Aspect Oriented Pluggable Support for Parallel Computing*

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Abstract. In this paper, we present an approach to develop parallel applications based on aspect oriented programming. We propose a collection of aspects to implement group communication mechanisms on parallel applications. In our approach, parallelisation code is developed by composing the collection into the application core functionality. The approach requires fewer changes to sequential applications to parallelise the core functionality than current alternatives and yields more modular code. The paper presents the collection and shows how the aspects can be used to develop efficient parallel applications.

1 Introduction

The widespread use of multithreaded and multi-core architectures requires adequate tools to refactor current applications to take advantage of this kind of platforms. Unfortunately, parallelising compilers do not yet produce acceptable results, forcing programmers to rewrite their applications to take advantage of this kind of systems. When they do this, parallelisation concerns become intertwined with application core functionality, increasing complexity and decreasing maintainability and evolvability.

Tangling concurrency and parallelisation concerns with core functionality was identified as one of the main problems in parallel applications, increasing development complexity and decreasing code reuse [1, 2]. Similar negative phenomena of *code scattering* and *tangling* were identified as symptoms of the presence of *crosscutting concerns* in traditional object oriented applications [3]. Aspect Oriented Programming (AOP) was proposed to deal with such concerns, enabling programmers to localise within a single module code related to a crosscutting concern.

The use of AOP to implement parallelisation concerns provides the same benefits of modularisation as in other fields, namely improved code readability and an increased potential for reusability and (un)pluggability, for both parallelisation concerns and sequential code. AOP techniques were successful in modularising distribution code [4, 5, 6], middleware features [7], and, to a lesser extent, in isolating parallel code in loop based parallel applications [2].

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This paper presents a collection of aspect oriented abstractions for parallel computing that replace traditional parallel computing constructs and presents several case studies that illustrate how this collection supports the develop parallel applications. Section 2 presents related work. Section 3 presents a brief overview of AspectJ, an AOP extension to Java that was used to implement the collection. Section 4 presents the collection. Section 5 presents several case studies and section 6 presents a performance evaluation. Section 7 concludes the paper.

2 Related Work

We classify related work in two main areas: concurrent object oriented languages (COOL) and approaches to separate parallel code from core functionality.

COOLs received a lot of attention in the beginning of the 1990s. ABCL [8] provides active objects to model concurrent activities. Each active object is implemented by a process and inter-object communication can be performed by asynchronous or synchronous method invocation. Concurrent Aggregates [9] is a similar approach but supports groups of active objects than can work in a coordinated way and includes mechanisms to identify an object within a group. Recent COOLs are based on extensions to sequential object oriented languages [10, 11, 12]. These extensions introduce new language constructs to specify active objects and/or asynchronous method calls. ProActive [13] is an exception, as it relies on an implicit wait by necessity mechanism, however, when a more fine grain control is required, an object body should be provided (to replace the default active object body). Object groups, similar to concurrent aggregates, were recently introduced [14, 15]. With these approaches, the introduction of concurrency primitives and/ or object groups entails major modifications to source code. Parallelisation concerns are intertwined with core functionality, yielding the aforementioned negative phenomena of code *scattering* and *tangling*.

One approach to separate core functionality from parallel code is based on *skeletons* where the parallelism structure is expressed through the implementation of off-the-shelf designs [16, 17, 18, 19]. In generative patterns [20], the skeletons are generated and the programmer must fill the provided *hooks* with core functionality.

AspectJ was used in [4, 5, 6] to compose distribution concerns into sequential applications. In [2], an attempt is made to move all parallelism related issues into a single aspect and [21] proposes a more fine-grained decomposition. In [22], a collection of reusable implementations of concurrency concerns is presented.

OpenMP [23] introduces concurrency concerns by means of programming annotations that can be ignored by the compiler in a sequential execution.

Our approach differs from the aforementioned efforts in that we propose a collection of reusable aspects that achieve the same goals, by supporting object group relationships. We use concurrency constructs equivalent to traditional COOLs but we deploy all code related to parallelism within (un)pluggable aspects. Our approach differs from skeleton approaches as it uses a different way to compose core functionality and parallel code. Our approach requires less intrusive modifications to the core functionality to achieve a parallel application, yields code with greater potential for reuse and supports (un)plugability of parallelisation concerns.

