AURORA ESP TRAINING WEBINAR

Argonne NATIONAL LABORATORY

OPENMP 5.0

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This material is mostly based on slides of Michael Klemm (OpenMP.org) and Tom Scogland (LLNL).

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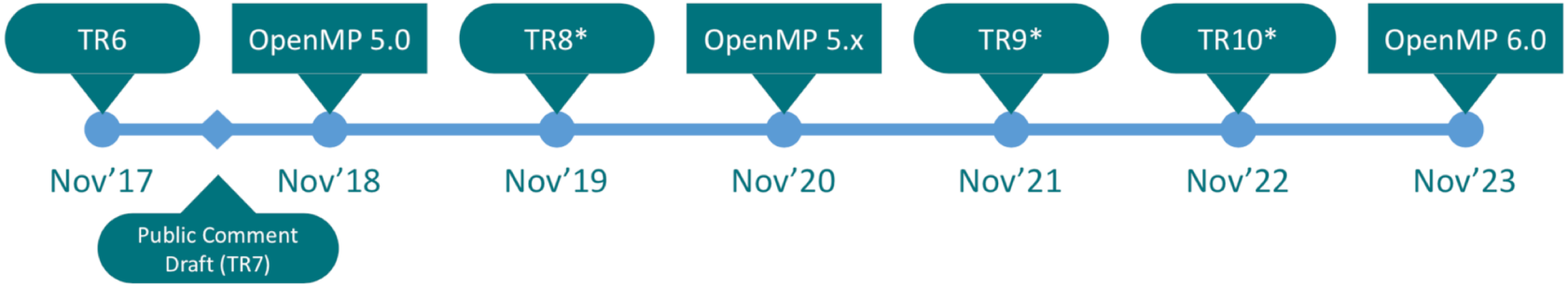
OPENMP ROADMAP

- OpenMP 4.5 Specifications were released in November 2015. (359 pages)
- OpenMP 5.0 Specifications were released in November 2018. (646 pages)
- OpenMP 5.x Specifications will be released in November 2020. (??? pages)



MAJOR NEW FEATURES IN OPENMP 5.0

- Significant extensions to improve usability and offload flexibility
  - OpenMP contexts, `metadirective` and `declare variant`
  - Addition of `requires` directive, including support for unified shared memory
  - Memory allocators and support for deep memory hierarchies
  - Descriptive `loop` construct
  - Release/acquire semantics added to memory model
- Host extensions that sometimes help
  - Ability to quiesce OpenMP threads
  - Support to print/inspect affinity state
  - Support for C/C++ array shaping
- First (OMPT) and third (OMPD) party tool support

MAJOR NEW FEATURES IN OPENMP 5.0

- Some significant extensions to existing functionality
  - Verbosity reducing changes such as implicit `declare target` directives
  - User defined mappers provide deep copy support for map clauses
  - Support for reverse offload
  - Support for task reductions , including on `taskloop` construct, task affinity, new dependence types, depend objects and detachable tasks
  - Allows `teams` construct outside of `target` (i.e., on host)
  - Supports collapse of non-rectangular loops
  - Scan extension of reductions
- Major advances for base language normative references
  - Completed support for Fortran 2003
  - Added Fortran 2008, C11, C++11, C++14 and C++17

AN OPENMP 4.5 EXAMPLE

- map clause is required to transfer data to target devices
- map cannot provide deep copy on a single construct
- No support for unified memory

```
typedef struct mypoints {
       int len;
       double *needed_data;
       double useless_data[500000];
} mypoints_t;
```

```
#pragma omp declare target
int do_something_with_p(mypoints_t &p_ref);
#pragma omp end declare target

mypoints_t * p = new_array_of_mypoints_t(N);

#pragma omp target enter data map(p[0:N])
for(int i=0; i<N; ++i){
       #pragma omp target enter data\
              map(p[i].needed_data[0:p[i].len])
}

#pragma omp target // can't express map here
{
do_something_with_p(*p);
}
```

“REQUIRES” CONSTRUCT

- Informs the compiler that the code **requires** an optional feature or setting to work
- OpenMP 5.0 adds the **requires** construct so that a program can declare that it assumes shared memory between devices

```
typedef struct mypoints {
       int len;
       double *needed_data;
       double useless_data[500000];
} mypoints_t;
```

```
#pragma omp declare target
int do_something_with_p(mypoints_t &p_ref);
#pragma omp end declare target

#pragma omp requires unified_shared_memory

mypoints_t * p = new_array_of_mypoints_t(N);

#pragma omp target // no map clauses needed
{
do_something_with_p(*p);
}
```

