From DSL to HPC Component-Based Runtime: A Multi-Stencil DSL Case Study

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ABSTRACT

High performance architectures evolve continuously to be more powerful. Such architectures also usually become more difficult to use efficiently. As a scientist is not a low level and high performance programming expert, Domain Specific Languages (DSLs) are a promising solution to automatically and efficiently write high performance codes. However, if DSLs ease programming for scientists, maintainability and portability issues are transferred from scientists to DSL designers. This paper deals with an approach to improve maintainability and programming productivity of DSLs through the generation of a component-based parallel runtime. To study it, the paper presents a DSL for *multi-stencil* programs, that is evaluated on a real-case of shallow water equations.

1. INTRODUCTION

Programming complex scientific applications on high performance architectures, such as clusters of multi-core nodes containing accelerators, requires for a scientist to be an expert in his own domain, but also in low level parallel and high performance programming. It can take months to years for a scientist to learn HPC programming, as it is not his main activity. As hardware continue to evolve to become more powerful but also usually more complex and difficult to use efficiently, the learning is never over.

Domain Specific Languages (DSLs) are a promising solution to hide intricate details of HPC programming from non experts. By being specific to a well-defined set of problems, those languages enable the generation of well parallelized and optimized code for various architectures while requiring only a limited amount of information from the developer; part of the knowledge is directly embedded in the compiler. A critical question however concerns the specificity of DSLs. Actually, the less specific the DSL is, the more information its users must provide, and the less automatic optimizations can be embedded in the compiler. Conversely, the more specific the DSL is, the less applications can use it, and the more difficult it is to amortize the implementation cost of the DSL (language, compiler, and runtime). Programming complexity, as well as non-maintainability and non-portability often seem to be simply transferred from scientists to DSL designers.

For this reason, solutions to ease the design and implementation of DSLs have recently appeared [11]. The main idea of those solutions is to propose a single DSL or a framework to write new DSLs. In this paper, we study a first contribution to another approach to improve maintainability and portability in DSLs. This approach proposes a transformation from a DSL to a component-based runtime. Component-based Software Engineering has proved many times good properties for code re-use, separation of concerns, maintainability and productivity of codes. For this reason, we think that combining DSLs and component-based runtimes could enable those properties, by inheritance, in DSLs. This paper proposes a first evaluation of this approach though a use-case study that is a DSL for *multi-stencil* programs, *i.e.,* a subclass of numerically solved partial differential equations (PDEs), and its compiler.

Many solutions to automatically optimize and parallelize numerical simulations have been proposed in the literature, either as specific frameworks [3, 8] or as DSLs [7, 10, 14, 23]. Most of the time, DSLs focus on the parallelization and the optimization of a single numerical computation, also called a stencil kernel. However, a real case numerical simulation (such as fluid dynamics, magneto-hydrodynamics, molecular dynamics etc.) is most of the time not composed of a single stencil kernel, but of a set of stencil kernels and a set of additional local auxiliary computations [18]. The DSL proposed in this paper, called *Multi-Stencil Language* or MSL, is a DSL to generate a parallel component-based structure of a numerical simulation, that we call a *multi-stencil program.* As discussed in the related work, this work is complementary to the optimization and parallelization of a single stencil kernel and is independent from implementation choices (as for example the form of the studied mesh).

The rest of this paper is organized as follows. The concepts of *stencil kernels* and *multi-stencil programs* are formalized in Section 2. Section 3 gives an overview of the proposed solution while Section 4 details the MSL language and its compiler which automatically generates the parallel computation part. Section 5 introduces component models and describes the proposed component-based runtime of

MSL. Section 6 focuses on a real-case simulation, solving the Shallow-water equations, and analyzes preliminary performance and usability results. Sections 7 states on related work, while Section 8 concludes the paper.

2. STENCIL AND MULTI-STENCIL

2.1 Stencil Kernels

To numerically solve a set of PDEs, iterative methods (finite difference, finite volume, finite element methods etc.) are frequently used to approximate the solution through a discretized (step by step) process. Thus, the continuous time and space domains are discretized so that a set of numerical computations are iteratively (time discretization) applied onto a mesh (space discretization). In other words, in a mesh-based numerical simulation, the PDEs are transformed to a set of numerical computations applied at each time step on elements of the discretized space domain (the mesh). This paper focuses on one specific category of such numerical schemes based on *stencil kernels* [23], also called in applied mathematics explicit numerical schemes. This section introduces some definitions related to stencil kernels.

A *mesh* is the discretization of a physical domain. It is a connected undirected graph without bridges (an edge is a bridge if its removal results in two disconnected graphs), where nodes and edges are linked to form cells (closure). Most of the time, nodes of a mesh are linked to coordinates in the real space domain. An example of structured mesh is illustrated in Figure 1a. Each cell contains four nodes and four edges. *Mesh entities* are elements of the mesh, such as the center of cells, edges or nodes. In Figure 1a, two mesh entities are illustrated, the center of the cells (named `Cells`, in red) and edges on the horizontal axis (named `Edgex`, in blue on left and right of each cell). A *data* is a simulated quantity on which computations are performed. Each data is mapped onto mesh entities. For example, in Figure 1b, data A and B are mapped onto the center of cells, while, in Figure 1c, C is mapped onto the edges.