3 Overview of AspectJ

AspectJ [24, 25] is a backwards compatible extension to Java that includes mechanisms for AOP. It supports two kinds of crosscutting composition: static and dynamic. Static crosscutting allows type-safe modifications to the application static structure that include member introduction and type-hierarchy modification. AspectJ's mechanism of *inter-type declarations* enables the introduction of additional members (i.e. fields, methods and constructors). AspectJ's type-hierarchy modifications add super-types and interfaces to target classes. Fig. 1 presents a point class and Fig. 2 presents an Aspect that changes class *Point*, to implement interface *Serializable*, and to include an additional method, called *migrate*.

```
public class Point {
        private int x=0;
        private int y=0;

        public void moveX(int delta) {  x+=delta; }
        public void moveY(int delta) {  y+=delta; }

        public static void main(String[] args) {
                Point p = new Point();
                p.moveX(10);
                p.moveY(5);
        }
}
```

Fig. 1. Sample point class

```
public aspect StaticIntroduction {
      declare parents: Point implements Serializable;
      public void Point.migrate(String node) {  System.out.println("Migrate to node" + node); }
}
```

Fig. 2. Example of a static crosscutting aspect

Dynamic crosscutting enables the *capture* of various kinds of execution events, dubbed *join points*, including object creation, method calls or accesses to instance fields. The construct specifying a set of interesting join points is a *pointcut*. A pointcut specifies a set of join points and collects context information from the captured join points. The general form of a named pointcut is:

```
<visibility-modifier> pointcut <name>(ParameterList): <pointcut_expression>;
```

The *pointcut_expression* is composed by pointcut designators (PCDs), through operators *&&*, ||, and *!*. AspectJ PCDs identify sets of join points, by filtering a subset of all join points in the program. Join point matching can be based on the kind of join point, on scope and on join point context. For more information on PCDs, see [24].

Dynamic crosscutting also enables composing behaviour before, after or instead of each of the captured join points using the *advice* construct. Advices have the following syntax:

```
[before | after | <Type> around] (<ParameterList>): <pointcut_expression>
    {… // added behaviour }
```

The *before* advice adds the specified behaviour before the execution point associated to the join points quantified by the *pointcut_expression*. *around* advices replace the original join point with new behaviour and is also capable of executing the original join point through the *proceed* construct. *after* advice adds new behaviour immediately after the original execution point. The *pointcut_expression* is an expression comprising one or several PCDs that can also reuse previous pointcut definitions. Objects and primitive values specific to the context of the captured join point are obtained through PCDs *this*, *target* and *args*. Fig. 3 shows the example of a logging aspect, applied to class Point. In this example, a message is printed on the screen on every call to methods moveX or moveY. The wildcard in the poincut expression is used to specify a pattern for the call's signature to intercept.

```
public aspect Logging {
    void around(Point obj, int disp) : call(void Point.move*(int)) && target(obj) && args(disp) {
        System.out.println("Move called: target object = " + obj + " Displacement " + disp);
        proceed(obj,disp);                          // proceed the original call
    }
}
```

Fig. 3. Example of a dynamic crosscutting aspect

Modularisation of crosscutting concerns is an achievement that contributes to code reusability. Though it is a necessary condition, it is not a sufficient one, as only the non case-specific code is reusable. Essential parts of the aspect's behaviour are the same in different join points, whereby other parts vary from join point to join point. Reuse of crosscutting concerns requires the localisation of reusable code within *abstract base aspects* that can be reused by concrete sub-aspects. Concrete aspects contain the variable parts tailored to a specific code base, specifying the case-specific join points to be captured in the logic declared by the abstract aspect. Abstract aspects rely on abstract pointcuts and/or marker interfaces. In both cases, the abstract aspect only refers to abstract pointcut(s) or to the interface(s) and is therefore potentially reusable. Each concrete implementation entails the creation of one or several concrete sub-aspects that concretise inherited pointcuts by specifying the set of join points specific to the system at hand, and by making case-specific types implement the marker interfaces. In addition, aspects can hold their own state and behaviour.

An aspect is supposed to localise code related to a concern that otherwise would be crosscutting. A composition phase called *weaving* enables the placement of aspect code in multiple non-contiguous points in the system. As an example, the behaviour specified by the around advice in Fig. 3 is composed in all base classes that call moveX or moveY methods.

