Modular Software Design with Crosscutting Interfaces

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Crosscut programming interfaces can significantly improve modularity in the design of programs employing AspectJ-style aspect-oriented programming.

Aspect-oriented programming (AOP) languages such as AspectJ[1] offer new mechanisms and possibilities for decomposing systems into modules and composing modules into systems. The key mechanism in AspectJ is the *advising* of crosscutting sets of *join points*. An aspect module uses a *pointcut descriptor* (PCD) to declaratively specify sets of points in program executions (join points) where anonymous methods (advice[2]) should run. An advice can run before, after, or around the specified join points. For example, the PCD in the `DisplayUpdate` aspect in figure 1a specifies all calls to methods in the `FigureElement` class hierarchy named `moveBy` or whose names start with `set`. The advice updates a graphical display after any such call completes.

We've devised a practical design approach that can significantly improve the modularity of programs written using AspectJ-style AOP. Our approach employs *crosscut programming interfaces*, or XPIs. XPIs are explicit, abstract interfaces that decouple aspects from details of advised code.[3] Without limiting the possibilities for AO advising or requiring new programming languages or mechanisms, our approach better modularizes aspects and advised code. It allows for their separate and parallel evolution and produces a better correspondence between programs and designs.

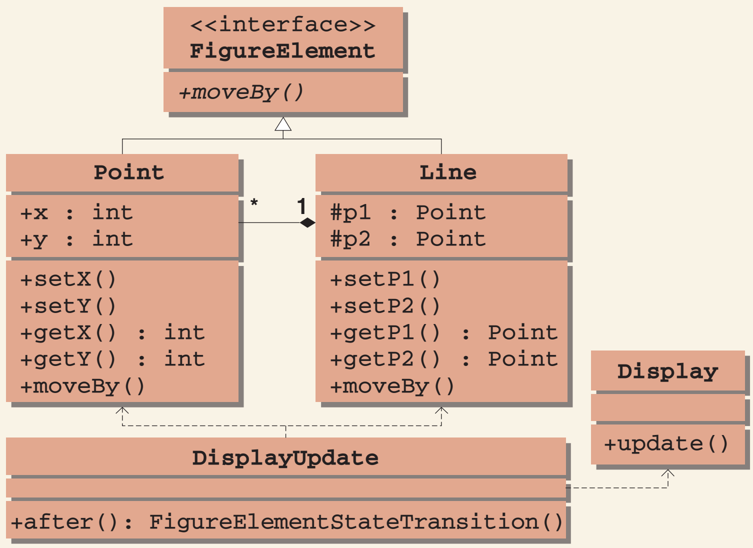
The problem

Our approach emerged from an experiment using common AOP methods to improve the design of HyperCast,[4] a 300-class, 50,000-LOC Java system for multicast overlay networks. The common approach for developing aspects is to write PCDs directly against the implementations of the code to be advised. Some AOP methodologists even argue that designers should be able to write programs without knowing aspect modules' actual or potential integration, a goal called *obliviousness*.[5] This idea has found currency in the practitioner-oriented press.[6]

We found that such approaches led to programs that were unnecessarily hard to develop, understand, and change. First, our designers had to inspect all the code to identify the relevant join points for the PCDs to encompass. Second, these join points weren't exposed consistently, so we needed complex PCDs and advice

```
public aspect DisplayUpdate {
  pointcut FigureElementStateTransition():
    call (* FigureElement+.set*(..))
    || call (* FigureElement+.moveBy(..));

  after(FigureElement f):
    FigureElementStateTransition() && target(f) {
    Display.update();
  }
}
```

(a)



(b)

Figure 1. Building a figure editor in the traditional aspect-oriented manner: (a) a display-updating aspect and (b) the resulting design.

bodies to effect the desired advising. Moreover, apparently innocuous changes or extensions to the code base could then change the matched join points, violating assumptions the aspects made. Also, the resulting class and aspect abstractions didn't reflect the underlying conceptual design adequately.

HyperCast's protocols are state machines. We needed aspects to advise state transitions. Although the aspects did modularize policy decisions on how to respond to transitions, the state machines themselves weren't exposed as explicit, design-level abstractions.

