
OmpSs-2 Specification

Release

BSC Programming Models

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INTRODUCTION

OmpSs-2 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-2 extends the tasking model of OmpSs/OpenMP to support both task nesting and fine-grained dependences across different nesting levels, which enables the effective parallelization of applications using a top-down methodology.

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 run-time this information can be used to determine if the parallel execution of two tasks may cause data races.

The goal of OmpSs-2 is to provide a productive environment to develop applications for modern High-Performance Computing (HPC) systems. Two concepts add to make OmpSs-2 a productive programming model: performance and ease of use. Programs developed in OmpSs-2 must be able to deliver a reasonable performance when compared to other programming models targeting the same architecture(s). Ease of use is a concept difficult to quantify but OmpSs-2 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/or API services or general features to better support asynchronous data-flow parallelism and heterogeneity. These are, currently, the most prominent features introduced in the OmpSs-2 programming model:

- **Lifetime of task data environment:** A task is completed once the last statement of its body is executed. It becomes deeply completed when also all its children become deeply completed. The data environment of a task, which includes all the variables captured when the task is created, is preserved until the task is deeply completed. Notice that the stack of the thread that is executing the task is NOT part of the task data environment.
- **Nested dependency domain connection:** Incoming dependences of a task propagate to its children as if the task did not exist. When a task finishes, its outgoing dependences are replaced by those generated by its children.
- **Early release of dependences:** By default, once a task is completed it will release all the dependences that are not included on any unfinished descendant task. If the wait clause is specified in the task construct, all its dependences will be released at once when the task becomes deeply completed.
- **Weak dependences:** The weakin/weakout clauses specify potential dependences only required by descendant tasks. These annotations do not delay the execution of the task.
- **Native offload API:** A new asynchronous API to execute OmpSs-2 kernels on a specified set of CPUs from any kind of application, including Java, Python, R, etc.
- **Task Pause/Resume API:** A new API that can be used to programmatically suspend and resume the execution of a task. It is currently used to improve the interoperability and performance of hybrid MPI and OmpSs-2 applications.

1.1 Reference implementation

The reference implementation of OmpSs-2 is based on the Mercurium source-to-source compiler and the Nanos6 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 *Nanos6* run-time system 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

OmpSs-2 is the second generation of the OmpSs programming model. The name originally comes from two other programming models: OpenMP and StarSs. The design principles of these two programming models constitutes the fundamental ideas used to conceive the OmpSs philosophy.

OmpSs takes from OpenMP its viewpoint 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.

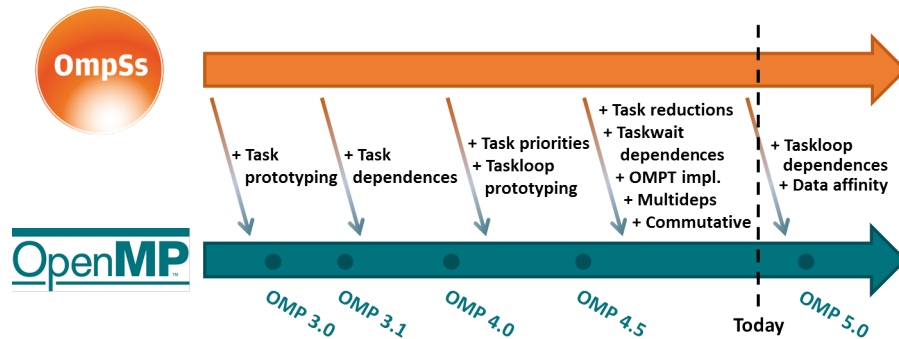
StarSs, or Star SuperScalar, is a family of programming models that also offer implicit parallelism through a set of compiler annotations. It differs from OpenMP in some important areas. StarSs uses a different execution model, thread-pool where OpenMP implements fork-join parallelism. StarSs also includes features to target heterogeneous architectures through leveraging native kernels implementation while OpenMP targets accelerator support through direct compiler code generation. Finally StarSs offers asynchronous parallelism as the main mechanism of expressing parallelism whereas OpenMP only started to implement it since its version 3.0. Also StarSs offers task synchronization by means of dependences as the main mechanism of expressing the task execution order, enabling the look-ahead instantiation of task whereas OpenMP included it since its version 4.0.

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 in the standard:



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. This feature was tested using Mercurium source-to-source compiler and the [Nanos++ RTL](#).

In OpenMP 4.5 (released on November 2015, and current version), the tasking model was extended with the `taskloop` construct using Nanos++ as the reference implementation to validate these ideas. BSC also contributed to version 4.5 adding the `priority` clause to `task` and `taskloop` constructs.