4 Aspect Oriented Collection for Parallel Computing

The aspect oriented collection (Table 1) presented in this paper is based on three programming abstractions: *separable/migrable objects*, *asynchronous method calls*

and *object aggregates*. By implementing the abstractions through aspects, it becomes possible to turn a given sequential application (i.e., sequential, domain-specific, object oriented code) into a parallel application. However, the base code should be amenable for parallelisation, i.e., the amount of parallelism that can be introduced by the aspect collection is subject to dependencies in application tasks and data. The composition of the collection with core functionality requires a set of suitable join points. If these are not available, the source code must be refactored to expose the necessary join points.

Table 1. Aspect oriented collection of abstractions for parallel computing

Abstraction	Scope	Description
Separate	Class	Separate object - can be placed in any node
Migrable	Class	Migrable object - can migrate among nodes
Grid1D, Grid2D	Class	Object aggregate in a 1 or 2d GRID
OneWay	Method	Spawns a new thread to execute the method
Future	Method	Spawns a new thread and returns a future
Synchronised	Method	Implements object-based mutual exclusion
Broadcast/scatter	Aggregate	Broadcast/scatter method among members
Reduction/gather	Aggregate	Reduce/gather method among members
Redirection	Aggregate	Redirect method call to one member (round-robin)
DRedirection	Aggregate	Redirect call to one member (demand-driven)
Barrier	Aggregate	Barrier among aggregate members

Separable objects are objects that can be placed in remote nodes, selected by the run-time system. *Migrable objects* are similar but they can migrate to a different node after their creation. These two abstractions are specified through the separable and migrable interfaces using the declare parents AspectJ construct (see section 2).

Asynchronous method calls introduce parallel processing between a client and a server. The client can proceed while the server executes the requested method. Asynchronous calls can be *OneWay* and *Future*. One-way calls are used when no return value is required. Fig. 4 shows the synopsis for the use of one-way calls.

```
public aspect aspectName extends OnewayProtocol {
   protected pointcut onewayMethodExecution(Object servant) : <pointcut definition>;
   protected pointcut join() : <pointcut definition>;
}
```

Fig. 4. One-way introduction

Pointcut *onewayMethodExecution* specifies the join points associated to invocation of methods that run into a new parallel task. Pointcut *join* can optionally be used to specify join points where the main thread blocks, waiting for the termination of the spawned tasks.

Future calls are used for asynchronous calls that require a return value. In typical situations, a variable stores the result of a given method call, which is used in a later phase. Instead of blocking in the method call, the client blocks when the variable that stores the result (i.e., the value returned by the method) is actually accessed. Fig. 5 shows the synopsis for the implementation of futures.

```
public aspect aspectName extends FutureProtocol {
   protected pointcut futureMethodExecution(Object servant): <pointcut definition>;
   protected pointcut useOfFuture(Object servant): <pointcut definition>;
}
```

Fig. 5. Future introduction

Pointcut *futureMethodExecution* indicates the asynchronous method calls and pointcut *useOfFuture* defines the join points where the result of the call is needed. The client blocks on join points captured by *useOfFuture*, in case the methods defined in *futureMethodExecution* have not completed execution.

A richer set of primitives for synchronisation is also available [22], namely Java's synchronised methods, barriers and waiting guards, but their description is out of scope of this paper.

Object aggregates are used to transparently represent a set of object instances in the core functionality. An object aggregate deploys one or several object instances in each node (usually one per physical processor/core) and provides additional constructs to access the members of the aggregate. There are two main interfaces to support aggregates: *Grid1D* and *Grid2D*; they differ only in the way the internal members of the aggregate are referenced. For instance, a *Grid1D* aggregate provides two calls: *getAggregateElems()* and *getAggregateElemId()*. *Grid1D* and *Grid2D* aggregates are specified in a way similar to separate objects (i.e., using *declare parents*).

