ABSTRACT
In earlier work, we showed that the AspectJ notions of aspect and class can be unified in a new module construct that we called the classpect, and that this new model is simpler and able to accommodate a broader set of requirements for modular solutions to complex integration problems. We embodied our unified model in the Eos language design. The main contribution of this paper is a case study, which considers the implementation of the Gang-of-Four (GOF) design patterns [3] in Eos to analyze the effect of new programming language constructs on these implementations. We also compare these implementations with the AspectJ’s implementation. Our result shows that the Eos implementation showed improvement in 7 out of 23 design patterns, and are no worse in case of other 16 patterns. These improvements were mainly manifested in being able to realize the intent of the design patterns more clearly. The design structures realized in the Eos implementation provide supporting evidence for the potential benefits of the unified model.

Categories and Subject Descriptors
D.2.11 [Software Engineering]: Software Architectures—patterns, information hiding, and languages; D.3.3 [Programming Languages]: Language Constructs and Features—patterns, classes and objects

General Terms
Design, Languages

Keywords
Design Patterns, Classpect, Unified Aspect Language Model, Binding, Eos

1. INTRODUCTION
In prior work, we showed that the notions of aspect and class in the AspectJ language model [10], can be unified in a new module construct that we called the classpect [18]. We also showed that this new model is significantly simpler, more compositional, and able to accommodate a broader set of requirements for modular solutions to complex integration problems [22, 24].

We embodied our unified model in the Eos language design [15], in which the basic unit of modularity is a classpect. We demonstrated the benefits of the unified language design in the context of small but representative examples and case studies [17]. These demonstrations did provide some basis for further speculations about the language model’s potential to solve large-scale problems. The representative examples, however, does not provide direct evidence that the unified model is beneficial beyond the challenge problems and the case studies. The concerns to which we have applied the unified model are largely component integration concerns, in that they co-ordinate the behavior of two or more components. Component integration concerns are extremely important class of concerns; however, they are not the only cutting-cross concerns aspect-oriented programming addresses.

In earlier work, Hannemann et al. [6] described the crosscutting concerns in the OO implementations of the Gang-of-Four (GOF) patterns and showed that an AspectJ-based solution modularizes these concerns. They argued that the concerns represented by these patterns are scattered and tangled across several classes in the software system that play various roles in the pattern’s implementation. Hannemann and Kiczales described an aspect-oriented implementation of these patterns with the intent to modularize these crosscutting concern.

The main contribution of this paper is a case study in a similar vein, which considers the implementation of the Gang-of-Four (GOF) design patterns [3] in the Eos language to analyze the effect of new programming language constructs on these implementations. GoF design patterns are design structures commonly occurring in and extracted from real software systems. The benefits observed in the context of these models—to some extent—could be extrapolated to modularity benefits that might be perceived in real systems.

Three properties of this evaluation make it more valuable from an empirical standpoint. First, GOF design patterns are standard well-documented design structures. Selecting a standard problem for evaluation allows others to reproduce the results independently. Second, a prior implementation of these patterns in AspectJ is available. Having a prior independent implementation in the AspectJ language provides an opportunity to present a careful un-biased analysis. Third, we are not the first to argue that the AspectJ-based solution could be improved. Sakurai et al. [20] briefly observed that the type-level aspect-oriented implementation of the design patterns described by Hannemann et al. exhibit the design problems and performance overhead of the form described by Rajan and Sullivan [15].

We evaluated the Eos implementations using the set of met-
metrics proposed by Hannemann et al. [6] namely locality, reusability, composition transparency, and (un)pluggability. These metrics showed that Eos implementation has similar modularity properties that the AspectJ implementation enjoys. Our further evaluation also showed that for 7 out of 23 design patterns the Eos implementation was able to better realize the intent of the design patterns. Eos implementation was also more concise in terms of the line of code. For other 16 patterns, AspectJ and Eos implementation were the same. In other words, Eos constructs did not offer any improvements for these patterns.

The result that all GoF pattern implementations in Eos were at least as good as the pattern implementations in AspectJ, was not surprising since the Eos language model is a superset of the AspectJ language model. Moreover, the 7 GoF patterns, where the new Eos constructs did show benefits provides insight into their potential utility. Applying the language model to standard problems demonstrates that the benefits of the unified aspect language model are not limited to component integration concerns. Our assessments of the resulting designs provide evidence for the design structuring benefits of the Eos model, and the usability of the Eos language. In a nutshell, we contribute a demonstration of the immediate practical value of our conceptual work.

The rest of this paper is organized as follows. The next section gives background on aspect-oriented programming and the unified model. Section 4 describes the Eos implementation of the design patterns and compares it with the AspectJ implementation. Section 5 discusses related work and Section 6 concludes.

2. BACKGROUND

In this section, we briefly review the AspectJ and unified language model embodied by Eos. The focus is on their key differences. The AspectJ language model is described in detail by Kiczales et al. [10]. The unified language model is described in detail by Rajan et al. [18].

