p$ is not initialized with the value of the corresponding variable on the host device, and at the end of the target region the variable $p$ is assigned to the corresponding variable on the host device.

```
S-1 extern void init(float*, float*, int);
S-2 extern void output(float*, int);
S-3 void vec_mult(int N)
S-4 {
S-5     int i;
S-6     float p[N], v1[N], v2[N];
S-7     init(v1, v2, N);
S-8     #pragma omp target map(to: v1, v2) map(from: p)
S-9     #pragma omp parallel for
S-10   for (i=0; i<N; i++)
S-11     p[i] = v1[i] * v2[i];
S-12   output(p, N);
S-13 }
```

The to and from map-types allow programmers to optimize data motion. Since data for the $v$ arrays are not returned, and data for the $p$ array are not transferred to the device, only one-half of the data is moved, compared to the default behavior of an implicit mapping.
2 4.1.4 map Clause with Array Sections

The following example shows how the target construct offloads a code region to a target device. In the map clause, map-types are used to optimize the mapping of variables to the target device. Because variables \( p \), \( v1 \) and \( v2 \) are pointers, array section notation must be used to map the arrays. The notation \( :N \) is equivalent to \( 0:N \).
In C, the length of the pointed-to array must be specified. In Fortran the extent of the array is known and the length need not be specified. A section of the array can be specified with the usual Fortran syntax, as shown in the following example. The value 1 is assumed for the lower bound for array section \( v2(:N) \).

```fortran
module mults
  contains
  subroutine vec_mult(p, v1, v2, N)
    real, pointer, dimension(:) :: p, v1, v2
    integer :: N, i
    call init(v1, v2, N)
    !$omp target map(to: v1(1:N), v2(:N)) map(from: p(1:N))
    !$omp parallel do
    do i = 1, N
      p(i) = v1(i) * v2(i)
    end do
    !$omp end target
    call output(p, N)
  end subroutine
end module
```

A more realistic situation in which an assumed-size array is passed to `vec_mult` requires that the length of the arrays be specified, because the compiler does not know the size of the storage. A section of the array must be specified with the usual Fortran syntax, as shown in the following example. The value 1 is assumed for the lower bound for array section \( v2(:N) \).
### Example target.4b.f90

```fortran
module mults
  contains
  subroutine vec_mult(p,v1,v2,N)
    real,dimension(*) :: p, v1, v2
    integer :: N,i
    call init(v1, v2, N)
    !$omp target map(to: v1(1:N), v2(:N)) map(from: p(1:N))
    !$omp parallel do
    do i=1,N
      p(i) = v1(i) * v2(i)
    end do
    !$omp end target
    call output(p, N)
  end subroutine
  end module
```

### 4.1.5 target Construct with if Clause

The following example shows how the `target` construct offloads a code region to a target device.

The `if` clause on the `target` construct indicates that if the variable \( N \) is smaller than a given threshold, then the `target` region will be executed by the host device.

The `if` clause on the `parallel` construct indicates that if the variable \( N \) is smaller than a second threshold then the `parallel` region is inactive.

### Example target.5.c

```c
#define THRESHOLD1 1000000
#define THRESHOLD2 1000
extern void init(float*, float*, int);
extern void output(float*, int);
void vec_mult(float *p, float *v1, float *v2, int N)
{
  int i;
  init(v1, v2, N);
  #pragma omp target if(N>THRESHOLD1) map(to: v1[0:N], v2[:N])
  map(from: p[0:N])
  #pragma omp parallel for if(N>THRESHOLD2)
```
The following example is a modification of the above `target.5` code to show the combined `target` and parallel loop directives. It uses the `directive-name` modifier in multiple `if` clauses to specify the component directive to which it applies.

The `if` clause with the `target` modifier applies to the `target` component of the combined directive, and the `if` clause with the `parallel` modifier applies to the `parallel` component of the combined directive.
Example target.6.c

```c
#define THRESHOLD1 1000000
#define THRESHOLD2 1000
extern void init(float*, float*, int);
extern void output(float*, int);
void vec_mult(float *p, float *v1, float *v2, int N)
{
    int i;
    init(v1, v2, N);
    #pragma omp target parallel for \\
    if(target: N>THRESHOLD1) if(parallel: N>THRESHOLD2) \\
    map(to: v1[0:N], v2[:N]) map(from: p[0:N])
    for (i=0; i<N; i++)
        p[i] = v1[i] * v2[i];
output(p, N);
}
```

Example target.6.f90

```fortran
module params
integer,parameter :: THRESHOLD1=1000000, THRESHOLD2=1000
end module
subroutine vec_mult(p, v1, v2, N)
use params
real :: p(N), v1(N), v2(N)
integer :: i
call init(v1, v2, N)
!$omp target parallel do &
!$omp& if(target: N>THRESHOLD1) if(parallel: N>THRESHOLD2) &
!$omp& map(to: v1, v2 ) map(from: p)
    do i=1,N
        p(i) = v1(i) * v2(i)
    end do
!$omp end target parallel do
end subroutine
```
### 4.1.6 target Reverse Offload

Beginning with OpenMP 5.0, implementations are allowed to offload back to the host (reverse offload).

In the example below the `error_handler` function is executed back on the host, if an erroneous value is detected in the `A` array on the device.

This is accomplished by specifying the `device-modifier ancestor` modifier, along with a device number of 1, to indicate that the execution is to be performed on the immediate parent (1st ancestor)– the host.

The `requires` directive (another 5.0 feature) uses the `reverse_offload` clause to guarantee that the reverse offload is implemented.

Note that the `declare target` directive uses the `device_type` clause (another 5.0 feature) to specify that the `error_handler` function is compiled to execute on the host only. This ensures that no attempt will be made to create a device version of the function. This feature may be necessary if the function exists in another compile unit.

#### C / C++

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

#define N 100

#pragma omp requires reverse_offload
void error_handler(int wrong_value, int index)
{
    printf(" Error in offload: A[%d]=%d\n", index,wrong_value);
    printf(" Expecting: A[i ]=i\n");
    exit(1);
    // output: Error in offload: A[99]=-1
    // Expecting: A[i ]=i
}

#pragma omp declare target device_type(host) to(error_handler)

int main()
{
    int A[N];
    for (int i=0; i<N; i++) A[i] = i;
```
A[N-1]=-1;

#pragma omp target map(A)
{
    for (int i=0; i<N; i++)
    {
        if (A[i] != i)
        {
            #pragma omp target device(ancestor: 1) map(always,to: A[i:1])
            error_handler(A[i], i);
        }
    }
}
return 0;

Example target_reverse_offload.7.f90

!$omp requires reverse_offload

subroutine error_handler(wrong_value, index)
    integer :: error_value,index
    !$omp declare target device_type(host)
    write( *,'(Error in offload: A(',i3,')=',i3) ) index,wrong_value
    write( *,'( Expecting: A( i)= i')
    stop
    !!output: Error in offload: A( 99)= -1
    !! Expecting: A( i)= i
end subroutine

program rev_off
    use omp_lib
    integer, parameter :: N=100
    integer :: A(N) = (/ (i, i=1,100) /)
    A(N-1)=-1
    !$omp target map(A)
    do i=1,N
        if (A(i) /= i) then
            !$omp omp target device(ancestor: 1) map(always,to :A(i))
            call error_handler(A(i), i)
            !$omp omp end target
endif
end do
!$omp end target
end program
4.2 Pointer mapping

The following example shows the basics of mapping pointers with and without associated storage on the host.

Storage for pointers `ptr1` and `ptr2` is created on the host. To map storage that is associated with a pointer on the host, the data can be explicitly mapped as an array section so that the compiler knows the amount of data to be assigned in the device (to the "corresponding" data storage area). On the `target` construct array sections are mapped; however, the pointer `ptr1` is mapped, while `ptr2` is not. Since `ptr2` is not explicitly mapped, it is firstprivate. This creates a subtle difference in the way these pointers can be used.

As a firstprivate pointer, `ptr2` can be manipulated on the device; however, as an explicitly mapped pointer, `ptr1` becomes an attached pointer and cannot be manipulated. In both cases the host pointer is not updated with the device pointer address—as one would expect for distributed memory. The storage data on the host is updated from the corresponding device data at the end of the `target` region.

As a comparison, note that the `array` array is automatically mapped, since the compiler knows the extent of the array.

The pointer `ptr3` is used in the `target` region and has a data-sharing attribute of firstprivate. The pointer is implicitly mapped to a zero-length array section. Neither the pointer address nor any of its locally assigned data on the device is returned to the host.

---

C / C++

```
#include <stdio.h>
#include <stdlib.h>
#define N 100

int main()
{
    int *ptr1;
    int *ptr2;
    int *ptr3;
    int array[N];

    ptr1 = (int *)malloc(sizeof(int)*N);
    ptr2 = (int *)malloc(sizeof(int)*N);

    #pragma omp target map(ptr1, ptr1[:N]) map(ptr2[:N])
    {
        for (int i=0; i<N; i++)
        {
            ptr1[i] = i;
        }
    }
```

---
In the following example the global pointer \( p \) appears in a `declare target` directive. Hence, the pointer \( p \) will persist on the device throughout executions in all target regions.

The pointer is also used in an array section of a `map` clause on a `target` construct. When storage associated with a `declare target` pointer is mapped, as for the array section \( p[:N] \) in the `target` construct, the array section on the device is `attached` to the device pointer \( p \) on entry to the construct, and the value of the device pointer \( p \) becomes undefined on exit. (Of course, storage allocation for the array section on the device will occur before the pointer on the device is `attached`.)

```c
#include <stdio.h>
#include <stdlib.h>
#define N 100

#pragma omp declare target
int *p;
extern void use_arg_p(int *p, int n);
extern void use_global_p( int n);
#pragma omp end declare target
```

```c
printf(" %d  %d\n",ptr1[1],ptr2[1]);
```

```c
free(ptr1);
free(ptr2);
return 0;
```
int main()
{
    int i;
    p = (int *)malloc(sizeof(int)*N);

    #pragma omp target map(p[:N]) // device p attached to array section
    {
        for (i=0; i<N; i++) p[i] = i;
        use_arg_p(p, N);
        use_global_p(N);
    } // value of host p is preserved

    printf(" %3.3d %3.3d\n", p[1], p[N-1]);
    // 003 297 <- output

    free(p);
    return 0;
}

//pragma omp declare target (optional here because of prototype spec)
void use_arg_p(int *q, int n)
{
    int i;
    for (i=0; i<n; i++)
        q[i] *= 2;
}

void use_global_p(int n)
{
    int i;
    for (i=0; i<n; i++)
        p[i] += i; // valid since p is in declare target and called from
                     // inside target region where p was attached to valid memory
}

//pragma omp end declare target (optional here because of prototype spec)
4.3 Structure mapping

In the example below, only structure elements $S.a$, $S.b$ and $S.p$ of the $S$ structure appear in map clauses of a target construct. Only these components have corresponding variables and storage on the device. Hence, the large arrays, $S.buffera$ and $S.bufferb$, and the $S.x$ component have no storage on the device and cannot be accessed.

Also, since the pointer member $S.p$ is used in an array section of a map clause, the array storage of the array section on the device, $S.p[:N]$, is attached to the pointer member $S.p$ on the device.

Explicitly mapping the pointer member $S.p$ is optional in this case.

Note: The buffer arrays and the $x$ variable have been grouped together, so that the components that will reside on the device are all together (without gaps). This allows the runtime to optimize the transfer and the storage footprint on the device.

---

**C / C++**

Example target_struct_map.1.c

```c
#include <stdio.h>
#include <stdlib.h>
#define N 100
#define BAZILLION 2000000

struct foo {
    char buffera[BAZILLION];
    char bufferb[BAZILLION];
    float x;
    float a, b;
    float *p;
};

#pragma omp declare target
void saxpyfun(struct foo *S) {
    int i;
    for(i=0; i<N; i++)
        S->p[i] = S->p[i]*S->a + S->b;
}

#pragma omp end declare target

int main() {
    struct foo S;
    int i;
    S.a = 2.0;
    S.b = 4.0;
```
The following example is a slight modification of the above example for a C++ class. In the member function `SAXPY::driver` the array section `p[:N]` is attached to the pointer member `p` on the device.

```cpp
#include <cstdio>
#include <cstdlib>
#define N 100

class SAXPY {
    private:
    float a, b, *p;
    public:
    float buffer[N];

    SAXPY(float arg_a, float arg_b){ a=arg_a; b=arg_b; }
    void driver();
    void saxpyfun(float *p);
};

#pragma omp declare target
void SAXPY::saxpyfun(float *q)
{
    for(int i=0; i<N; i++)
        buffer[i] = q[i]*a + b;
}

#pragma omp end declare target

void SAXPY::driver()
{
    p = (float *) malloc(N*sizeof(float));
    for(int i=0; i<N; i++) p[i]=i;

    #pragma omp target map(alloc:p) map(to:p[:N]) map(to:a,b) \
```
map(from:buffer[:N]) // attach(p) to device_malloc()
{
    saxpyfun(p);
}
free(p);
}
int main()
{
    SAXPY my_saxpy(2.0, 4.0);
    my_saxpy.driver();
    printf(" %4.0f %4.0f\n", my_saxpy.buffer[0], my_saxpy.buffer[N-1]);
    // 4 202 <- output
    return 0;
}
4.4 Array Sections in Device Constructs

The following examples show the usage of array sections in map clauses on target and target data constructs.

This example shows the invalid usage of two separate sections of the same array inside of a target construct.

---

C / C++

Example array_sections.1.c

```c
void foo ()
{
    int A[30];
    #pragma omp target data map( A[0:4] )
    {
        /* Cannot map distinct parts of the same array */
        #pragma omp target map( A[7:20] )
        {
            A[2] = 0;
        }
    }
}
```

---

Fortran

Example array_sections.1.f90

```fortran
subroutine foo()
  integer :: A(30)
  A = 1
  !$omp target data map( A(1:4) )
  ! Cannot map distinct parts of the same array
  !$omp target map( A(8:27) )
  A(3) = 0
  !$omp end target
  !$omp end target data
end subroutine
```
This example shows the invalid usage of two separate sections of the same array inside of a `target` construct.

Example array_sections.2.c

```c
void foo ()
{
    int A[30], *p;
    #pragma omp target data map( A[0:4] )
    {
        p = &A[0];
        /* invalid because p[3] and A[3] are the same
         * location on the host but the array section
         * specified via p[...] is not a subset of A[0:4] */
        #pragma omp target map( p[3:20] )
        {
            A[2] = 0;
            p[8] = 0;
        }
    }
}
```

Example array_sections.2.f90

```fortran
subroutine foo()
integer,target :: A(30)
integer,pointer :: p(:)
A=1
!$omp target data map( A(1:4) )
p=>A
! invalid because p(4) and A(4) are the same
! location on the host but the array section
! specified via p(...) is not a subset of A(1:4)
!$omp target map( p(4:23) )
    A(3) = 0
    p(9) = 0
!$omp end target
!$omp end target data
end subroutine
```
This example shows the valid usage of two separate sections of the same array inside of a target construct.

Example array_sections.3.c

```c
void foo ()
{
    int A[30], *p;
    #pragma omp target data map( A[0:4] )
    {
        p = &A[0];
        #pragma omp target map( p[7:20] )
        {
            A[2] = 0;
            p[8] = 0;
        }
    }
}
```

Example array_sections.3.f90

```fortran
subroutine foo()
integer,target :: A(30)
integer,pointer :: p(:)
!$omp target data map( A(1:4) )
p=>A
!$omp target map( p(8:27) )
    A(3) = 0
    p(9) = 0
!$omp end target
!$omp end target data
end subroutine
```
This example shows the valid usage of a wholly contained array section of an already mapped array section inside of a `target` construct.

```
Example array_sections.4.c

```C / C++```  ```Fortran```

```
Example array_sections.4.f90

```C / C++```  ```Fortran```
4.5 Array Shaping

A pointer variable can be shaped to a multi-dimensional array to facilitate data access. This is achieved by a *shape-operator* casted in front of a pointer (lvalue expression):

\[(s_1 \times s_2 \ldots \times s_n) pointer\]

where each \(s_i\) is an integral-type expression of positive value. The shape-operator can appear in either the *motion-clause* of the *target update* directive or the *depend* clause.

The following example shows the use of the shape-operator in the *target update* directive. The shape-operator \(([nx][ny+2])\) casts pointer variable \(a\) to a 2-dimensional array of size \(nx\times(ny+2)\). The resulting array is then accessed as array sections (such as \([0:nx][1]\) and \([0:nx][ny]\)) in the *from* or *to* clause for transferring two columns of noncontiguous boundary data from or to the device. Note the use of additional parentheses around the shape-operator and \(a\) to ensure the correct precedence over array-section operations.

*Example array_shaping.1.c*

```
#include <stdio.h>

// void array_shaping(double *a, int nx, int ny) {
   // map data to device and do work
   #pragma omp target data map(a[0:nx*(ny+2)])
   {
      // do work on the device
      #pragma omp target // map(a[0:nx*(ny+2)]) is optional here
      do_work(a, nx, ny);
   }
   // update boundary points (two columns of 2D array) on the host
   // pointer is shaped to 2D array using the shape-operator
   #pragma omp target update from( ([nx][ny+2])a[0:nx][1], \n                                      ([nx][ny+2])a[0:nx][ny] )
   // exchange ghost points with neighbors
   exch_data(a, nx, ny);
   // update ghost points (two columns of 2D array) on the device
   // pointer is shaped to 2D array using the shape-operator
   #pragma omp target update to( ([nx][ny+2])a[0:nx][0], \n                                ([nx][ny+2])a[0:nx][ny+1] )
```

```
# pragma omp declare target
int do_work(double *a, int nx, int ny);
int other_work(double *a, int nx, int ny);
# pragma omp end declare target

void exch_data(double *a, int nx, int ny);

void array_shaping(double *a, int nx, int ny) {
   // map data to device and do work
   #pragma omp target data map(a[0:nx*(ny+2)])
   {
      // do work on the device
      #pragma omp target // map(a[0:nx*(ny+2)]) is optional here
      do_work(a, nx, ny);
   }
   // update boundary points (two columns of 2D array) on the host
   // pointer is shaped to 2D array using the shape-operator
   #pragma omp target update from( ([nx][ny+2])a[0:nx][1], \n                                      ([nx][ny+2])a[0:nx][ny] )
   // exchange ghost points with neighbors
   exch_data(a, nx, ny);
   // update ghost points (two columns of 2D array) on the device
   // pointer is shaped to 2D array using the shape-operator
   #pragma omp target update to( ([nx][ny+2])a[0:nx][0], \n                                ([nx][ny+2])a[0:nx][ny+1] )
```
S-28 \(((nx)[ny+2]) a[0:nx][ny+1] \)  
S-29  
S-30  // perform other work on the device  
S-31  #pragma omp target  // map(a[0:nx*(ny+2)]) is optional here  
S-32  other_work(a, nx, ny);  
S-33  }  
S-34  }

C / C++
4.6 **declare mapper** Construct

The following examples show how to use the `declare mapper` directive to prescribe a map for later use. It is also quite useful for pre-defining partitioned and nested structure elements.

In the first example the `declare mapper` directive specifies that any structure of type `myvec_t` for which implicit data-mapping rules apply will be mapped according to its map clause. The variable `v` is used for referencing the structure and its elements within the map clause. Within the map clause the `v` variable specifies that all elements of the structure are to be mapped. Additionally, the array section `v.data[0:v.len]` specifies that the dynamic storage for data is to be mapped.

Within the main program the `s` variable is typed as `myvec_t`. Since the variable is found within the target region and the type has a mapping prescribed by a `declare mapper` directive, it will be automatically mapped according to its prescription: full structure, plus the dynamic storage of the `data` element.

---

**Example target_mapper.1.c**

```c
#include <stdlib.h>
#include <stdio.h>
#define N 100

typedef struct myvec{
  size_t len;
  double *data;
} myvec_t;

#pragma omp declare mapper(myvec_t v) \
  map(v, v.data[0:v.len])
void init(myvec_t *s);

int main(){
  myvec_t s;
  s.data = (double *)calloc(N,sizeof(double));
  s.len = N;
  #pragma omp target
  init(&s);
  printf("s.data[%d]=%lf\n",N-1,s.data[N-1]); //s.data[99]=99.000000
}

void init(myvec_t *s)
```

---
Example target mapper.1.f90

```
module my_structures
    type myvec_t
        integer :: len
        double precision, pointer :: data(:)
    end type
end module

program main
    use my_structures
    integer, parameter :: N=100

    !$omp declare mapper(myvec_t :: v) &
    !$omp& map(v, v%data(1:v%len))

    type(myvec_t) :: s
    allocate(s%data(N))
    s%data(1:N) = 0.0d0
    s%len = N

    !$omp target
    call init(s)
    !$omp end target

    print*,"s%data(",N,")=",s%data(N) !! s%data( 100 )=100.00000000000
end program

subroutine init(s)
    use my_structures
    type(myvec_t) :: s
    s%data = [ (i, i=1,s%len) ]
end subroutine
```
The next example illustrates the use of the mapper-identifier and deep copy within a structure. The structure, \textit{dzmat\_t}, represents a complex matrix, with separate real ($r_m$) and imaginary ($i_m$) elements. Two map identifiers are created for partitioning the \textit{dzmat\_t} structure.

For the C/C++ code the first identifier is named \textit{top\_id} and maps the top half of two matrices of type \textit{dzmat\_t}; while the second identifier, \textit{bottom\_id}, maps the lower half of two matrices. Each identifier is applied to a different target construct, as \texttt{map(mapper(top\_id), tofrom: a,b)} and \texttt{map(mapper(bottom\_id), tofrom: a,b)}. Each target offload is allowed to execute concurrently on two different devices ($0$ and $1$) through the \texttt{nowait} clause. The OpenMP 5.0 parallel master construct creates a region of two threads for these target constructs, with a single thread (master) generator.

The Fortran code uses the \textit{left\_id} and \textit{right\_id} map identifiers in the \texttt{map(mapper(left\_id), tofrom: a,b)} and \texttt{map(mapper(right\_id), tofrom: a,b)} map clauses. The array sections for these left and right contiguous portions of the matrices were defined previously in the declare mapper directive.

Note, the \texttt{is} and \texttt{ie} scalars are firstprivate by default for a target region, but are declared firstprivate anyway to remind the user of important firstprivate data-sharing properties required here.

---

\texttt{C / C++}

---

\texttt{Example target\_mapper.2.c}

\begin{verbatim}
#include <stdio.h>

// N MUST BE EVEN
#define N 100

typedef struct dzmat
{
    double r_m[N][N];
    double i_m[N][N];
} dzmat_t;

#pragma omp declare mapper( top_id: dzmat_t v) \
    map(v.r_m[0:N/2][0:N], \
        v.i_m[0:N/2][0:N] )

#pragma omp declare mapper(bottom_id: dzmat_t v) \
    map(v.r_m[N/2:N/2][0:N], \
        v.i_m[N/2:N/2][0:N] )

void dzmat_init(dzmat_t *z, int is, int ie, int n); //initialization
void host_add( dzmat_t *a, dzmat_t *b, dzmat_t *c, int n); //matrix add: c=a+b

int main()
{

}
\end{verbatim}
module complex_mats

integer, parameter :: N=100 !N must be even

type dzmat_t
  double precision :: r_m(N,N), i_m(N,N)
end type

!$omp declare mapper( left_id: dzmat_t :: v) map( v%r_m(N, 1:N/2), &
!$omp& v%i_m(N, 1:N/2))

!$omp declare mapper(right_id: dzmat_t :: v) map( v%r_m(N,N/2+1:N), &
!$omp& v%i_m(N,N/2+1:N))

dzmat_t a,b,c;

int is,ie;

is=0; ie=N/2-1; //top N/2 rows on device 0
#pragma omp target map(mapper(top_id), tofrom: a,b) device(0) 
  firstprivate(is,ie) nowait
{
dzmat_init(&a,is,ie,N);
dzmat_init(&b,is,ie,N);
}

is=N/2; ie=N-1; //bottom N/2 rows on device 1
#pragma omp target map(mapper(bottom_id), tofrom: a,b) device(1) 
  firstprivate(is,ie) nowait
{
dzmat_init(&a,is,ie,N);
dzmat_init(&b,is,ie,N);
}

#pragma omp taskwait

host_add(&a,&b,&c,N);

end module

program main
  use complex_mats
  type(dzmat_t) :: a,b,c
external dzmat_init, host_add  !initialization and matrix add: a=b+c

integer :: is, ie

is=1; ie=N/2       !left N/2 columns on device 0
!$omp target map(mapper( left_id), tofrom: a,b) device(0) &
!$omp& firstprivate(is,ie) nowait
    call dzmat_init(a,is,ie)
    call dzmat_init(b,is,ie)
!$omp end target

is=N/2+1; ie=N       !right N/2 columns on device 1
!$omp target map(mapper(right_id), tofrom: a,b) device(1) &
!$omp& firstprivate(is,ie) nowait
    call dzmat_init(a,is,ie)
    call dzmat_init(b,is,ie)
!$omp end target

!omp taskwait

call host_add(a,b,c)

end program main
In the third example myvec structures are nested within a mypoints structure. The myvec_t type is mapped as in the first example. Following the mypoints structure declaration, the mypoints_t type is mapped by a declare mapper directive. For this structure the hostonly_data element will not be mapped; also the array section of x (v.x[:1]) and x will be mapped; and scratch will be allocated and used as scratch storage on the device. The default map-type mapping, tofrom, applies to the x array section, but not to scratch which is explicitly mapped with the alloc map-type. Note: the variable v is not included in the map list (otherwise the hostonly_data would be mapped)—just the elements to be mapped are listed.

The two mappers are combined when a mypoints_t structure type is mapped, because the mapper myvec_t structure type is used within a mypoints_t type structure.

```c
S-1 #include <stdlib.h>
S-2 #include <stdio.h>
S-3 #define N 100
S-4
S-5 typedef struct myvec {
S-6   size_t len;
S-7   double *data;
S-8 } myvec_t;
S-9
S-10 #pragma omp declare mapper(mypoints_t v) \ 
S-11   map(v.x, v.x[0]) map(alloc:v.scratch)
S-12
S-13 typedef struct mypoints {
S-14   struct myvec scratch;
S-15   struct myvec *x;
S-16   double hostonly_data[500000];
S-17 } mypoints_t;
S-18
S-19 #pragma omp declare mapper(mypoints_t v) \ 
S-20   map(v.x, v.x[0]) map(alloc:v.scratch)
S-21
S-22 void init_mypts_array(mypoints_t *P, int n);
S-23 void eval_mypts_array(mypoints_t *P, int n);
S-24
S-25 int main(){
S-26   mypoints_t P;
S-27   init_mypts_array(&P, N);
S-28
```
module my_structures

  type myvec_t
    integer :: len
    double precision, pointer :: data(:)
  end type

  !$omp declare mapper(myvec_t :: v) &
  !$omp& map(v)

  type mypoints_t
    type(myvec_t) :: scratch
    type(myvec_t), pointer :: x(:)
    double precision :: hostonly_data(500000)
  end type

  !$omp declare mapper(mypoints_t :: v) &
  !$omp& map(v%x, v%x(1)) map(alloc:v%scratch)

end module

program main
  use my_structures
  external init_mypts_array, eval_mypts_array

  type(mypoints_t) :: P
  call init_mypts_array(P)
  !$omp target map(P)
  call eval_mypts_array(P)
end program
4.7 target data Construct

4.7.1 Simple target data Construct

This example shows how the target data construct maps variables to a device data environment. The target data construct creates a new device data environment and maps the variables v1, v2, and p to the new device data environment. The target construct enclosed in the target data region creates a new device data environment, which inherits the variables v1, v2, and p from the enclosing device data environment. The variable N is mapped into the new device data environment from the encountering task’s data environment.

```
Example target_data.1.c

S-1 extern void init(float*, float*, int);
S-2 extern void output(float*, int);
S-3 void vec_mult(float *p, float *v1, float *v2, int N)
S-4 {
S-5     int i;
S-6     init(v1, v2, N);
S-7     #pragma omp target data map(to: v1[0:N], v2[:N]) map(from: p[0:N])
S-8     {
S-9         #pragma omp target
S-10         #pragma omp parallel for
S-11         for (i=0; i<N; i++)
S-12             p[i] = v1[i] * v2[i];
S-13     }
S-14     output(p, N);
S-15 }
```

C / C++
The Fortran code passes a reference and specifies the extent of the arrays in the declaration. No length information is necessary in the map clause, as is required with C/C++ pointers.

Example target_data.1.f90

```fortran
subroutine vec_mult(p, v1, v2, N)

  real :: p(N), v1(N), v2(N)
  integer :: i

  call init(v1, v2, N)

  !$omp target data map(to: v1, v2) map(from: p)
  !$omp target
  !$omp parallel do
  do i=1,N
    p(i) = v1(i) * v2(i)
  end do
  !$omp end target
  !$omp end target data

  call output(p, N)
end subroutine
```

4.7.2 target data Region Enclosing Multiple target Regions

The following examples show how the `target data` construct maps variables to a device data environment of a target region. The `target data` construct creates a device data environment and encloses target regions, which have their own device data environments. The device data environment of the `target data` region is inherited by the device data environment of an enclosed target region. The `target data` construct is used to create variables that will persist throughout the `target data` region.

In the following example the variables v1 and v2 are mapped at each target construct. Instead of mapping the variable p twice, once at each target construct, p is mapped once by the target data construct.
Example target_data.2.c

```c
extern void init(float*, float*, int);
extern void init_again(float*, float*, int);
extern void output(float*, int);

void vec_mult(float *p, float *v1, float *v2, int N)
{
    int i;
    init(v1, v2, N);
    #pragma omp target data map(from: p[0:N])
    {
        #pragma omp target map(to: v1[:N], v2[:N])
        #pragma omp parallel for
        for (i=0; i<N; i++)
            p[i] = v1[i] * v2[i];
        init_again(v1, v2, N);
        #pragma omp target map(to: v1[:N], v2[:N])
        #pragma omp parallel for
        for (i=0; i<N; i++)
            p[i] = p[i] + (v1[i] * v2[i]);
    }
    output(p, N);
}
```

The Fortran code uses reference and specifies the extent of the p, v1 and v2 arrays. No length information is necessary in the map clause, as is required with C/C++ pointers. The arrays v1 and v2 are mapped at each target construct. Instead of mapping the array p twice, once at each target construct, p is mapped once by the target data construct.

Example target_data.2.f90

```fortran
subroutine vec_mult(p, v1, v2, N)
    real       :: p(N), v1(N), v2(N)
    integer    :: i
    call init(v1, v2, N)
    !$omp target data map(from: p)
    !$omp target map(to: v1, v2 )
    !$omp parallel do
    do i=1,N
        p(i) = v1(i) * v2(i)
    end do
    !$omp end target
    call init_again(v1, v2, N)
end subroutine
```
In the following example, the array $Q$ is mapped once at the enclosing `target data` region instead of at each `target` construct. In OpenMP 4.0, a scalar variable is implicitly mapped with the `tofrom` map-type. But since OpenMP 4.5, a scalar variable, such as the `tmp` variable, has to be explicitly mapped with the `tofrom` map-type at the first `target` construct in order to return its reduced value from the parallel loop construct to the host. The variable defaults to firstprivate at the second `target` construct.

---

**Example target_data.3.c**

```c
#include <math.h>

#define COLS 100
define void gramSchmidt(float Q[][COLS], const int rows)
{
    int cols = COLS;
    #pragma omp target data map(Q[0:rows][0:cols])
    for(int k=0; k < cols; k++)
    {
        double tmp = 0.0;

        #pragma omp target map(tofrom: tmp)
        #pragma omp parallel for reduction(+:tmp)
        for(int i=0; i < rows; i++)
        {
            tmp += (Q[i][k] * Q[i][k]);
        }
        tmp = 1/sqrt(tmp);

        #pragma omp target
        #pragma omp parallel for
        for(int i=0; i < rows; i++)
        {
            Q[i][k] *= tmp;
        }
    }
}
```
Example target_data.3.f90

```fortran
subroutine gramSchmidt(Q, rows, cols)
  integer :: rows, cols, i, k
  double precision :: Q(rows, cols), tmp
  !$omp target data map(Q)
  do k=1, cols
    tmp = 0.0d0
    !$omp target map(tofrom: tmp)
    !$omp parallel do reduction(+:tmp)
    do i=1, rows
      tmp = tmp + (Q(i, k) * Q(i, k))
    end do
    !$omp end target
  end do
  !$omp target
  !$omp parallel do
  do i=1, rows
    Q(i, k) = Q(i, k)*tmp
  enddo
  !$omp end target
  !$omp end target data
end subroutine
```

Note: The variable tmp is now mapped with tofrom, for correct execution with 4.5 (and pre-4.5) compliant compilers. See Devices Intro.
The following two examples show how the `target data` construct maps variables to a device data environment. The `target data` construct's device data environment encloses the `target` construct's device data environment in the function `vec_mult()`.

When the type of the variable appearing in an array section is pointer, the pointer variable and the storage location of the corresponding array section are mapped to the device data environment. The pointer variable is treated as if it had appeared in a `map` clause with a map-type of `alloc`. The array section’s storage location is mapped according to the map-type in the `map` clause (the default map-type is `tofrom`).

The `target` construct’s device data environment inherits the storage locations of the array sections $v1[0:N], v2[:n]$, and $p0[0:N]$ from the enclosing target data construct’s device data environment. Neither initialization nor assignment is performed for the array sections in the new device data environment.

The pointer variables $p1, v3$, and $v4$ are mapped into the target construct’s device data environment with an implicit map-type of alloc and they are assigned the address of the storage location associated with their corresponding array sections. Note that the following pairs of array section storage locations are equivalent ($p0[:N], p1[:N]$), ($v1[:N], v3[:N]$), and ($v2[:N], v4[:N]$).