Our approach

After some thought, we realized that a second category of crosscutting concerns existed, ingrained into HyperCast and distinct from those modularized in aspects—namely, HyperCast's core protocols and other crosscutting abstract behaviors. We needed to expose these behaviors through interfaces against which we could write aspects. Benefits would include improvements to both abstraction (for example, the program would reflect key abstractions in the designers' minds and conversations) and modularity (for example, parallel development, modular evolution, and modular reasoning).

To develop and test this idea, we repeated our experiment using abstract interfaces, called XPIs, that expose PCDs and impose contracts and *design rules*.[7] We found that aspects were easier to develop, aspect code was separated better from the details of advised code, and the overall conceptual design was clearer.

Unlike our earlier, more theoretical work,[3] in this article we show how to realize XPIs as syntactic constructs in AspectJ, with weakest precondition invariants defining the semantics.

An XPI has four elements: the XPI's name, a scope over which the XPI abstracts join points, one or more sets of abstract join points, and a partial implementation. We express each abstract set of join points as

- a PCD *signature* declaring a name and exposed parameters, and
- a semantic *specification* stating preconditions that must be satisfied at each point where an advice can run (called a *provides clause*) and postconditions that must be satisfied after an advice runs (called a *requires clause*).

The partial implementation comprises, for each set of abstract join points,

- a join-point pattern that matches the corresponding concrete join points;
- a `before`, an `after`, or an `around` designator; and
- a corresponding set of constraints (design rules).

The constraints prescribe how code must be written to ensure that all and only the desired points in program execution match the given pattern. The rest of the XPI implementation is in the code's conformance to the stated design rules.

In AspectJ, these elements are declared in a stylized aspect. (In AspectJ, `before`, `after`, or `around` designators are associated not with PCDs per se but only with advice constructs that use PCDs.) Some invariants can be checked with separate pluggable aspects.

An XPI, like an API, abstracts changeable

Related Work on Aspect-Oriented Mechanisms for Software Design

Most research on improving program modularity through aspect-oriented mechanisms focuses on language models and expressiveness rather than software design methodology. Two recent developments that address design more directly are relevant here.

Join-point scoping

David Larochelle and his colleagues proposed a mechanism based on a pointcut descriptor (PCD) for hiding a crosscutting set of join points, thus preventing aspects from advising them.[1] Daniel Dantas and David Walker's AspectML provides advice access controls to a function definition's parameters, hence modifying the join-point signature of calls on the function.[2] Our *crosscut programming interface* (XPI) approach doesn't provide a hiding mechanism; rather, it specifies the exposure of given abstract execution phenomena. Combining such approaches might produce interesting support mechanisms for software design.

Jonathan Aldrich, among others, has proposed language constructs—and, by implication, a design method—for module-based join-point interfaces. Open Modules expose only PCD-selected join points on private state.[3] It enables the exposure of join points such that a module state that's intended to be hidden can't be advised. Simply, a module must declare a pointcut to export join points on its private state. Thus, Open Modules let a module implementation evolve without reworking aspects. However, the resulting interface is limited to crosscutting the module's implementation. Capturing the broadly crosscutting concepts in our HyperCast case study (see the main article) would be awkward at best. Also, Open Modules don't make clear the constraints that would have to be observed in writing new code to avoid inadvertently compromising the advising PCD semantics.

Aspect-aware interfaces

Gregor Kiczales and Mira Mezini recognized the need to program against crosscutting interfaces. In *aspect-aware interfaces* (AAIs), aspects extend the interfaces of modules they advise.[4] Specifically, this approach computes aspects' dependences on a system's join points and shows these dependences as annotations on the explicit interfaces of advised code.

Revealing such dependences can support modular reasoning and change. A programmer can see how join points are being advised and avoid making changes that invalidate those uses. Before stable modular interfaces emerge (for example, in Extreme Programming-style development[5]), AAIs can serve as a valuable substitute—they inform, even if they don't decouple and abstract. Likewise, the cross-references that AAIs provide could help guide refactoring activities, perhaps resulting in XPIs.