2.1 The AspectJ Language Model

In this subsection, we will review basic concepts in the AspectJ model. AspectJ [10] is an extension to Java [5]. Other languages using AspectJ’s model include AspectC++ [21], AspectR [2], AspectWerkz [1], AspectC [8], Caesar [13], etc. While Eos [15] is not AspectJ-like, it is in the broader class of Pointcut-Advice-based AO languages [11]. The central goal of such languages is to enable the modular representation of crosscutting concerns, including the representation of concerns conceived after the initial system design. The programs in these languages are typically developed in two phases [23]. The concerns that can be modularized using the traditional object-oriented modularization techniques are put in classes. Aspects then modularize the crosscutting concerns by advising these classes. Differentiating between classes and aspects makes these language asymmetric.

These languages add five key constructs to the object-oriented model: join points, pointcuts, advice, inter-type declarations, and aspects. A simple example is shown in Figure 1 to make these concepts concrete. The aspect Tracing, modifies the behavior of the class TracedClass before, after, and around certain selected execution events exposed to such modification by the semantics of the programming language. These events are called join points. The execution of the method TracedMethod in the class TracedClass is

```java
class TracedClass{
    public void TracedMethod()
        System.out.println("In\_Traced\_Method");
}
}

aspect Tracing { // An aspect
    pointcut tracedExecution(): //A pointcut
        execution(public void TracedMethod());
    before(): tracedExecution() //A before advice
        System.out.println("Before\_Traced\_Method");
}

after(): tracedExecution() //An after advice
    System.out.println("After\_Traced\_Method");

Object around(): tracedExecution() {
    System.out.println("Around\_Traced\_Method\_\_1");
    proceed(); //Proceeding the join point
    System.out.println("Around\_Traced\_Method\_\_2");
}
}

Output Trace:
Before Traced Method
In Traced Method //Result of calling proceed
Around Traced Method - 1
Around
After Traced Method
```

**Figure 1: A Simple Example Aspect**

an example of a join point. A pointcut is a predicate that selects a subset of join points for such modification — here, execution of the method TracedMethod in the class TracedClass. An advice is a special `method-like` construct that effects such a modification at each join point selected by a pointcut. An aspect is a class-like module that uses these constructs to modify behaviors defined by the classes of a software system. In the example, we have three different types of advice in the aspect: before, after, and around that affect the behavior of the method TracedMethod as shown in the output trace in the figure.

Like classes, aspects also support data abstraction and inheritance, but they do differ from classes. First, aspects can use pointcuts, advice, and inter-type declarations. In this sense, they are strictly more expressive than classes. Second, instantiation of aspects and binding of advice to join points are wholly controlled by the Aspect language runtime. There is no `new` for aspects. Aspect instances are thus not first-class, and, in this dimension, classes are strictly more expressive than aspects. Third, although aspects can advise methods with fine selectivity, they can select advice bodies to advise only in coarse-grained ways.

2.2 The Unified Language Model

Rajan et al. addressed the limits of aspects in a new language model that unifies aspects and objects in three ways [18]. First, it unifies aspects and classes as classpects. A classpect has all the capabilities of classes, all of the essential capabilities of aspects in AspectJ-like languages, and the extensions to aspects needed to make them first class objects. Second, the unified model eliminates advice in favor of using methods only, with a separate and explicit join-point-method binding construct. Third, it supports a generalized advising model. To the usual object-oriented mechanisms of explicit or implicit method call and overriding based on inheritance, the unified model adds implicit invocation using before and after advice, and overriding using around advice.

To make these points concrete we revisit the example presented in the previous section in Figure 2. A classpect (lines 1-8), similar to the aspect in the previous section, declares the example presented in the next section.
2-3) to select the execution of any method, exactly as in AspectJ. It then forms the pointcut with the within(Trace) pointcut expression to exclude its own methods, to avoid recursion. A static binding (line 4) binds the method Trace (lines 5-7) to execute before all join points selected by the pointcut tracedExecution. Note that by statically binding, join points in all instances are affected. A non-static binding would bind to instances selectively. The key difference in this implementation is that all concerns are modularized as classpects and methods. The crosscutting concerns, however, uses bindings to bind the method containing the implementation of the crosscutting concerns to join points. In the next section, we demonstrate that this unification shows benefits in the Gang-of-Four design patterns.

3. CASE STUDY SETTING

The results described in this work are based on a case study that we conducted to compare the implementation of 23 GoF patterns in AspectJ and Eos. The AspectJ implementation that we compared against is described in detail by Hannemann and Kiczales [6]. The implementation provided by Hannemann and Kiczales uses these design patterns in the context of small examples. The first step was to translate the AspectJ implementation to Eos, adjusting for minor differences in underlying languages (Java and C#). In this step, no change in the Eos implementation was attempted. Eos languages is a superset of AspectJ, which means that all constructs were available in the host language. Unlike the study setting by Garcia et al. [4], we did not modify the implementation examples. This translation was done by hand.