```c
#include <omp.h>

void vec_mult(float*, float*, float*, int);
extern void init(float*, float*, int);
extern void output(float*, int);

void foo(float *p0, float *v1, float *v2, int N)
{
    init(v1, v2, N);
    #pragma omp target data map(to: v1[0:N], v2[:N]) map(from: p0[0:N])
    {
        vec_mult(p0, v1, v2, N);
    }
    output(p0, N);
}
```

Example target_data.4.c

---

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The Fortran code maps the pointers and storage in an identical manner (same extent, but uses indices from 1 to $N$).

The target construct’s device data environment inherits the storage locations of the arrays $v1$, $v2$ and $p0$ from the enclosing target data constructs’ device data environment. However, in Fortran the associated data of the pointer is known, and the shape is not required.

The pointer variables $p1$, $v3$, and $v4$ are mapped into the target construct’s device data environment with an implicit map-type of alloc and they are assigned the address of the storage location associated with their corresponding array sections. Note that the following pair of array storage locations are equivalent ($p0, p1$), ($v1, v3$), and ($v2, v4$).

---

**C / C++**

```c
void vec_mult(float *p1, float *v3, float *v4, int N)
{
    int i;
    #pragma omp target map(to: v3[0:N], v4[:N]) map(from: p1[0:N])
    #pragma omp parallel for
    for (i=0; i<N; i++)
    {
        p1[i] = v3[i] * v4[i];
    }
}
```

**Fortran**

```fortran
Example target_data.4.f90

module mults
contains
subroutine foo(p0,v1,v2,N)
real,pointer,dimension(:) :: p0, v1, v2
integer :: N,i
    call init(v1, v2, N)
    !$omp target data map(to: v1, v2) map(from: p0)
    call vec_mult(p0,v1,v2,N)
    !$omp end target data
    call output(p0, N)
end subroutine

subroutine vec_mult(p1,v3,v4,N)
real,pointer,dimension(:) :: p1, v3, v4
```
integer :: N, i

!$omp target map(to: v3, v4) map(from: p1)
!$omp parallel do
  do i=1,N
    p1(i) = v3(i) * v4(i)
  end do
!$omp end target
end subroutine
end module

In the following example, the variables p1, v3, and v4 are references to the pointer variables p0, v1 and v2 respectively. The target construct's device data environment inherits the pointer variables p0, v1, and v2 from the enclosing target data construct's device data environment. Thus, p1, v3, and v4 are already present in the device data environment.

Example target_data.5.cpp

void vec_mult(float* &, float* &, float* &, int &);
extern void init(float*, float*, int);
extern void output(float*, int);
void foo(float *p0, float *v1, float *v2, int N)
{
  init(v1, v2, N);
  #pragma omp target data map(to: v1[0:N], v2[0:N]) map(from: p0[0:N])
  {
    vec_mult(p0, v1, v2, N);
  }
  output(p0, N);
}

void vec_mult(float* &p1, float* &v3, float* &v4, int &N)
{
  int i;
  #pragma omp target map(to: v3[0:N], v4[0:N]) map(from: p1[0:N])
  #pragma omp parallel for
  for (i=0; i<N; i++)
    p1[i] = v3[i] * v4[i];
}

In the following example, the usual Fortran approach is used for dynamic memory. The p0, v1, and v2 arrays are allocated in the main program and passed as references from one routine to another. In vec_mult, p1, v3 and v4 are references to the p0, v1, and v2 arrays, respectively. The target
construct’s device data environment inherits the arrays $p0$, $v1$, and $v2$ from the enclosing target data construct’s device data environment. Thus, $p1$, $v3$, and $v4$ are already present in the device data environment.

```fortran
Example target_data.5.f90

module my_mult
contains
subroutine foo(p0,v1,v2,N)
  real,dimension(:) :: p0, v1, v2
  integer :: N
  call init(v1, v2, N)
  !$omp target data map(to: v1, v2) map(from: p0)
  call vec_mult(p0,v1,v2,N)
  !$omp end target data
  call output(p0, N)
end subroutine

subroutine vec_mult(p1,v3,v4,N)
  real,dimension(:) :: p1, v3, v4
  integer :: N
  !$omp target map(to: v3, v4) map(from: p1)
  !$omp parallel do
  do i=1,N
    p1(i) = v3(i) * v4(i)
  end do
  !$omp end target
end subroutine
end module

program main
use my_mult
integer, parameter :: N=1024
real,allocatable, dimension(:) :: p, v1, v2
allocate( p(N), v1(N), v2(N) )
call foo(p,v1,v2,N)
end program
```
4.7.4 target data Construct with if Clause

The following two examples show how the target data construct maps variables to a device data environment.

In the following example, the if clause on the target data construct indicates that if the variable $N$ is smaller than a given threshold, then the target data construct will not create a device data environment.

The target constructs enclosed in the target data region must also use an if clause on the same condition, otherwise the pointer variable $p$ is implicitly mapped with a map-type of tofrom, but the storage location for the array section $p[0:N]$ will not be mapped in the device data environments of the target constructs.

```c
Example target_data.6.c

#define THRESHOLD 1000000
extern void init(float*, float*, int);
extern void init_again(float*, float*, int);
extern void output(float*, int);
void vec_mult(float *p, float *v1, float *v2, int N)
{
    int i;
    init(v1, v2, N);
    #pragma omp target data if(N>THRESHOLD) map(from: p[0:N])
    {
        #pragma omp target if (N>THRESHOLD) map(to: v1[:N], v2[:N])
        #pragma omp parallel for
        for (i=0; i<N; i++)
            p[i] = v1[i] * v2[i];
        init_again(v1, v2, N);
        #pragma omp target if (N>THRESHOLD) map(to: v1[:N], v2[:N])
        #pragma omp parallel for
        for (i=0; i<N; i++)
            p[i] = p[i] + (v1[i] * v2[i]);
    }
    output(p, N);
}
```
The *if* clauses work the same way for the following Fortran code. The *target* constructs enclosed in the *target data* region should also use an *if* clause with the same condition, so that the *target data* region and the *target* region are either both created for the device, or are both ignored.

```fortran
module params
  integer, parameter :: THRESHOLD=1000000
end module
subroutine vec_mult(p, v1, v2, N)
  use params
  real :: p(N), v1(N), v2(N)
  integer :: i
  call init(v1, v2, N)
  !$omp target data if(N>THRESHOLD) map(from: p)
  !$omp target if(N>THRESHOLD) map(to: v1, v2)
  !$omp parallel do
  do i=1,N
    p(i) = v1(i) * v2(i)
  end do
  !$omp end target
  call init_again(v1, v2, N)
  !$omp target if(N>THRESHOLD) map(to: v1, v2)
  !$omp parallel do
  do i=1,N
    p(i) = p(i) + v1(i) * v2(i)
  end do
  !$omp end target
  !$omp end target data
  call output(p, N)
end subroutine
```
In the following example, when the \texttt{if} clause conditional expression on the \texttt{target} construct evaluates to \texttt{false}, the target region will execute on the host device. However, the \texttt{target data} construct created an enclosing device data environment that mapped \texttt{p[0:N]} to a device data environment on the default device. At the end of the \texttt{target data} region the array section \texttt{p[0:N]} will be assigned from the device data environment to the corresponding variable in the data environment of the task that encountered the \texttt{target data} construct, resulting in undefined values in \texttt{p[0:N]}.

---

\texttt{C / C++}

\textit{Example target\textunderscore data.7.c}

\begin{verbatim}
#define THRESHOLD 1000000
extern void init(float*, float*, int);
extern void output(float*, int);
void vec\_mult(float *p, float *v1, float *v2, int N)
{
    int i;
    init(v1, v2, N);
    #pragma omp target data map(from: p[0:N])
    {
        #pragma omp target if (N>THRESHOLD) map(to: v1[:N], v2[:N])
        #pragma omp parallel for
        for (i=0; i<N; i++)
            p[i] = v1[i] * v2[i];
    } /* UNDEFINED behavior if N<=THRESHOLD */
    output(p, N);
}
\end{verbatim}

---

The **if** clauses work the same way for the following Fortran code. When the **if** clause conditional expression on the **target** construct evaluates to **false**, the **target** region will execute on the host device. However, the **target data** construct created an enclosing device data environment that mapped the **p** array (and **v1** and **v2**) to a device data environment on the default target device. At the end of the **target data** region the **p** array will be assigned from the device data environment to the corresponding variable in the data environment of the task that encountered the **target data** construct, resulting in undefined values in **p**.

---

**Example target_data.7.f90**

```fortran
module params
integer, parameter :: THRESHOLD=1000000
end module

subroutine vec_mult(p, v1, v2, N)
  use params
  real :: p(N), v1(N), v2(N)
  integer :: i
  call init(v1, v2, N)
  !$omp target data map(from: p)
  !$omp target if(N>THRESHOLD) map(to: v1, v2)
  !$omp parallel do
  do i=1,N
    p(i) = v1(i) * v2(i)
  end do
  !$omp end target
  !$omp end target data
  call output(p, N) !*** UNDEFINED behavior if N<=THRESHOLD
end subroutine
```

---

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4.8 **target enter data and target exit data**

Constructs

The structured data construct (**target data**) provides persistent data on a device for subsequent **target** constructs as shown in the **target data** examples above. This is accomplished by creating a single **target data** region containing **target** constructs.

The unstructured data constructs allow the creation and deletion of data on the device at any appropriate point within the host code, as shown below with the **target enter data** and **target exit data** constructs.

The following C++ code creates/deletes a vector in a constructor/destructor of a class. The constructor creates a vector with **target enter data** and uses an **alloc** modifier in the **map** clause to avoid copying values to the device. The destructor deletes the data (**target exit data**) and uses the **delete** modifier in the **map** clause to avoid copying data back to the host. Note, the stand-alone **target enter data** occurs after the host vector is created, and the **target exit data** construct occurs before the host data is deleted.

```cpp
class Matrix {
    Matrix(int n) {
        len = n;
        v = new double[len];
        #pragma omp target enter data map(alloc:v[0:len])
    }

    ~Matrix() {
        // NOTE: delete map type should be used, since the corresponding
        // host data will cease to exist after the deconstructor is called.
        #pragma omp target exit data map(delete:v[0:len])
        delete[] v;
    }

private:
    double* v;
    int len;
};
```

---

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The following C code allocates and frees the data member of a Matrix structure. The
\texttt{init\_matrix} function allocates the memory used in the structure and uses the
\texttt{target enter data} directive to map it to the target device. The \texttt{free\_matrix} function
removes the mapped array from the target device and then frees the memory on the host. Note, the
stand-alone \texttt{target enter data} occurs after the host memory is allocated, and the
\texttt{target exit data} construct occurs before the host data is freed.

\begin{verbatim}
#include <stdlib.h>
typedef struct {
  double *A;
  int N;
} Matrix;

void init_matrix(Matrix *mat, int n) {
  mat->A = (double *)malloc(n*sizeof(double));
  mat->N = n;
  #pragma omp target enter data map(alloc:mat->A[:n])
}

void free_matrix(Matrix *mat) {
  #pragma omp target exit data map(delete:mat->A[:mat->N])
  mat->N = 0;
  free(mat->A);
  mat->A = NULL;
}
\end{verbatim}
The following Fortran code allocates and deallocates a module array. The `initialize` subroutine allocates the module array and uses the `target enter data` directive to map it to the target device. The `finalize` subroutine removes the mapped array from the target device and then deallocates the array on the host. Note, the stand-alone `target enter data` occurs after the host memory is allocated, and the `target exit data` construct occurs before the host data is deallocated.

```
module example
  real(8), allocatable :: A(:)
contains
  subroutine initialize(N)
    integer :: N
    allocate(A(N))
    !$omp target enter data map(alloc:A)
  end subroutine initialize

  subroutine finalize()
    !$omp target exit data map(delete:A)
    deallocate(A)
  end subroutine finalize
end module example
```

---

Example target_unstructured_data.1.f90

```
module example
  real(8), allocatable :: A(:)
contains
  subroutine initialize(N)
    integer :: N
    allocate(A(N))
    !$omp target enter data map(alloc:A)
  end subroutine initialize

  subroutine finalize()
    !$omp target exit data map(delete:A)
    deallocate(A)
  end subroutine finalize
end module example
```
4.9 target update Construct

4.9.1 Simple target data and target update Constructs

The following example shows how the target update construct updates variables in a device data environment.

The target data construct maps array sections v1[:N] and v2[:N] (arrays v1 and v2 in the Fortran code) into a device data environment.

The task executing on the host device encounters the first target region and waits for the completion of the region.

After the execution of the first target region, the task executing on the host device then assigns new values to v1[:N] and v2[:N] (v1 and v2 arrays in Fortran code) in the task’s data environment by calling the function init_again().

The target update construct assigns the new values of v1 and v2 from the task’s data environment to the corresponding mapped array sections in the device data environment of the target data construct.

The task executing on the host device then encounters the second target region and waits for the completion of the region.

The second target region uses the updated values of v1[:N] and v2[:N].

Example target_update.1.c

```c
extern void init(float *, float *, int);
extern void init_again(float *, float *, int);
extern void output(float *, int);
void vec_mult(float *p, float *v1, float *v2, int N)
{
    int i;
    init(v1, v2, N);
    #pragma omp target data map(to: v1[:N], v2[:N]) map(from: p[0:N])
    {
        #pragma omp target
        #pragma omp parallel for
        for (i=0; i<N; i++)
            p[i] = v1[i] * v2[i];
    init_again(v1, v2, N);
    #pragma omp target update to(v1[:N], v2[:N])
    #pragma omp target
    #pragma omp parallel for
    for (i=0; i<N; i++)
...```

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subroutine vec_mult(p, v1, v2, N)
  real :: p(N), v1(N), v2(N)
  integer :: i
  call init(v1, v2, N)
  !$omp target data map(to: v1, v2) map(from: p)
  !$omp parallel do
  do i=1,N
    p(i) = v1(i) * v2(i)
  end do
  !$omp end target
  call init_again(v1, v2, N)
  !$omp target update to(v1, v2)
  !$omp target
  !$omp parallel do
  do i=1,N
    p(i) = p(i) + v1(i) * v2(i)
  end do
  !$omp end target
  !$omp end target data
  call output(p, N)
end subroutine

Example target_update.1.f90
4.9.2 target update Construct with if Clause

The following example shows how the target update construct updates variables in a device data environment.

The target data construct maps array sections $v1[N]$ and $v2[N]$ (arrays $v1$ and $v2$ in the Fortran code) into a device data environment. In between the two target regions, the task executing on the host device conditionally assigns new values to $v1$ and $v2$ in the task’s data environment. The function `maybe_init_again()` returns true if new data is written.

When the conditional expression (the return value of `maybe_init_again()`) in the if clause is true, the target update construct assigns the new values of $v1$ and $v2$ from the task’s data environment to the corresponding mapped array sections in the target data construct’s device data environment.

---

Example target_update.2.c

```c
extern void init(float *, float *, int);
extern int maybe_init_again(float *, int);
extern void output(float *, int);

void vec_mult(float *p, float *v1, float *v2, int N)
{
    int i;
    int changed;

    init(v1, v2, N);

    #pragma omp target data map(to: v1[N], v2[N]) map(from: p[0:N])
    {
        for (i=0; i<N; i++)
            p[i] = v1[i] * v2[i];
        changed = maybe_init_again(v1, N);
        #pragma omp target update if (changed) to(v1[N])
        changed = maybe_init_again(v2, N);
        #pragma omp target update if (changed) to(v2[N])
        for (i=0; i<N; i++)
            p[i] = p[i] + (v1[i] * v2[i]);
    }
    output(p, N);
}
```

---
subroutine vec_mult(p, v1, v2, N)

interface
  logical function maybe_init_again (v1, N)
    real :: v1(N)
    integer :: N
  end function
end interface

real :: p(N), v1(N), v2(N)
integer :: i
logical :: changed

call init(v1, v2, N)

!$omp target data map(to: v1, v2) map(from: p)
!$omp target
!$omp parallel do
  do i=1, N
    p(i) = v1(i) * v2(i)
  end do
!$omp end target
changed = maybe_init_again(v1, N)
!$omp target update if(changed) to(v1(:N))

changed = maybe_init_again(v2, N)
!$omp target update if(changed) to(v2(:N))

!$omp target
!$omp parallel do
  do i=1, N
    p(i) = p(i) + v1(i) * v2(i)
  end do
!$omp end target
!$omp target data

end subroutine
4.10 declare target Construct

4.10.1 declare target and end declare target for a Function

The following example shows how the declare target directive is used to indicate that the corresponding call inside a target region is to a fib function that can execute on the default target device.

A version of the function is also available on the host device. When the if clause conditional expression on the target construct evaluates to false, the target region (thus fib) will execute on the host device.

For C/C++ codes the declaration of the function fib appears between the declare target and end declare target directives.

```
#pragma omp declare target
extern void fib(int N);
#pragma omp end declare target
#define THRESHOLD 1000000
void fib_wrapper(int n)
{
    #pragma omp target if(n > THRESHOLD)
    {
        fib(n);
    }
}
```

The Fortran fib subroutine contains a declare target declaration to indicate to the compiler to create an device executable version of the procedure. The subroutine name has not been included on the declare target directive and is, therefore, implicitly assumed.

The program uses the module_fib module, which presents an explicit interface to the compiler with the declare target declarations for processing the fib call.
Example declare_target.1.f90

module module_fib
  contains
  subroutine fib(N)
    integer :: N
    !$omp declare target
    ...
  end subroutine
end module
module params
  integer :: THRESHOLD=1000000
end module
program my_fib
  use params
  use module_fib
  !$omp target if( N > THRESHOLD )
  call fib(N)
  !$omp end target
end program

Example declare_target.2.f90

program my_fib
  integer :: N = 8
  !$omp declare target(fib)
  !$omp target
  call fib(N)
  !$omp end target
end program
subroutine fib(N)
  integer :: N
  !$omp declare target
  print*,"hello from fib"
  ...
end subroutine

The next Fortran example shows the use of an external subroutine. Without an explicit interface (through module use or an interface block) the declare target declarations within an external subroutine are unknown to the main program unit; therefore, a declare target must be provided within the program scope for the compiler to determine that a target binary should be available.
4.10.2 declare target Construct for Class Type

The following example shows how the declare target and end declare target directives are used to enclose the declaration of a variable varY with a class type typeY. The member function typeY::foo() cannot be accessed on a target device because its declaration did not appear between declare target and end declare target directives.

Example declare_target.2.cpp

```cpp
struct typeX
{
    int a;
};

class typeY
{
    int a;
    public:
    int foo() { return a^0x01;}
};

#pragma omp declare target
struct typeX varX; // ok

class typeY varY; // ok if varY.foo() not called on target device

#pragma omp end declare target

void foo()
{
    #pragma omp target
    {
        varX.a = 100; // ok
        varY.foo(); // error foo() is not available on a target device
    }
}
```

4.10.3 declare target and end declare target for Variables

The following examples show how the declare target and end declare target directives are used to indicate that global variables are mapped to the implicit device data environment of each target device.

In the following example, the declarations of the variables p, v1, and v2 appear between declare target and end declare target directives indicating that the variables are mapped to the
implicit device data environment of each target device. The `target update` directive is then used to manage the consistency of the variables p, v1, and v2 between the data environment of the encountering host device task and the implicit device data environment of the default target device.

---

### C / C++

#### Example declare_target.3.c

```c
#include <iostream>

int main() {
    int i;
    init(v1, v2, N);
    #pragma omp target update to(v1, v2)
    #pragma omp target
    #pragma omp parallel for
    for (i=0; i<N; i++)
        p[i] = v1[i] * v2[i];
    #pragma omp target update from(p)
    output(p, N);
    return 0;
}
```

---

The Fortran version of the above C code uses a different syntax. Fortran modules use a list syntax on the `declare target` directive to declare mapped variables.

---

### Fortran

#### Example declare_target.3.f90

```fortran
module my_arrays

!$omp declare target (N, p, v1, v2)
integer, parameter :: N=1000
real :: p(N), v1(N), v2(N)
end module

subroutine vec_mult()
use my_arrays
integer :: i
    call init(v1, v2, N);
    !$omp target update to(v1, v2)
    !$omp target
    !$omp parallel do
    do i = 1,N
        p(i) = v1(i) * v2(i)
    end do
end subroutine
```

---

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The following example also indicates that the function \texttt{Pfun()} is available on the target device, as well as the variable \texttt{Q}, which is mapped to the implicit device data environment of each target device. The \texttt{target update} directive is then used to manage the consistency of the variable \texttt{Q} between the data environment of the encountering host device task and the implicit device data environment of the default target device.

In the following example, the function and variable declarations appear between the \texttt{declare target} and \texttt{end declare target} directives.

The Fortran version of the above C code uses a different syntax. In Fortran modules a list syntax on the \texttt{declare target} directive is used to declare mapped variables and procedures. The \texttt{N} and \texttt{Q} variables are declared as a comma separated list. When the \texttt{declare target} directive is used to declare just the procedure, the procedure name need not be listed – it is implicitly assumed, as illustrated in the \texttt{Pfun()} function.
Example declare_target.4.f90

module my_global_array
  !$omp declare target (N,Q)
  integer, parameter :: N=10
  real :: Q(N,N)
contains
function Pfun(i,k)
  !$omp declare target
  real :: Pfun
  integer,intent(in) :: i,k
  Pfun=(Q(i,k) * Q(k,i))
end function
end module

function accum(k) result(tmp)
use my_global_array
real :: tmp
integer :: i, k
tmp = 0.0e0
  !$omp target map(tofrom: tmp)
  !$omp parallel do reduction(+:tmp)
  do i=1,N
    tmp = tmp + Pfun(k,i)
  end do
  !$omp end target
end function

! Note: The variable tmp is now mapped with tofrom, for correct
! execution with 4.5 (and pre-4.5) compliant compilers. See Devices Intro.

4.10.4 declare target and end declare target
with declare simd

The following example shows how the declare target and end declare target directives
are used to indicate that a function is available on a target device. The declare simd directive
indicates that there is a SIMD version of the function P () that is available on the target device as
well as one that is available on the host device.
Example declare_target.5.c

```c
#define N 10000
#define M 1024
#pragma omp declare target
float Q[N][N];
#pragma omp declare simd uniform(i) linear(k) notinbranch
float P(const int i, const int k)
{
    return Q[i][k] * Q[k][i];
}
#pragma omp end declare target

float accum(void)
{
    float tmp = 0.0;
    int i, k;
    #pragma omp target map(tofrom: tmp)
    #pragma omp parallel for reduction(+:tmp)
    for (i=0; i < N; i++) {
        float tmp1 = 0.0;
        #pragma omp simd reduction(+:tmp1)
        for (k=0; k < M; k++) {
            tmp1 += P(i,k);
        }
        tmp += tmp1;
    }
    return tmp;
}

/* Note: The variable tmp is now mapped with tofrom, for correct
execution with 4.5 (and pre-4.5) compliant compilers. See Devices Intro. */
```

The Fortran version of the above C code uses a different syntax. Fortran modules use a list syntax of the `declare target` declaration for the mapping. Here the \( N \) and \( Q \) variables are declared in the list form as a comma separated list. The function declaration does not use a list and implicitly assumes the function name. In this Fortran example row and column indices are reversed relative to the C/C++ example, as is usual for codes optimized for memory access.
Example declare_target.5.f90

```fortran
module my_global_array

!$omp declare target (N,Q)
integer, parameter :: N=10000, M=1024
real :: Q(N,N)
contains
function P(k,i)

!$omp declare simd uniform(i) linear(k) notinbranch
!$omp declare target
real :: P
integer,intent(in) :: k,i
P=(Q(k,i) * Q(i,k))
end function
end module

function accum() result(tmp)
use my_global_array
real :: tmp, tmp1
integer :: i
tmp = 0.0e0
!$omp target map(tofrom: tmp)
!$omp parallel do private(tmp1) reduction(+:tmp)
do i=1,N
  tmp1 = 0.0e0
  !$omp simd reduction(+:tmp1)
do k = 1,M
    tmp1 = tmp1 + P(k,i)
  end do
  tmp = tmp + tmp1
end do
!$omp end target
end function

! Note: The variable tmp is now mapped with tofrom, for correct
! execution with 4.5 (and pre-4.5) compliant compilers. See Devices Intro.
```
4.10.5 declare target Directive with link Clause

In the OpenMP 4.5 standard the declare target directive was extended to allow static data to be mapped, when needed, through a link clause.

Data storage for items listed in the link clause becomes available on the device when it is mapped implicitly or explicitly in a map clause, and it persists for the scope of the mapping (as specified by a target construct, a target data construct, or target enter/exit data constructs).

Tip: When all the global data items will not fit on a device and are not needed simultaneously, use the link clause and map the data only when it is needed.

The following C and Fortran examples show two sets of data (single precision and double precision) that are global on the host for the entire execution on the host; but are only used globally on the device for part of the program execution. The single precision data are allocated and persist only for the first target region. Similarly, the double precision data are in scope on the device only for the second target region.

C / C++

Example declare_target.6.c

```c
#define N 100000000

float sp[N], sv1[N], sv2[N];
double dp[N], dv1[N], dv2[N];
#pragma omp declare target link(sp,sv1,sv2) \
    link(dp,dv1,dv2)

void s_init(float *, float *, int);
void d_init(double *, double *, int);
void s_output(float *, int);
void d_output(double *, int);

#pragma omp declare target
void s_vec_mult_accum()
{
    int i;

    #pragma omp parallel for
    for (i=0; i<N; i++)
        sp[i] = sv1[i] * sv2[i];
}

void d_vec_mult_accum()
{
    int i;
```
#pragma omp parallel for
for (i=0; i<N; i++)
dp[i] = dv1[i] * dv2[i];
}
#include omp end declare target

int main()
{
s_init(sv1, sv2, N);
#pragma omp target map(to:sv1,sv2) map(from:sp)
s_vec_mult_accum();
s_output(sp, N);

d_init(dv1, dv2, N);
#pragma omp target map(to:dv1,dv2) map(from:dp)
d_vec_mult_accum();
d_output(dp, N);

return 0;
}

Example declare_target.6.f90

module m_dat
    integer, parameter :: N=100000000
    !$omp declare target link(sp,sv1,sv2)
    real :: sp(N), sv1(N), sv2(N)
    !$omp declare target link(dp,dv1,dv2)
    double precision :: dp(N), dv1(N), dv2(N)
contains
    subroutine s_vec_mult_accum()
        !$omp declare target
        integer :: i
        !$omp parallel do
        do i = 1,N
            sp(i) = sv1(i) * sv2(i)
        end do
    end subroutine s_vec_mult_accum
    subroutine d_vec_mult_accum()
        !$omp declare target
integer :: i
!
!$omp parallel do
do i = 1,N
    dp(i) = dv1(i) * dv2(i)
end do
end subroutine
end module m_dat

program prec_vec_mult
use m_dat

call s_init(sv1, sv2, N)
!$omp target map(to:sv1,sv2) map(from:sp)
call s_vec_mult_accum()
!$omp end target
call s_output(sp, N)

call d_init(dv1, dv2, N)
!$omp target map(to:dv1,dv2) map(from:dp)
call d_vec_mult_accum()
!$omp end target
call d_output(dp, N)
end program
4.11 teams Constructs

4.11.1 target and teams Constructs with omp_get_num_teams and omp_get_team_num Routines

The following example shows how the target and teams constructs are used to create a league of thread teams that execute a region. The teams construct creates a league of at most two teams where the master thread of each team executes the teams region.

Theomp_get_num_teams routine returns the number of teams executing in a teams region. Theomp_get_team_num routine returns the team number, which is an integer between 0 and one less than the value returned byomp_get_num_teams. The following example manually distributes a loop across two teams.

```c
#include <stdlib.h>
#include <omp.h>

float dotprod(float B[], float C[], int N)
{
    float sum0 = 0.0;
    float sum1 = 0.0;
    #pragma omp target map(to: B[:N], C[:N]) map(tofrom: sum0, sum1)
    #pragma omp teams num_teams(2)
    {
        int i;
        if (omp_get_num_teams() != 2)
            abort();
        if (omp_get_team_num() == 0)
            {
                #pragma omp parallel for reduction(+:sum0)
                for (i=0; i<N/2; i++)
                    sum0 += B[i] * C[i];
            }
        else if (omp_get_team_num() == 1)
            {
                #pragma omp parallel for reduction(+:sum1)
                for (i=N/2; i<N; i++)
                    sum1 += B[i] * C[i];
            }
    }
return sum0 + sum1;
```

/* Note: The variables sum0,sum1 are now mapped with tofrom, for correct
Example teams.1.f90

```fortran
function dotprod(B,C,N) result(sum)
use omp_lib, ONLY : omp_get_num_teams, omp_get_team_num
real :: B(N), C(N), sum,sum0, sum1
integer :: N, i
sum0 = 0.0e0
sum1 = 0.0e0
!$omp target map(to: B, C) map(tofrom: sum0, sum1)
!$omp teams num_teams(2)
if (omp_get_num_teams() /= 2) stop "2 teams required"
if (omp_get_team_num() == 0) then
!$omp parallel do reduction(+:sum0)
do i=1,N/2
  sum0 = sum0 + B(i) * C(i)
end do
else if (omp_get_team_num() == 1) then
!$omp parallel do reduction(+:sum1)
do i=N/2+1,N
  sum1 = sum1 + B(i) * C(i)
end do
end if
$omp end teams
$omp end target
sum = sum0 + sum1
end function

! Note: The variables sum0,sum1 are now mapped with tofrom, for correct execution with 4.5 (and pre-4.5) compliant compilers. See Devices Intro.
```
The following example shows how the target, teams, and distribute constructs are used to execute a loop nest in a target region. The teams construct creates a league and the master thread of each team executes the teams region. The distribute construct schedules the subsequent loop iterations across the master threads of each team.

The number of teams in the league is less than or equal to the variable num_blocks. Each team in the league has a number of threads less than or equal to the variable block_threads. The iterations in the outer loop are distributed among the master threads of each team.

When a team’s master thread encounters the parallel loop construct before the inner loop, the other threads in its team are activated. The team executes the parallel region and then workshares the execution of the loop.

Each master thread executing the teams region has a private copy of the variable sum that is created by the reduction clause on the teams construct. The master thread and all threads in its team have a private copy of the variable sum that is created by the reduction clause on the parallel loop construct. The second private sum is reduced into the master thread’s private copy of sum created by the teams construct. At the end of the teams region, each master thread’s private copy of sum is reduced into the final sum that is implicitly mapped into the target region.

```
C / C++

Example teams.2.c

#define min(x, y) (((x) < (y)) ? (x) : (y))

float dotprod(float B[], float C[], int N, int block_size,
int num_teams, int block_threads)
{
    float sum = 0.0;
    int i, i0;
    #pragma omp target map(to: B[0:N], C[0:N]) map(tofrom: sum)
    #pragma omp teams num_teams(num_teams) thread_limit(block_threads) \
    reduction(+:sum)
    #pragma omp distribute
    for (i0=0; i0<N; i0 += block_size)
        #pragma omp parallel for reduction(+:sum)
        for (i=i0; i< min(i0+block_size,N); i++)
            sum += B[i] * C[i];
    return sum;
}

/* Note: The variable sum is now mapped with tofrom, for correct
execution with 4.5 (and pre-4.5) compliant compilers. See Devices Intro. */
```

C / C++
Example teams:2.f90

```fortran
function dotprod(B,C,N, block_size, num_teams, block_threads) result(sum)

  implicit none

  real :: B(N), C(N), sum
  integer :: N, block_size, num_teams, block_threads, i, i0

  sum = 0.0e0

  !$omp target map(to: B, C) map(tofrom: sum)
  !$omp teams num_teams(num_teams) thread_limit(block_threads) &
  !$omp& reduction(+:sum)
  !$omp distribute

  do i0=1,N, block_size
    !$omp parallel do reduction(+:sum)
    do i = i0, min(i0+block_size,N)
      sum = sum + B(i) * C(i)
    end do
  end do

  !$omp end teams
  !$omp end target

end function

! Note: The variable sum is now mapped with tofrom, for correct
! execution with 4.5 (and pre-4.5) compliant compilers. See Devices Intro.
```

4.11.3 target teams, and Distribute Parallel Loop Constructs

The following example shows how the target teams and distribute parallel loop constructs are used to execute a target region. The target teams construct creates a league of teams where the master thread of each team executes the teams region.

The distribute parallel loop construct schedules the loop iterations across the master threads of each team and then across the threads of each team.
C / C++

Example teams.3.c

```c
float dotprod(float B[], float C[], int N)
{
    float sum = 0;
    int i;
    #pragma omp target teams map(to: B[0:N], C[0:N])
    defaultmap(tofrom:scalar) reduction(+:sum)
    #pragma omp distribute parallel for reduction(+:sum)
    for (i=0; i<N; i++)
        sum += B[i] * C[i];
    return sum;
}
```

/* Note: The variable sum is now mapped with tofrom from the defaultmap clause on the combined target teams construct, for correct execution with 4.5 (and pre-4.5) compliant compilers. See Devices Intro. */

Fortran

Example teams.3.f90

```fortran
function dotprod(B,C,N) result(sum)
  real :: B(N), C(N), sum
  integer :: N, i
  sum = 0.0e0
  !$omp target teams map(to: B, C) &
  !$omp defaultmap(tofrom:scalar) reduction(+:sum)
  !$omp distribute parallel do reduction(+:sum)
  do i = 1,N
    sum = sum + B(i) * C(i)
  end do
  !$omp end target teams
end function
```

! Note: The variable sum is now mapped with tofrom from the defaultmap clause on the combined target teams construct, for correct execution with 4.5 (and pre-4.5) compliant compilers. See Devices Intro.
4.11.4 target teams and Distribute Parallel Loop Constructs with Scheduling Clauses

The following example shows how the target teams and distribute parallel loop constructs are used to execute a target region. The teams construct creates a league of at most eight teams where the master thread of each team executes the teams region. The number of threads in each team is less than or equal to 16.

The distribute parallel loop construct schedules the subsequent loop iterations across the master threads of each team and then across the threads of each team.

The dist_schedule clause on the distribute parallel loop construct indicates that loop iterations are distributed to the master thread of each team in chunks of 1024 iterations.

The schedule clause indicates that the 1024 iterations distributed to a master thread are then assigned to the threads in its associated team in chunks of 64 iterations.

```
#define N 1024*1024
float dotprod(float B[], float C[])
{
  float sum = 0.0;
  int i;
  #pragma omp target map(to: B[0:N], C[0:N]) map(tofrom: sum)
  #pragma omp teams num_teams(8) thread_limit(16) reduction(+:sum)
  #pragma omp distribute parallel for reduction(+:sum) \
    dist_schedule(static, 1024) schedule(static, 64)
  for (i=0; i<N; i++)
    sum += B[i] * C[i];
  return sum;
}
/* Note: The variable sum is now mapped with tofrom, for correct
   execution with 4.5 (and pre-4.5) compliant compilers. See Devices Intro. */
```
Example teams.4.f90

module arrays
integer, parameter :: N=1024*1024
real :: B(N), C(N)
end module

function dotprod() result(sum)
use arrays
real :: sum
integer :: i
sum = 0.0e0
!$omp target map(to: B, C) map(tofrom: sum)
!$omp teams num_teams(8) thread_limit(16) reduction(+:sum)
!$omp distribute parallel do reduction(+:sum) &
!$omp dist_schedule(static, 1024) schedule(static, 64)
do i = 1,N
    sum = sum + B(i) * C(i)
end do
!$omp end teams
!$omp end target
end function

! Note: The variable sum is now mapped with tofrom, for correct
! execution with 4.5 (and pre-4.5) compliant compilers. See Devices Intro.

4.11.5 target teams and distribute simd Constructs

The following example shows how the target teams and distribute simd constructs are
used to execute a loop in a target region. The target teams construct creates a league of
teams where the master thread of each team executes the teams region.