Upcoming versions of OpenMP will include: `task reductions`, as a way to use tasks as the participants of a reduction operation; `iterators` and `multidependences`, mechanism to specify a variable number of dependences for a task instance; `taskwait dependences`, to relax the set of descendants we need to wait for before proceeding with the `taskwait` construct; and the `mutexinoutset` (a.k.a. `commutative`), a new type of dependence to support mutually exclusive tasks. The Nanos++ RTL was also used to validate the new interface included in the OpenMP standard with respect third party tools.

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.

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-2 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*.

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-2 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 run-time system 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).

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 run-time system must execute them: all the *predecessor task* must complete before a *successor task* can be executed.

task A task is the minimum execution entity that can be managed independently by the run-time scheduler (although a single task may be executed at different phases according with its *task scheduling points*). Tasks in OmpSs-2 can be created by any *task generating code*.

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

task generating code The code which execution create a new task. In OmpSs-2 it can occurs when encountering a `task` construct, a `loop` construct or when calling a routine annotated with a `task` declarative directive.

task scheduling point The different points in wich the run-time system may suspend the execution of the current task and execute a different one.

PROGRAMMING MODEL

2.1 Execution model

The most notable difference from OmpSs-2 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-2 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.

| |
|---|
| <p>Warning: The user has no control over this pool of threads, so the standard OpenMP methods <code>omp_get_num_threads()</code> or its variants are not available to use.</p> |
|---|

At the beginning of the execution, the OmpSs-2 run-time system creates an initial pool of worker threads (i.e., there is no master thread in OmpSs-2). The main function is wrapped in an implicit task, which is called the main task, and it is added into the queue of ready tasks. Then, one of the worker threads gets that task from the queue, and it starts executing it. Meanwhile, the rest of threads wait for more ready tasks, which could be instantiated by the main task or other running tasks.

Multiple threads execute tasks that are defined implicitly or explicitly by annotating programs with OmpSs-2 directives. The OmpSs-2 programming model is intended to support programs that will execute correctly both as parallel and as sequential programs (if the OmpSs-2 language is ignored).

OmpSs-2 allows the expression of parallelism through tasks. Tasks are independent pieces of code that can be executed by parallel resources at run-time. Whenever the program flow reaches a section of code that has been declared as a task, instead of executing the task's body code, the program will create an instance of the task and will delegate its execution to the OmpSs-2 run-time system. The OmpSs-2 run-time system will eventually execute the task on a parallel resource. The execution of this explicitly generated tasks is assigned to one of the worker threads in the pool of threads, subject to the thread's availability to execute work. Thus, the 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.

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-2 run-time system can exploit factors like data or temporal locality between tasks. Supporting multi-level parallelism is also required to allow the implementation of recursive algorithms.

The synchronization of tasks of an 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.

Regular OmpSs-2 applications are linked as whole OmpSs-2 applications, however, the run-time system also has a library mode. In library mode, there is no implicit task for the `main` function. Instead, the user code defines functions

that contain regular OmpSs-2 code (i.e., tasks, ...), and offloads them to the run-time system through an API. In this case, the code is not linked as an OmpSs-2 application, but as a regular application that is linked to the run-time library.

2.2 Data sharing attributes

OmpSs-2 allows to specify the **explicit data sharing attributes** for the variables referenced in a construct body using the following clauses:

- `private(<list>)`
- `firstprivate(<list>)`
- `shared(<list>)`

The `private` and `firstprivate` clauses declare one or more variables to be private to the construct (i.e., a new variable will be created). All internal references to the original variable are replaced by references to this new variable. Variables privatized using the `private` clause are uninitialized when the execution of the construct body begins. Variables privatized using the `firstprivate` clause are initialized with the value of the corresponding original variable when the construct was encountered.

The `shared` clause declares one or more variables to be shared to the construct (i.e., the construct still will refer the original variable). Programmers must ensure that shared variables do not reach the end of their lifetime before other constructs referencing them have finished.

There are a few exceptions in which the data sharing clauses can not be used on certain variables due the nature of the symbol. In these cases we talk about **pre-determined data sharing attributes** and they are defined by the following rules:

- Dynamic storage duration objects are shared (e.g., `malloc`, `new`, ...).
- Static data members are shared.
- Variables declared inside the construct body with static storage duration are shared.
- Variables declared inside the construct body with automatic storage duration are private.
- The loop iteration variable(s) of a `task for` construct is/are private.

When the variable does not have a *pre-determined behaviour* and it is not referenced by any of the *explicit data sharing rules* it is considered to have an **implicit data sharing attribute** according with the following rules:

- If the variable appears in a `depend` clause, the variable will be shared.
- If a `default` clause is present in the construct, the implicit data sharing attribute will be the one defined as a parameter of this clause.
- If no `default` clause is present and the variable was private/local in the context encountering the construct, the variable will be `firstprivate`.
- If no `default` clause is present and the variable was shared/global in the context encountering the construct, the variable will be shared.

