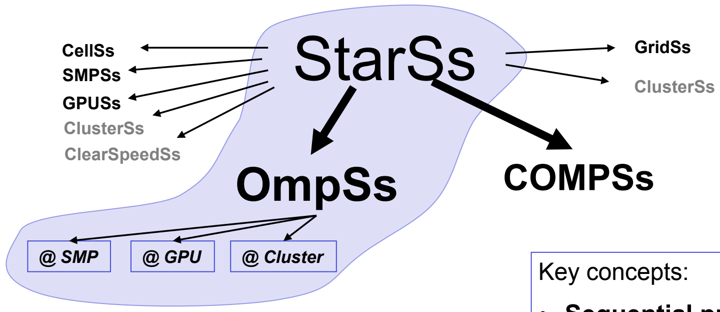
Agenda

- StarSs overview
- OmpSs syntax
- OmpSs environment
- Single node handson
- Hybrid model MPI/OmpSs
- MPI/OmpSs handson

- Slides and single-node source code: /tmp/tutorial_ompss_PATC_single.ppt
- /tmp/tutorial_PATC_singlenode.tar.bz2
- /tmp/StarSs hands_PATC.pdf
- Contact: pm-tools@bsc.es
- Source code available from http://pm.bsc.es/ompss/

The StarSs family of programming models

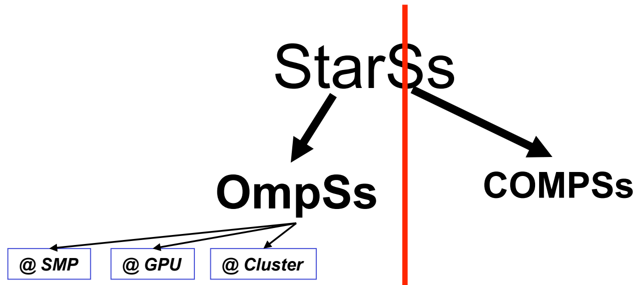


Key concepts:
- **Sequential program**
- **Directionality annotations on tasks arguments**

- Task based. Asynchrony, data-flow.
- Simple linear address space
- Malleable
- Nicely hybridizes (MPI/StarSs)
- Natural support for heterogeneity

Key objectives:
- **Same program any platform**
- **Productive / Incremental programming**

The StarSs "Granularities"

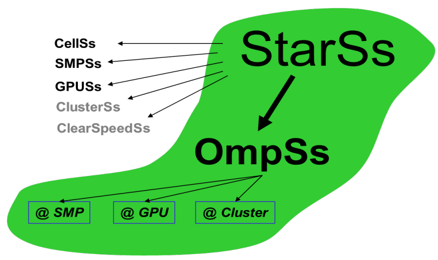


	OmpSs	COMPSs
Average task Granularity:	100 microseconds – 10 milliseconds	1second - 1 day
Address space to compute dependences:	Memory	Files, Objects
Language binding:	C, C++, FORTRAN	Java, Python

StarSs: history/strategy/versions

Basic SMPSs

must provide directionality ∀argument
Contiguous, non partially overlapped
Renaming
Several schedulers (priority, locality,…)
No nesting
C/Fortran
MPI/SMPSs optims.



SMPSs regions

C, No Fortran
must provide directionality ∀argument
ovelaping &strided
Reshaping strided accesses
Priority and locality aware scheduling

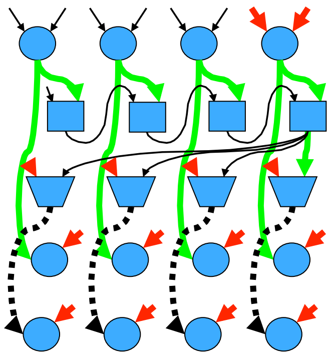
OMPSs

C, C++, Fortran
OpenMP compatibility (~)
Contiguous and strided args.
Separate dependences/transfers
Inlined/outlined pragmas
Nesting
Heterogeneity: SMP/GPU/Cluster
No renaming,
Several schedulers: "Simple" locality aware sched,…

Evolving research since 2005

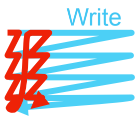
StarSs: the potential of data access information

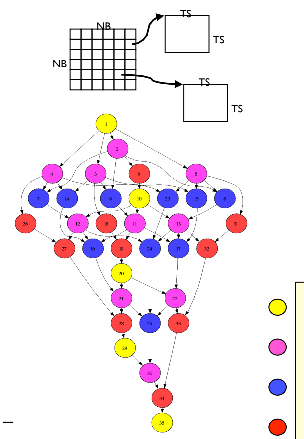
- **Flat global address space seen by programmer**
- Flexibility to dynamically traverse dataflow graph "optimizing"
  - Concurrency. Critical path
  - Memory access: data transfers performed by run time
- Opportunities for runtime to
  - Prefetch
  - Reuse
  - Eliminate antidependences (rename)
  - Replication management
    - Coherency/consistency handled by the runtime



StarSs: data-flow execution of sequential programs

Decouple
how we write
form
how it is executed





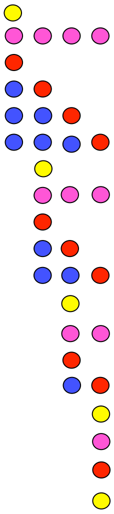

```
void Cholesky( float *A ) {
   int i, j, k;
   for (k=0; k<NT; k++) {
      spotrf (A[k*NT+k]) ;
      for (i=k+1; i<NT; i++)
         strsm (A[k*NT+k], A[k*NT+i]);
      // update trailing submatrix
      for (i=k+1; i<NT; i++) {
         for (j=k+1; j<i; j++)
            sgemm( A[k*NT+i], A[k*NT+j],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


StarSs tasks

- Task
  - Computation unit. Amount of work (granularity) may vary in a wide range (microseconds to milliseconds or even seconds), may depend on input arguments,…
  - Once started can execute to completion independent of other tasks
- States:
  - Instantiated: when task is created by main program. Dependences are computed at the moment of instantiation.
  - 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.

StarSs vs OpenMP

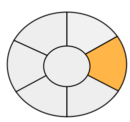