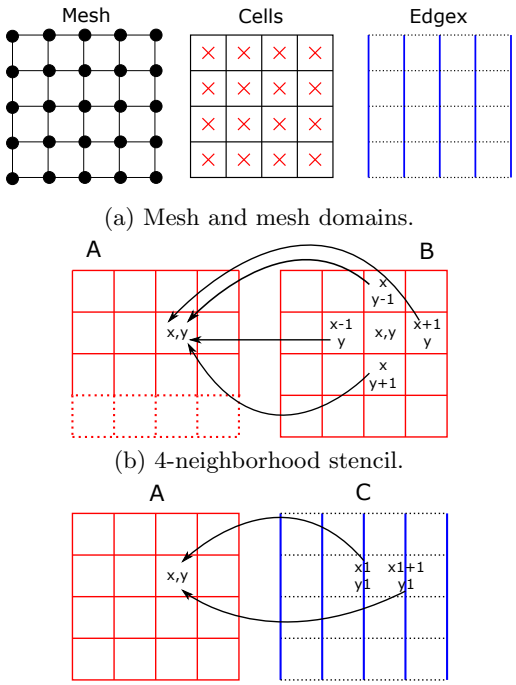
A *stencil kernel* computes the value of one data or a subpart of it (the kernel *computation domain*) using a *numerical expression* which takes as input one or more data. For example, the stencil kernel illustrated in Figure 1b computes A using B, while the one in Figure 1c computes A using C. Thus, a stencil kernel is defined by its numerical expression, a set of input data (only one in the examples), and its unique output data, the result. The *computation domain* is a subset of the mesh entities on which the output data is mapped. For example, in the first stencil, the computation of A is performed on elements represented with full lines, while dotted elements are not computed. On the other hand, on the second computation, the computation domain of A contains all the mesh entities on which it is mapped. This computation domain defines the elements over which the space loop iterates.

The numerical expression of a stencil kernel has the particularity to compute each element of the result independently using some elements of the inputs in a given neighborhood. Accessed elements form a *neighborhood* of the output known as the *stencil shape*. For example, the stencil shape of the first computation in Figure 1b contains direct neighbors on the right, left, top and bottom. Sometimes, the neighborhood can also access different mesh entities, as for example in Figure 1c. Actually, in this computation, the neighborhood contains edges on the left and on the right of a cell. As an example, the numerical expression of the first example could be:

$$A(x,y) = B(x+1,y)+B(x-1,y)+B(x,y+1)+B(x,y-1),$$

and the numerical expression of the second kernel could be:

$$A(x,y) = A(x,y) + C(x1,y1) + C(x1+1,y1).$$



(a) Mesh and mesh domains.

(b) 4-neighborhood stencil.

(c) 2-neighborhood 2-entity stencil.

Figure 1: (a) a Cartesian mesh and two kind of mesh entities, (b) an example of stencil kernel on cells, (c) an example of stencil kernel on two different entities of the mesh.

As it can be seen from these definitions, stencil kernels implementations share many properties from an algorithmic point of view that can be used to apply well known optimization and parallelization strategies. Many solutions (languages or frameworks) thus propose to ease their programming by producing optimized and parallelized code from a simple description of the local computation to apply on each element. These are further discussed in Sections 7.

While stencil kernels have been studied a lot, the formalization of real overall mesh-based numerical simulations is poorly studied and not exactly for the same kind of appication [18]. Actually, paying attention to complex numerical simulations, it appears that most of them are composed of more than one stencil kernel, with one or more stencil shapes and of additional local computations. For example, we would like to formalize and parallelize a numerical simulation which chains the stencil kernels of Figures 1b and 1c. The next section formalizes concepts of *stencil kernel*, *local kernel* and *multi-stencil program*.

2.2 A Multi-Stencil Formalization

This section introduces some formal definitions used in the rest of the paper. Let Δ be the set of data of the simulation A stencil kernel s is defined as the quadruplet:

$$s(R, w, exp, d), \tag{1}$$

where R is a set of pairs (r, n), with $r \in \Delta$ a data read by the computation, and n the stencil shape (neighborhood) used to access r. The data written by the kernel is denoted $w \in \Delta$. exp is the numerical expression of the stencil kernel. Finally the numerical expression is applied on the computation domain d.

For example, in Figure 1b, assuming the computation domain (full lines) is $dc1$ and the stencil shape is $n1$, the stencil kernel can be defined as:

$$R : \{(B, n1)\}, \quad w : A, \quad d : dc1,$$

$$exp : A(x, y) = B(x{+}1, y){+}B(x{-}1, y){+}B(x, y{+}1){+}B(x, y{-}1).$$

On the other hand, in the example of Figure 1c, assuming the computation domain is $dc2$ and the stencil shape is $n2$, the stencil kernel is defined as:

$$R : \{(C, n2), (A, local)\}, \quad w : A, \quad d : dc2,$$

$$exp : A(x, y) = A(x, y) + C(x1, y1) + C(x1 + 1, y1).$$

One can notice that the input data A is associated to the stencil shape *local*. This means that the stencil shape applied on A is limited to the element with the exact same coordinate as the result element.

The specificities of kernels whose stencil shapes are all local makes it possible to apply specific optimizations. We therefore provide a specific definition in this case. A local (or auxiliary) kernel l is defined as the quadruplet:

$$l(R_l, w, exp, d), \tag{2}$$

where R_l is the set of input data locally accessed, and other parameters are the same as for normal stencil kernels.

We define a multi-stencil program as a sextuplet:

$$\mathcal{MSP}(T, \mathcal{M}, \mathcal{E}, \mathcal{D}, \Delta, \Gamma), \tag{3}$$

where T is the set of time iteration to run the simulation, $\mathcal{M}$ is the mesh of the simulation, $\mathcal{E}$ is the set of mesh entities, $\mathcal{D}$ is the set of computation domains used for computations, Δ is the set of data of the simulation, each one mapped onto a mesh entity, and finally Γ is the set of computations. The set of computations Γ is an ordered list of stencil and local kernels. One can notice that this work, for now, is limited to a single mesh type for a given simulation.

3. MSL AND MSCAC OVERVIEW

The solution proposed in this paper is based on both a domain specific language to describe a multi-stencil program, *i.e.,* a complete numerical simulation, and on a compiler which parses the language, applies transformations for automatic parallelization, and dumps the representation to a component-based runtime, ready-to-fill with the user code.