The `default (none)` clause disables all implicit data sharing attributes of a construct, which forces the user to specify the data sharing attribute of each variable that appears inside the construct body.

2.3 Dependence model

Asynchronous parallelism is enabled in OmpSs-2 by the use data-dependencies between the different tasks of the program. OmpSs-2 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 used by other tasks or parts of the program.

When an OmpSs-2 program is being executed, the underlying run-time system 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 run-time. Tasks are scheduled for execution as soon as all their predecessors in the graph have finished (which does not mean they are executed immediately) or at creation if they have no predecessors.

In the general case, the statement that follows the pragma is to be executed asynchronously. Whenever a thread encounters a task construct, it instantiates the task and resumes its execution after the construct. The task instance can be executed either by that same thread at some other time or by another thread. The semantics can be altered through additional clauses and through the properties of the enclosing environment in which the task is instantiated.

Dependencies allow tasks to be scheduled after other tasks using the `depend` clause. 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 is a responsibility of the programmer.

The `depend` clause admits the following keywords: `in`, `out`, `inout`, `concurrent` or `commutative`. The keyword is followed by a colon and a comma separated list of elements (memory references). 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.

The semantics of the `depend` clause are also extended with the `in` (standing for input), `out` (standing for output), `inout` (standing for input/output), `concurrent` and `commutative` clauses to this end. All these clauses also admit a comma separated list of elements (memory references) as described in the previous paragraph.

The meaning of each clause/keyword 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.

The usual scope of the dependency calculation is restricted to that determined by the enclosing (possibly implicit) task. That is, the contents of the `depend` clause of two tasks can determine dependencies between them only if they share

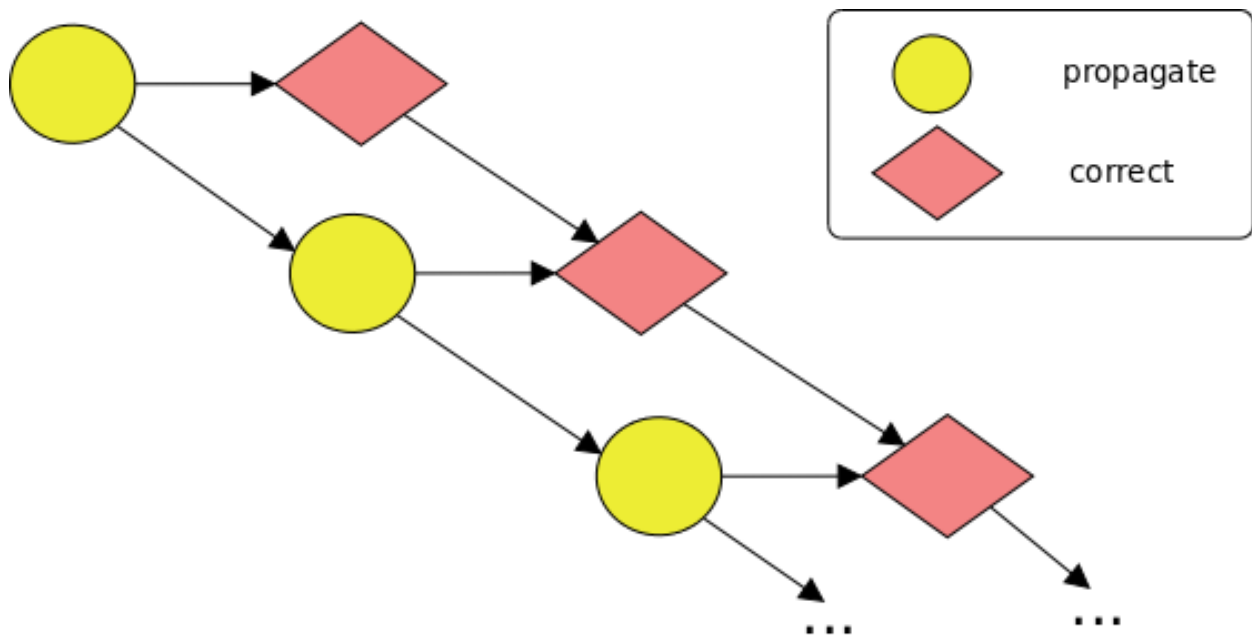
the same parent task. In this sense, tasks define an inner dependency domain into which to calculate the dependencies between its direct children. However, OmpSs-2 improves the combination of data dependencies and task nesting, as will be explained in the next sections.

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

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

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

This code generates at run-time 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 oss task concurrent(*sum)
    {
      #pragma oss 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 oss task in(sum)
printf("The sum of all elements of 'a' is: %d\n", sum);

#pragma oss 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.