```
void Cholesky( float *A ) {
   int i, j, k;
   for (k=0; k<NT; k++) {
      spotrf (A[k*NT+k]);
      #pragma omp parallel for
      for (i=k+1; i<NT; i++)
         strsm (A[k*NT+k], A[k*NT+i]);
      for (i=k+1; i<NT; i++) {
         #pragma o
         for (j=k+
            sgemm(
         ssyrk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

```
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

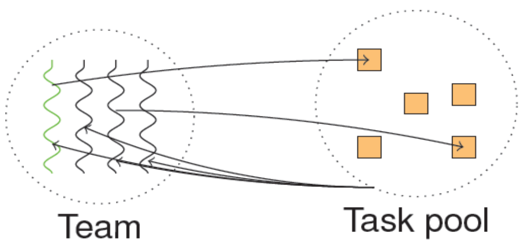


OmpSs = OpenMP + StarSs extensions

- 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

Execution Model

- Thread-pool model
  - OpenMP parallel "ignored"
- 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, 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 kernel invocation syntax

Support for multiple implementations of a task

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

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

```
#pragma omp task [ input (...)] [ output (...)] [ inout (...)] [ concurrent (...)]
{ function or code block }
```

To compute dependences

To allow concurrent execution of commutative tasks

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

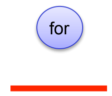
Wait for sons or specific data availability

Relax consistency to main program

Main element: inlined tasks

- Pragmas inlined
  - Applies to a statement
  - The compiler outlines the statement (as in OpenMP)

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

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

      ...
}
```



Main element: inlined tasks

- Pragmas inlined
  - Standard OpenMP clauses private, firstprivate, ... can be used

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

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

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

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

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

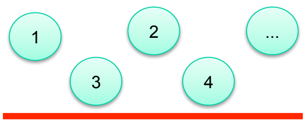
```
#pragma  omp   task
void   foo (int Y[size], int size) {
int j;

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

int main()
{
   int X[100];

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

Synchronization

`#pragma omp taskwait`

- Suspends the current task until all children tasks are completed

```
void traverse_list ( List l )
{
   Element e ;
   for ( e = l-> first; e ; e = e->next )
      #pragma omp task
       process ( e ) ;

   #pragma omp taskwait
}
```

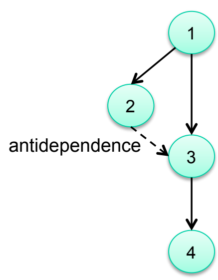


Without taskwait the subroutine will return immediately after spawning the tasks allowing the calling function to continue spawning tasks

Defining dependences

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

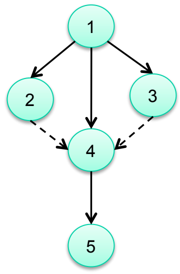
```
#pragma omp task output( x )
x = 5;                                //1
#pragma omp task input( x )
printf("%d\n" , x ) ;                 //2
#pragma omp task inout( x )
x++;                                  //3
#pragma omp task input( x )
printf ("%d\n" , x ) ;                //4
```



Defining dependences

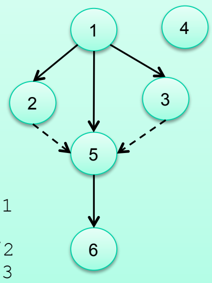
non-taskified: executed sequentially

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

int main()
{
int x;

x=3;

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



Defining dependences

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

#pragma omp task input (x) // compiler warning, input clause discarded
void print_do (int x) {     // value captured at instantiation time
   printf(”from print_do %d\n" , x ) ;
}

int main()
{
int x;

x=3;
#pragma omp task output( x )
x = 5;                       //1
#pragma omp task input( x )
printf(”from main %d\n" , x );//2
do_print(&x);                //3
print_do(x);                 //4
#pragma omp task inout( x )
x++;                         //5
#pragma omp task input( x )
printf (”from main %d\n" , x );//6
}
```

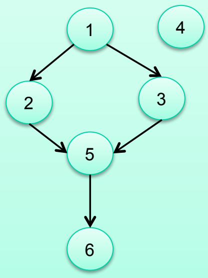


Output:

```
(4) from print_do 3
(2) from main 5
(3) from do_print 5
(6) from main 6
```

Defining dependences

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

#pragma omp task input (x) // compiler warning, input clause discarded
void print_do (int x) {
   printf("from print_do %d\n" , x ) ;
}

int main()
{
int x;

x=3;
#pragma omp task output( x )
x = 5;//1
#pragma omp task input( x )
printf("from main %d\n" , x );//2
do_print(&x);//3
print_do(x);//4
#pragma omp task inout( x )
x++;//5
#pragma omp task input( x )
printf ("from main %d\n" , x ) ;//6
}
```

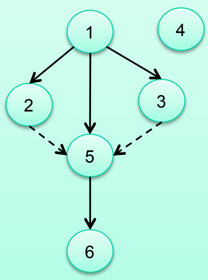


but also:

```
(2) from main 5
(4) from print_do 3
(3) from do_print 5
(6) from main 6
```

Defining dependences

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

#pragma omp task input (x) // compiler warning, input clause discarded
void print_do (int x) {
   printf("from print_do %d\n" , x ) ;
}

int main()
{
int x;

x=3;
#pragma omp task output( x )
x = 5;//1
#pragma omp task input( x )
printf("from main %d\n" , x );//2
do_print(&x);//3
print_do(x);//4
#pragma omp task inout( x )
x++;//5
#pragma omp task input( x )
printf ("from main %d\n" , x ) ;//6
}
```