IMPLICIT “DECLARE TARGET”

- Heterogeneous programming requires compiler to generate versions of functions for the devices on which they will execute
- Generally requires the programmer to inform compiler of the devices on which the functions will execute
- OpenMP 5.0 requires the compiler to assume device versions exist and to generate them when it can “see” the definition and a use on the device

```
typedef struct mypoints {
       int len;
       double *needed_data;
       double useless_data[500000];
} mypoints_t;
```

```
// no declare target needed
int do_something_with_p(mypoints_t &p_ref);

#pragma omp requires unified_shared_memory

mypoints_t * p = new_array_of_mypoints_t(N);

#pragma omp target // no map clauses needed
{
do_something_with_p(*p);
}
```

DEEP COPY WITH "DECLARE MAPPER"

- Not all devices support shared memory so requiring it makes a program less portable
- Painstaking care was required to map complex data before 5.0
- OpenMP 5.0 adds deep copy support so that programmer can ensure that compiler correctly maps complex (pointer- based) data

```
typedef struct mypoints {
       int len;
       double *needed_data;
       double useless_data[500000];
} mypoints_t;
```

```
// no declare target needed
int do_something_with_p(mypoints_t &p_ref);

#pragma omp declare mapper(mypoints_t v)\
               map(v.len, v.needed_data, \
                   v.needed_data[0:v.len])

mypoints_t * p = new_array_of_mypoints_t(N);

#pragma omp target map(p[:N])
{
do_something_with_p(*p);
}
```

REVERSE OFFLOAD

When you need to go back to the host in a target region

```
#pragma omp requires reverse_offload

#pragma omp target map(inout: data[0:N])
{
       do_something_offloaded(data);
       #pragma omp target device(ancestor: 1)
       printf("back on the host right now\n");
       do_something_after_print_completes();
       #pragma omp target device(ancestor: 1)\
                           map(inout: data[0:N])
       MPI_Isend(... data ...);
       do_more_work_after_MPI();
}
```

```
#pragma omp requires reverse_offload
#pragma omp target teams parallel num_teams(T) num_threads(N)
{
       #pragma omp target device(ancestor: 1)
       printf("back on the host right now\n");
       // called N*T times on the host, probably serially!
}
```

METADIRECTIVE

- a directive that can specify multiple directive variants of which one may be conditionally selected to replace the `metadirective` based on the enclosing OpenMP context.

```
#pragma omp target map(to:v1,v2) map(from:v3)
#pragma omp metadirective \
        when( device={arch(nvptx)}: teams loop ) \
        default( parallel loop )
for (i = lb; i < ub; i++)
        v3[i] = v1[i] * v2[i];
```

```
!$omp begin metadirective &
        when( implementation={unified_shared_memory}: target ) &
        default( target map(mapper(vec_map),tofrom: vec) )
!$omp teams distribute simd
do i=1, vec%size()
        call vec(i)%work()
end do
!$omp end teams distribute simd
!$omp end metadirective
```

DECLARE VARIANT DIRECTIVE

- The declare variant directive declares a specialized variant of a base function and specifies the context in which that specialized variant is used.

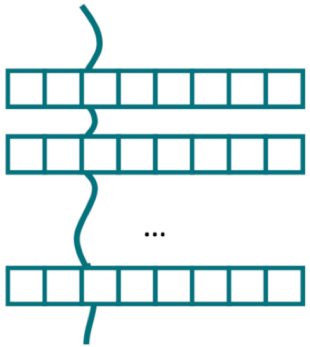
```
#pragma omp declare variant( int important_stuff(int x) ) \
             match( context={target,simd} device={arch(nvptx)} )
int important_stuff_nvidia(int x)
{ /* Specialized code for NVIDIA target */ }
#pragma omp declare variant(int important_stuff (int x)) \
             match( context={target, simd(simdlen(4))}, device={isa(avx2)} )
__m256i _mm256_epi32_important_stuff(__m256i x);
{ /* Specialized code for simd loop called on an AVX2 processor */ }


...
int y =important_stuff(x);
```

LOOP DIRECTIVE

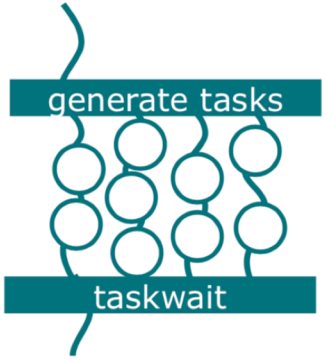
- Existing loop constructs are tightly bound to execution model:

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


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




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



- The loop construct is meant to let the OpenMP implementation pick the right parallelization scheme for a parallel loop.