Calls to the original object instance (i.e., calls in the core functionality) are replaced by calls to the first object in the aggregate (called the aggregate representative). These calls can also be *broadcasted*, *scattered* and *reduced* among members of the aggregate. Broadcasted calls are executed in parallel by all aggregate members, using the same parameters of the core functionality call. Such call returns when all broadcasted calls complete. Fig. 6 shows the synopsis for the use of broadcasted calls. Pointcut *broadcastMethodExecution* specifies method calls broadcasted to all aggregate members.

```
protected pointcut broadcastMethodExecution(Object servant) : <pointcut definition>;
```

Fig. 6. Broadcasted calls introduction

Scattered calls (Fig. 7) are similar to broadcasted calls but they provide a mechanism to specify a different parameter for each call into aggregates member. This is specified by implementing the abstract method *scatter* which returns a vector whose elements correspond to the parameters sent to aggregate members.

```
protected Vector scatter(Object callParameter) {
    …
}
protected pointcut scatterMethodExecution(Object serv, Object arg) : <pointcut definition>;
```

Fig. 7. Scattered calls introduction

Reduced calls are also similar to broadcasted calls, but they provide a mechanism to combine return values of each aggregate member call. This type of calls should be used instead of a broadcasted call, when the call returns a value. In this case a reduction function specifies how to combine the returned values of each aggregate member call (Fig. 8).

```
protected Object reduce(Vector returnValues) {
    …
}
protected pointcut reduceMethodExecution(Object serv, Object arg) : <pointcut definition>;
```

Fig. 8. Reduced calls introduction

An additional function (scatter/reduce) performs a combination of scatter and reduce calls. Other aggregate functions can redirect a call to one aggregate member in a round-robin fashion (*redirectCall*) or in a demand driven scheme (*dredirectCall*).

Broadcasted, scattered and reduced calls are valid just for object aggregates (e.g., method calls on objects that implement interfaces *Grid1D* or *Grid2D*).

Fig. 9 shows a simple application that illustrates the use of this collection of aspects. The object *Filter* in the core functionality (left column of Fig. 9) is replaced by an aggregate in the parallelisation code (right column, *declare parents* statement) and calls to method *filter* are broadcasted, in parallel, to all aggregate members (pointcuts *broadcastMethodExecution* and *onewayMethodExecution*). Before *filter* method execution (advice *before() execution(* Filter.filter)*), each aggregate member displays its identification within the aggregate.

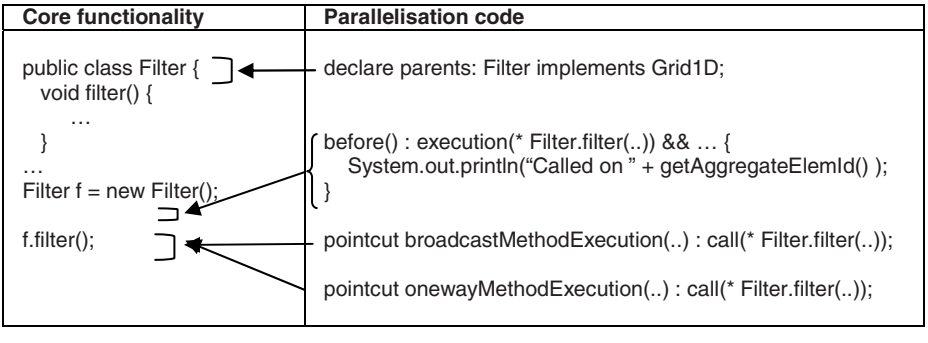

Fig. 9. Simple application example

5 Case Studies

This section presents two case studies that illustrate the use of the aspect collection to develop modular parallel applications. The case studies are taken from the parallel Java Grande Forum Benchmark (JGF) [26]. This benchmark includes several sequential scientific codes and parallel versions of the same applications, using

mpiJava (a bind of MPI to Java). Their parallel implementations introduce modifications to the sequential code, intermingling domain specific code with MPI primitives to achieve a parallel execution. Tangling makes it difficult to understand the parallelisation strategy as well as the domain specific code. Our approach entails introducing as fewer modifications as possible to the domain scientific code by introducing the parallelisation logic through non-invasive composition of the aspects from the collection. We believe that this approach makes the implementation of the parallelisation strategy more modular and explicit.

The first case study is a Successive Over-Relation method (SOR), an iterative algorithm to solve Partial Differential Equations (PDEs). This application is parallelised using a heartbeat scheme, where each parallel task processes part of the original matrix. After each iteration, neighbour parallel tasks must exchange information required for the next iteration.