The distribute simd construct schedules the loop iterations across the master thread of each
team and then uses SIMD parallelism to execute the iterations.
**Example teams.5.c**

```c
extern void init(float *, float *, int);
extern void output(float *, int);

void vec_mult(float *p, float *v1, float *v2, int N) {
  int i;
  init(v1, v2, N);
  #pragma omp target teams map(to: v1[0:N], v2[:N]) map(from: p[0:N])
  #pragma omp distribute simd
  for (i=0; i<N; i++)
    p[i] = v1[i] * v2[i];
  output(p, N);
}
```

**Example teams.5.f90**

```fortran
subroutine vec_mult(p, v1, v2, N)
  real :: p(N), v1(N), v2(N)
  integer :: i
  call init(v1, v2, N)
  !$omp target teams map(to: v1, v2) map(from: p)
  !$omp distribute simd
  do i=1,N
    p(i) = v1(i) * v2(i)
  end do
  !$omp end target teams
  call output(p, N)
end subroutine
```
4.11.6 target teams and Distribute Parallel Loop
SIMD Constructs

The following example shows how the target teams and the distribute parallel loop SIMD constructs are used to execute a loop in a target teams region. The target teams construct creates a league of teams where the master thread of each team executes the teams region.

The distribute parallel loop SIMD construct schedules the loop iterations across the master thread of each team and then across the threads of each team where each thread uses SIMD parallelism.

---

Example teams.6.c

```c
extern void init(float *, float *, int);
extern void output(float *, int);
void vec_mult(float *p, float *v1, float *v2, int N)
{
    int i;
    init(v1, v2, N);
    #pragma omp target teams map(to: v1[0:N], v2[:,N]) map(from: p[0:N])
    #pragma omp distribute parallel for simd
    for (i=0; i<N; i++)
        p[i] = v1[i] * v2[i];
    output(p, N);
}
```

---

Example teams.6.f90

```fortran
subroutine vec_mult(p, v1, v2, N)
    real :: p(N), v1(N), v2(N)
    integer :: i
    call init(v1, v2, N)
    !$omp target teams map(to: v1, v2) map(from: p)
    !$omp distribute parallel do simd
    do i=1,N
        p(i) = v1(i) * v2(i)
    end do
    !$omp end target teams
    call output(p, N)
end subroutine
```
4.12 Asynchronous target Execution and Dependences

Asynchronous execution of a target region can be accomplished by creating an explicit task around the target region. Examples with explicit tasks are shown at the beginning of this section.

As of OpenMP 4.5 and beyond the nowait clause can be used on the target directive for asynchronous execution. Examples with nowait clauses follow the explicit task examples.

This section also shows the use of depend clauses to order executions through dependences.

4.12.1 Asynchronous target with Tasks

The following example shows how the task and target constructs are used to execute multiple target regions asynchronously. The task that encounters the task construct generates an explicit task that contains a target region. The thread executing the explicit task encounters a task scheduling point while waiting for the execution of the target region to complete, allowing the thread to switch back to the execution of the encountering task or one of the previously generated explicit tasks.

```
C / C++  

Example async_target.1.c  

S-1  
S-2  
S-3  
S-4  
S-5  
S-6  
S-7  
S-8  
S-9  
S-10  
S-11  
S-12  
S-13  
S-14  
S-15  
S-16  
S-17  
S-18  

C / C++  
```
The Fortran version has an interface block that contains the `declare target`. An identical statement exists in the function declaration (not shown here).

```fortran
Example async_target_1.f90

module parameters
  integer, parameter :: N=1000000000, CHUNKSZ=1000000
end module

subroutine pipedF()
  use parameters, ONLY: N, CHUNKSZ
  integer :: C, i
  real :: z(N)
  interface
    function F(z)
      !$omp declare target
      real, intent(IN) :: z
      real :: F
    end function F
  end interface

  call init(z,N)
  do C=1,N,CHUNKSZ
    !$omp task shared(z)
    !$omp target map(z(C:C+CHUNKSZ-1))
    !$omp parallel do
    do i=C,C+CHUNKSZ-1
      z(i) = F(z(i))
    end do
    !$omp end target
    !$omp end task
  end do
  !$omp taskwait
  print*, z
  end subroutine pipedF
```

The following example shows how the task and target constructs are used to execute multiple target regions asynchronously. The task dependence ensures that the storage is allocated and initialized on the device before it is accessed.
The Fortran example below is similar to the C version above. Instead of pointers, though, it uses the convenience of Fortran allocatable arrays on the device. In order to preserve the arrays allocated on the device across multiple target regions, a target data region is used in this case.
If there is no shape specified for an allocatable array in a **map** clause, only the array descriptor (also called a dope vector) is mapped. That is, device space is created for the descriptor, and it is initially populated with host values. In this case, the \( v_1 \) and \( v_2 \) arrays will be in a non-associated state on the device. When space for \( v_1 \) and \( v_2 \) is allocated on the device in the first **target** region the addresses to the space will be included in their descriptors.

At the end of the first **target** region, the arrays \( v_1 \) and \( v_2 \) are preserved on the device for access in the second **target** region. At the end of the second **target** region, the data in array \( p \) is copied back, the arrays \( v_1 \) and \( v_2 \) are not.

A **depend** clause is used in the **task** directive to provide a wait at the beginning of the second **target** region, to insure that there is no race condition with \( v_1 \) and \( v_2 \) in the two tasks. It would be noncompliant to use \( v_1 \) and/or \( v_2 \) in lieu of \( N \) in the **depend** clauses, because the use of non-allocated allocatable arrays as list items in a **depend** clause would lead to unspecified behavior.

**Note** – This example is not strictly compliant with the OpenMP 4.5 specification since the allocation status of allocatable arrays \( v_1 \) and \( v_2 \) is changed inside the **target** region, which is not allowed. (See the restrictions for the **map** clause in the Data-mapping Attribute Rules and Clauses section of the specification.) However, the intention is to relax the restrictions on mapping of allocatable variables in the next release of the specification so that the example will be compliant.

---

**Fortran**

---

Example async_target.2.f90

```
subroutine mult(p, N, idev)
  use omp_lib, ONLY: omp_is_initial_device
  real :: p(N)
  real, allocatable :: v1(:), v2(:)
  integer :: i, idev
  !$omp declare target (init)
  !$omp target data map(v1,v2)
  !$omp task shared(v1,v2) depend(out: N)
  !$omp target device(idev)
  if( omp_is_initial_device() ) &
    stop "not executing on target device"
  allocate(v1(N), v2(N))
  call init(v1,v2,N)
  !$omp end target
  !$omp end task
  call foo() ! execute other work asychronously
  !$omp task shared(v1,v2,p) depend(in: N)
  !$omp target device(idev) map(from: p)
```
```
The following example shows how to execute code asynchronously on a device without an explicit task. The \texttt{nowait} clause on a \texttt{target} construct allows the thread of the \texttt{target task} to perform other work while waiting for the \texttt{target} region execution to complete. Hence, the \texttt{target} region can execute asynchronously on the device (without requiring a host thread to idle while waiting for the \texttt{target task} execution to complete).

In this example the product of two vectors (arrays), \texttt{v1} and \texttt{v2}, is formed. One half of the operations is performed on the device, and the last half on the host, concurrently.

After a team of threads is formed the master thread generates the \texttt{target task} while the other threads can continue on, without a barrier, to the execution of the host portion of the vector product. The completion of the \texttt{target task} (asynchronous target execution) is guaranteed by the synchronization in the implicit barrier at the end of the host vector-product worksharing loop region. See the \texttt{barrier} glossary entry in the OpenMP specification for details.

The host loop scheduling is \texttt{dynamic}, to balance the host thread executions, since one thread is being used for offload generation. In the situation where little time is spent by the \texttt{target task} in setting up and tearing down the the target execution, \texttt{static} scheduling may be desired.
Example async_target.3.c

```c
#include <stdio.h>

#define N 1000000 //N must be even

void init(int n, float *v1, float *v2);

int main()
{
    int i, n=N;
    int chunk=1000;
    float v1[N], v2[N], vxv[N];

    init(n, v1, v2);

    #pragma omp parallel
    {
        #pragma omp master
        #pragma omp target teams distribute parallel for nowait
            map(to: v1[0:n/2])
            map(to: v2[0:n/2])
            map(from: vxv[0:n/2])
        for(i=0; i<n/2; i++) { vxv[i] = v1[i]*v2[i]; }

        #pragma omp for schedule(dynamic,chunk)
        for(i=n/2; i<n; i++) { vxv[i] = v1[i]*v2[i]; }

    }
    printf(" vxv[0] vxv[n-1] %f %f\n", vxv[0], vxv[n-1]);
    return 0;
}
```

Example async_target.3.f90

```fortran
program concurrent_async
    use omp_lib
    integer, parameter :: n=1000000 !n must be even
    integer :: i, chunk=1000
    real :: v1(n), v2(n), vxv(n)

    call init(n, v1, v2)
```
Asynchronous target with nowait and depend Clauses

More details on dependences can be found in Section 3.3 on page 89, Task Dependences. In this example, there are three flow dependences. In the first two dependences the target task does not execute until the preceding explicit tasks have finished. These dependences are produced by arrays \( v1 \) and \( v2 \) with the \textbf{out} dependence type in the first two tasks, and the \textbf{in} dependence type in the target task.

The last dependence is produced by array \( p \) with the \textbf{out} dependence type in the target task, and the \textbf{in} dependence type in the last task. The last task does not execute until the target task finishes.

The \textbf{nowait} clause on the \textbf{target} construct creates a deferrable \textit{target task}, allowing the encountering task to continue execution without waiting for the completion of the \textit{target task}.
**Example async_target.4.c**

```c
extern void init(float *, int);
extern void output(float*, int);

void vec_mult(int N)
{
  int i;
  float p[N], v1[N], v2[N];
  #pragma omp parallel num_threads(2)
  {
    #pragma omp single
    {
      #pragma omp task depend(out:v1)
      init(v1, N);
      #pragma omp task depend(out:v2)
      init(v2, N);
      #pragma omp target nowait depend(in:v1,v2) depend(out:p) map(to:v1,v2) map(from: p)
      for (i=0; i<N; i++)
        p[i] = v1[i] * v2[i];
      #pragma omp task depend(in:p)
      output(p, N);
    }
  }
}
```

**Example async_target.4.f90**

```fortran
subroutine vec_mult(N)
  implicit none
  integer :: i, N
  real, allocatable :: p(:), v1(:), v2(:)
  allocate( p(N), v1(N), v2(N) )
  !$omp parallel num_threads(2)
```
!$omp single

call init(v1, N)

!$omp end task

!$omp task depend(out:v2)
call init(v2, N)
!$omp end task

!$omp target nowait depend(in:v1,v2) depend(out:p) &

!$omp&

!$omp parallel do
  do i=1,N
    p(i) = v1(i) * v2(i)
  end do
!$omp end target

!$omp task depend(in:p)
call output(p, N)
!$omp end task

!$omp end single
!$omp end parallel

deallocate( p, v1, v2 )

end subroutine
4.13 Device Routines

4.13.1 omp_is_initial_device Routine

The following example shows how the `omp_is_initial_device` runtime library routine can be used to query if a code is executing on the initial host device or on a target device. The example then sets the number of threads in the `parallel` region based on where the code is executing.

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

#pragma omp declare target
void vec_mult(float *p, float *v1, float *v2, int N);
extern float *p, *v1, *v2;
extern int N;
#pragma omp end declare target
extern void init_vars(float *, float *, int);
extern void output(float *, int);

void foo()
{
  init_vars(v1, v2, N);
  #pragma omp target device(42) map(p[:N], v1[:N], v2[:N])
  {
    vec_mult(p, v1, v2, N);
  }
  output(p, N);
}
void vec_mult(float *p, float *v1, float *v2, int N)
{
  int i;
  int nthreads;
  if (!omp_is_initial_device())
  {
    printf("1024 threads on target device\n");
    nthreads = 1024;
  }
  else
  {
    printf("8 threads on initial device\n");
    nthreads = 8;
  }
  #pragma omp parallel for private(i) num_threads(nthreads)
  for (i=0; i<N; i++)
```
module params
  integer, parameter :: N = 1024
end module params

module vmult
  contains
    subroutine vec_mult(p, v1, v2, N)
      use omp_lib, ONLY: omp_is_initial_device
      !$omp declare target
      real :: p(N), v1(N), v2(N)
      integer :: i, nthreads, N
      if (.not. omp_is_initial_device()) then
        print*, "1024 threads on target device"
        nthreads = 1024
      else
        print*, "8 threads on initial device"
        nthreads = 8
      endif
      !$omp parallel do private(i) num_threads(nthreads)
      do i = 1, N
        p(i) = v1(i) * v2(i)
      end do
    end subroutine vec_mult
end module vmult

program prog_vec_mult
  use params
  use vmult
  real :: p(N), v1(N), v2(N)
  call init(v1, v2, N)
  !$omp target device(42) map(p, v1, v2)
  call vec_mult(p, v1, v2, N)
  !$omp end target
  call output(p, N)
end program
4.13.2 omp_get_num_devices Routine

The following example shows how the `omp_get_num_devices` runtime library routine can be used to determine the number of devices.

```c
#include <omp.h>
extern void init(float *, float *, int);
extern void output(float *, int);

void vec_mult(float *p, float *v1, float *v2, int N)
{
    int i;
    init(v1, v2, N);
    int ndev = omp_get_num_devices();
    int do_offload = (ndev>0 && N>1000000);
    #pragma omp target if(do_offload) map(to: v1[0:N], v2[:N]) map(from: p[0:N])
    #pragma omp parallel for if(N>1000) private(i)
    for (i=0; i<N; i++)
        p[i] = v1[i] * v2[i];
    output(p, N);
}
```

```fortran
subroutine vec_mult(p, v1, v2, N)
use omp_lib, ONLY : omp_get_num_devices
real :: p(N), v1(N), v2(N)
integer :: N, i, ndev
logical :: do_offload

call init(v1, v2, N)
ndev = omp_get_num_devices()
do_offload = (ndev>0) .and. (N>1000000)
!$omp target if(do_offload) map(to: v1, v2) map(from: p)
!$omp parallel do if(N>1000)
do i=1,N
    p(i) = v1(i) * v2(i)
end do
!$omp end target
call output(p, N)
end subroutine
```
4.13.3 **omp_set_default_device** and **omp_get_default_device** Routines

The following example shows how the **omp_set_default_device** and **omp_get_default_device** runtime library routines can be used to set the default device and determine the default device respectively.

```
C / C++
```

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

void foo(void)
{
    int default_device = omp_get_default_device();
    printf("Default device = %d\n", default_device);
    omp_set_default_device(default_device+1);
    if (omp_get_default_device() != default_device+1)
        printf("Default device is still = %d\n", default_device);
}
```

```
Fortran
```

```
program foo
    use omp_lib, ONLY : omp_get_default_device, omp_set_default_device
    integer :: old_default_device, new_default_device
    old_default_device = omp_get_default_device()
    print*, "Default device = ", old_default_device
    new_default_device = old_default_device + 1
    call omp_set_default_device(new_default_device)
    if (omp_get_default_device() == old_default_device) &
        print*, "Default device is STILL = ", old_default_device
end program
```

```
```
4.13.4 Target Memory and Device Pointers Routines

The following example shows how to create space on a device, transfer data to and from that space, and free the space, using API calls. The API calls directly execute allocation, copy and free operations on the device, without invoking any mapping through a target directive. The omp_target_alloc routine allocates space and returns a device pointer for referencing the space in the omp_target_memcpy API routine on the host. The omp_target_free routine frees the space on the device.

The example also illustrates how to access that space in a target region by exposing the device pointer in an is_device_ptr clause.

The example creates an array of cosine values on the default device, to be used on the host device. The function fails if a default device is not available.

Example device.4.c

```c
#include <stdio.h>
#include <math.h>
#include <stdlib.h>
#include <omp.h>

void get_dev_cos(double *mem, size_t s)
{
    int h, t, i;
    double * mem_dev_cpy;
    h =omp_get_initial_device();
    t =omp_get_default_device();

    if(omp_get_num_devices() < 1 || t < 0){
        printf(" ERROR: No device found.\n");
        exit(1);
    }

    mem_dev_cpy = (double *)omp_target_alloc( sizeof(double) * s, t);
    if(mem_dev_cpy == NULL){
        printf(" ERROR: No space left on device.\n");
        exit(1);
    }

    /* dst src */
    omp_target_memcpy(mem_dev_cpy, mem, sizeof(double)*s, 0, 0, t, h);

    #pragma omp target is_device_ptr(mem_dev_cpy) device(t)
```
#pragma omp teams distribute parallel for
for(i=0;i<s;i++) { mem_dev_cpy[i] = cos((double)i); } /* init data */

/* dst src */
omp_target_memcpy(mem, mem_dev_cpy, sizeof(double)*s, 0, 0, h, t);
omp_target_free(mem_dev_cpy, t);
SIMD

Single instruction, multiple data (SIMD) is a form of parallel execution in which the same operation is performed on multiple data elements independently in hardware vector processing units (VPU), also called SIMD units. The addition of two vectors to form a third vector is a SIMD operation. Many processors have SIMD (vector) units that can perform simultaneously 2, 4, 8 or more executions of the same operation (by a single SIMD unit).

Loops without loop-carried backward dependency (or with dependency preserved using ordered simd) are candidates for vectorization by the compiler for execution with SIMD units. In addition, with state-of-the-art vectorization technology and declare simd construct extensions for function vectorization in the OpenMP 4.5 specification, loops with function calls can be vectorized as well. The basic idea is that a scalar function call in a loop can be replaced by a vector version of the function, and the loop can be vectorized simultaneously by combining a loop vectorization (simd directive on the loop) and a function vectorization (declare simd directive on the function).

A simd construct states that SIMD operations be performed on the data within the loop. A number of clauses are available to provide data-sharing attributes (private, linear, reduction and lastprivate). Other clauses provide vector length preference/restrictions (simdlen / safelen), loop fusion (collapse), and data alignment (aligned).

The declare simd directive designates that a vector version of the function should also be constructed for execution within loops that contain the function and have a simd directive. Clauses provide argument specifications (linear, uniform, and aligned), a requested vector length (simdlen), and designate whether the function is always/never called conditionally in a loop (branch/inbranch). The latter is for optimizing performance.

Also, the simd construct has been combined with the worksharing loop constructs (for simd and do simd) to enable simultaneous thread execution in different SIMD units.
5.1 **simd and declare simd Constructs**

The following example illustrates the basic use of the **simd** construct to assure the compiler that the loop can be vectorized.

---

**Example SIMD.1.c**

```c
void star( double *a, double *b, double *c, int n, int *ioff )
{
    int i;
    #pragma omp simd
    for ( i = 0; i < n; i++ )
        a[i] *= b[i] * c[i + *ioff];
}
```

---

**Example SIMD.1.f90**

```fortran
subroutine star(a,b,c,n,ioff_ptr)
    implicit none
    double precision :: a(*),b(*),c(*)
    integer :: n, i
    integer, pointer :: ioff_ptr
    !$omp simd
    do i = 1,n
        a(i) = a(i) * b(i) * c(i+ioff_ptr)
    end do
end subroutine
```

---
When a function can be inlined within a loop the compiler has an opportunity to vectorize the loop. By guaranteeing SIMD behavior of a function’s operations, characterizing the arguments of the function and privatizing temporary variables of the loop, the compiler can often create faster, vector code for the loop. In the examples below the `declare simd` construct is used on the `add1` and `add2` functions to enable creation of their corresponding SIMD function versions for execution within the associated SIMD loop. The functions characterize two different approaches of accessing data within the function: by a single variable and as an element in a data array, respectively. The `add3` C function uses dereferencing.

The `declare simd` constructs also illustrate the use of `uniform` and `linear` clauses. The `uniform(fact)` clause indicates that the variable `fact` is invariant across the SIMD lanes. In the `add2` function `a` and `b` are included in the `uniform` list because the C pointer and the Fortran array references are constant. The `i` index used in the `add2` function is included in a `linear` clause with a constant-linear-step of 1, to guarantee a unity increment of the associated loop. In the `declare simd` construct for the `add3` C function the `linear(a,b:1)` clause instructs the compiler to generate unit-stride loads across the SIMD lanes; otherwise, costly `gather` instructions would be generated for the unknown sequence of access of the pointer dereferences.

In the `simd` constructs for the loops the `private(tmp)` clause is necessary to assure that each vector operation has its own `tmp` variable.

```
#include <stdio.h>

#pragma omp declare simd uniform(fact)
double add1(double a, double b, double fact)
{
    double c;
    c = a + b + fact;
    return c;
}

#pragma omp declare simd uniform(a,b,fact) linear(i:1)
double add2(double *a, double *b, int i, double fact)
{
    double c;
    c = a[i] + b[i] + fact;
    return c;
}

#pragma omp declare simd uniform(fact) linear(a,b:1)
double add3(double *a, double *b, double fact)
{
    double c;
    c = *a + *b + fact;
```
return c;

void work( double *a, double *b, int n )
{
    int i;
    double tmp;
    #pragma omp simd private(tmp)
    for ( i = 0; i < n; i++ ) {
        tmp = add1( a[i], b[i], 1.0);
        a[i] = add2( a, b, i, 1.0) + tmp;
        a[i] = add3(&a[i], &b[i], 1.0);
    }
}

int main(){
    int i;
    const int N=32;
    double a[N], b[N];
    for ( i=0; i<N; i++ ) {
        a[i] = i; b[i] = N-i;
    }
    work(a, b, N );
    for ( i=0; i<N; i++ ) {
        printf("%d %f\n", i, a[i]);
    }
    return 0;
}

Example SIMD.2.f90
do i = 1,N
    print*, i,a(i)
end do
end program

function add1(a,b,fact) result(c)
    !$omp declare simd(add1) uniform(fact)
    implicit none
    double precision :: a,b,fact, c
    c = a + b + fact
end function

function add2(a,b,i, fact) result(c)
    !$omp declare simd(add2) uniform(a,b,fact) linear(i:1)
    implicit none
    integer :: i
    double precision :: a(*),b(*),fact, c
    c = a(i) + b(i) + fact
end function

subroutine work(a, b, n )
    implicit none
    double precision :: a(n),b(n), tmp
    integer :: n, i
    double precision, external :: add1, add2
    !$omp simd private(tmp)
    do i = 1,n
        tmp = add1(a(i), b(i), 1.0d0)
        a(i) = add2(a, b, i, 1.0d0) + tmp
        a(i) = a(i) + b(i) + 1.0d0
    end do
end subroutine
A thread that encounters a SIMD construct executes a vectorized code of the iterations. Similar to the concerns of a worksharing loop a loop vectorized with a SIMD construct must assure that temporary and reduction variables are privatized and declared as reductions with clauses. The example below illustrates the use of `private` and `reduction` clauses in a SIMD construct.

```c
C / C++
```
```
#include <omp.h>

double work( double *a, double *b, int n )
{
    int i;
    double tmp, sum;
    sum = 0.0;
    #pragma omp simd private(tmp) reduction(+:sum)
    for (i = 0; i < n; i++) {
        tmp = a[i] + b[i];
        sum += tmp;
    }
    return sum;
}
```

```fortran
Fortran
```
```
subroutine work( a, b, n, sum )
    implicit none
    integer :: i, n
    double precision :: a(n), b(n), sum, tmp
    sum = 0.0d0
    !$omp simd private(tmp) reduction(+:sum)
    do i = 1,n
        tmp = a(i) + b(i)
        sum = sum + tmp
    end do
end subroutine work
```

Example SIMD.3.c

Example SIMD.3.f90

CHAPTER 5. SIMD
A `safelen(N)` clause in a `simd` construct assures the compiler that there are no loop-carried dependencies for vectors of size $N$ or below. If the `safelen` clause is not specified, then the default safelen value is the number of loop iterations.

The `safelen(16)` clause in the example below guarantees that the vector code is safe for vectors up to and including size 16. In the loop, $m$ can be 16 or greater, for correct code execution. If the value of $m$ is less than 16, the behavior is undefined.

```
C / C++

Example SIMD.4.c

void work( float *b, int n, int m )
{
    int i;
    #pragma omp simd safelen(16)
    for (i = m; i < n; i++)
        b[i] = b[i-m] - 1.0f;
}

Fortran

Example SIMD.4.f90

subroutine work( b, n, m )
    implicit none
    real :: b(n)
    integer :: i,n,m
    !$omp simd safelen(16)
    do i = m+1, n
        b(i) = b(i-m) - 1.0
    end do
end subroutine work
```
The following SIMD construct instructs the compiler to collapse the $i$ and $j$ loops into a single SIMD loop in which SIMD chunks are executed by threads of the team. Within the workshared loop chunks of a thread, the SIMD chunks are executed in the lanes of the vector units.

```
void work( double **a, double **b, double **c, int n )
{
    int i, j;
    double tmp;
    #pragma omp for simd collapse(2) private(tmp)
    for (i = 0; i < n; i++) {
        for (j = 0; j < n; j++) {
            tmp = a[i][j] + b[i][j];
            c[i][j] = tmp;
        }
    }
}
```

```
subroutine work( a, b, c, n )
    implicit none
    integer :: i,j,n
    double precision :: a(n,n), b(n,n), c(n,n), tmp

!$omp do simd collapse(2) private(tmp)
    do j = 1,n
        do i = 1,n
            tmp = a(i,j) + b(i,j)
            c(i,j) = tmp
        end do
    end do
end subroutine work
```
5.2 **inbranch and notinbranch Clauses**

The following examples illustrate the use of the `declare simd` construct with the `inbranch` and `notinbranch` clauses. The `notinbranch` clause informs the compiler that the function `foo` is never called conditionally in the SIMD loop of the function `myaddint`. On the other hand, the `inbranch` clause for the function `goo` indicates that the function is always called conditionally in the SIMD loop inside the function `myaddfloat`.

```
Example SIMD.6.c
```

```
#pragma omp declare simd linear(p:1) notinbranch
int foo(int *p){
    *p = *p + 10;
    return *p;
}

int myaddint(int *a, int *b, int n)
{
    #pragma omp simd
    for (int i=0; i<n; i++){
        a[i] = foo(&b[i]); /* foo is not called under a condition */
    }
    return a[n-1];
}
```

```
#pragma omp declare simd linear(p:1) inbranch
float goo(float *p){
    *p = *p + 18.5f;
    return *p;
}

int myaddfloat(float *x, float *y, int n)
{
    #pragma omp simd
    for (int i=0; i<n; i++){
        x[i] = (x[i] > y[i]) ? goo(&y[i]) : y[i];
        /* goo is called under the condition (or within a branch) */
    }
    return x[n-1];
}
```
Example SIMD.6.f90

```fortran
function foo(p) result(r)
!$omp declare simd(foo) notinbranch
implicit none
integer :: p, r
p = p + 10
r = p
end function foo

function myaddint(a, b, n) result(r)
implicit none
integer :: a(*), b(*), n, r
integer :: i
integer, external :: foo
!
!$omp simd
do i=1, n
    a(i) = foo(b(i)) ! foo is not called under a condition
end do
r = a(n)
end function myaddint

function goo(p) result(r)
!$omp declare simd(goo) inbranch
implicit none
real :: p, r
p = p + 18.5
r = p
end function goo

function myaddfloat(x, y, n) result(r)
implicit none
real :: x(*), y(*), r
integer :: n
integer :: i
real, external :: goo
!
!$omp simd
do i=1, n
    if (x(i) > y(i)) then
        x(i) = goo(y(i))
    ! goo is called under the condition (or within a branch)
    else
        x(i) = y(i)
```
In the code below, the function \textit{fib()} is called in the main program and also recursively called in the function \textit{fib()} within an \textbf{if} condition. The compiler creates a masked vector version and a non-masked vector version for the function \textit{fib()} while retaining the original scalar version of the \textit{fib()} function.

\textit{Example SIMD.7.c}

```c
#include <stdio.h>
#include <stdlib.h>

#define N 45
int a[N], b[N], c[N];

#pragma omp declare simd inbranch
int fib( int n )
{
    if (n <= 1)
        return n;
    else {
        return fib(n-1) + fib(n-2);
    }
}

int main(void)
{
    int i;

    #pragma omp simd
    for (i=0; i < N; i++) b[i] = i;

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

    printf("Done a[%d] = %d\n", N-1, a[N-1]);
    return 0;
}
```
Example SIMD.7.f90

program fibonacci
   implicit none
   integer, parameter :: N=45
   integer :: a(0:N-1), b(0:N-1)
   integer :: i
   integer, external :: fib
!
!$omp simd
do i = 0,N-1
   b(i) = i
end do
!
!$omp simd
do i=0,N-1
   a(i) = fib(b(i))
end do
!
write(*,*) "Done a(" N-1, ") = ", a(N-1)

! 44 701408733
end program
!
recursive function fib(n) result(r)
!
!$omp declare simd(fib) inbranch
!
implicit none
!
integer :: n, r
!
if (n <= 1) then
   r = n
else
   r = fib(n-1) + fib(n-2)
endif
!
end function fib
5.3 Loop-Carried Lexical Forward Dependence

The following example tests the restriction on an SIMD loop with the loop-carried lexical forward-dependence. This dependence must be preserved for the correct execution of SIMD loops.

A loop can be vectorized even though the iterations are not completely independent when it has loop-carried dependences that are forward lexical dependences, indicated in the code below by the read of $A[j+1]$ and the write to $A[j]$ in C/C++ code (or $A(j+1)$ and $A(j)$ in Fortran). That is, the read of $A[j+1]$ (or $A(j+1)$ in Fortran) before the write to $A[j]$ (or $A(j)$ in Fortran) ordering must be preserved for each iteration in $j$ for valid SIMD code generation.

This test assures that the compiler preserves the loop carried lexical forward-dependence for generating a correct SIMD code.

```c
#include <stdio.h>
#include <math.h>

int P[1000];
float A[1000];

float do_work(float *arr)
{
    float pri;
    int i;

    #pragma omp simd lastprivate(pri)
    for (i = 0; i < 999; ++i) {
        int j = P[i];

        pri = 0.5f;
        if (j % 2 == 0) {
            pri = A[j+1] + arr[i];
        }
        A[j] = pri * 1.5f;
        pri = pri + A[j];
    }
    return pri;
}

int main(void)
{
    float pri, arr[1000];
    int i;
    for (i = 0; i < 1000; ++i) {
```
P[i] = i;
A[i] = i * 1.5f;
arr[i] = i * 1.8f;
}

pri = do_work(&arr[0]);
if (pri == 8237.25) {
    printf("passed: result pri = %7.2f (8237.25) \n", pri);
}
else {
    printf("failed: result pri = %7.2f (8237.25) \n", pri);
}

return 0;

Example SIMD.8.f90

module work

integer :: P(1000)
real :: A(1000)
contains

function do_work(arr) result(pri)
implicit none
real, dimension(*) :: arr
real :: pri
integer :: i, j
!
$omp simd private(j) lastprivate(pri)
do i = 1, 999
    j = P(i)
pri = 0.5
if (mod(j-1, 2) == 0) then
    pri = A(j+1) + arr(i)
endif
A(j) = pri * 1.5
pri = pri + A(j)
end do

end function do_work

end module work
program simd_8f
  use work
  implicit none
  real :: pri, arr(1000)
  integer :: i
  do i = 1, 1000
    P(i) = i
    A(i) = (i-1) * 1.5
    arr(i) = (i-1) * 1.8
  end do
  pri = do_work(arr)
  if (pri == 8237.25) then
    print 2, "passed", pri
  else
    print 2, "failed", pri
  endif
  2 format(a, ": result pri = ", f7.2, " (8237.25)"")
end program
Synchronization

The **barrier** construct is a stand-alone directive that requires all threads of a team (within a contention group) to execute the barrier and complete execution of all tasks within the region, before continuing past the barrier.

The **critical** construct is a directive that contains a structured block. The construct allows only a single thread at a time to execute the structured block (region). Multiple critical regions may exist in a parallel region, and may act cooperatively (only one thread at a time in all **critical** regions), or separately (only one thread at a time in each **critical** regions when a unique name is supplied on each **critical** construct). An optional (lock) **hint** clause may be specified on a named **critical** construct to provide the OpenMP runtime guidance in selection a locking mechanism.

On a finer scale the **atomic** construct allows only a single thread at a time to have atomic access to a storage location involving a single read, write, update or capture statement, and a limited number of combinations when specifying the **capture atomic-clause** clause. The **atomic-clause** clause is required for some expression statements, but is not required for **update** statements. The **memory-order** clause can be used to specify the degree of memory ordering enforced by an **atomic** construct. From weakest to strongest, they are **relaxed** (the default), acquire and/or release clauses (specified with **acquire**, **release**, or **acq_rel**), and **seq_cst**. Please see the details in the **atomic Construct** subsection of the **Directives** chapter in the OpenMP Specifications document.

The **ordered** construct either specifies a structured block in a loop, simd, or loop SIMD region that will be executed in the order of the loop iterations. The ordered construct sequentializes and orders the execution of ordered regions while allowing code outside the region to run in parallel.

Since OpenMP 4.5 the **ordered** construct can also be a stand-alone directive that specifies cross-iteration dependences in a doacross loop nest. The **depend** clause uses a **sink dependence-type**, along with a iteration vector argument (vec) to indicate the iteration that satisfies the dependence. The **depend** clause with a **source dependence-type** specifies dependence satisfaction.
The flush directive is a stand-alone construct for enforcing consistency between a thread’s view of memory and the view of memory for other threads (see the Memory Model chapter of this document for more details). When the construct is used with an explicit variable list, a strong flush that forces a thread’s temporary view of memory to be consistent with the actual memory is applied to all listed variables. When the construct is used without an explicit variable list and without a memory-order clause, a strong flush is applied to all locally thread-visible data as defined by the base language, and additionally the construct provides both acquire and release memory ordering semantics. When an explicit variable list is not present and a memory-order clause is present, the construct provides acquire and/or release memory ordering semantics according to the memory-order clause, but no strong flush is performed. A resulting strong flush that applies to a set of variables effectively ensures that no memory (load or store) operation for the affected variables may be reordered across the flush directive.

General-purpose routines provide mutual exclusion semantics through locks, represented by lock variables. The semantics allows a task to set, and hence own a lock, until it is unset by the task that set it. A nestable lock can be set multiple times by a task, and is used when in code requires nested control of locks. A simple lock can only be set once by the owning task. There are specific calls for the two types of locks, and the variable of a specific lock type cannot be used by the other lock type.

Any explicit task will observe the synchronization prescribed in a barrier construct and an implied barrier. Also, additional synchronizations are available for tasks. All children of a task will wait at a taskwait (for their siblings to complete). A taskgroup construct creates a region in which the current task is suspended at the end of the region until all sibling tasks, and their descendants, have completed. Scheduling constraints on task execution can be prescribed by the depend clause to enforce dependence on previously generated tasks. More details on controlling task executions can be found in the Tasking Chapter in the OpenMP Specifications document.
6.1 The critical Construct

The following example includes several critical constructs. The example illustrates a queuing model in which a task is dequeued and worked on. To guard against multiple threads dequeuing the same task, the dequeuing operation must be in a critical region. Because the two queues in this example are independent, they are protected by critical constructs with different names, xaxis and yaxis.

