OmpSs Specification

BSC Programming Models

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Note: There is a PDF version of this document at http://pm.bsc.es/ompss-docs/spec/OmpSsSpecification.pdf

CHAPTER

ONE

INTRODUCTION TO OMPSS

OmpSs is a programming model composed of a set of directives and library routines that can be used in conjunction with a high level programming language in order to develop concurrent applications. This programming model is an effort to integrate features from the StarSs programming model family, developed by the Programming Models group of the Computer Sciences department at Barcelona Supercomputing Center (BSC), into a single programming model.

OmpSs is based on tasks and dependences. Tasks are the elementary unit of work which represents a specific instance of an executable code. Dependences let the user annotate the data flow of the program, this way at runtime this information can be used to determine if the parallel execution of two tasks may cause data races.

The goal of OmpSs is to provide a productive environment to develop applications for modern High-Performance Computing (HPC) systems. Two concepts add to make OmpSs a productive programming model: performance and ease of use. Programs developed in OmpSs must be able to deliver a reasonable performance when compared to other programming models that target the same architectures. Ease of use is a concept difficult to quantify but OmpSs has been designed using principles that have been praised by their effectiveness in that area.

In particular, one of our most ambitious objectives is to extend the OpenMP programming model with new directives, clauses and API services or general features to better support asynchronous data-flow parallelism and heterogeneity (as in GPU-like devices).

This document, except when noted, makes use of the terminology defined in the OpenMP Application Program Interface version 3.0 *[OPENMP30]*

1.1 Reference implementation

The reference implementation of OmpSs is based on the Mercurium source-to-source compiler and the Nanos++ Runtime Library:

- The Mercurium source-to-source compiler provides the necessary support for transforming the high-level directives into a parallelized version of the application.
- The Nanos++ runtime library provides the services to manage all the parallelism in the user-application, including task creation, synchronization and data movement, and provide support for resource heterogeneity.

1.2 A bit of history

The name OmpSs comes from the name of two other programming models, OpenMP and StarSs. The design principles of these two programming models form the basic ideas used to conceive OmpSs.

OmpSs takes from OpenMP its philosophy of providing a way to, starting from a sequential program, produce a parallel version of the same by introducing annotations in the source code. This annotations do not have an explicit effect in the semantics of the program, instead, they allow the compiler to produce a parallel version of it. This

characteristic feature allows the users to parallelize applications incrementally. Starting from the sequential version, new directives can be added to specify the parallelism of different parts of the application. This has an important impact on the productivity that can be achieved by this philosophy. Generally when using more explicit programming models the applications need to be redesigned in order to implement a parallel version of the application, the user is responsible of how the parallelism is implemented. A direct consequence of this is the fact that the maintenance effort of the source code increases when using a explicit programming model, tasks like debugging or testing become more complex.

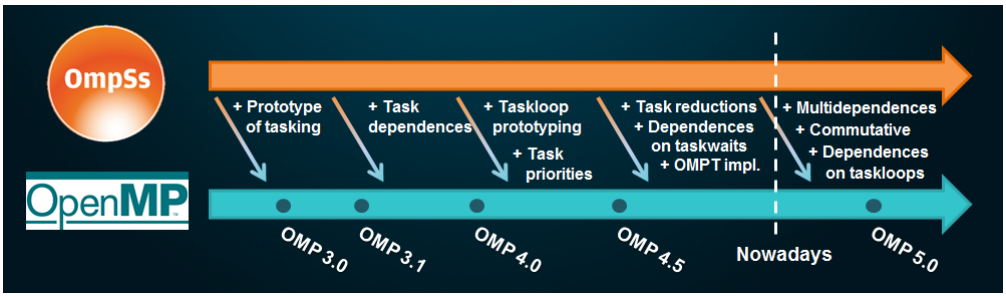
StarSs, or Star SuperScalar, is a family of programming models that also offer implicit parallelism through a set of compiler annotations. It differs from OpenMP in some important areas. StarSs uses a different execution model, thread-pool where OpenMP implements fork-join parallelism. StarSs also includes features to target heterogeneous architectures while OpenMP only targets shared memory systems. Finally StarSs offers asynchronous parallelism as the main mechanism of expressing parallelism whereas OpenMP only started to implement it since its version 3.0.

StarSs raises the bar on how much implicitness is offered by the programming model. When programming using OpenMP, the developer first has to define which regions of the program will be executed on parallel, then he or she has to express how the inner code has to be executed by the threads forming the parallel region, and finally it may be required to add directives to synchronize the different parts of the parallel execution. StarSs simplifies part of this process by providing an environment where parallelism is implicitly created from the beginning of the execution, thus the developer can omit the declaration of parallel regions. The definition of parallel code is used using the concept of tasks, which are pieces of code which can be executed asynchronously in parallel. When it comes to synchronizing the different parallel regions of a StarSs applications, the programming model also offers a dependency mechanism which allows to express the correct order in which individual tasks must be executed to guarantee a proper execution. This mechanism enables a much richer expression of parallelism by StarSs than the one achieved by OpenMP, this makes StarSs applications to exploit the parallel resources more efficiently.

OmpSs tries to be the evolution that OpenMP needs in order to be able to target newer architectures. For this, OmpSs takes key features from OpenMP but also new ideas that have been developed in the StarSs family of programming models.

1.3 Influence in OpenMP

Many OmpSs and StarSs ideas have been introduced into the OpenMP programming model. The next figure summarizes our contributions:



Starting from the version 3.0, released on May 2008, OpenMP included the support for asynchronous tasks. The reference implementation, which was used to measure the benefits that tasks provided to the programming model, was developed at BSC and consisted on the Nanos4 run-time library and the Mercurium source-to-source compiler.

Our next contribution, which was included in OpenMP 4.0 (released on July 2013), was the extension of the tasking model to support data dependences, one of the strongest points of OmpSs that allows to define fine-grain synchronization among tasks.