The proposed DSL, named MSL (*Multi-Stencil Language*), is an agnostic descriptive language for multi-stencil simulations. Agnostic means that the description of a numerical simulation does not depend on implementation choices as, for example, the type of mesh (structured or unstructured), or its associated interfaces (how to define a stencil shape, etc.). Descriptive, on the other hand, means that MSL is not made to handle the expression of numerical computations, but only the description of a multi-stencil simulation, in a coarse-grain fashion. A MSL description is made of six main sections that match the six tuples elements of the definition of a multi-stencil program of Equation 3.

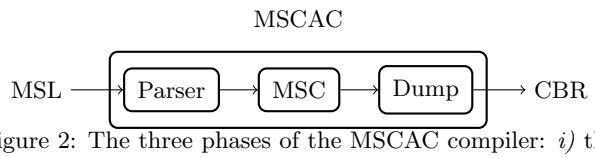


Figure 2: The three phases of the MSCAC compiler: *i)* the parser of the MSL description; *ii)* the MSC parallelization; *iii)* the dump to the Component-Based Runtime (CBR).

As illustrated in Figure 2, the compiler, named MSCAC for *Multi-Stencil Component Assembly Compiler*, is composed of three different phases. The first phase *parses* the MSL description into an intermediate representation (IR). The second phase called MSC transforms the computation part (Γ) of the IR into a series-parallel tree decomposition [24] to introduce parallelism in the overall numerical simulation. Finally, the third phase dumps the IR to an actual implementation of the parallel pattern of the simulation.

The parallelization techniques handled by MSC are *data parallelism*, where data is split among processors or cores while applying the same computation on every piece of data, and *task parallelism* where the program is transformed into a graph of tasks with dependencies. Different strategies can be used to schedule the tasks of this graph, *i.e.,* to plan their execution in a valid order. The MSC compiler presented in this paper handles the transformation of the dependency graph to a static scheduling.

The final phase of compilation, the dump, uses the static scheduling of the tasks, created from Γ, and additional information on T, $\mathcal{M}$, Δ, $\mathcal{E}$ and $\mathcal{D}$. It generates a program in the back-end language which embeds the parallel pattern or skeleton of the overall simulation. Various models could be used as back-end, such as OpenMP [9] for example. However this paper adopts a novel approach where the dump targets a component-based runtime. This approach makes it possible to leverage good properties of software component models such as increased code re-use, eased separation of concerns, and increased maintainability and productivity. These properties counter some known limitations of DSLs.

Thanks to the software components based approach, the generated code is made of four independent parts that loosely match the elements of the multi-stencil program definition. Those are the components implementing: *a)* the computations scheduling (Γ), **b)** the data structures ($\mathcal{M}$ and $\mathcal{E}$), **c)** data of the simulation (Δ and $\mathcal{D}$), and **d)** the time loop (T). The actual implementation of the numerical expressions are provided by the user and used in the computations scheduling. This component-based parallel structure enables to change the technology used for each part while limiting

```
1  program ::= "mesh:" meshid
2              "mesh entities:" listmeshent
3              "computation domains:"
4                        listcompdom
5              "independent:"
6                        listinde
7              "data:" listdata
8              "time:" iteration
9              "computations:" listcomp
10 listmeshent ::= meshent listmeshent
11              |  meshent
12 listcompdom ::= compdom listcompdom
13              |  compdom
14 compdom ::= compdomid "in" listmeshent
15 listinde ::= inde listinde
16           |  inde
17 inde ::= compdomid "and" compdomid
18 listdata ::= data listdata
19           |  data
20 data ::= dataid "," meshent
21 iteration ::= num
22 listcomp ::= comp listcomp
23           |  comp
24 comp ::= dataid "[" compdomid "]=" compid
25             "(" listdataread ")"
26 listdataread ::= dataread listdataread
27               |  dataread
28 dataread ::= dataid "[" neighborid "]"
29           |  dataid
```

Figure 3: Grammar of the Multi-Stencil Language.

```
1  mesh: cart
2  mesh entities: cell,edgex,edgey
3  computation domains:
4    allcell in cell
5    alledgex in edgex
6    alledgey in edgey
7    part1edgex in edgex
8    part2edgex in edgex
9  independent:
10   part1edgex and part2edgex
11 data:
12   a,cell
13   b,cell
14   c,edgex
15   d,edgex
16   e,edgey
17   f,cell
18   g,edgey
19   h,edgex
20   i,cell
21   j,edgex
22 time:500
23 computations:
24   b[allcell]=c0(a)
25   c[alledgex]=c1(b[n1])
26   d[alledgex]=c2(c)
27   e[alledgey]=c3(c)
28   f[allcell]=c4(d[n1])
29   g[alledgey]=c5(e)
30   h[alledgex]=c6(f)
31   i[allcell]=c7(g,h)
32   j[partedgex]=c8(i[n1])
```

Figure 4: Example of a MSL program.

the impact on the other parts, as discussed in Section 5.

4. LANGUAGE AND PARALLELIZATION

4.1 Multi Stencil Language

As mentioned in the previous section, the Multi Stencil Language (MSL) is an agnostic descriptive language for multi-stencil simulations. Six main sections are required in a MSL description that match the six elements of the formal definition; they describe: **1)** the mesh, **2)** the mesh entities, **3)** the computation domains with their inter-dependencies, **4)** the data, **5)** the time iterations, and finally **6)** the computations. Figure 3 shows the grammar of MSL. Lines 1 to 9 define what is a MSL program with the different parts mentioned above. The remaining of this section describes these different parts of a MSL program and presents an example. One can notice that terminals are the string identifiers `meshid`, `meshdom`, `compdomid`, `dataid`, `compid` and `neighborid`. The terminal `num` is an integer terminal.

