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Barcelona Supercomputing Center
Centro Nacional de Supercomputación

Tutorial OmpSs: single node programming

PATC course
Parallel Programming Workshop

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Tutorial OmpSs

Agenda

10:00 – 11:00	Tasking in OpenMP 3.0 and 4.0	60 min
11:00 – 11:15	Coffee break	15 min
11:15 – 12:15	Introduction to OmpSs programming model • Introduction to StarSs • OmpSs syntax • Simple examples • Development methodology and infrastructure	60 min
12:15– 12:45	Practical: heat equation example and divide-and-conquer (part I)	30 min
12:45 – 14:00	Lunch	75 min
14:00 – 15:00	Practical: heat equation example and divide-and-conquer (part I)	90 min
15:00 – 15:30	Programming using a hybrid MPI/OmpSs approach	15 min
15:30 – 17:00	Practical: heat equation example and matrix-multiply	105 min

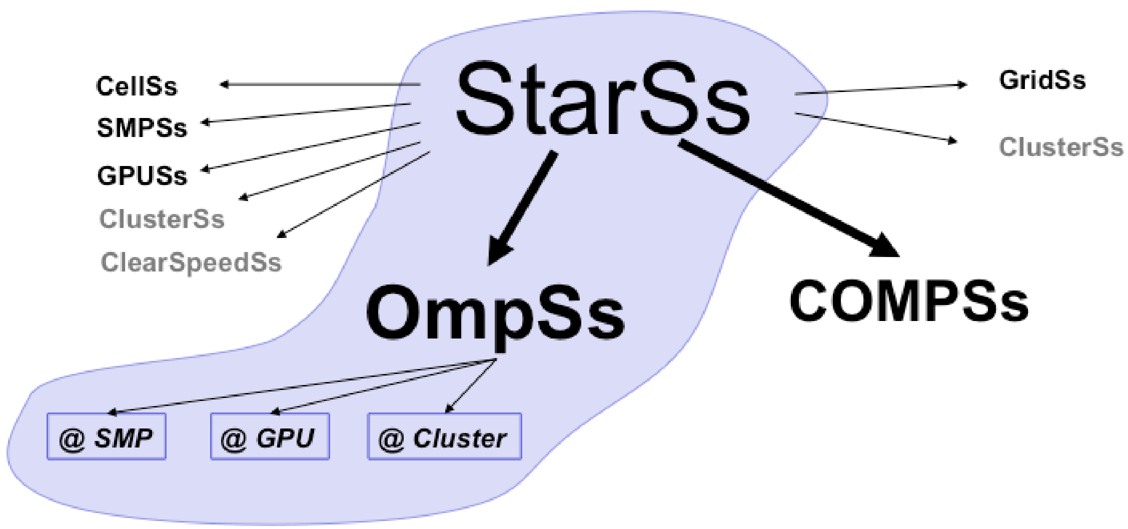
Outline

- Introduction to StarSs
- OmpSs overview
- OmpSs syntax
- OmpSs environment
- Hands-on

- Contact: pm-tools@bsc.es
- Source code available from http://pm.bsc.es/ompss/

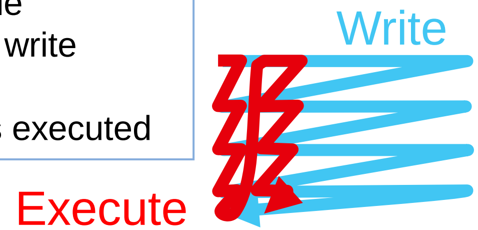
StarSs principles

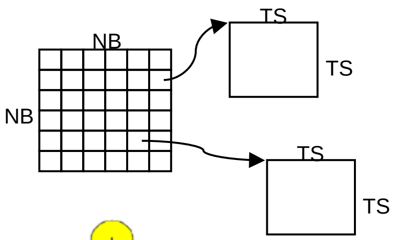
- StarSs: a family of **task based** programming models
  - Basic concept: **write sequential on a flat single address space** + **directionality annotations**
    - Order **IS** defined
    - Dependence and data access related **information** (NOT specification) in a single mechanism
    - Think global, specify local
    - Intelligent runtime

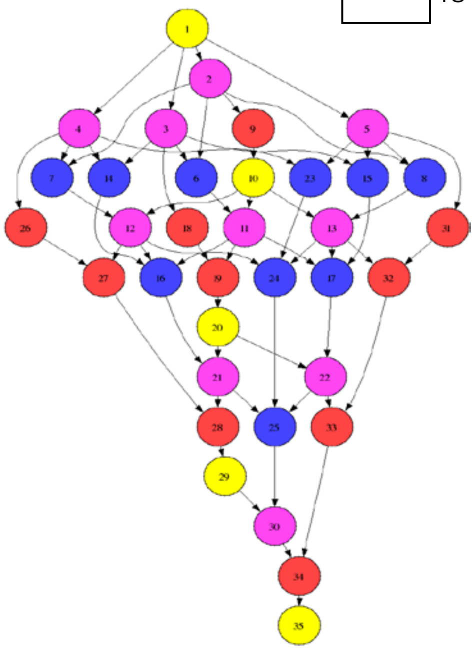


StarSs: data-flow execution of sequential programs

Decouple
how we write
form
how it is executed



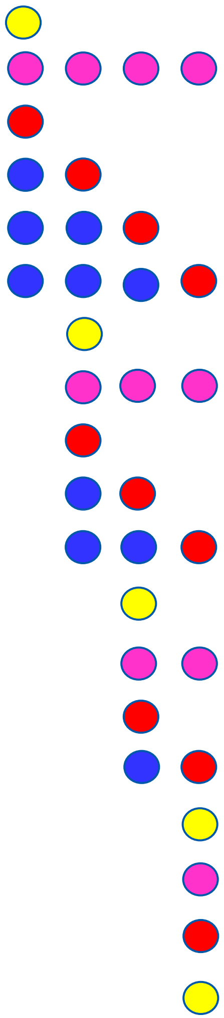




```
void Cholesky( float *A ) {
   int i, j, k;
   for (k=0; k<NT; k++) {
      spotrf (A[k*NT+k]) ;
      for (i=k+1; i<NT; i++)
         strsm (A[k*NT+k], A[k*NT+i]);
      // update trailing submatrix
      for (i=k+1; i<NT; i++) {
         for (j=k+1; j<i; j++)
            sgemm( A[k*NT+i], A[k*NT+j], A[j*NT+i]);
         ssyrk (A[k*NT+i], A[i*NT+i]);
   }
}
```

```
#pragma omp task inout ([TS][TS]A)
void spotrf (float *A);
#pragma omp task in ([TS][TS]T) inout ([TS][TS]B)
void strsm (float *T, float *B);
#pragma omp task in ([TS][TS]A,[TS][TS]B) inout ([TS][TS]C )
void sgemm (float *A, float *B, float *C);
#pragma omp task in ([TS][TS]A) inout ([TS][TS]C)
void ssyrk (float *A, float *C);
```