In the next step, patterns in Eos were improved by utilizing the new mechanisms namely: unified language model, instance-level advising, and first-class aspect instances.

In earlier work, we showed that translation of programs from the AspectJ language model to their equivalent in the proposed unified model is possible [19]. This translation does not require any non-local changes. The design space of the modular solutions using unified model is essentially a super set of the design space of the modular solutions in the AspectJ-like language model. Based on that observation one would expect to be able to translate the implementation of design patterns from AspectJ to Eos, which is indeed the case. The pattern implementations provided by Hannemann et al. can be translated to Eos without any non-modular changes. By non-modular changes we mean changes that are localized within a module boundary, but rather fragmented and spread across the system. The translation or pattern protocols is straightforward. The examples provided with the pattern implementation; however, are heavily dependent upon the platform. As a result, their translation is not quite direct owing to the host framework differences. AspectJ operates on Java Virtual Machine (JVM), whereas Eos operates on .Net Framework.

The translation rules from AspectJ model to Eos model does not require any non-modular changes, preserving the modularity of AspectJ based solution, and implying that the results in Hannemann and Kiczales [6] may apply to the Eos implementation as well. To measure that we applied the four metrics applied by Hannemann and Kiczales namely: locality, reusability, composability, and (un)pluggability. We also applied some metrics used by Garcia et al. [4] such as Line of Code (LOC) to measure size. We also used an additional metric Close Match to Pattern Intent. (CMPI) that evaluates to true for a pattern implementation, if the intent of the implementation closely matches the pattern specification.

Due to the space limitations, we only describe five of these patterns in some detail in the rest of this paper. The Subsection 4.1 to 4.8 describe the Observer, the Chain of Responsibility, the Mediator, the bridge and the decorator pattern respectively. Similar design structuring benefits were observed in case of the Composite pattern, Command pattern, Singleton pattern and Strategy pattern. Next, we describe the result of the analysis of these implementations to determine whether the Eos implementation strategy is better then AspectJ’s strategy.

4. DESIGN PATTERNS

In this section, we will describe some patterns in which we noticed major improvements compared to other patterns. These improvements were in metric (CMPI) and (LOC), while other metric values largely remained unchanged.

4.1 Observer Pattern

The intent of the observer pattern is to define a one-to-many dependency between objects so that on an object’s state change, all dependents are notified and updated automatically [3, p.293]. The AspectJ implementation divides the pattern implementation into two parts: parts that are common to all instantiations of the pattern and parts specific to an instantiation. The implementation abstracts the common part as a reusable ObserverProtocol aspect as shown in Figure 3. It provides an abstract pointcut subjectChange (lines 23–24) to represent observable state change of the subject. A concrete observer implementation defines this pointcut. The implementation also provides an abstract method; update (lines 24–25) to define concrete observers to implement the observer’s logic.

The AspectJ language model does not fully support aspect instantiation and selective advising of object-instances [16]. In the Observer pattern, an instance of Observer needs to selectively advise instances of Subject. To emulate instance-level advising using type-level aspects, Hannemann and Kiczales’s implementation of the Observer protocol needs to manipulate instances of participants. To be able to do so without coupling the ObserverProtocol with participants, it defines two new interfaces that are introduced by the concrete observers into participants so that ObserverProtocol can manipulate them. The pattern implementation therefore modifies the implementation of the participants using declare parents constructs such that they do not implement two new interfaces subjects (line 2) and observers (line 3). An example of the declare parents construct is shown in Figure 6.

The implementation also keeps a HashMap (line 4) of observers corresponding to an instance of the subject. It provides methods to add (lines 17–19) and remove (lines 20–22) observers corresponding to a subject. It also provides methods to retrieve observers for a subject (lines 5–16). The observer protocol logic is implemented by the advice (line 26–31). This advice is invoked by each instance of the class being advised, even if no observer is observing the instance. On being invoked, the advice looks up the invoking instance and retrieves the list of observers. It then iterates through the list to invoke each observer. In summary, the AspectJ implementation tangles the instance–level advising and instance–emulation concern [15] with the observer pattern concern. The need for roles
public abstract aspect ObserverProtocol{
  protected interface Subject {
  protected interface Observer {
  private WeakHashMap perSubjectObservers;
  protected List getObservers(Subject s){
    if(perSubjectObservers == null)
      perSubjectObservers = new WeakHashMap();
    return observers = (List) perSubjectObservers.get(s);
  }
  if (observers == null )
    observers = new LinkedList();
  perSubjectObservers.put(s, observers);
  }
  return observers;
  }
  public void addObserver(Subject s, Observer o){
    getObservers(s).add(o);
  }
  public void removeObserver(Subject s, Observer o){
    getObservers(s).remove(o);
  }
  protected abstract pointcut subjectChange(Subject s);
  protected abstract void update (Subject s, Observer o);
  after (Subject s): subjectChange(s)({
    Iterator iter = getObservers(s).iterator();
    while (iter.hasNext()){
      update (s, ((Observer) iter.next()));
    }
  }
}