LOOP CONSTRUCT

Simplified loop construct on OpenMP 5

```
int main(int argc, const char* argv[]) {
       float *x = (float*) malloc(n * sizeof(float));
       float *y = (float*) malloc(n * sizeof(float));
       // Define scalars n, a, b & initialize x, y

       #pragma omp target map(to:x[0:n]) map(tofrom:y)
       {
              #pragma omp teams distribute parallel for \
                            num_teams(num_blocks) thread_limit(bsize)
              #pragma omp loop
              for (int i = 0; i < n; ++i){
                     y[i] = a*x[i] + y[i];
              }
       }
}
```

OpenMP 4.5 Multi-level Device Parallelism

Simplifying Multi-level Device Parallelism

LOOP: REPRISING AN OPENACC EXAMPLE

```
while ( error > tol && iter < iter_max ) {
  error = 0.0;
  #pragma acc parallel loop reduction(max:error)
  for ( int j = 1; j < n - 1; j++) {
    #pragma acc loop reduction(max:error)
    for ( int i = 1; i < m - 1; i++ ) {
      Anew[j][i] = 0.25 * ( A[j][i + 1] + A[j][i - 1]
                  + A[j - 1][i] + A[j + 1][i]);
      error = fmax( error, fabs(Anew[j][i] - A[j][i]));
    }
  }
  #pragma acc parallel loop
  for ( int j = 1; j < n - 1; j++) {
    #pragma acc loop
    for ( int i = 1; i < m - 1; i++ ) {
      A[j][i] = Anew[j][i];
    }
  }
  if (iter++ % 100 == 0) printf("%5d, %0.6f\n", iter,error);
}
```

OpenMP 4.5

```
while (error > tol && iter < iter_max) {
  error = 0.0;
  #pragma omp target teams distribute reduction(max:error)
  for (int j = 1; j < n - 1; j++) {
    #pragma omp parallel for reduction(max:error)
    for (int i = 1; i < m - 1; i++) {
      Anew[j][i] = 0.25*(A[j][i+1]+A[j][i-1]
                  +A[j-1][i]+A[j+1][i]);
      error = fmax(error, fabs(Anew[j][i] - A[j][i]));
    }
  }
  #pragma omp target teams distribute
  for (int j = 1; j < n - 1; j++) {
    #pragma omp parallel for
    for (int i = 1; i < m - 1; i++) {
      A[j][i] = Anew[j][i];
    }
  }
  if (iter++ % 100 == 0) printf("%5d, %0.6f\n", iter, error);
}
```

LOOP: REPRISING AN OPENACC EXAMPLE

```
while ( error > tol && iter < iter_max ) {
  error = 0.0;
  #pragma acc parallel loop reduction(max:error)
  for ( int j = 1; j < n - 1; j++) {
    #pragma acc loop reduction(max:error)
    for ( int i = 1; i < m - 1; i++ ) {
      Anew[j][i] = 0.25 * ( A[j][i + 1] + A[j][i - 1]
                  + A[j - 1][i] + A[j + 1][i]);
      error = fmax( error, fabs(Anew[j][i] - A[j][i]));
    }
  }
  #pragma acc parallel loop
  for ( int j = 1; j < n - 1; j++) {
    #pragma acc loop
    for ( int i = 1; i < m - 1; i++ ) {
      A[j][i] = Anew[j][i];
    }
  }
  if (iter++ % 100 == 0) printf("%5d, %0.6f\n", iter,error);
}
```

OpenMP 5.0

```
while (error > tol && iter < iter_max) {
  error = 0.0;
  #pragma omp target teams
  #pragma omp loop reduction(max : error)
  for (int j = 1; j < n - 1; j++) {
    #pragma omp loop reduction(max : error)
    for (int i = 1; i < m - 1; i++) {
      Anew[j][i] = 0.25*(A[j][i+1]+A[j][i-1]
                  +A[j-1][i]+A[j+1][i]);
      error = fmax(error, fabs(Anew[j][i] - A[j][i]));
    }
  }
  #pragma omp target teams
  #pragma omp loop
  for (int j = 1; j < n - 1; j++) {
    #pragma omp loop
    for (int i = 1; i < m - 1; i++) {
      A[j][i] = Anew[j][i];
    }
  }
  if (iter++ % 100 == 0) printf("%5d, %0.6f\n", iter, error);
}
```

