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Observers and Assistants:

A Proposal for Modular Aspect-Oriented Reasoning

by

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A Proposal for Modular Aspect-Oriented Reasoning

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ABSTRACT
In general, aspect-oriented programs require a whole-program analysis to understand the semantics of a single method invocation. This property can make reasoning difficult, impeding maintenance efforts, contrary to a stated goal of aspect-oriented programming. We propose some simple modifications to AspectJ that permit modular reasoning. This eliminates the need for whole-program analysis and makes code easier to understand and maintain.

1. INTRODUCTION
Much of the work on aspect-oriented programming languages makes reference to the work of Parnas [23]. That work argues that the modules into which a system is decomposed should be chosen to provide benefits in three areas. Parnas writes (p. 1054):

“The benefits expected of modular programming are: (1) managerial—development time should be shortened because separate groups would work on each module with little need for communication; (2) product flexibility—it should be possible to make drastic changes to one module without a need to change others; (3) comprehensibility—it should be possible to study the system one module at a time. The whole system can therefore be better designed because it is better understood.”

While much has been written about aspect-oriented programming as it relates to Parnas’s second point, his third point is the primary concern of this paper. We contend that current aspect-oriented programming languages do not provide this third benefit in general, because they require systems to be studied in their entirety.

After describing and motivating the problem in this introduction, in Section 2 we propose a simple set of restrictions that we believe, would bring these languages much closer to Parnas’s ideal without any practical loss of expressiveness. This proposal is preliminary work and is presented in the hopes of generating discussion and feedback.

We begin by defining a notion of modular reasoning corresponding to Parnas’s third benefit. Subsequent subsections in this introduction show how such modular reasoning is possible in the Java Programming Language™ [1, 9] but problematic in the current version of AspectJ™ [11].

For concreteness, our examples are shown in AspectJ. To support abstract reasoning we specify the examples using new aspect-oriented extensions to the Java Modeling Language (JML) [13, 14]. We believe our ideas are independent of Java and JML. We also believe that they are independent of the details of AspectJ and are generally applicable to the class of aspect-oriented languages.

1.1 Modular Reasoning
Before delving into the details, it is useful to define our terms. Modular reasoning is the process of understanding a system one module at a time. A language supports modular reasoning if the actions of a module M written in that language can be understood based solely on the code contained in M along with the specifications of any modules referred to by M. For example, in Java a single compilation unit, typically a file declaring a single top-level type (class or interface), is a module. The specification of that module is the behavior of objects of that type. Code is one form of specification. In a more expressive language, such as Eiffel [19] or Java annotated with JML, a specification can be given explicitly using pre- and postconditions, frame axioms, and invariants; such specifications serve as contracts that allow one to separately reason about the behavior and correctness of an implementation.

Our interest in modular reasoning in aspect-oriented programming languages is motivated in part by our earlier work on MultiJava [5, 6]. In that work we were concerned with modular static typechecking and compilation. This is closely related to the issue of modular reasoning, because the source code of a method body is a very precise behavioral specification of that method. A language that supports modular reasoning can therefore also permit separate compilation, as well as modular implementations of other tools (e.g., optimizers, verifiers, and model checkers). Thus, mechanisms that permit modular reasoning would have many benefits.

1.2 Modular Reasoning in Java
Java without aspect-oriented extensions supports modular reasoning. We illustrate this after giving some background on JML.

1.2.1. JML Background
Consider the examples in Figure 1 and Figure 2, modified slightly from Kiczales, et al. [11] and annotated with JML specifications. Specification annotations are enclosed in special comments; annotations (8) at the beginning of lines in annotations are ignored.

In JML, model fields, like xctr and yctr in Figure 1, specify the abstract state of an object. They are specification-only constructs, but are treated formally as locations. The keyword instance says that they are considered to be model fields in all classes that implement the interface. A represents-clause (with keyword represents, as in Figure 2) says how the values of model fields are related to the actual, concrete fields of an object; and a depends-clause (also in Figure 2) allows such concrete fields to be assigned to when the model fields that depend on them are assignable [15].

In our JML examples, each method’s specification is written preceding its signature. We use a desugared form of JML method specifications in this paper, in which a visibility level, which describes who can see the specification, is followed by the keyword behavior, which introduces a specification case. A specification case consists of several clauses. The forall-clause introduces logical
package foal02;

interface FigureElement {
  /*@ model instance int xctr, yctr; */
  /*@ public behavior
   @ for all int oldx, oldy;
   @ requires oldx == xctr && oldy == yctr
   @ assignable xctr, yctr;
   @ ensures xctr == oldx + dx
   @ && yctr == oldy + dy
   @ && \result == this;
   @ signals (Exception z) false; */
  FigureElement moveNE( int dx, int dy );
  /*@ public behavior
   @ ensures \result == xctr;
   @ signals (Exception z) false; */
  @ pure @*/ int getX()
  @ pure /*@*/ int getY();
}

/*@ public behavior
 @ requires dx >= 0 && dy >= 0;
 @ assignable xctr, yctr;
 @ signals (Exception z) false; */
FigureElement moveNE( int dx, int dy );

package foal02;

class Point implements FigureElement {
  private int _x = 0, _y = 0;
  /*@ private depends xctr <- _x;
   @ private represents xctr <- _x; */
  /*@ private depends yctr <- _y;
   @ private represents yctr <- _y; */
  /*@ public behavior
   @ assignable xctr, yctr;
   @ ensures xctr == x && yctr == y;
   @ signals (Exception z) false; */
  public Point( int x, int y ) {
    _x = x; _y = y;
  }
  public /*@ pure @*/ int getX() { return _x; }
  public /*@ pure @*/ int getY() { return _y; }
  /*@ public behavior
   @ assignable xctr;
   @ ensures xctr == x;
   @ signals (Exception z) false; */
  public FigureElement setX( int x ) {
    _x = x;
  }
  /*@ public behavior
   @ assignable yctr;
   @ ensures yctr == y;
   @ signals (Exception z) false; */
  public FigureElement setY( int y ) {
    _y = y;
  }
  /*@ also
   @ requires dx < 0 || dy < 0;
   @ ensures false;
   @ signals (Exception z);
   @ z instanceof IllegalArgException;
   @*/
  public FigureElement moveNE( int dx, int dy ) { if (dx < 0 || dy < 0) {
    throw new IllegalArgException();
  }
    setX( getX() + dx );
    setY( getY() + dy );
}
}