```
C / C++

Example critical.1.c
int dequeue(float *a);
void work(int i, float *a);
void critical_example(float *x, float *y)
{
    int ix_next, iy_next;
    #pragma omp parallel shared(x, y) private(ix_next, iy_next)
    {
        #pragma omp critical (xaxis)
        ix_next = dequeue(x);
        work(ix_next, x);
        #pragma omp critical (yaxis)
        iy_next = dequeue(y);
        work(iy_next, y);
    }
}
```

```
C / C++

Fortran

Example critical.1.f
SUBROUTINE CRITICAL_EXAMPLE(X, Y)
REAL X(*), Y(*)
INTEGER IX_NEXT, IY_NEXT
!$OMP PARALLEL SHARED(X, Y) PRIVATE(IX_NEXT, IY_NEXT)
!$OMP CRITICAL(XAXIS)
CALL DEQUEUE(IX_NEXT, X)
!$OMP END CRITICAL(XAXIS)
CALL WORK(IX_NEXT, X)
```
The following example extends the previous example by adding the `hint` clause to the `critical` constructs.

```
#include <omp.h>

int dequeue(float *a);
void work(int i, float *a);

void critical_example(float *x, float *y)
{
    int ix_next, iy_next;

    #pragma omp parallel shared(x, y) private(ix_next, iy_next)
    {
        #pragma omp critical (xaxis) hint(omp_lock_hint_contended)
        ix_next = dequeue(x);
        work(ix_next, x);

        #pragma omp critical (yaxis) hint(omp_lock_hint_contended)
        iy_next = dequeue(y);
        work(iy_next, y);
    }
}
```
SUBROUTINE CRITICAL_EXAMPLE(X, Y)
USE OMP_LIB  ! or INCLUDE "omp_lib.h"

REAL X(*), Y(*)
INTEGER IX_NEXT, IY_NEXT

!$OMP PARALLEL SHARED(X, Y) PRIVATE(IX_NEXT, IY_NEXT)

!$OMP CRITICAL(XAXIS) HINT(OMP_LOCK_HINT_CONTENDED)
CALL DEQUEUE(IX_NEXT, X)
!$OMP END CRITICAL(XAXIS)
CALL WORK(IX_NEXT, X)

!$OMP CRITICAL(YAXIS) HINT(OMP_LOCK_HINT_CONTENDED)
CALL DEQUEUE(IY_NEXT, Y)
!$OMP END CRITICAL(YAXIS)
CALL WORK(IY_NEXT, Y)

!$OMP END PARALLEL

END SUBROUTINE CRITICAL_EXAMPLE
6.2 Worksharing Constructs Inside a critical Construct

The following example demonstrates using a worksharing construct inside a critical construct. This example is conforming because the worksharing single region is not closely nested inside the critical region. A single thread executes the one and only section in the sections region, and executes the critical region. The same thread encounters the nested parallel region, creates a new team of threads, and becomes the master of the new team. One of the threads in the new team enters the single region and increments i by 1. At the end of this example i is equal to 2.

```c
void critical_work()
{
    int i = 1;
    #pragma omp parallel sections
    {
        #pragma omp section
        {
            #pragma omp critical (name)
            {
                #pragma omp parallel
                {
                    #pragma omp single
                    {
                        i++;
                        
                    }
                }
            }
        }
    }
}
```

Example worksharing_critical.1.c
Example worksharing_critical.1.f

S-1    SUBROUTINE CRITICAL_WORK()
S-2
S-3    INTEGER I
S-4    I = 1
S-5
S-6    !$OMP PARALLEL SECTIONS
S-7    !$OMP SECTION
S-8    !$OMP CRITICAL (NAME)
S-9    !$OMP PARALLEL
S-10   !$OMP SINGLE
S-11   I = I + 1
S-12   !$OMP END SINGLE
S-13   !$OMP END PARALLEL
S-14   !$OMP END CRITICAL (NAME)
S-15   !$OMP END PARALLEL SECTIONS
S-16   END SUBROUTINE CRITICAL_WORK
6.3 Binding of barrier Regions

The binding rules call for a **barrier** region to bind to the closest enclosing **parallel** region.

In the following example, the call from the main program to *sub2* is conforming because the **barrier** region (in *sub3*) binds to the **parallel** region in *sub2*. The call from the main program to *sub1* is conforming because the **barrier** region binds to the **parallel** region in subroutine *sub2*.

The call from the main program to *sub3* is conforming because the **barrier** region binds to the implicit inactive **parallel** region enclosing the sequential part. Also note that the **barrier** region in *sub3* when called from *sub2* only synchronizes the team of threads in the enclosing **parallel** region and not all the threads created in *sub1*.

---

**Example barrier_regions.1.c**

```c
void work(int n) {}

void sub3(int n)
{
  work(n);
  #pragma omp barrier
  work(n);
}

void sub2(int k)
{
  #pragma omp parallel shared(k)
  sub3(k);
}

void sub1(int n)
{
  int i;
  #pragma omp parallel private(i) shared(n)
  {
    #pragma omp for
    for (i=0; i<n; i++)
      sub2(i);
  }
}

int main()
{
  sub1(2);
  sub2(2);
```
Example barrier_regions.1.f

```fortran
SUBROUTINE WORK(N)
   INTEGER N
END SUBROUTINE WORK

SUBROUTINE SUB3(N)
   INTEGER N
   CALL WORK(N)
   !$OMP BARRIER
   CALL WORK(N)
END SUBROUTINE SUB3

SUBROUTINE SUB2(K)
   INTEGER K
   !$OMP PARALLEL SHARED(K)
   CALL SUB3(K)
   !$OMP END PARALLEL
END SUBROUTINE SUB2

SUBROUTINE SUB1(N)
   INTEGER N
   INTEGER I
   !$OMP PARALLEL PRIVATE(I) SHARED(N)
   !$OMP DO
   DO I = 1, N
      CALL SUB2(I)
   END DO
   !$OMP END PARALLEL
END SUBROUTINE SUB1

PROGRAM EXAMPLE
   CALL SUB1(2)
   CALL SUB2(2)
   CALL SUB3(2)
END PROGRAM EXAMPLE
```
6.4 The atomic Construct

The following example avoids race conditions (simultaneous updates of an element of \( x \) by multiple threads) by using the \texttt{atomic} construct.

The advantage of using the \texttt{atomic} construct in this example is that it allows updates of two different elements of \( x \) to occur in parallel. If a \texttt{critical} construct were used instead, then all updates to elements of \( x \) would be executed serially (though not in any guaranteed order).

Note that the \texttt{atomic} directive applies only to the statement immediately following it. As a result, elements of \( y \) are not updated atomically in this example.

\begin{verbatim}
Example atomic.1.c

float work1(int i)
{
  return 1.0 * i;
}

float work2(int i)
{
  return 2.0 * i;
}

void atomic_example(float *x, float *y, int *index, int n)
{
  int i;
  #pragma omp parallel for shared(x, y, index, n)
  for (i=0; i<n; i++) {
    #pragma omp atomic update
    x[index[i]] += work1(i);
    y[i] += work2(i);
  }

int main()
{
  float x[1000];
  float y[10000];
  int index[10000];
  int i;
  for (i = 0; i < 10000; i++) {
    index[i] = i % 1000;
    y[i] = 0.0;
  }

  return 0;
}
\end{verbatim}
for (i = 0; i < 1000; i++)
    x[i] = 0.0;
atomic_example(x, y, index, 10000);
return 0;

Example atomic.1.f

REAL FUNCTION WORK1(I)
    INTEGER I
    WORK1 = 1.0 * I
    RETURN
END FUNCTION WORK1

REAL FUNCTION WORK2(I)
    INTEGER I
    WORK2 = 2.0 * I
    RETURN
END FUNCTION WORK2

SUBROUTINE SUB(X, Y, INDEX, N)
    REAL X(*), Y(*)
    INTEGER INDEX(*), N
    INTEGER I
    !$OMP PARALLEL DO SHARED(X, Y, INDEX, N)
    DO I=1,N
        !$OMP ATOMIC UPDATE
        X(INDEX(I)) = X(INDEX(I)) + WORK1(I)
        Y(I) = Y(I) + WORK2(I)
    ENDDO
    END SUBROUTINE SUB

PROGRAM ATOMIC_EXAMPLE
    REAL X(1000), Y(10000)
    INTEGER INDEX(10000)
    INTEGER I
    DO I=1,10000
        INDEX(I) = MOD(I, 1000) + 1
        Y(I) = 0.0
    ENDDO
The following example illustrates the `read` and `write` clauses for the `atomic` directive. These clauses ensure that the given variable is read or written, respectively, as a whole. Otherwise, some other thread might read or write part of the variable while the current thread was reading or writing another part of the variable. Note that most hardware provides atomic reads and writes for some set of properly aligned variables of specific sizes, but not necessarily for all the variable types supported by the OpenMP API.

```c/c++
Example atomic.2.c

int atomic_read(const int *p)
{
    int value;
    /* Guarantee that the entire value of *p is read atomically. No part of *p can change during the read operation. */
    #pragma omp atomic read
    value = *p;
    return value;
}

void atomic_write(int *p, int value)
{
    /* Guarantee that value is stored atomically into *p. No part of *p can change until after the entire write operation is completed. */
    #pragma omp atomic write
    *p = value;
}
```
The following example illustrates the `capture` clause for the `atomic` directive. In this case the value of a variable is captured, and then the variable is incremented. These operations occur atomically. This particular example could be implemented using the fetch-and-add instruction available on many kinds of hardware. The example also shows a way to implement a spin lock using the `capture` and `read` clauses.
* Use fetch_and_add to implement a lock

```c
*/

```C

```c
struct locktype {
    int ticketnumber;
    int turn;
};
```

```c
void do_locked_work(struct locktype *lock)
{
    int atomic_read(const int *p);
    void work();

    // Obtain the lock
    int myturn = fetch_and_add(&lock->ticketnumber);
    while (atomic_read(&lock->turn) != myturn)
    {
        // Do some work. The flush is needed to ensure visibility of
        // variables not involved in atomic directives
        #pragma omp flush
        work();
        #pragma omp flush
    }

    // Release the lock
    fetch_and_add(&lock->turn);
}
```

---

```
Example atomic.3.f
```

```fortran
function fetch_and_add(p)
    integer:: fetch_and_add
    integer, intent(inout) :: p

    ! Atomically read the value of p and then increment it. The previous value is
    ! returned. This can be used to implement a simple lock as shown below.
    !$omp atomic capture
    fetch_and_add = p
    p = p + 1
    !$omp end atomic
end function fetch_and_add
```

```fortran
module m
interface
function fetch_and_add(p)
    integer :: fetch_and_add
    integer, intent(inout) :: p
end function
```

```fortran
function atomic_read(p)
```

---

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integer :: atomic_read

type locktype
  integer ticketnumber
  integer turn
end type

contains

subroutine do_locked_work(lock)
  type(locktype), intent(inout) :: lock
  integer myturn
  integer junk
  ! obtain the lock
  myturn = fetch_and_add(lock%ticketnumber)
  do while (atomic_read(lock%turn) .ne. myturn)
    continue
  enddo
  ! Do some work. The flush is needed to ensure visibility of variables
  ! not involved in atomic directives
  !$omp flush
  call work
  !$omp flush
  ! Release the lock
  junk = fetch_and_add(lock%turn)
end subroutine
end module

Fortran
6.5 Restrictions on the atomic Construct

The following non-conforming examples illustrate the restrictions on the atomic construct.

Example atomic_restrict.1.c

```c
void atomic_wrong ()
{
    union {int n; float x;} u;
    #pragma omp parallel
    {
        #pragma omp atomic update
        u.n++;
        #pragma omp atomic update
        u.x += 1.0;
        /* Incorrect because the atomic constructs reference the same location
           through incompatible types */
    }
}
```

Example atomic_restrict.1.f

```fortran
SUBROUTINE ATOMIC_WRONG()
    INTEGER:: I
    REAL:: R
    EQUIVALENCE(I,R)
    !$OMP PARALLEL
    !$OMP ATOMIC UPDATE
    I = I + 1
    !$OMP ATOMIC UPDATE
    R = R + 1.0
    ! incorrect because I and R reference the same location
    ! but have different types
    !$OMP END PARALLEL
END SUBROUTINE ATOMIC_WRONG
```
Example atomic_restrict.2.c

```c
void atomic_wrong2 ()
{
    int x;
    int *i;
    float *r;

    i = &x;
    r = (float *)&x;

    #pragma omp parallel
    {
        #pragma omp atomic update
        *i += 1;
        #pragma omp atomic update
        *r += 1.0;

        /* Incorrect because the atomic constructs reference the same location
         * through incompatible types */
    }
}
```

The following example is non-conforming because \texttt{I} and \texttt{R} reference the same location but have different types.

Example atomic_restrict.2.f

```fortran
SUBROUTINE SUB()
    COMMON /BLK/ R
    REAL R

    !$OMP ATOMIC UPDATE
    R = R + 1.0
END SUBROUTINE SUB

SUBROUTINE ATOMIC_WRONG2()
    COMMON /BLK/ I
    INTEGER I

    !$OMP PARALLEL
```
Although the following example might work on some implementations, this is also non-conforming:

Example atomic_restrict.3.f

```fortran
SUBROUTINE ATOMIC_WRONG3
  INTEGER:: I
  REAL:: R
  EQUIVALENCE(I,R)

  !$OMP PARALLEL
  !$OMP ATOMIC UPDATE
  I = I + 1
  ! incorrect because I and R reference the same location
  ! but have different types
  !$OMP END PARALLEL

  !$OMP PARALLEL
  !$OMP ATOMIC UPDATE
  R = R + 1.0
  ! incorrect because I and R reference the same location
  ! but have different types
  !$OMP END PARALLEL

END SUBROUTINE ATOMIC_WRONG3
```
6.6 The `flush` Construct without a List

The following example distinguishes the shared variables affected by a `flush` construct with no list from the shared objects that are not affected:

```
Example flush_nolist.1.c
```

```c
int x, *p = &x;

void f1(int *q)
{
    *q = 1;
    #pragma omp flush
    /* x, p, and *q are flushed */
    /* because they are shared and accessible */
    /* q is not flushed because it is not shared. */
}

void f2(int *q)
{
    #pragma omp barrier
    *q = 2;
    #pragma omp barrier
    /* a barrier implies a flush */
    /* x, p, and *q are flushed */
    /* because they are shared and accessible */
    /* q is not flushed because it is not shared. */
}

int g(int n)
{
    int i = 1, j, sum = 0;
    *p = 1;
    #pragma omp parallel reduction(+: sum) num_threads(10)
    {
        f1(&j);
        /* i, n and sum were not flushed */
        /* because they were not accessible in f1 */
        /* j was flushed because it was accessible */
        sum += j;
    }
    f2(&j);
    /* i, n, and sum were not flushed */
```
Example flush_nolist.1.f

```c
SUBROUTINE F1(Q)
  COMMON /DATA/ X, P
  INTEGER, TARGET :: X
  INTEGER, POINTER :: P
  INTEGER Q
  Q = 1
  !$OMP FLUSH
  ! X, P and Q are flushed
  ! because they are shared and accessible
END SUBROUTINE F1

SUBROUTINE F2(Q)
  COMMON /DATA/ X, P
  INTEGER, TARGET :: X
  INTEGER, POINTER :: P
  INTEGER Q
  !$OMP BARRIER
  Q = 2
  !$OMP BARRIER
  ! a barrier implies a flush
  ! X, P and Q are flushed
  ! because they are shared and accessible
END SUBROUTINE F2

INTEGER FUNCTION G(N)
  COMMON /DATA/ X, P
  INTEGER, TARGET :: X
  INTEGER, POINTER :: P
```

C / C++

Fortran
INTEGER N
INTEGER I, J, SUM

I = 1
SUM = 0
P = 1
!
!$OMP PARALLEL REDUCTION(+: SUM) NUM_THREADS(10)
CALL F1(J)
! I, N and SUM were not flushed
! because they were not accessible in F1
! J was flushed because it was accessible
SUM = SUM + J

CALL F2(J)
! I, N, and SUM were not flushed
! because they were not accessible in f2
! J was flushed because it was accessible
SUM = SUM + I + J + P + N
!
!$OMP END PARALLEL

G = SUM
END FUNCTION G

PROGRAM FLUSH_NOLIST
COMMON /DATA/ X, P
INTEGER, TARGET :: X
INTEGER, POINTER :: P
INTEGER RESULT, G
P => X
RESULT = G(7)
PRINT *, RESULT
END PROGRAM FLUSH_NOLIST
6.7 Synchronization Based on Acquire/Release Semantics

As explained in the Memory Model chapter of this document, a flush operation may be an acquire flush and/or a release flush, and OpenMP 5.0 defines acquire/release semantics in terms of these fundamental flush operations. For any synchronization between two threads that is specified by OpenMP, a release flush logically occurs at the source of the synchronization and an acquire flush logically occurs at the sink of the synchronization. OpenMP 5.0 added memory ordering clauses – acquire, release, and acq_rel – to the flush and atomic constructs for explicitly requesting acquire/release semantics. Furthermore, implicit flushes for all OpenMP constructs and runtime routines that synchronize OpenMP threads in some manner were redefined in terms of synchronizing release and acquire flushes to avoid the requirement of strong memory fences (see the Flush Synchronization and Happens Before and Implicit Flushes sections of the OpenMP Specifications document).

The examples that follow in this section illustrate how acquire and release flushes may be employed, implicitly or explicitly, for synchronizing threads. A flush directive without a list and without any memory ordering clause can also function as both an acquire and release flush for facilitating thread synchronization. Flushes implied on entry to, or exit from, an atomic operation (specified by an atomic construct) may function as an acquire flush or a release flush if a memory ordering clause appears on the construct. On entry to and exit from a critical construct there is now an implicit acquire flush and release flush, respectively.

The first example illustrates how the release and acquire flushes implied by a critical region guarantee a value written by the first thread is visible to a read of the value on the second thread. Thread 0 writes to x and then executes a critical region in which it writes to y; the write to x happens before the execution of the critical region, consistent with the program order of the thread. Meanwhile, thread 1 executes a critical region in a loop until it reads a non-zero value from y in the critical region, after which it prints the value of x; again, the execution of the critical regions happen before the read from x based on the program order of the thread. The critical regions executed by the two threads execute in a serial manner, with a pair-wise synchronization from the exit of one critical region to the entry to the next critical region. These pair-wise synchronizations result from the implicit release flushes that occur on exit from critical regions and the implicit acquire flushes that occur on entry to critical regions; hence, the execution of each critical region in the sequence happens before the execution of the next critical region. A “happens before” order is therefore established between the assignment to x by thread 0 and the read from x by thread 1, and so thread 1 must see that x equals 10.
Example acquire_release.1.c

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

int main()
{
    int x = 0, y = 0;
    #pragma omp parallel num_threads(2)
    {
        int thrd = omp_get_thread_num();
        if (thrd == 0) {
            x = 10;
            #pragma omp critical
            { y = 1; }
        } else {
            int tmp = 0;
            while (tmp == 0) {
                #pragma omp critical
                { tmp = y; }
            }
            printf("x = %d\n", x); // always "x = 10"
        }
    }
    return 0;
}
```

Example acquire_release.1.f90

```fortran
program rel_acq_ex1
use omp_lib
integer :: x, y, thrd, tmp
x = 0
y = 0
 !$omp parallel num_threads(2) private(thrd, tmp)
    thrd = omp_get_thread_num()
    if (thrd == 0) then
        x = 10
        !$omp critical
        y = 1
        !$omp end critical
    else
```
In the second example, the critical constructs are exchanged with atomic constructs that have explicit memory ordering specified. When the atomic read operation on thread 1 reads a non-zero value from y, this results in a release/acquire synchronization that in turn implies that the assignment to x on thread 0 happens before the read of x on thread 1. Therefore, thread 1 will print "x = 10".
Example acquire_release_2.f90

```fortran
program rel_acq_ex2
  use omp_lib
  integer :: x, y, thrd, tmp
  x = 0
  y = 0
  !$omp parallel num_threads(2) private(thrd, tmp)
  thrd = omp_get_thread_num()
  if (thrd == 0) then
    x = 10
    !$omp atomic write release ! or seq_cst
    y = 1
    !$omp end atomic
  else
    tmp = 0
    do while (tmp == 0)
      !$omp atomic read acquire ! or seq_cst
      tmp = y
      !$omp end atomic
    end do
    print *, "x = ", x !! always "x = 10"
  end if
  !$omp end parallel
end program
```

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In the third example, **atomic** constructs that specify relaxed atomic operations are used with explicit **flush** directives to enforce memory ordering between the two threads. The explicit **flush** directive on thread 0 must specify a release flush and the explicit **flush** directive on thread 1 must specify an acquire flush to establish a release/acquire synchronization between the two threads. The **flush** and **atomic** constructs encountered by thread 0 can be replaced by the **atomic** construct used in Example 2 for thread 0, and similarly the **flush** and **atomic** constructs encountered by thread 1 can be replaced by the **atomic** construct used in Example 2 for thread 1.

---

**Example acquire_release.3.c**

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

int main()
{
    int x = 0, y = 0;
    #pragma omp parallel num_threads(2)
    {
        int thrd = omp_get_thread_num();
        if (thrd == 0) {
            x = 10;
            #pragma omp flush // or with acq_rel or release clause
            #pragma omp atomic write // or with relaxed clause
            y = 1;
        } else {
            int tmp = 0;
            while (tmp == 0) {
                #pragma omp atomic read // or with relaxed clause
                tmp = y;
            }
            #pragma omp flush // or with acq_rel or acquire clause
            printf("x = %d\n", x); // always "x = 10"
        }
    }
    return 0;
}
```

---
Example acquire_release.3.f90

```fortran
program rel_acq_ex3
    use omp_lib
    integer :: x, y, thrd, tmp
    x = 0
    y = 0
    !$omp parallel num_threads(2) private(thrd, tmp)
    thrd = omp_get_thread_num()
    if (thrd == 0) then
        x = 10
        !$omp flush ! or with acq_rel or release clause
        !$omp atomic write
        y = 1
        !$omp end atomic
    else
        tmp = 0
        do while (tmp == 0)
            !$omp atomic read
            tmp = y
            !$omp end atomic
        end do
        !$omp flush ! or with acq_rel or acquire clause
        print *, "x = ", x  ! always "x = 10"
    end if
end program
```

Example 4 will fail to order the write to $x$ on thread 0 before the read from $x$ on thread 1. Importantly, the implicit release flush on exit from the critical region will not synchronize with the acquire flush that occurs on the atomic read operation performed by thread 1. This is because implicit release flushes that occur on a given construct may only synchronize with implicit acquire flushes on a compatible construct (and vice-versa) that internally makes use of the same synchronization variable. For a critical construct, this might correspond to a lock object that is used by a given implementation (for the synchronization semantics of other constructs due to implicit release and acquire flushes, refer to the Implicit Flushes section of the OpenMP Specifications document). Either an explicit flush directive that provides a release flush (i.e., a flush without a list that does not have the acquire clause) must be specified between the critical construct and the atomic write, or an atomic operation that modifies $y$ and provides release semantics must be specified.
#include <stdio.h>
#include <omp.h>

int main()
{
    int x = 0, y;
    #pragma omp parallel num_threads(2)
    {
        int thrd = omp_get_thread_num();
        if (thrd == 0) {
            #pragma omp critical
            { x = 10; }
            // an explicit flush directive that provides
            // release semantics is needed here
            #pragma omp atomic write
            y = 1;
        } else {
            int tmp = 0;
            while (tmp == 0) {
                #pragma omp atomic read acquire // or seq_cst
                tmp = y;
            }
            #pragma omp critical
            { printf("x = %d\n", x); } // !! NOT ALWAYS 10
        }
    }
    return 0;
}
Example acquire_release_broke.4.f90

```fortran
program rel_acq_ex4
  use omp_lib
  integer :: x, y, thrd
  integer :: tmp
  x = 0

  !$omp parallel num_threads private(thrd) private(tmp)
    thrd = omp_get_thread_num()
    if (thrd == 0) then
      !$omp critical
      x = 10
      !$omp end critical
    else
      tmp = 0
      do while(tmp == 0)
        !$omp atomic read acquire ! or seq_cst
        tmp = x
        !$omp end atomic
      end do
      !$omp critical
      print *, "x = ", x !! !! NOT ALWAYS 10
    !$omp end critical
  else if
  !$omp end parallel
end program
```

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6.8 The ordered Clause and the ordered Construct

Ordered constructs are useful for sequentially ordering the output from work that is done in parallel. The following program prints out the indices in sequential order:

```
#include <stdio.h>

void work(int k)
{
    #pragma omp ordered
    printf(" %d\n", k);
}

void ordered_example(int lb, int ub, int stride)
{
    int i;
    #pragma omp parallel for ordered schedule(dynamic)
    for (i=lb; i<ub; i+=stride)
    {
        work(i);
    }

int main()
{
    ordered_example(0, 100, 5);
    return 0;
}
```

---

```
SUBROUTINE WORK(K)
    INTEGER k

!$OMP ORDERED
    WRITE(*,*) K
!$OMP END ORDERED
END SUBROUTINE WORK

SUBROUTINE SUB(LB, UB, STRIDE)
    INTEGER LB, UB, STRIDE

    SUBROUTINE WORK(K)
        INTEGER k

        !$OMP ORDERED
            WRITE(*,*) K
        !$OMP END ORDERED
    END SUBROUTINE WORK

    INTEGER I
```

---
It is possible to have multiple ordered constructs within a loop region with the ordered clause specified. The first example is non-conforming because all iterations execute two ordered regions. An iteration of a loop must not execute more than one ordered region:

```c/c++
void work(int i) {}

void ordered_wrong(int n) {
    int i;
    #pragma omp for ordered
    for (i=0; i<n; i++) {
        /* incorrect because an iteration may not execute more than one
           ordered region */
        #pragma omp ordered
        work(i);
        #pragma omp ordered
        work(i+1);
    }
}
```

```
Fortran

!$OMP PARALLEL DO ORDERED SCHEDULE(DYNAMIC)
    DO I=LB,UB,STRIDE
        CALL WORK(I)
    END DO
!$OMP END PARALLEL DO
END SUBROUTINE SUB

PROGRAM ORDERED_EXAMPLE
    CALL SUB(1,100,5)
END PROGRAM ORDERED_EXAMPLE
```

```fortran
SUBROUTINE SUB
    DO I=LB,UB,STRIDE
        CALL WORK(I)
    END DO
END SUBROUTINE SUB
```

```
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```
Example ordered.2.f

SUBROUTINE WORK(I)
   INTEGER I
END SUBROUTINE WORK

SUBROUTINE ORDERED_WRONG(N)
   INTEGER N
   INTEGER I
   !$OMP DO ORDERED
   DO I = 1, N
      ! incorrect because an iteration may not execute more than one 
      ! ordered region
      !$OMP ORDERED
      CALL WORK(I)
      !$OMP END ORDERED
   !$OMP ORDERED
   CALL WORK(I+1)
   !$OMP END ORDERED
   END DO
END SUBROUTINE ORDERED_WRONG

The following is a conforming example with more than one ordered construct. Each iteration
will execute only one ordered region:

Example ordered.3.c

void work(int i) {}
void ordered_good(int n)
{
   int i;
   #pragma omp for ordered
   for (i=0; i<n; i++) {
      if (i <= 10) {
         #pragma omp ordered
         work(i);
      }
      if (i > 10) {
         #pragma omp ordered
         work(i+1);
      }
   }
Example ordered.3.f

SUBROUTINE ORDERED_GOOD(N)
    INTEGER N

    !$OMP DO ORDERED
    DO I = 1,N
        IF (I <= 10) THEN
            !$OMP ORDERED
            CALL WORK(I)
            !$OMP END ORDERED
        ENDIF
   ENDIF
    ENDIF
    ENDDO
END SUBROUTINE ORDERED_GOOD
6.9 The depobj Construct

The stand-alone depobj construct provides a mechanism to create a depend object that expresses a dependence to be used subsequently in the depend clause of another construct. The dependence is created from a dependence type and a storage location, within a depend clause of an depobj construct; and it is stored in the depend object. The depend object is represented by a variable of type omp_depend_t in C/C++ (by a scalar variable of integer kind omp_depend_kind in Fortran).

In the example below the stand-alone depobj construct uses the depend, update and destroy clauses to initialize, update and uninitialize a depend object (obj).

The first depobj construct initializes the obj depend object with an inout dependence type with a storage location defined by variable a. This dependence is passed into the driver routine via the obj depend object.

In the first driver routine call, Task 1 uses the dependence of the object (inout), while Task 2 uses an in dependence specified directly in a depend clause. For these task dependences Task 1 must execute and complete before Task 2 begins.

Before the second call to driver, obj is updated using the depobj construct to represent an in dependence. Hence, in the second call to driver, Task 1 will have an in dependence; and Task 1 and Task 2 can execute simultaneously. Note: in an update clause, only the dependence type can be (is) updated.

The third depobj construct uses the destroy clause. It frees resources as it puts the depend object in an uninitialized state—effectively destroying the depend object. After an object has been uninitialized it can be initialized again with a new dependence type and a new variable.

--- C / C++ ---

Example depobj.1.c

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

#define N 100
#define TRUE 1
#define FALSE 0

void driver(int update, float a[], float b[], int n, omp_depend_t *obj);

void update_copy(int update, float a[], float b[], int n);

void checkpoint(float a[], int n);

void init(float a[], int n);
```


```c
int main()
{
    float a[N], b[N];
    omp_depend_t obj;
    init(a, N);
    #pragma omp depobj(obj) depend(inout: a)
    driver(TRUE, a, b, N, &obj); // updating a occurs
    #pragma omp depobj(obj) update(in)
    driver(FALSE, a, b, N, &obj); // no updating of a
    #pragma omp depobj(obj) destroy // obj is set to uninitialized state,
    // resources are freed
    return 0;
}

void driver(int update, float a[], float b[], int n, omp_depend_t *obj)
{
    #pragma omp parallel num_threads(2)
    #pragma omp single
    {
        #pragma omp task depend(depobj: *obj) // Task 1, uses depend object
        update_copy(update, a, b, n); // update a or not, always copy a to b
        #pragma omp task depend(in: a[:n]) // Task 2, only read a
        checkpoint(a, n);
    }
}

void update_copy(int update, float a[], float b[], int n)
{
    if(update)
        for(int i=0; i<n; i++) a[i]+=1.0f;
    for(int i=0; i<n; i++) b[i]=a[i];
}

void checkpoint(float a[], int n)
{
    for(int i=0; i<n; i++) printf(" %f ", a[i]);
    printf("\n");
```

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void init(float a[], int n)
{
    for(int i=0; i<n; i++) a[i] = i;
}

Example depobj.1.f90

program main
    use omp_lib
    implicit none
    integer, parameter :: N=100
    real :: a(N), b(N)
    integer(omp_depend_kind) :: obj

    call init(a, N)

    !$omp depobj(obj) depend(inout: a)

    call driver(.true., a, b, N, obj)  ! updating occurs

    !$omp depobj(obj) update(in)

    call driver(.false., a, b, N, obj)  ! no updating

    !$omp depobj(obj) destroy  ! obj is set to unitialized state,
                             ! resources are freed

end program

subroutine driver(update, a, b, n, obj)
    use omp_lib
    implicit none
    logical :: update
    real :: a(n), b(n)
    integer :: n
    integer(omp_depend_kind) :: obj

    !$omp parallel num_threads(2)

    !$omp single

    !$omp single
!$omp task depend(depobj: obj) ! Task 1, uses depend object
!$omp end task
!
%!$omp task depend(in: a) ! Task 2, only read a
!$omp end task

!$omp end single
!$omp end parallel

end subroutine

subroutine update_copy(update, a, b, n)
implicit none
logical :: update
real :: a(n), b(n)
integer :: n
if (update) a = a + 1.0
b = a
end subroutine

subroutine checkpoint(a, n)
implicit none
integer :: n
real :: a(n)
inguar :: i
write(*,'( *(f5.0) )') (a(i), i=1,n)
end subroutine

subroutine init(a,n)
implicit none
integer :: n
real :: a(n)
inguar :: i
a=[ (i, i=1,n) ]
end subroutine
An **ordered** clause can be used on a loop construct with an integer parameter argument to define the number of associated loops within a *doacross loop nest* where cross-iteration dependences exist. A **depend** clause on an **ordered** construct within an ordered loop describes the dependences of the *doacross* loops.

In the code below, the **depend(sink: i-1)** clause defines an *i*-1 to *i* cross-iteration dependence that specifies a wait point for the completion of computation from iteration *i*-1 before proceeding to the subsequent statements. The **depend(source)** clause indicates the completion of computation from the current iteration (*i*) to satisfy the cross-iteration dependence that arises from the iteration. For this example the same sequential ordering could have been achieved with an **ordered** clause without a parameter, on the loop directive, and a single **ordered** directive without the **depend** clause specified for the statement executing the *bar* function.

```
float foo(int i);
float bar(float a, float b);
float baz(float b);

void work( int N, float *A, float *B, float *C )
{
    int i;
    #pragma omp for ordered(1)
    for (i=1; i<N; i++)
    {
        A[i] = foo(i);
        #pragma omp ordered depend(sink: i-1)
        B[i] = bar(A[i], B[i-1]);
        #pragma omp ordered depend(source)
        C[i] = baz(B[i]);
    }
}
```

---

C / C++
The following code is similar to the previous example but with *doacross loop nest* extended to two nested loops, *i* and *j*, as specified by the **ordered(2)** clause on the loop directive. In the C/C++ code, the *i* and *j* loops are the first and second associated loops, respectively, whereas in the Fortran code, the *j* and *i* loops are the first and second associated loops, respectively. The **depend(sink:i-1,j)** and **depend(sink:i,j-1)** clauses in the C/C++ code define cross-iteration dependences in two dimensions from iterations (*i*-1, *j*) and (*i*, *j*-1) to iteration (*i*, *j*). Likewise, the **depend(sink:j-1,i)** and **depend(sink:j,i-1)** clauses in the Fortran code define cross-iteration dependences from iterations (*j*-1, *i*) and (*j*, *i*-1) to iteration (*j*, *i*).
The following example shows the incorrect use of the \texttt{ordered} directive with a \texttt{depend} clause. There are two issues with the code. The first issue is a missing \texttt{ordered depend(source)} directive, which could cause a deadlock. The second issue is the \texttt{depend(sink:i+1,j)} and \texttt{depend(sink:i,j+1)} clauses define dependences on lexicographically later source iterations \((i+1,j)\) and \((i,j+1)\), which could cause a deadlock as well since they may not start to execute until the current iteration completes.
Example doacross.3.c

```c
#define N 100

void work_wrong(double p[][N][N])
{
    int i, j, k;

    #pragma omp parallel for ordered(2) private(i,j,k)
    for (i=1; i<N-1; i++)
    {
        for (j=1; j<N-1; j++)
        {
            #pragma omp ordered depend(sink: i-1,j) depend(sink: i+1,j) \
            depend(sink: i,j-1) depend(sink: i,j+1)
            for (k=1; k<N-1; k++)
            {
                double tmp1 = p[i-1][j][k] + p[i+1][j][k];
                double tmp2 = p[i][j-1][k] + p[i][j+1][k];
                double tmp3 = p[i][j][k-1] + p[i][j][k+1];
                p[i][j][k] = (tmp1 + tmp2 + tmp3) / 6.0;
            }
        }
    }
    /* missing #pragma omp ordered depend(source) */
}
```

Example doacross.3.f90

```fortran
subroutine work_wrong(N, p)
    integer :: N
    real(8), dimension(N,N,N) :: p
    integer :: i, j, k
    real(8) :: tmp1, tmp2, tmp3

    !$omp parallel do ordered(2) private(i,j,k,tmp1,tmp2,tmp3)
    do i=2, N-1
        do j=2, N-1
            !$omp ordered depend(sink: i-1,j) depend(sink: i+1,j) \
            &
            !$omp& depend(sink: i,j-1) depend(sink: i,j+1)
            do k=2, N-1
                tmp1 = p(k-1,j,i) + p(k+1,j,i)
                tmp2 = p(k,j-1,i) + p(k,j+1,i)
                tmp3 = p(k,j,i-1) + p(k,j,i+1)
```
The following example illustrates the use of the `collapse` clause for a `doacross loop nest`. The $i$ and $j$ loops are the associated loops for the collapsed loop as well as for the `doacross loop nest`. The example also shows a compliant usage of the dependence source directive placed before the corresponding sink directive. Checking the completion of computation from previous iterations at the sink point can occur after the source statement.