MEMORY ALLOCATORS

- New clause on all constructs with data sharing clauses:
  - `allocate( [allocator:] list )`
- Allocation:
  - `omp_alloc(size_t size, omp_allocator_t *allocator)`
- Deallocation:
  - `omp_free(void *ptr, const omp_allocator_t *allocator)`
  - `allocator` argument is optional
- `allocate` directive
  - Standalone directive for allocation, or declaration of allocation stmt.

EXAMPLE: MEMORY ALLOCATORS

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

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

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

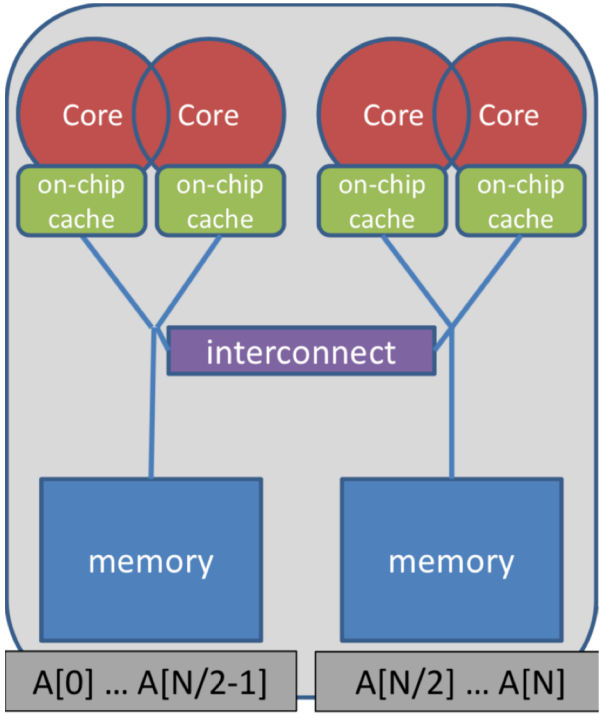
EXAMPLE: TEAM-LOCAL MEMORY

```
// CUDA
__global__ void staticReverse(int *d, int n) {
        __shared__ int s[64];
        int t = threadIdx.x;
        int tr = n-t-1;
        s[t] = d[t];
        __syncthreads();
        d[t] = s[tr];
}
// OpenMP 5
#pragma omp target parallel private(s)
{
        int s[64];
        #pragma omp allocate(s) allocator(omp_pteam_mem_alloc)
        int t = omp_get_thread_num();
        int tr = n-t-1;
        s[t] = d[t];
        #pragma omp barrier
        d[t] = s[tr];
}
```

PARTITIONING MEMORY

Optimized memory access by partitioning on OpenMP 5

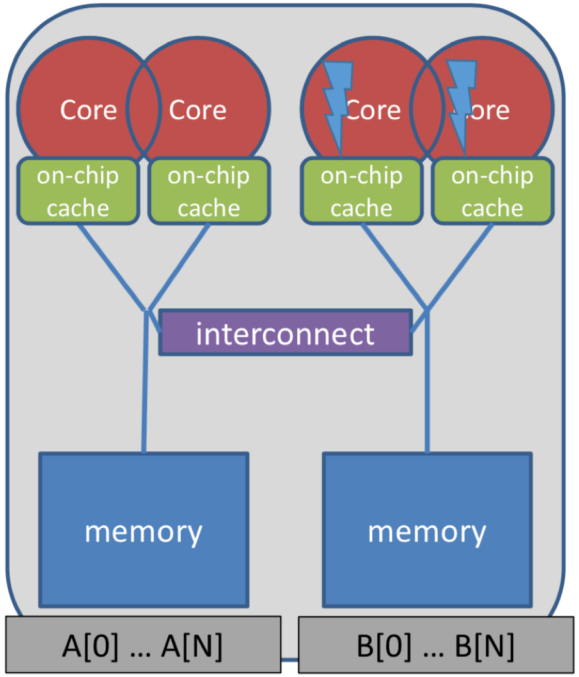
```
void allocator_example() {
        double *array;

        omp_allocator_t *allocator;
        omp_alloctrait_t traits[] = {
                {OMP_ATK_PARTITION, OMP_ATV_BLOCKED}
        };
        int ntraits = sizeof(traits) / sizeof(*traits);
        allocator = omp_init_allocator(omp_default_mem_space, ntraits, traits);

        array = omp_alloc(sizeof(*array) * N, allocator);
        #pragma omp parallel for proc_bind(spread)
        for (int i = 0; i < N; ++i) {
                important_computation(&array[i]);
        }

        omp_free(array);
}
```