Figure 1: A Java module declaring an interface, with (unsugared) JML specifications

Figure 2: A Java module declaring a class
package foal02;

aspect PointMoveChecking {
  private final String MOVE_SW =
      "did you mean to call moveSW()?";
  before(Point p, int dx, int dy):
    target(p) && args(dx, dy)
    && call(FigureElement moveNE(int,int))
  {
    if (dx < 0 && dy < 0)
      throw new
      IllegalArgException(MOVE_SW);
  }
}

Figure 3: An AspectJ module providing advice for Point

1.3 Non-modular Reasoning in AspectJ

Next we show that modular reasoning is not a general property of AspectJ by considering an aspect-oriented extension to our previous example. Figure 3 gives an aspect, PointMoveChecking, that modifies the behavior of Point's moveNE method [24]:

```
public behavior
  forall int oldx, oldy;
  requires oldx == xctr && oldy == yctr
  && dx >= 0 && dy >= 0;
  assignable xctr, yctr;
  ensures xctr == oldx + dx
  && yctr == oldy + dy
  && \result == this;
  signals (Exception z) false;
  also
  public behavior
    requires dx < 0 || dy < 0;
    ensures false;
    signals (Exception z)
      z instanceof IllegalArgException;
```

JML's also keyword combines specification cases; it says that when the precondition of one of the combined cases holds, then the rest of that specification case must be satisfied. So, in addition to the specification inherited from FigureElement, this effective specification says that when a client fails to satisfy the original precondition the implementation must throw an IllegalArgumentException. (This inheritance enforces behavioral subtyping [7, 18].)

Unfortunately, this behavior is only available to the programmer via non-modular reasoning. That is, in AspectJ the programmer must potentially consider every aspect that refers to the Point class in order to reason about the Point module. So, in general, a programmer cannot “study the system one module at a time” [23].

1.4 Problem Summary

In a paper from ECOOP 2001, arguing for aspect-oriented programming, Kiczales, et al. state [12] (p. 327):

“We would like the modularity of a system to reflect the way ‘we want to think about it’ rather than the way the language or other tools force us to think about it.”

However, we have seen that the lack of support for modular reasoning can sometimes prevent us from thinking about a system “the way we want to think about it.” In AspectJ, tool support is provided to compensate for this lack of modularity. Such tools perform the necessary whole program analysis to direct the programmer to the applicable aspects that affect pieces of a module’s source code. Other tools for processing AspectJ source code (e.g., typecheckers, compilers, and optimizers) also require a whole program analysis.

We seek a small set of modifications to AspectJ that obviate the need for this whole program analysis either by the programmer or by supporting tools.

The remainder of this paper is organized as follows. Section 2 gives our proposal for modular reasoning. Section 3 evaluates our proposal. Section 4 discusses some limitations of our proposal and considers separate compilation. Section 5 concludes.

2. A PROPOSAL

We have shown that AspectJ in general does not support modular reasoning; in general the effective specification of a module can only be determined by a whole-program analysis. In this section we propose modifying AspectJ by categorizing aspects into two sorts: assistants and observers. “Observers” are limited in that they may not change the effective specifications of the modules they apply to, “assistants” are not limited in this way. Since observers do not change effective specifications, they preserve modular reasoning even when applied without explicit reference by the modules they

---

2. Join points in AspectJ are actually more general than what we describe. For example, join points can refer to field references and exception handlers [2]. We leave generalization for future work.

3. We will formalize this intuition in Section 2.
When a client invokes a method for which either the client or a client of that module.

2.1 Assistants
We call aspects that can change the effective specification of a module assistants. The PointMoveChecking aspect of Figure 3 is an assistant. The term “assistant” is intended to connote a participatory role for these aspects.

What information is needed to modularly reason about behavior when assistants are present? Quite simply, a module must explicitly name those assistants that may change its effective specification or the effective specifications of modules that it uses. We say that a module accepts assistance when it names the assistants that are allowed to change its effective specification or the effective specifications of modules that it uses. Assistance may be accepted by:

- the module to which the assistance applies, or
- a client of that module.

AspectJ does not currently include syntax for explicitly accepting assistance. We propose a simple syntax extension for this purpose:

```java
accept TypeName;
```

where `TypeName` must be a canonical name of an assistant, i.e., a fully qualified name of the package containing the assistant, followed by a “dot” (.), followed by the assistant’s identifier. Multiple accept-clauses may appear in a single module, following any import-clauses. For example, the `Point` module could accept the `PointMoveChecking` assistance by declaring:

```java
accept foal02.PointMoveChecking;
```

Since `Point` (the module implementing the `moveNE` method) accepts `PointMoveChecking`’s assistance, this assistance is applied to every call to `Point`’s `moveNE` method, regardless of the client making the call.

On the other hand, if `PointMoveChecking`’s assistance was accepted by a client module, then that assistance would only be applied to calls from that client to `Point`’s `moveNE` method. Other clients that did not accept the assistance would not have it applied to their calls.

Figure 4 depicts the control flow of an invocation of `moveNE` with `PointMoveChecking`’s assistance. This depiction shows that there are multiple paths by which control may return to the client code, depending on the values of the parameters. The two arrows from the implementation of `moveNE` back to the client code correspond to the two postconditions (normal and exceptional) in the method’s specification. Dashed lines indicate exceptional control flow.