```c
Example doacross.4.c

double foo(int i, int j);
void work( int N, int M, double **A, double **B, double **C )
{
    int i, j;
    double alpha = 1.2;
    #pragma omp for collapse(2) ordered(2)
    for (i = 1; i < N-1; i++)
    {
        for (j = 1; j < M-1; j++)
        {
            A[i][j] = foo(i, j);
            #pragma omp ordered depend(source)
            B[i][j] = alpha * A[i][j];
            #pragma omp ordered depend(sink: i-1,j) depend(sink: i,j-1)
            C[i][j] = 0.2 * (A[i-1][j] + A[i+1][j] +
        }
    }
}
```
Example doacross.4.f90

```fortran
subroutine work( N, M, A, B, C )

integer :: N, M
real(8), dimension(M, N) :: A, B, C
real(8), external :: foo
integer :: i, j
real(8) :: alpha = 1.2

!$omp do collapse(2) ordered(2)
do j=2, N-1
doi=2, M-1
   A(i, j) = foo(i, j)
!$omp ordered depend(source)
   B(i, j) = alpha * A(i, j)
!$omp ordered depend(sink: j,i-1) depend(sink: j-1,i)
   C(i, j) = 0.2 * (A(i-1,j) + A(i+1,j) + &
               A(i,j-1) + A(i,j+1) + A(i,j))
end do
end do
end subroutine
```

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6.11 Lock Routines

This section is about the use of lock routines for synchronization.

6.11.1 The omp_init_lock Routine

The following example demonstrates how to initialize an array of locks in a parallel region by using omp_init_lock.

C++

```cpp
#include <omp.h>

omp_lock_t *new_locks() {
    int i;
    omp_lock_t *lock = new omp_lock_t[1000];

    #pragma omp parallel for private(i)
    for (i=0; i<1000; i++)
        omp_init_lock(&lock[i]);

    return lock;
}
```

Fortran

```fortran
FUNCTION NEW_LOCKS()
    USE OMP_LIB ! or INCLUDE "omp_lib.h"
    INTEGER(OMP_LOCK_KIND), DIMENSION(1000) :: NEW_LOCKS
    INTEGER I

    !$OMP PARALLEL DO PRIVATE(I)
    DO I=1,1000
        CALL OMP_INIT_LOCK(NEW_LOCKS(I))
    END DO
    !$OMP END PARALLEL DO

END FUNCTION NEW_LOCKS
```
6.11.2 The omp_init_lock_with_hint Routine

The following example demonstrates how to initialize an array of locks in a parallel region by using omp_init_lock_with_hint. Note, hints are combined with an | or + operator in C/C++ and a + operator in Fortran.

```cpp
#include <omp.h>

omp_lock_t *new_locks()
{
    int i;
    omp_lock_t *lock = new omp_lock_t[1000];

    #pragma omp parallel for private(i)
    for (i=0; i<1000; i++)
    {
        omp_init_lock_with_hint(&lock[i],
            static_cast<omp_lock_hint_t>(omp_lock_hint_contended |
            omp_lock_hint_speculative));
    }
    return lock;
}
```

```fortran
FUNCTION NEW_LOCKS()
    USE OMP_LIB ! or INCLUDE "omp_lib.h"
    INTEGER(OMP_LOCK_KIND), DIMENSION(1000) :: NEW_LOCKS
    INTEGER I

    !$OMP PARALLEL DO PRIVATE(I)
    DO I=1,1000
        CALL OMP_INIT_LOCK_WITH_HINT(NEW_LOCKS(I),
            & OMP_LOCK_HINT_CONTENDED + OMP_LOCK_HINT_SPECULATIVE)
    END DO
    !$OMP END PARALLEL DO

END FUNCTION NEW_LOCKS
```

Example init_lock_with_hint.1.cpp

Example init_lock_with_hint.1.f
Ownership of locks has changed since OpenMP 2.5. In OpenMP 2.5, locks are owned by threads; so a lock released by the `omp_unset_lock` routine must be owned by the same thread executing the routine. Beginning with OpenMP 3.0, locks are owned by task regions; so a lock released by the `omp_unset_lock` routine in a task region must be owned by the same task region.

This change in ownership requires extra care when using locks. The following program is conforming in OpenMP 2.5 because the thread that releases the lock `lck` in the parallel region is the same thread that acquired the lock in the sequential part of the program (master thread of parallel region and the initial thread are the same). However, it is not conforming beginning with OpenMP 3.0, because the task region that releases the lock `lck` is different from the task region that acquires the lock.

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

int main()
{
    int x;
    omp_lock_t lck;
    omp_init_lock (&lck);
    omp_set_lock (&lck);
    x = 0;
    /* Some more stuff. */
    #pragma omp parallel shared (x)
    {
        #pragma omp master
        {
            x = x + 1;
            omp_unset_lock (&lck);
        }
        /* Some more stuff. */
    }
    omp_destroy_lock (&lck);
    return 0;
}
```
Example lock_owner.1.f

program lock
use omp_lib
integer :: x
integer (kind=omp_lock_kind) :: lck

call omp_init_lock (lck)
call omp_set_lock(lck)
x = 0
!
$omp parallel shared (x)
$omp master
x = x + 1
call omp_unset_lock(lck)
$omp end master
!
Some more stuff.
$omp end parallel
!
call omp_destroy_lock(lck)
end

6.11.4 Simple Lock Routines

In the following example, the lock routines cause the threads to be idle while waiting for entry to the first critical section, but to do other work while waiting for entry to the second. The omp_set_lock function blocks, but the omp_test_lock function does not, allowing the work in skip to be done.

Note that the argument to the lock routines should have type omp_lock_t, and that there is no need to flush it.
Example simple_lock.1.c

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

void skip(int i) {}
void work(int i) {}

int main()
{
    omp_lock_t lck;
    int id;
    omp_init_lock(&lck);

    #pragma omp parallel shared(lck) private(id)
    {
        id = omp_get_thread_num();

        omp_set_lock(&lck);
        /* only one thread at a time can execute this printf */
        printf("My thread id is %d.\n", id);
        omp_unset_lock(&lck);

        while (! omp_test_lock(&lck)) {
            skip(id); /* we do not yet have the lock,
                        so we must do something else */
        }

        work(id); /* we now have the lock
                  and can do the work */
        omp_unset_lock(&lck);
    }

    omp_destroy_lock(&lck);
    return 0;
}
```

Note that there is no need to flush the lock variable.
Example simple_lock.1.f

SUBROUTINE SKIP(ID)
END SUBROUTINE SKIP

SUBROUTINE WORK(ID)
END SUBROUTINE WORK

PROGRAM SIMPLELOCK

INCLUDE "omp_lib.h" ! or USE OMP_LIB

INTEGER(OMP_LOCK_KIND) LCK
INTEGER ID

CALL OMP_INIT_LOCK(LCK)

!$OMP PARALLEL SHARED(LCK) PRIVATE(ID)
ID = OMP_GET_THREAD_NUM()
CALL OMP_SET_LOCK(LCK)
PRINT *, 'My thread id is ', ID
CALL OMP_UNSET_LOCK(LCK)

DO WHILE (.NOT. OMP_TEST_LOCK(LCK))
CALL SKIP(ID) ! We do not yet have the lock
! so we must do something else
END DO

CALL WORK(ID) ! We now have the lock
! and can do the work

CALL OMP_UNSET_LOCK(LCK)

!$OMP END PARALLEL

CALL OMP_Destroy_LOCK(LCK)

END PROGRAM SIMPLELOCK
6.11.5 Nestable Lock Routines

The following example demonstrates how a nestable lock can be used to synchronize updates both to a whole structure and to one of its members.

```
#include <omp.h>

typedef struct {
  int a,b;
  omp_nest_lock_t lck;
} pair;

int work1();
int work2();
int work3();

void incr_a(pair *p, int a)
{
  p->a += a;
}

void incr_b(pair *p, int b)
{
  omp_set_nest_lock(&p->lck);
  p->b += b;
  omp_unset_nest_lock(&p->lck);
}

void incr_pair(pair *p, int a, int b)
{
  omp_set_nest_lock(&p->lck);
  incr_a(p, a);
  incr_b(p, b);
  omp_unset_nest_lock(&p->lck);
}
```
void nestlock(pair *p)
{
#pragma omp parallel sections
{
#pragma omp section
    incr_pair(p, work1(), work2());
#pragma omp section
    incr_b(p, work3());
}
}

Example nestable_lock.1.f

MODULE DATA
    USE OMP_LIB, ONLY: OMP_NEST_LOCK_KIND
    TYPE LOCKED_PAIR
        INTEGER A
        INTEGER B
        INTEGER (OMP_NEST_LOCK_KIND) LCK
    END TYPE
END MODULE DATA

SUBROUTINE INCR_A(P, A)
    ! called only from INCR_PAIR, no need to lock
    USE DATA
    TYPE(LOCKED_PAIR) :: P
    INTEGER A
    P%A = P%A + A
END SUBROUTINE INCR_A

SUBROUTINE INCR_B(P, B)
    ! called from both INCR_PAIR and elsewhere,
    ! so we need a nestable lock
    USE OMP_LIB ! or INCLUDE "omp_lib.h"
    USE DATA
    TYPE (LOCKED_PAIR) :: P
    INTEGER B
    CALL OMP_SET_NEST_LOCK(P%LCK)
    P%B = P%B + B
    CALL OMP_UNSET_NEST_LOCK(P%LCK)
END SUBROUTINE INCR_B

SUBROUTINE INCR_PAIR(P, A, B)
  USE OMP_LIB ! or INCLUDE "omp_lib.h"
  USE DATA
  TYPE(LOCKED_PAIR) :: P
  INTEGER A
  INTEGER B
  CALL OMP_SET_NEST_LOCK(P%LCK)
  CALL INCR_A(P, A)
  CALL INCR_B(P, B)
  CALL OMP_UNSET_NEST_LOCK(P%LCK)
END SUBROUTINE INCR_PAIR

SUBROUTINE NESTLOCK(P)
  USE OMP_LIB ! or INCLUDE "omp_lib.h"
  USE DATA
  TYPE(LOCKED_PAIR) :: P
  INTEGER WORK1, WORK2, WORK3
  EXTERNAL WORK1, WORK2, WORK3
  !$OMP PARALLEL SECTIONS
  !$OMP SECTION
  CALL INCR_PAIR(P, WORK1(), WORK2())
  !$OMP SECTION
  CALL INCR_B(P, WORK3())
  !$OMP END PARALLEL SECTIONS
END SUBROUTINE NESTLOCK
The OpenMP data environment contains data attributes of variables and objects. Many constructs (such as parallel, simd, task) accept clauses to control data-sharing attributes of referenced variables in the construct, where data-sharing applies to whether the attribute of the variable is shared, is private storage, or has special operational characteristics (as found in the firstprivate, lastprivate, linear, or reduction clause).

The data environment for a device (distinguished as a device data environment) is controlled on the host by data-mapping attributes, which determine the relationship of the data on the host, the original data, and the data on the device, the corresponding data.

DATA-SHARING ATTRIBUTES

Data-sharing attributes of variables can be classified as being predetermined, explicitly determined or implicitly determined.

Certain variables and objects have predetermined attributes. A commonly found case is the loop iteration variable in associated loops of a for or do construct. It has a private data-sharing attribute. Variables with predetermined data-sharing attributes can not be listed in a data-sharing attribute clause; but there are some exceptions (mainly concerning loop iteration variables).

Variables with explicitly determined data-sharing attributes are those that are referenced in a given construct and are listed in a data-sharing attribute clause on the construct. Some of the common data-sharing clauses are: shared, private, firstprivate, lastprivate, linear, and reduction.

Variables with implicitly determined data-sharing attributes are those that are referenced in a given construct, do not have predetermined data-sharing attributes, and are not listed in a data-sharing attribute clause of an enclosing construct. For a complete list of variables and objects with predetermined and implicitly determined attributes, please refer to the Data-sharing Attribute Rules for Variables Referenced in a Construct subsection of the OpenMP Specifications document.
DATA-MAPPING ATTRIBUTES

The `map` clause on a device construct explicitly specifies how the list items in the clause are mapped from the encountering task’s data environment (on the host) to the corresponding item in the device data environment (on the device). The common list items are arrays, array sections, scalars, pointers, and structure elements (members).

Procedures and global variables have predetermined data mapping if they appear within the list or block of a `declare target` directive. Also, a C/C++ pointer is mapped as a zero-length array section, as is a C++ variable that is a reference to a pointer.

Without explicit mapping, non-scalar and non-pointer variables within the scope of the `target` construct are implicitly mapped with a map-type of `tofrom`. Without explicit mapping, scalar variables within the scope of the `target` construct are not mapped, but have an implicit firstprivate data-sharing attribute. (That is, the value of the original variable is given to a private variable of the same name on the device.) This behavior can be changed with the `defaultmap` clause.

The `map` clause can appear on `target`, `target data` and `target enter/exit data` constructs. The operations of creation and removal of device storage as well as assignment of the original list item values to the corresponding list items may be complicated when the list item appears on multiple constructs or when the host and device storage is shared. In these cases the item’s reference count, the number of times it has been referenced (+1 on entry and -1 on exited) in nested (structured) map regions and/or accumulative (unstructured) mappings, determines the operation. Details of the `map` clause and reference count operation are specified in the `map Clause` subsection of the OpenMP Specifications document.
7.1 The threadprivate Directive

The following examples demonstrate how to use the threadprivate directive to give each thread a separate counter.

```
Example threadprivate.1.c
int counter = 0;
#pragma omp threadprivate(counter)
int increment_counter()
{
    counter++;
    return(counter);
}
```

```
Example threadprivate.1.f
INTEGER FUNCTION INCREMENT_COUNTER()
    COMMON/INC_COMMON/COUNTER
    !$OMP THREADPRIVATE(/INC_COMMON/)
    COUNTER = COUNTER +1
    INCREMENT_COUNTER = COUNTER
    RETURN
END FUNCTION INCREMENT_COUNTER
```

The following example uses threadprivate on a static variable:

```
Example threadprivate.2.c
int increment_counter_2()
{
    static int counter = 0;
    #pragma omp threadprivate(counter)
    counter++;
    return(counter);
}
```
The following example demonstrates unspecified behavior for the initialization of a
\texttt{threadprivate} variable. A \texttt{threadprivate} variable is initialized once at an unspecified
point before its first reference. Because \texttt{a} is constructed using the value of \texttt{x} (which is modified by
the statement \texttt{x++}), the value of \texttt{a.val} at the start of the \texttt{parallel} region could be either 1 or
2. This problem is avoided for \texttt{b}, which uses an auxiliary \texttt{const} variable and a copy-constructor.

\textit{Example \texttt{threadprivate.3.cpp}}

\begin{verbatim}
class T {
public:
  int val;
  T (int);
  T (const T&);
};
T :: T (int v) {
  val = v;
}
T :: T (const T& t) {
  val = t.val;
}
void g(T a, T b) {
  a.val += b.val;
}
int x = 1;
T a(x);
const T b_aux(x); /* Capture value of \texttt{x = 1} */
T b(b_aux);
#pragma omp threadprivate(a, b)
void f(int n) {
  x++;
  #pragma omp parallel for
  /* In each thread:
  * \texttt{a} is constructed from \texttt{x} (with value 1 or 2?)
  * \texttt{b} is copy-constructed from \texttt{b_aux}
  */
  for (int i=0; i<n; i++) {
    g(a, b); /* Value of \texttt{a} is unspecified. */
  }
}
\end{verbatim}
The following examples show non-conforming uses and correct uses of the `threadprivate` directive.

```fortran
MODULE INC_MODULE
  COMMON /T/ A
END MODULE INC_MODULE

SUBROUTINE INC_MODULE_WRONG()
  USE INC_MODULE
  !$OMP THREADPRIVATE(/T/)
  !non-conforming because /T/ not declared in INC_MODULE_WRONG
END SUBROUTINE INC_MODULE_WRONG
```

The following example is also non-conforming because the common block is not declared local to the subroutine that refers to it:

```fortran
SUBROUTINE INC_WRONG()
  COMMON /T/ A
  !$OMP THREADPRIVATE(/T/)
  CONTAINS
    SUBROUTINE INC_WRONG_SUB()
    COMMON /T/ A
    !$OMP THREADPRIVATE(/T/)
    !$OMP PARALLEL COPYIN(/T/)
    !non-conforming because /T/ not declared in INC_WRONG_SUB
    !$OMP END PARALLEL
    END SUBROUTINE INC_WRONG_SUB
END SUBROUTINE INC_WRONG
```

The following example is a correct rewrite of the previous example:

```fortran
SUBROUTINE INC_GOOD()
  COMMON /T/ A
  !$OMP THREADPRIVATE(/T/)
  CONTAINS
    SUBROUTINE INC_GOOD_SUB()
    COMMON /T/ A
    !$OMP THREADPRIVATE(/T/)
    !$OMP PARALLEL COPYIN(/T/)
```

The following example is non-conforming because the common block is not declared local to the subroutine that refers to it:

```fortran
SUBROUTINE INC_MODULE_WRONG()
  USE INC_MODULE
  !$OMP THREADPRIVATE(/T/)
  !non-conforming because /T/ not declared in INC_MODULE_WRONG
END SUBROUTINE INC_MODULE_WRONG
```
The following is an example of the use of **threadprivate** for local variables:

```
Example threadprivate.5.f
```

```fortran
PROGRAM INC_GOOD2
  INTEGER, ALLOCATABLE, SAVE :: A(:)
  INTEGER, POINTER, SAVE :: PTR
  INTEGER, SAVE :: I
  INTEGER, TARGET :: TARG
  LOGICAL :: FIRSTIN = .TRUE.
  !$OMP THREADPRIVATE(A, I, PTR)
  ALLOCATE (A(3))
  A = (/1,2,3/)
  PTR => TARG
  I = 5
  !$OMP PARALLEL COPYIN(I, PTR)
  !$OMP CRITICAL
  IF (FIRSTIN) THEN
    TARG = 4 ! Update target of ptr
    I = I + 10
    IF (ALLOCATED(A)) A = A + 10
    FIRSTIN = .FALSE.
  END IF
  IF (ALLOCATED(A)) THEN
    PRINT *, 'a = ', A
  ELSE
    PRINT *, 'A is not allocated'
  END IF
  PRINT *, 'ptr = ', PTR
  PRINT *, 'i = ', I
  PRINT *
  !$OMP END CRITICAL
  !$OMP END PARALLEL
END PROGRAM INC_GOOD2
```

The above program, if executed by two threads, will print one of the following two sets of output:
a = 11 12 13
ptr = 4
i = 15

A is not allocated
ptr = 4
i = 5

or

A is not allocated
ptr = 4
i = 15

a = 1 2 3
ptr = 4
i = 5

The following is an example of the use of \texttt{threadprivate} for module variables:

\textit{Example threadprivate.6.f}

\begin{verbatim}
MODULE INC_MODULE_GOOD3
   REAL, POINTER :: WORK(:)
   SAVE WORK
   !$OMP THREADPRIVATE(WORK)
   END MODULE INC_MODULE_GOOD3

SUBROUTINE SUB1(N)
   USE INC_MODULE_GOOD3
   !$OMP PARALLEL PRIVATE(THE_SUM)
   ALLOCATE(WORK(N))
   CALL SUB2(THE_SUM)
   WRITE(*,*)THE_SUM
   !$OMP END PARALLEL
END SUBROUTINE SUB1

SUBROUTINE SUB2(THE_SUM)
   USE INC_MODULE_GOOD3
   WORK(:) = 10
   THE_SUM=SUM(WORK)
END SUBROUTINE SUB2

PROGRAM INC_GOOD3
   N = 10
   CALL SUB1(N)
\end{verbatim}
The following example illustrates initialization of `threadprivate` variables for class-type `T`. `t1` is default constructed, `t2` is constructed taking a constructor accepting one argument of integer type, `t3` is copy constructed with argument `f()`:

```cpp
struct T
{  
  T ();  
  T (int);  
  ~T ();  
  int t;  
};

int f();

static T t1;
#pragma omp threadprivate(t1)
static T t2( 23 );
#pragma omp threadprivate(t2)
static T t3 = f();
#pragma omp threadprivate(t3)
```

The following example illustrates the use of `threadprivate` for static class members. The `threadprivate` directive for a static class member must be placed inside the class definition:

```cpp
class T
{  
  public:
  
  static int i;
  
  #pragma omp threadprivate(i)
};
```
7.2 The default (none) Clause

The following example distinguishes the variables that are affected by the `default(none)` clause from those that are not.

```
#include <omp.h>
int x, y, z[1000];
#pragma omp threadprivate(x)

void default_none(int a) {
  const int c = 1;
  int i = 0;

  #pragma omp parallel default(none) private(a) shared(z, c)
  {
    int j = omp_get_num_threads();
    /* O.K. - j is declared within parallel region */
    a = z[j]; /* O.K. - a is listed in private clause */
    /* - z is listed in shared clause */
    x = c; /* O.K. - x is threadprivate */
    /* - c has const-qualified type and
    is listed in shared clause */
    z[i] = y; /* Error - cannot reference i or y here */

    #pragma omp for firstprivate(y)
    /* Error - Cannot reference y in the firstprivate clause */
    for (i=0; i<10 ; i++) {
      z[i] = i; /* O.K. - i is the loop iteration variable */
    }
  }
}
```

Beginning with OpenMP 4.0, variables with `const`-qualified type and no mutable member are no longer predetermined shared. Thus, these variables (variable `c` in the example) need to be explicitly listed in data-sharing attribute clauses when the `default(none)` clause is specified.
SUBROUTINE DEFAULT_NONE(A)

INCLUDE "omp_lib.h" ! or USE OMP_LIB

INTEGER A

INTEGER X, Y, Z(1000)
COMMON/BLOCKX/X
COMMON/BLOCKY/Y
COMMON/BLOCKZ/Z

!$OMP THREADPRIVATE(/BLOCKX/)

INTEGER I, J
i = 1

!$OMP PARALLEL DEFAULT(NONE) PRIVATE(A) SHARED(Z) PRIVATE(J)
J = OMP_GET_NUM_THREADS();
! O.K. - J is listed in PRIVATE clause
A = Z(J) ! O.K. - A is listed in PRIVATE clause
! Z is listed in SHARED clause
X = 1 ! O.K. - X is THREADPRIVATE
Z(I) = Y ! Error - cannot reference I or Y here

!$OMP DO firstprivate(y)
! Error - Cannot reference y in the firstprivate clause
DO I = 1,10
Z(I) = I ! O.K. - I is the loop iteration variable
END DO

Z(I) = Y ! Error - cannot reference I or Y here

!$OMP END PARALLEL

END SUBROUTINE DEFAULT_NONE
7.3 The private Clause

In the following example, the values of original list items $i$ and $j$ are retained on exit from the 
parallel region, while the private list items $i$ and $j$ are modified within the parallel 
construct.

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

int main()
{
    int i, j;
    int *ptr_i, *ptr_j;
    i = 1;
    j = 2;

    ptr_i = &i;
    ptr_j = &j;

    #pragma omp parallel private(i) firstprivate(j)
    {
        i = 3;
        j = j + 2;
        assert (*ptr_i == 1 && *ptr_j == 2);
    }

    assert(i == 1 && j == 2);
    return 0;
}
```

Example private.1.c

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In the following example, all uses of the variable $a$ within the loop construct in the routine $f$ refer to a private list item $a$, while it is unspecified whether references to $a$ in the routine $g$ are to a private list item or the original list item.
The following example demonstrates that a list item that appears in a `private` clause in a `parallel` construct may also appear in a `private` clause in an enclosed worksharing construct, which results in an additional private copy.
for (i=0; i<10; i++)
{
    a = 2;
}
assert(a == 1);

Example private.3.f

SUBROUTINE PRIV_EXAMPLE3()
    INTEGER I, A
    !$OMP PARALLEL PRIVATE(A)
    A = 1
    !$OMP PARALLEL DO PRIVATE(A)
    DO I = 1, 10
        A = 2
    END DO
    !$OMP END PARALLEL DO
    PRINT *, A ! Outer A still has value 1
    !$OMP END PARALLEL
END SUBROUTINE PRIV_EXAMPLE3
7.4 Fortran Private Loop Iteration Variables

In general loop iteration variables will be private, when used in the do-loop of a do and parallel do construct or in sequential loops in a parallel construct (see Section 2.7.1 and Section 2.14.1 of the OpenMP 4.0 specification). In the following example of a sequential loop in a parallel construct the loop iteration variable \( I \) will be private.

Example fort_loopvar.1.f90

```fortran
SUBROUTINE PLOOP_1(A,N)
INCLUDE "omp_lib.h" ! or USE OMP_LIB
REAL A(*)
INTEGER I, MYOFFSET, N

!$OMP PARALLEL PRIVATE(MYOFFSET)
MYOFFSET = OMP_GET_THREAD_NUM()*N
DO I = 1, N
  A(MYOFFSET+I) = FLOAT(I)
ENDDO
!$OMP END PARALLEL
END SUBROUTINE PLOOP_1
```

In exceptional cases, loop iteration variables can be made shared, as in the following example:

Example fort_loopvar.2.f90

```fortran
SUBROUTINE PLOOP_2(A,B,N,I1,I2)
REAL A(*), B(*)
INTEGER I1, I2, N

!$OMP PARALLEL SHARED(A,B,I1,I2)
!$OMP SECTIONS
!$OMP SECTION
DO I1 = I1, N
  IF (A(I1).NE.0.0) EXIT
ENDDO
!$OMP SECTION
DO I2 = I2, N
  IF (B(I2).NE.0.0) EXIT
ENDDO
!$OMP END SECTIONS
!$OMP SINGLE
IF (I1.LE.N) PRINT *, 'ITEMS IN A UP TO ', I1, 'ARE ALL ZERO.'
IF (I2.LE.N) PRINT *, 'ITEMS IN B UP TO ', I2, 'ARE ALL ZERO.'
```

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Note however that the use of shared loop iteration variables can easily lead to race conditions.
7.5 Fortran Restrictions on shared and private Clauses with Common Blocks

When a named common block is specified in a `private`, `firstprivate`, or `lastprivate` clause of a construct, none of its members may be declared in another data-sharing attribute clause on that construct. The following examples illustrate this point.

The following example is conforming:

```
Example fort_sp_common.1.f

S-1 SUBROUTINE COMMON_GOOD()
S-2 COMMON /C/ X,Y
S-3 REAL X, Y
S-4
S-5 !$OMP PARALLEL PRIVATE (/C/)
S-6 ! do work here
S-7 !$OMP END PARALLEL
S-8 !$OMP PARALLEL SHARED (X,Y)
S-9 ! do work here
S-10 !$OMP END PARALLEL
S-11 END SUBROUTINE COMMON_GOOD
```

The following example is also conforming:

```
Example fort_sp_common.2.f

S-1 SUBROUTINE COMMON_GOOD2()
S-2 COMMON /C/ X,Y
S-3 REAL X, Y
S-4 INTEGER I
S-5 !$OMP PARALLEL
S-6 !$OMP DO PRIVATE (/C/)
S-7 DO I=1,1000
S-8 ! do work here
S-9 ENDDO
S-10 !$OMP END DO
S-11 !$OMP DO PRIVATE (X)
S-12 DO I=1,1000
S-13 ! do work here
S-14 ENDDO
S-15 !$OMP END DO
S-16 !$OMP END PARALLEL
S-17 END SUBROUTINE COMMON_GOOD2
```
The following example is conforming:

Example fort_sp_common.3.f

```fortran
S-1 SUBROUTINE COMMON_GOOD3()
S-2 COMMON /C/ X,Y
S-3 !$OMP PARALLEL PRIVATE (/C/)
S-4 ! do work here
S-5 !$OMP END PARALLEL
S-6 !$OMP PARALLEL SHARED (/C/)
S-7 ! do work here
S-8 !$OMP END PARALLEL
S-9 END SUBROUTINE COMMON_GOOD3
```

The following example is non-conforming because `x` is a constituent element of `c`:

Example fort_sp_common.4.f

```fortran
S-1 SUBROUTINE COMMON_WRONG()
S-2 COMMON /C/ X,Y
S-3 ! Incorrect because X is a constituent element of C
S-4 !$OMP PARALLEL PRIVATE(/C/), SHARED(X)
S-5 ! do work here
S-6 !$OMP END PARALLEL
S-7 END SUBROUTINE COMMON_WRONG
```

The following example is non-conforming because a common block may not be declared both shared and private:

Example fort_sp_common.5.f

```fortran
S-1 SUBROUTINE COMMON_WRONG2()
S-2 COMMON /C/ X,Y
S-3 ! Incorrect: common block C cannot be declared both
S-4 ! shared and private
S-5 !$OMP PARALLEL PRIVATE (/C/), SHARED(/C/)
S-6 ! do work here
S-7 !$OMP END PARALLEL
S-8 END SUBROUTINE COMMON_WRONG2
```
The following non-conforming examples illustrate the implications of the \texttt{private} clause rules with regard to storage association.

\textit{Example fort\_sa\_private.1.f}

```
SUBROUTINE SUB()
  COMMON /BLOCK/ X
  PRINT *,X ! X is undefined
END SUBROUTINE SUB

PROGRAM PRIV_RESTRICT
  COMMON /BLOCK/ X
  X = 1.0
  !$OMP PARALLEL PRIVATE (X)
  X = 2.0
  CALL SUB()
  !$OMP END PARALLEL
END PROGRAM PRIV_RESTRICT
```

\textit{Example fort\_sa\_private.2.f}

```
PROGRAM PRIV_RESTRICT2
  COMMON /BLOCK2/ X
  X = 1.0
  !$OMP PARALLEL PRIVATE (X)
  X = 2.0
  CALL SUB()
  !$OMP END PARALLEL
  CONTAINS
  SUBROUTINE SUB()
    COMMON /BLOCK2/ Y
    PRINT *,Y ! Y is undefined
  END SUBROUTINE SUB
END PROGRAM PRIV_RESTRICT2
```

\textit{Example fort\_sa\_private.3.f}
Fortran (cont.)

Example fort_sa_private.4.f

```
S-1 PROGRAM PRIV_RESTRICT3
S-2 EQUIVALENCE (X,Y)
S-3 X = 1.0
S-4
S-5 !$OMP PARALLEL PRIVATE(X)
S-6 PRINT *,Y ! Y is undefined
S-7 Y = 10
S-8 PRINT *,X ! X is undefined
S-9 !$OMP END PARALLEL
S-10 END PROGRAM PRIV_RESTRICT3
```

Example fort_sa_private.4.f

```
S-1 PROGRAM PRIV_RESTRICT4
S-2 INTEGER I, J
S-3 INTEGER A(100), B(100)
S-4 EQUIVALENCE (A(51), B(1))
S-5
S-6 !$OMP PARALLEL DO DEFAULT(PRIVATE) PRIVATE(I,J) LASTPRIVATE(A)
S-7 DO I=1,100
S-8 DO J=1,100
S-9 B(J) = J - 1
S-10 ENDDO
S-11
S-12 DO J=1,100
S-13 A(J) = J ! B becomes undefined at this point
S-14 ENDDO
S-15
S-16 DO J=1,50
S-17 B(J) = B(J) + 1 ! B is undefined
S-18 ! A becomes undefined at this point
S-19 ENDDO
S-20 ENDDO
S-21 !$OMP END PARALLEL DO ! The LASTPRIVATE write for A has
S-22 ! undefined results
S-23
S-24 PRINT *, B ! B is undefined since the LASTPRIVATE
S-25 ! write of A was not defined
S-26 END PROGRAM PRIV_RESTRICT4
```

Example fort_sa_private.5.f

```
S-1 SUBROUTINE SUB1(X)
S-2 DIMENSION X(10)
S-3
S-4 ! This use of X does not conform to the
```
! specification. It would be legal Fortran 90, but the OpenMP private directive allows the compiler to break the sequence association that A had with the rest of the common block.

```fortran
FORALL (I = 1:10) X(I) = I
END SUBROUTINE SUB1

PROGRAM PRIV_RESTRICT5
  COMMON /BLOCK5/ A
  DIMENSION B(10)
  EQUIVALENCE (A,B(1))
  ! the common block has to be at least 10 words
  A = 0

!$OMP PARALLEL PRIVATE(/BLOCK5/)

  ! Without the private clause,
  ! we would be passing a member of a sequence
  ! that is at least ten elements long.
  ! With the private clause, A may no longer be
  ! sequence-associated.

  CALL SUB1(A)

!$OMP MASTER
  PRINT *, A
!$OMP END MASTER
!$OMP END PARALLEL
END PROGRAM PRIV_RESTRICT5
```

---

Fortran

---
The following example illustrates the size and value of list items of array or pointer type in a `firstprivate` clause. The size of new list items is based on the type of the corresponding original list item, as determined by the base language.

In this example:

- The type of `A` is array of two arrays of two ints.
- The type of `B` is adjusted to pointer to array of `n` ints, because it is a function parameter.
- The type of `C` is adjusted to pointer to int, because it is a function parameter.
- The type of `D` is array of two arrays of two ints.
- The type of `E` is array of `n` arrays of `n` ints.

Note that `B` and `E` involve variable length array types.