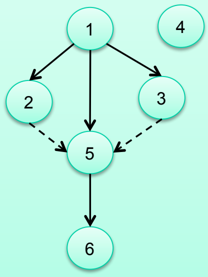
and also:

```
(2) from main 5
(3) from do_print 5
(4) from print_do 3
(6) from main 6
```

depending on actual schedule

Defining dependences

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

#pragma omp task input (x) // compiler warning, input clause discarded
void print_do (int x) {
   printf(”from print_do %d\n" , x ) ;
}

int main()
{
int x;

x=3;
#pragma omp task output( x )
x = 5;//1
#pragma omp task input( x )
printf(”from main %d\n" , x );//2
do_print(&x);//3
print_do(x);//4
#pragma omp task inout( x )
x++;//5
#pragma omp task input( x )
printf (”from main %d\n" , x ) ;//6
}
```



and even:

```
(2) from main 5
(3) from do_print 5
(4) from print_do 5
(6) from main 6
```

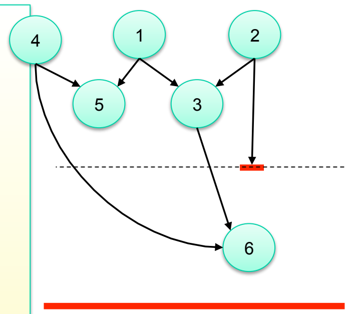
- because there is no dependence to 4
- the value of x is captured at instantion time
- other tasks may alter the value
  - in this case, execution of 1 before instantiation of 4

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 input([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:

  input (A[i])

  → the input argument is element *i* of A

- Indicating an array section:

  input ([BS]A)

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

  input (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)

  input (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 input(a)
```

=

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

=

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

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

```
int a[N];
#pragma omp task input(a[2:3])
//elements 2 and 3 of the array used to compute dependences
```

=

```
int a[N];
#pragma omp task input(a[2;2])
//elements 2 and 3 of the array used to compute dependences
```

Examples dependency clauses, array sections

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

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

```
int *a;
#pragma omp task input(a[2:3])
//elements 2 and 3 of the array used to compute dependences
```

```
int *a;
#pragma omp task input(a[2:N-1])
//elements 2 to N-1 of the array used to compute dependences
```


Examples dependency clauses, array sections (multidimensions)

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

=

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

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

=

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

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

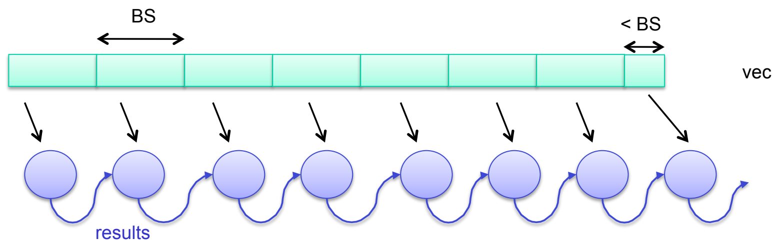
Examples dependency clauses, array sections (multidimensions)

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

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

```
int *a;
#pragma omp task input([N][M]a)
//whole matrix
```

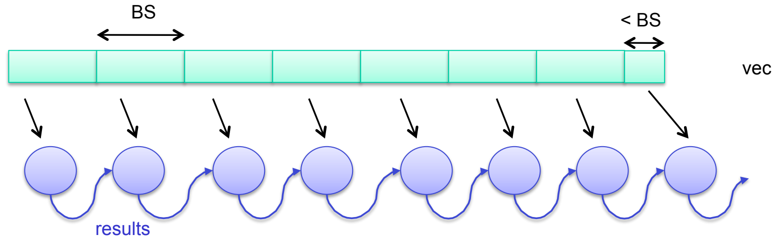

Examples dependency clauses, array sections




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

void main(){
int actual_size;
   for (int j; 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; j<N; j+=BS){
   actual_size = (N- j> BS ? BS: N-j);
#pragma omp task input (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([n*4] pl, [n*4] pr ) output([n*4] pn)
void loop1_task(int n, double *pl, double *pr, double *tl, double *tr, double
{
        double t1, t2;
        int i;

        for (i = 0;  i < n;  i++)
        {
                t1 = pl[0] * tl[0] + pl[1] * tl[1] + pl[2] * tl[2] + pl[3] * tl[3];
                t2 = pr[0] * tr[0] + pr[1] * tr[1] + pr[2] * tr[2] + pr[3] * tr[3];
                pn[0] = t1 * t2;

                t1 = pl[0] * tl[4] + pl[1] * tl[5] + pl[2] * tl[6] + pl[3] * tl[7];
                t2 = pr[0] * tr[4] + pr[1] * tr[5] + pr[2] * tr[6] + pr[3] * tr[7];
                pn[1] = t1 * t2;

                t1 = pl[0] * tl[8] + pl[1] * tl[9] + pl[2] * tl[10] + pl[3] * tl[11];
                t2 = pr[0] * tr[8] + pr[1] * tr[9] + pr[2] * tr[10] + pr[3] * tr[11];
                pn[2] = t1 * t2;

                t1 = pl[0] * tl[12] + pl[1] * tl[13] + pl[2] * tl[14] + pl[3] * tl[15];
}
```

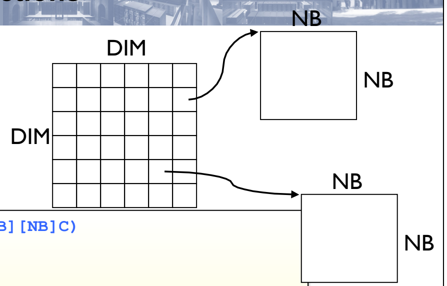
Not all parameters necessary in the dependence clauses

```
for( iPattern = 0; iPattern < g_ds.nPattern; iPattern += TASK_ITERATIONS)
{
   int n = (g_ds.nPattern - iPattern > TASK_ITERATIONS ? TASK_ITERATIONS: g_ds.nPattern - iPattern);
          loop1_task(n, pl, pr, tl, tr, pn);
          pn  = pn  + 4 * n;
          pl  = pl  + 4 * n;
          pr  = pr  + 4 * n;
}
```

Examples dependency clauses, array sections