The following example shows how we can use the `commutative` clause:

```

#include <stdio.h>

int main() {
    int a;

    #pragma oss task out(a) // Task T1
    a = 10;

    #pragma oss task commutative(a) // Task T2
    printf("Intermediate alue of 'a': %d\n", a++);

    #pragma oss task commutative(a) // Task T3
    printf("Intermediate value of 'a': %d\n", a++);

    #pragma oss task in(a) // Task T4
    printf("Final value of 'a' is: %d\n", a);

    #pragma oss taskwait
    return 0;
}

```

Note that the commutative tasks (T2 and T3) will be executed after the task that initializes `a` (T1), and before the task that prints the final value of `a` (T4). No execution order of the commutative tasks is not guaranteed but they will not be executed at the same time by definition. Thus, it is safe to modify the value of `a` inside those tasks.

2.3.1 Combining task nesting and dependencies

Being able to combine task nesting and dependences is important for programmability. The code below shows an example that combines nesting and dependencies with two levels of tasks. For brevity, the inner tasks do not have dependencies between their siblings.

```

#pragma oss task inout(a, b) // Task T1
{
    a++; b++;
    #pragma oss task inout(a) // Task T1.1
    a += ...;
    #pragma oss task inout(b) // Task T1.2
    b += ...;
}

```

```
#pragma oss task in(a, b) out(z, c, d) // Task T2
{
  z = ...;
  #pragma oss task in(a) out(c) // Task T2.1
  c = ... + a + ...;
  #pragma oss task in(b) out(d) // Task T2.2
  d = ... + b + ...;
}
#pragma oss task in(a, b, d) out(e, f) // Task T3
{
  #pragma oss task in(a, d) out(e) // Task T3.1
  e = ... + a + d + ...;
  #pragma oss task in(b) out(f) // Task T3.2
  f = ... + b + ...;
}
#pragma oss task in(c, d, e, f) // Task T4
{
  #pragma oss task in(c, e) // Task T4.1
  ... = ... + c + e + ...;
  #pragma oss task in(d, f) // Task T4.2
  ... = ... + d + f + ...;
}
#pragma oss taskwait
```

To parallelize the original code using a top-down approach we would perform the following steps. First, we would add the pragmas of the outer tasks. Since they have conflicting accesses over some variables, we add the corresponding dependency clauses (e.g., `in` and `out`) for each of their accessed variables. In general, it is a good practice to have entries to protect all the accesses of a task. Doing this reduces the burden on the programmer, improves the maintainability of the code and reduces the chances to overlook conflicting accesses.

Then, inside each task, we identify separate functionalities and convert each into a task. If we follow the same approach, the depend clause of each inner task will contain entries to protect its own accesses.

When we consider how the depend clauses are composed, we observe that outer tasks contain a combination of elements to protect their own accesses and elements that are only needed by their subtasks. This is necessary to avoid data-races between subtasks with different parents. Note that parent tasks do not execute a `taskwait` at the end of their task body. Unlike OpenMP and OmpSs, OmpSs-2 automatically links the dependency domain of a task with that of its subtasks. Once a task finishes its execution, the dependencies that are not included in any of its unfinished subtasks are released. In contrast, the release of the dependencies that appear in any of its unfinished subtasks is delayed until these latter finish.

We strongly recommend avoiding the `taskwaits` at the end of task bodies. They delay the finalization of tasks, and also, they hinder the discovery of parallelism. Moreover, `taskwait` delays the release of all dependencies until all subtasks finish, even the dependencies not declared by any subtask. Nevertheless, it is worth noting that the variables stored in the stack of the parent task are no longer valid once it returns from its task body. In the next section, we explain in detail the benefits of automatically linking dependency domains across task nesting levels without `taskwaits`.

2.3.2 Fine-grained release of dependencies across nesting levels

Detaching the `taskwait` at the end of a task from the task code allows the run-time system to be made aware earlier of the fact that the task code has finished and that it will not create further subtasks. In an scenario with task nesting and dependencies, this knowledge allows it to make assumptions about dependencies. Since the task code is finished, the task will no longer perform by itself any action that may require the enforcement of its dependencies. Only the dependencies needed by its live subtasks need to be preserved. In most cases, these dependencies are the ones associated to an element of the depend clause that also appears in a live subtask. Therefore, the dependencies that do not need to be enforced anymore could be released.

This incremental fine-grained release of dependencies is the default behaviour in OmpSs-2 tasks. However, this behaviour can be disabled with the `wait` clause, which defers the release of all dependencies of a task until it has finished the execution of its body and all its subtasks deeply complete. This clause emulates a `taskwait`-like operation immediately after exiting from the task code, but avoiding the overhead and drawbacks of a `taskwait`.