TASK-TO-DATA AFFINITY

OpenMP 5 supports affinity hints for OpenMP tasks

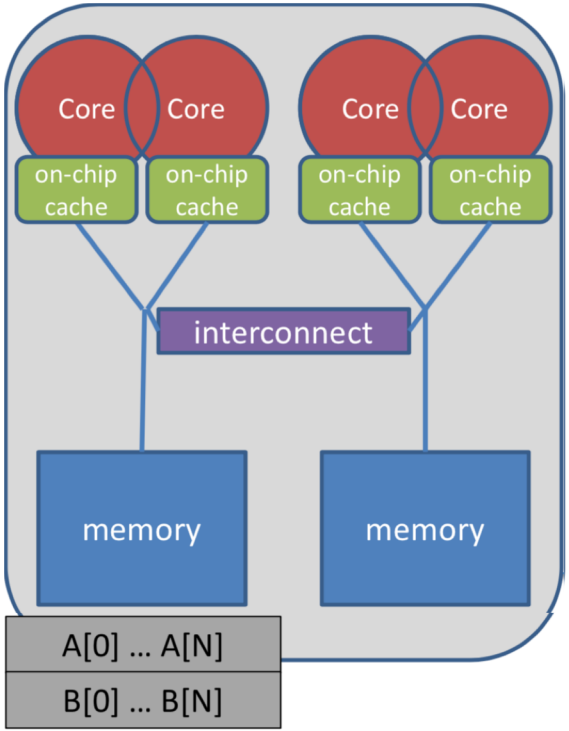
```
void task_affinity() {
      double* B;
      #pragma omp task shared(B)
      {
            B = init_B_and_important_computation(A);
      }
      #pragma omp task firstprivate(B)
      {
            important_computation_too(B);
      }
      #pragma omp taskwait
}
```



TASK-TO-DATA AFFINITY

OpenMP 5 supports affinity hints for OpenMP tasks

```
void task_affinity() {
      double* B;
      #pragma omp task shared(B) affinity(A[0:N])
      {
            B = init_B_and_important_computation(A);
      }
      #pragma omp task firstprivate(B) affinity(B[0:N])
      {
            important_computation_too(B);
      }
      #pragma omp taskwait
}
```



TASK REDUCTIONS

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

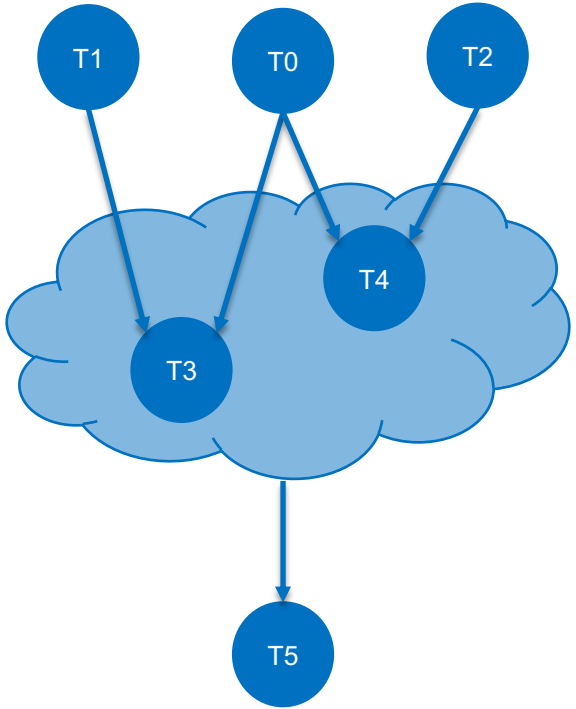
```
int res = 0;
node_t* node = NULL;
...
#pragma omp parallel
{
  #pragma omp single
  {
    #pragma omp taskgroup task_reduction(+: res)
    {
      while (node) {
        #pragma omp task in_reduction(+: res) \
                         firstprivate(node)
        {
          res += node->value;
  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

`depend(mutexinoutset:var)`
only one task using *var* can run at a time

NEW TASK DEPENDENCIES

OpenMP 5 provides new task dependencies for better performance