In OpenMP 4.5, which is the newest version, the tasking model was extended with the `taskloop` construct. The reference implementation of this construct was developed at BSC. Apart from that, we also contributed to this version adding the `priority` clause to the `task` and `taskloop` constructs.

For the upcoming OpenMP versions, we plan to propose more tasking ideas that we already have in OmpSs like task reductions or new extensions to the tasking dependence model.

1.4 Glossary of terms

ancestor tasks The set of tasks formed by your *parent* task and all of its *ancestor tasks*.

base language The *base language* is the programming language in which the program is written.

child task A task is a child of the task which encounters its *task generating code*.

construct A *construct* is an executable directive and its associated statement. Unlike the OpenMP terminology, we will explicitly refer to the *lexical scope* of a constructor or the *dynamic extent* of a construct when needed.

data environment The *data environment* is formed by the set of variables associated with a given *task*.

declarative directive A directive that annotates a declarative statement.

dependence Is the relationship existing between a *predecessor task* and one of its *successor tasks*.

descendant tasks The descendant tasks of a given task is the set of all its child tasks and the descendant tasks of them.

device A device is an abstract component, including hardware and/or software elements, allowing to execute tasks. Devices may be accessed by means of the offload technique. That means that there are tasks generated in one device that may execute in a different device. All OmpSs programs have at least one device (i.e. the *host device*) with one or more processors.

directive In C/C++ a *#pragma* preprocessor entity.

In Fortran a comment which follows a given syntax.

dynamic extent The *dynamic extent* is the interval between establishment of the execution entity and its explicit disestablishment. Dynamic extent always obey to a stack-like discipline while running the code and it includes any code in called routines as well as any implicit code introduced by the OmpSs implementation.

executable directive A directive that annotates an executable statement.

expression Is a combination of one or more data components and operators that the base program language may understand.

function task In C, an task declared by a `task` directive at *file-scope* that comes before a *declaration* that declares a single function or comes before a *function-definition*. In both cases the *declarator* should include a parameter type list.

In C++, a task declared by a `task` directive at *namespace-scope* or *class-scope* that comes before a *function-definition* or comes before a *declaration* or *member-declaration* that declares a single function.

In Fortran, a task declared by a `task` directive that comes before a the `SUBROUTINE` statement of an *external-subprogram*, *internal-subprogram* or an *interface-body*.

host device The *host device* is the device in which the program begins its execution.

inline task In C/C++ an explicit task created by a `task` directive in a statement inside a *function-definition*.

In Fortran, an explicit task created by a `task` directive in the executable part of a *program unit*.

lexical scope The *lexical scope* is the portion of code which is lexically (i.e. textually) contained within the establishing construct including any implicit code lexically introduced by the OmpSs implementation. The lexical scope does not include any code in called routines.

outline tasks An outlined task is also know as a *function tasks*.

predecessor task A task becomes *predecessor* of another task(s) when there are dependence(s) between this task and the other ones (i.e. its *successor tasks*. That is, there is a restriction in the order the runtime must execute them: all *predecessor tasks* must complete before a *successor task* can be executed.

parent task The task that encountered a *task generating code* is the parent task of the new created task(s).

ready task pool Is the set of tasks ready to be executed (i.e. they are not blocked by any condition).

sliceable task A task that may generate other tasks in order to compute the whole computational unit.

slicer policy The slicer policy determines the way a sliceable task must be segmented.

structured block An executable statement with a single entry point (at the top) and a single exit point (at the bottom).

successor task A task becomes *successor* of another task(s) when there are dependence(s) between these tasks (i.e. its *predecessors tasks*) and itself. That is, there is a restriction in the order the runtime must execute them: all the *predecessor task* must complete before a *successor task* can be executed.

target device A device onto which tasks may be offloaded from the *host device* or other *target devices*. The ability of offloading tasks from a *target device* onto another *target device* is implementation defined.

task A task is the minimum execution entity that can be managed independently by the runtime scheduler (although a single task may be executed at different phases according with its *task switching points*). Tasks in OmpSs can be created by any *task generating code*.

task dependency graph The set of tasks and its relationships (*successor* / *predecessor*) with respect the correspondant scheduling restrictions.

task generating code The code which execution create a new task. In OmpSs it can occurs when encountering a `task` construct, a `loop` construct or when calling a routine annotated with a `task` declarative directive.

thread A thread is an execution entity that may execute concurrently with other threads within the same process. These threads are managed by the OmpSs runtime system. In OmpSs a thread executes tasks.

CHAPTER

TWO

PROGRAMMING MODEL

2.1 Execution model

The OmpSs runtime system creates a team of threads when starting the user program execution. This team of threads is called the initial team, and it is composed by a single master thread and several additional workers threads. The number of threads that forms the team depend on the number of workers the user have asked for. So, if the user have required 4 workers then one single master thread is created and three additional workers threads will be attached to that initial team.

The master thread, also called the initial thread, executes sequentially the user program in the context of an implicit task region called the initial task (surrounding the whole program). Meanwhile, all the other additional worker threads will wait until concurrent tasks were available to be executed.

Multiple threads execute tasks defined implicitly or explicitly by OmpSs directives. The OmpSs programming model is intended to support programs that will execute correctly both as parallel and as sequential programs (if the OmpSs language is ignored).

When any thread encounters a loop construct, the iteration space which belongs to the loop inside the construct is divided in different chunks according with the given schedule policy. Each chunk becomes a separate task. The members of the team will cooperate, as far as they can, in order to execute these tasks. There is a default `taskwait` at the end of each loop construct unless the `nowait` clause is present.