2.1.1. Composing Advice Specifications
When a client invokes a method for which either the client or the implementation module has accepted assistance, the behavior of that invocation is based on the sequential composition of the code along a particular control flow path. We can reason abstractly about the possible behavior of the invocation by considering specifications for the method and the assistants. In this subsection we extend JML to specify advice in AspectJ and we show how to modularly reason about the effective specification of a method in the presence of accepted assistance.

A specification language for an aspect-oriented programming language must take possible control flow paths into account. Figure 5 gives another version of the `PointMoveChecking` assistant that adds a specification for the before-advice. In before-advice an ensures-clause gives a normal postcondition, which must hold before control passes to the advised method (or any other applicable advice). We use the ensures-clause in this way since passing control to the advised method is the “normal” behavior for before-advice. So the specification of the before-advice in Figure 5 says that if the advice is entered with `dx > 0` and `dy > 0`, then control flow must pass to the advised method. The implicit frame axiom for this case says that no relevant locations may be assigned when this precondition holds.

The second specification case in Figure 5 says that if the advice is entered with `dx < 0` and `dy < 0` then control flow must return to the caller by throwing an `IllegalArgException` whose message is “did you mean to call `moveSW()`?”.

When reasoning about a call to `Point`’s `moveNE` method from the client’s perspective we would like to use an effective specification that abstracts away the details of the control flow and intermediate
state transformations. That is, the effective specification from the
client’s perspective should just concern the preconditions as control
flow leaves the client and the postconditions as control flow returns
to the client, along with the relevant frame axioms.

Just as the effective behavior along any control flow path is the
sequential composition of the code along that path, the effective
specification along any control flow path is formed by a kind of
sequential composition of the specifications along that path. When
a set of paths are in parallel, as in our example, then the effective
specification of the set is a kind of parallel composition of the paral-
lel paths’ specifications. To formalize these notions we will begin
by just considering before-advice and after-returning advice.4 Then
we will use the model to determine the effective specification of
moveNE in our running example. Later we will sketch extensions to
our formal model to accommodate around-advice.

We present our model in two stages. We first describe how to con-
struct a specification composition graph, from the specifications of
the implementation module and those of any assistants accepted by
that module or the client module. We then describe how the graph
is used to determine the effective specification of the invocation.

Constructing a Specification Composition Graph

A specification composition graph is a graph whose vertices repre-
sent a single method specification, the specifications of all advice
applicable to the method (and accepted by the method’s implemen-
tation module) , and the prestate and poststate from the client’s view. The specification composition graph is anal-
ogous to the control flow graph for the corresponding code. The
specification composition graph is used to determine the possible
paths through the advice and method specifications (and hence the
code if the implementation is correct). These paths are used to cal-
culate the effective specification.

In general a module may accept assistance from multiple assistants
and both a client and an implementation module may accept assis-
tance. The specification composition graph is formed respecting the
following order:

1. Apply any before-advice accepted by the client module in the
   order that it is accepted.
2. Apply any before-advice accepted by the implementation mod-
   ule in the order that it is accepted.
3. Execute the method body.
4. Apply any after-advice accepted by the implementation module in
   the reverse order from which it is accepted.
5. Apply any after-advice accepted by the client module in the
   reverse order from which it is accepted.

This ordering ensures, for example, that the first assistance
accepted by the client is “nearest” to the client and that the last
acceptance accepted by the implementation is nearest to the imple-
mentation on any path.

We will denote this ordering of before-advice, the method, and
after-advice by the sequence \( \langle a_1, a_2, \ldots, a_n \rangle \) where \( a_1 \) through \( a_{m-1} \) represent the before-advice, \( a_m \) represents the method, and
\( a_{m+1} \) through \( a_n \) represents the after-advice.

4. AspectJ supports three kinds of after-advice. After-returning ad-
dvice is only applicable when the advised method exits normally.
After-throwing advice is only applicable when the advised meth-
   od exits by throwing an exception. Regular after-advice, without
   a returning- or throwing-clause, is applicable in either case. To
   avoid complications in this preliminary proposal we are only con-
   sidering after-returning advice. It is a simple matter to modify
   the edge construction algorithm, presented below, to accommodate
   the other kinds of after-advice.

(For simplicity and modularity we have decided for the present to
confine acceptance of assistance to the module in which it is explic-
itly accepted. For example, if ColorPoint is a subclass of Point,
assistance accepted by Point is not automatically applied to invo-
cations of methods declared in ColorPoint. On the other hand, if
for a particular method ColorPoint does not override Point’s
implementation, then the inherited method carries with it the assis-
tance accepted in the Point module. This approach also provides
flexibility since the programmer can always add an accept-clause to
the subclass module or override a superclass method (gaining assis-
tance in the first case and “shadowing” assistance acceptance in the
second). Similar considerations apply for assistance accepted by a
superclass module of a client class. Also for simplicity we do not
allow interfaces to accept assistance. Future work may reevaluate
these decisions.)

Figure 6 gives the specification composition graph for Point’s
moveNE method with assistance from PointMoveChecking. It is
helpful to refer to this figure while considering the graph construc-
tion algorithm.

Formally, a specification composition graph is a directed acyclic
graph, \( G = (V, E) \), where \( V = \{\text{start}, \text{end}\} \cup \{a_i | 1 \leq i \leq n\} \) is
the set of vertices and \( E \) is the set of edges.

As Figure 6 shows, each vertex in \( V \), except \( \text{start} \) and \( \text{end} \), is annot-
ated with the signature of the corresponding method or advice.
This information is used reason about the passing of parameters.

To define the edges of the specification composition graph, we first
define a function \( \text{next} \) that orders the vertices. Let \( \text{next}(\text{start}) = a_1 \), for all \( 1 \leq i \leq n-1 \), \( \text{next}(a_i) = a_{i+1} \), and
\( \text{next}(a_n) = \text{end} \).