Figure 3: Observer in AspectJ

for maintaining a HashMap are examples of design-time overheads incurred due to the asymmetry of the language model.

public abstract class ObserverProtocol {
  protected abstract pointcut subjectChange();
  protected abstract void update (Subject s, Observer o);
  after subjectChange(s): update(Subject s);
}

Figure 4: Observer in Eos 78% Smaller

The AspectJ implementation of the observer pattern is localized, reusable, compositionally transparent, and (un) pluggable. The Eos implementation mimics the implementation strategy by similarly partitioning the pattern implementation into abstract class aspect ObserverProtocol and concrete realization of observers inheriting from this class aspect. The abstracted pattern is shown in Figure 4.

The Eos implementation does not tangle emulation concern with observer protocol concern. It clearly abstracts the behavior of the pattern. It clearly (and more concisely) conveys the intent of the pattern, which is to update an observer when a subject changes. The binding (Line 6) states that after the join points selected by the abstract pointcut SubjectChange, the method Update should be called. All the interfaces and additional code required to emulate instance-level behavior is not necessary in the Eos implementation.

With respect to the metrics used by Garcia et al. [4], Eos implementation of the Observer pattern achieves nearly 78 percent reduction in LOC (Line of Code) of the observer protocol concern without increasing the complexity of the remaining concerns. Each line in Eos implementation corresponds to a line in AspectJ implementation. The Eos implementation, however, does not require the emulation code in the pattern implementation since it utilizes the instance-level constructs in the language. This implementation is also localized, reusable, compositionally transparent, and (un) pluggable. It also decreases the Number of Attributes (NOA) [4] of the Observer protocol concern to zero from one.
The intent of the Chain of Responsibility pattern is to avoid coupling the sender of a request to its receiver by giving more than one object a chance to handle the request. The idea is to chain the receiving objects and pass the requests along the chain until an object handles it. [3, p.223].

Similar to the AspectJ implementation, the AspectJ implementation of the Chain of Responsibility pattern provided by Hanne mann et al. divides the pattern implementation into two parts: parts that are common to all instantiations of the pattern and parts specific to an instantiation. The implementation abstracts the common part as a reusable aspect CORProtocol as shown in Figure 9. The aspect introduces two roles, Handler (line 2) and Request (line 3) corresponding to a handler and a request as interfaces. It further uses the inter-type declaration feature to introduce acceptRequest (lines 18–20) and handleRequest (line 21) methods into the interface Handler as default behavior. The aspect provides an abstract pointcut eventTrigger (lines 22–23) to represent the event that is to be handled by the chain. A concrete implementation defines this pointcut.

The aspect CORProtocol keeps a HashMap (line 4) to keep track of the successors of a given handler. It provides methods to set the successor of a handler (lines 28–31) and to retrieve the successors of a given handler (lines 32–34). The main logic of the chain of responsibility pattern is in method receiveRequest (lines 5–17). This method first checks whether a supplied handler can handle this request. If not, it tries the successors of the handler. If there is a successor, it passes the request to the successor. Otherwise, it throws an exception to signify end of the chain (lines 11–13). The method receiveRequest is triggered by a delegating advice (line 24–27). This advice is triggered at the join points selected by the pointcut eventTrigger (line 22–23).

Similar to the AspectJ implementation, the Eos implementation shown in Figure 10 defines two roles, Handler (line 2) and Request (line 3) corresponding to a handler and a request as interfaces. It further uses the inter-type declaration feature to introduce the methods acceptRequest (lines 5–7) and handleRequest (line 8) into the interface Handler as default behavior. In addition, it also introduces a method receiveRequest to receive requests in all handlers (lines 9–16). In the AspectJ implementation the aspect CORProtocol had a similar method (lines 5–17 in Figure 9). The difference is now in the implementation technique that can be realized due to the new instance-level advising features in Eos [15]. The method receiveRequest in the Eos implementation first checks whether the current Handler object can handle the request, otherwise it throws an exception of type CORException.