When any thread encounters a task construct, a new explicit task is generated. Execution of explicitly generated tasks is assigned to one of the threads in the initial team, subject to the thread's availability to execute work. Thus, execution of the new task could be immediate, or deferred until later according to task scheduling constraints and thread availability. Threads are allowed to suspend the current task region at a task scheduling point in order to execute a different task. If the suspended task region is for a tied task, the initially assigned thread later resumes execution of the suspended task region. If the suspended task region is for an untied task, then any thread may resume its execution.

The OmpSs specification makes no guarantee that input or output to the same file is synchronous when executed in parallel. In this case, the programmer is responsible for synchronizing input and output statements (or routines) using the provided synchronization constructs or library routines. For the case where each thread accesses a different file, no synchronization by the programmer is necessary

2.2 Memory model

One of the most relevant features of OmpSs is to handle architectures with disjoint address spaces. By disjoint address spaces we refer to those architectures where the memory of the system is not contained in a single address space. Examples of these architectures would be distributed environments like clusters of SMPs or heterogeneous systems built around accelerators with private memory.

2.2.1 Single address space view

OmpSs hides the existence of other address spaces present on the system. Offering the single address space view fits the general OmpSs philosophy of freeing the user from having to explicitly expose the underlying system resources. Consequently, a single OmpSs program can be run on different system configurations without any modification.

In order to correctly support these systems, the programmer has to specify the data that each task will access. Usually this information is the same as the one provided by the data dependencies, but there are cases where there can be extra data needed by the task that is not declared in the dependencies specification (for example because the programmer knows it is a redundant dependence), so OmpSs differentiates between the two mechanisms.

2.2.2 Specifying task data

A set of directives allows to specify the data that a task will use. The OmpSs run-time is responsible for guaranteeing that this data will be available to the task code when its execution starts. Each directive also specifies the directionality of the data. The data specification directives are the following:

- `copy_in(memory-reference-list)` The data specified must be available in the address space where the task is finally executed, and this data will be read only.
- `copy_out(memory-reference-list)` The data specified will be generated by the task in the address space where the task will be executed.
- `copy_inout(memory-reference-list)` The data specified must be available in the address space where the task runs, in addition, this data will be be updated with new values.
- `copy_deps` Use the data dependencies clauses (`in/out/inout`) also as if they were `copy_[in/out/inout]` clauses.

The syntax accepted on each clause is the same as the one used to declare data dependencies (see Dependence flow section). Each data reference appearing on a task code must either be a local variable or a reference that has been specified inside one of the copy directives. Also, similar to the specification of data dependencies, the data referenced is also limited by the data specified by the parent task, and the access type must respect the access type of the data specified by the parent. The programmer can assume that the implicit task that represents the sequential part of the code has a read and write access to the whole memory, thus, any access specified in a user defined top level task is legal. Failure to respect these restrictions will cause an execution error. Some of these restrictions limit the usage of complex data structures with this mechanism.

The following code shows an OmpSs program that defines two tasks:

```
float x[128];
float y[128];

int main () {
  for (int i = 0; i < N; i++) {
    #pragma omp target device(smp)
    #pragma omp task inout(x) copy_deps // implicit copy_inout(x)
    do_computation_CPU(x);

    #pragma omp target device(cuda)
    #pragma omp task inout(y) copy_deps // implicit copy_inout(x)
    do_computation_GPU(y);
  }
#pragma omp taskwait
  return 0;
}
```

One that must be run on a regular CPU, which is marked as `target device(smp)`, and the second which must be run on a CUDA GPU, marked with `target device(cuda)`. This OmpSs program can run on different system configurations, with the only restriction of having at least one GPU available. For example, it can run on a SMP machine with one or more GPUs, or a cluster of SMPs with several GPUs on each node. OmpSs will internally do the required data transfers between any GPU or node of the system to ensure that each tasks receives the required data. Also, there are no references to these disjoint address spaces, data is always referenced using a single address space. This address space is usually referred to as the host address space.

2.2.3 Accessing children task data from the parent task

Data accessed by children tasks may not be accessible by the parent task code until a synchronization point is reached. This is so because the status of the data is undefined since the children tasks accessing the data may not have completed the execution and the corresponding internal data transfers. The following code shows an example of this situation:

```
float y[128];

int main () {
  #pragma omp target device(cuda)
  #pragma omp task copy_inout(y)
  do_computation_GPU(y);

  float value0 = y[64]; // illegal access

  #pragma omp taskwait

  float value1 = y[64]; // legal access

  return 0;
}
```

The parent task is the implicitly created task and the child task is the single user defined task declared using the task construct. The first assignment (`value0 = y[64]`) is illegal since the data may be still in use by the child task, the `taskwait` in the code guarantees that following access to array `y` is legal.

Synchronization points, besides ensuring that the tasks have completed, also serve to synchronize the data generated by tasks in other address spaces, so modifications will be made visible to parent tasks. However, there may be situations when this behavior is not desired, since the amount of data can be large and updating the host address space with the values computed in other address spaces may be a very expensive operation. To avoid this update, the clause `noflush` can be used in conjunction with the synchronization `taskwait` construct. This will instruct OmpSs to create a synchronization point but will not synchronize the data in separate address spaces. The following code illustrates this situation:

```
float y[128];

int main() {
  #pragma omp target device(cuda)
  #pragma omp task copy_inout(y)
  do_computation_GPU(y);

  #pragma omp taskwait noflush
  float value0 = y[64]; // task has finished, but 'y' may not contain updated data

  #pragma omp taskwait
  float value1 = y[64]; // contains the computed values

  return 0;
}
```

The assignment `value0 = y[64]` may not use the results computed by the previous task since the `noflush` clause instructs the underlying run-time to not trigger data transfers from separate address spaces. The following access (`value1 = y[64]`) after the taskwait (withouth the `noflush` clause) will access the updated values.