Notice that this improvement is only possible once the run-time system is aware of the end of the code of a task. However, it may also be desirable to trigger this mechanism earlier. For instance, a task may use certain data only at the beginning and then perform other lengthy operations that delay the release of the dependencies associated to that data. The `release` directive asserts that a task will no longer perform accesses that conflict with the contents of the associated `depend` clause. The contents of the `depend` clause must be a subset of that of the task construct that is no longer referenced in the rest of the lifetime of the task and its future subtasks.

2.3.3 Weak dependences

Some of the elements of the `depend` clause may be needed by the task itself, others may be needed only by its subtasks, and others may be needed by both. The ones that are only needed for the subtasks only serve as a mechanism to link the outer domain of dependencies to the inner one. In this sense, allowing them to defer the execution of the task is unnecessary, since the task does not actually perform any conflicting accesses by itself.

The dependence model in OmpSs-2 has been extended to define the *weak* counterparts of `in`, `out`, `inout` and `commutative` dependences. Their semantics are analogous to the ones without the weak prefix. However, the weak variants indicate that the task does not perform by itself any action that requires the enforcement of the dependency. Instead those actions can be performed by any of its deeply nested subtasks. Any subtask that may directly perform those actions needs to include the element in its `depend` clause in the non-weak variant. In turn, if the subtask delegates the action to a subtask, the element must appear in its `depend` clause using at least the weak variant.

Weak variants do not imply a direct dependency, and thus do not defer the execution of tasks. Their purpose is to serve as linking point between the dependency domains of each nesting level. Until now, out of all the tasks with the same parent, the first one with a given element in its `depends` clause was assumed to not have any input dependency. However, this assumption is no longer true since the dependency domains are no longer isolated. Instead, if the parent has that same element with a weak dependency type, there may actually be a previous and unfinished task with a `depend` clause that has a dependency to it. If we calculated dependencies as if all types were non-weak, in such a case, the source of the dependency, if any, would be the source of the non-enforced dependency on its parent over the same element.

This change, combined with the fine-grained release of dependencies, merges the inner dependency domain of a task into that of its parent. Since this happens at every nesting level, the result is equivalent to an execution in which all tasks had been created in a single dependency domain.

2.3.4 Extended data dependencies expressions

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 a 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.

Implementations may choose not to support the extended data dependencies model, in which case array sections and shaping expressions will register a single dependency to the first element of the specified range. For example, an expression of the form `a[lower : upper]` will be interpreted as a dependency over `a[lower]`.

The following example shows examples of these extended expressions:

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

    #pragma oss task inout(a[0:(n/2)-1]) // equivalent to inout(a[0;n/2])
    sort(n/2, a);

    #pragma oss task inout(a[n/2:n-1]) // equivalent to inout(a[n/2;n-(n/2)])
    sort(n/2, &a[n/2]);

    #pragma oss task inout(a[0:(n/2)-1], a[n/2:n-1])
    merge(n/2, a, a, &a[n/2]);

    #pragma oss taskwait
}
```

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.

2.3.5 Dependences on the taskwait construct

In addition to the dependencies mechanism, there is a way to set synchronization points in an OmpSs-2 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 deeply complete.

OmpSs-2 also offers synchronization points that can wait until certain tasks are completed. These synchronization points are defined adding any kind of task dependence clause to the `taskwait` construct.

2.3.6 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 following 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 oss task inout({v[i], i=0;n})
    {
```

```

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])
  !$oss task inout([v(i), i=1, n])
  v = v + 1
  !$omp end task
end subroutine foo

```

2.4 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 taskwait directive.
- Just after the completion of a task.
- When entering or exiting a critical section.
- When explicitly blocking or unblocking a task through the blocking API.

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 to resume 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 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 tasks that have been previously executed by a different thread).
- When creating a task with the `if` clause for which expression evaluated to false, the run-time system 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 predecessors of a task have finished yet) or blocked tasks in any other condition (e.g., tasks executing a taskwait with non-finished child tasks).

2.5 Conditional compilation

In implementations that support a preprocessor, the `_OMPSS_2` macro name is defined to have a value. In order to keep non OmpSs-2 programs still compiling programmers should use the symbol definition to guard all OmpSs-2 routine calls or any specific mechanism used by the OmpSs-2 programming model.

2.6 Runtime options

OmpSs-2 uses the run-time library routines to check and configure different Control Variables (CVs) during the program execution. These variables define certain aspects of the program and run-time behaviour. A set of shell environment variables may also be used to configure the CVs before executing the program.

A list of library routines can be found in chapter *Library Routines* from this specification. However, some library routines and environment variables are implementation defined and programmers will find them documented in the *OmpSs-2 User Guide*.