In addition to the method receiveRequest, the classpoint CORProtocol introduces a binding (lines 17–19) and another method setPredecessor (lines 20–22). This binding selects the join point execution of the method Handler::handleRequest when an exception is being thrown and calls the method receiveRequest on the current Handler instance. Note that this binding is a non-static binding and
public abstract class CORProtocol{
  
  protected interface Handler {
    protected interface Request {
      
      public void acceptRequest(Request r){
        return false;
      } 
    } 
  } 

  public boolean acceptRequest(Request r) {
    if (acceptRequest(r)) {
      return true;
    } else {
      throw new CORException("End of chain reached");
    }
  }

  
  after throwing(CORException) 
  execution(Handler.receiveRequest(...)) 
  & & args[2]: receiveRequest(Request r); 
  public void setPredecessor(Handler h){
    addObject(h);
  } 

  
  protected abstract pointcut eventTrigger 
  (Handler h, Request r); 
  after eventTrigger(h, r): 
  TriggerRequest(Handler h, Request r); 
  public void TriggerRequest {
    (Handler h, Request r) { 
      handler.receiveRequest(r);
    }
  } 

  
  public void setTrigger(Handler h){
    addObject(h);
  } 
}

Figure 10: Chain of Responsibility in Eos

that would not be easy to simulate in AspectJ. A non-static binding affects object instances selectively. The effect of this binding is to
call the method receiveRequest on the current handler if the pre-
vious handler threw an exception. The method setPredecessor
is provided to set a handler’s predecessor. It calls the implicit method
addObject to advise the predecessor instance. The effect of call-
ing the implicit method addObject is to register the bound methods
in the Handler instance with the join points in the object instance
supplied as argument. The Eos implementation thus eliminates the
need to keep a HashMap to represent the chain of responsibility,
instead the chain is now implicit in the advising structure. The
code for hash table lookup for each successor invocation is also
eliminated. In addition, the Eos implementation also allows events
to be triggered on an instance-level basis, which requires complex
emulation code when written in AspectJ. We will describe this dif-
culty in more detail in the context of a concrete example.

To illustrate the difference in the implementation technique let
us look at the example system presented by Hannemann et al. This
example system has three type of GUI objects Buttons, Panels,
and Frames. The objective is to handle the request Button.Click
and propagate it through the chain Button-to-Panel-to-Frame if re-
quired. The concrete implementation of this example system in
AspectJ declares another aspect ClickChain (Figure 11) that inher-
its from the aspect CORProtocol. This concrete aspect modifies
the inheritance hierarchy of Button, Panel, and Frame to include the
interface Handler and the inheritance hierarchy of the event
Click to include the interface Request. It provides concrete im-
plementation of the methods acceptRequest and handleRequest for
these classes. The concrete aspect ClickChain also provides a con-
crete definition for the abstract pointcut eventTrigger as protected

pointcut eventTrigger(Handler handler, Request request): call(void 
Button.doClick(Click)) & & target(handler) & & args(request).

The effect of defining this pointcut is that for all instances of the button
class, whenever the method doClick is called the delegating advice
(line 24–27 in Figure 9) will be invoked. However, this invocation
is desired only when the method doClick is called in the context of
a specific button instance that is the supplier of the request. Thus
commitment to type-level advice invocation fails to achieve the de-
sired objective in this case.

1 public aspect ClickChain extends CORProtocol{
  2 declare parents: Frame implements Handler;
  3 declare parents: Panel implements Handler;
  4 declare parents: Button implements Handler;
  5 declare parents: Click implements Request;
  6 protected pointcut eventTrigger 
  7 (Handler h, Request r); 
  8 call(void Button.doClick(Click)) & & 
  9 target(h) & & args(r); 
  10 public boolean Button.acceptRequest(Request r){
    ...
  11 } 
  12 public void Button.handleRequest(Request r){
    ...
  13 } 
}

Figure 11: Concrete Aspect ClickChain in AspectJ

The Eos implementation (Figure 12) of this example system is
similar. The concrete class aspect ClickChain in Eos also modifies
the inheritance hierarchy of Button, Panel, Frame, and Click, pro-
vides concrete implementation of the methods acceptRequest and
handleRequest for these classes, and a concrete definition for the
abstract pointcut eventTrigger. However, the effect of defining this
pointcut is that for a specified instance of the button class, whenever
the method doClick is called the delegating method TriggerRequest
(line 24–27 in Figure 10) will be invoked. This instance is specified
using the method SetTrigger defined in the abstract class aspect
COR-Protocol. The client code for AspectJ and Eos shows this difference
clearly. For comparison, the listing in Figure 13 shows the key parts
of the client code. The common code is preceded by Common:, the
AspectJ code is preceded by AspectJ:, and the corresponding
Eos code is preceded by Eos:.

The client code creates an instance of Frame, an instance of
Panel, and two instances of Button. In the AspectJ code, the Panel
instance panel is set as a successor to the Button instance button1
and the Frame instance frame is set as a successor to the Panel instance panel. In this implementation, on each button click, complete chain of responsibility pattern is executed for both buttons because the aspect ClickChain ends up advising both instances of the button. The objective is to execute the chain of responsibility for only the Button instance button1.