The second application is a ray-tracer that renders a scene with 64 spheres. It is parallelised using a farming strategy, where each worker renders a set of image lines.

5.1 Successive Over-Relation

The SOR method is used to iteratively solve a system of PDE equations. The method successively calculates each new matrix element using its neighbour points. The sequential Java program of the JGF method is outlined in Fig. 10. This code iterates a number of pre-defined iterations, given by *num_iterations*, over matrix *G*.

In this particular case, the sequential version could limit parallelism due to dependencies among calculations. To overcome this limitation the *SORrun* implementation was changed to use the Red-Black parallel version, becoming more amenable for parallel execution. This strategy was also followed in the JGF parallel benchmark to derive the parallel version of the application.

```
public class SOR {
    …
    public static final void SORrun(double omega, double G[][], int num_iterations) {
        …
        for (int p=0; p<num_iterations; p++) {
                … // performs one iteration
        }
        …
    }
}
```

Fig. 10. JGF SOR sequential code

The sequential code from the JGF does not provide adequate join points to compose with our collection. Our first step is to use the static crosscutting of AspectJ to make this code suitable for composition with parallelisation code (Fig. 11). This code introduces two new methods into the SOR class: the *init* method (lines 04-05) initialises the SOR matrix and the *iterate* method (lines 07-08) performs one iteration. In lines 10-17 the original SORrun call is redefined to call these methods. An

```
01   double SOR.MyG[][],
02   static int SOR.omega;
03
04   // initialise matrix
05   public void SOR.init(double G[][]) { MyG = G; }
06
07   // performs one iteration
08   public void SOR.iterate() { SORrun(omega, MyG, 1); }
09
10   // redirects SORrun calls to use SOR instances, init call and iterate calls
11   void around(double omega, double G[][], int iterations) call(* SOR.SORrun(..)) && … {
12        SOR.omega = omega;
13        SOR so = new SOR();
14        so.init(G);
15        for(int i=0; i<iterations; i++)
16             so.iterate();
17   }
```

Fig. 11. SOR method core functionality

alternative would be to refactor all the JGF SOR sequential code to use SOR instances, *init* and *iterate* calls.

SOR core functionality can be parallelised through a typical heartbeat strategy. According to this strategy, each parallel task iterates over a subset of the matrix, periodically exchanging boundary information with its neighbours. The parallelisation aspect has four parts: 1) creates multiple SOR objects; 2) assigns a subset of the matrix to each SOR object; 3) performs a call to the *iterate* method on all the objects in the set and 4) exchanges matrix lines among objects after each iteration.

The first step creates an aggregate of SOR objects in place of a single object (Fig. 12), by specifying that the SOR class implements the Grid1D interface (line 01 in Fig. 13). Our system intercepts the creation of SOR instances in the core functionality and creates one SOR object on each node/CPU.

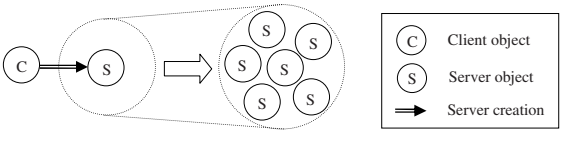

Fig. 12. Transparent creation of several SOR objects

The second step distributes the G matrix among the elements of the aggregate (Fig. 14). The code for this step intercepts the *init* method, splits the received matrix into blocks, using method *scatter* (line 02 in Fig. 13) and calls the *init* method on each object in the set, passing a different block to each element using the scatter method (line 03 in Fig. 13). Code for the matrix partition (*scatter* method in line 02 in Fig. 13) is a bit tricky to implement since there are lines from the matrix that are replicated in several objects and the first and the last objects receive one line less than other

```
13  SOR so = new SOR();          01  declare parents: SOR implements Grid1D;

14  so.init(G);                  02  Vector scatter(Object arg) { … }
                                 03  pointcut scatterMethodExecution(..) :
                                                    call (* SOR.init(..)) && ...;
15  for(int i=0; i<iterations; i++)
16        so.iterate();          04  pointcut broadcastMethodExecution(..) :
                                                    call(* SOR.iterate(..)) && …;

                                 05  after() : execution(* SOR.iterate(..)) && … { … }
```

Fig. 13. Parallelisation of the SOR application using our AOP collection

objects. However, this code is also required in a traditional parallel application and it is usually tangled with the algorithm core functionality.