We also need some notation that will be used to label edges in the
graph with information from the advice and method specifications.
We will use \( \Sigma \) to represent the set of all possible program states,
i.e., the set of all legal assignments of values to locations. For each
\( a_i \) in \( V \), let its specification, \( \mathcal{S}(a_i) \), be represented by a set of tuples,
\( \mathcal{S}(a_i) = \{(Q_k, r_k, f_k, e_k, \epsilon_k) | 1 \leq k \leq p_i\} \), where \( p_i \)
is the number of cases in the specification and for all \( k \), \( 1 \leq k \leq p_i \),
\( Q_k \) represents the \( k \)th specification case, in which:

- \( Q_k \) represents its set of quantified variables (from forall),
  along with the implicitly bound \( \text{result} \) variable for methods
  and after-advice and any variables bound in signals-clauses.
- \( r_k : \Sigma \rightarrow \text{Bool} \) represents its precondition (requires),
- \( f_k \) is a set of variables that represents its frame (assignable),
- \( e_k : \Sigma \rightarrow \text{Bool} \) represents its normal postcondition (ensures),
  and
- \( \epsilon_k : \Sigma \rightarrow \text{Bool} \) represents its exceptional postcondition (sig-
  nals).5

Each edge in \( E \) is represented by a tuple, \( \langle \rho, x, y, S_k(x, \sigma) \rangle \), with

- \( \rho \in \{\text{v, e}\} \) indicating normal (v) or exceptional (e) control
  flow,
- \( x \) and \( y \) being the beginning and ending vertices of the edge,
- \( S_k(x) \) being the \( k \)th specification case (as above), and
- \( \sigma \in \Sigma \) being the state of the program when control flow
  traverses that edge.

---

5. To avoid unnecessary additional complexity we assume each
   specification in this representation already includes the specifi-
   cations inherited from its supertypes. Also, typically postconditions
   are modeled as relations on two states, but we are assuming a
   form for postconditions that cannot refer to pre-state values.
3. Let this algorithm when Figure 6 shows the specification composition graph generated by 4. Repeat until: The specification composition graph, Composing Specifications Along A Path

To model all the possible normal and exceptional control paths, construct $E$ as follows:

1. Let $J$ be an index set of distinct indexes. These will be used to label the state information in the edge tuples.
2. Add a directed edge $\langle v, \text{start next}(v), \sigma \rangle$ to $E$, where $j \in J$ is an unused index. The empty specification $\cdot$ is not used when computing the effective specification.
3. Let $x := \text{next}(v)$.
4. Repeat until $x = \text{end}$:
   4.1. For each specification case $S_i(x)$ in $S(x)$, if $e_i$ is not false, add a normal edge $\langle v, x, \text{next}(v), S_i(x), \sigma \rangle$ to $E$ and if $e_i$ is not false, add an exceptional edge $\langle e, x, \text{end}, S_i(x), \sigma \rangle$ to $E$, where $i, j \in J$ are unused indices.
   4.2. Let $x := \text{next}(v)$.

Figure 6 shows the specification composition graph generated by this algorithm when $\text{Point}$ accepts assistance from $\text{PointMoveChecking}$.

**Composing Specifications Along A Path**

The specification composition graph, $G$, contains all the information needed to calculate the effective specification of a method invocation. We first describe how to compose specifications along any single path in $G$.

Consider a unique path from start to end in the graph. Because of exceptional return edges this path may not visit every node in the graph. For simplicity of notation we will sequentially renumber the states and for each $a_i$ we will write $S_i$ for the specification case from $S(a_i)$ used on this path. Thus, the path is:

$$\langle \langle v, \text{start}, a_1, \ldots, a_0 \rangle, \langle p, a_1, a_2, S_1, \sigma_1 \rangle, \ldots, \langle p, a_q, \text{end}, S_q, \sigma_q \rangle \rangle,$$

where there are $q+1$ edges on the path. (For a path without exceptional edges $q = n$, otherwise $a_q$ throws the exception.)

To prevent capture of the locally bound variables when composing the specifications, we $\alpha$-convert the specification cases and related method and advice signatures so that all bound variable names are unique. We reserve the method’s formal parameter names for prestate values, so we must $\alpha$-convert the signature and out-edges of the method vertex. We also reserve the $\text{result}$ keyword for the poststate of the effective specification and so all instances of $\text{result}$ in the graph must be $\alpha$-converted. We will use a fresh variable in signals-clauses of the effective specification. Figure 7 shows the normal control flow path through the specification control graph of Figure 6, after $\alpha$-conversion.

If a given path is traversed in a program execution, then it must be the case that all the specifications along the path hold. We use this to reason inductively about the path’s effective specification.

If control flow enters vertex $a_1$ then $r_1(\sigma_1)$ holds and the formals in the vertex's signature must be bound to the actual parameters. We use the predicate $\text{bind}(x, y)$ to model the binding of actual arguments, results, or exceptions from vertex $x$ to parameters in the signature of vertex $y$. This binding is according to the parameter passing semantics of AspectJ and Java, a full definition of which is beyond the scope of this paper. As examples, here are the values of bind for the path in Figure 7, respecting the $\alpha$-conversion shown there:

- $\text{bind}(\text{start}, a_1) = (\text{pl=\text{this}} \&\& \text{dx}=\text{dx} \&\& \text{dy}=\text{dy})$
- $\text{bind}(a_1, a_2) = (\text{this=pl} \&\& \text{dx2}=\text{dx} \&\& \text{dy2}=\text{dy})$
- $\text{bind}(a_2, \text{end}) = (\text{this=\text{this}} \&\& \text{dx2}=\text{dx} \&\& \text{dy2}=\text{dy2} \&\& \text{\text{result}=\text{\text{result2}}})$

If control flow leaves vertex $a_1$ on edge $\langle p, a_1, y, S_1, \sigma_1 \rangle$ then the implementation code corresponding to that vertex must ensure that the set of possibly mutated locations is $f_1$ and that if $p = \nu$ then $e_1(\sigma_1)$ holds else if $p = \epsilon$ then $x_1(\sigma_1)$ holds.