Yet AAIs don't clearly express concerns in conceptual design. Instead of textually distinct interface constructs, they merely consist of scattered annotations. Nor do they provide textually localized interface definitions where behavior contracts can be documented or against which clients can be programmed. In addition, modularity support is limited. The display of dependences between existing code and PCDs can't tell developers how to shape new code to correctly expose behaviors to those PCDs or how to write new PCDs to capture the existing code's desired behaviors.

References

1. D. Larochelle et al., "Join Point Encapsulation," *Proc. Workshop Software Eng. Properties of Languages for Aspect Technologies* (SPLAT), 2003, www.daimi.au.dk/~eernst/splat03.
2. D.S. Dantas and D. Walker, *Aspects, Information Hiding and Modularity*, tech. report TR-696-04, Princeton Univ., Nov. 2003.
3. J. Aldrich, "Open Modules: Modular Reasoning about Advice," *Proc. 2005 European Conf. Object-Oriented Programming* (ECOOP 05), LNCS 3586, Springer 2005, pp. 144–168.
4. G. Kiczales and M. Mezini, "Aspect-Oriented Programming and Modular Reasoning," *Proc. 27th Int'l Conf. Software Eng.* (ICSE 05), ACM Press, 2005, pp. 49–58.
5. K. Beck, *Extreme Programming Explained: Embrace Change*, Addison-Wesley, 1999.

and complex design decisions and operates as a decoupling contract between providers and users. Unlike an API, an XPI abstracts a crosscutting behavior rather than a localized procedure implementation. In the case of AspectJ-style AOP, an XPI abstracts advised join points, as we mentioned before. To paraphrase David Parnas,[8] XPIs modularize crosscutting design decisions that are complex or likely to change. You then implement an XPI not by providing a procedure implementation, but by writing PCD patterns and shaping code to expose specified behaviors through join points matching the given patterns. Designers need not know about specific aspects, such as logging, but they must decide which abstractions to expose as XPIs to facilitate aspect development and evolution. The method that we found to work is to expose key domain abstractions that the class design doesn't adequately capture. So, to design XPIs, you don't need any explicit references to aspects, although you can check the XPIs' usefulness against anticipated aspects.

For examples of other approaches to aspect-oriented mechanisms for software design, see the sidebar.

XPIs let you insulate aspects from the details of the code they advise and constrain that code to expose behaviors in specified ways.

Two designs for a figure editor

Two designs for the classic figure editor example[1] illustrate our approach and its potential benefits. We evaluate how well the designs manifest fundamental design concerns, abstract irrelevant details, and accommodate change.

A traditional AO design

Consider a simple tool for editing drawings comprising points and lines (figure elements), where a display depicts each figure element, always reflecting the figure elements' current states. The `FigureElement` class provides an interface for the concrete subclasses `Point` and `Line`. The `Display` class manages the display and provides a method, `update()`, to display all figure elements' current states. The specification requires a call to `update()` whenever a figure element's abstract state changes.

Researchers have used this example to illustrate crosscutting concerns, scattering and tangling, and how AOP addresses these issues. The crosscutting concern in this case is the policy that states *when the abstract state of a `FigureElement` changes, the `Display` must be updated.* Implementing this policy in an OO style leads to scattered `update()` calls throughout `FigureElement` subclass implementations and to the tangling of these calls into code concerned with `FigureElement` updating.

The `Observer` design pattern could remove the explicit calls by enabling a display manager to register for a callback to `update()` on a state change event. However, this approach still requires that event-related code be scattered and tangled in the `FigureElement` code and elsewhere. AOP provides an alternative to such preparation in support of display updating. The `DisplayUpdate` aspect (see figure 1a) satisfies the update specification.

We implemented this aspect using the common approach we described in the section "The problem." We studied the `FigureElement` code to find points where changes in the `FigureElement` abstract state occur. We generalized and described this set of points in the form of a PCD, `FigureElementStateTransition()`. This PCD captures calls to mutator methods of `Line` and `Point` and to `moveBy()`, which moves a figure element by a certain offset. Figure 1b presents a UML model of this design. As is typical in straightforward AOP, the `DisplayUpdate` aspect depends on implementation details of the `Point` and `Line` classes.