```
for( iPattern = 0; iPattern < g_ds.nPattern; iPattern += TASK_ITERATIONS)
{
 int n = (g_ds.nPattern - iPattern > TASK_ITERATIONS ? TASK_ITERATIONS: g_ds.nPattern -
iPattern);
   #pragma omp task input (pl[iPattern*4;n*4], pr[iPattern*4;n*4]) \
   output (pn[iPattern*4;n*4]) firstprivate (n) private (i)
   for (i = iPattern;  i < iPattern+n;  i++)
   {
       t1 = pl[i*4+0] * tl[0] + pl[i*4+1] * tl[1] + pl[i*4+2] * tl[2] + pl[i*4+3] * tl[3];
       t2 = pr[i*4+0] * tr[0] + pr[i*4+1] * tr[1] + pr[i*4+2] * tr[2] + pr[i*4+3] * tr[3];
       pn[i*4+0] = t1 * t2;

       t1 = pl[i*4+0] * tl[4] + pl[i*4+1] * tl[5] + pl[i*4+2] * tl[6] + pl[i*4+3] * tl[7];
       t2 = pr[i*4+0] * tr[4] + pr[i*4+1] * tr[5] + pr[i*4+2] * tr[6] + pr[i*4+3] * tr[7];
       pn[i*4+1] = t1 * t2;

       t1 = pl[i*4+0] * tl[8] + pl[i*4+1] * tl[9] + pl[i*4+2] * tl[10] + pl[i*4+3] * tl[11];
       t2 = pr[i*4+0] * tr[8] + pr[i*4+1] * tr[9] + pr[i*4+2] * tr[10] + pr[i*4+3] * tr[11];
       pn[i*4+2] = t1 * t2;

       t1 = pl[i*4+0] * tl[12] + pl[i*4+1] * tl[13] + pl[i*4+2] * tl[14] + pl[i*4+3] * tl[15];
       t2 = pr[i*4+0] * tr[12] + pr[i*4+1] * tr[13] + pr[i*4+2] * tr[14] + pr[i*4+3] * tr[15];
       pn[i*4+3] = t1 * t2;

   }
}
```

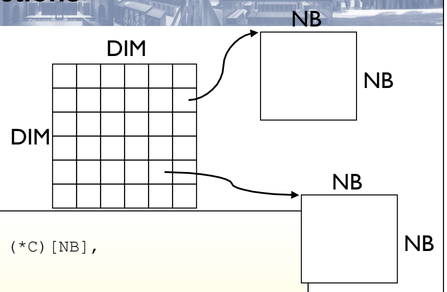

Examples dependency clauses, array sections




```
#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);
}
```

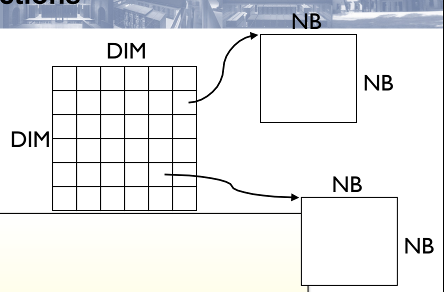
Examples dependency clauses, array sections




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

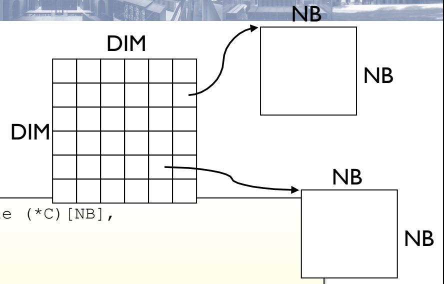

Examples dependency clauses, array sections




```
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])
        matmul (A[i][k], B[k][j], C[i][j], NB);
}
```

Examples dependency clauses, array sections

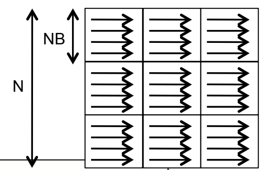



```
void matmul(double  (*A)[NB], double (*B)[NB], double (*C)[NB],
unsigned long NB)
{
  int i, j, k;

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

```
void compute(struct timeval *start, struct timeval *stop, 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])
        matmul ((double (*)[NB])A[i][k], (double (*)[NB])B[k][j],
           (double (*)[NB])C[i][j], NB);
}
```

Examples dependency clauses, array sections

N = total size of matrix
NB = block size
DIM = number of blocks



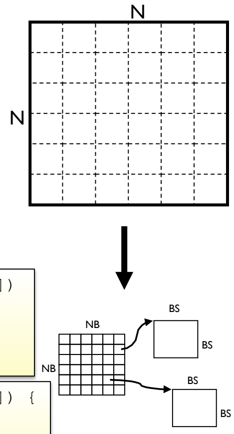

```
#pragma omp task input([NB][NB]A, [NB][NB]B) inout([NB][NB]C)
void matmul(double  *A, double *B, double *C, unsigned long NB)
{
  int i, j, k;

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

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

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

converting from standard row-wise matrix association to blocked

```
void flat_cholesky( int N, float *A ) {
    float **Ah;
    int nt = n/BS;
    Ah = allocate_block_matrix();
    convert_to_blocks(n, nt, A, Ah);
    blocked_cholesky (nt, Ah);
    convert_to_linear(n, bs, Ah, A);
    #pragma omp taskwait
    free_block_matrix(Ah)
}
```

Local memory management
Temporary work arrays




```
void convert_to_block( int n, int nt, float (*A)[n], float *Ah[nt][nt])
     {
   for (i=0; i<nt; i++)
      for (j=0; j<nt; j++) gather_block (n, bs, A, i, j, Ah[i][j]]);
}
```

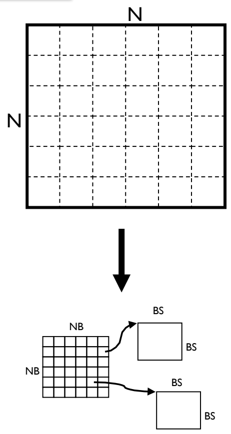
```
void convert_to_linear(int n, int bs, float *Ah[nt][nt], float (*A)[n]) {
  for (i=0; i<nt; i++)
      for (j=0; j<nt; j++) scatter_block (n, bs, A, Ah[i][j], i, j);
}
```