If control flow exits vertex $a_i$ on a normal edge $\langle v, a_i, a_{i+1}, S_i, \sigma_i \rangle$, $1 \leq i \leq q$, then the set of possibly mutated locations is $f_i \cup \ldots \cup f_j$ and the following predicate holds:

$$\text{bind}(\text{start}, a_1) \land \ldots \land \text{bind}(a_{i-1}, a_i) \land \text{bind}(a_i, a_{i+1}) \land \ldots \land \text{bind}(a_{q}, \text{end})$$

If control flow exits vertex $a_i$ on an exceptional edge, then $i = q$, and the following predicate holds:
To reason about the effective specification from the client’s perspective, we must eliminate the intermediate states from these predicates. One way to do this would be to quantify over the states, like:

\[
(\forall \sigma_1, \ldots, \sigma_q \cdot \text{bind}(start, a_1) \land \cdots \land \text{bind}(a_{q-1}, a_q) \land r_1(\sigma_0) \land \cdots \land r_q(\sigma_q) \land e_1(\sigma_1) \land \cdots \land e_q(\sigma_{q-1}) \land s_q(\sigma_q))
\]

This predicate involves most of the normal postconditions; these just record what happens along the path before the last edge, which is the only one that throws an exception.

The second line of Figure 8 gives the explicitly quantified variables of the original specification cases, along with the α-converted parameters from the advice and method signatures.

The requires-, ensures-, and signals-clauses are based on the predicates derived above, with appropriate substitution for the intermediate values of the variables. That is, we write \( r_i(\sigma_0) \land \cdots \land r_i(\sigma_q) \land e_i(\sigma_1) \land \cdots \land e_i(\sigma_{q-1}) \land s_i(\sigma_q) \) for the precondition \( r_i \) where for each variable \( y \in \mathcal{T} \), each free occurrence of \( y \) is changed to \( y_i \). We use the same kind of abbreviation for \( e_i[\cdot] \).

The general form of the effective specification also must equate the prestate to \( \sigma_0 \) and the poststate to \( \sigma_q \) and include the information provided by the frame axioms. We write \( \text{equal}(\gamma_i, \tilde{\gamma}_i) \) for the predicate that asserts the equality of the variables in \( \gamma_i \) and \( \tilde{\gamma}_i \), using \( \text{equals} \) as appropriate for their types, and \( \text{notmod}(f_i, j, i, j) \) for the predicate that says that variables not listed in the frame \( f \) are unchanged; this is defined conceptually as follows (although this quantification is not expressible directly in JML, we can write the equivalent set of conjunctions in any particular case).

\[
\text{notmod}(f_i, j, i, j) = (\forall y \in \mathcal{T} \cdot y \notin f \implies \text{equal}(y, \tilde{y}))
\]

Taken together, we arrive at a single specification case for a single path through the specification composition graph, as Figure 8 shows. Since each possible parallel path is represented by such a specification case, we simply conjoin (using JML’s \&\& operator) the effective specifications for each path to form the effective specification of the entire invocation (the “parallel composition” alluded to earlier).

**Finding the Effective Specification**

We can use this formal model to find the effective specification of Point’s \texttt{moveNE} method with the \texttt{PointMoveChecking} assistant. Consider the path shown in Figure 7. On this path, the free variables are \( xCtr \) and \( yCtr \). Counting the initial state, we need to quantify over 3 states. The effective specification is as shown in Figure 9.

Lines from Figure 8 to Figure 9 relate the terms in the general form to the terms in the example. This example specification can be simplified to the following by using transitivity of equality (within clauses), the rule that \texttt{false} is the zero of conjunction, and dropping vacuous quantifiers:

\[
\begin{align*}
\text{forall int oldx, oldy;} \\
\text{requires dx >= 0 \&\& dy <= 100} \\
\text{\&\& oldx == xCtr \&\& oldy == yCtr;}
\end{align*}
\]

This is exactly the body of the first specification case arrived at intuitively in Section 1.3. We can analyze the other paths in the graph to calculate the other specification cases. Combining them with also yields the full effective specification.

### 2.1.2. Composition with Around-Advice

Figure 10 gives another assistant, called \texttt{PointMoveFixing}. It uses around-advice to change \texttt{moveNE} to accommodate negative arguments. Around-advice in AspectJ can execute both before and after the execution of the advised method’s body. Unlike before-advice, around-advice can also skip the execution of the advised method’s body without throwing an exception. The code (as opposed to the specification) in the body of the advice in Figure 10 illustrates these ideas. If \( dx \) and \( dy \) are both non-negative then the statement

---

6. Though not shown in this paper, JML provides constructs for locally binding names in expressions, such as quantifiers.
proceed(p, dx, dy);

causes control flow to pass to the original moveNE method body with the same arguments as the original invocation. Otherwise, in the else-clause the advice calls the setX and setY methods on point directly, avoiding the IllegalArgument exception that would be thrown if execution continued into moveNE. After the if-statement an acknowledgment message is printed to System.err.

Figure 10 also includes a JML specification of the around-advice. As with methods, before-advice, and after-advice, the specification of around advice consists of one or more specification cases joined with the keyword also. To specify the additional control flow possible via proceed in around-advice, we propose adding the AspectJ proceed-clause to JML as a mechanism for forming compound specification cases. In a specification the proceed-clause joins a specification case called the before-part, and a specification case called the after-part. The before-part specifies the code executed before proceeding to the original method (and any additional advice if present). The after-part specifies the code executed after returning from the original method (and advice).