```
int x = 0, y = 0, res = 0;
#pragma omp parallel
#pragma omp single
{
  #pragma omp task depend(out: res) //T0
  res = 0;
  #pragma omp task depend(out: x) //T1
  long_computation(x);
  #pragma omp task depend(out: y) //T2
  short_computation(y);
  #pragma omp task depend(in: x) depend(mutexinoutset: res) //T3 – OpenMP 5
  res += x;
  #pragma omp task depend(in: y) depend(mutexinoutset: res) //T4 – OpenMP 5
  res += y;
  #pragma omp task depend(in: res) //T5
  std::cout << res << std::endl;
}
```



ASYNCHRONOUS API INTERACTION

- Some APIs are based on asynchronous operations
  - MPI asynchronous send and receive
  - Asynchronous I/O
  - CUDA and OpenCL stream-based offloading
  - In general: any other API/model that executes asynchronously with OpenMP (tasks)
- Example: CUDA memory transfers

```
do_something();
cudaMemcpyAsync(dst, src, nbytes, cudaMemcpyDeviceToHost, stream);
do_something_else();
cudaStreamSynchronize(stream);
do_other_important_stuff(dst);
```

- Programmers need a mechanism to marry asynchronous APIs with the parallel task model of OpenMP
  - How to synchronize completions events with task execution?

ASYNCHRONOUS API INTERACTION

Use OpenMP Tasks

```
void cuda_example() {
        #pragma omp task // task A
        {
                do_something();
                cudaMemcpyAsync(dst, src, nbytes, cudaMemcpyDeviceToHost, stream);
        }
        #pragma omp task // task B
        {
                do_something_else();
        }
        #pragma omp task // task C
        {
                cudaStreamSynchronize(stream);
                do_other_important_stuff(dst);
        }
}
```

Race condition between the tasks A & C, task C may start execution before task A enqueues memory transfer.

ASYNCHRONOUS API INTERACTION

Detaching Tasks

1. Task detaches
2. `taskwait` contruct cannot complete
3. Signal event for completion
4. Task completes and `taskwait` can continue

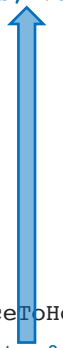
```
omp_event_t *event;
void detach_example() {
  #pragma omp task detach(event)
  {
    important_code();
  } 1
  #pragma omp taskwait 2 4
}
```

```
omp_fulfill_event(event); 3     // some other thread/task
```

ASYNCHRONOUS API INTERACTION

Detachable Tasks and Asynchronous APIs

```
void CUDART_CB callback(cudaStream_t stream, cudaError_t status, void *cb_dat) {
  3  omp_fulfill_event((omp_event_t *) cb_data);
}
void cuda_example() {
      omp_event_t *cuda_event;
      #pragma omp task detach(cuda_event)      // task A
      {
            do_something();
            cudaMemcpyAsync(dst, src, nbytes, cudaMemcpyDeviceToHost, stream);
            cudaStreamAddCallback(stream, callback, cuda_event, 0);
      } 1
      #pragma omp task                         // task B
            do_something_else();
      #pragma omp taskwait 2 4
      #pragma omp task                         // task C
      {
            do_other_important_stuff(dst);
}     }
```



1. Task A detaches
2. `taskwait` does not continue
3. When memory transfer completes, callback is invoked to signal the event for task completion
4. `taskwait` continues, task C executes

ASYNCHRONOUS API INTERACTION

Detachable Tasks and Asynchronous APIs

```
void CUDART_CB callback(cudaStream_t stream, cudaError_t status, void *cb_dat) {
   2  omp_fulfill_event((omp_event_t *) cb_data);
}
void cuda_example() {
       omp_event_t *cuda_event;
       #pragma omp task depend(out:dst) detach(cuda_event)   // task A
       {
              do_something();
              cudaMemcpyAsync(dst, src, nbytes, cudaMemcpyDeviceToHost, stream);
              cudaStreamAddCallback(stream, callback, cuda_event, 0);
       } 1
       #pragma omp task                          // task B
              do_something_else();
       #pragma omp task depend (in: dst)     3 // task C
       {
              do_other_important_stuff(dst);
}      }
```

1. Task A detaches and task C will not execute because of its unfulfilled dependency on A
2. The Memory transfer completes and the callback is invoked to signal the event for task completion
3. Task A completes and C's dependency is fulfilled

THANK YOU!