The taskwait's dependence clauses (`in, out, inout and on`) can also be used to synchronize specific pieces of data instead of synchronizing the whole set of currently tracked memory. The following code shows an example of this scenario:

```
float x[128];
float y[128];

int main () {
  #pragma omp target device(cuda)
  #pragma omp task inout(x) copy_deps // implicit copy_inout(x)
  do_computation_GPU(x);

  #pragma omp target device(cuda)
  #pragma omp task inout(y) copy_deps // implicit copy_inout(y)
  do_computation_GPU(y);

  #pragma omp taskwait on(y)
  float value0 = x[64]; // may be a not updated value
  float value1 = y[64]; // this value has been updated

  ...
}
```

The value read by the definition of `value0` corresponds to the value already computed by one of the previous generated tasks (i.e. the one annotated with `inout(y) copy_deps`). However, the value read by the definition of `value1` may not corresponds with the updated value of `x`. The `taskwait` in this code only synchronizes data referenced in the clause `on` (i.e. the array `y`).

2.3 Data sharing rules

TBD .. ticket #17

2.4 Asynchronous execution

The most notable difference from OmpSs to OpenMP is the absence of the `parallel` clause in order to specify where a parallel region starts and ends. This clause is required in OpenMP because it uses a fork-join execution model where the user must specify when parallelism starts and ends. OmpSs uses the model implemented by StarSs where parallelism is implicitly created when the application starts. Parallel resources can be seen as a pool of threads–hence the name, thread-pool execution model–that the underlying run-time will use during the execution. The user has no control over this pool of threads, so the standard OpenMP methods `omp_get_num_threads()` or its variants are not available to use.

OmpSs allows the expression of parallelism through tasks. Tasks are independent pieces of code that can be executed by the parallel resources at run-time. Whenever the program flow reaches a section of code that has been declared as task, instead of executing the task code, the program will create an instance of the task and will delegate the execution of it to the OmpSs run-time environment. The OmpSs run-time will eventually execute the task on a parallel resource.

Another way to express parallelism in OmpSs is using the clause `for`. This clause has a direct counterpart in OpenMP and in OmpSs has an almost identical behavior. It must be used in conjunction with a for loop (in C or C++) and it

encapsulates the iterations of the given for loop into tasks, the number of tasks created is determined by the OmpSs run-time, however the user can specify the desired scheduling with the clause `schedule`.

Any directive that defines a task or a series of tasks can also appear within a task definition. This allows the definition of multiple levels of parallelism. Defining multiple levels of parallelism can lead to a better performance of applications, since the underlying OmpSs run-time environment can exploit factors like data or temporal locality between tasks. Supporting multi-level parallelism is also required to allow the implementation of recursive algorithms.

Synchronizing the parallel tasks of the application is required in order to produce a correct execution, since usually some tasks depend on data computed by other tasks. The OmpSs programming model offers two ways of expressing this: data dependencies, and explicit directives to set synchronization points.

2.5 Dependence flow

Asynchronous parallelism is enabled in OmpSs by the use data-dependencies between the different tasks of the program. OmpSs tasks commonly require data in order to do meaningful computation. Usually a task will use some input data to perform some operations and produce new results that can be later on be used by other tasks or parts of the program.

When an OmpSs programs is being executed, the underlying runtime environment uses the data dependence information and the creation order of each task to perform dependence analysis. This analysis produces execution-order constraints between the different tasks which results in a correct order of execution for the application. We call these constraints task dependences.

Each time a new task is created its dependencies are matched against of those of existing tasks. If a dependency, either Read-after-Write (RaW), Write-after-Write (WaW) or Write-after-Read(WaR), is found the task becomes a successor of the corresponding tasks. This process creates a task dependency graph at runtime. Tasks are scheduled for execution as soon as all their predecessor in the graph have finished (which does not mean they are executed immediately) or at creation if they have no predecessors.

The OpenMP task construct is extended with the `in` (standing for input), `out` (standing for output), `inout` (standing for input/output), `concurrent` and `commutative` clauses to this end. They allow to specify for each task in the program what data a task is waiting for and signaling is readiness. Note that whether the task really uses that data in the specified way its the programmer responsibility. The meaning of each clause is explained below:

- `in(memory-reference-list)`: If a task has an `in` clause that evaluates to a given lvalue, then the task will not be eligible to run as long as a previously created sibling task with an `out`, `inout`, `concurrent` or `commutative` clause applying to the same lvalue has not finished its execution.
- `out(memory-reference-list)`: If a task has an `out` clause that evaluates to a given lvalue, then the task will not be eligible to run as long as a previously created sibling task with an `in`, `out`, `inout concurrent` or `commutative` clause applying to the same lvalue has not finished its execution.
- `inout(memory-reference-list)`: If a task has an `inout` clause that evaluates to a given lvalue, then it is considered as if it had appeared in an `in` clause and in an `out` clause. Thus, the semantics for the `in` and `out` clauses apply.
- `concurrent(memory-reference-list)`: the `concurrent` clause is a special version of the `inout` clause where the dependencies are computed with respect to `in`, `out`, `inout` and `commutative` but not with respect to other concurrent clauses. As it relaxes the synchronization between tasks users must ensure that either tasks can be executed concurrently either additional synchronization is used.
- `commutative(memory-reference-list)`: If a task has a `commutative` clause that evaluates to a given lvalue, then the task will not become a member of the commutative task set for that lvalue as long as a previously created sibling task with an `in`, `out`, `inout` or `concurrent` clause applying to the same lvalue has not finished its execution. Given a non-empty commutative task set for a certain lvalue, any task of that set

may be eligible to run, but just one at the same time. Thus, tasks that are members of the same commutative task set are executed keeping mutual exclusion among them.

All of these clauses receive a list of memory references as argument. The syntax permitted to specify memory references is described in Language section. The data references provided by these clauses are commonly named the data dependencies of the task.