The new items of array type are initialized as if each integer element of the original array is assigned to the corresponding element of the new array. Those of pointer type are initialized as if by assignment from the original item to the new item.

*Example carrays_fpriv.1.c*

```c
#include <assert.h>

int A[2][2] = {1, 2, 3, 4};

void f(int n, int B[n][n], int C[])
{
    int D[2][2] = {1, 2, 3, 4};
    int E[n][n];

    assert(n >= 2);
    E[1][1] = 4;

    #pragma omp parallel firstprivate(B, C, D, E)
    {
        assert(sizeof(B) == sizeof(int (*)[n]));
        assert(sizeof(C) == sizeof(int*));
        assert(sizeof(D) == 4 * sizeof(int));
        assert(sizeof(E) == n * n * sizeof(int));

        /* Private B and C have values of original B and C. */
        assert(&B[1][1] == &A[1][1]);
        assert(&C[3] == &A[1][1]);
        assert(D[1][1] == 4);
        assert(E[1][1] == 4);
    }
```

```
int main() {
    f(2, A, A[0]);
    return 0;
}
7.8 The lastprivate Clause

Correct execution sometimes depends on the value that the last iteration of a loop assigns to a variable. Such programs must list all such variables in a lastprivate clause so that the values of the variables are the same as when the loop is executed sequentially.

\begin{verbatim}
Example lastprivate.1.c

void lastpriv (int n, float *a, float *b)
{
    int i;
    #pragma omp parallel
    {
        #pragma omp for lastprivate(i)
        for (i=0; i<n-1; i++)
            a[i] = b[i] + b[i+1];
    }
    a[i]=b[i]; /* i == n-1 here */
}

Example lastprivate.1.f

SUBROUTINE LASTPRIV(N, A, B)
INTEGER N
REAL A(*), B(*)
INTEGER I
!$OMP PARALLEL
!$OMP DO LASTPRIVATE(I)
DO I=1,N-1
    A(I) = B(I) + B(I+1)
ENDDO
!$OMP END PARALLEL
A(I) = B(I) ! I has the value of N here
END SUBROUTINE LASTPRIV
\end{verbatim}
This section covers ways to perform reductions in parallel, task, taskloop, and SIMD regions.

### 7.9.1 The reduction Clause

The following example demonstrates the `reduction` clause; note that some reductions can be expressed in the loop in several ways, as shown for the `max` and `min` reductions below:

```c
#include <math.h>

void reduction1(float *x, int *y, int n)
{
    int i, b, c;
    float a, d;
    a = 0.0;
    b = 0;
    c = y[0];
    d = x[0];
    #pragma omp parallel for private(i) shared(x, y, n) \
    reduction(+:a) reduction(^:b) \
    reduction(min:c) reduction(max:d)
    for (i=0; i<n; i++) {
        a += x[i];
        b ^= y[i];
        if (c > y[i]) c = y[i];
        d = fmaxf(d,x[i]);
    }
}
```

Example reduction1.c
Example reduction.1.f90

SUBROUTINE REDUCTION1(A, B, C, D, X, Y, N)
  REAL :: X(*), A, D
  INTEGER :: Y(*), N, B, C
  INTEGER :: I
  A = 0
  B = 0
  C = Y(1)
  D = X(1)
  !$OMP PARALLEL DO PRIVATE(I) SHARED(X, Y, N) REDUCTION(+:A) &
  !$OMP& REDUCTION(IEOR:B) REDUCTION(MIN:C) REDUCTION(MAX:D)
  DO I=1,N
    A = A + X(I)
    B = IEOR(B, Y(I))
    C = MIN(C, Y(I))
    IF (D < X(I)) D = X(I)
  END DO
END SUBROUTINE REDUCTION1

A common implementation of the preceding example is to treat it as if it had been written as follows:

Example reduction.2.c

#include <limits.h>
#include <math.h>
void reduction2(float *x, int *y, int n)
{
  int i, b, b_p, c, c_p;
  float a, a_p, d, d_p;
  a = 0.0f;
  b = 0;
  c = y[0];
  d = x[0];
  #pragma omp parallel shared(a, b, c, d, x, y, n) \private(a_p, b_p, c_p, d_p)
  {
    a_p = 0.0f;
    b_p = 0;
    c_p = INT_MAX;
    d_p = -HUGE_VALF;
    #pragma omp for private(i)
for (i=0; i<n; i++) {
    a_p += x[i];
    b_p ^= y[i];
    if (c_p > y[i]) c_p = y[i];
    d_p = fmaxf(d_p, x[i]);
}
#pragma omp critical
{
    a += a_p;
    b ^= b_p;
    if (c > c_p) c = c_p;
    d = fmaxf(d, d_p);
}
}
Example reduction.2.f90

SUBROUTINE REDUCTION2(A, B, C, D, X, Y, N)
    REAL :: X(*), A, D
    INTEGER :: Y(*), N, B, C
    REAL :: A_P, D_P
    INTEGER :: I, B_P, C_P
A = 0
B = 0
C = Y(1)
D = X(1)
!$OMP PARALLEL SHARED(X, Y, A, B, C, D, N) &
A_P = 0.0
B_P = 0
C_P = HUGE(C_P)
D_P = -HUGE(D_P)
!$OMP DO PRIVATE(I)
    DO I=1,N
        A_P = A_P + X(I)
        B_P = IEOR(B_P, Y(I))
        C_P = MIN(C_P, Y(I))
        IF (D_P < X(I)) D_P = X(I)
    END DO
!$OMP CRITICAL
    A = A + A_P
    B = IEOR(B, B_P)
    C = MIN(C, C_P)
    D = MAX(D, D_P)

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The following program is non-conforming because the reduction is on the *intrinsic procedure name* `MAX` but that name has been redefined to be the variable named `MAX`.

*Example reduction.3.f90*

```fortran
S-1 PROGRAM REDUCTION_WRONG
S-2 MAX = HUGE(0)
S-3 M = 0
S-4 S-5 !$OMP PARALLEL DO REDUCTION(MAX: M)
S-6 ! MAX is no longer the intrinsic so this is non-conforming
S-7 DO I = 1, 100
S-8 CALL SUB(M,I)
S-9 END DO
S-10 S-11 END PROGRAM REDUCTION_WRONG
S-12 S-13 SUBROUTINE SUB(M,I)
S-14 M = MAX(M,I)
S-15 END SUBROUTINE SUB
```

The following conforming program performs the reduction using the *intrinsic procedure name* `MAX` even though the intrinsic `MAX` has been renamed to `REN`.

*Example reduction.4.f90*

```fortran
S-1 MODULE M
S-2 INTRINSIC MAX
S-3 END MODULE M
S-4 S-5 PROGRAM REDUCTION3
S-6 USE M, REN => MAX
S-7 N = 0
S-8 !$OMP PARALLEL DO REDUCTION(REN: N) ! still does MAX
S-9 DO I = 1, 100
S-10 N = MAX(N,I)
S-11 END DO
S-12 END PROGRAM REDUCTION3
```

The following conforming program performs the reduction using *intrinsic procedure name* `MAX` even though the intrinsic `MAX` has been renamed to `MIN`.

*Example reduction.5.f90*
MODULE MOD
  INTRINSIC MAX, MIN
END MODULE MOD

PROGRAM REDUCTION4
  USE MOD, MIN=>MAX, MAX=>MIN
  REAL :: R
  R = -HUGE(0.0)
  !$OMP PARALLEL DO REDUCTION(MIN: R) ! still does MAX
  DO I = 1, 1000
    R = MIN(R, SIN(REAL(I)))
  END DO
  PRINT *, R
END PROGRAM REDUCTION4
The following example is non-conforming because the initialization \( a = 0 \) of the original list item \( a \) is not synchronized with the update of \( a \) as a result of the reduction computation in the \textbf{for} loop. Therefore, the example may print an incorrect value for \( a \).

To avoid this problem, the initialization of the original list item \( a \) should complete before any update of \( a \) as a result of the \textbf{reduction} clause. This can be achieved by adding an explicit barrier after the assignment \( a = 0 \), or by enclosing the assignment \( a = 0 \) in a \textbf{single} directive (which has an implied barrier), or by initializing \( a \) before the start of the \textbf{parallel} region.

\begin{verbatim}
#include <stdio.h>

int main (void)
{
    int a, i;

    #pragma omp parallel shared(a) private(i)
    {
        #pragma omp master
        a = 0;
        // To avoid race conditions, add a barrier here.

        #pragma omp for reduction(+:a)
        for (i = 0; i < 10; i++) {
            a += i;
        }

        #pragma omp single
        printf ("Sum is %d\n", a);
    }

    return 0;
}
\end{verbatim}

\textit{Example reduction.6.c}
The following example demonstrates the reduction of array \( a \). In C/C++ this is illustrated by the explicit use of an array section \( a[0:N] \) in the \texttt{reduction} clause. The corresponding Fortran example uses array syntax supported in the base language. As of the OpenMP 4.5 specification the explicit use of array section in the \texttt{reduction} clause in Fortran is not permitted. But this oversight will be fixed in the next release of the specification.
```c
for(i=0; i<N; i++) a[i]=0.0e0;

#pragma omp parallel for reduction(+:a[0:N]) private(j)
for(i=0; i<N; i++){
    for(j=0; j<N; j++){
        a[j] += b[i][j];
    }
}

printf(" a[0] a[N-1]: %f %f\n", a[0], a[N-1]);
return 0;
```

---

```fortran
program array_red
    integer,parameter :: n=100
    integer :: j
    real :: a(n), b(n,n)
    call init(n,b)
    a(:) = 0.0e0
    !$omp parallel do reduction(+:a)
    do j = 1, n
        a(:) = a(:) + b(:,j)
    end do
    print*, " a(1) a(n): ", a(1), a(n)
end program
```

---

Example reduction.7.f90
7.9.2 Task Reduction

The following C/C++ and Fortran examples show how to implement a task reduction over a linked list.

Task reductions are supported by the `task_reduction` clause which can only be applied to the `taskgroup` directive, and a `in_reduction` clause which can be applied to the `task` construct among others.

The `task_reduction` clause on the `taskgroup` construct is used to define the scope of a new reduction, and after the `taskgroup` region the original variable will contain the final value of the reduction. In the task-generating while loop the `in_reduction` clause of the `task` construct is used to specify that the task participates "in" the reduction.

Note: The `res` variable is private in the `linked_list_sum` routine and is not required to be shared (as in the case of a `parallel` construct reduction).

```c
Example task_reduction.1.c

#include<stdlib.h>
#include<stdio.h>
define N 10
typedef struct node_tag {
    int val;
    struct node_tag *next;
} node_t;

int linked_list_sum(node_t *p)
{
    int res = 0;
    #pragma omp taskgroup task_reduction(+: res)
    {
        node_t* aux = p;
        while(aux != 0)
        {
            #pragma omp task in_reduction(+: res)
            res += aux->val;
            aux = aux->next;
        }
    }
    return res;
}
```
```c
int main(int argc, char *argv[]) {
    int i;
    // Create the root node.
    node_t* root = (node_t*) malloc(sizeof(node_t));
    root->val = 1;

    node_t* aux = root;

    // Create N-1 more nodes.
    for(i=2;i<=N;++i) {
        aux->next = (node_t*) malloc(sizeof(node_t));
        aux = aux->next;
        aux->val = i;
    }
    aux->next = 0;

    #pragma omp parallel
    #pragma omp single
    {
        int result = linked_list_sum(root);
        printf( "Calculated: %d Analytic:%d\n", result, (N*(N+1)/2) );
    }
    return 0;
}
```

---

### Fortran

```fortran
module m
    type node_t
        integer :: val
        type(node_t), pointer :: next
    end type
end module m

function linked_list_sum(p) result(res)
    use m
    implicit none
    type(node_t), pointer :: p
```
type(node_t), pointer :: aux
integer :: res

res = 0

!$omp taskgroup task_reduction(+: res)
aux => p
do while (associated(aux))
  !$omp task in_reduction(+: res)
  res = res + aux%val
  !$omp end task
  aux => aux%next
end do
!$omp end taskgroup
end function linked_list_sum

program main
use m
implicit none
type(node_t), pointer :: root, aux
integer :: res, i
integer, parameter :: N=10

interface
  function linked_list_sum(p) result(res)
    use m
    implicit none
type(node_t), pointer :: p
integer :: res
end function
end interface

! Create the root node.
allocate(root)
root%val = 1
aux => root

! Create N-1 more nodes.
do i = 2,N
  allocate(aux%next)
  aux => aux%next
  aux%val = i
end do
aux%next => null()

7.9.3 Taskloop Reduction

In the OpenMP 5.0 Specification the taskloop construct was extended to include the reductions. The following two examples show how to implement a reduction over an array using taskloop reduction in two different ways. In the first example we apply the reduction clause to the taskloop construct. As it was explained above in the task reduction examples, a reduction over tasks is divided in two components: the scope of the reduction, which is defined by a taskgroup region, and the tasks that participate in the reduction. In this example, the reduction clause defines both semantics. First, it specifies that the implicit taskgroup region associated with the taskloop construct is the scope of the reduction, and second, it defines all tasks created by the taskloop construct as participants of the reduction. About the first property, it is important to note that if we add the nogroup clause to the taskloop construct the code will be nonconforming, basically because we have a set of tasks that participate in a reduction that has not been defined.

Example taskloop_reduction_1.c

```c
#include <stdio.h>

int array_sum(int n, int *v) {
  int i;
  int res = 0;
  #pragma omp taskloop reduction(+: res)
  for(i = 0; i < n; ++i)
    res += v[i];
  return res;
}

int main(int argc, char *argv[]) {
```
int n = 10;
int v[10] = {1,2,3,4,5,6,7,8,9,10};

#pragma omp parallel
#pragma omp single
{
    int res = array_sum(n, v);
    printf("The result is %d\n", res);
}
return 0;

---

Example taskloop_reduction.1.f90

function array_sum(n, v) result(res)
    implicit none
    integer :: n, v(n), res
    integer :: i
    res = 0
    !$omp taskloop reduction(+: res)
    do i=1, n
        res = res + v(i)
    end do
    !$omp end taskloop
end function array_sum

program main
    implicit none
    integer :: n, v(10), res
    integer :: i
    integer, external :: array_sum
    n = 10
    do i=1, n
        v(i) = i
    end do
    !$omp parallel
    !$omp single
    res = array_sum(n, v)
    print *, "The result is", res
    !$omp end single
The second example computes exactly the same value as in the preceding `taskloop_reduction.1` code section, but in a very different way. First, in the `array_sum` function a `taskgroup` region is created that defines the scope of a new reduction using the `task_reduction` clause. After that, a task and also the tasks generated by a taskloop participate in that reduction by using the `in_reduction` clause on the `task` and `taskloop` constructs, respectively. Note that the `nogroup` clause was added to the `taskloop` construct. This is allowed because what is expressed with the `in_reduction` clause is different from what is expressed with the `reduction` clause. In one case the generated tasks are specified to participate in a previously declared reduction (`in_reduction` clause) whereas in the other case creation of a new reduction is specified and also that all tasks generated by the taskloop will participate on it.

---

```
#include <stdio.h>

int array_sum(int n, int *v) {
    int i;
    int res = 0;
    #pragma omp taskgroup task_reduction(+: res)
    {
        if (n > 0) {
            #pragma omp task in_reduction(+: res)
            res = res + v[0];
            #pragma omp taskloop in_reduction(+: res) nogroup
            for(i = 1; i < n; ++i)
                res += v[i];
        }
    }
    return res;
}

int main(int argc, char *argv[]) {
    int n = 10;
    int v[10] = {1,2,3,4,5,6,7,8,9,10};
    #pragma omp parallel
    #pragma omp single
    {
```
```c
int res = array_sum(n, v);
printf("The result is %d\n", res);
return 0;
}
```

```
Example taskloop_reduction.2.f90
```

```fortran
function array_sum(n, v) result(res)

    implicit none
    integer :: n, v(n), res
    integer :: i

    res = 0

    !$omp taskgroup task_reduction(+: res)
    if (n > 0) then
        !$omp task in_reduction(+: res)
        res = res + v(1)
        !$omp end task
    !$omp taskloop in_reduction(+: res) nogroup
    do i=2, n
        res = res + v(i)
    end do
    !$omp end taskloop
    endif
    !$omp end taskgroup

end function array_sum

program main

    implicit none
    integer :: n, v(10), res
    integer :: i
    integer, external :: array_sum

    n = 10
    do i=1, n
        v(i) = i
    end do

    !$omp parallel
    !$omp single
    res = array_sum(n, v)
    !$omp end single
    !$omp end parallel
In the OpenMP 5.0 Specification, reduction clauses for the taskloop simd construct were also added.

The examples below compare reductions for the taskloop and the taskloop simd constructs. These examples illustrate the use of reduction clauses within "stand-alone" taskloop constructs, and the use of in_reduction clauses for tasks of taskloops to participate with other reductions within the scope of a parallel region.

**taskloop reductions:**

In the taskloop reductions section of the example below, taskloop 1 uses the reduction clause in a taskloop construct for a sum reduction, accumulated in asum. The behavior is as though a taskgroup construct encloses the taskloop region with a task_reduction clause, and each taskloop task has an in_reduction clause with the specifications of the reduction clause. At the end of the taskloop region asum contains the result of the reduction.

The next taskloop, taskloop 2, illustrates the use of the in_reduction clause to participate in a previously defined reduction scope of a parallel construct.

The task reductions of task 2 and taskloop 2 are combined across the taskloop construct and the single task construct, as specified in the reduction(task, + :asum) clause of the parallel construct. At the end of the parallel region asum contains the combined result of all reductions.

**taskloop simd reductions:**

Reductions for the taskloop simd construct are shown in the second half of the code. Since each component construct, taskloop and simd, can accept a reduction-type clause, the taskloop simd construct is a composite construct, and the specific application of the reduction clause is defined within the taskloop simd construct section of the OpenMP 5.0 Specification.

The code below illustrates use cases for these reductions.

In the taskloop simd reduction section of the example below, taskloop simd 3 uses the reduction clause in a taskloop simd construct for a sum reduction within a loop. For this case a reduction clause is used, as one would use for a simd construct. The SIMD reductions of each task are combined, and the results of these tasks are further combined just as in the taskloop construct with the reduction clause for taskloop 1. At the end of the taskloop region asum contains the combined result of all reductions.

If a taskloop simd construct is to participate in a previously defined reduction scope, the reduction participation should be specified with a in_reduction clause, as shown in the parallel region enclosing task 4 and taskloop simd 4 code sections.
Here the taskloop simd construct’s in_reduction clause specifies participation of the construct’s tasks as a task reduction within the scope of the parallel region. That is, the results of each task of the taskloop construct component contribute to the reduction in a broader level, just as in parallel reduction a code section above. Also, each simd-component construct occurs as if it has a reduction clause, and the SIMD results of each task are combined as though to form a single result for each task (that participates in the in_reduction clause). At the end of the parallel region asum contains the combined result of all reductions.

### C / C++

```c
#include <stdio.h>

#define N 100

int main(){
    int i, a[N], asum=0;
    for(i=0;i<N;i++) a[i]=i;

    // taskloop reductions
    #pragma omp parallel master
    #pragma omp taskloop reduction(+:asum) //taskloop 1
    for(i=0;i<N;i++){ asum += a[i]; }

    #pragma omp parallel reduction(task, +:asum) // parallel reduction a
    {
        #pragma omp master
        #pragma omp task in_reduction(+:asum) //task 2
        for(i=0;i<N;i++){ asum += a[i]; }
    }

    #pragma omp parallel master
    #pragma omp taskloop simd reduction(+:asum) //taskloop simd 3
    for(i=0;i<N;i++){ asum += a[i]; }

    // taskloop simd reductions
    #pragma omp parallel master
    #pragma omp taskloop simd reduction(+:asum) //taskloop simd 3
    for(i=0;i<N;i++){ asum += a[i]; }

    #pragma omp parallel reduction(task, +:asum) // parallel reduction b
    {
        #pragma omp master
```
Example taskloop_simd_reduction.f90

```fortran
program main
  
  use omp_lib

  integer, parameter :: N=100
  integer :: i, a(N), asum=0

  a = [( i, i=1,N )]  !! initialize

  ! taskloop reductions

  !$omp parallel master
  !$omp taskloop reduction(+:asum)  !! taskloop 1
  do i=1,N; asum = asum + a(i); enddo
  !$omp end taskloop
  !$omp end parallel master

  !$omp parallel reduction(task, +:asum)  !! parallel reduction a
  !$omp master
  !$omp task in_reduction(+:asum)  !! task 2
  do i=1,N; asum = asum + a(i); enddo
  !$omp end task
  !$omp end master
  !$omp end parallel
```

```c++

```
!! taskloop simd reductions

!$omp parallel master
!$omp taskloop simd reduction(+:asum) !! taskloop simd 3
do i=1,N; asum = asum + a(i); enddo
!$omp end taskloop simd
!$omp end parallel master

!! parallel reduction b
!$omp parallel reduction(task, +:asum) !! parallel reduction b
!$omp master
!$omp task in_reduction(+:asum) !! task 4
do i=1,N; asum = asum + a(i); enddo
!$omp end task
!$omp end master
!$omp master taskloop simd in_reduction(+:asum) !! taskloop simd 4
do i=1,N; asum = asum + a(i); enddo
!$omp end master taskloop simd
!$omp end parallel
print*,"asum=",asum !! output: asum=30300
end program

---

1 7.9.4 User-Defined Reduction

The declare reduction directive can be used to specify user-defined reductions (UDR) for user data types.

In the following example, declare reduction directives are used to define min and max operations for the point data structure for computing the rectangle that encloses a set of 2-D points.

Each declare reduction directive defines new reduction identifiers, min and max, to be used in a reduction clause. The next item in the declaration list is the data type (struct point) used in the reduction, followed by the combiner, here the functions minproc and maxproc perform the min and max operations, respectively, on the user data (of type struct point). In the function argument list are two special OpenMP variable identifiers, omp_in and omp_out, that denote the two values to be combined in the "real" function; the omp_out identifier indicates which one is to hold the result.
The initializer of the \texttt{declare reduction} directive specifies the initial value for the private variable of each implicit task. The \texttt{omp_priv} identifier is used to denote the private variable.

\begin{c-code}
Example udr.1.c

```c
#include <stdio.h>
#include <limits.h>

struct point {
    int x;
    int y;
};

void minproc ( struct point *out, struct point *in )
{
    if ( in->x < out->x ) out->x = in->x;
    if ( in->y < out->y ) out->y = in->y;
}

void maxproc ( struct point *out, struct point *in )
{
    if ( in->x > out->x ) out->x = in->x;
    if ( in->y > out->y ) out->y = in->y;
}

#pragma omp declare reduction(min : struct point : \
    minproc(&omp_out, &omp_in)) \ 
    initializer( omp_priv = { INT_MAX, INT_MAX } )

#pragma omp declare reduction(max : struct point : \
    maxproc(&omp_out, &omp_in)) \ 
    initializer( omp_priv = { 0, 0 } )

void find_enclosing_rectangle ( int n, struct point points[] )
{
    struct point minp = { INT_MAX, INT_MAX }, maxp = {0,0};
    int i;

#pragma omp parallel for reduction(min:minp) reduction(max:maxp)
    for ( i = 0; i < n; i++ )
    {
        minproc(&minp, &points[i]);
        maxproc(&maxp, &points[i]);
    }
    printf("min = (%d, %d)\n", minp.x, minp.y);
    printf("max = (%d, %d)\n", maxp.x, maxp.y);
```
\end{c-code}

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The following example shows the corresponding code in Fortran. The \textit{declare reduction} directives are specified as part of the declaration in subroutine \textit{find_enclosing_rectangle} and the procedures that perform the min and max operations are specified as subprograms.

\begin{verbatim}
module data_type

  type :: point
    integer :: x
    integer :: y
  end type

end module data_type

subroutine find_enclosing_rectangle ( n, points )
  use data_type
  implicit none
  integer :: n
  type(point) :: points(*)

  !$omp declare reduction(min : point : minproc(omp_out, omp_in)) &
     !$omp& initializer( omp_priv = point( HUGE(0), HUGE(0) ) )

  !$omp declare reduction(max : point : maxproc(omp_out, omp_in)) &
     !$omp& initializer( omp_priv = point( 0, 0 ) )

  type(point) :: minp = point( HUGE(0), HUGE(0) ), maxp = point( 0, 0 )
  integer :: i

  !$omp parallel do reduction(min:minp) reduction(max:maxp)
     do i = 1, n
       call minproc(minp, points(i))
       call maxproc(maxp, points(i))
     end do

  print *, "min = (", minp%x, minp%y, ")"
  print *, "max = (", maxp%x, maxp%y, ")"

contains

subroutine minproc ( out, in )
  implicit none
  type(point), intent(inout) :: out
  type(point), intent(in) :: in

end subroutine minproc
\end{verbatim}
The following example shows the same computation as udr.1 but it illustrates that you can craft complex expressions in the user-defined reduction declaration. In this case, instead of calling the minproc and maxproc functions we inline the code in a single expression.

```c
#include <stdio.h>
#include <limits.h>

struct point {
    int x;
    int y;
};

#pragma omp declare reduction(min : struct point : \ 
    omp_out.x = omp_in.x > omp_out.x ? omp_out.x : omp_in.x, \ 
    omp_out.y = omp_in.y > omp_out.y ? omp_out.y : omp_in.y ) \ 
    initializer( omp_priv = { INT_MAX, INT_MAX } )

#pragma omp declare reduction(max : struct point : \ 
    omp_out.x = omp_in.x < omp_out.x ? omp_out.x : omp_in.x, \ 
    omp_out.y = omp_in.y < omp_out.y ? omp_out.y : omp_in.y ) \ 
    initializer( omp_priv = { 0, 0 } )

void find_enclosing_rectangle ( int n, struct point points[] )
{
    struct point minp = { INT_MAX, INT_MAX }, maxp = {0,0};
    int i;
    #pragma omp parallel for reduction(min:minp) reduction(max:maxp)
```
for ( i = 0; i < n; i++ ) {
    if ( points[i].x < minp.x ) minp.x = points[i].x;
    if ( points[i].y < minp.y ) minp.y = points[i].y;
    if ( points[i].x > maxp.x ) maxp.x = points[i].x;
    if ( points[i].y > maxp.y ) maxp.y = points[i].y;
}
printf("min = (%d, %d)\n", minp.x, minp.y);
printf("max = (%d, %d)\n", maxp.x, maxp.y);

The corresponding code of the same example in Fortran is very similar except that the assignment expression in the declare reduction directive can only be used for a single variable, in this case through a type structure constructor point(.).

```
Example udr.2.f90

module data_type
  type :: point
    integer :: x
    integer :: y
  end type
end module data_type

subroutine find_enclosing_rectangle ( n, points )
  use data_type
  implicit none
  integer :: n
  type(point) :: points(*)
  type(point) :: minp = point( HUGE(0), HUGE(0) ), maxp = point( 0, 0 )
  !$omp parallel do reduction(min: minp) reduction(max: maxp)
```
The following example shows the use of special variables in arguments for combiner (omp_in and omp_out) and initializer (omp_priv and omp_orig) routines. This example returns the maximum value of an array and the corresponding index value. The declare reduction directive specifies a user-defined reduction operation maxloc for data type struct mx_s. The function mx_combine is the combiner and the function mx_init is the initializer.

Example udr.3.c

```c
#include <stdio.h>
#define N 100

struct mx_s {
    float value;
    int index;
};

/* prototype functions for combiner and initializer in the declare reduction */
void mx_combine(struct mx_s *out, struct mx_s *in);

void mx_init(struct mx_s *priv, struct mx_s *orig);

#pragma omp declare reduction(maxloc: struct mx_s: \  
    mx_combine(&omp_out, &omp_in)) \  
    initializer(mx_init(&omp_priv, &omp_orig))

void mx_combine(struct mx_s *out, struct mx_s *in) {
    if ( out->value < in->value ) {
        out->value = in->value;
        out->index = in->index;
    }
```
void mx_init(struct mx_s *priv, struct mx_s *orig)
{
  priv->value = orig->value;
  priv->index = orig->index;
}

int main(void)
{
  struct mx_s mx;
  float val[N], d;
  int i, count = N;

  for (i = 0; i < count; i++) {
    d = (N*0.8f - i);
    val[i] = N * N - d * d;
  }

  mx.value = val[0];
  mx.index = 0;
  #pragma omp parallel for reduction(maxloc: mx)
  for (i = 1; i < count; i++) {
    if (mx.value < val[i])
      {
        mx.value = val[i];
        mx.index = i;
      }
  }

  printf("max value = %g, index = %d\n", mx.value, mx.index);
  /* prints 10000, 80 */
  return 0;
}

Below is the corresponding Fortran version of the above example. The `declare reduction` directive specifies the user-defined operation `maxloc` for user-derived type `mx_s`. The combiner `mx_combine` and the initializer `mx_init` are specified as subprograms.
program max_loc
  implicit none
  type :: mx_s
    real value
    integer index
  end type

  !$omp declare reduction(maxloc: mx_s:: &
  !$omp& mx_combine(omp_out, omp_in)) &
  !$omp& initializer(mx_init(omp_priv, omp_orig))

  integer, parameter :: N = 100
  type(mx_s) :: mx
  real :: val(N), d
  integer :: i, count

  count = N
  do i = 1, count
    d = N*0.8 - i + 1
    val(i) = N * N - d * d
  enddo
  
  mx%value = val(1)
  mx%index = 1
  !$omp parallel do reduction(maxloc: mx)
  do i = 2, count
    if (mx%value < val(i)) then
      mx%value = val(i)
      mx%index = i
    endif
  enddo

  print *, 'max value = ', mx%value, ' index = ', mx%index
  ! prints 10000, 81
contains

  subroutine mx_combine(out, in)
    implicit none
    type(mx_s), intent(inout) :: out
    type(mx_s), intent(in) :: in
    if ( out%value < in%value ) then
out%value = in%value
out%index = in%index
endif
der subroutine mx_combine
der subroutine mx_init(priv, orig)
implicit none
type(mx_s), intent(out) :: priv
type(mx_s), intent(in) :: orig
priv%value = orig%value
priv%index = orig%index
der end subroutine mx_init
der end program

The following example explains a few details of the user-defined reduction in Fortran through
modules. The declare reduction directive is declared in a module (data_red). The
reduction-identifier .add. is a user-defined operator that is to allow accessibility in the scope that
performs the reduction operation. The user-defined operator .add. and the subroutine dt_init
specified in the initializer clause are defined in the same subprogram.

The reduction operation (that is, the reduction clause) is in the main program. The reduction
identifier .add. is accessible by use association. Since .add. is a user-defined operator, the explicit
interface should also be accessible by use association in the current program unit. Since the
declare reduction associated to this reduction clause has the initializer clause, the
subroutine specified on the clause must be accessible in the current scoping unit. In this case, the
subroutine dt_init is accessible by use association.

Example udr.4.f90

module data_red
! Declare data type.
type dt
  real :: r1
  real :: r2
end type
!

interface operator(.add.)
  module procedure addc
end interface
!

! Declare the user-defined reduction operator .add.
!$omp declare reduction(.add.:dt:omp_out=omp_out.add.omp_in) &
The following example uses user-defined reductions to declare a plus (+) reduction for a C++ class.

As the **declare reduction** directive is inside the context of the V class the expressions in the **declare reduction** directive are resolved in the context of the class. Also, note that the **initializer** clause uses a copy constructor to initialize the private variables of the reduction and it uses as parameter to its original variable by using the special variable **omp_orig**.

---

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The following examples show how user-defined reductions can be defined for some STL containers. The first `declare reduction` defines the plus (+) operation for `std::vector<int>` by making use of the `std::transform` algorithm. The second and third define the merge (or concatenation) operation for `std::vector<int>` and `std::list<int>`. It shows how the user-defined reduction operation can be applied to specific data types of an STL.

```
#include <algorithm>
#include <list>
#include <vector>

#pragma omp declare reduction( + : std::vector<int> : \ 
    std::transform (omp_out.begin(), omp_out.end(), \ 
    omp_in.begin(), omp_in.end(),std::plus<int>())

#pragma omp declare reduction( merge : std::vector<int> : \ 
    omp_out.insert(omp_out.end(), omp_in.begin(), omp_in.end()))

#pragma omp declare reduction( merge : std::list<int> : \ 
    omp_out.merge(omp_in))
```
The **copyin** clause is used to initialize threadprivate data upon entry to a `parallel` region. The value of the threadprivate variable in the master thread is copied to the threadprivate variable of each other team member.

```c
#include <stdlib.h>

float* work;
int size;
float tol;

#pragma omp threadprivate(work,size,tol)

void build()
{
    int i;
    work = (float*)malloc( sizeof(float)*size );
    for( i = 0; i < size; ++i ) work[i] = tol;
}

void copyin_example( float t, int n )
{
    tol = t;
    size = n;
    #pragma omp parallel copyin(tol,size)
    {
        build();
    }
}
```
Example copyin.1.f

```fortran
MODULE M
  REAL, POINTER, SAVE :: WORK(:)
  INTEGER :: SIZE
  REAL :: TOL
  !$OMP THREADPRIVATE(WORK,SIZE,TOL)
END MODULE M

SUBROUTINE COPYIN_EXAMPLE( T, N )
  USE M
  REAL :: T
  INTEGER :: N
  TOL = T
  SIZE = N
  !$OMP PARALLEL COPYIN(TOL,SIZE)
  CALL BUILD
  !$OMP END PARALLEL
END SUBROUTINE COPYIN_EXAMPLE

SUBROUTINE BUILD
  USE M
  ALLOCATE(WORK(SIZE))
  WORK = TOL
END SUBROUTINE BUILD
```
7.11 The copyprivate Clause

The copyprivate clause can be used to broadcast values acquired by a single thread directly to all instances of the private variables in the other threads. In this example, if the routine is called from the sequential part, its behavior is not affected by the presence of the directives. If it is called from a parallel region, then the actual arguments with which a and b are associated must be private.

The thread that executes the structured block associated with the single construct broadcasts the values of the private variables a, b, x, and y from its implicit task’s data environment to the data environments of the other implicit tasks in the thread team. The broadcast completes before any of the threads have left the barrier at the end of the construct.