```
#pragma omp task input ([n]A) output ([bs][bs]bA)
void gather_block (int n, int bs, float (*A)[n], int I, int J, float *bA);
#pragma omp task input ( [bs][bs]bA) concurrent([n]A)
void scatter_block (int n, bs, float (*A)[n], float *bA, I, J);
```


converting from standard row-wise matrix association to blocked

```
#pragma omp task input ([n]A) output ([bs][bs]bA)
void gather_block (int n, int bs, float (*A)[n], int I, int J, float *bA);
#pragma omp task input ( [bs][bs]bA) concurrent([n]A)
void scatter_block (int n, bs, float (*A)[n], float *bA, I, J);
```

```
void gather_block(int n, int bs, float (*Alin)[n], int I, int J,
    float *bA)
{
     int i, j;

     for (i = 0; i < bs; i++)
        for (j = 0; j < bs; j++) {
           bA[i*bs+ j] = Alin[I+i][J+j];
        }
}
```



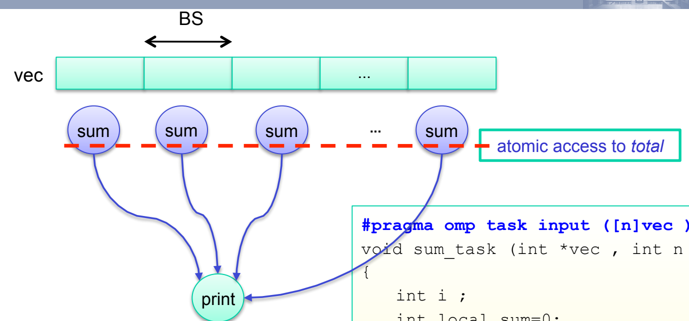

```
void scatter_block (int n, bs, float (*A)[n], float *bA, I, J)
{
     int i, j;

     for (i = 0; i < bs; i++)
        for (j = 0; j < bs; j++) {
           Alin[I+i][J+j]= A[i*bs+ j];
        }
}
```

Concurrent

`#pragma omp task input ( ...) output (...) 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 input ([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 input (total)
   printf ("TOTAL is %d\n", total);
}
```

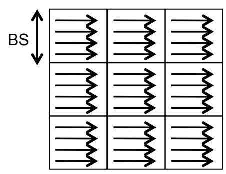
Hierarchical task graph

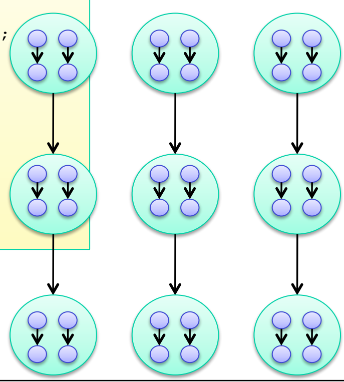
- Nesting
  - Tasks can generate tasks themselves
- Hierarchical task dependences
  - Dependences only checked between siblings
    - Several task graphs
    - Hierarchical
    - Implicit taskwait at the end of a task waiting for its children
  - Different level tasks share the same resources
    - When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

Hierarchical task graph

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

#pragma omp task input([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_dgem(&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

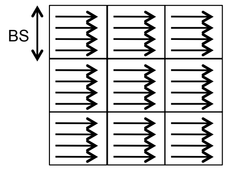


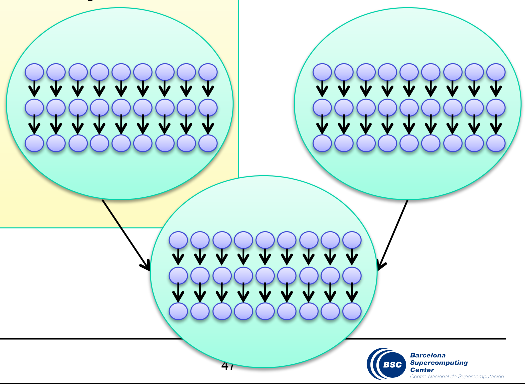


Hierarchical task graph

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

#pragma omp task input([N]A, [N]B) output([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_dgem(&A[i][k*BS], &B[k][j*BS], &C[i][j*BS]);
}

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

}
```

Block data-layout





Heterogeneity: the target directive

- Directive to specify device specific information:

  #pragma omp target [clauses]

  - Clauses:
    - device: which device (smp, gpu)
    - copy_in, copy_out, copy_inout:
      - consistent copy needed in the device, may require a transfer
    - copy_deps: same as above, to copy data specified in input/output/inout clauses
    - implements: specifies alternate implementations
  - Not only for tasks, also to indicate to the compiler that a given function or kernel is specific of a device

```
#pragma target device (smp) copy_deps
//#pragma target device (smp) copy_in ([size] c) copy_out([size]b)
#pragma omp task input ([size] c) output ([size] b)
void scale_task (double *b, double *c, double scalar, int size)
{
    int j;
    for (j=0; j < BSIZE; j++)
        b[j] = scalar*c[j];
}
```

Heterogeneity: the target directive

- Directive to specify device specific information:

  #pragma omp target [clauses]

  - Clauses:
    - device: which device (smp, gpu)
    - copy_in, copy_out, copy_inout: data to be moved in and out
    - copy_deps: same as above, to copy data specified in input/output/inout clauses
    - implements: specifies alternate implementations

```
#pragma omp target device (cuda) copy_deps implements (scale_task)
#pragma omp task input ([size] c) output ([size] b)
void scale_task_cuda(double *b, double *c, double scalar, int size)
{

    const int threadsPerBlock = 128;
    dim3 dimBlock;
    dimBlock.x = threadsPerBlock;
    dimBlock.y = dimBlock.z = 1;

    dim3 dimGrid;
    dimGrid.x = size/threadsPerBlock+1;

    scale_kernel<<<dimGrid,dimBlock>>>(size, 1, b, c, scalar);