StarSs vs OpenMP 3.1



```
void Cholesky( float *A ) {
   int i, j, k;
   for (k=0; k<NT; k++) {
      spotrf (A[k*NT+k]);
      #pragma omp parallel for
      for (i=k+1; i<NT; i++)
         strsm (A[k*NT+k], A[k*NT+i]);
      for (i=k+1; i<NT; i++) {
         #pragma omp parallel for
         for (j=k+1; j<i; j++)
            sgemm( A[k
         ssyrk (A[k*NT+
   }
}
```

```
void Cholesky( float *A ) {
   int i, j, k;
   for (k=0; k<NT; k++) {
      spotrf (A[k*NT+k]);
      #pragma omp parallel for
      for (i=k+1; i<NT; i++)
         strsm (A[k*NT+k], A[k*NT+i]);
      for (i=k+1; i<NT; i++) {
         for (j=k+1; j<i; j++) {
            #pragma omp task
            sgemm( A[k*NT+i], A[k*NT+j], A[j*NT+i]);
         }
         #pragma omp task
         ssyrk (A[k*NT+i], A[i*NT+i]);
         #pragma omp taskwait
      }
}
```

```
void Cholesky( float *A ) {
   int i, j, k;
   for (k=0; k<NT; k++) {
      spotrf (A[k*NT+k]);
      #pragma omp parallel for
      for (i=k+1; i<NT; i++)
         strsm (A[k*NT+k], A[k*NT+i]);
      // update trailing submatrix
      for (i=k+1; i<NT; i++) {
         #pragma omp task
         {
         #pragma omp parallel for
         for (j=k+1; j<i; j++)
            sgemm( A[k*NT+i], A[k*NT+j], A[j*NT+i]);
          }
         #pragma omp task
         ssyrk (A[k*NT+i], A[i*NT+i]);
         }
         #pragma omp taskwait
   }
}
```

OmpSs syntax

- OmpSs execution model and memory model
- Inlined pragmas
- Outlined pragmas
- Array sections
- Concurrent
- Commutative
- Nesting
- Sentinels

OmpSs = OpenMP + StarSs extensions

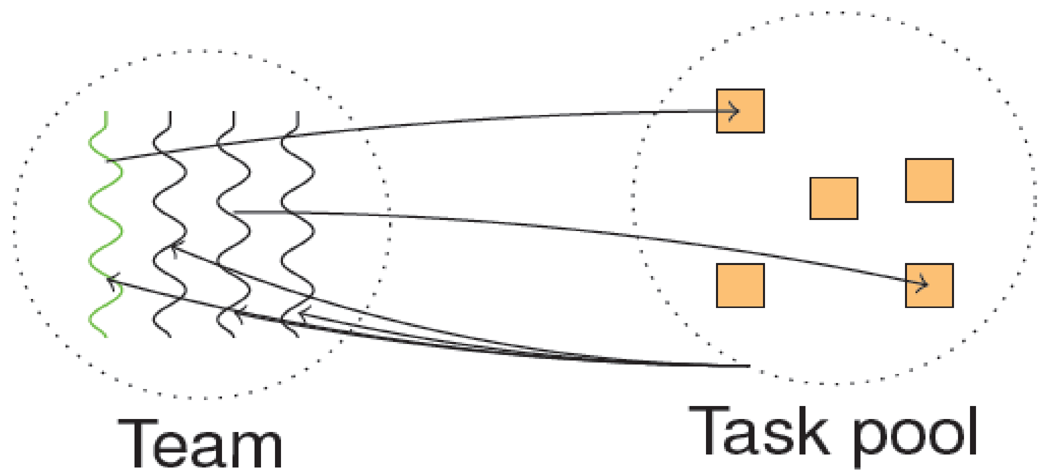
- OmpSs is based on OpenMP + StarSs with some differences:
  - Different execution model
  - Extended memory model
  - Extensions for point-to-point inter-task synchronizations
    - data dependencies
  - Extensions for heterogeneity
  - Other minor extensions

Main Program

- Sequential control flow
  - Defines a single address space
  - Executes sequential code that
    - Can spawn/instantiate tasks than will be executed sometime in the future
    - Can stall/wait for tasks
- Tasks annotated with directionality clauses
  - Input, output, inout
  - Used to build dependences between tasks and for main to wait for data to be produced
  - Can be used for memory management functionalities (replication, locality, movement,…)

Execution Model

- Thread-pool model
  - OpenMP parallel not required
- All threads created on startup
  - One of them starts executing main
- All get work from a task pool
  - And can generate new work



Memory Model

- From the point of view of the programmer a single naming space exists

- From the point of view of the runtime and target platform, different possible scenarios
  - Pure SMP:
    - Single address space
  - Distributed/heterogeneous (cluster, gpus, ...):
    - Multiple address spaces exist
      - Versions of same data may exist in multiple of these
    - Data consistency ensured by the implementation

OmpSs: Directives

Task implementation for a GPU device
The compiler parses CUDA/OpenCL kernel invocation syntax

Provides configuration for CUDA/OpenCL kernel

```
#pragma omp target device ({ smp | cuda | opencl })     \
                [ndrange (…)]\
                [ implements ( function_name )]           \
                { copy_deps | [ copy_in ( array_spec ,...)] [ copy_out (...)] [ copy_inout (...)] }
```

Support for multiple implementations of a task

To compute dependences

Ask the runtime to ensure data is accessible in the address space of the device

```
#pragma omp task [ in (...)] [ out (...)] [ inout (...)] [ concurrent (…)] [ commutative (…)] [priority(…)]\
 [label(tasklabel)]
 { function or code block }
```

To relax dependence order allowing concurrent execution of tasks

To relax dependence order allowing change of order of execution of commutative tasks

To set priorities to tasks

```
#pragma omp taskwait [on (...)] [noflush]
```

Wait for sons or specific data availability

Relax consistency to main program

OpenMP: Directives

OpenMP dependence specification

#pragma omp task [depend (in: …)] [depend(out:…)] [depend(inout:...)]

{ function or code block }

Direct contribution of BSC at OpenMP promoting dependences and heterogeneity clauses

Main element: tasks

- Task
  - Computation unit. Amount of work (granularity) may vary in a wide range (μsecs to msecs or even seconds), may depend on input arguments,…
  - Once started can execute to completion independent of other tasks
  - Can be declared inlined or outlined
- States:
  - **Instantiated**: when task is created. Dependences are computed at the moment of instantiation. At that point in time a task may or may not be ready for execution
  - **Ready**: When all its input dependences are satisfied, typically as a result of the completion of other tasks
  - **Active**: the task has been scheduled to a processing element. Will take a finite amount of time to execute.
  - **Completed**: the task terminates, its state transformations are guaranteed to be globally visible and frees its output dependences to other tasks.