Example copyprivate.1.c

```c
#include <stdio.h>
float x, y;
#pragma omp threadprivate(x, y)

void init(float a, float b) {
    #pragma omp single copyprivate(a, b, x, y)
    {
        scanf("%f %f %f %f", &a, &b, &x, &y);
    }
}
```

Example copyprivate.1.f

```fortran
SUBROUTINE INIT(A,B)
REAL A, B
COMMON /XY/ X,Y
!$OMP THREADPRIVATE (/XY/)
!$OMP SINGLE
READ (11) A,B,X,Y
!$OMP END SINGLE COPYPRIVATE (A,B,/XY/)
END SUBROUTINE INIT
```

In this example, assume that the input must be performed by the master thread. Since the master construct does not support the copyprivate clause, it cannot broadcast the input value that is read. However, copyprivate is used to broadcast an address where the input value is stored.
Example copyprivate.2.c

```c
#include <stdio.h>
#include <stdlib.h>

float read_next() {
    float * tmp;
    float return_val;
    
    #pragma omp single copyprivate(tmp)
    {
        tmp = (float *) malloc(sizeof(float));
    } /* copies the pointer only */

    #pragma omp master
    {
        scanf("%f", tmp);
    }

    #pragma omp barrier
    return_val = *tmp;
    #pragma omp barrier

    #pragma omp single nowait
    {
        free(tmp);
    }

    return return_val;
}
```

Example copyprivate.2.f

```fortran
REAL FUNCTION READ_NEXT()

REAL, POINTER :: TMP

!$OMP SINGLE
ALLOCATE (TMP)
!$OMP END SINGLE COPYPRIVATE (TMP) ! copies the pointer only

!$OMP MASTER
READ (11) TMP
!$OMP END MASTER
```
Suppose that the number of lock variables required within a parallel region cannot easily be determined prior to entering it. The copyprivate clause can be used to provide access to shared lock variables that are allocated within that parallel region.

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

omp_lock_t *new_lock()
{
    omp_lock_t *lock_ptr;
    #pragma omp single copyprivate(lock_ptr)
    {
        lock_ptr = (omp_lock_t *) malloc(sizeof(omp_lock_t));
        omp_init_lock(lock_ptr);
    }
    return lock_ptr;
}
```
Example copyprivate.3.f

S-1 FUNCTION NEW_LOCK()
S-2 USE OMP_LIB ! or INCLUDE "omp_lib.h"
S-3 INTEGER(OMP_LOCK_KIND), POINTER :: NEW_LOCK
S-4
S-5 !$OMP SINGLE
S-6 ALLOCATE(NEW_LOCK)
S-7 CALL OMP_INIT_LOCK(NEW_LOCK)
S-8 !$OMP END SINGLE COPYPRIVATE(NEW_LOCK)
S-9 END FUNCTION NEW_LOCK

Note that the effect of the copyprivate clause on a variable with the allocatable attribute is different than on a variable with the pointer attribute. The value of A is copied (as if by intrinsic assignment) and the pointer B is copied (as if by pointer assignment) to the corresponding list items in the other implicit tasks belonging to the parallel region.

Example copyprivate.4.f

S-1 SUBROUTINE S(N)
S-2 INTEGER N
S-3
S-4 REAL, DIMENSION(:), ALLOCATABLE :: A
S-5 REAL, DIMENSION(:), POINTER :: B
S-6
S-7 ALLOCATE (A(N))
S-8 !$OMP SINGLE
S-9 ALLOCATE (B(N))
S-10 READ (11) A,B
S-11 !$OMP END SINGLE COPYPRIVATE(A,B)
S-12 ! Variable A is private and is
S-13 ! assigned the same value in each thread
S-14 ! Variable B is shared
S-15
S-16 !$OMP BARRIER
S-17 !$OMP SINGLE
S-18 !$OMP DEALLOCATE (B)
S-19 !$OMP END SINGLE NOWAIT
S-20 END SUBROUTINE S
C++ Reference in Data-Sharing Clauses

C++ reference types are allowed in data-sharing attribute clauses as of OpenMP 4.5, except for the `threadprivate`, `copyin` and `copyprivate` clauses. (See the Data-Sharing Attribute Clauses Section of the 4.5 OpenMP specification.) When a variable with C++ reference type is privatized, the object the reference refers to is privatized in addition to the reference itself. The following example shows the use of reference types in data-sharing clauses in the usual way. Additionally it shows how the data-sharing of formal arguments with a C++ reference type on an orphaned task generating construct is determined implicitly. (See the Data-sharing Attribute Rules for Variables Referenced in a Construct Section of the 4.5 OpenMP specification.)

Example `cpp_reference.1.cpp`

```cpp
void task_body (int &);
void gen_task (int &x) { // on orphaned task construct reference argument
    #pragma omp task // x is implicitly determined firstprivate(x)
    task_body (x);
}
void test (int &y, int &z) {
    #pragma omp parallel private(y)
    {
        y = z + 2;
        gen_task (y); // no matter if the argument is determined private
        gen_task (z); // or shared in the enclosing context.
        y++; // each thread has its own int object y refers to
        gen_task (y);
    }
}
```
Fortran ASSOCIATE Construct

The following is an invalid example of specifying an associate name on a data-sharing attribute clause. The constraint in the Data Sharing Attribute Rules section in the OpenMP 4.0 API Specifications states that an associate name preserves the association with the selector established at the `ASSOCIATE` statement. The associate name `b` is associated with the shared variable `a`. With the predetermined data-sharing attribute rule, the associate name `b` is not allowed to be specified on the `private` clause.

Example `associate.1.f`

```fortran
program example
  real :: a, c
  associate (b => a)
  !$omp parallel private(b, c) ! invalid to privatize b
  c = 2.0*b
  !$omp end parallel
end associate
end program
```

In the next example, within the `parallel` construct, the association name `thread_id` is associated with the private copy of `i`. The print statement should output the unique thread number.

Example `associate.2.f`

```fortran
program example
  use omp_lib
  integer i
  !$omp parallel private(i)
  i = omp_get_thread_num()
  associate(thread_id => i)
  print *, thread_id ! print private i value
end associate
 !$omp end parallel
end program
```

The following example illustrates the effect of specifying a selector name on a data-sharing attribute clause. The associate name `u` is associated with `v` and the variable `v` is specified on the `private` clause of the `parallel` construct. The construct association is established prior to the `parallel` region. The association between `u` and the original `v` is retained (see the Data Sharing Attribute Rules section in the OpenMP 4.0 API Specifications). Inside the `parallel` region, `v` has the value of -1 and `u` has the value of the original `v`.

Example `associate.3.f90`
program example
integer :: v
v = 15
associate(u => v)
!$omp parallel private(v)
v = -1
print *, v ! private v=-1
print *, u ! original v=15
!$omp end parallel
end associate
end program
CHAPTER 8

Memory Model

OpenMP provides a shared-memory model that allows all threads on a given device shared access to memory. For a given OpenMP region that may be executed by more than one thread or SIMD lane, variables in memory may be shared or private with respect to those threads or SIMD lanes. A variable’s data-sharing attribute indicates whether it is shared (the shared attribute) or private (the private, firstprivate, lastprivate, linear, and reduction attributes) in the data environment of an OpenMP region. While private variables in an OpenMP region are new copies of the original variable (with same name) that may then be concurrently accessed or modified by their respective threads or SIMD lanes, a shared variable in an OpenMP region is the same as the variable of the same name in the enclosing region. Concurrent accesses or modifications to a shared variable may therefore require synchronization to avoid data races.

OpenMP’s memory model also includes a temporary view of memory that is associated with each thread. Two different threads may see different values for a given variable in their respective temporary views. Threads may employ flush operations for the purposes of making their temporary view of a variable consistent with the value of the variable in memory. The effect of a given flush operation is characterized by its flush properties – some combination of strong, release, and acquire – and, for strong flushes, a flush-set.

A strong flush will force consistency between the temporary view and the memory for all variables in its flush-set. Furthermore all strong flushes in a program that have intersecting flush-sets will execute in some total order, and within a thread strong flushes may not be reordered with respect to other memory operations on variables in its flush-set. Release and acquire flushes operate in pairs. A release flush may “synchronize” with an acquire flush, and when it does so the local memory operations that precede the release flush will appear to have been completed before the local memory operations on the same variables that follow the acquire flush.

Flush operations arise from explicit flush directives, implicit flush directives, and also from the execution of atomic constructs. The flush directive forces a consistent view of local variables of the thread executing the flush. When a list is supplied on the directive, only the items (variables) in the list are guaranteed to be flushed. Implied flushes exist at prescribed locations of
certain constructs. For the complete list of these locations and associated constructs, please refer to the flush Construct section of the OpenMP Specifications document.

In this chapter, examples illustrate how race conditions may arise for accesses to variables with a shared data-sharing attribute when flush operations are not properly employed. A race condition can exist when two or more threads are involved in accessing a variable in which not all of the accesses are reads; that is, a WaR, RaW or WaW condition exists (R=read, a=after, W=write). A RaR does not produce a race condition. In particular, a data race will arise when conflicting accesses do not have a well-defined completion order. The existence of data races in OpenMP programs result in undefined behavior, and so they should generally be avoided for programs to be correct. The completion order of accesses to a shared variable is guaranteed in OpenMP through a set of memory consistency rules that are described in the OpenMP Memory Consistency section of the OpenMP Specifications document.
8.1 The OpenMP Memory Model

In the following example, at Print 1, the value of \(x\) could be either 2 or 5, depending on the timing of the threads, and the implementation of the assignment to \(x\). There are two reasons that the value at Print 1 might not be 5. First, Print 1 might be executed before the assignment to \(x\) is executed. Second, even if Print 1 is executed after the assignment, the value 5 is not guaranteed to be seen by thread 1 because a flush may not have been executed by thread 0 since the assignment.

The barrier after Print 1 contains implicit flushes on all threads, as well as a thread synchronization, so the programmer is guaranteed that the value 5 will be printed by both Print 2 and Print 3.

---

Example mem_model.1.c

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

int main()
{
    int x;
    x = 2;
    #pragma omp parallel num_threads(2) shared(x)
    {
        if (omp_get_thread_num() == 0) {
            x = 5;
        } else {
            /* Print 1: the following read of x has a race */
            printf("1: Thread# %d: x = %d\n", omp_get_thread_num(), x);
        }
        #pragma omp barrier
        if (omp_get_thread_num() == 0) {
            /* Print 2 */
            printf("2: Thread# %d: x = %d\n", omp_get_thread_num(), x);
        } else {
            /* Print 3 */
            printf("3: Thread# %d: x = %d\n", omp_get_thread_num(), x);
        }
    }
    return 0;
}
```

---
Example mem_model.1.f90

PROGRAM MEMMODEL
   INCLUDE "omp_lib.h"  ! or USE OMP_LIB
   INTEGER X

   X = 2
   !$OMP PARALLEL NUM_THREADS(2) SHARED(X)
   IF (OMP_GET_THREAD_NUM() .EQ. 0) THEN
      X = 5
   ELSE
      ! PRINT 1: The following read of x has a race
      PRINT *,"1: THREAD# ", OMP_GET_THREAD_NUM(), "X = ", X
   ENDIF
   !$OMP BARRIER
   IF (OMP_GET_THREAD_NUM() .EQ. 0) THEN
      ! PRINT 2
      PRINT *,"2: THREAD# ", OMP_GET_THREAD_NUM(), "X = ", X
   ELSE
      ! PRINT 3
      PRINT *,"3: THREAD# ", OMP_GET_THREAD_NUM(), "X = ", X
   ENDIF
   !$OMP END PARALLEL
END PROGRAM MEMMODEL
The following example demonstrates why synchronization is difficult to perform correctly through variables. The value of flag is undefined in both prints on thread 1 and the value of data is only well-defined in the second print.

---

**C / C++**

*Example mem_model.2.c*

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

int main()
{
    int data;
    int flag=0;
    #pragma omp parallel num_threads(2)
    {
        if (omp_get_thread_num()==0)
        {
            /* Write to the data buffer that will be read by thread */
            data = 42;
            /* Flush data to thread 1 and strictly order the write to data relative to the write to the flag */
            #pragma omp flush(flag, data)
            /* Set flag to release thread 1 */
            flag = 1;
            /* Flush flag to ensure that thread 1 sees the change */
            #pragma omp flush(flag)
        }
        else if(omp_get_thread_num()==1)
        {
            /* Loop until we see the update to the flag */
            #pragma omp flush(flag, data)
            while (flag < 1)
            {
                /* Values of flag and data are undefined */
                printf("flag=%d data=%d\n", flag, data);
                #pragma omp flush(flag, data)
                /* Values data will be 42, value of flag still undefined */
                printf("flag=%d data=%d\n", flag, data);
            }
        }
    }
}
```
PROGRAM EXAMPLE
INCLUDE "omp_lib.h" ! or USE OMP_LIB
INTEGER DATA
INTEGER FLAG

FLAG = 0
!$OMP PARALLEL NUM_THREADS(2)
IF(OMP_GET_THREAD_NUM() .EQ. 0) THEN
   ! Write to the data buffer that will be read by thread 1
   DATA = 42
   ! Flush DATA to thread 1 and strictly order the write to DATA
   ! relative to the write to the FLAG
   !$OMP FLUSH(FLAG, DATA)
   ! Set FLAG to release thread 1
   FLAG = 1;
   ! Flush FLAG to ensure that thread 1 sees the change */
   !$OMP FLUSH(FLAG)
ELSE IF(OMP_GET_THREAD_NUM() .EQ. 1) THEN
   ! Loop until we see the update to the FLAG
   !$OMP FLUSH(FLAG, DATA)
   DO WHILE(FLAG .LT. 1)
      !$OMP FLUSH(FLAG, DATA)
   ENDDO
ENDIF
!$OMP END PARALLEL
END
The next example demonstrates why synchronization is difficult to perform correctly through variables. Because the `write(1)-flush(1)-flush(2)-read(2)` sequence cannot be guaranteed in the example, the statements on thread 0 and thread 1 may execute in either order.

```
Example mem_model.3.c

```C / C++```
```c
#include <omp.h>
#include <stdio.h>
int main()
{
    int flag=0;

    #pragma omp parallel num_threads(3)
    {
        if(omp_get_thread_num()==0)
        {
            /* Set flag to release thread 1 */
            #pragma omp atomic update
            flag++;
            /* Flush of flag is implied by the atomic directive */
        }
        else if(omp_get_thread_num()==1)
        {
            /* Loop until we see that flag reaches 1*/
            #pragma omp flush(flag)
            while(flag < 1)
            {
                /* Loop until we see that flag reaches 2 */
                #pragma omp atomic update
                flag++;
                /* Flush of flag is implied by the atomic directive */
            }
            printf("Thread 1 awoken\n");
        }
        else if(omp_get_thread_num()==2)
        {
            /* Loop until we see that flag reaches 2 */
            #pragma omp flush(flag)
            while(flag < 2)
            {
                #pragma omp flush(flag)
            }
            printf("Thread 2 awoken\n");
        }
    }
```
Example mem_model.3.f

```fortran
PROGRAM EXAMPLE
  INCLUDE "omp_lib.h" ! or USE OMP_LIB
  INTEGER FLAG
  FLAG = 0
  !$OMP PARALLEL NUM_THREADS(3)
  IF(OMP_GET_THREAD_NUM() .EQ. 0) THEN
    ! Set flag to release thread 1
    !$OMP ATOMIC UPDATE
    FLAG = FLAG + 1
    !Flush of FLAG is implied by the atomic directive
  ELSE IF(OMP_GET_THREAD_NUM() .EQ. 1) THEN
    ! Loop until we see that FLAG reaches 1
    !$OMP FLUSH(FLAG)
    DO WHILE(FLAG .LT. 1)
      !$OMP FLUSH(FLAG)
    ENDDO
    PRINT *, 'Thread 1 awoken'
  ELSE IF(OMP_GET_THREAD_NUM() .EQ. 2) THEN
    ! Loop until we see that FLAG reaches 2
    !$OMP FLUSH(FLAG)
    DO WHILE(FLAG .LT. 2)
      !$OMP FLUSH(FLAG)
    ENDDO
    PRINT *, 'Thread 2 awoken'
  ENDIF
  !$OMP END PARALLEL
END
```

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8.2 Memory Allocators

OpenMP memory allocators can be used to allocate memory with specific allocator traits. In the following example an OpenMP allocator is used to specify an alignment for arrays x and y. The general approach for attributing traits to variables allocated by OpenMP is to create or specify a pre-defined memory space, create an array of traits, and then form an allocator from the memory space and trait. The allocator is then specified in an OpenMP allocation (using an API `omp_alloc()` function for C/C++ code and an allocate directive for Fortran code in the allocators). In the example below the `xy_memspace` variable is declared and assigned the default memory space (`omp_default_mem_space`). Next, an array for traits is created. Since only one trait will be used, the array size is 1. A trait is a structure in C/C++ and a derived type in Fortran, containing 2 components: a key and a corresponding value (key-value pair). The trait key used here is `omp_atk_alignment` (an enum for C/C++ and a parameter for Fortran) and the trait value of 64 is specified in the `xy_traits` declaration. These declarations are followed by a call to the `omp_init_allocator()` function to combine the memory space (`xy_memspace`) and the traits (`xy_traits`) to form an allocator (`xy_alloc`).

In the C/C++ code the API `omp_allocate()` function is used to allocate space, similar to `malloc`, except that the allocator is specified as the second argument. In Fortran an allocate directive is used to specify an allocator for a following Fortran allocate statement. A variable list may be supplied if the allocator is to be applied to a subset of variables in the Fortran allocate statement. Specifying the complete list is optional. Here, the `xy_alloc` allocator is specified in the allocator clause, and the set of all variables used in the allocate statement is specified in the list.
if( ((intptr_t)(y))%64 != 0 || ((intptr_t)(x))%64 != 0 )
{ printf("ERROR: x|y not 64-Byte aligned\n"); exit(1); }

#pragma omp parallel
{
    #pragma omp for simd simdlen(16) aligned(x,y:64)
    for(int i=0; i<N; i++) x[i]=i+1; y[i]=i+1; } // initialize
    #pragma omp for simd simdlen(16) aligned(x,y:64)
    for(int i=0; i<N; i++) y[i] = s*x[i] + y[i];

printf("y[0],y[N-1]: %5.0f %5.0f\n",y[0],y[N-1]); //output: y... 3 3000

omp_free(x, xy_alloc);
omp_free(y, xy_alloc);
omp_destroy_allocator(xy_alloc);

return 0;

Example allocators.1.f90

program main
use omp_lib
integer, parameter :: N=1000, align=64
real, allocatable :: x(:),y(:)
real :: s = 2.0e0
integer :: i

integer(omp_memspace_handle_kind ) :: xy_memspace = omp_default_mem_space

type( omp_alloctrait ) :: xy_traits(1) = [omp_alloctrait(omp_atk_alignment,64)]

integer(omp_allocator_handle_kind) :: xy_alloc

xy_alloc = omp_init_allocator( xy_memspace, 1, xy_traits)

!$omp allocate(x,y) allocator(xy_alloc)
allocate(x(N),y(N))
!! loc is non-standard, but found everywhere
!! remove these lines if not available
if(modulo(loc(x),align) /= 0 .and. modulo(loc(y),align) /=0 ) then
  print*,"ERROR: x|y not 64-byte aligned"; stop
endif

!$omp parallel
S-25
!$omp do simd simdlen(16) aligned(x,y: 64) !! 64B aligned
S-26
do i=1,N   !! initialize
S-27    x(i)=i
S-28    y(i)=i
S-29   end do
S-30
!$omp do simd simdlen(16) aligned(x,y: 64) !! 64B aligned
S-31
do i = 1,N
S-32    y(i) = s*x(i) + y(i)
S-33   end do
S-34
!$omp end parallel
S-35
write(*,'("y(1),y(N):",2f6.0)') y(1),y(N) !!output: y... 3. 3000.
S-36
deallocate(x,y)
S-37
call omp_destroy_allocator(xy_alloc)
S-38
end program
8.3 Race Conditions Caused by Implied Copies of Shared Variables in Fortran

The following example contains a race condition, because the shared variable, which is an array section, is passed as an actual argument to a routine that has an assumed-size array as its dummy argument. The subroutine call passing an array section argument may cause the compiler to copy the argument into a temporary location prior to the call and copy from the temporary location into the original variable when the subroutine returns. This copying would cause races in the parallel region.

Example fort_race.1.f90

```fortran
SUBROUTINE SHARED_RACE
   INCLUDE "omp_lib.h" ! or USE OMP_LIB
   REAL A(20)
   INTEGER MYTHREAD
   !$OMP PARALLEL SHARED(A) PRIVATE(MYTHREAD)
   MYTHREAD = OMP_GET_THREAD_NUM()
   IF (MYTHREAD .EQ. 0) THEN
      CALL SUB(A(1:10)) ! compiler may introduce writes to A(6:10)
   ELSE
      A(6:10) = 12
   ENDIF
   !$OMP END PARALLEL
END SUBROUTINE SHARED_RACE

SUBROUTINE SUB(X)
   REAL X(*)
   X(1:5) = 4
END SUBROUTINE SUB
```
Some specific and elementary concepts of controlling program execution are illustrated in the examples of this chapter. Control can be directly managed with conditional control code (ifdef's with the _OPENMP macro, and the Fortran sentinel (!$) for conditionally compiling). The if clause on some constructs can direct the runtime to ignore or alter the behavior of the construct. Of course, the base-language if statements can be used to control the "execution" of stand-alone directives (such as flush, barrier, taskwait, and taskyield). However, the directives must appear in a block structure, and not as a substatement as shown in examples 1 and 2 of this chapter.

CANCELLATION

Cancellation (termination) of the normal sequence of execution for the threads in an OpenMP region can be accomplished with the cancel construct. The construct uses a construct-type-clause to set the region-type to activate for the cancellation. That is, inclusion of one of the construct-type-clause names parallel, for, do, sections or taskgroup on the directive line activates the corresponding region. The cancel construct is activated by the first encountering thread, and it continues execution at the end of the named region. The cancel construct is also a cancellation point for any other thread of the team to also continue execution at the end of the named region.

Also, once the specified region has been activated for cancellation any thread that encounters a cancellation point construct with the same named region (construct-type-clause), continues execution at the end of the region.

For an activated cancel taskgroup construct, the tasks that belong to the taskgroup set of the innermost enclosing taskgroup region will be canceled.

A task that encounters the cancel taskgroup construct continues execution at the end of its task region. Any task of the taskgroup that has already begun execution will run to completion, unless it encounters a cancellation point; tasks that have not begun execution "may" be discarded as completed tasks.
CONTROL VARIABLES

Internal control variables (ICV) are used by implementations to hold values which control the execution of OpenMP regions. Control (and hence the ICVs) may be set as implementation defaults, or set and adjusted through environment variables, clauses, and API functions. Many of the ICV control values are accessible through API function calls. Also, initial ICV values are reported by the runtime if the OMP_DISPLAY_ENV environment variable has been set to TRUE.

NESTED CONSTRUCTS

Certain combinations of nested constructs are permitted, giving rise to a combined construct consisting of two or more constructs. These can be used when the two (or several) constructs would be used immediately in succession (closely nested). A combined construct can use the clauses of the component constructs without restrictions. A composite construct is a combined construct which has one or more clauses with (an often obviously) modified or restricted meaning, relative to when the constructs are uncombined.

Certain nestings are forbidden, and often the reasoning is obvious. Worksharing constructs cannot be nested, and the barrier construct cannot be nested inside a worksharing construct, or a critical construct. Also, target constructs cannot be nested.

The parallel construct can be nested, as well as the task construct. The parallel execution in the nested parallel construct(s) is control by the OMP_NESTED and OMP_MAX_ACTIVE_LEVELS environment variables, and the omp_set_nested() and omp_set_max_active_levels() functions.

More details on nesting can be found in the Nesting of Regions of the Directives chapter in the OpenMP Specifications document.
9.1 Conditional Compilation

The following example illustrates the use of conditional compilation using the OpenMP macro \_OPENMP. With OpenMP compilation, the \_OPENMP macro becomes defined.

---

**Example cond_comp.1.c**

```c
#include <stdio.h>

int main()
{
    #ifdef \_OPENMP
        printf("Compiled by an OpenMP-compliant implementation.\n");
    #endif
    return 0;
}
```

---

The following example illustrates the use of the conditional compilation sentinel. With OpenMP compilation, the conditional compilation sentinel \!\$ is recognized and treated as two spaces. In fixed form source, statements guarded by the sentinel must start after column 6.

---

**Example cond_comp.1.f**

```fortran
PROGRAM EXAMPLE
C234567890
!$ PRINT *, "Compiled by an OpenMP-compliant implementation."
END PROGRAM EXAMPLE
```

---
9.2 Internal Control Variables (ICVs)

According to Section 2.3 of the OpenMP 4.0 specification, an OpenMP implementation must act as if there are ICVs that control the behavior of the program. This example illustrates two ICVs, \textit{nthreads-var} and \textit{max-active-levels-var}. The \textit{nthreads-var} ICV controls the number of threads requested for encountered parallel regions; there is one copy of this ICV per task. The \textit{max-active-levels-var} ICV controls the maximum number of nested active parallel regions; there is one copy of this ICV for the whole program.

In the following example, the \textit{nest-var}, \textit{max-active-levels-var}, \textit{dyn-var}, and \textit{nthreads-var} ICVs are modified through calls to the runtime library routines \texttt{omp_set_nested}, \texttt{omp_set_max_active_levels}, \texttt{omp_set_dynamic}, and \texttt{omp_set_num_threads} respectively. These ICVs affect the operation of \texttt{parallel} regions. Each implicit task generated by a \texttt{parallel} region has its own copy of the \textit{nest-var}, \textit{dyn-var}, and \textit{nthreads-var} ICVs.

In the following example, the new value of \textit{nthreads-var} applies only to the implicit tasks that execute the call to \texttt{omp_set_num_threads}. There is one copy of the \textit{max-active-levels-var} ICV for the whole program and its value is the same for all tasks. This example assumes that nested parallelism is supported.

The outer \texttt{parallel} region creates a team of two threads; each of the threads will execute one of the two implicit tasks generated by the outer \texttt{parallel} region.

Each implicit task generated by the outer \texttt{parallel} region calls \texttt{omp_set_num_threads(3)}, assigning the value 3 to its respective copy of \textit{nthreads-var}. Then each implicit task encounters an inner \texttt{parallel} region that creates a team of three threads; each of the threads will execute one of the three implicit tasks generated by that inner \texttt{parallel} region.

Since the outer \texttt{parallel} region is executed by 2 threads, and the inner by 3, there will be a total of 6 implicit tasks generated by the two inner \texttt{parallel} regions.

Each implicit task generated by an inner \texttt{parallel} region will execute the call to \texttt{omp_set_num_threads(4)}, assigning the value 4 to its respective copy of \textit{nthreads-var}.

The print statement in the outer \texttt{parallel} region is executed by only one of the threads in the team. So it will be executed only once.

The print statement in an inner \texttt{parallel} region is also executed by only one of the threads in the team. Since we have a total of two inner \texttt{parallel} regions, the print statement will be executed twice – once per inner \texttt{parallel} region.
Example icv.1.c

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

int main (void)
{
    omp_set_nested(1);
    omp_set_max_active_levels(8);
    omp_set_dynamic(0);
    omp_set_num_threads(2);

#pragma omp parallel
{
    omp_set_num_threads(3);

#pragma omp parallel
{
    omp_set_num_threads(4);

#pragma omp single
{
    // The following should print:
    // Inner: max_act_level=8, num_thds=3, max_thds=4
    // Inner: max_act_level=8, num_thds=3, max_thds=4
    printf("Inner: max_act_level=%d, num_thds=%d, max_thds=%d\n",
           omp_get_max_active_levels(), omp_get_num_threads(),
           omp_get_max_threads());
}
}

#pragma omp barrier

#pragma omp single
{
    // The following should print:
    // Outer: max_act_level=8, num_thds=2, max_thds=3
    printf("Outer: max_act_level=%d, num_thds=%d, max_thds=%d\n",
            omp_get_max_active_levels(), omp_get_num_threads(),
            omp_get_max_threads());
}

    return 0;
}
```
Example icv.1.f

```
program icv
use omp_lib

call omp_set_nested(.true.)
call omp_set_max_active_levels(8)
call omp_set_dynamic(.false.)
call omp_set_num_threads(2)

!$omp parallel
  call omp_set_num_threads(3)
!$omp parallel
  call omp_set_num_threads(4)
!$omp single
  ! The following should print:
  ! Inner: max_act_lev= 8 , num_thds= 3 , max_thds= 4
  ! Inner: max_act_lev= 8 , num_thds= 3 , max_thds= 4
  print *, "Inner: max_act_lev=" , omp_get_max_active_levels(),
  & num_thds=" , omp_get_num_threads(),
  & max_thds=" , omp_get_max_threads()
!$omp end single
!$omp end parallel

!$omp barrier
!$omp single
! The following should print:
! Outer: max_act_lev= 8 , num_thds= 2 , max_thds= 3
! Outer: max_act_lev=" , omp_get_max_active_levels(),
& num_thds=" , omp_get_num_threads(),
& max_thds=" , omp_get_max_threads()
!$omp end single
!$omp end parallel
end
```
9.3 Placement of `flush`, `barrier`, `taskwait` and `taskyield` Directives

The following example is non-conforming, because the `flush`, `barrier`, `taskwait`, and `taskyield` directives are stand-alone directives and cannot be the immediate substatement of an `if` statement.

```c
void standalone_wrong()
{
    int a = 1;

    if (a != 0)
        #pragma omp flush(a)
        /* incorrect as flush cannot be immediate substatement of if statement */

    if (a != 0)
        #pragma omp barrier
        /* incorrect as barrier cannot be immediate substatement of if statement */

    if (a != 0)
        #pragma omp taskyield
        /* incorrect as taskyield cannot be immediate substatement of if statement */

    if (a != 0)
        #pragma omp taskwait
        /* incorrect as taskwait cannot be immediate substatement of if statement */
}
```
The following example is non-conforming, because the `flush`, `barrier`, `taskwait`, and `taskyield` directives are stand-alone directives and cannot be the action statement of an `if` statement or a labeled branch target.

Fortran

Example standalone.1.f90

```fortran
SUBROUTINE STANDALONE_WRONG()
  INTEGER A
  A = 1
  IF (A .NE. 0) !$OMP FLUSH(A)
  IF (A .NE. 0) !$OMP BARRIER
  IF (A .NE. 0) !$OMP TASKWAIT
  IF (A .NE. 0) !$OMP TASKYIELD
  GOTO 100
  100 !$OMP FLUSH(A)
  GOTO 200
  200 !$OMP BARRIER
  GOTO 300
  300 !$OMP TASKWAIT
  GOTO 400
```

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The following version of the above example is conforming because the `flush`, `barrier`, `taskwait`, and `taskyield` directives are enclosed in a compound statement.

Example standalone.2.c

```c
void standalone_ok()
{
    int a = 1;
    #pragma omp parallel
    {
        if (a != 0) {
            #pragma omp flush(a)
        }
        if (a != 0) {
            #pragma omp barrier
        }
        if (a != 0) {
            #pragma omp taskwait
        }
        if (a != 0) {
            #pragma omp taskyield
        }
    }
}
```

The following example is conforming because the `flush`, `barrier`, `taskwait`, and `taskyield` directives are enclosed in an `if` construct or follow the labeled branch target.

---

**Fortran**

---

*Example standalone.2.f90*

```
S-1 SUBROUTINE STANDALONE_OK()
S-2   INTEGER A
S-3   A = 1
S-4   IF (A .NE. 0) THEN
S-5     !$OMP FLUSH(A)
S-6     ENDIF
S-7   IF (A .NE. 0) THEN
S-8     !$OMP BARRIER
S-9     ENDIF
S-10  IF (A .NE. 0) THEN
S-11    !$OMP TASKWAIT
S-12   ENDIF
S-13  IF (A .NE. 0) THEN
S-14    !$OMP TASKYIELD
S-15   ENDIF
S-16  GOTO 100
S-17  100 CONTINUE
S-18  !$OMP FLUSH(A)
S-19  GOTO 200
S-20  200 CONTINUE
S-21  !$OMP BARRIER
S-22  GOTO 300
S-23  300 CONTINUE
S-24  !$OMP TASKWAIT
S-25  GOTO 400
S-26  400 CONTINUE
S-27  !$OMP TASKYIELD
S-28 END SUBROUTINE
```

---
1 9.4 Cancellation Constructs

The following example shows how the *cancel* directive can be used to terminate an OpenMP region. Although the *cancel* construct terminates the OpenMP worksharing region, programmers must still track the exception through the pointer *ex* and issue a cancellation for the *parallel* region if an exception has been raised. The master thread checks the exception pointer to make sure that the exception is properly handled in the sequential part. If cancellation of the *parallel* region has been requested, some threads might have executed *phase_1()*. However, it is guaranteed that none of the threads executed *phase_2()*. 

---

Example cancellation.1.cpp

```c++
#include <iostream>
#include <exception>
#include <cassert>

#define N 10000

extern void causes_an_exception();
extern void phase_1();
extern void phase_2();

void example() {
    std::exception *ex = NULL;
    #pragma omp parallel shared(ex)
    {
        #pragma omp for
        for (int i = 0; i < N; i++) {
            // no 'if' that prevents compiler optimizations
            try {
                causes_an_exception();
            } catch (std::exception *e) {
            }
            // still must remember exception for later handling
            #pragma omp atomic write
            ex = e;
            // cancel worksharing construct
        }
        // if an exception has been raised, cancel parallel region
        if (ex) {
            #pragma omp cancel parallel
        }
        phase_1();
    }
}
```
The following example illustrates the use of the `cancel` construct in error handling. If there is an error condition from the `allocate` statement, the cancellation is activated. The encountering thread sets the shared variable `err` and other threads of the binding thread set proceed to the end of the worksharing construct after the cancellation has been activated.
The following example shows how to cancel a parallel search on a binary tree as soon as the search value has been detected. The code creates a task to descend into the child nodes of the current tree node. If the search value has been found, the code remembers the tree node with the found value through an **atomic** write to the result variable and then cancels execution of all search tasks. The function `search_tree_parallel` groups all search tasks into a single task group to control the effect of the **cancel taskgroup** directive. The `level` argument is used to create deferred tasks after the first ten levels of the tree.

```
#include <stddef.h>

typedef struct binary_tree_s {
    int value;
    struct binary_tree_s *left, *right;
} binary_tree_t;

binary_tree_t *search_tree(binary_tree_t *tree, int value, int level) {
    binary_tree_t *found = NULL;
    if (tree) {
        if (tree->value == value) {
            found = tree;
        } else {
            #pragma omp task shared(found) if(level < 10)
            {
                binary_tree_t *found_left = NULL;
                found_left = search_tree(tree->left, value, level + 1);
                if (found_left) {
                    #pragma omp atomic write
                    found = found_left;
                    #pragma omp cancel taskgroup
                    }
            }
            #pragma omp task shared(found) if(level < 10)
            {
                binary_tree_t *found_right = NULL;
                found_right = search_tree(tree->right, value, level + 1);
                if (found_right) {
                    #pragma omp atomic write
                    found = found_right;
                    #pragma omp cancel taskgroup
                    }
            }
            #pragma omp taskwait
        }
    }

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binary_tree_t *search_tree_parallel(binary_tree_t *tree, int value) {
    binary_tree_t *found = NULL;
    #pragma omp parallel shared(found, tree, value)
    {
        #pragma omp master
        {
            #pragma omp taskgroup
            {
                found = search_tree(tree, value, 0);
            }
        }
    }
    return found;
}

The following is the equivalent parallel search example in Fortran.