Such a design raises three concerns. First, we had to write the `Point` and `Line` implementations before we wrote the aspect, which limited the available parallelism in development. Second, the aspect implementer had to study the `Point` and `Line` implementations to be able to write the aspect correctly. The lack of an abstraction layer between the aspect and the advised code adds to the cognitive load on the aspect implementer. The aspect lets the `FigureElement` writer ignore display updating, but the aspect writer can't ignore `FigureElement`'s low-level details. Third, the aspect's correctness depends on unstable details of the `Point` and `Line` implementations. So, apparently innocuous changes could compromise the design.

An AO design with XPIs

By employing XPIs, the designer seeks to not only insulate aspects from the details of the code they advise but also constrain that code to expose specified behaviors in specified ways. In the process, important crosscutting concerns that were previously embedded in the implementation become manifest as XPIs in the program. In the figure-editing case, an XPI will separate the `DisplayUpdate` aspect from `FigureElement` details. Our XPI reifies the concept *a transition has occurred in a `FigureElement`'s abstract state.* It provides simple PCDs by which aspects can advise all such actions without depending on the underlying source code. In addition, it constrains the system implementer to implement all and only all abstract state changes in a way that matches the PCD patterns.

The XPI's syntactic part exposes two named PCDs: `joinpoint()` and `topLevelJoinpoint()`. The PCD signature (name and parameters) constitutes the abstract interface. The part of the PCD that matches points in the code is part of the XPI's hidden implementation (see figure 2a). It's only here that dependences on details of the underlying code arise.

We document the semantics informally in the following prose. The `joinpoint()` PCD exposes all `FigureElement` state transitions. This abstraction is implemented, in a sense, by the pattern that matches calls to `FigureElement` mutators. The system designer is constrained to ensure that the PCD pattern matches all and only such `FigureElement` mutator calls and that state transitions occur only as a result of such calls. The `topLevelJoinpoint()` PCD

```
public aspect XFigureElementChange {
/*
 The purpose of the joinpoint() PCD is to expose all and only FigureElement abstract
 state transitions. We require that all such transitions be implemented by calls to
 FigureElement mutators with names that match the PCDs of this XPI, and we assume that
 any such call causes such a state transition. Advisors of this XPI may not change the
 state of any FigureElement directly or indirectly. The topLevelJoinpoint() PCD exposes
 all and only "top level" transitions in the abstract states of compound FigureElement
 objects.
*/
  public pointcut joinpoint(FigureElement fe):
    target(fe)
    && (call(void FigureElement+.set*(..))
        || call(void FigureElement+.moveBy(..))
        || call(FigureElement+.new(..)));

  public pointcut topLevelJoinpoint(FigureElement fe):
    joinpoint(fe) && !cflowbelow(joinpoint(FigureElement));

  protected pointcut staticscope():
    within(FigureElement+);

  protected pointcut staticmethodscope():
    withincode (void FigureElement+.set*(..))
    || withincode(void FigureElement+.moveBy(..))
    || withincode (FigureElement+.new(..));
}
```

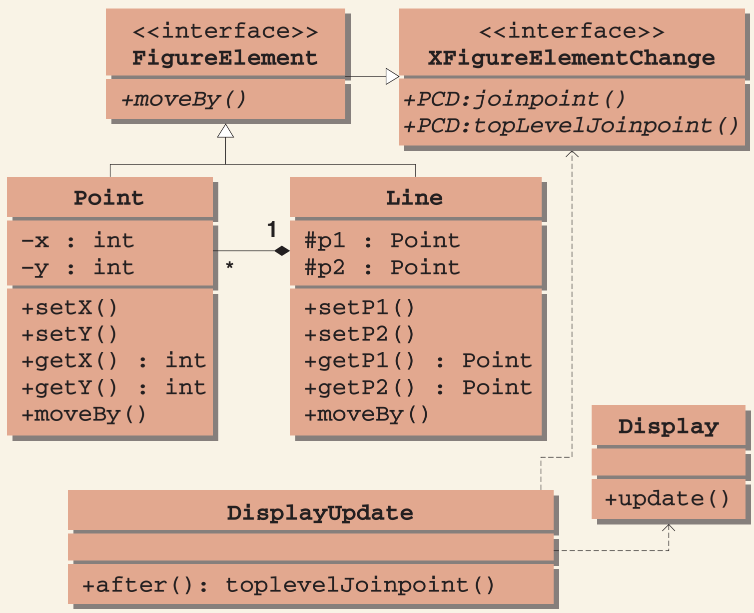
(a)

```
/*
 Checks the contracts for the XFigureElementChange XPI.
*/
public aspect FigureElementChangeContract {
  /*
   PROVIDES: XPI matches all calls and only calls to FigureElement mutators
  */
  declare error:
    (!XFigureElementChange.staticmethodscope()
     && set(int FigureElement+.*)):
    "Contract violation: must set FigureElement"
    + " field inside setter method!";

  /*
   REQUIRES: advisers of this XPI must not change the abstract state of any
   FigureElement object
  */
  private pointcut advisingXPI(): adviceexecution();

  before(): cflow(advisingXPI())
    && XFigureElementChange.joinpoint(FigureElement) {
    ErrorHandling.signalFatal("Contract violation:"
      + " advisor of XFigureElementChange cannot"
      + " change FigureElement instances");
  }
}
```