Inlined and outlined tasks

- **Pragmas inlined**
  - Pragma applies to immediately following statement
  - The compiler outlines the statement (as in OpenMP)

- Pragmas outlined:
  - Attached to function declaration
    - All function invocations become a task
    - The programmer gives a name, this enables later to provide several implementations

Main element: inlined tasks

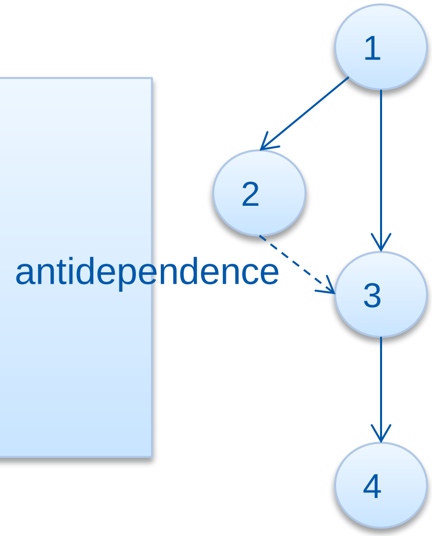
- Pragmas inlined
  - Applies to a statement
  - The compiler outlines the statement (as in OpenMP)
- Pragmas parallel and single not required

```
int   main   (    )
{
   int X[100];

   #pragma  omp   task
   for (int i =0; i< 100; i++) X[i]=i;
#pragma omp taskwait

   ...
}
```

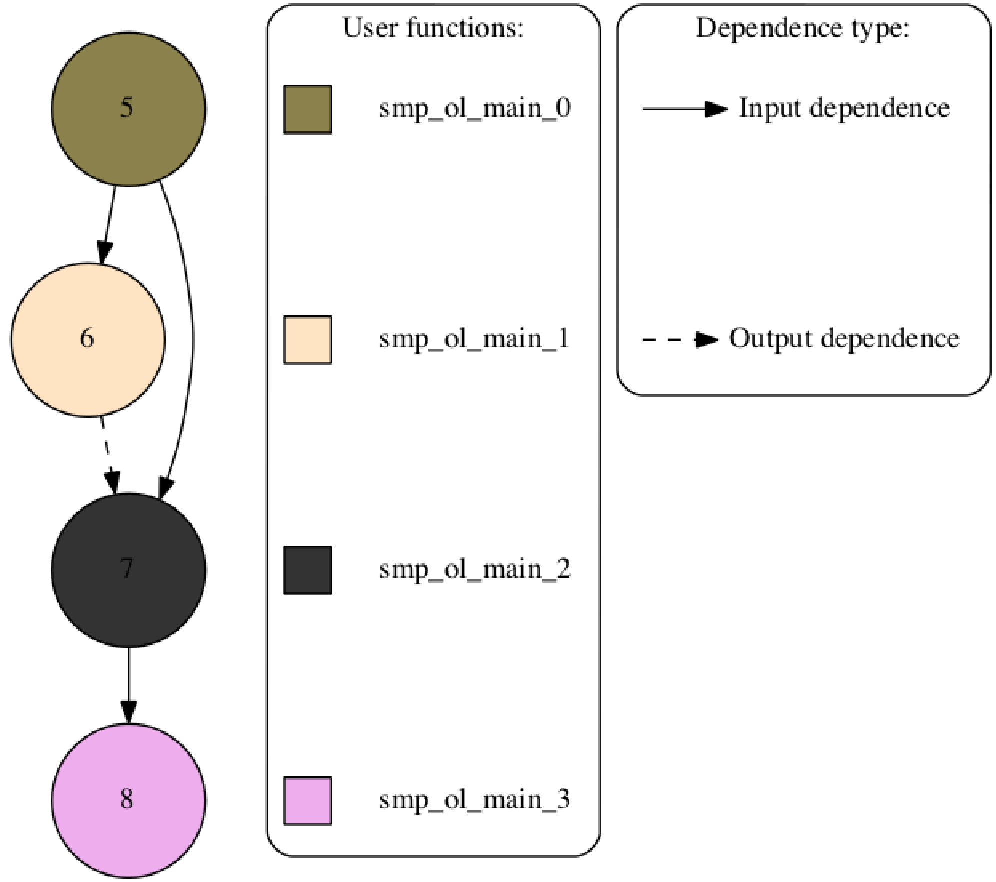
Defining dependences

- Clauses that express data direction:
  - in
  - out
  - inout
- Dependences computed at runtime taking into account these clauses

```
#pragma omp task out( x )
x = 5;                       //1
#pragma omp task in( x )
printf("%d\n" , x ) ;        //2
#pragma omp task inout( x )
x++;                         //3
#pragma omp task in( x )
printf ("%d\n" , x ) ;       //4
```



Graph automatically generated

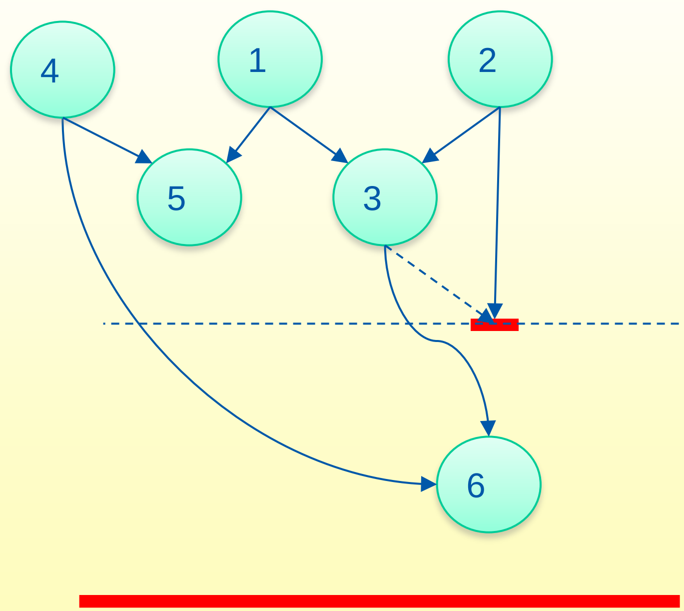


Partial control flow synchronization

#pragma taskwait on (expression)

- Expressions allowed are the same as for the directionality clauses
- Stalls the encountering control flow until the data is available

```
double A[N][N], B[N][N], C[N][N], D[N][N], E[N][N],
       F[N][N], G[N][N], H[N][N], I[N][N], J[N][N];

main() {
  #pragma omp task in(A, B) inout(C)
  dgemm(A,B,C);    //1
  #pragma omp task in(D, E) inout(F)
  dgemm(D,E,F);    //2
  #pragma omp task in(C, F) inout(G)
  dgemm(C,F,G);    //3
  #pragma omp task in(A, D) inout(H)
  dgemm(A,D,H);    //4
  #pragma omp task in(C, H) inout(I)
  dgemm(C,H,I);    //5

  #pragma omp taskwait on (F)
  prinft ("result F = %f\n", F[0][0]);

  #pragma omp task in(C, H) inout(I)
  dgemm(H,G,J);    //6

  #pragma omp taskwait
  prinft ("result J = %f\n", J[0][0]);
}
```



Main element: outlined tasks

- Pragmas outlined: attached to function definition
  - All function invocations become a task
  - The programmer gives a name, this enables later to provide several implementations

```
#pragma omp task
void   foo (int Y[size], int size) {
int j;

   for (j=0; j < size; j++) Y[j]= j;
}

int main()
{
int X[100];

foo (X, 100) ;
#pragma omp taskwait
...
}
```

Main element: outlined tasks

- Pragmas attached to function definition
  - The semantic is capture value
    - For scalars is equivalent to firstprivate
    - For pointers, the address is captured

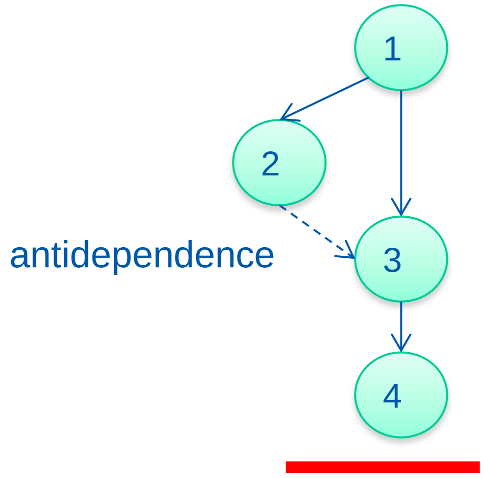
```
#pragma  omp task
void   foo (int Y[size], int size) {
int j;

   for (j=0; j < size; j++) Y[j]= j;
}

int main()
{
int X[100];

foo (X, 100) ;
#pragma omp taskwait
...
}
```