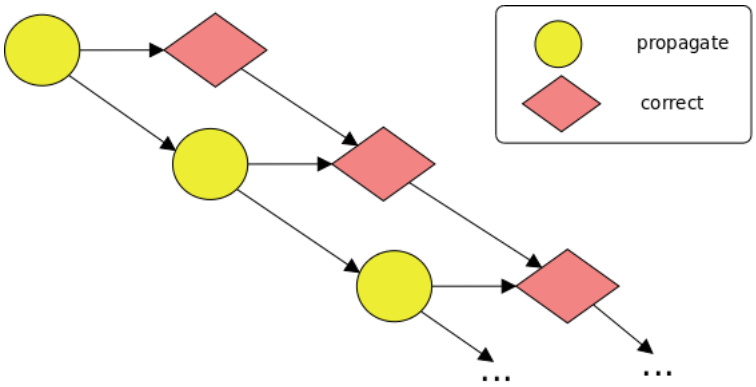
Note: For compatibility with earlier versions of OmpSs, you can use clauses `input` and `output` with exactly the same semantics of clauses `in` and `out` respectively.

The following example shows how to define tasks with task dependences:

```
void foo (int *a, int *b) {
  for (int i = 1; i < N; i++) {
#pragma omp task in(a[i-1]) inout(a[i]) out(b[i])
      propagate(&a[i-1], &a[i], &b[i]);

#pragma omp task in(b[i-1]) inout(b[i])
       correct(&b[i-1], &b[i]);
  }
}
```

This code generates at runtime the following task graph:



The following example shows how we can use the `concurrent` clause to parallelize a reduction over an array:

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

void reduce(int n, int *a, int *sum) {
  for (int i = 0; i < n; i++) {
#pragma omp task concurrent(*sum)
    {
#pragma omp atomic
      *sum += a[i];
    }
  }
}

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

```
  int sum = 0;
  reduce(N, a, &sum);

#pragma omp task in(sum)
printf("The sum of all elements of 'a' is: %d\n", sum);

#pragma omp taskwait
  return 0;
}
```

Note that all tasks that compute the sum of the values of 'a' may be executed concurrently. For this reason we have to protect with an atomic construct the access to the 'sum' variable. As soon as all of these tasks finish their execution, the task that prints the value of 'sum' may be executed.

Note that the previous example can also be implemented using the `commutative` clause (we only show the reduce function, the rest of the code is exactly the same):

```
void reduce(int n, int *a, int *sum) {
  for (int i = 0; i < n; i++) {
#pragma omp task commutative(*sum)
      *sum += a[i];
  }
}
```

Note that using the `commutative` clause only one task of the commutative task set may be executed at the same time. Thus, we don't need to add any synchronization when we access to the 'sum' variable.

2.5.1 Extended lvalues

All dependence clauses allow extended lvalues from those of C/C++. Two different extensions are allowed:

- Array sections allow to refer to multiple elements of an array (or pointed data) in single expression. There are two forms of array sections:
  - `a[lower : upper]`. In this case all elements of 'a' in the range of lower to upper (both included) are referenced. If no lower is specified it is assumed to be 0. If the array section is applied to an array and upper is omitted then it is assumed to be the last element of that dimension of the array.
  - `a[lower; size]`. In this case all elements of 'a' in the range of lower to lower+(size-1) (both included) are referenced.
- Shaping expressions allow to recast pointers into array types to recover the size of dimensions that could have been lost across function calls. A shaping expression is one or more `[size]` expressions before a pointer.

The following example shows examples of these extended expressions:

```
void sort(int n, int *a) {
  if (n < small) seq_sort(n, a);

#pragma omp task inout(a[0:(n/2)-1]) // equivalent to inout(a[0;n/2])
      sort(n/2, a);
#pragma omp task inout(a[n/2:n-1]) // equivalent to inout(a[n/2;n-(n/2)])
      sort(n/2, &a[n/2]);
#pragma omp task inout(a[0:(n/2)-1], a[n/2:n-1])
      merge (n/2, a, a, &a[n/2]);
#pragma omp taskwait
}
```

Note: Our current implementation only supports array sections that completely overlap. Implementation support for partially overlapped sections is under development.

Note that these extensions are only for C/C++, since Fortran supports, natively, array sections. Fortran array sections are supported on any dependence clause as well.

2.5.2 Dependences on the taskwait construct

In addition to the dependencies mechanism, there is a way to set synchronization points in an OmpSs application. These points are defined using the `taskwait` directive. When the control flow reaches a synchronization point, it waits until all previously created sibling tasks complete their execution.

OmpSs also offers synchronization point that can wait until certain tasks are completed. These synchronization points are defined adding any kind of task dependence clause to the taskwait construct.

In the following example we have two tasks whose execution is serialized via dependences: the first one produces the value of `x` whereas the second one consumes `x` and produces the value of `y`. In addition to this, we have a taskwait construct annotated with an input dependence over `x`, which enforces that the execution of the region is suspended until the first task complete execution. Note that this construct does not introduce any restriction on the execution of the second task:

```
int main() {
  int x = 0, y = 2;

  #pragma omp task inout(x)
  x++;

  #pragma omp task in(x) inout(y)
  y -= x;

  #pragma omp taskwait in(x)
  assert(x == 1);

  // Note that the second task may not be executed at this point

  #pragma omp taskwait
  assert(x == y);
}
```

Note: For compatibility purposes we also support the `on` clause on the taskwait construct, which is an alias of `inout`.

2.5.3 Multidependences

Multidependences is a powerful feature that allow us to define a dynamic number of any kind of dependences. From a theoretical point of view, a multidependence consists on two different parts: first, an lvalue expression that contains some references to an identifier (the iterator) that doesn't exist in the program and second, the definition of that identifier and its range of values. Depending on the base language the syntax is a bit different:

- `dependence-type({memory-reference-list, iterator-name = lower; size})` for C/C++.
- `dependence-type([memory-reference-list, iterator-name = lower, size])` for Fortran.