Mesh and Mesh Entities

As illustrated in the first line of the grammar in Figure 3, a mesh is simply defined by a string identifier. The different kind of mesh entities are described as a list of identifiers (Lines 2, 10 and 11 in Figure 3). Figure 4 gives an example of a mesh named `cart` used to represent a Cartesian mesh, and three kinds of mesh entities: `cell`, `edgex`, and `edgey`.

Computation Domains and Their Dependencies

A computation domain is a subset of a given kind of mesh entities, used for at least one computation. For each computation domain, the kind of mesh entities on which it is mapped is specified (lines 3-4 and 12-14 on Figure 3). By default, two computation domains of the same entities are handled as intersecting except when an explicit independence relation is mentioned in the *independent* section of the language (lines 5-6 and 15-17 in Figure 3). On lines 4 to 6 of Figure 4, computation domains are defined for each kind of mesh entities: `allcell`, `alledgex` and `alledgey`; they are used to represent the whole domain. On lines 7 and 8, two other domains of `edgex` are defined: `part1edgex` and `part2edgex`; they could be used to represent the boundaries of the domain, for example, or any other sub-part of the whole domain. It is the user's responsability to define the needed domains for his simulation. On line 10 the independence relation between `part1edgex` and `part2edgex` is specified.

Data and Time

A data element is a quantity to simulate. It is mapped on a given kind of mesh entities, as illustrated in lines 7 and 18-20 of Figure 3. The `time` section simply indicates a number of iterations to perform in the simulation. In the example of Figure 4 ten data elements are defined and 500 iterations (lines 11-22).

Computation Description

The last part of the language contains the specifications of stencil and local kernels as defined in Section 2.2. This description does not contain a direct expression of the numerical expressions *exp*. Instead, the term *exp* of Equations 1 and 2 corresponds to an identifier that references an implementation in an external language (*cf.* Section 5). The description starts by the identifier of the computed data element (w in the formal description) with the computation

domain between brackets (d). Then, after the equal sign, the kernel identifier (exp) is specified. Finally, between the parenthesis is the list of identifiers of the data elements read by the computation with their stencil shape between brackets (R). If the computation is local, no brackets appear (R_l). In the example of Figure 4, nine computations are described. On line 24, the data element `b` is computed on the domain `allcell` by the kernel expression `c_0` which reads data `a` without any neighborhood shape.

4.2 MSC Parallelization

The MSC parallelization is a subpart of the overall compiler MSCAC. It makes use of the ordered list of computations Γ, which can directly be extracted from the parser, to build a parallel representation of the computations of the overall multi-stencil program. This parallelization phase is divided in five different steps to transform Γ to a series-parallel tree decomposition [24]. This sections describes these steps.

The Ordered List of Computations: Γ

Γ is directly obtained from the parser. Actually, the list of computations in the MSL program is already ordered: Γ is a direct map of this list. In the example of Figure 4, $\Gamma = [c_0, c_1, c_2, c_3, c_4, c_5, c_6, c_7, c_8]$.

The Synchronized Ordered List of Computations: Γ_{sync}

Data parallelization splits data among processors and the same program is applied on each sub-part of the data. However, this parallelization technique requires additional synchronizations between processors. The required synchronizations can be automatically computed from the ordered list of computations Γ. A synchronization is needed each time a data read by a stencil computation has been written by a previous computation. In such a case, a computation is added before the stencil computation. This *synchronization computation* reads the data to synchronize, and write the same data. The computation domain of such a synchronization computation encompasses the whole mesh entities on which the data is declared. As a result, Γ is transformed to a synchronized ordered list of computations Γ_{sync}. For example, in Figure 4, the stencil computation c_1 reads the data element b which has been written by c_0. For this reason the sublist $[c_0, c_1]$ of Γ is transformed into $[c_0, sync_1, c_1]$ in Γ_{sync}. The new computation $sync_1$ reads and writes b and is applied on `edgex`. As a result, a dependency is kept between c_0 and $sync_1$ and between $sync_1$, and c_1. The same transformation is performed for the two other stencils: c_4 and c_8. Thus, for the example of Figure 4, $\Gamma_{sync} = [c_0, sync_1, c_1, c_2, c_3, sync_4, c_4, c_5, c_6, c_7, sync_8, c_8]$.

The Dependency Graph: Γ_{dep}

From the synchronized ordered list of computations Γ_{sync}, a dependency graph Γ_{dep} is built. A dependency exists between computations a and b (including synchronizations) if and only if a data element read by b has been written by a in Γ_{sync} with intersecting domains. Nodes of the dependency graph represent computations of Γ_{sync}, while edges are dependencies between them. The dependency graph Γ_{dep} is a directed acyclic graph (DAG). For example, the dependency DAG Γ_{dep} of the example of Figure 4 is presented in Figure 5.

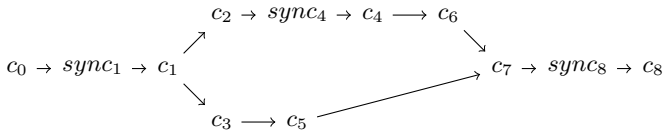
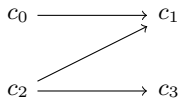


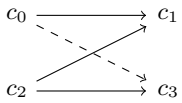
Figure 5: Γ_{dep} of the example of Figure 4.

The Minimal Series-Parallel Graph: Γ_{msp}

Once a dependency graph is built, many solutions can be used to build a parallel application, as for example dynamic schedulers [2, 13]. In this work a static scheduling of the dependency graph is built. To do so the dependency graph is transformed to a minimal series-parallel graph [24]. As it has been shown in [24], the transitive reduction of a DAG is a minimal series-parallel graph if and only if the *forbidden* shape called *N-shape*, illustrated in Figure 6a, is not found in the DAG. Thus, to transform Γ_{dep} to the minimal series-parallel graph Γ_{msp}, an algorithm is applied to remove all *N-shapes* by an over-constraint [15], as illustrated in Figure 6b.