```fortran
module parallel_search
  type binary_tree
    integer :: value
    type(binary_tree), pointer :: right
    type(binary_tree), pointer :: left
  end type
contains
  recursive subroutine search_tree(tree, value, level, found)
    type(binary_tree), intent(in), pointer :: tree
    integer, intent(in) :: value, level
    type(binary_tree), pointer :: found
    type(binary_tree), pointer :: found_left => NULL(), found_right => NULL()
    if (associated(tree)) then
      if (tree%value .eq. value) then
        found => tree
      else
        !$omp task shared(found) if(level<10)
        call search_tree(tree%left, value, level+1, found_left)
        if (associated(found_left)) then
          !$omp critical
          found => found_left
      end if
    end if
end subroutine search_tree
```

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!$omp end critical
S-28
!$omp end task
S-29
!$omp task shared(found) if(level<10)
S-31
call search_tree(tree%right, value, level+1, found_right)
S-32
if (associated(found_right)) then
S-33
!$omp critical
S-34
found => found_right
S-35
!$omp end critical
S-36
!$omp cancel taskgroup
S-38
endif
S-39
!$omp end task
S-40
!$omp taskwait
S-42
endif
S-43
endif
S-44
end subroutine
S-45

subroutine search_tree_parallel(tree, value, found)
S-47
type(binary_tree), intent(in), pointer :: tree
S-48
integer, intent(in) :: value
S-49
type(binary_tree), pointer :: found
S-50
found => NULL()
S-52
!$omp parallel shared(found, tree, value)
S-53
!$omp master
S-54
!$omp taskgroup
S-55
call search_tree(tree, value, 0, found)
S-56
!$omp end taskgroup
S-57
!$omp end master
S-58
!$omp end parallel
S-59
end subroutine
S-60
end module parallel_search

Fortran
9.5 The requires Directive

The declarative requires directive can be used to specify features that an implementation must provide to compile and execute correctly.

In the following example the unified_shared_memory clause of the requires directive ensures that the host and all devices accessible through OpenMP provide a unified address space for memory that is shared by all devices.

The example illustrates the use of the requires directive specifying unified shared memory in file scope, before any device directives or device routines. No map clause is needed for the p structure on the device (and its address &p, for the C++ code, is the same address on the host and device). However, scalar variables referenced within the target construct still have a default data-sharing attribute of firstprivate. The q scalar is incremented on the device, and its change is not updated on the host.

```
#include <iostream>
using namespace std;

#pragma omp requires unified_shared_memory
typedef struct mypoints
{
    double res;
    double data[500];
} mypoints_t;

void do_something_with_p(mypoints_t *p, int q);

int main()
{
    mypoints_t p;
    int q=0;

    #pragma omp target // no map clauses needed
    { // q is firstprivate
        q++; // q is firstprivate
        do_something_with_p(&p,q);
    }
    cout<< p.res << " " << q << endl; // output 1 0
    return 0;
}

void do_something_with_p(mypoints_t *p, int q)
```
Example requires.1.f90

module data
  !$omp requires unified_shared_memory
  type,public :: mypoints
    double precision :: res
    double precision :: data(500)
  end type
end module

program main
  use data
  type(mypoints) :: p
  integer :: q=0
  !$omp target !! no map clauses needed
  q = q + 1 !! q is firstprivate
  call do_something_with_p(p,q)
  !$omp end target
  write(*,'(f5.0,i5)') p%res, q !! output 1. 0
end program

subroutine do_something_with_p(p,q)
  use data
  type(mypoints) :: p
  integer :: q
  p%res = q;
  do i=1,size(p%data)
    p%data(i)=q*i
  enddo
end subroutine
A **declare variant** directive specifies an alternate function, *function variant*, to be used in place of the *base function* when the trait within the *match* clause matches the OpenMP context at a given call site. The base function follows the directive in the C and C++ languages. In Fortran, either a subroutine or function may be used as the *base function*, and the **declare variant** directive must be in the specification part of a subroutine or function (unless a *base-proc-name* modifier is used, as in the case of a procedure declaration statement). See the OpenMP 5.0 Specification for details on the modifier.

When multiple **declare variant** directives are used a function variant becomes a candidate for replacing the base function if the context at the base function call matches the traits of all selectors in the **match** clause. If there are multiple candidates, a score is assigned with rules for each of the selector traits. The scoring algorithm can be found in the OpenMP 5.0 Specification.

In the first example the *vxv()* function is called within a **parallel** region, a **target** region, and in a sequential part of the program. Two function variants, *p_vxv()* and *t_vxv()* are defined for the first two regions by using **parallel** and **target** selectors (within the **construct** trait set) in a **match** clause. The *p_vxv()* function variant includes a **for** construct (**do** construct for Fortran) for the **parallel** region, while *t_vxv()* includes a **distribute simd** construct for the **target** region. The *t_vxv()* function is explicitly compiled for the device using a **declare target** directive.

Since the two **declare variant** directives have no selectors that match traits for the context of the base function call in the sequential part of the program, the base *vxv()* function is used there, as expected. (The vectors in the *p_vxv* and *t_vxv* functions have been multiplied by 3 and 2, respectively, for checking the validity of the replacement. Normally the purpose of a function variant is to produce the same results by a different method.)

---

**Example declare_variant.1.c**

```c
#define N 100
#include <stdio.h>
#include <omp.h>

void p_vxv(int *v1, int *v2, int *v3, int n);

void t_vxv(int *v1, int *v2, int *v3, int n);

#pragma omp declare variant( p_vxv ) match( construct={parallel} )
#pragma omp declare variant( t_vxv ) match( construct={target} )

void vxv(int *v1, int *v2, int *v3, int n) // base function
{
    for (int i = 0; i < n; i++)
        v3[i] = v1[i] * v2[i];
}
```

---
void p_vxv(int *v1, int *v2, int *v3, int n) // function variant
{
#pragma omp for
  for (int i= 0; i< n; i++) v3[i] = v1[i] * v2[i]*3;
}

#pragma omp declare target
void t_vxv(int *v1, int *v2, int *v3, int n) // function variant
{
#pragma omp distribute simd
  for (int i= 0; i< n; i++) v3[i] = v1[i] * v2[i]*2;
}

int main()
{
  int v1[N], v2[N], v3[N];
  for(int i=0; i<N; i++){ v1[i]=(i+1); v2[i]=-(i+1); v3[i]=0; } //init
  #pragma omp parallel
  {
    vxv(v1,v2,v3,N);
  }
  printf(" %d %d\n",v3[0],v3[N-1]); //from p_vxv -- output: -3 -30000
  #pragma omp target teams map(to: v1[:N],v2[:N]) map(from: v3[:N])
  {
    vxv(v1,v2,v3,N);
  }
  printf(" %d %d\n",v3[0],v3[N-1]); //from t_vxv -- output: -2 -20000
  vxv(v1,v2,v3,N);
  printf(" %d %d\n",v3[0],v3[N-1]); //from vxv -- output: -1 -10000
  return 0;
}

Example declare_variant.1.f90

module subs
  use omp_lib
  contains
    subroutine vxv(v1, v2, v3) !! base function
      integer,intent(in) :: v1(:),v2(:)
integer, intent(out) :: v3(:)
integer :: i, n
!
omp declare variant( p_vxv ) match( construct={parallel} )
!
omp declare variant( t_vxv ) match( construct={target} )

n = size(v1)
do i = 1, n; v3(i) = v1(i) * v2(i); enddo
end subroutine

end module subs

program main
  use omp_lib
  use subs
  integer, parameter :: N = 100
  integer :: v1(N), v2(N), v3(N)
do i = 1, N; v1(i) = i; v2(i) = -i; v3(i) = 0; enddo
!
omp parallel
call vxv(v1, v2, v3)
!
omp end parallel
end program main
In this example, traits from the device set are used to select a function variant. In the declare variant directive, an isa selector specifies that if the implementation of the "core-avx512" instruction set is detected at compile time the avx512_saxpy() variant function is used for the call to base_saxpy().

A compilation of avx512_saxpy() is aware of the AVX-512 instruction set that supports 512-bit vector extensions (for Xeon or Xeon Phi architectures). Within avx512_saxpy(), the parallel for simd construct performs parallel execution, and takes advantage of 64-byte data alignment. When the avx512_saxpy() function variant is not selected, the base base_saxpy() function variant containing only a basic parallel for construct is used for the call to base_saxpy().
// Above may be in another file scope.

#include <stdio.h>
#include <stdlib.h>
#include <stdint.h>
#define N 1000

int main()
{
    static float x[N], y[N] __attribute__ ((aligned(64)));
    float s=2.0;
    // Check for 64-byte aligned
    if( ((intptr_t)y)%64 != 0 || ((intptr_t)x)%64 != 0 )
    {
        printf("ERROR: x|y not 64-Byte aligned\n"); exit(1); }

    for(int i=0; i<N; i++) { x[i]=i+1; y[i]=i+1; } // initialize

    base_saxpy(N, s, x, y);

    printf("y[0],y[N-1]: %5.0f %5.0f\n", y[0], y[N-1]); // output: y... 3 3000

    return 0;
}

Example declare_variant.2.f90

module subs
    use omp_lib
    contains
    subroutine base_saxpy(s,x,y) !! base function
        real,intent(inout) :: s,x(:),y(:)
        !$omp declare variant( avx512_saxpy ) &
        !$omp& match( device={isa("core-avx512")})
        y = s*x + y
    end subroutine

    subroutine avx512_saxpy(s,x,y) !! function variant
        real,intent(inout) :: s,x(:),y(:)
        integer :: i,n
        n=size(x)
!!assume 64-byte alignment for AVX-512

$omp parallel do simd simdlen(16) aligned(x,y: 64)
do i = 1,n
  y(i) = s*x(i) + y(i)
end do

end subroutine

end module subs

program main
  use omp_lib
  use subs

  integer, parameter :: N=1000, align=64
  real, allocatable :: x(:), y(:)
  real :: s = 2.0e0
  integer :: i

  allocate(x(N), y(N)) !! Assumes allocation is 64-byte aligned
  !! (using compiler options, or another
  !! allocation method).

  !! loc is non-standard, but found everywhere
  !! remove these lines if not available
  if(modulo(loc(x),align) /= 0 .and. modulo(loc(y),align) /=0 ) then
    print*,"ERROR: x|y not 64-byte aligned"; stop
  endif

  do i=1,N !! initialize
    x(i)=i
    y(i)=i
  end do

  call base_saxpy(s,x,y)

  write(*,'("y(1),y(N):",2f6.0)') y(1),y(N) !!output: y... 3. 3000.

  deallocate(x,y)
end program
9.7 Metadirective Directive

A **metadirective** directive provides a mechanism to select a directive in a **when** clause to be used, depending upon one or more contexts: implementation, available devices and the present enclosing construct. The directive in a **default** clause is used when a directive of the **when** clause is not selected.

In the **when** clause the **context selector** (or just **selector**) defines traits that are evaluated for selection of the directive that follows the selector. This "selectable" directive is called a **directive variant**. Traits are grouped by **construct**, **implementation** and **device sets** to be used by a selector of the same name.

In the first example the architecture trait **arch** of the **device** selector set specifies that if an **nvptx** (NVIDIA) architecture is active in the OpenMP context, then the **teams loop directive variant** is selected as the directive; otherwise, the **parallel loop directive variant** of the **default** clause is selected as the directive. That is, if a **device** of **nvptx** architecture is supported by the implementation within the enclosing **target** construct, its **directive variant** is selected. The architecture names, such as **nvptx**, are implementation defined. Also, note that **device** as used in a **target** construct specifies a device number, while **device**, as used in the **metadirective** directive as selector set, has traits of **kind**, **isa** and **arch**.

---

```
#define N 100
#include <stdio.h>

int main()
{
    int v1[N], v2[N], v3[N];
    for(int i=0; i<N; i++) { v1[i]=(i+1); v2[i]=-(i+1); }

    #pragma omp target map(to:v1,v2) map(from:v3) device(0)
    #pragma omp metadirective
            when( device={arch("nvptx")}: teams loop) \
            default( parallel loop )
        for (int i=0; i<N; i++) v3[i] = v1[i] * v2[i];

    printf(" %d %d\n",v3[0],v3[N-1]); //output: -1 -10000
    return 0;
}
```
Example metadirective.1.f90

program main
  integer, parameter :: N = 100
  integer :: v1(N), v2(N), v3(N);
  do i = 1, N; v1(i) = i; v2(i) = -i; enddo ! initialize
  !$omp target map(to:v1,v2) map(from:v3) device(0)
  !$omp metadirective &
  !$omp & when( device={arch("nvptx")}: teams loop) &
  !$omp & default( parallel loop)
  do i = 1, N; v3(i) = v1(i) * v2(i); enddo
  print *, v3(1), v3(N) ! output: -1 -10000
end program

In the second example, the implementation selector set is specified in the when clause to
distinguish between AMD and NVIDIA platforms. Additionally, specific architectures are specified
with the device selector set.

In the code, different teams constructs are employed as determined by the metadirective
directive. The number of teams is restricted by a num_teams clause and a thread limit is also set
by a thread_limit clause for vendor AMD and NVIDIA platforms and specific architecture
traits. Otherwise, just the teams construct is used without any clauses, as prescribed by the
default clause.

Example metadirective.2.c

#define N 100
#include <stdio.h>
#include <omp.h>

void work_on_chunk(int idev, int i);

int main() // Driver
{
  int i, idev;
  for (idev = 0; idev < omp_get_num_devices() - 1; idev++)
  {
    #pragma omp target device(i)
#pragma omp metadirective
    when( implementation={vendor(nvidia)}, device={arch("kepler")}: \
        teams num_teams(512) thread_limit(32) ) \
    when( implementation={vendor(amd)}, device={arch("fiji")}: \
        teams num_teams(512) thread_limit(64) ) \
    default( \
        teams)
#pragma omp distribute parallel for
for (i=0; i<N; i++) work_on_chunk(idev,i);
}
}
end program

Example metadirective.2.f90

program main       !!Driver
    use omp_lib
    implicit none
    integer, parameter :: N=1000
    external :: work_on_chunk
    integer :: i,idev
    do idev=0,omp_get_num_devices()-1
        !$omp target device(i)
        !$omp metadirective  \n        !$omp& when( implementation={vendor(nvidia)}, device={arch("kepler")}: &
        !$omp& teams num_teams(512) thread_limit(32) ) &
        !$omp& when( implementation={vendor(amd)}, device={arch("fiji")}: &
        !$omp& teams num_teams(512) thread_limit(64) ) &
        !$omp& default( &
        !$omp& teams)
        !$omp distribute parallel for
        do i=1,N
            call work_on_chunk(idev,i)
        end do
        end do
    end do
end program

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In the third example, a `construct` selector set is specified in the `when` clause. Here, a
`metadirective` directive is used within a function that is also compiled as a function for a
target device as directed by the `declare target` directive. The `target` directive name of the
`construct` selector ensures that the `distribute parallel for/do` construct is employed
for the target compilation. Otherwise, for the host-compiled version the
`parallel for/do simd` construct is used.

In the first call to the `exp_pi_diff()` routine the context is a `target teams` construct and the
`distribute parallel for/do` construct version of the function is invoked, while in the
second call the `parallel for/do simd` construct version is used.

This case illustrates an important point for users that may want to hoist the `target` directive out of
a function that contains the usual `target teams distribute parallel for/do` construct
(for providing alternate constructs through the `metadirective` directive as here). While this
combined construct can be decomposed into a `target` and `teams distribute parallel
for/do` constructs, the OpenMP 5.0 specification has the restriction: “If a `teams` construct is
nested within a `target` construct, that `target` construct must contain no statements, declarations
or directives outside of the `teams` construct”. So, the `teams` construct must immediately follow
the `target` construct without any intervening code statements (which includes function calls).
Since the `target` construct alone cannot be hoisted out of a function, the `target teams`
construct has been hoisted out of the function, and the `distribute parallel for/do`
construct is used as the `variant` directive of the `metadirective` directive within the function.

---

Example metadirective.3.c

```c
#include <stdio.h>
#include <math.h>
define N 1000

#pragma omp declare target
void exp_pi_diff(double *d, double my_pi){
    #pragma omp metadirective \
        when( construct={target}: distribute parallel for ) \
        default( parallel for simd)
    for(int i = 0; i<N; i++) d[i] = exp( (M_PI-my_pi)*i );
}
#pragma omp end declare target

int main()
{
    //Calculates sequence of exponentials: (M_PI-my_pi) * index
    //M_PI is from math.h, and my_pi is user provided.
    double d[N];
    double my_pi=3.14159265358979e0;
```
# S-22
#pragma omp target teams map(tofrom: d[0:N])
S-23
exp_pi_diff(d,my_pi);
S-24
// value should be near 1
S-25
printf("d[N-1] = %20.14f\n",d[N-1]); // ...= 1.00000000000311
S-26
S-27
exp_pi_diff(d,my_pi);
S-28
// value should be near 1
S-29
printf("d[N-1] = %20.14f\n",d[N-1]); // ...= 1.00000000000311
}

Example metadirective.3.f90

S-1
module params
S-2
integer, parameter :: N=1000
S-3
DOUBLE PRECISION, PARAMETER::M_PI=4.0d0*DATAN(1.0d0) !3.1415926535897932_8
S-4
double precision :: d(N)
S-5
double precision :: my_pi=3.14159265358979d0
S-6
end module
S-7

S-8
subroutine exp_pi_diff(d, my_pi)
S-9
use params
S-10
implicit none
S-11
integer :: i
S-12
double precision :: d(N), my_pi
S-13
!$omp declare target
S-14
!$omp metadirective &
S-15
!$omp& when( construct={target}: distribute parallel do ) &
S-16
!$omp& default( parallel do simd)
S-17
S-18
do i = 1,size(d)
S-19
d(i) = exp( (M_PI-my_pi)*i )
S-20
end do
S-21
end subroutine
S-22

S-23
program main
S-24
! Calculates sequence of exponentials: (M_PI-my_pi) * index
S-25
! M_PI is from usual way, and my_pi is user provided.
S-26
! Fortran Standard does not provide PI
S-27
use params
S-28
implicit none
S-29
double precision :: d(N)
S-30
double precision :: my_pi=3.14159265358979d0
S-31

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S-35 !$omp target teams map(from: d)
S-36 call exp_pi_diff(d,my_pi)
S-37 ! value should be near 1
S-38 print*, "d(N) = ",d(N) ! 1.00000000000311
S-39 call exp_pi_diff(d,my_pi) ! value should be near 1
S-40 print*, "d(N) = ",d(N) ! 1.00000000000311
S-42 end program

Fortran
9.8 Nested Loop Constructs

The following example of loop construct nesting is conforming because the inner and outer loop regions bind to different `parallel` regions:

```
C / C++
```
The following variation of the preceding example is also conforming:

```c++
void work1(int i, int n)
{
    int j;
    #pragma omp parallel default(shared)
    {
        #pragma omp for
        for (j=0; j<n; j++)
            work(i, j);
    }
}

void good_nesting2(int n)
{
    int i;
    #pragma omp parallel default(shared)
    {
        #pragma omp for
        for (i=0; i<n; i++)
            work1(i, n);
    }
}
```

```fortran
END SUBROUTINE GOOD_NESTING
END DO
!$OMP END PARALLEL

!$OMP END PARALLEL
```

**Example nested_loop.2.c**
Example nested_loop.2.f

S-1       SUBROUTINE WORK(I, J)
S-2       INTEGER I, J
S-3       END SUBROUTINE WORK
S-4
S-5       SUBROUTINE WORK1(I, N)
S-6       INTEGER J
S-7       !$OMP PARALLEL DEFAULT(SHARED)
S-8       !$OMP DO
S-9            DO J = 1, N
S-10           CALL WORK(I,J)
S-11          END DO
S-12          !$OMP END PARALLEL
S-13         END SUBROUTINE WORK1
S-14
S-15       SUBROUTINE GOOD_NESTING2(N)
S-16       INTEGER N
S-17       !$OMP PARALLEL DEFAULT(SHARED)
S-18       !$OMP DO
S-19            DO I = 1, N
S-20              CALL WORK1(I, N)
S-21             END DO
S-22          !$OMP END PARALLEL
S-23         END SUBROUTINE GOOD_NESTING2
9.9 Restrictions on Nesting of Regions

The examples in this section illustrate the region nesting rules.

The following example is non-conforming because the inner and outer loop regions are closely nested:

```c
void wrong1(int n)
{
    #pragma omp parallel default(shared)
    {
        int i, j;
        #pragma omp for
        for (i=0; i<n; i++) {
            #pragma omp for
            for (j=0; j<n; j++)
                work(i, j);
        }
    }
}
```

**Example nesting_restrict.1.c**

```fortran
SUBROUTINE WORK(I, J)
INTEGER I, J
END SUBROUTINE WORK

SUBROUTINE WRONG1(N)
INTEGER N
INTEGER I,J
!$OMP PARALLEL DEFAULT(SHARED)
!$OMP DO
DO I = 1, N
    DO I = 1, N
        work(i, j);
    END DO
END DO
```

**Example nesting_restrict.1.f**
The following orphaned version of the preceding example is also non-conforming:

```
void work(int i, int j) {}
void work1(int i, int n) {
  int j;
  /* incorrect nesting of loop regions */
  #pragma omp for
  for (j=0; j<n; j++)
    work(i, j);
}

void wrong2(int n) {
  #pragma omp parallel default(shared)
  {
    int i;
    #pragma omp for
    for (i=0; i<n; i++)
      work1(i, n);
  }
}
```
Fortran

Example nesting_restrict.2.f

1

S-1 SUBROUTINE WORK1(I,N)
S-2 INTEGER I, N
S-3 INTEGER J
S-4 !$OMP DO ! incorrect nesting of loop regions
S-5 DO J = 1, N
S-6 CALL WORK(I,J)
S-7 END DO
S-8 END SUBROUTINE WORK1
S-9 SUBROUTINE WRONG2(N)
S-10 INTEGER N
S-11 INTEGER I
S-12 !$OMP PARALLEL DEFAULT(SHARED)
S-13 !$OMP DO
S-14 DO I = 1, N
S-15 CALL WORK1(I,N)
S-16 END DO
S-17 !$OMP END PARALLEL
S-18 END SUBROUTINE WRONG2

Fortran

The following example is non-conforming because the loop and single regions are closely nested:

Example nesting_restrict.3.c

2

S-1 void work(int i, int j) {}  
S-2 void wrong3(int n)  
S-3 {  
S-4 #pragma omp parallel default(shared)   
S-5 {  
S-6 int i;  
S-7 #pragma omp for  
S-8 for (i=0; i<n; i++) {  
S-9 /* incorrect nesting of regions */  
S-10 #pragma omp single  
S-11 work(i, 0);  
S-12 }  
S-13 }  
S-14 }

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Fortran

Example nesting_restrict.3.f

1

SUBROUTINE WRONG3(N)
   INTEGER N
   INTEGER I

   !$OMP PARALLEL DEFAULT(SHARED)
   !$OMP DO
   DO I = 1, N
   !$OMP SINGLE ! incorrect nesting of regions
   CALL WORK(I, 1)
   !$OMP END SINGLE
   END DO
   !$OMP END PARALLEL
   END SUBROUTINE WRONG3

2

The following example is non-conforming because a barrier region cannot be closely nested inside a loop region:

C / C++

Example nesting_restrict.4.c

4

void work(int i, int j) {}
void wrong4(int n)
{

#pragma omp parallel default(shared)
{
   int i;
   #pragma omp for
   for (i=0; i<n; i++) {
      work(i, 0);
   }
   /* incorrect nesting of barrier region in a loop region */
   #pragma omp barrier
   work(i, 1);
}
}
The following example is non-conforming because the barrier region cannot be closely nested inside the critical region. If this were permitted, it would result in deadlock due to the fact that only one thread at a time can enter the critical region:

C / C++

Example nesting_restrict.5.c

```c
void work(int i, int j) {}
void wrong5(int n)
{
    #pragma omp parallel
    {
        #pragma omp critical
        {
            work(n, 0);
        }
        /* incorrect nesting of barrier region in a critical region */
        #pragma omp barrier
        work(n, 1);
    }
}
```
Example nesting_restrict.5.f

```fortran
SUBROUTINE WRONG5(N)
  INTEGER N
  !$OMP PARALLEL DEFAULT(SHARED)
  !$OMP CRITICAL
  CALL WORK(N,1)
  ! incorrect nesting of barrier region in a critical region
  !$OMP BARRIER
  CALL WORK(N,2)
  !$OMP END CRITICAL
  !$OMP END PARALLEL
END SUBROUTINE WRONG5
```

The following example is non-conforming because the barrier region cannot be closely nested inside the single region. If this were permitted, it would result in deadlock due to the fact that only one thread executes the single region:

Example nesting_restrict.6.c

```c
void work(int i, int j) {}
void wrong6(int n)
{
  #pragma omp parallel
  {
    #pragma omp single
    {
      work(n, 0);
      /* incorrect nesting of barrier region in a single region */
      #pragma omp barrier
      work(n, 1);
    }
  }
}
```

---
Example nesting_restrict.6.f

SUBROUTINE WRONG6(N)
  INTEGER N

  !$OMP PARALLEL DEFAULT(SHARED)
  !$OMP SINGLE
  CALL WORK(N,1)
  ! incorrect nesting of barrier region in a single region
  !$OMP BARRIER
  CALL WORK(N,2)
  !$OMP END SINGLE
  !$OMP END PARALLEL
END SUBROUTINE WRONG6
9.10 Target Offload

In the OpenMP 5.0 implementation the `OMP_TARGET_OFFLOAD` environment variable was defined to change default offload behavior. By default the target code (region) is executed on the host if the target device does not exist or the implementation does not support the target device.

In an OpenMP 5.0 compliant implementation, setting the `OMP_TARGET_OFFLOAD` variable to `MANDATORY` will force the program to terminate execution when a `target` construct is encountered and the target device is not supported or is not available. With a value `DEFAULT` the target region will execute on a device if the device exists and is supported by the implementation, otherwise it will execute on the host. Support for the `DISABLED` value is optional; when it is supported the behavior is as if only the host device exists (other devices are considered non-existent to the runtime), and target regions are executed on the host.

The following example reports execution behavior for different values of the `OMP_TARGET_OFFLOAD` variable. A handy routine for extracting the `OMP_TARGET_OFFLOAD` environment variable value is deployed here, because the OpenMP API does not have a routine for obtaining the value.

Note: The example issues a warning when a pre-5.0 implementation is used, indicating that the `OMP_TARGET_OFFLOAD` is ignored. The value of the `OMP_TARGET_OFFLOAD` variable is reported when the `OMP_DISPLAY_ENV` environment variable is set to `TRUE` or `VERBOSE`.

```
#include <omp.h>
#include <stdio.h>
#include <ctype.h>
#include <stdlib.h>
#include <string.h>

typedef enum offload_policy
{MANDATORY, DISABLED, DEFAULT, UNKNOWN, NOTSET} offload_policy_t;

offload_policy_t get_offload_policy()
{
    char *env, *end;
    size_t n;
    env = getenv("OMP_TARGET_OFFLOAD");
    if(env == NULL) return NOTSET;
    end = env + strlen(env); //Find trimmed beginning/end
    while ( *env && isspace(*(env )) ) env++;
```
while (end != env && isspace(*(end-1)) ) end--;  
n = (int)(end - env);

    //Find ONLY string -nothing more, case insensitive
    if (n == 9 && !strncasecmp(env, "MANDATORY",n)) return MANDATORY;
    else if (n == 8 && !strncasecmp(env, "DISABLED",n)) return DISABLED;
    else if (n == 7 && !strncasecmp(env, "DEFAULT",n)) return DEFAULT;
    else return UNKNOWN;
}

int main()
{
    int i;
    int device_num, on_init_dev;
    // get policy from OMP_TARGET_OFFLOAD variable
    offload_policy_t policy = get_offload_policy();

    if(_OPENMP< 201811)
    {
        printf("Warning: OMP_TARGET_OFFLOAD NOT supported by VER. %d\n",_OPENMP );
        printf(" If OMP_TARGET_OFFLOAD is set, it will be ignored.\n");
    }

    device_num = omp_get_num_devices() + 1;
    // Set target device number to an unavailable
    // device# out of range--not supported
    #pragma omp target device(device_num) map(tofrom: on_init_dev)
    on_init_dev=omp_is_initial_device();

    if (policy == MANDATORY && _OPENMP >= 201811)
        printf("ERROR: OpenMP 5.0 implementation ignored MANDATORY policy.\n");
    printf("Target region executed on init dev %s\n", on_init_dev ? "TRUE":"FALSE"
Example target_offload_control.f90

module offload_policy
  implicit none
  integer, parameter :: LEN_POLICY=10
  contains
    character(LEN_POLICY) function get_offload_policy()
      character(64) :: env
      integer :: length, i
      env=repeat(' ',len(env))
      !policy is blank if not found *
      call get_environment_variable("OMP_TARGET_OFFLOAD",env,length)
      do i = 1,len(env) !Makes a-z upper case
        if(iachar(env(i:i))>96) env(i:i)=achar(iachar(env(i:i))-32)
      end do
      get_offload_policy = trim(adjustl(env)) !remove peripheral spaces
      if(length==0) get_offload_policy="NOTSET"
      return
    end function
  end module

program policy_test
  use omp_lib
  use offload_policy
  integer :: i, device_num
  logical :: on_init_dev
  character(LEN_POLICY) :: policy
  policy = get_offload_policy() !!Get OMP_TARGET_OFFLOAD value
  if (OPENMP_VERSION < 201811) then
Warning: OMP_TARGET_OFFLOAD NOT supported by VER.

If OMP_TARGET_OFFLOAD is set, it will be ignored.

!Set target device number to an unavailable device to test offload policy.

device_num = omp_get_num_devices() + 1

!!Report OMP_TARGET_OFFLOAD value

select CASE (policy)
  case("MANDATORY")
    print*,"Policy: MANDATORY-Terminate if dev. not avail."
  case("DISABLED")
    print*,"Policy: DISABLED-(if supported) Only on Host."
  case("DEFAULT")
    print*,"Policy: DEFAULT On host if device not avail."
  case("NOTSET")
    print*," OMP_TARGET_OFFLOAD is not set."
  case DEFAULT
    print*," OMP_TARGET_OFFLOAD has unknown value."
    print*," UPPER CASE VALUE=",policy
end select

on_init_dev = .FALSE.

!! device# out of range--not supported

 !$omp target device(device_num) map(tofrom: on_init_dev)
  on_init_dev=omp_is_initial_device()

 !$omp end target

if (policy=="MANDATORY" .and. OPENMP_VERSION>=201811) then
  print*,"OMP ERROR: OpenMP 5.0 implementation ignored MANDATORY policy."
  print*," Termination should have occurred at target directive."
endif

print*, "Target executed on init dev (T|F): ", on_init_dev

end program policy_test
Document Revision History

A.1 Changes from 4.5.0 to 5.0.0

- Added the following examples for the 5.0 features:
  - Extended `teams` construct for host execution (Section 1.3 on page 8)
  - `loop` and `teams loop` constructs specify loop iterations that can execute concurrently (Section 1.15 on page 38)
  - Task data affinity is indicated by `affinity` clause of `task` construct (Section 2.2 on page 52)
  - Display thread affinity with `OMP_DISPLAY_AFFINITY` environment variable or `omp_display_affinity()` API routine (Section 2.3 on page 53)
  - `taskwait` with dependences (Section 3.3.6 on page 94)
  - `mutextinoutset` task dependences (Section 3.3.7 on page 101)
  - Multidependence Iterators (in `depend` clauses) (Section 3.3.8 on page 104)
  - Combined constructs: `parallel master taskloop` and `parallel master taskloop simd` (Section 3.7 on page 116)
  - Reverse Offload through `ancestor` modifier of `device` clause. (Section 4.1.6 on page 127)
  - Array Shaping with the `shape-operator` (Section 4.5 on page 140)
  - The `declare mapper` construct (Section 4.6 on page 142)
  - Acquire and Release Semantics Synchronization: Memory ordering clauses `acquire`, `release`, and `acq_rel` were added to flush and atomic constructs (Section 6.7 on page 240)
  - `depobj` construct provides dependence objects for subsequent use in `depend` clauses (Section 6.9 on page 252)
– reduction clause for task construct (Section 7.9.2 on page 303)
– reduction clause for taskloop construct (Section 7.9.3 on page 306)
– reduction clause for taskloop simd construct (Section 7.9.3 on page 306)
– Memory Allocators for making OpenMP memory requests with traits (Section 8.2 on page 341)
– requires directive specifies required features of implementation (Section 9.5 on page 360)
– declare variant directive - for function variants (Section 9.6 on page 362)
– metadirective directive - for directive variants (Section 9.7 on page 368)

• Included the following additional examples for the 4.x features:
  – more taskloop examples (Section 3.6 on page 112)
  – user-defined reduction (UDR) (Section 7.9.4 on page 313)

A.2 Changes from 4.0.2 to 4.5.0

• Reorganized into chapters of major topics
• Included file extensions in example labels to indicate source type
• Applied the explicit map(tofrom) for scalar variables in a number of examples to comply with the change of the default behavior for scalar variables from map(tofrom) to firstprivate in the 4.5 specification
• Added the following new examples:
  – linear clause in loop constructs (Section 1.9 on page 25)
  – priority clause for task construct (Section 3.2 on page 87)
  – taskloop construct (Section 3.6 on page 112)
  – directive-name modifier in multiple if clauses on a combined construct (Section 4.1.5 on page 124)
  – unstructured data mapping (Section 4.8 on page 162)
  – link clause for declare target directive (Section 4.10.5 on page 177)
  – asynchronous target execution with nowait clause (Section 4.12 on page 189)
  – device memory routines and device pointers (Section 4.13.4 on page 202)
A.3 Changes from 4.0.1 to 4.0.2

• Names of examples were changed from numbers to mnemonics
• Added SIMD examples (Section 5.1 on page 205)
• Applied miscellaneous fixes in several source codes
• Added the revision history

A.4 Changes from 4.0 to 4.0.1

Added the following new examples:
• the proc_bind clause (Section 2.1 on page 46)
• the taskgroup construct (Section 3.4 on page 107)

A.5 Changes from 3.1 to 4.0

• Beginning with OpenMP 4.0, examples were placed in a separate document from the specification document.
• Version 4.0 added the following new examples:
  – task dependences (Section 3.3 on page 89)
  – target construct (Section 4.1 on page 119)
- **target data** construct (Section 4.7 on page 149)
- **target update** construct (Section 4.9 on page 165)
- **declare target** construct (Section 4.10 on page 169)
- **teams** constructs (Section 4.11 on page 180)
  - asynchronous execution of a **target** region using tasks (Section 4.12.1 on page 189)
- array sections in device constructs (Section 4.4 on page 136)
- device runtime routines (Section 4.13 on page 198)
- Fortran ASSOCIATE construct (Section 7.13 on page 331)
- cancellation constructs (Section 9.4 on page 355)