Despite having different syntax for C/C++ and Fortran, the semantics of this feature is the same for the 3 languages: the lvalue expression will be duplicated as many times as values the iterator have and all the references to the iterator will be replaced by its values.

The folllowing code shows how to define a multidependence in C/C++:

```
void foo(int n, int *v)
{
// This dependence is equivalent to inout(v[0], v[1], ..., v[n-1])
#pragma omp task inout({v[i], i=0;n})
    {
        int j;
        for (int j = 0; j < n; ++j)
            v[j]++;
    }
}
```

And a similar code in Fortran:

```
subroutine foo(n, v)
    implicit none
    integer :: n
    integer :: v(n)

    ! This dependence is equivalent to inout(v[1], v[2], ..., v[n])
    !$omp task inout([v(i), i=1, n])
        v = v + 1
    !$omp end task
end subroutine foo
```

Warning: Multidependences syntax may change in a future

2.6 Task scheduling

When the current executed task reaches a *task scheduling point*, the implementation may decide to switch from this task to another one from the set of eligible tasks. Task scheduling points may occur at the following locations:

- in a task generating code
- in a taskyield directive
- in a taskwait directive
- just after the completion of a task

The fact of switching from a task to a different one is known as *task switching* and it may imply to begin the execution of a non-previously executed task or resumes the execution of a partially executed task. Task switching is restricted in the following situations:

- the set of eligible tasks (at a given time) is initially formed by the set of tasks included in the ready task pool (at this time).
- once a tied task has been executed by a given thread, it can be only resumed by the very same thread (i.e. the set of eligible tasks for a thread does not include tied tasks that has been previously executed by a different thread).
- when creating a task with the if clause for which expression evaluated to false, the runtime must offer a mechanism to immediately execute this task (usually by the same thread that creates it).

- when executing in a final context all the encountered *task generating codes* will execute the task immediately after creating it as if it was a simple routine call (i.e. the set of eligible tasks in this situation is restricted to include only the newly generated task).

Note: Remember that the *ready task pool* does not include tasks with dependences still not fulfilled (i.e. not all its predecessors have finished yet) or blocked tasks in any other condition (e.g. tasks executing a taskwait with non-finished child tasks).

2.7 Task reductions

The reduction clause allow us to define an asynchronous task reduction over a list of items. For each item, a private copy is created for each thread that participates in the reduction. At task synchronization (dependence or `taskwait`), the original list item is updated with the values of the private copies by applying the combiner associated with the `reduction-identifier`. Consequently, the scope of a reduction begins when the first reduction task is created and ends at a task synchronization point. This region is called the reduction domain.

The `taskwait` construct specifies a wait on the completion of child tasks in the context of the current task and combines all privately allocated list items of all child tasks associated with the current reduction domain. A `taskwait` therefore represents the end of a domain scope.

The following example computes the sum of all values of the nodes of a linked-list. The final result of the reduction is computed at the `taskwait`:

```
struct node_t {
  int val;
  struct node_t* next;
};

int sum_values(struct node_t* node) {
  int red=0;
  struct node_t* current = node;

  while (current != 0) {
#pragma omp task reduction(+: red)
    {
      red += current->val;
    }
    node = node->next;
  }
#pragma omp taskwait

  return red;
}
```

Data-flow based task execution allows a streamline work scheduling that in certain cases results in higher hardware utilization with relatively small development effort. Task-parallel reductions can be easily integrated into this execution model but require the following assumption. A list item declared in the task reduction directive is considered as if declared `concurrent` by the depend clause.

In the following code we can see an example where a reduction domain begins with the first occurrence of a participating task and is implicitly ended by a dependency of a successor task.:

```
#include<assert.h>

int main(int argc, char *argv[]) {
```

```
  const int SIZE  = 1024;
  const int BLOCK =   32;
  int array[SIZE];

  int i;

  for (i = 0; i < SIZE; ++i)
    array[i] = i+1;

  int red = 0;
  for (int i = 0; i < SIZE; i += BLOCK) {
#pragma omp task shared(array) reduction(+:red)
    {
      for (int j = i; j < i+BLOCK; ++j)
        red += array[j];
    }
  }
#pragma omp task in(red)
    assert(red == ((SIZE * (SIZE+1))/2));

#pragma omp taskwait
}
```

Nested task constructs typically occur in two cases. In the first, each task at each nesting level declares a reduction over the same variable. This is called multilevel reduction. It is important to point out that only task synchronization that occurs at the same nesting level at which a reduction scope was created (that is the nesting level that first encounter a reduction task for a list item), ends the scope and reduces private copies. Within the reduction domain, the value of the reduction variable is unspecified.

In the second occurrence each nesting level reduces over a different reduction variable. This happens for example if a nested task performs a reduction on task local data. In this case a `taskwait` at the end of each nesting level is required. We call this occurrence a nested-domain reduction.

2.8 Runtime Library Routines

OmpSs uses runtime library routines to set and/or check the current execution environment, locks and timing services. These routines are implementation defined and you can find a list of them in the correspondant runtime library user guide.

2.9 Environment Variables

OmpSs uses environment variables to configure certain aspects of its execution. The set of these variables is implementation defined and you can find a list of them in the correspondant runtime library user guide.

CHAPTER

THREE

LANGUAGE DESCRIPTION

This section describes the OmpSs language, this is, all the necessary elements to understand how an application programmed in OmpSs executes and/or behaves in a parallel architecture. OmpSs provides a simple path for users already familiarized with the OpenMP programming model to easily write (or port) their programs to OmpSs.