Defining dependences for outlined tasks

- Clauses that express data direction:
  - Input, output, inout
  - The argument is an lvalue expression based on data visible at the point of declaration (global variables and arguments)
  - The object pointed by the lvalue expression will be used to compute dependences.

```
#pragma omp task out(*px)
void set (int *px, int v) {*px = v;}

#pragma omp task inout(*px)
void incr (int *px) {(*px)++;}

#pragma omp task in(x)
void do_print (int x) {
   printf("from do_print %d\n" , x );
}
```

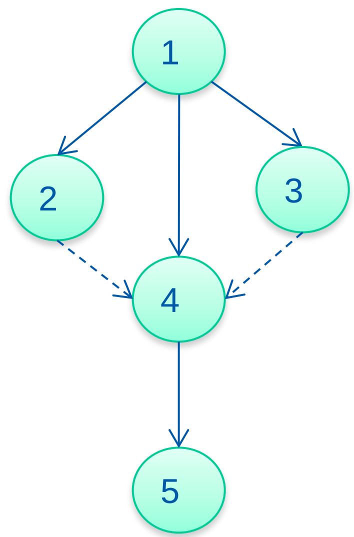
```
set(&x,5);      //1
do_print(x);   //2
incr(&x);       //3
do_print(x);   //4
#pragma omp taskwait
```



Mixing inlined and outlined tasks

```
#pragma omp task input (x)
void do_print (int x) {
   printf(”from do_print %d\n" , x ) ;
}

int main()
{
int x;

   x=3;

   #pragma omp task out( x )
   x = 5;                           //1
   #pragma omp task in( x )
   printf(”from main %d\n" , x );   //2
   do_print(x);                     //3
   #pragma omp task inout( x )
   x++;                             //4
   #pragma omp task in( x )
   printf (”from main %d\n" , x ); //5
}
```

non-taskified: executed sequentially

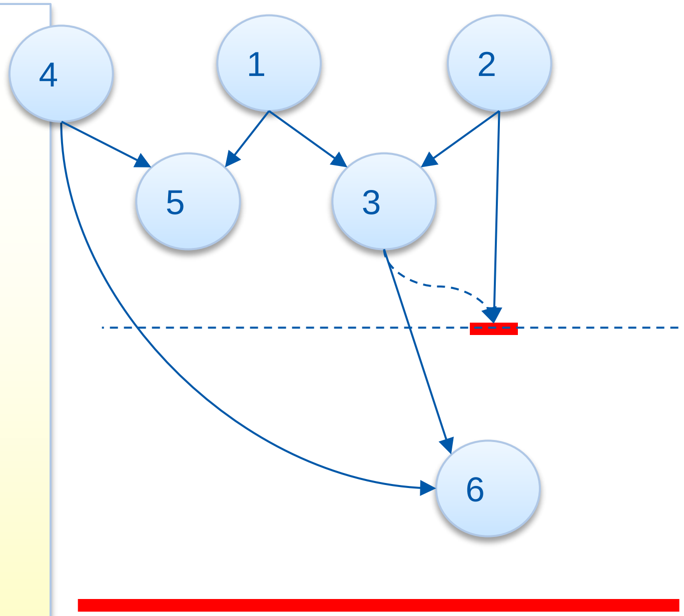


Partial control flow synchronization

#pragma taskwait on (expression)

- Expressions allowed are the same as for the dependency clauses
- Blocks the encountering task until the data is available

```
#pragma omp task in([N][N]A, [N][N]B) inout([N][N]C)
void dgemm(float *A, float *B, float *C);
main() {
(
  ...
dgemm(A,B,C); //1
dgemm(D,E,F); //2
dgemm(C,F,G); //3
dgemm(A,D,H); //4
dgemm(C,H,I); //5

#pragma omp taskwait on (F)
prinft ("result F = %f\n", F[0][0]);


dgemm(H,G,C); //6


#pragma omp taskwait
prinft ("result C = %f\n", C[0][0]);
}
```



Task directive: array regions

- Indicating as input/output/inout subregions of a larger structure:

  in (A[i])

  → the input argument is element *i* of A

- Indicating an array section:

  In ([BS]A)

  → the input argument is a block of size BS from address A

  in (A[i;BS])

  → the input argument is a block of size BS from address &A[i]

  → the lower bound can be omitted (default is 0)

  → the upper bound can be omitted if size is known (default is N-1, being N the size)

  In (A[i:j])

  → the input argument is a block from element A[i] to element A[j] (included)

  → A[i:i+BS-1] equivalent to A[i; BS]

Examples dependency clauses, array sections

```
int a[N];
#pragma omp task in(a)
```

=

```
int a[N];
#pragma omp task in(a[0:N-1])
//whole array used to compute dependences
```

=

```
int a[N];
#pragma omp task in([N]a)
//whole array used to compute dependences
```

=

```
int a[N];
#pragma omp task in(a[0;N])
//whole array used to compute dependences
```

```
int a[N];
#pragma omp task in(a[0:3])
//first 4 elements of the array used to compute dependences
```

=

```
int a[N];
#pragma omp task in(a[0;4])
//first 4 elements of the array used to compute dependences
```

Examples dependency clauses, array sections (multidimensions)

```
int a[N][M];
#pragma omp task in(a[0:N-1][0:M-1])
//whole matrix used to compute dependences
```

=

```
int a[N][M];
#pragma omp task in(a[0;N][0;M])
//whole matrix used to compute dependences
```

```
int a[N][M];
#pragma omp task in(a[2:3][3:4])
// 2 x 2 subblock of a at a[2][3]
```

=

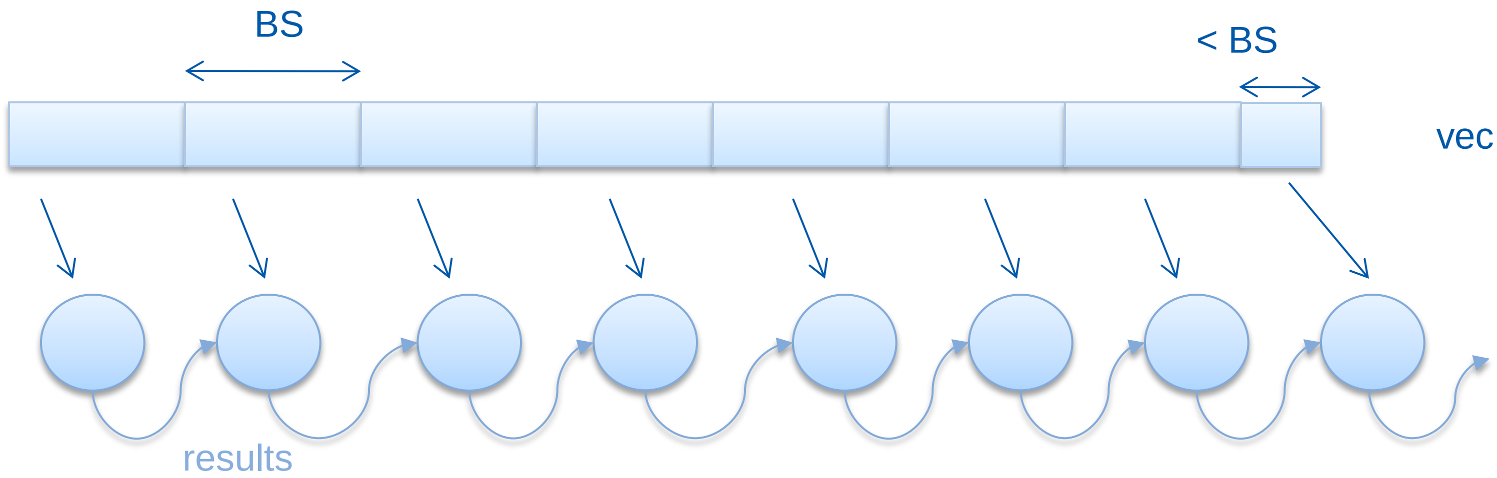
```
int a[N][M];
#pragma omp task in(a[2;2][3;2])
// 2 x 2 subblock of a at a[2][3]
```

```
int a[N][M];
#pragma omp task in(a[2:3][0:M-1])
//rows 2 and 3
```