The first specification case in Figure 10 (from the beginning up to the also) is such a compound specification consisting of before- and after-parts. The case is applicable when dx and dy are both non-negative, as specified by the requires-clause. In general an ensures-clause in the before-part says that if control flow proceeds to the original method body then the assistant must ensure that the clause’s predicate holds. In the example, ensures true indicates that control flow can always proceed in this manner. The proceed-clause itself specifies (possibly abstractly) the arguments that will be passed to the original method. A requires-clause in the after-part gives a predicate that can be assumed by the implementation of the after-part. The remainder of the after-part has the usual semantics.

The second specification case, following the also keyword in Figure 10, is applicable when at least one of the arguments is negative. The absence of a proceed-clause in this specification case says that control never proceeds to the original method body when this case’s precondition is met. The assignable- and ensures-clauses say that control flow can always proceed in this manner. The proceed-clause. We envision encoding the specification of around-advice we would need to extend our formal model. The extension would handle the additional control flow information provided by the proceed-clause. We envision encoding the specification of around-advice with multiple vertices in the specification composition graph. For each piece of around-advice one common vertex would represent the before-parts of all the cases. Separate vertices, one for each case, would represent the after-parts. The edge creation algorithm would require extensions to connect the vertices
package foal02;

aspect PointMoveFixing {
    /*@ public behavior */
    requires dx >= 0 && dy >= 0;
    ensures true;
    proceed(p, dx, dy);
    requires true;
    assignable System.err.value;
    ensures true;
    + signals (Exception z) false;
    also
    /*@ public behavior */
    forall int oldx, oldy;
    requires (dx < 0 || dy < 0)
    && oldx == xctr && oldy == yctr;
    assignable p.xctr, p.yctr,
    System.err.value;
    ensures p.xctr == oldx + dx
    && p.yctr == oldy + dy;
    + signals (Exception z) false;
    @
    FigureElement around(Point p, int dx, int dy):
    target(p) && args(dx, dy)
    && call(FigureElement moveNE(int,int))
    {
      if (dx >= 0 && dy >= 0) {
        proceed(p, dx, dy);
      } else {
        p.setX( p.getX() + dx );
        p.setY( p.getY() + dy );
      }
      System.err.println("OK");
    }
}

Figure 10: An AspectJ module giving around-advice to Point

appropriately. The calculation of the composed specification for a
given path in the graph would have to account for the expressions in
proceed-clauses of the specification.

2.1.3. Summary

We have argued that modular reasoning in aspect-oriented program-
mimg languages can be achieved for assistants if we require mod-
ules to explicitly accept assistance. We have given a formal model
for advice composition that allows us to determine the effective
specification of a method. This model also illustrates the reasoning
a programmer must undertake even in the absence of formal speci-
fications.

But what impact does our requirement that assistants be explicitly
accepted have on the expressiveness of the language? On the one
hand, assistants are very expressive in that they are given free rein
to change the effective specifications of modules that they assist.
On the other hand, requiring assistance to be explicitly accepted
dramatically curtails the applicability of assistants. To wit, a com-
mon example of the use of aspects is to add tracing capability to an
existing program. In a language that just supported explicitly
accepted assistance, a programmer would need to make an invasive
change to the source code of every module containing a method to
be traced (or alternatively, every module calling a method to be
traced). We would have gained support for modular reasoning at the
expense of modular editing.

2.2 Observers

To resolve this situation we propose that an aspect-oriented pro-
gramming language should also support a category of aspects that
we call observers. An observer is an aspect that does not change the
effective specification of any other module. Equivalently, an
observer may only mutate the state that it owns (in the sense of alias
control systems like [20, 21]). It also seems reasonable to allow
observers to change accessible global state as well, since a Java
module cannot rely on that state not changing during an invocation

(modulo synchronization mechanisms). The term “observer” is
intended to connote the hands-off role of these aspects. We use the
term observation to discuss the “advice” in an observer.

For example, Figure 11 gives an observer called PointMoveTrac-
ing. The observer modifier declares that this aspect must not
change the effective specification of any other module. This
observer mutates its own state by appending to myBuffer and
mutates the global state by printing to System.err. However, it
does not change the effective pre- or postconditions of Point’s
method. PointMoveTracing merely observes the arguments
to the moveNE method and reports them. The arguments are passed
on to the method unchanged and the method’s results are
unchanged.

In addition to cross-cutting concerns like tracing, it seems that
observers should be useful for logging and as the observer in the
observer design pattern [8] (pp. 293–303).

Because observers do not change the effective specifications of the
methods they observe, code outside an existing program can apply
an observer to any join point in the original program without loss of
modular reasoning. In reasoning about the client and implementa-
tion code for a method a maintainer of the original program does
not need any information from the observer.

2.2.1. Verifying Observerness

The primary challenge of implementing this part of our proposal
lies in determining whether a given aspect is really an observer. We
envision a static analysis that conservatively verifies this. This anal-
ysis is closely related to the problem of verifying frame axioms. In
fact we can think of observers as having an implicit frame axiom
that prevents modification of locations that are relevant to the
receiver and arguments of the observed method.

The main difficulty with statically verifying this lack of relevant
side effects is how to deal with aliasing. For example, suppose we
have a logging observer that uses an array to track the elements
added to some Set object. Suppose Set uses an array for its repre-
sentation. If the observer’s array and the Set’s array are aliased,
we might end up with an element being added to the array twice—pos-
sibly violating Set’s invariant and changing its effective specifi-
cation. There is a substantial body of work on alias control that may
be useful in attacking this [20, 21].

3. EVALUATION

This section briefly evaluates the practical consequences of our
proposal. Because we have not yet had the opportunity to develop
applications using our proposed restrictions, our evaluation is lim-
ited to a review of existing programs. We first consider the aspect-
oriented programming guidelines suggested in the ATLAS case
study [10]. Then we survey the example aspects from the AspectJ
Programmers Guide [2].
3.1 ATLAS Case Study

In the ATLAS case study [10], the authors proposed several guidelines to make working with aspects easier. These were proposed since they had discovered that (p. 346):

“[t]he extra flexibility provided by aspects is not always an advantage. If too much functionality is introduced from an aspect it may be difficult for the next developer—or the same developer a few months later—to read through and understand the code base.”