In the Eos code, first an instance of the ClickChain is created. The method setTrigger is called on this instance with the Button instance button1 as argument to set the event method doClick on button1 as the request trigger. The Button instance button1 is then set as predecessor of the Panel instance panel in the chain of responsibility by calling the method setPredecessor on the Panel instance panel. The effect is that the binding in the instance panel bounds the method receiveRequest to execute in the context of the instance panel whenever the method receiveRequest executing in the context of the instance button1 throws an exception of type CORException, i.e. whenever button1 is not able to accept a request. Similarly, the Frame instance frame is set as the predecessor of the Panel instance panel in the chain of responsibility. No instance is setting the Frame instance frame as a predecessor, as a result if this instance is unable to handle the request the exception CORException is finally thrown to denote unhandled requests.

The implementation strategy in Eos completely realizes the intent of the chain of responsibility pattern without the need to maintain the chain of successors in a HashMap. The chain is implicitly maintained in the recursive advising structure in the classaspect Handler. A key property of this design structure is that an instance of a classaspect advises another instance of the same classaspect. This benefit is observed as a result of the generalized advising mechanism provided by our unified aspect language model [18]. In the AspectJ language model, realization of such design structures requires aspect-instance emulation and instance-level weaving emulation, adding addition complexity to the solution. In addition, the Eos implementation strategy also overcomes the problem with the AspectJ implementation where the intention is to advise one Button instance but the ClickChain aspect ends up advising all Button instances.

Figure 13: Chain of Responsibility Clients in AspectJ and Eos

4.3 Mediator Pattern

The intent of the Mediator pattern is to define an object that encapsulates how a set of objects interact. Mediator promotes loose coupling by keeping objects from referring to each other explicitly, and it lets you vary their interaction independently [3, p.273].

Similar to the Chain of Responsibility and the Observer pattern’s implementation, the AspectJ implementation provided by Hanne-
and additional code required to emulate instance-level advising is required.

4.4 Other Patterns

We observed similar design structuring benefits in the Eos implementation of the Composite, Command, Strategy, and Singleton patterns. For example, in case of the Composite pattern, the AspectJ implementation represents the Composite-Child containment relationship using a visitor pattern that triggers operations on the components of a composite. In the Eos implementation, this pattern is not needed. Instead, the Composite-Child containment relationship is implicitly represented as an advising relationship. In addition, the emulation code in the CompositeProtocol aspect to keep a list of children is not needed. Similarly, in case of the Strategy pattern the emulation code to store the relationship between a strategy and its context is replaced by implicit instance-level advising relationship. In case of other 16 design patterns, the Eos implementation was the same as the AspectJ implementation, so we are no worse off than before in these cases as well.

4.5 Bridge Pattern

It is worth discussing and analyzing a pattern, where we did not get any design structuring benefits from using Eos. In this case, AspectJ’s implementation also did not get any design structuring benefits. The intent of this pattern is to separate an abstraction from its implementation, so that they can be varied independently. The implementation strategy followed by the AspectJ (and that we followed in Eos as well) is to separate out common members from various versions of abstraction into a separate aspect, represent the abstraction as an interface, specify the variations as concrete classes that implement that interface, and have the aspect insert the commonalities into these classes. Similar, design structuring benefits would have been obtained by representing common parts of the abstraction as an abstract OO class, therefore, the AO solution did not advance over the OO solution. Eos solution was also similar to AspectJ Solution.

4.6 Summary

The implementation of design patterns in Eos showed that the unified language model eliminates the need for emulation strategies in 7 patterns making the resulting implementation much simpler. The simplification in these cases is the result of including instantiation and instance-level advising as language features, unifying aspect and class, and unifying method and advice. The composition of participants and patterns is also much more intuitive now.

4.7 Mediator Pattern

The intent of the Mediator pattern is to define an object that encapsulates how a set of objects interact. Mediator promotes loose coupling by keeping objects from referring to each other explicitly, and it lets you vary their interaction independently [3, p.273].

Similar to the Chain of Responsibility and the Observer pattern’s implementation, the AspectJ implementation provided by Hanne mann and Kiczales divides the pattern implementation into two parts: parts that are common to all instantiations of the pattern and parts specific to an instantiation. The implementation abstracts the common part as a reusable MediatorProtocol aspect as shown in Figure 16. It provides an abstract pointcut change (lines 14–15) to represent state change of the colleagues. A concrete mediator implementation defines this pointcut. The implementation provides an abstract method; notify (lines 19–20) to be redefined in concrete mediators to implement the notification logic. The MediatorProtocol aspect also keeps a HashMap as the key. When these calls are completed, the last setMediator(Colleague colleague) with Colleague c as the key. For these calls to be kept, the value supplied in the old mapping.

Like the Observer pattern, the Eos implementation shown in Figure 17 does not tangle the emulation concern with the mediator protocol concern, resulting in a modular implementation of the mediator protocol. The implementation clearly represents the behavior of the pattern, decreasing the conceptual gap between the specification and implementation of the pattern. It clearly (and only) conveys the intent of the pattern. The intent of the pattern is that after change in a colleague mediator notifies the changes to other colleagues. The binding states that after the join points selected by the abstract pointcut change, the method notify should be called. No interfaces and additional code required to emulate instance-level advising is required.