=

```
int a[N][M];
#pragma omp task in(a[2;2][0;M])
//rows 2 and 3
```

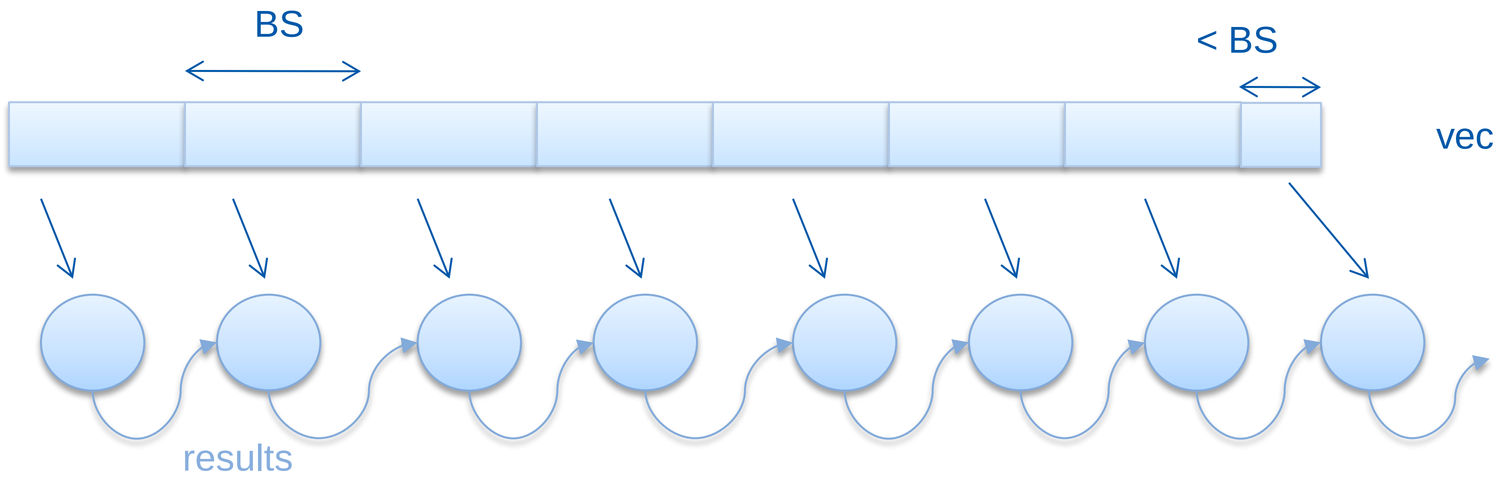
Examples dependency clauses, array sections




```
#pragma omp task in([n]vec) inout (*results)
void sum_task ( int *vec , int n , int  *results);

void main(){
int actual_size;
   for (int j=0; j<N; j+=BS){
    actual_size = (N- j> BS ? BS: N-j);
    sum_task (&vec[j], actual_size, &total);
   }
}
```

dynamic size of argument

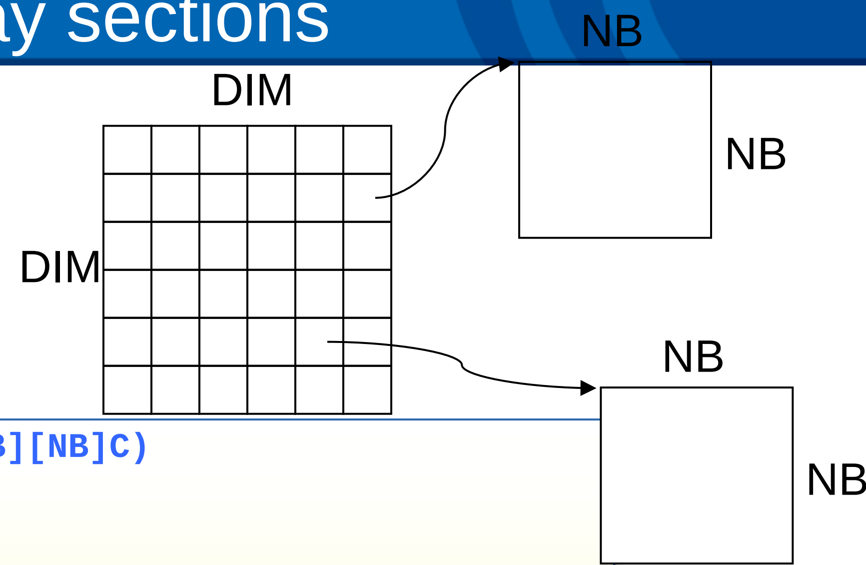
Examples dependency clauses, array sections




```
for (int j=0; j<N; j+=BS){
   actual_size = (N- j> BS ? BS: N-j);
#pragma omp task in (vec[j;actual_size]) inout(results) firtprivate(actual_size,j)
for (int count = 0; count < actual_size; count++)
   results += vec [j+count] ;
}
```

dynamic size of argument

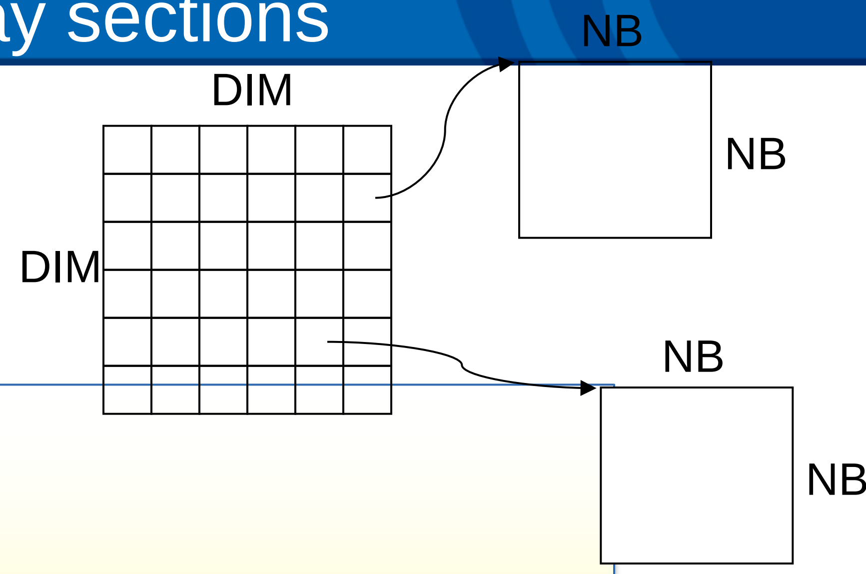
Examples dependency clauses, array sections




```
#pragma omp task input([NB][NB]A, [NB][NB]B) inout([NB][NB]C)
void matmul(double *A, double *B, double *C,
unsigned long NB)
{
  int i, j, k;

  for (i = 0; i < NB; i++)
   for (j = 0; j < NB; j++)
    for (k = 0; k < NB; k++)
       C[i][j] +=A[i*NB+k]*B[k*NB+j];
}
```

```
void compute(unsigned long NB, unsigned long DIM,
double *A[DIM][DIM], double *B[DIM][DIM], double *C[DIM][DIM])
{
  unsigned i, j, k;

  for (i = 0; i < DIM; i++)
    for (j = 0; j < DIM; j++)
      for (k = 0; k < DIM; k++)
        matmul (A[i][k], B[k][j], C[i][j], NB);
}
```