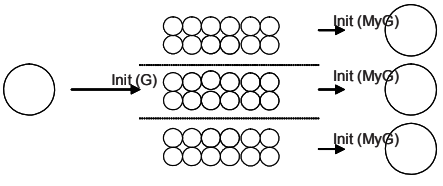

Fig. 14. Matrix distribution among SOR objects

Third, *iterate* method calls are executed by all SOR aggregate objects (Fig. 15). Code for this operation implements the broadcast pointcut (line 04 in Fig. 13).

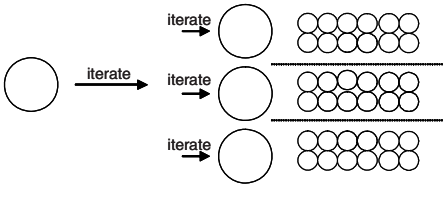

Fig. 15. Iteration distribution among SOR objects

The last step exchanges matrix boundary lines among SOR objects, after an iterate method execution (Fig. 16 and line 05 in Fig. 13).

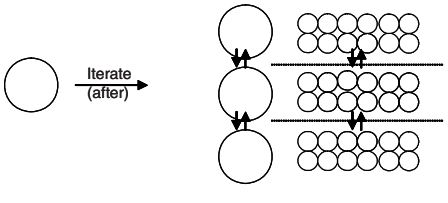

Fig. 16. Boundary exchange among SOR objects

5.2 RayTracer

The JGF RayTrace renders an image of sixty-four spheres. A simplified version of the JGF sequential code is provided in Fig. 17. Method *JGFinitialise* initialises the scene to be rendered and method *JGFapplication* renders the scene. The class *Interval* allows the specification of a subset of the lines to be rendered.

```
public class JGFRayTracerBench extends RayTracer … {
    …
    public void JGFinitialise(){
        …
        scene = createScene();      // create the objects to be rendered
        setScene(scene);            // get lights, objects etc. from scene.
        …
    }

    public void JGFapplication() {
        …
        // Set interval to be rendered to the whole picture
        Interval interval = new Interval(0,width,height,0,height,1);

        render(interval);           // Do the business!
        …
    }
}
```

Fig. 17. JGF RayTracer sequential code

The parallelisation aspect for this benchmark (Fig. 18) declares the class *JGFRayTracerBench* to implement the *Grid1D* interface (line 01). Calls to *JGFinitialise* are broadcasted to all aggregate members (line 03) and a call to the *render* method is scattered throughout aggregate elements. The *scatter* function builds a vector with the arguments for each call to one aggregate member. This is the same strategy followed in the JGF parallel version of this application.

```
01  declare parents: RayTracerBench implements Grid1D;
02
03  pointcut broadcastMethodExecution(Object servant) : call(* *. JGFinitialise(..)) && … ;
04
05  Vector scatter(Object arg) {      // calculates the parameters of each call
06      Vector v = new Vector();
07      Interval in = (Interval) arg;
08      …
09      for(int i=0; i<workers; i++) {
10          Interval inp = new Interval(/* sub-interval range */);
11          v.add(inp);     // saves the range of each worker
12      }
13      return(v);
14  }
15
16  pointcut scatterMethodExecution(Object serv, Object arg) : call (* *.render(..)) && … ;
17
```

Fig. 18. JGF RayTracer parallelisation aspect

6 Performance Results

This section presents a performance evaluation of the proposed aspect collection. The results presented in this section were measured on an unloaded cluster of 8 dual-Xeon 3.2 GHz machines, with hyper-threading enabled, connected through a 1 Gbit Ethernet. This cluster runs Rocks 4.0.0 and Sun Java JDK 1.5.0_3 in client mode. Presented execution times are the median of five executions. Sequential execution times were measured on JGF versions where our parallelisation aspects were unplugged. Speed-up values are relative to these sequential execution times.

Fig. 19 presents the execution time for a SOR (4000x4000 matrix) and a RayTracer (500x500 image) on a single machine. With two aggregate members the ray tracer presents better speed-ups, due to less communication required among tasks. Both applications can benefit from hyper-threading (i.e., using more than two aggregate members per node). In this case, higher gains in the SOR can be due to stronger dependencies among matrix elements calculations; leading to higher parallelism when the user performs an explicit parallelisation (e.g., provides more independent tasks, by means of a higher number of aggregate members).