(a) The forbidden N shape.



(b) Over-constraint on the forbidden N shape.

Figure 6: Forbidden N subgraph shape for a DAG to be minimal series-parallel.

The Tree Decomposition: Γ_{tsp}

Many works [21, 24] explains how to build a series-parallel tree decomposition from a minimal series-parallel graph. This transformation decomposes the minimal series-parallel graph as a tree where internal nodes are *sequences*, indicated by a S node, and *parallel* sections, indicated as a P node, while leaves of the tree are the nodes of Γ_{msp}. For example, the series-parallel tree decomposition Γ_{tsp} of Figure 5 is illustrated in Figure 7.

Data parallelism optimizations: Γ_{data}

The series-parallel tree decomposition Γ_{tsp} is used to build the hybrid parallelization of the simulation, but it can also be used to optimize the data parallelization. In fact, it first seems natural to create the data parallel structure directly from Γ_{sync}, as the program is parallelized from data decomposition and applying the same sequential tasks on each processor. However, as a computation kernel writes a single data w (to finely manage dependencies between tasks), the same computation domain might be iterated more than once, while some numerical expressions could be computed inside a joint space loop. For this reason, an optimized and *merged* ordered list of computation Γ_{data} is built from Γ_{tsp}. Actually, in Γ_{tsp}, computations of a parallel subtree with a same computation domain can be computed in the same space loop, in any order. Moreover, in Γ_{tsp}, two consecutive computations of a sequence subtree with a same computation domain can be computed in the same space loop, if the computation order of the sequence is kept. For example,

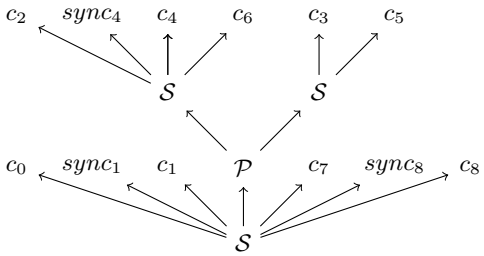


Figure 7: Γ_{tsp} of Figure 5. Nodes S represent sequences, nodes P represent parallel sections.

from Γ_{tsp} of Figure 7, as kernels c_3 and c_5 are executed inside a parallel section, and as their computation domains are the same (`alledgey`), a single component K can be written peforming both computations in the same domain loop.

5. A COMPONENT BASED BACK-END

This section describes the projection of a MSL program to a component-based runtime, including the components used to implement the static scheduling of Γ_{tsp}. The section first gives an overview of component models, and especially the Low Level Components (L^{2}C) used in this work.

5.1 Component-Based Software Engineering

Component-based software engineering (CBSE) is a domain of software engineering [22] which promotes code re-use, separations of concerns, and thus maintainability. An application is made of a set of component instances. A component is a black box that implements an independent functionality of the application, and which interacts with its environment only through well defined interfaces: its ports. A port can, for example, specify services provided or required by the component. With respect to high performance computing, some works have also shown that component models can achieve the needed level of performance, and scalability while also helping in application portability [1, 6, 19]

Many component models exist, each of them with its own specificities. Well known component models include, for example, the CORBA Component Model (CCM) [17], and the Grid Component Model (GCM) [4] for distributed computing, while the Common Component Architecture (CCA) [1], and Low Level Components (L^{2}C) [5] are HPC-oriented. This work makes use of L^{2}C for the experiments.

5.2 L^{2}C

L^{2}C [5] is a minimalist `C++` based HPC-oriented component model where a component extends the concept of class. The services offered by the components are specified trough *provide* ports, those used either by *use* ports for a single service instance, or $use - multiple$ ports for multiple service instances. Services are specified as `C++` interfaces. L^{2}C also offers MPI ports that enable components to share MPI communicators. Components can also have attribute ports to be configured. As illustrated in Figures 8, a *provide* port is represented by a white circle, a *use* port with a black circle, a $use - multiple$ port by a black circle with a white m in it. MPI port are connected with a black rectangle. A L^{2}C-based application is a static *assembly* of components

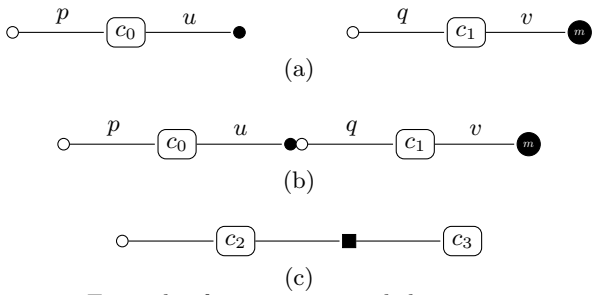


Figure 8: Example of components and their ports representation. a) Component c_0 has a provide port (p) and a use port (u); Component c_1 has also a provide port (q) but also a use multiple port (v). b) A use port is connected to a (compatible) provide port. c) Component c_2 and c_3 shares an MPI communicator.

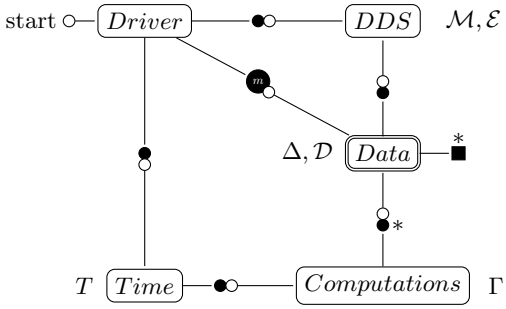


Figure 9: MSCAC Component-based Runtime Overview.

instances and connections between their ports. Such an assembly is described in LAD, an XML dialect.