Examples dependency clauses, array sections




```
void matmul(double *A, double *B, double *C,
unsigned long NB)
{
  int i, j, k;

  for (i = 0; i < NB; i++)
   for (j = 0; j < NB; j++)
    for (k = 0; k < NB; k++)
       C[i][j];+=A[i*NB+k]*B[k*NB+j];
}
```

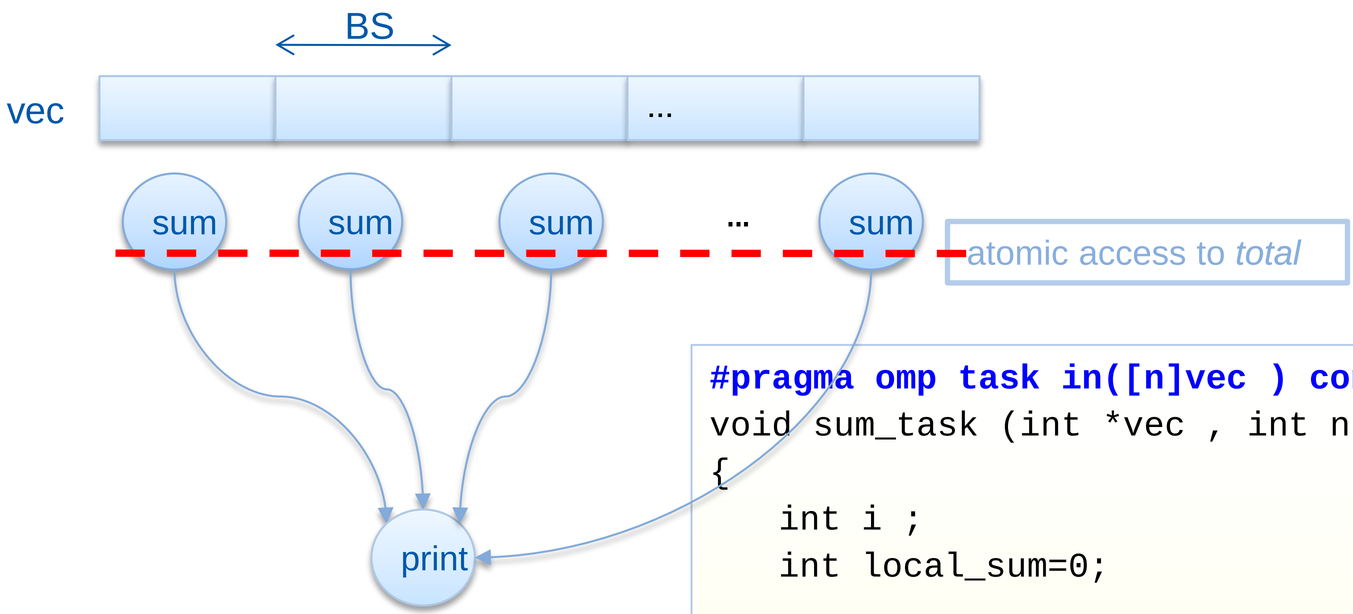
```
void compute(unsigned long NB, unsigned long DIM,
double *A[DIM][DIM], double *B[DIM][DIM], double *C[DIM][DIM])
{
  unsigned i, j, k;

  for (i = 0; i < DIM; i++)
    for (j = 0; j < DIM; j++)
      for (k = 0; k < DIM; k++)
#pragma omp task input([NB][NB]A[i][k], [NB][NB]B[k][j]) inout(NB][NB]C[i][j])\
firstprivate (i, j, k)
        matmul (A[i][k], B[k][j], C[i][j], NB);
}
```

Concurrent

`#pragma omp task in ( ...) out (...) concurrent (var)`

- Less-restrictive than regular data dependence
  - → Concurrent tasks can run in parallel
  - Enables the scheduler to change the order of execution of the tasks, or even execute them concurrently
    - → alternatively the tasks would be executed sequentially due to the inout accesses to the variable in the concurrent clause
  - Dependences with other tasks will be handled normally
    - → Any access input or inout to *var* will imply to wait for all previous *concurrent* tasks
- The task may require additional synchronization
  - i.e., atomic accesses
  - programmer responsibility: with pragma atomic, mutex, ...

Concurrent



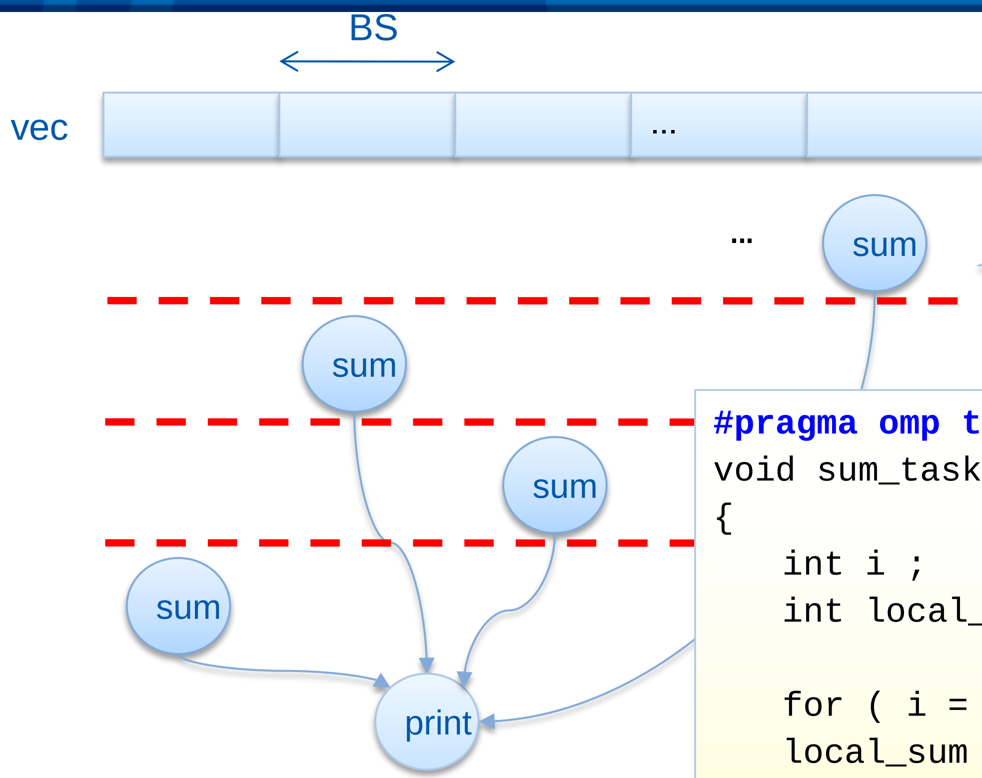

```
#pragma omp task in([n]vec ) concurrent (*results)
void sum_task (int *vec , int n , int  *results)
{
    int i ;
    int local_sum=0;

    for ( i = 0; i < n ; i ++)
    local_sum += vec [i] ;

#pragma omp atomic
    *results += local_sum;
}

void main(){
   for (int j=0; j<N; j+=BS) sum_task (&vec[j], BS, &total);
   #pragma omp task in (total)
printf (“TOTAL is %d\n”, total);
   #pragma omp taskwait
}
```

