EXPERIENCES WITH ASPECT-BASED PARALLELIZATION OF SCIENTIFIC CODE

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ABSTRACT
This paper discusses the use of Aspect-Oriented Programming (AOP) to support the parallelization of scientific code. The idea is to develop parallelism concerns in separate aspects so that the weaving process can inject the code structures which allow the sequential scientific core to be executed in parallel. A series of advantages can initially be derived from this aspect-based approach. As parallelism is modularized into separate units, the code-tangling level is reduced. The parallel version is developed by reusing the code pieces which implement the numerical computation sequentially. Moreover, different aspects can be written to adapt the application to different high-performance environments. This paper describes some experiences with the code parallelization using aspects. Specifically, the integration of both task and data parallelism in the context of two parallel scenarios (i.e. multithreading and message-passing) is addressed in a case study. The work is an attempt to assess the benefits and limitations of applying AOP for these purposes.

INTRODUCTION
Scientific software frequently exploits parallelism for achieving high-performance when tackling large-scale and realistic engineering problems. Implementations are typically based on parallel programming libraries (e.g. PThreads, MPI, PVM) which provide the developer with a set of primitives to code parallelism concerns. However, code-tangling problems often arise in these applications as the statements describing the numerical computation are mixed with those expressing parallelism.

Aspect-Oriented Programming (Kiczales et al. 1997) helps the developer to achieve the separation of concerns, especially in those situations when such concerns cut across multiple parts (classes, components, modules) of a system. The modular management of cross-cutting concerns leads to a simpler application code which is easier to develop and maintain and has a greater potential for reuse. A well-modularized cross-cutting concern is called an aspect.

The management of high-performance concerns using AOP is emerging as a promising line of research. In (Harbulot and Gurd 2004), the separation of the parallel structure cross-cutting Java scientific applications is addressed using the general-purpose language AspectJ (Kiczales et al. 2001). The work in (Harbulot and Gurd 2006) describes an extension of the AspectJ join point model aimed at allowing loops to be parallelized without re-factoring the base-code. A methodology for the modular development of parallel programs which is based on the composition of multiple fine-grain aspects such as concurrency, partition, distribution and so on, is discussed in (Sobral 2006). The proposal in (Díaz et al. 2005) is focused on a component framework for the efficient development of high-performance applications. Specific concerns which affect a set of scientific components, such as the communication scheme underlying the application, are modeled into a special type of entities called aspect components.

This paper focuses on the idea that scientific programs can (possibly) be written sequentially in a way that enables parallelism to be added later, for instance, once the code has been tested and debugged. Although the parallelization of a scientific program may require many changes of diverse nature in different parts of its code, we can consider the effects of these changes as the result of weaving what we have called parallelization aspects into the sequential scientific core (i.e. the part in charge of the numerical computation). The bodies of these aspects will implement additional functionalities such as distribution, communication and synchronization, in order to enable the sequential core to be executed in parallel.

We can anticipate a series of advantages derived from this aspect-based parallelization approach:

- Parallel statements don’t obscure the mathematical model, as the former are isolated into aspects, which results in a reduction of code-tangling.
- The parallel application is set-up by weaving aspects into the sequential core, promoting core reuse.
- The applied parallelism model can be replaced simply selecting different aspects to be woven.
Despite the potential benefits, this approach may also lead to some serious shortcomings. The characteristics of the aspect-oriented language used determine the type of interaction between aspects and base-code. For instance, in a general-purpose language such as AspectJ, the interactions are mainly based on intercepting method calls (pointcuts plus advice code), augmenting data structures (introductions), and so on. However, the parallelization of code following these mechanisms can be very difficult unless the programs are written assuming (explicitly) the fact that the code pieces which will be parallelized must be accessed and managed through valid join points. This leads us to consider new sequential designs which include sets of interfaces and/or classes aimed at allowing aspects to inject parallelism. In some sense, the parallelization concern must be somehow considered from the initial design of the code. Obviously, this represents an extra effort in the development of the sequential scientific core.

This work is an attempt to assess the feasibility and suitability of the approach. The purpose is to describe a real experience which allows us to determine the overall advantages and limitations of using aspects for the code parallelization. At first, we describe a sequential program which computes the 2D-Fast Fourier Transform (Briham 1988) of a collection of matrices. Then, aspect weaving is used to integrate both task and data parallelism into the scientific code. This is carried out in the context of two different parallel scenarios: multithreading with shared memory, and message-passing based on MPI.