One of Kersten and Murphy’s suggestions is to limit coupling between aspects and classes to promote reuse. Specifically, they suggest that one should avoid the case where an aspect explicitly references a class and that class explicitly references the aspect, since then the class and aspect are mutually dependent. Such mutual dependencies prevent independent reuse. Is this suggestion problematic for our requirement that modules explicitly accept assistance? No, because the suggestion is concerned with mutual dependence between aspects and classes. Suppose an implementation module, $M$, accepts assistance from an assistant, $A$, and $A$ changes $M$’s effective specification. This says nothing about whether $M$ and $A$ are mutually dependent. If $A$ explicitly references $M$ the modules are mutually dependent. However, if $A$ only applies to $M$ because of wildcard-based pattern matching and does not explicitly reference $M$, then the modules are not mutually dependent. Next, suppose a client module, $C$, accepts assistance from an assistant, $A'$, and $A'$ only changes the effective specification of modules referenced by $C$, but does not change $C$’s effective specification. In this case $A'$ and $C$ are not mutually dependent. In sum, programmers can reduce mutual dependency by having clients accept assistance or by limiting explicit references to classes from assistants.

Kersten and Murphy also suggest using aspects as factories by having them provide only after-returning advice on constructors. This after-returning advice mutates the state of every object instantiated to change its default behavior. Limiting the aspects in this way restricts the scope of object–aspect interaction. In our proposal a simple assistant can fill the role of a factory aspect.

For aspects that do not act as factories Kersten and Murphy propose three style rules that restrict the use of aspects (pp. 349–350):

“Rule #1: Exceptions introduced by a weave must be handled in the code comprising the weave. ... Rule #2: Advise weave must maintain the pre- and post-conditions of a method. ... Rule #3: Before advise weave must not include a return statement.”

These rules are essentially equivalent to our definition of observers in that they prevent aspects from changing the effective specification of the advised method. Though we propose elevating these style rules to the level of statically checked restrictions.

3.2 Dynamic Aspects

The ATLAS case study uses dynamic aspects, or the substitution of different aspect code at runtime to modify the behavior of a program. One way to support this technique within the framework of our proposal would be to have modules accept assistance from abstract assistants. Specifications would be associated with these abstract assistants. The various desired behaviors would be implemented as separate assistants, each extending the abstract assistant and implementing its specification. This approach permits modular reasoning. The language would also need a mechanism to support the runtime selection of a particular concrete assistant.

Related to this idea of dynamic aspects is that of a mechanism for combining observers and other modules. In the current version of AspectJ aspects and classes are combined by naming their modules on the command line in a single invocation of ajc, Xerox’s AspectJ compiler. Thus combination takes place “outside the language”. To support observation of separately compiled programs, we would like to have a mechanism in the language for instantiating observers. It seems that the same language mechanism might support instantiating observers and selecting concrete assistants.

3.3 Impact of Restrictions

We would like to better understand how our restrictions might limit the practical expressiveness of AspectJ. For a preliminary evaluation we use the examples in the AspectJ Programming Guide to see if our restrictions prohibit any recommended idioms. The programming guide’s examples can serve this purpose since they “not only show the features [of AspectJ] being used, but also try to illustrate recommended practice” [2] (from Preface). We separate the example aspects into categories based on how we would implement them with our restrictions. An appendix lists the examples by category; we describe the categories here.

Observers. Many of the example aspects clearly meet our definition of observer. To satisfy our restrictions these would only require the new observer annotation.

Assistants. Aspects in the examples that could be implemented as assistants can be divided into two kinds. Client utilities are used by client modules to change the effective behavior of objects from other modules. The changes in effective behavior do not affect the representation of those objects. To satisfy our restrictions their assistance would have to be explicitly accepted by the clients. In fact, some of the client utility assistants are declared as nested aspects, i.e., aspects declared inside class declarations. These are similar in spirit to explicitly expected assistance.

There is one example that could be implemented as an assistant but that is not a client utility. This example uses an aspect to separate a simple concern that cross-cuts a single implementation module.

Dynamic Aspects. To satisfy our restrictions some example aspects would require the dynamic aspect mechanisms alluded to in Section 3.2. One such example is a debugging aspect. This aspect would be an observer, except that it provides after-advice to a GUI frame’s constructor to add debugging options to the frame’s menu bar. To support this pattern with our restrictions requires the mechanisms for dynamic aspects. The GUI frame would have to accept assistance from an abstract assistant, say additionMenuConcern, that allowed a concrete assistant, instantiated at runtime, to add to its menu bar. The debugging aspect would become a concrete assistant extending additionMenuConcern. The GUI frame could then be instantiated with the debugging assistant or with an assistant that did nothing.

4. DISCUSSION

As presented, our formal model for reasoning about explicitly accepted assistance does not accommodate advice that applies to join points other than those for method invocations. It seems a simple matter to extend the model to accommodate some other kinds of join points, such as those for field access or exception handling. However, it is not clear whether our model can accommodate dynamic context join points [2], like $cFlow(pointcut)$, which rely on runtime information for applicability tests. It seems that advice
on dynamic context join points can only be modularly reasoned about if this advice is confined to observations. There is one aspect in the AspectJ examples we studied, the Registry.\textit{RegistrationProtection} aspect of the spacewar example, that uses a dynamic context join point with advice that changes the effective specification of the advised method. This example is not supported by the current work.

Because of the generality of aspects without our restrictions and limitations of the target Java Virtual Machine (or JVM) [17], AspectJ currently requires whole-program compilation [12]. In our proposal, because assistance is explicitly accepted, it is a simple matter to support separate compilation for modules that accept assistance; the compiler just weaves it into the accepting modules.