}
```


Avoiding data transfers

- Need to synchronize
- No need for synchronous data output

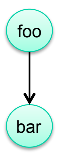
```
void compute_perlin_noise_device(pixel * output, float time, unsigned int
rowstride, int img_height, int img_width)
{
    unsigned int i, j;
    float vy, vt;
    const int BSy = 1;
    const int BSx = 512;
    const int BS = img_height/16;

    for (j = 0; j < img_height; j+=BS) {
#pragma omp target device(cuda) copy_out(output[j*rowstride;BS*rowstride])
#pragma omp task
        {
            dim3 dimBlock, dimGrid;
            dimBlock.x = (img_width < BSx) ? img_width : BSx;
            dimBlock.y = (BS < BSy) ? BS : BSy;
            dimBlock.z = 1;
            dimGrid.x = img_width/dimBlock.x;
            dimGrid.y = BS/dimBlock.y;
            dimGrid.z = 1;
            cuda_perlin <<<dimGrid, dimBlock>>> (&output[j*rowstride],
                       time, j, rowstride);
        }
    }
#pragma omp taskwait noflush
}
```

Executed in the host

Host address space

Example sentinels

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

...
}

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

...
}
main () {
   int sentinel;

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

}
```

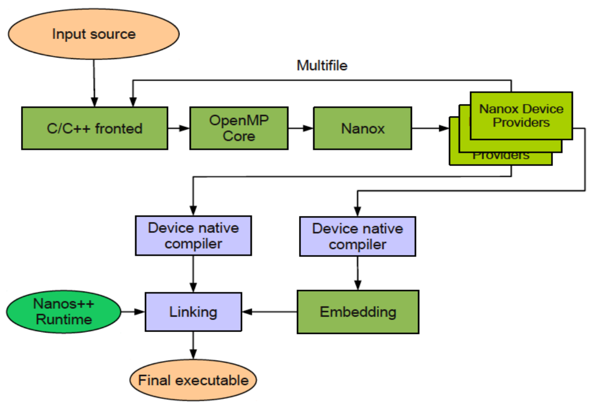


- Mechanism to handle complex dependences
  - when difficult to specify proper input/output clauses
- To be avoided if possible
  - the use of an element or group of elements as sentinels to represent a larger data-structure is valid
  - however might made code non-portable to heterogeneous platforms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

Mercurium Compiler

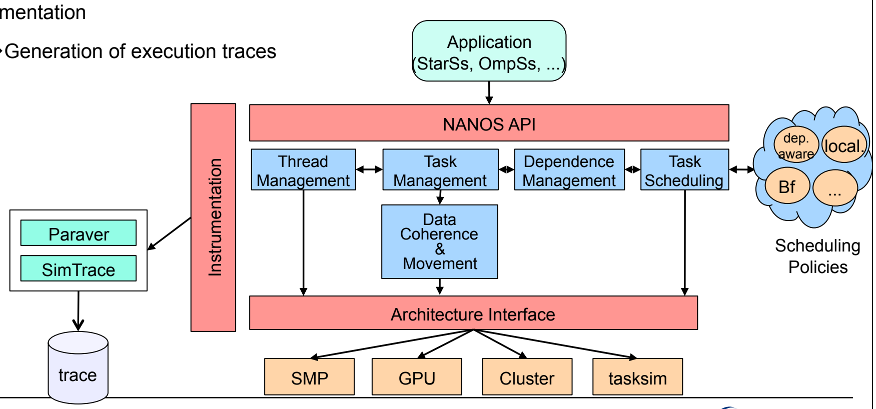
- Recognizes constructs and transforms them to calls to the runtime
- Manages code restructuring for different target devices
  - Device-specific handlers
  - May generate code in a separate file
  - Invokes different back-end compilers
    → nvcc for NVIDIA

Mercurium

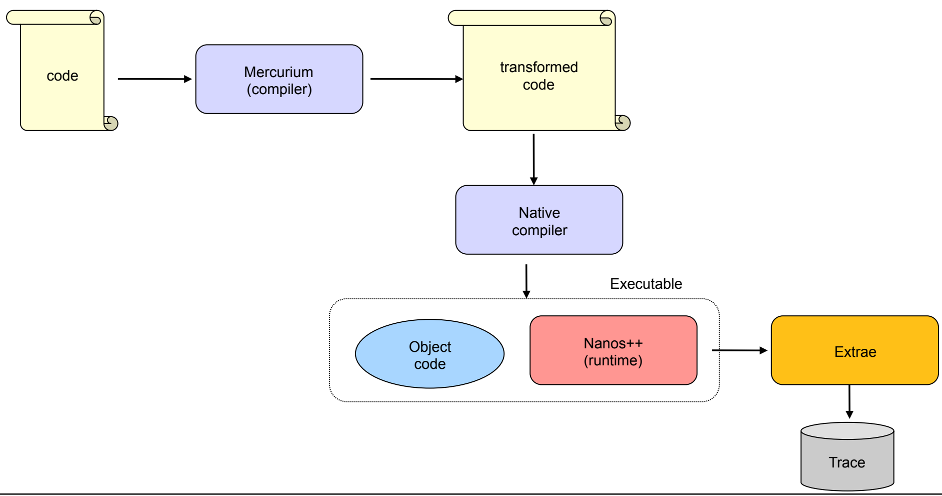


Runtime structure

- Support to different programming models: OpenMP (OmpSs), StarSs, Chapel
- Independent components for thread, task, dependence management, task scheduling, ...
- Most of the runtime independent of the target architecture: SMP, GPU, tasksim simulator, cluster
- Support to heterogeneous targets
  - → i.e., threads running tasks in regular cores and in GPUs
- Instrumentation
  - →Generation of execution traces



OmpSs Environment



Compiling

- Compiling

  `frontend --ompss  -c bin.c`
- Linking

  `frontend --ompss -o bin bin.o`
- where frontend is one of:

mcc	C
mcxx	C++
mnvcc	CUDA & C
mnvcxx	CUDA & C++
mfc	Fortran (In development)

Compiling

- Compatibility flags:
  - -I, -g, -L, -l, -E, -D, -W
- Other compilation flags:

-k	Keep intermediate files
--debug	Use Nanos++ debug version
--instrument	Use Nanos++ instrumentation version
--version	Show Mercurium version number
--verbose	Enable Mercurium verbose output
--Wp,flags	Pass flags to preprocessor (comma separated)
--Wn,flags	Pass flags to native compiler (comma separated)
--Wl,flags	Pass flags to linker (comma separated)
--help	To see many more options :-)

Executing

- No LD_LIBRARY_PATH or LD_PRELOAD needed

```
./bin
```

- Adjust number of threads with OMP_NUM_THREADS

```
OMP_NUM_THREADS=4 ./bin
```


Nanos++ options

- Other options can be passed to the Nanos++ runtime via NX_ARGS

```
NX_ARGS="options" ./bin
```

--schedule=name	Use name task scheduler
--throttle=name	Use name throttle-policy
--throttle-limit=limit	Limit of the throttle-policy (exact meaning depends on the policy)
--instrumentation=name	Use name instrumentation module
--disable-yield	Nanos++ won't yield threads when idle
--spins=number	Number of spin loops when idle
--disable-binding	Nanos++ won't bind threads to CPUs
--binding-start=cpu	First CPU where a thread will be bound
--binding-stride=number	Stride between bound CPUs

Nanox helper

- Nanos++ utility to
  - list available modules:

    ```
    nanox --list-modules
    ```
  - list available options:

    ```
    nanox --help
    ```


Schedulers

- Available schedulers for --schedule option
  - default
    - centralize queue, LIFO scheduler, follows dependency edges
  - bf
    - centralized queue, FIFO scheduler
  - dbf
    - multiple queues, FIFO scheduler with work-stealing
  - affinity
    - multiple queues, uses copy-information to decide which thread to schedule to
  - wf
    - multiple queues, work-first approach with work-stealing
    - Several options to modify behavior
- Example

  ```
  NX_ARGS="--schedule=bf" ./exec
  ```

Throttle policies

- Available policies for --throttle option
  - num-tasks (default)
    - stop creating tasks if more than limit * #threads are in flight
  - taskdepth
    - stop creating tasks if recursion depth is bigger than limit
  - idlethreads
    - stop creating tasks if no thread is idle
  - readytasks
    - stop creating tasks if more than limit * #threads tasks are ready
- Example

```
NX_ARGS="--throttle=taskdepth --throttle-limit=4" ./exec
```


Tracing

- Compile and link with --instrument

```
mcc --ompss --instrument -c bin.c
mcc -o bin --ompss --instrument bin.o
```

- When executing specify which instrumentation module to use:

```
NX_ARGS="--instrumentation=extrae" ./bin
```

- Will leave trace files in executing directory
  - 3 files: prv, pcf, rows
  - Use paraver to analyze

Reporting problems

- Compiler problems
  - http://pm.bsc.es/projects/mcxx/newticket
- Runtime problems
  - http://pm.bsc.es/projects/nanox/newticket
- Support mail
  - pm-tools@bsc.es
- Please include snapshot of the problem

Programming methodology

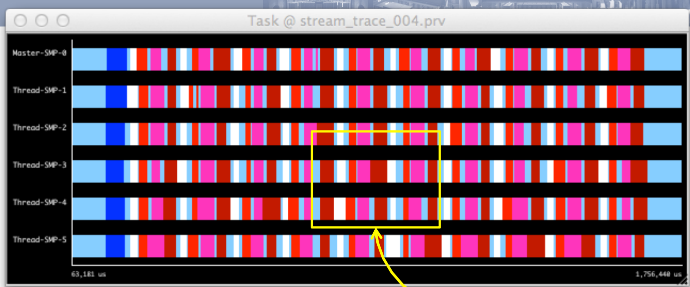
- Correct sequential program
- Incremental taskification
  - Test every individual task with forced sequential in-order execution
    - → 1 thread, scheduler = FIFO, throtle=1
- Single thread out-of-order execution
- Increment number of threads
  - Use taskwaits to force certain levels of serialization

Visualizing Paraver tracefiles

- Set of Paraver configuration files ready for OmpSs. Organized in directories
  - **Tasks: related to application tasks**
  - Runtime, nanox-configs: related to OmpSs runtime internals
  - **Graph_and_scheduling: related to task-graph and task scheduling**
  - DataMgmgt: related to data management
  - CUDA: specific to GPU

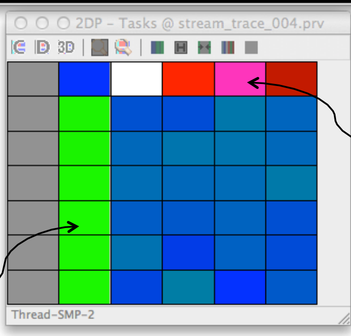
Tasks' profile

- 2dp_tasks.cfg
- Tasks' profile



control window:
timeline where each
color represent the
task been executed
by each thread

light blue: not executing
tasks



threads

different colours
represent different
task type

gradient color,
indicates given estadístic:
i.e., number of tasks instances

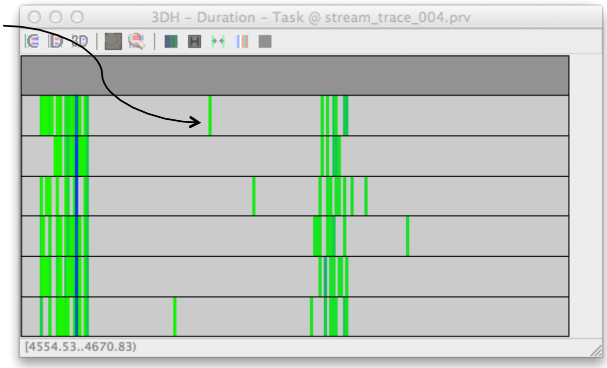
Tasks duration histogram

- 3dh_duration_task.cfg

time intervals

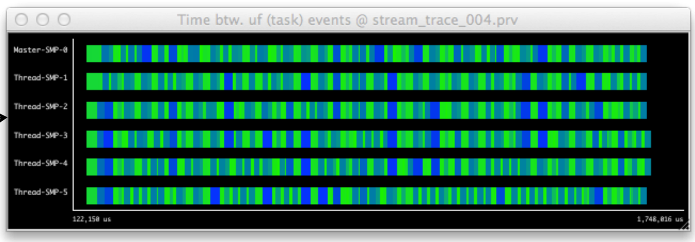
gradient color,
indicates given estadístic:
i.e., number of tasks instances