The implementation is based on the aspect-oriented language AspectC++ (Spinczyk et al. 2002). In AspectC++, almost all the language elements are efficiently implemented at compile-time, which makes the tool more suitable for the development of high-performance concerns than other approaches using Java-based dynamic weaving such as AspectJ.

The paper is structured as follows. Section 2 provides an overview of AspectC++. The case study is presented in section 3, where the sequential solution is described. Sections 4 and 5 provide an in-depth description of the parallelization using multithread programming and MPI, respectively. The paper finishes with some conclusions.

**ASPECTC++ FUNDAMENTALS**

AspectC++ is a general purpose language extension to C++ for the support of Aspect-Oriented Programming. An aspect can be understood as a modularized unit that implements a cross-cutting concern. The points at which an aspect can interfere with the base-code are called join points.

A pointcut identifies a set of join points. Pointcuts are described by means of pointcut expressions, which can refer to combinations of static program entities, such as classes, functions or namespaces, and other points in the control flow of the program. For instance, the expression:

```
execution("void Dialog::set%(...)")
```

refers to the execution of any method of `Dialog` having both a name beginning with `set` and `void` as return type. In the match expression, `*` is used as a wildcard symbol and `...` represents any sequence of arguments. A pointcut declaration allows a pointcut to be named so that it can be reused in different parts of the program.

The advice is the mechanism which defines the way the aspect affects the base-code. An advice declaration indicates the block of code to be executed when specific join points are reached. The advice code can be executed before, after, or both before and after (i.e. around) the join point. For instance, the following advice can be used to trace the execution of “setter” methods in `Dialog`:

```
advice execution("void Dialog::set%(...)") & that(d) : before(Dialog &d) {
    cout << "Dialog: " << d.name
        << " will be modified."
        << endl;
}
```

The code in the example above is triggered just before the method execution. The function that() binds a variable to the object on which the method is invoked (i.e. the object referred to by this). Other pointcut functions can be used to access information such as the arguments of a function and its return value. Furthermore, the object tp (of class `JoinPoint`) allows the programmer to retrieve context information from within the advice code.

A different type of advice is that represented by introductions, which are used to augment data structures. For instance, the following code uses a slice element to add data members and methods to the class `Dialog`. A method which is defined this way can access even private data members:

```
advice "Dialog" : slice class {
    Time creation;
    int isExpired() {
        return ((Time::now() - creation) > 3600) ? 1:0;
    }
}
```

The aspect is the language construction in which all these elements are combined for the implementation of modularized cross-cutting concerns. In terms of syntax, an aspect is very similar to a C++ class definition. In this sense, aspects can have data members and methods, and can inherit from classes and even other aspects. The code below shows an aspect which implements an “expiration” concern for the class `Dialog`.

The functionality consists of preventing the modification of any dialog window which has already...
CASE STUDY: THE SEQUENTIAL 2D-FFT

The Fast Fourier Transform (FFT) is used to produce frequency analysis of discrete signals in a wide range of application domains: image analysis, signal processing, speech recognition, astronomy, etc. The processing of a vector of N elements (i.e. complex numbers) involves O(N logN) operations. The FFT of a matrix (called 2D-FFT) consists of using FFT to transform each row and then uses the result to transform each column (again using FFT).

This section describes a C++ code for the sequential processing of a stream of complex matrices using the 2D-FFT. The problem has been broken down into four main activities (sensor, FFT on columns, FFT on rows, writer) which are coupled following a pipeline scheme, so that each activity consumes the result of the previous one. The class diagram is shown in figure 1.