On the other hand, observers present interesting challenges for separate compilation. On the surface, since observers do not change the effective specifications of other modules, it should be possible to separately compile them. And indeed this is true—except for the issue of dispatching to observers. The generality of observers means that they can potentially be dispatched to from any join point.

Thus, the only obstacle to separate compilation of AspectJ programs given our restrictions is that of dispatch to observers. Others have suggested that separate compilation for AspectJ is possible using techniques such as specialized class loaders or modified virtual machines [12] (p. 343). With our proposed restrictions the scope of the problem is reduced, likely making it easier to implement these solutions.

5. CONCLUSIONS
To summarize, we have shown that with a few simple modifications AspectJ can support modular reasoning. Our proposal separates aspects into two categories, assistants and observers, which provide complementary features. Assistants are extremely powerful, but require subtle reasoning techniques and are limited in their applicability to maintain modular reasoning. Observers are less powerful but are easy to reason about and are broadly applicable. This broad applicability is achieved by placing heavier burdens on the type system.

A preliminary evaluation showed that for many cases our modifications to the language provide sufficient flexibility. However, we also noted that there is a need for some mechanism to support dynamic aspects.

The other major open problem for our proposal is statically checking that aspects declared as observers meet our definition, as discussed in Section 2.2.1. To attack this problem we propose:

- developing an aspect-oriented calculus for investigating these ideas in a formal setting, and
- developing and proving sound a type-system for the calculus that statically enforces our proposed restrictions on observers.

Other future work on the problem of modular reasoning for aspect-oriented programming languages includes:

- refining our proposed specification constructs for AspectJ and formalizing their semantics, perhaps using something like the refinement calculus [3], and
- investigating behavioral subtyping and formal techniques for verification of aspect-oriented programs.

We are also interested in demonstrating the utility and effectiveness of our ideas by:

- programming non-trivial systems using our restrictions,
- integrating the proposed restrictions into AspectJ, and
- understanding the potential benefits of our restrictions for separate compilation, static analysis, and optimization.

In this paper we have focused on adding support for modular reasoning to the AspectJ language. Future work will also investigate the relevance of our proposal to other aspect-orientation programming languages and techniques, such as composition filters [4], adaptive methods [16], and multidimensional separation of concerns as embodied by Hyper-J [22, 25].

ACKNOWLEDGMENTS
We would like to thank Yoonsik Cheon, Todd Millstein, Markus Lumpe, and Robyn Lutz, for their helpful comments on a draft of this paper. The work of Leavens was supported in part by the US National Science Foundation grants CCR-0097907 and CCR-0113181. The work of both authors was supported in part by a grant from Electronics and Telecommunications Research Institute (ETRI) of South Korea.

APPENDIX
Table 1 below lists the aspects from the examples directory of the Version 1.0.1 release of AspectJ. The second column of the table gives the categorization of each example based on the categories of Section 3.3.

<table>
<thead>
<tr>
<th>Example Category</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>telecom/TimerLog</td>
<td>observer</td>
</tr>
<tr>
<td>tjp/GetInfo</td>
<td>observer</td>
</tr>
<tr>
<td>tracing/lib/AbstractTrace</td>
<td>observer</td>
</tr>
<tr>
<td>tracing/lib/TraceMyClasses</td>
<td>observer</td>
</tr>
<tr>
<td>tracing/version1/TraceMyClasses</td>
<td>observer</td>
</tr>
<tr>
<td>tracing/version2/Trace</td>
<td>observer</td>
</tr>
<tr>
<td>tracing/version2/TraceMyClasses</td>
<td>observer</td>
</tr>
<tr>
<td>tracing/version3/Trace</td>
<td>observer</td>
</tr>
<tr>
<td>tracing/version3/TraceMyClasses</td>
<td>observer</td>
</tr>
<tr>
<td>bean/BoundPoint</td>
<td>client utility</td>
</tr>
<tr>
<td>introduction/CloneablePoint</td>
<td>client utility</td>
</tr>
<tr>
<td>introduction/ComparablePoint</td>
<td>client utility</td>
</tr>
<tr>
<td>introduction/HashablePoint</td>
<td>client utility</td>
</tr>
<tr>
<td>observer/SubjectObserverProtocol</td>
<td>client utility</td>
</tr>
<tr>
<td>observer/SubjectObserverProtocolImpl</td>
<td>client utility</td>
</tr>
<tr>
<td>spacewar/Display.DisplayAspect</td>
<td>client utility</td>
</tr>
<tr>
<td>spacewar/Display1.SpaceObjectPainting</td>
<td>client utility</td>
</tr>
<tr>
<td>spacewar/Display2.SpaceObjectPainting</td>
<td>client utility</td>
</tr>
<tr>
<td>telecom/Billing</td>
<td>client utility</td>
</tr>
<tr>
<td>telecom/Timing</td>
<td>client utility</td>
</tr>
<tr>
<td>spacewar/EnsureShipIsAlive</td>
<td>assistant a</td>
</tr>
<tr>
<td>coordination/Coordinator</td>
<td>dynamic</td>
</tr>
<tr>
<td>spacewar/Debug</td>
<td>dynamic</td>
</tr>
<tr>
<td>spacewar/GameSynchronization</td>
<td>dynamic</td>
</tr>
</tbody>
</table>

Table 1: Example Aspects and their Categories

<table>
<thead>
<tr>
<th>Example</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>spacewar/RegistrySynchronization</td>
<td>dynamic</td>
</tr>
<tr>
<td>spacewar/Registry.RegistrationProtection</td>
<td>unsupported</td>
</tr>
</tbody>
</table>

a. The EnsureShipIsAlive aspect considered to be a poor design in the discussion of Section 3.3.
b. The aspect, Registry.RegistrationProtection, uses dynamic context join points, which aren’t supported by the current work.

REFERENCES


[8] E. Gamma, R. Helm, R. Johnson, and J. Vlissides. Design Patterns: Elements of Reusable Object-Oriented Software. Addison-Wesley, Reading, Mass., 1995.