This description is completely guided by the list of OmpSs directive constructs. In each of the following sections we will find a short description of the directive, its specific syntax, the list of its clauses (including the list of valid parameters for each clause and a short description for them). In addition, each section finalizes with a simple example showing how this directive can be used in a valid OmpSs program.

As is the case of OpenMP in C and C++, OmpSs directives are specified using the *#pragma* mechanism (provided by the base language) and in Fortran they are specified using special comments that are identified by a unique sentinel. The sentinel used in OmpSs (as is the case of OpenMP) is *omp*. Compilers will typically ignore OmpSs directives if support is disabled or not provided.

3.1 Task construct

The programmer can specify a task using the `task` construct. This construct can appear inside any code block of the program, which will mark the following statement as a task.

The syntax of the `task` construct is the following:

```
#pragma omp task [clauses]
structured-block
```

The valid clauses for the `task` construct are:

- private(<list>)
- firstprivate(<list>)
- shared(<list>)
- depend(<type>: <memory-reference-list>)
- <depend-type>(<memory-reference-list>)
- priority(<value>)
- if(<scalar-expression>)
- final(<scalar-expresion>)
- label(<string>)
- tied

The `private` and `firstprivate` clauses declare one or more list items to be private to a task (i.e. the task receives a new list item). All internal references to the original list item are replaced by references to this new list item.

List items privatized using the `private` clause are uninitialized when the execution of the task begins. List items privatized using the `firstprivate` clause are initialized with the value of the corresponding original item at task creation.

The `shared` clause declare one or more list items to be shared to a task (i.e. the task receives a reference to the original list item). The programmer must ensure that shared storage does not reach the end of its lifetime before tasks referencing this storage have finished.

The `depend` clause allows to infer additional task scheduling restrictions from the parameters it defines. These restrictions are known as dependences. The syntax of the `depend` clause include a dependence type, followed by colon and its associated list items. The list of valid type of dependences are defined in section "Dependence flow" in the previous chapter. In addition to this syntax, OmpSs allows to specify this information using as the name of the clause the type of dependence. Then, the following code:

```
#pragma omp task depend(in: a,b,c) depend(out: d)
```

Is equivalent to this one:

```
#pragma omp task in(a,b,c) out(d)
```

If the expression of the `if` clause evaluates to *true*, the execution of the new created task can be deferred, otherwise the current task must suspend its execution until the new created task has complete its execution.

If the expression of the `final` clause evaluates to *true*, the new created task will be a final tasks and all the *task generating code* encountered when executing its *dynamic extent* will also generate final tasks. In addition, when executing within a final task, all the encountered *task generating codes* will execute these tasks immediately after its creation as if they were simple routine calls. And finally, tasks created within a final task can use the data environment of its parent task.

The `tied` clause defines a new task scheduling restriction for the newly created tasks. Once a thread begins the execution of this task, the task becomes tied to this thread. In the case this task has suspended its execution by any *task scheduling point* only the same thread (i.e. the thread to which the task is tied to) may resume its execution.

The `label` clause defines a string literal that can be used by any performance or debugger tool to identify the task with a more *human-readable* format.

The following C code shows an example of creating tasks using the `task` construct:

```
float x = 0.0;
float y = 0.0;
float z = 0.0;

int main() {

  #pragma omp task
  do_computation(x);

  #pragma omp task
  {
    do_computation(y);
    do_computation(z);
  }

  return 0;
}
```

When the control flow reaches `#pragma omp task` construct, a new task instance is created, however when the program reaches `return 0` the previously created tasks may not have been executed yet by the OmpSs run-time.

The task construct is extended to allow the annotation of function declarations or definitions in addition to structured-blocks. When a function is annotated with the task construct each invocation of that function becomes a task creation point. Following C code is an example of how task functions are used:

```
extern void do_computation(float a);
#pragma omp task
extern void do_computation_task(float a);

float x = 0.0;
int main() {
   do_computation(x); //regular function call
   do_computation_task(x); //this will create a task
   return 0;
}
```

Invocation of `do_computation_task` inside `main` function create an instance of a task. As in the example above, we cannot guarantee that the task has been executed before the execution of the `main` finishes.

Note that only the execution of the function itself is part of the task not the evaluation of the task arguments. Another restriction is that the task is not allowed to have any return value, that is, the return must be void.

3.2 Target construct

To support heterogeneity a new construct is introduced: the target construct. The intent of the target construct is to specify that a given element can be run in a set of devices. The target construct can be applied to either a task construct or a function definition. In the future we will allow to allow it to work on worksharing constructs.

The syntax of the `target` construct is the following:

```
#pragma omp target [clauses]
task-construct  | function-definition | function-header
```

The valid clauses for the `target` construct are the following:

- device(target-device) - It allows to specify on which devices should be targeting the construct. If no device clause is specified then the SMP device is assumed. Currently we also support the CUDA device that allows the execution of native CUDA kernels in GPGPUs.
- copy_in(list-of-variables) - It specifies that a set of shared data may be needed to be transferred to the device before the associated code can be executed.
- copy_out(list-of-variables) - It specifies that a set of shared data may be needed to be transferred from the device after the associated code is executed.
- copy_inout(list-of-variables) - This clause is a combination of copy_in and copy_out.
- copy_deps - It specifies that if the attached construct has any dependence clauses then they will also have copy semantics (i.e., in will also be considered copy_in, output will also be considered copy_out and inout as copy_inout).
- implements(function-name) - It specifies that the code is an alternate implementation for the target devices of the function name specified in the clause. This alternate can be used instead of the original if the implementation considers it appropriately.

Additionally, both SMP and CUDA tasks annotated with the target construct are eligible for execution a cluster environment in an experimental implementation. Please, contact us if you are interested in using it.

3.3 Loop construct

When a task encounters a loop construct it starts creating tasks for each of the chunks in which the loop's iteration space is divided. Programmers can choice among different schedule policies in order to divide the iteration space.