The class FFT2D models the problem as a sequential pipeline. The activities inherit from Stage. Data and Rect represent, respectively, complex matrices and rectangular regions. The implementation of some of the methods is described below:

```cpp
int main(int argc, char **argv) {
    Pipe *pipe = new FFT2D;
    pipe->create();
    pipe->execute(NUM_MATS, pipe->getStages());
    delete pipe;
}

void FFT2D::create() {
    Stage *s1 = new Sensor(1);
    Stage *s2 = new FFTCols(2);
    Rect r(1,DIMX,1,DIMY);
    linkStages(s1,s2,&r);
    addStage(s1);
}
```

Compared to a classical implementation, the solution presented here offers some additional elements which are atypical in sequential scientific programs. They have been considered specifically with the aim of facilitating the parallelism integration by means of an AO language. Let us enumerate some of the elements:

- The degree of decomposition in terms of methods, interfaces and classes is high, therefore providing a rich set of join points to be intercepted.
- Activities are represented by different classes in the system, making the potential use of active elements easier (threads, distributed objects, etc.).
- Stages have to be linked explicitly and the linkage is based on sharing an object of class Data. This can be used as the basis for communicating active elements.
- Additional arguments in method calls are especially useful in two cases: for indicating the list of stages in the computation, and for setting the stage iteration range through an object of class Rect. The arguments can be altered by the aspect code.

Regarding the parallel execution, the solution can exploit both task and data parallelism. On the one hand, the pipeline can run its stages concurrently, which means that up to four matrices can be processed simultaneously. On the other hand, the stages
computing the FFT, which are the ones with higher computational cost, can divide the matrix into several blocks for an “embarrassingly” parallel computation. The following aspect establishes the degree of parallelism by setting both the type of data distribution and the number of blocks for every stage. This aspect declaration can be reused regardless of the parallelism implementation:

```java
aspect Parallelism {
  advice "Stage" : slice class {
    int blocks;  // Number of blocks
    int distribution;  // Type of data distribution
  };
  advice construction("Stage") && that(s) :
    after(Stage &s) {
      switch (s.id) {
        case 1:s.blocks=1; break;
        case 2:s.blocks=4;s.distribution=BY_COLS; break;
        case 3:s.blocks=4;s.distribution=BY_ROWS; break;
        case 4:s.blocks=1; break;
      }
    }
};
```

MULTITHREAD-BASED DESIGN

The execution of multiple threads is a way to exploit parallel hardware, as the operating system is able to run each thread on a different processor. Thread interactions can be based on variables which are allocated to a global memory space. Synchronization mechanisms are required to ensure the consistency of the shared data.

We have based the multithread implementation on the Adaptive Communication Environment ACE (Schmidt 2002), an object-oriented framework for the efficient development of concurrent communication software. The portability of ACE enables the same multithread code to be run on top of different interfaces such as POSIX PThreads, Solaris threads and Win32 threads.

The application described here uses groups of threads to execute the stages in parallel (one group per stage). The group size is indicated by the attribute blocks introduced in Stage by the aspect Parallelism, as stated at the end of the previous section.

Stage Connection

In the sequential version, the stages were connected by sharing a single instance of Data. This is a shortcoming in the parallel version since a stage running slower than the others will block the preceding ones, which will not be able to write in their output Data objects. A way to increase the performance is to link the stages using a buffer which supports the storage of multiple data elements. Figure 2 illustrates the idea. Four threads are running the code of FFTCols. Each time a result is produced, it is placed into a FIFO buffer from which the next stage (FFTRows, using four threads as well) retrieves its input data.

As the Fifo objects will be accessed by different threads, synchronization mechanisms have to be considered. In our approach, the synchronization concern is developed in a separate aspect to be woven into the class Fifo:

```java
aspect SynchFifo {
  advice "Fifo" : slice class {
    ACE_Thread_Mutex *mutex;
    ACE_Condition<ACE_Thread_Mutex> *notEmpty;
    ACE_Condition<ACE_Thread_Mutex> *notFull;
  };
  advice execution("void Fifo::get(...)") && that(f) :
    around(Fifo &f) {
      f.mutex->acquire();   // mutex acquired
      while (f.size() == 0)
        f.notEmpty->wait(); // Blocks if buffer is empty
      tjp->proceed();       // Element removal
      f.notFull->signal();  // The buffer has free space
      f.mutex->release();   // mutex released
    }
};
```

The application described here uses groups of threads to execute the stages in parallel (one group per stage). The group size is indicated by the attribute blocks introduced in Stage by the aspect Parallelism, as stated at the end of the previous section.