5.3 MSP Component Runtime Overview

As described in Section 3, the compiler generates four independent parts in a component assembly in addition to a static part as represented in Figure 9: each rounded box represents one component instance, drawn with simple lines, or more, drawn with double lines. For example, the component `Data` is instantiated more than once. `Driver` is static and drives the whole application. The four other parts are generated based on the content of the different sections of the MSL program: `Computations`, from the parallelization of Γ (done by MSC as explained in Section 4.2), *DDS* from $\mathcal{M}$ and $\mathcal{E}$, *Data* from Δ and $\mathcal{D}$, and *Time* from T.

`DDS` manages the structure and the partitioning of the mesh, a single instance is generated as MSL only supports a single mesh for now. The back-end presented in this paper uses the distributed data structure proposed in SkelGIS library [8]. `DDS` is used by `Data`, for which one instance represents one data element in the MSL program. `Time` is parametrized by the `iteration` value from MSL and uses the `Computations` component as many times as required.

`Computations` contains the static scheduling Γ_{tsp}, or the data parallel transformation Γ_{data}, both computed by MSC. Both transformations, Γ_{tsp} and Γ_{data}, are encoded using three specific components, detailed in Section 5.4, which manage the P, S, and *sync* operations. At the leaves of Γ_{tsp}

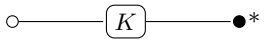


Figure 10: A kernel component K.

a) Comp. SEQ b) Comp. PAR c) Comp. SYNC

Figure 11: The three control components.

and Γ_{data}, the computation components instances (denoted K), provided by the user, are connected to `Data`. As shown in Figure 10, a K component provides a port to launch the computation and exposes a use port for each data element manipulated in the computation; a star is added on the use port to `Data` to denote it.

A complete assembly is obtained by replicating the component assembly of Figure 9 on available processors (or cores). Connections is done with MPI ports of `Data` components.

As a result of this approach, each part of the generated code is rather independent. Changing the main time loop to use a convergence criteria rather than a fixed number of iterations would only require changing the `Time` component. Similarly, changing the approach used for scheduling would only impact the code generated in `Computations`. The technology used for data parallelism can also be changed by replacing the `DDS` and `Data` components, and by using the adequate interfaces in K. As a matter of fact, we have started evaluating an alternative based on Global Arrays [16] instead of SkelGIS.

5.4 Control Components and Dump

The series-parallel tree decomposition Γ_{tsp} represents a static scheduling of the simulation. Γ_{data}, on the other hand, is an optimized merged ordered list of computations. Both are dumped to components by generating an assembly that exactly matches their structure. We introduce what we call *control components* to represent all nodes of Γ_{tsp} or Γ_{data}. These components can be used for any simulation, which increases code reuse between simulations. A control component exposes a single *provide* port containing a *control-only* method, without any parameter. Three control components have been needed: SEQ, PAR, and SYNC. They are represented in Figure 11.

Sequence component (SEQ) It is the direct representation of a sequence node of Γ_{tsp} or Γ_{data}. This component sequentially calls an ordered list of other components. It exposes an ordered *use-multiple* port to be connected to the components to call in sequence.

Parallel component (PAR) It is the direct representation of a parallel node of Γ_{tsp} (not Γ_{data}). This component simultaneously calls a set of other components. It exposes a *use-multiple* port to be connected to the components to call in parallel.

Synchronization component (SYNC) It is the direct representation to an update leaf of Γ_{tsp} or Γ_{data}. This component calls the synchronization of a given data. It exposes a *use* port to be connected to the data to be updated.

Then, from Γ_{tsp} or Γ_{data}, and using the control components described above, a direct dump can be done to a component assembly for a data or hybrid (data and task) parallelization of a simulation. Figure 12 displays the assembly part corresponding to Γ_{tsp} of Figure 7. In this figure, the ports linked to data (use and use-multiple ports of SYNC and K) are represented but are not connected for readability. Moreover, each computation component is an instance of a specific K component using the identification name of the computation of an MSL instance. Thus, this figure represents what the component `Computations` of Figure 9 contains if an hybrid parallelization is performed. On the other hand, if a data parallelization is performed, a single SEQ component is used by `Time`, which invokes in the appropriate order the computation kernels and synchronizations. Among those kernels, a single *merged* kernel would represent c_3 and c_5.

6. REAL-CASE EVALUATION

Navier-Stokes equations is a well known set of PDEs in fluid dynamics to simulate a flow evolution in time. At the University of Orléans, France, the MAPMO laboratory works on a software, called FullSWOF[1], which solves the Shallow water equations obtained from the three dimensional Navier-Stokes equations, by averaging on the vertical direction [12]. Those equations are solved using a two-dimensional Cartesian discretization of the space domain, and a finite volume numerical methods more described in [8]. We have developed a MSL version of FullSWOF that contains 3 mesh entities, 7 computation domains, 48 data and 98 computations. These computations are made of 32 stencil kernels and 66 local kernels.

6.1 Compiler Evaluation

The series-parallel tree decomposition Γ_{tsp} of this simulation, extracted by the MSC transformation, is composed of 17 sequence nodes and 18 parallel nodes. Figure 13 represents for a given level of parallelism, *i.e.,* the number of tasks to perform concurrently, the number of time this level is observed in the final component assembly. One can notice that the level of task parallelism extracted from the Shallow water equations is limited by two sequential parts in the application (level 1). As a level of 16 parallel tasks is reached two times, and also five times for the fourth level, sequential restrictions could be amortized. Moreover, each identified task can itself be parallelized, introducing data parallelism on loops. Thus, it is rather clear that the task parallelization technique should be used to improve the data parallelism when reaching its limits, but not to use alone. Moreover, as the level of parallelism in the application is heterogenous, the number of threads to launch for task parallelism, and the number of cores to keep for data parallelism is difficult to choose.