The syntax of the `loop` construct is the following:

```
#pragma omp for [clauses]
loop-block
```

The valid clauses for the `loop` construct are the following:

- schedule(schedule-policy[, chunk-size]) - It specifies one of the valid partition policies and, optionally, the chunk-size used to divide the iteration space. Valid schedule policies are one the following options:
  - dynamic - loop is divided to team's threads in tasks of chunk-size granularity. Tasks are assigned as threads request them. Once a thread finishes the execution of one of these tasks it will request another task. Default chunk-size is 1.
  - guided - loop is divided as the executing threads request them. The chunk-size is proportional to the number of unassigned iterations, so it starts to be bigger at the beginning, but it becomes smaller as the loop execution progresses. Chunk-size will never be smaller than chunk-size parameter (except for the last iteration chunk).
  - static - loop is divided into chunks of size chunk-size. Each task is divided among team's threads following a round-robin fashion. If no chunk-size is provided all the iteration space is divided by number-of-threads chunks of the same size (or proximately the same size if number-of-threads does not divide number-of-iterations).
- nowait - When this option is specified the encountering task can immediately proceed with the following code without wait for all the tasks created to execute each of the loop's chunks.

Following C code shows an example on loop distribution:

```
float x[10];
int main() {
#pragma omp for schedule(static)
   for (int i = 0; i < 10; i++) {
      do_computation(x[i]);
   }
   return 0;
}
```

3.4 Taskwait construct

Apart from implicit synchronization (task dependences) OmpSs also offers mechanism which allow users to synchronize task execution. `taskwait` construct is an stand-alone directive (with no code block associated) and specifies a wait on the completion of all direct descendant tasks.

The syntax of the `taskwait` construct is the following:

```
#pragma omp taskwait [clauses]
```

The valid clauses for the `taskwait` construct are the following:

- on(list-of-variables) - It specifies to wait only for the subset (not all of them) of direct descendant tasks. `taskwait` with an `on` clause only waits for those tasks referring any of the variables appearing on the list of variables.

The `on` clause allows to wait only on the tasks that produces some data in the same way as in clause. It suspends the current task until all previous tasks with an out over the expression are completed. The following example illustrates its use:

```
int compute1 (void);

int compute2 (void);

int main()
{
  int result1, result2;

#pragma omp task out(result1)
  result1 = compute1();

#pragma omp task out(result2)
  result2 = compute2();

#pragma omp taskwait on(result1)
  printf("result1 = %d\n",result1);

#pragma omp taskwait on(result2)
  printf("result2 = %d\n",result2);

  return 0;
}
```

3.5 Taskyield directive

The `taskyield` directive specifies that the current task can be suspended and the scheduler runtime is allowed to scheduler a different task. The `taskyield` explicitly includes a *task schedule point*.

The syntax of the `taskyield` directive is the following:

```
#pragma omp taskyield
```

The `taskyield` directive has no related clauses.

In the following example we can see how to use the `taskyield` directive:

```
void compute ( void ) {
   int a=0,b=0;

   #pragma omp task shared(a)
   { a++;}

   #pragma omp taskyield

   #pragma omp task shared(b)
   { b++; }

   #pragma omp taskwait
}

int main() {
   #pragma omp task
   compute();
```

```
   #pragma omp taskwait
   return 0;
}
```

When encountering the `taskyield` directive the runtime system may decide among continue execute the task compute (i.e. the current task) or begins the execution of the a++ task (if not yet executed).

3.6 Atomic construct

The atomic construct ensures that following expression is executed atomically. Runtime systems will use native machine mechanism to guarantee atomic execution. If there is no native mechanism to guarantee atomicity (e.g. function call) it will use a regular critical section to implement the atomic construct.

The syntax of the `atomic` construct is the following:

```
#pragma omp atomic
structured-block
```

Atomic construct has no related clauses.

3.7 Critical construct

The `critical` construct allows programmers to specify regions of code that will be executed in mutual exclusion. The associated region will be executed by a single thread at a time, other threads will wait at the beginning of the critical section until no thread in the team was executing it.

The syntax of the `critical` construct is the following:

```
#pragma omp critical
structured-block
```

Critical construct has no related clauses.

3.8 Declare reduction construct

The user can define its own reduction-identifier using the `declare reduction` directive. After declaring the UDR, the reduction-identifier can be used in a reduction clause. The syntax of this directive is the following one:

```
#pragma omp declare reduction(reduction-identifier : type-list : combiner-expr) [initializer(init-exp
```

where:

- *reduction-identifier* is the identifier of the reduction which is being declared
- *type-list* is a list of types
- *combiner-expr* is the expression that specifies how we have to combine the partial results. We can use two predefined identifiers in this expression: *omp_out* and *omp_in*. The *omp_out* identifier is used to represent the result of the combination whereas the *omp_in* identifier is used to represent the input data.
- *init-expr* is the expression that specifies how we have to initialize the private copies. We can use also two predefined identifiers in this expression: *omp_priv* and *omp_orig*. The *omp_priv* identifier is used to represent a private copy whereas the *omp_orig* identifier is used to represent the original variable that is being involved in a reduction.

In the following example we can see how we declare a UDR and how we use it:

```
struct C {
    int x;
};

void reducer(struct C* out, struct C* in) {
    (*out).x += (*in).x;
}

#pragma omp declare reduction(my_UDR : struct C : reducer(&omp_out,&omp_in)) initializer(omp_priv =

int main() {
    struct C res = { 0 };
    struct C v[N];

    init(&v);

    for (int i = 0; i < N; ++i) {
#pragma omp task reduction(my_UDR : res) in(v) firstprivate(i)
        {
           res.x += v[i].x;
        }
    }
#pragma omp taskwait
}
```

[OPENMP30] OpenMP Application Program Interface, version 3.0 May 2008