The second advice introduces code before and after the get() operation in order to control the removal of data. The body of the advice is accessed in mutual exclusion. If the Fifo buffer is empty, the thread is blocked in the notEmpty condition variable, waiting for any other thread to insert new data. Otherwise, a call to tjp->proceed() executes the code of get(). Then, we are sure that the buffer is not full, and so the variable notFull can be signaled, which will possibly wake up other threads which may be blocked in this variable because they can not complete a put() operation.

In order to integrate the new connection mechanism, the following advice is used to intercept the method linkStages(). Instead of sharing a single Data instance, adjacent stages will share a synchronized Fifo object.

```java
aspect SynchFifo {
  advice "Fifo" : slice class {
    ACE_Thread_Mutex *mutex;
    ACE_Condition<ACE_Thread_Mutex> *notEmpty;
    ACE_Condition<ACE_Thread_Mutex> *notFull;
  };
  advice execution("void Fifo::get(...)") && that(f) :
    around(Fifo &f) {
      f.mutex->acquire();   // mutex acquired
      while (f.size() == 0)
        f.notEmpty->wait(); // Blocks if buffer is empty
      tjp->proceed();       // Element removal
      f.notFull->signal();  // The buffer has free space
      f.mutex->release();   // mutex released
    }
};
```

Figure 2: Stage connection scheme
Thread Creation

The creation of threads is considered in the following advice, which affects the method execute() of Pipe:

```
advice execute("void Pipe::execute(...)") & & that(p) & & !cflow(execution("void *work(...)"))
  : around(Pipe 4p) |
  ...
  Vector<Rect> vr;
  for (int i=0; i<p.getStages()->size(); i++) |
    Stage *s = *(p.getStages())->i; // For each stage
    s->rect.distribute(s->distribution,s->blocks,&vr);
    for (int j=0; j<s->blocks; j++) |
      // For each block
      arg = new ThrArg(j,lites,s,s,s,(vr[j]));
      ACE_Thread_Manager::instance()->spawn(
        (ACE_THR_FUNC)work,arg,
        THR_NEW_LWP|THR_JOINABLE); // Thread launched
  )
  ACE_Thread_Manager::instance()->wait(); // Wait

There is no call to tjp->proceed(), which means that the code join point will not be executed in this context. For each stage, the iteration range represented by the attribute rect is partitioned. Then, the group of threads is launched. The number of threads to be started is indicated in the attribute blocks. Every thread receives information through an object of type ThrArg, which includes the block identifier, the number of matrices to process, and references to the pipeline, the stage, and the new iteration range.

Parallel Execution

The function work() executed by the threads saves the ThrArg variable and executes the pipeline using, this time, a stage list of only one element. The ACE_TSS template implements thread specific storage, which allows each thread to manage its own copy of arg:

```
ACE_TSS<ThrArg> arg;
static void *work(void *argument) {
  arg->set((ThrArg *)argument);
  arg->pipeline->execute(arg->iters,&(arg->stages));
}
```

Finally, data have to be moved from the Fifo buffers to the input and output Data objects each time a stage is executed. This involves the synchronization of threads:

```
poincut invokesions() =
  execution("void Sensor::execute(...)") & &
  execution("void FFTCols::execute(...)") & &
  execution("void FFTRows::execute(...)") & &
  execution("void Writer::execute(...)") & &
  execution("void Sensor::execute(...)") & &
  advice invokeocations() & & that(s) : around(Stage &s) |
    if ((s.getInputData()!= NULL) && (arg->id == 0))
      s.inputBarrier->wait(); // Waits to end computation
    s.inputFifo->get(s.getInputData());
    if ((s.getInputData()!= NULL) && (arg->id == 0))
      ad\cure invocations() && that(s) : around(Stage &s) |
      advice invocations() & & that(s) : around(Stage &s) |
      if ((s.getInputData()!= NULL) && (arg->id == 0))
      s.inputBarrier->wait(); // Waits to end computation
```

The advice code is triggered, the thread with id zero retrieves a new matrix from the input Fifo buffer and updates the input Data object. The other threads assigned to the stage are blocked until this operation is complete. Before the call to tjp->proceed(), the Rect argument, which denotes the iteration range, is replaced with the value stored in the variable arg. The threads wait until the code of the stage is executed. Then all the parts of the output Data object has been correctly updated with new values. The thread with id zero is allowed to insert the result into the output Fifo buffer.

MPI-BASED DESIGN

MPI is a collection of routines widely used in the development of parallel programs on architectures with distributed memory including computer networks. The programming model consists of a set of processes communicating by means of message-passing.

The aspect presented in this section will transform the sequential program into an SPMD application using MPI.

Application Set-up

The following advice ensures that the message-passing environment is initialized and terminated correctly:

```
advice execute("int main(...)") & & args(ac,av)
  : around(int ac, char **av) |
  MPI_Init(&ac,&av);
  tjp->proceed();
  MPI_Finalize();
}
```

Unlike the code in section 4, the group of processes of an MPI application is created in a static way when the application is started. A specific computation has to be assigned to each process in the group. So, correspondence between the process rank and the pair (stage, iteration range) is required. The association in the opposite direction is also needed. The aspect defines the methods mpiToProblem() and problemToMpi() in order to carry out these mappings. Their codes are quite simple as they use the information set by the aspect Parallelism.

In the multithread version, the threads accessed data using shared memory, so the parallelization aspect was mainly focused on the creation and synchronization of threads. Owing to the distributed nature of MPI, the data flow in the pipeline has to be implemented by means of message-passing. The parallelization aspect in this section will be mainly focused on communications.

Data distribution must be taken into account in order to implement efficient point-to-point communications on the stage interactions. Figure 3 depicts this scenario. The stage on the left uses four processes, each one computing the FFT (on columns). When the result is passed to the next stage, data is partitioned to send remote processes the exact data pieces they require. In
this figure, process 3 has to send specific data to processes 5, 6, 7 and 8. As can be noted, the information about the data distribution and the number of blocks of the stages is essential. New attributes and methods are introduced in some classes:

The meaning of the code is simple. The class Stage is augmented with two attributes which represent two data processes. For instance, the list of the two data partition lists of the stage pointed to by advice execution("void Pipe::execute(...)""); before |
vector<Stage *> **stglist = (vector<Stage *> **)(tjp->arg(1));
stglist = &mystglist; // Replaces the stage list
|

The first advice is needed to replace the original list of stages, which is the second argument of execute(), with another list containing one stage only. This way, the active element (i.e. the process) will address the execution of a single stage, instead of the complete pipeline.

The second advice uses the pointcut invocations() which was described in the previous section. The advice code is triggered when execute() is called on any of the subclasses of Stage. First, the process has to receive new data. More specifically, every object of inputPartition receives data from the corresponding remote process. These values are used to update the input Data object. Before the stage code is executed, the iteration range is restricted using the variable myrect. When the result is computed, it is sent to the processes associated with the next stage. This is done using the elements of the attribute outputPartition.

CONCLUSIONS

The parallelization of sequential scientific programs may entail significant changes in the code for tackling the creation, communication and synchronization of the computational tasks. In addition, the algorithm itself may be sufficiently different in the parallel version. Once these changes are applied, the resulting code probably suffers from code-tangling problems because the parallelism concerns obscure the numerical computation. Therefore, the applications become more difficult to maintain. This paper discusses the use of AOP to improve the management of the code parallelization. The benefits of the approach, as mentioned in section 1, can be expressed in terms of code modularization and reuse. It can be very difficult
to determine a theoretical result on the advantages and disadvantages of this approach. The code parallelization is traditionally done ad-hoc, so the process may vary significantly from one application to another. Thus, our conclusions will be based on the case study presented in this paper.

We consider the results to be quite promising. The complexity of the case study is moderated as it deals with the efficient integration of both task and data parallelism. The scientific core that calculates the 2D-FFT sequentially was successfully adapted to two distinct parallel scenarios (multithreading and MPI) which are characterized by quite different programming models. The only mechanism used in the code parallelization was aspect weaving (based on AspectC++, in this case). As a result, the new parallel applications have the parallelism concerns modularized into one or several aspects, and thereby code-tangling is reduced. Moreover, the same scientific core can be reused in different applications which can exploit very different parallelism models.

Regarding the development of the sequential core, the mechanisms that allowed the core to be parallelized using aspects were not difficult to implement. Basically, we have considered a good decomposition in terms of classes and interfaces, and we have included some elements, such as the iteration range of the stage, as additional arguments in some methods. Although this paper is focused on a particular case study, we are currently applying this approach to other numerical applications with more complex parallelism patterns successfully.

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