4.8 Decorator

The intent of the decorator pattern is to attach additional responsibilities to an object dynamically. Decorators provide a flexible alternative to subclassing for extending functionality [3]. Decorator pattern implementation in AspectJ exposed the limitations of advising all instances of classes, a typical advising model in the
Implementations for Facade, Abstract Factory, Bridge, and Builder, and Factory method remained almost the same for components of a composite. In the Eos implementation, this pattern is not needed. Instead, the Composite-Child containment relationship is implicitly represented as an advising relationship. In addition, the emulation code in the CompositeProtocol aspect to keep a list of children is not needed. Instead, first class aspect instances model the composition relationships in the system, which more clearly represents the design intent in the runtime structure.

Similarly, in case of the Strategy pattern the emulation code to store the relationship between a strategy and it’s context is replaced by implicit instance-level advising relationship. In case of other 16 design patterns, the Eos implementation was the same as the AspectJ implementation, so we are no worse off then before in these cases as well.

### 4.11 Analysis

The implementation of design patterns in Eos showed that the unified language model eliminates the need for emulation strategies in 7 patterns making the resulting implementation much simpler. The simplification in these cases is the result of including instantiation and instance-level advising as language features, unifying aspect and class, and unifying method and advice. The composition of participants and patterns is also much more intuitive now.

Figure 20 shows the results of the case study for the patterns that we considered previously in the work and others. The rows in the figure represent the patterns and the column represents the metrics that we considered for this case study.

In particular, we considered four metrics used by Hannemann et al. namely: locality, reusability, composition transparency, and (Un) pluggability. They used these metrics to measure the modularity properties of the pattern implementations. Informally, a pattern implementation has locality if the code for the pattern is syntactically localized in a module. It is reusable, when most of the implementation can be imported in other application without much effort. It is composition transparent, if using one pattern implementation in an application does not hinder the option to use other patterns and finally, if it (Un) pluggable, if the pattern implementation can be put in the application and taken out with ease.

We also studied the size of the pattern implementation in both Eos and AspectJ. In particular, we report on the size of the reusable part of the pattern in Figure 20. All lines of code were measured after ignoring comments and ignore closing braces that often constitute a single line by themselves.

The third metrics we considered is Close Match to Pattern Intent (CMPI). This metric can take true or false value. By close match to pattern intent, we mean whether the implementation in the language closely matches the original intent of the pattern. For example, the intent of Class Adapter pattern is to convert the interface of a class into another interface clients expect so that classes can work together that couldn’t otherwise because of incompatible interfaces. The implementation of the Class Adapter pattern in a language without multiple inheritance (such as Java) will have CMPI value of false. In other words, CMPI demonstrate the naturalness of the pattern representation in the language.

Finally, we also studied the aspect-oriented language constructs and their role in enabling better representation of GoF patterns. In particular, we looked at the role of AspectJ specific constructs around advice, before advice, inter-type declaration, and declare parent construct. Eos also has these constructs. In addition, Eos has features for creating aspect instances, and for advising other object instances on a selective basis.

The key observations from our case study are as follows:

- Implementations for Facade, Abstract Factory, Bridge, Builder, and Factory method remained almost the same for.
Java, AspectJ and Eos. This is because the primary purpose for these patterns is to provide a passive abstraction. There implementation is already well-modularized.

- The declare parents constructs played a key role in both AspectJ’s and Eos’s AO implementation of GoF patterns. This construct allows one to impose another type-hierarchy on an existing type hierarchy. In the implementation of GoF patterns, it was mostly used to impose roles on pattern participants.

- Most usages of the advice construct in the GoF pattern implementation turned out to be for creating relationships between objects rather than for creating relationship between classes. In order to mimic the relationships between objects, AspectJ implementation used a hash map to store and retrieve these relationships.

- Eos implementation and the instance-level advising feature was able to avoid the need to mimic the relationships between objects. Instead, it had a direct representation such that the design mirrored the runtime structure.

- In some cases, savings in terms of code size (LOC) were as much as 78 % in case of Eos.

- Eos implementation for six patterns namely, decorator, command, composite, strategy, mediator, and observer closely followed the original intent of the pattern, whereas the AspectJ implementation did not. This is primarily because AspectJ did not provide a mechanism to efficiently represent relationships between pattern participant instances as advising relationships. The advising relationships between participant instances had to be emulated on top of the advising relations between participant classes.

- In most cases, improvement in Eos’s implementation was due to the combination of instance-level advising and first-class aspect instances e.g. decorator, command, strategy, etc, although in some cases, e.g. composite and singleton, design structuring benefits were largely due to first-class aspect instances.