LANGUAGE DIRECTIVES

This chapter describes the OmpSs-2 language, this is, all the necessary elements to understand how an OmpSs-2 application executes and/or behaves in a parallel architecture. OmpSs-2 provides a simple path for users already familiarized with the OpenMP programming model to easily write (or port) their programs to OmpSs-2.

This description is completely guided by the list of OmpSs-2 directives. In each of the following sections we will find a short description of the directive, its specific syntax, the list of 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-2 program.

As is the case of OpenMP in C and C++, OmpSs-2 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-2 is *oss*. Compilers will typically ignore OmpSs-2 directives if support is disabled or not provided.

C/C++ format:

```
#pragma oss directive-name [clause[ [,] clause] ... ] new-line
```

Fortran format:

```
sentinel directive-name [clause[ [,] clause]...]
```

Where depend on Fortran fixed/free form:

- The sentinels for *fixed form* can be: !\$oss, c\$oss or *\$oss. Sentinels must start in column 1. Continued directive line must have a character other than a space or a zero in column 6.
- The sentinel for *free form* must be !\$oss. This sentinel can appear in any column as long as is not preceded by any character different than space. Continued directive line must have an ampersand (&).

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 oss 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>)`
- `reduction(<operator>:<memory-reference-list>)`
- `priority(<expression>)`
- `cost(<expression>)`
- `if(<scalar-expression>)`
- `final(<scalar-expression>)`
- `wait`
- `for [chunksize(<expression>)]`
- `label(<string>)`

The `private`, `firstprivate` and `shared` clauses allow to specify the data sharing attribute of the variables referenced in the construct. A description of these clauses can be found in *Data sharing attributes* section.

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 model* in the previous chapter. In addition to this syntax, OmpSs-2 allows to specify this information using the type of dependence as the name of the clause. Then, the following code:

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

Is equivalent to this one:

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

The `reduction` clause allows to define the task as a participant of a reduction operation. The first occurrence of a participating task defines the begin of the scope for the reduction. The end of the scope is implicitly ended by a `taskwait` or a dependence over the `memory-reference-item`. More information about task reductions on OmpSs-2 at the following Master Thesis: <https://upcommons.upc.edu/handle/2117/129246>.

The `priority` clause indicates a priority hint for the task. Greater numbers indicate higher priority, and lower numbers indicate less priority. By default, tasks have priority 0. The expression of the priority is evaluated as a signed integer. This way, strictly positive priorities indicate higher priority than the default, and negative priorities indicate lower than default priority.

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 task 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.

Tasks with the `wait` clause will perform a `taskwait`-like operation immediately after exiting from the task code. Since it is performed outside the scope of the code of the task, this happens once the task has abandoned the stack. For this reason, its use is restricted to tasks that upon exiting do not have any subtask accessing its local variables. Otherwise, the regular `taskwait` shall be used instead.

The `for` clause (do in Fortran) marks the task as a worksharing task, which can be applied when the task body is a for-loop. This is explained in section Task For clause.

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 string literal must be wrapped in double quotes. For instance, a task that initializes an array could be labeled as `label("init array")`.

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 oss task
    do_computation(x);

    #pragma oss task
    {
        do_computation(y);
        do_computation(z);
    }
    #pragma oss taskwait

    return 0;
}
```

When the control flow reaches `#pragma oss task` construct, a new task instance is created. The execution order of the tasks is not guaranteed. Moreover, when the program reaches the `#pragma oss taskwait` the previously created tasks may not have been executed yet by the OmpSs-2 run-time system. After potentially being blocked in the `taskwait` construct for a while, it is guaranteed that both tasks have already deeply completed.

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. The following C code is an example of how task functions are used:

```
extern void do_computation(float a);

#pragma oss task
extern void do_computation_task(float a);

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

    #pragma oss taskwait
}
```

The invocation of `do_computation_task` inside `main` function creates an instance of a task. Note that OmpSs-2 does not guarantee that the task has been already executed after returning from the regular function call `do_computation(x)`.

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.

3.1.1 Task For clause

The `for` clause (do in Fortran) marks the task as a worksharing task, which can be applied when the task body is a for-loop. The key point of worksharing tasks is their ability to run concurrently on different threads, similarly to OpenMP `paralell for`. In contrast, worksharing tasks do not force all threads to collaborate neither introduce any kind of barrier.

The iteration space of the for-loop is partitioned in chunks of constant size that are going to be spreaded amongst the available collaborator threads. The chunksize can be modified by adding the `chunksize` clause and passing the desired number of iterations. Note that those chunks do not have the usual task-associated overheads such as memory allocation or dependency management. The default chunksize is implementation defined (see the [Runtime Section](#) on the User Guide for more information).

The iterations from a task `for` must be independent from each other since they may be executed concurrently without guaranteeing any order. The `depend` clause applies to the whole task `for`, which means that no iteration is executed until all dependencies are satisfied, and they are released once all iterations have finished. Moreover, the body of the task `for` cannot contain any *task generating code*, i.e., task `for`'s cannot have subtasks.

The following C code is an example of how task `for` is used:

```
const int N = 10000;
int array[N];

int main() {
    for (int i = 0; i < N; i+=1024) {
        #pragma oss task out(array[i;1024])
        for (int j = i; j < MIN(N,i+1024); ++j) {
            array[i] = 20;
        }
    }

    #pragma oss task for inout(array[0;N]) chunksize(1024)
    for (int i = 0; i < N; ++i) {
        array[i] += 100;
    }

    #pragma oss taskwait
}
```

Worksharing tasks are useful when facing scenarios where problem size per core is insufficient. In these scenarios, users must choose either (1) small granularities that hinder performance because of task management overheads but provide enough parallelism, or (2) big granularities that minimize task management overheads but do not provide enough parallelism. Thus, both options damage the overall performance. In contrast, worksharing tasks allow users to set bigger granularities that minimize task management overheads while still providing enough parallelism due to its ability to run in several threads concurrently.

3.2 Taskwait construct

Apart from implicit synchronization (task data dependences), OmpSs-2 also offers a mechanism that allow users to synchronize task execution. The `taskwait` construct is an stand-alone directive (with no code block associated) and specifies a wait on the deep completion of all descendant tasks, including the non-direct children tasks.

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

```
#pragma oss 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 descendant tasks that declared a dependency on any of the variables that appear on the list of variables.

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

```
int compute1(void);
int compute2(void);

int main()
{
    int result1, result2;

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

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

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

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

    return 0;
}
```

3.3 Release directive

The `release` directive asserts that a task will no longer perform accesses that conflict with the contents of the associated `depend` clause. The contents of the `depend` clause must be a subset of that of the task construct that is no longer referenced in the rest of the lifetime of the current task and its future subtasks. The `release` directive has not associated structured block.

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

```
#pragma oss release [clauses]
```

The valid clauses for the `release` directive are:

- `depend(<type>: <memory-reference-list>)`
- `<depend-type>(<memory-reference-list>)`

The following C code shows an example of partial release of the task dependences using the `release` directive:

```
#define SIZE 4096

float x[SIZE];
float y[SIZE];

int main() {

    #pragma oss task depend(out:x,y)
```

```

{
  for (int i=0; i<SIZE; i++) x[i] = 0.0;
  #pragma oss release depend(out:x)

  for (int i=0; i<SIZE; i++) y[i] = 0.0;
}
}

```

Warning: At this moment, the run-time system only supports releasing a dependency of the same dependency type that was specified at the task depend clause.

3.4 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 is executing it.

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

```

#pragma oss critical
structured-block

```

The syntax also allows named criticals with the following syntax:

```

#pragma oss critical(<name>)
structured-block

```

Named criticals prevent concurrency between threads with respect to all critical regions with the same name. Unnamed criticals prevent concurrency between threads with respect to all unnamed critical regions.

The `critical` construct has no related clauses. The beginning and ending of a critical section may be task scheduling points.

3.5 Restrictions

The point of exit of a structured block cannot be a branch out of it. The following C code shows an example where any of the `exit` calls may lead to undefined behavior:

```

int main() {
  for (int i = 0; i < 10; i++) {
    if (i > 5) exit(1);

    #pragma oss task
    {
      // computation
      exit(1);
    }
  }
  #pragma oss taskwait
}

```

LIBRARY ROUTINES

This chapter describes the set of OmpSs-2 run-time library routines available while executing an OmpSs-2 program. Programmers must guarantee the correctness of compiling and linking programs without OmpSs-2 support by the use of the conditional compilation mechanism (see *Conditional compilation* section).

In the following sections, we provide a short description of all public library routines. These routines are declared in the public header file named `nanos6.h`.

Warning: The run-time system library does not provide the Fortran header yet.

4.1 Spawning functions

The `nanos6_spawn_function` allows to asynchronously spawn a new function using the run-time system resources.

C/C++ format:

```
void nanos6_spawn_function(  
    void (*function)(void *),  
    void *args,  
    void (*completion_callback)(void *),  
    void *completion_args,  
    char const *label  
);
```

Where each of this routine's parameters are:

- `function` the function to be spawned.
- `args` a parameter that is passed to the function.
- `completion_callback` an optional function that will be called when the function finishes.
- `completion_args` a parameter that is passed to the completion callback.
- `label` an optional name for the function.