threads

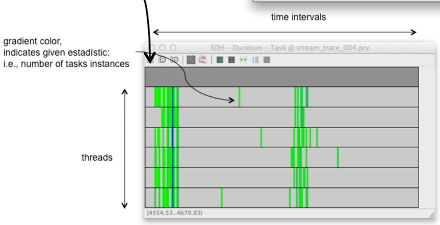


Tasks duration histogram

- 3dh_duration_task.cfg

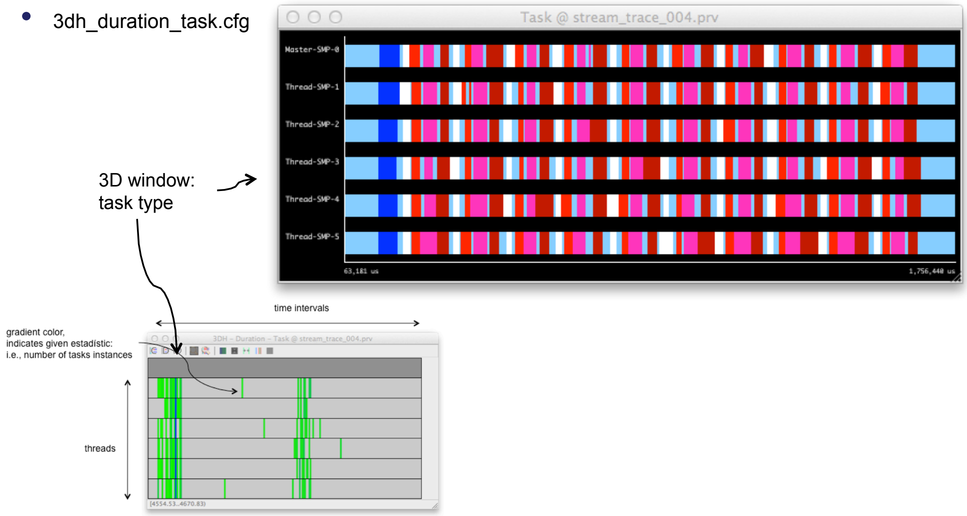


control window:
task duration



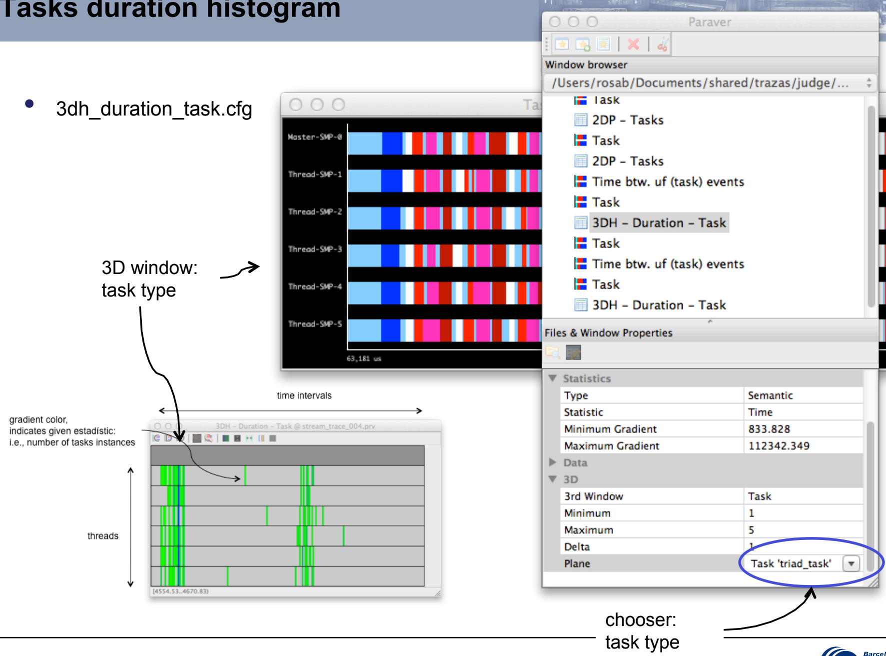
Tasks duration histogram

- 3dh_duration_task.cfg



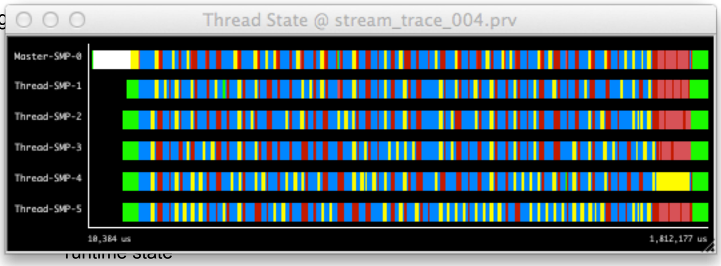
Tasks duration histogram

- 3dh_duration_task.cfg



Threads state profile

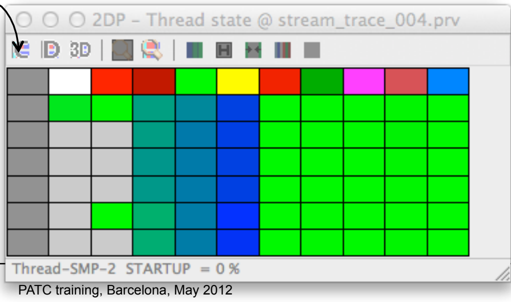
- 2dp_threads_state.cfg



control window:
timeline where each
color represent the
runtime state of each
thread

runtime state

threads



Single node hands-on