### 5. RELATED WORK

Most closely related to this work is the evaluation of aspect-oriented implementation of the Gang-of-Four design patterns [3] conducted by Hannemann and Kiczales [6] and Garcia et al. [4]. Hannemann and Kiczales compared the object-oriented implementation in Java with aspect-oriented implementation in AspectJ using qualitative metrics. Garcia et al. [4] used a set of quantitative metrics to compare the object-oriented and aspect-oriented implementations. Our work compares the design structures realized in an aspect-oriented implementation in Eos with another aspect-oriented implementation in AspectJ.

The subject of this evaluation, the unified aspect language model [18], is related to AspectJ [10], AspectWerkz [1], and Caesar [13]. In at least one early version of AspectJ, there was no separate aspect construct. In this version, the class was extended to support advice. To the best of our knowledge, the synthesis of OO and AO techniques achieved by our unified model was not present there. Advice bodies and methods were still separate constructs; and it is unclear to what extent advising as a general alternative to method...
invocation and implicit invocation was supported. In addition, flexi-
ble aspect instantiation and instance-level weaving were not sup-
ported. Rajan and Sullivan showed that first-class aspect instances
and instance-level advising improved the modularization of inte-
gration concerns [15, 22]. This work reinforces our earlier find-
ings.

Another closely related design is that of AspectWerkz [1]. The
aim of AspectWerkz is to provide the expressiveness of AspectJ
without sacrificing pure Java and the supporting tool infras-
structure. The solution is to use normal Java classes to represent
both classes and AspectJ-like aspects, with advice represented in
normal methods, and to separate all join-point-advice bindings ei-
ther into annotations in the form of comments, or into separate
XML binding files. AspectWerkz provides a proven solution to
the problem of AspectJ-like programming in pure Java, but it does
not achieve the unification that we have pursued.

First, and crucially, AspectWerkz does not support the concept
of aspects as objects under program control; rather it is really an
implementation of the AspectJ model. Instead, the use of Java
classes as aspects is highly constrained so that the runtime system
can maintain control. A class representing an aspect must have ei-
ther no constructor or one with one of two predefined signatures,
and a method representing an advice body has one argument of
type JoinPoint. AspectWerkz uses this interface to manage aspect
creation and advice invocation. AspectWerkz also lacks a single-
language design, in that it uses both Java and XML binding files.
Third, AspectWerkz lacks static type checking of advice parame-
ters. Rather, reflective information is marshaled from the JoinPoint
arguments to advice methods.

The design of Caesar [13] is also closely related to our approach.
The aim of Caesar is to decouple aspect implementation and the
aspect binding with a new feature called an aspect collaboration
interface (ACI). By separating these concepts from aspect abstrac-
tion, Caesar enables reuse and componentization of aspects. This
approach is similar to ours and to AspectWerkz in that it uses plain
Java to represent both classes and aspects; however, it represents
advice using AspectJ-like syntax. Methods and advices are still
separate constructs, and the advice constructs couple crosscut spec-
fications with advice bodies. Consequently, as in AspectJ, advice
bodies are still not addressable as individual entities. They can be
advised as a group using an advice-execution pointcut. In Caesar,
as in Eos, advice can be bound statically or dynamically; however,
aspects in Caesar cannot directly advise individual objects on a se-
lective basis.

Aspect languages such as HyperJ [25, 14] have one unit of mod-
ularity, classes, with a separate notation for expressing bindings.
However, they do not support program control over aspects as first-
class objects, and to date the join point models that they have im-
plemented have been limited mainly to methods [7].

Several others have evaluated aspect-oriented programming tech-
niques on different benchmarks. Early assessments were con-
ducted by Mendhekar et al. [12], Kersten and Murphy [9], Walker
et al. [26], etc. Mendhekar et al. [12] used RG, an environment for
creating image processing systems to evaluate aspect-oriented pro-
gramming. Kersten and Murphy [9] used Atlas, a web-based learn-
ing environment to evaluate aspect-oriented programming. Walker
et al. [26] also conducted an initial assessment of aspect-oriented
programming. These assessments describe the performance of an
aspect-oriented approach in isolation on unique problems; our ap-
proach compares two different aspect-oriented models using stan-
dard problems.

6. CONCLUSION

In this paper, we described a case study that analyzed the Eos
implementation of 23 GoF design patterns. This implementation
showed improvement in the case of 7 out of 23 design patterns
compared to the AspectJ implementation. The implementation was
no worse in other 16 patterns. A successful demonstration of the
capabilities of the language model on standard, broadly utilized,
design structures inspires confidence in its potential and practical
utility. In most cases, these benefits emerged from the ability to
model relationships between participant instances as implicit ad-
vising structures. The unification in Eos thus allowed new type of
design structures, for example, the reverse chain of predecessors
in the Chain of Responsibility pattern, to emerge. A new set of
patterns of advising structures is perhaps around the corner, wait-
foring for the wider adoption and use of aspect-oriented programming
mechanisms. We also contribute an analysis of the language con-
structs that were most useful during the GoF design pattern imple-
mentation, which provides insight into the design and use of AO
languages constructs.

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