Fig. 20 presents execution times on 8 cluster nodes. Also in this case the ray tracer presents better speed-ups, due to less communication among tasks. Note that using more than 16 aggregate members leads to a smaller performance improvement, since this additional gain is achieved by using multi-threading capabilities of these processors.

Execution times compared to equivalent Java versions (not shown), using MPP (message passing library built on top of Java nio) and Java Threads are within 5% execution time. This low overhead is due to static nature of AspectJ weaving, which can inline most aspect code into the core classes. The aspect overhead results from additional data structures and from some code that can not be in-lined in the original and is placed in new classes. Scatter and reduce functions can also be an additional source of overhead, since they may require additional data copies.

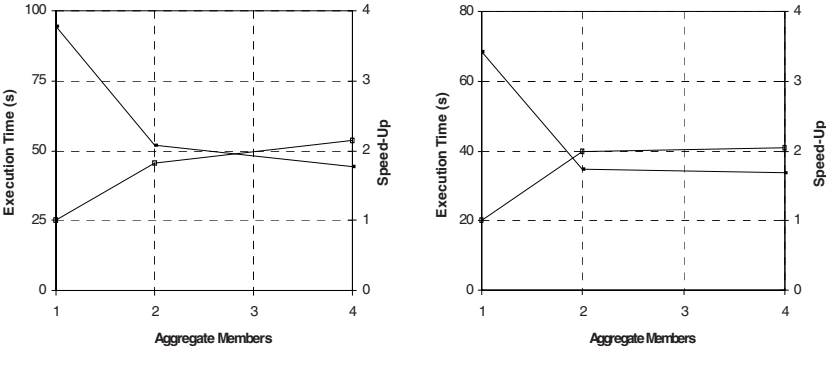

Fig. 19. Execution time and speed-ups for a SOR (at left) a RayTracer (at right)

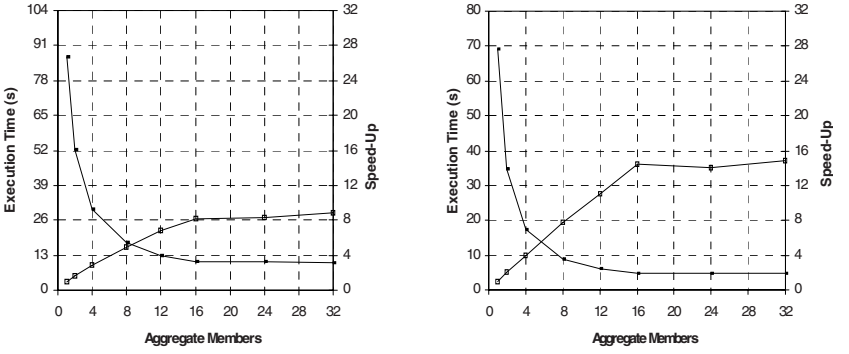

Fig. 20. Execution times and speed-ups for a SOR (at left) and a RayTracer (at right)

7 Conclusion

This paper presents a collection of aspects for parallel computing that requires fewer and smaller changes to parallelise sequential applications than current alternatives. It yields parallel object-oriented scientific applications that are more modular and easier to reuse. The collection was successfully applied to several JGF applications.

One of the main drawbacks of the approach stems from the non object-oriented nature of current scientific applications, as these do not provide adequate join point leverage to compose the sequential code with our collection. However, this limitation is expected to have less impact in the future, as scientific code becomes more object oriented. We can partially overcome this limitation by using the static crosscutting mechanisms of AspectJ to introduce the appropriate join points (as in the SOR application).

A second limitation is when the sequential code is not amenable for parallelisation. One solution is to refactor the core functionality in order to obtain a more fine grained decomposition. As an example, in the RayTracer example we could have a method *renderLine* which would provide more flexibility to derive the parallel version of RayTracer.

Current work includes the extension of this collection to support more orthogonal compositions of broadcast, scatter and reduce pointcuts; and a more efficient implementation of these pointcuts on distributed memory machines (e.g., using MPI collective primitives).

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