Commutative

`#pragma omp task in ( ...) out (...) commutative(var)`

- Less-restrictive than regular data dependence
  - → denoting that tasks can execute in any order but not concurrently
  - Enables the scheduler to change the order of execution of the tasks, but without executing them concurrently
    - → alternatively the tasks would be executed sequentially in the order of instantiation due to the inout accesses to the variable in the commutative clause
  - Dependences with other tasks will be handled normally
    - →Any access input or inout to *var* will imply to wait for all previous *commutative* tasks

Commutative



Tasks executed out of order but not concurrently

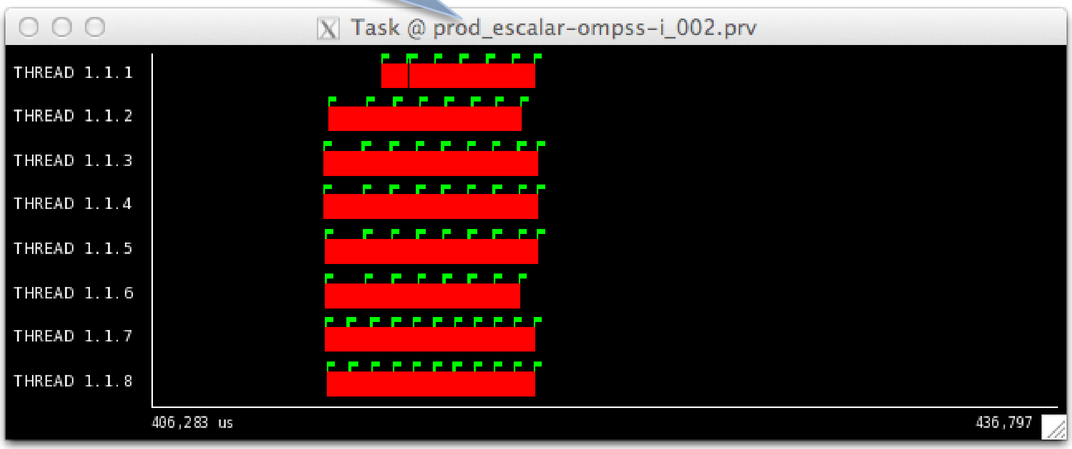
No mutual access required

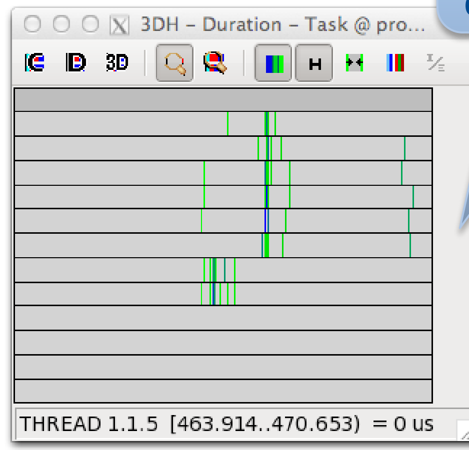
```
#pragma omp task in ([n]vec ) commutative(*results)
void sum_task (int *vec , int n , int  *results)
{
    int i ;
    int local_sum=0;

    for ( i = 0; i < n ; i ++)
    local_sum += vec [i] ;
*results += local_sum;
}

void main(){
   for (int j=0; j<N; j+=BS) sum_task (&vec[j], BS, &total);
   #pragma omp task in(total)
printf (“TOTAL is %d\n”, total);
   #pragma omp taskwait
}
```

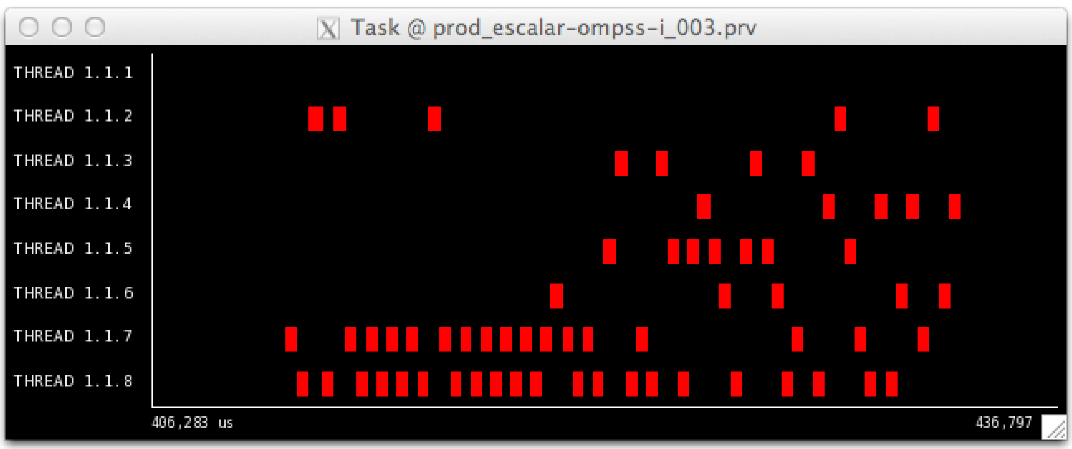
Differences between concurrent and commutative

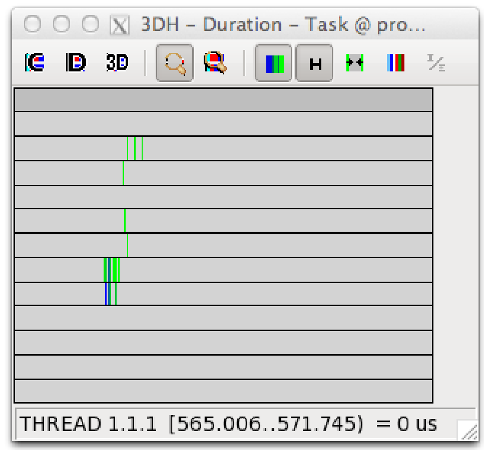
Tasks timeline: views at same time scale