Figure 14 illustrates the execution time for each step of the MSC transformation for an overall execution time of ten seconds. Execution times have been computed on a laptop with a bi-core Intel Core i5 1.4 GHz, and 8 GB of DDR3.

[1] `http://www.univ-orleans.fr/mapmo/soft/FullSWOF/`

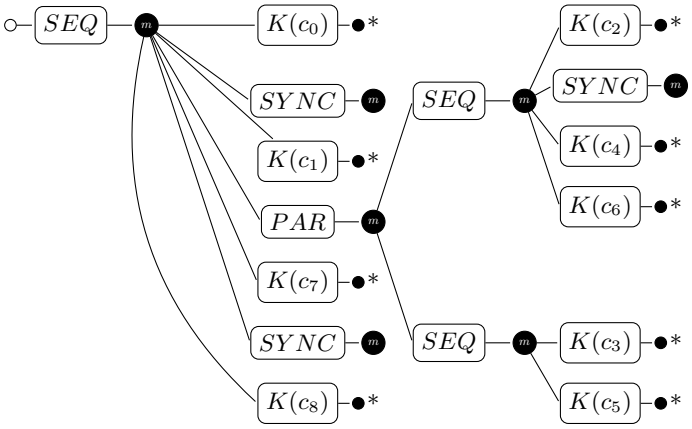


Figure 12: Component assembly representing the computation part generated from Γ_{tsp} of Figure 7.

Level	1	2	3	4	6	10	12	16
Frequency	2	1	3	5	3	1	1	2

Figure 13: Parallelism level (number of parallel tasks) and the number of times this level appears.

Step	Γ_{sync}	Γ_{dep}	Γ_{msp}	Γ_{tsp}
Time (ms)	2	530	8297	1133
%	0.02	5.3	83.3	11.37

Figure 14: Execution times of the MSC transformation steps

One can notice that the transformation of Γ_{dep} to a minimal series-parallel graph is the longest step of MSC, because of the removal of the forbidden N-shapes in the graph. Thus, the fact that many *N-shape* are removed in Γ_{dep} shows that the creation of a static schedule of tasks may not be the best solution for complex simulations. It has to be noticed, however, that the all computation of Γ_{tsp} is still usefull to detect how space loops can be merged in Γ_{data}.

6.2 Preliminary Performance Evaluation

To evaluate performance of the generated component-based parallel structure, we have proceeded as follows. Our current implementation of the MSCAC compiler generates a back-end code using the SkelGIS distributed data structure as an underlying library. For this reason, our evaluation compare the shallow water equations first parallelized with a pure SkelGIS code (data structures, applicators and interfaces of SkelGIS [8]), and second parallelized with MSL (which uses the SkelGIS data structure only). Moreover, as SkelGIS library handles data parallelization for distributed memory architectures, we have limited for now our evaluations to the merged data parallelization of MSCAC (dumped from Γ_{data}).

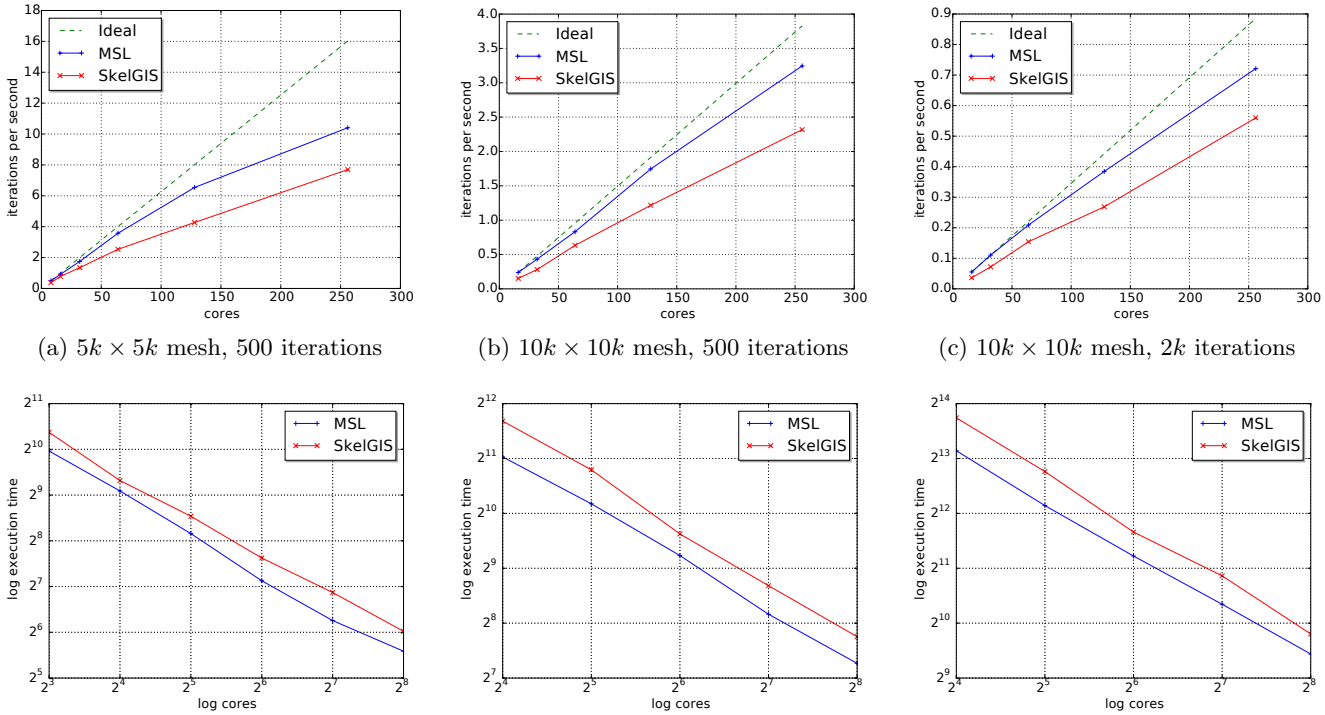
Evaluations have been performed on the cluster *Edel* of *Grid'5000*[2] for which each node is equiped with two 8-cores Intel Xeon E5520, 24GB of memory, and is interconnected with an Infiniband 40G network. On *Edel*, three different experiments have been performed that differ in the size of the Cartesian mesh and the number of time iterations: (1) $5,000 \times 5,000$, 500 iterations; (2) $10,000 \times 10,000$, 500 iterations; (3) $10,000 \times 10,000$, 2,000 iterations. Figure 15 reports the results of the three experiments. The first row of graphs is the number of iterations computed per second for various number of cores. The second row of graphs represents the execution time for various number of cores, using a logarithmic scale.