The routine will create a new OmpSs-2 task executing the `function` code and receiving the `args` parameters. Once the task finishes the run-time system will invoke the registered callback service (i.e., `completion_callback` using `completion_args` parameters). The callback is used as the provided synchronization mechanism.

The `label` string will be used for debugging/instrumentation purposes.

4.2 Task blocking

This API is composed by three functions and provides the functionality of pausing and resuming OmpSs-2 tasks at run-time. Firstly, the `nanos6_get_current_blocking_context` returns an opaque pointer that is used for blocking and unblocking the current task:

```
void *nanos6_get_current_blocking_context(void);
```

The underlying implementation may or may not return the same value for repeated calls to this function. Once the handler has been used once in a call to `nanos6_block_current_task` and a call to `nanos6_unblock_task`, the handler is discarded and a new one must be obtained to perform another cycle of blocking and unblocking.

Secondly, the `nanos6_block_current_task` function blocks the execution of the current task:

```
void nanos6_block_current_task(void *blocking_context);
```

The current task will block at least until another thread calls `nanos6_unblock_task` with the blocking context of that task. The run-time system may choose to execute other tasks within the execution scope of this call.

Finally, the `nanos6_unblock_task` routine mark as unblocked a task previously or about to be blocked:

```
void nanos6_unblock_task(void *blocking_context);
```

This function can be called even before the target task actually blocks. In that case, the target task will not block because someone already unblocked it. However, only one call to `nanos6_unblock_task` may precede its matching call to `nanos6_block_current_task`. The return of this function does not guarantee that the blocked task has resumed yet its execution; it only guarantees that it will be resumed.

Note that both `nanos6_block_current_task` and `nanos6_unblock_task` may be task scheduling points.

4.3 Polling services

The OmpSs-2 programming model offers a periodic callback mechanism which can be useful for third party libraries. With this API, libraries do not need to leverage an additional thread, for instance, for checking asynchronous operations periodically.

The `nanos6_register_polling_service` function registers a callback that will be called periodically:

```
void nanos6_register_polling_service(  
    char const *service_name,  
    nanos6_polling_service_t service_function,  
    void *service_data  
);
```

It receives a string parameter `service_name` that describes the function for debugging purposes, the callback function `service_function`, and an opaque pointer `service_data` to data to pass to the callback. The same `service_function` can be registered several times with different `service_data` parameters, and each combination will be considered as a different registration.

The prototype of the callback function is the following:

```
typedef int (*polling_service_t)(void *service_data);
```

The registered callback will be called by the run-time system at regular intervals and opportunistically. It receives as a parameter the opaque pointer passed when the callback was registered. It returns a Boolean value that indicates

whether its purpose has been attained: if true, the callback is automatically unregistered; otherwise the run-time system will continue to call it.

Lastly, the `nanos6_unregister_polling_service` unregisters a callback. It receives the same parameters as the registration function and returns once the callback has been completely disabled:

```
void nanos6_unregister_polling_service(
    char const *service_name,
    nanos6_polling_service_t service_function,
    void *service_data
);
```

4.4 Task external events

The task external events API provides the functionality of decoupling the release of task data dependencies to the completion of external events. A task fully completes (i.e., releases its dependencies) once it finishes the execution of its task body, and all external events bound during its execution are fulfilled. This allows binding the completion of a task to the finalization of any asynchronous operation.

This API is composed of three functions, which follow the style of the blocking API. Firstly, the `nanos6_get_current_event_counter` returns an opaque pointer that is used to increase/decrease the number of events:

```
void *nanos6_get_current_event_counter(void);
```

This function provides an implementation-specific data that we name *event counter* throughout the rest of this text. A task can bind its completion to new external events by calling the following function:

```
void nanos6_increase_current_task_event_counter(
    void *event_counter,
    unsigned int increment
);
```

This function atomically increases the number of pending external events of the calling task. The first parameter `event_counter` must be the event counter of the invoking task, while the second parameter `increment` is the number of external events to be bound. The presence of pending events in a task prevents the release of its dependencies, even if the task has finished its execution. Note that only the task itself can bind its external events.

Then, the task itself, or another task or external thread, can fulfill the events of the task by calling the following function:

```
void nanos6_decrease_task_event_counter(
    void *event_counter,
    unsigned int decrement
);
```

This function atomically decreases the number of pending external events of a given task. The first parameter `event_counter` is the event counter of the target task, while the second parameter `decrement` is the number of completed external events to be decreased. Once the number of external events of a task becomes zero and it finishes its execution, the task can release its dependencies.

Note that, all external events of a task can complete before it actually finishes its execution. In this case, the task will release its dependencies as soon as it finishes its execution. Otherwise, the last call that makes the counter become zero, will trigger the release of the dependencies.

Notice that the user is responsible for not fulfilling events that the target task has still not bound.

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