Histogram of tasks duration: at same control scale









In this case, concurrent is more efficient

… but tasks have more duration and variability

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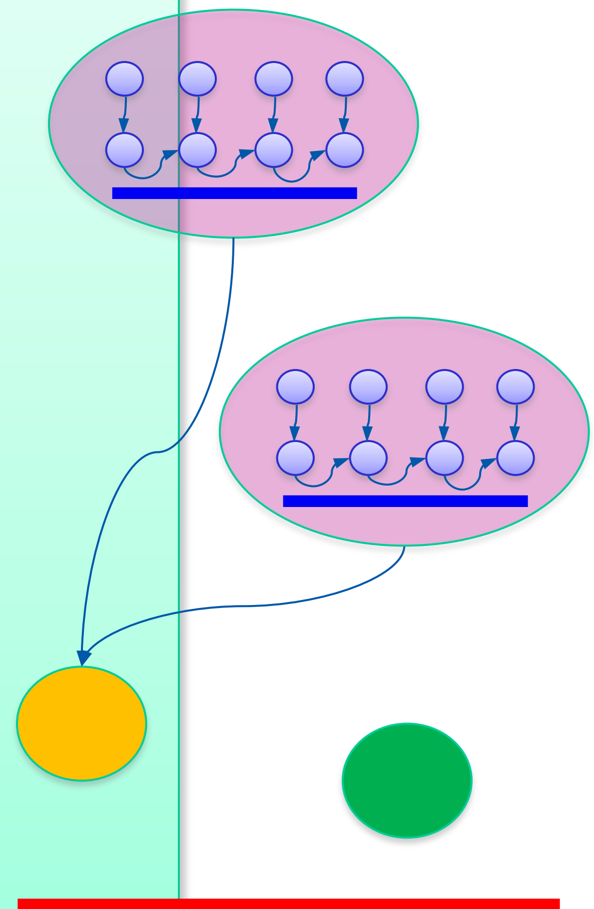
Hierarchical task graph

- Nesting
  - Tasks can generate tasks themselves
- Hierarchical task dependences
  - Dependences only checked between siblings
    - Several task graphs
    - Hierarchical
    - There is no implicit taskwait at the end of a task waiting for its children
  - Different level tasks share the same resources
    - When ready, queued in the same queues
    - Currently, no priority differences between tasks and its children

Nesting inlined tasks

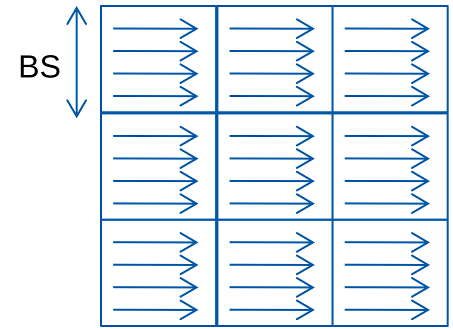
```
int Y[4]={1,2,3,4}

int main( )
{
int X[4]={5,6,7,8};

   for (int i=0; i<2; i++) {
      #pragma omp task out(Y[i]) firstprivate(i,X)
      {
         for (int j=0 ; j<3; j++) {
            #pragma omp task inout(X[j])
            X[j]=f(X[j], j);
            #pragma omp task in (X[j]) inout (Y[i])
            Y[i] +=g(X[j]);
         }
         #pragma omp taskwait
      }
   }
   #pragma omp task inout(Y[0;2])
    for (int i=0; i<2; i++) Y[i] += h(Y[i]);
   #pragma omp task inout (v) inout(Y[3])
   for (int i=1; i<N; i++) Y[3]=h(Y[3]);

   #pragma omp taskwait
}
```

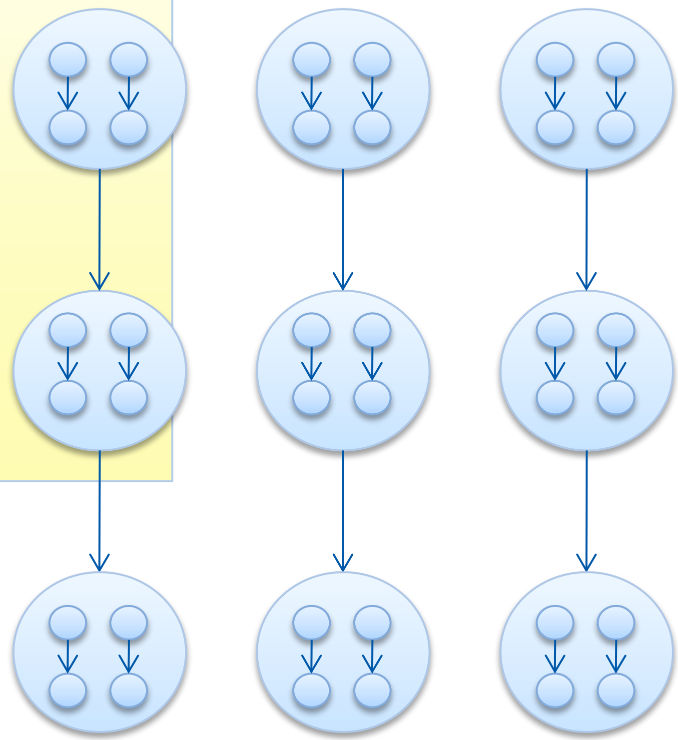


Nesting outlined tasks

```
#pragma omp task in([BS][BS]A, [BS][BS] B) inout([BS][BS]C)
void block_dgemm(float *A, float *B, float *C);

#pragma omp task in([N]A, [N]B) inout([N]C)
void dgemm(float (*A)[N], float (*B)[N], float (*C)[N]){
int i, j, k;
int NB= N/BS;

for (i=0; i< N; i+=BS)
for (j=0; j< N; j+=BS)
   for (k=0; k< N; k+=BS)
      block_dgemm(&A[i][k*BS], &B[k][j*BS], &C[i][j*BS]);
}

main() {
(
 ...
dgemm(A,B,C);
dgemm(D,E,F);
#pragma omp taskwait

}
```

Block data-layout





Incomplete directionalities specification

- Directionality not required for all arguments
- May even be used with variables not accessed in that way or even used
  - used to force dependences under complex structures (graphs, ...)

```
void compute(unsigned long NB, unsigned long DIM,
double *A[DIM][DIM], double *B[DIM][DIM], double *C[DIM][DIM])
{
  unsigned i, j, k;

  for (i = 0; i < DIM; i++)
    for (j = 0; j < DIM; j++)
      for (k = 0; k < DIM; k++) {
        #pragma omp task in(A[i][k], B[k][j]) inout(C[i][j])
        matmul (A[i][k], B[k][j], C[i][j], NB);
      }
}
```

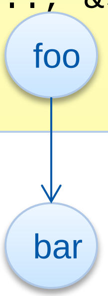
Using entry in C matrix of pointers as representative/sentinel for the whole block it points to.

Will build proper dependences between tasks.

Does NOT provide actual information of data access pattern. (see copy clauses)

Example sentinels

```
#pragma omp task out (*sentinel)
void foo ( .... , int *sentinel){ // used to force dependences under complex structures
   (graphs, ... )

...
}

#pragma omp task in (*sentinel)
void bar ( .... , int *sentinel){

...
}
main () {
   int sentinel;

   foo (..., &sentinel);
   bar (..., &sentinel)

}
```



- Mechanism to handle complex dependences
  - when difficult to specify proper input/output clauses
- To be avoided if possible
  - the use of an element or group of elements as sentinels to represent a larger data-structure is valid
  - however might made code non-portable to heterogeneous platforms if copy_in/out clauses cannot properly specify the address space that should be accessible in the devices

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Thank you!

For further information please contact

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