One can notice that, for the three different experiments, execution times of MSL, which itself uses the SkelGIS distributed data structure, are improved compared to a pure SkelGIS parallelization. This result can be explained by the automatic generation of the parallel component-based runtime. Actually, in a pure SkelGIS code, communications between processes are hidden from the user through specific interfaces called *applicators* [8]. Using MSL, on the other hand, communications are directly managed by $SYNC$ components, which are automatically placed in the component-based runtime by MSCAC. Thus, no overhead is introduced to hide communications. In addition to this, the scalability slope, shown by the number of iterations per second, is close to SkelGIS. This is an important result as the execution time of MSL is at the same time improved compared to SkelGIS. Actually, the less the execution time is, the less the scalability capacity is. Thus, these results confirm the result of [5] that using a component-based runtime does not damage performance of the back-end code. Finally, we notice that SkelGIS has proved its scalability on the Shallow water equations compared to an MPI parallelization [8], that makes our performance results relevant.

7. RELATED WORK

Many specific solutions exist to ease parallel programming of numerical simulations, as for example PATUS [7] and Pochoir [23] which propose a simple description to write stencil codes for general structured meshes, and OP2 [14] and Liszt [10] for general unstructured meshes. Those solutions can be considered as stencil compilers. Actually they produce optimized (cache tiling, etc.) or parallel (CUDA, OpenCL, etc.) codes for a *single* stencil computation. Recently, domain specific languages for very specific numerical methods such as ExaSlang [20] for multigrid solvers, have also been proposed.All those solutions let the user imple-

[2] `https://www.grid5000.fr/`



(a) $5k \times 5k$ mesh, 500 iterations (b) $10k \times 10k$ mesh, 500 iterations (c) $10k \times 10k$ mesh, $2k$ iterations

(d) $5k \times 5k$ mesh, 500 iterations (e) $10k \times 10k$ mesh, 500 iterations (f) $10k \times 10k$ mesh, $2k$ iterations

Figure 15: The first line represents, for each experiment, the number of iteration computed per second for a given number of cores. The second line represents, for each experiment, the execution time for a given number of cores, using a logarithmic scale.

ment their own stencil codes in a sequential programming style, and produce high performance codes for shared memory architectures and sometimes distributed memory architectures. Most stencil compilers, though, handle the parallelization or the optimization of a single stencil kernel, considering that it represents the main computation time of numerical simulations. However, most real case numerical simulation are composed of more than one stencil kernel, involving one or more stencil shapes, and additional local kernels, as explained in Section 2.2.

Other solutions, as SkelGIS library [8] or Global Arrays [16] propose more or less specialized distributed data structures (specific meshes for SkelGIS, general arrays for Global Arrays), which simplifies or totally hide communications and synchronizations between processes.

Halide [18] is a DSL which focusses on the automatic parallelization and optimization of stencil pipelines in image processing. Thus, this work is the closest to MSL. However, at least one important difference can be noticed: the specific domain it is applied on. Actually, image processing is applied onto 2D or 3D grids, while explicit numerical schemes to solve PDEs can be applied on many different meshes (grids, but also unstructured or hybrid meshes). This main difference is the reason why MSL is a descriptive and agnostic language, and why it does not target specific optimizations, as tiling for example.

The work presented in this paper takes place at a different abstraction level and can be seen as complementary to stencil compilers or distributed data structures. The MSCAC compiler only needs the agnostic description of the overall simulation to generate a parallel pattern of the program. This parallel pattern then needs to be filled with implementation parameters and computation codes. Those computation codes could be generated by stencil compilers or could be written using existing distributed data structures (as SkelGIS in this paper). As a result, MSL is not a new contribution to stencil compilers, to tiling optimizations, or to distributed data structures, but proposes a coarse-grain automatic parallelization of an overall multi-stencil program. Finally, MSL is a case study to show that component-based runtimes could improve maintainability adn flexibility of DSLs with a low impact on performance.

8. CONCLUSION

This paper has presented the domain specific language MSL and its compiler MSCAC designed to produce a parallel (data and hybrid) component-based runtime of an overall multi-stencil program, *i.e.,* a mesh-based numerical simulation reduced to explicit schemes. After details on the language and its compiler, MSL has been evaluated by the description of a real case numerical simulation: the shallow water equations. The component-based data parallelization of the simulation has been compared to a pure SkelGIS parallelization, and has shown improved execution times as well as a promising scalability. Those results demonstrate that component-based runtimes may be relevant back-end codes

for DSLs as they do not introduce performance damage. Moreover, components bring software engineering benefits such as separation of concerns, code re-use, improving maintainability.

Although MSL is a promising case study from DSLs to component-based runtimes, many works in progress aims at improving this first contribution. First, to more clearly show the improvement of DSLs maintainability using component-based back-end, an alternative `DDS` component is under study, using Global Arrays [16]. In addition to this, alternatives for the `Computations` component, computed by MSC, are under study such as a dump to a pure OpenMP [9] code or the use of dynamic schedulers [2, 13].

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