(b)

Figure 2. Building a figure editor using crosscut programming interfaces (XPIs): (a) the `XFigureElementChange` XPI and (b) a separate contract-checking aspect.

```
public aspect DisplayUpdate {
   after():
     XFigureElementChange.topLevelJoinpoint
        (FigureElement) {
     updateDisplay();
   }

   public void updateDisplay() {
     Display.update();
   }
}
```
(a)



(b)

Figure 3. Separating an aspect from implementation details: (a) a display-updating aspect using an XPI and (b) the resulting aspect-oriented design.

exposes all and only changes to the states of compound `FigureElement` objects (such as `Lines`) but not changes to their components (namely, `Points`).

An XPI's semantics can include behavioral constraints on aspects. In our example, we require that no advisor of this XPI cause a side effect on a `FigureElement` object. This constraint in effect prohibits an advice from calling `FigureElement` mutators either directly or indirectly.

Like APIs, XPIs enable a degree of contract checking.[9] When included in the program's build, the aspect in figure 2b constrains developers to modify a `FigureElement`'s internal state from only within the `FigureElement` mutators. To a degree, it also ensures that the aspects using the `XFigureElementChange` XPI can't modify any `FigureElement`'s abstract state. The aspect can't, however, verify the programmer's adherence to the naming requirements.

Figure 3 presents a `DisplayUpdate` aspect using this XPI and the resulting UML model. The aspect now depends only on the abstract, public PCD signatures of `XFigureElementChange`, not on implementation details of the `Point` and `Line` classes. These classes contribute to implementing the `XFigureElementChange` XPI by ensuring that method names match the given PCDs if they have the specified change semantics.

Analyzing the designs

To compare the two designs, we first change public data members to private ones,[10] forcing updates to occur through advisable method calls. We then extend `FigureElement` to include `Color`.

Data member access. In our original design, the coordinates in the Point class were public, permitting this implementation of `Line.moveBy()`:

```
public void moveBy(int dx, int dy) {
   p1.x += dx;
   p1.y += dy;
   p2.x += dx;
   p2.y += dy;
}
```

Making the fields private drives the `Line.moveBy()` designer to change to this implementation:

```
public void moveBy(int dx, int dy) {
   p1.moveBy(dx, dy);
   p2.moveBy(dx, dy);
}
```

Consider the `DisplayUpdate` aspect implemented without the XPI. When `Line.moveBy()` is invoked, the advice is invoked three times: once for the call to `Line.moveBy()` and once for each call to `Point.moveBy()` in the body of `Line.moveBy()`. The apparently innocuous change broke the aspect's assumption about `Line`'s otherwise-hidden implementation.[11]

The XPI approach avoids such problems by establishing interfaces that impose design rules. Aspects can assume that the rules are followed, and code within the XPI's scope must conform to its terms. The reverse also applies: aspects must conform to the XPI's terms, and the code can assume that the rules are followed. It's important that XPIs have both syntax, in the form of convenient abstract PCDs, and semantics. Our XPI specifies that the PCD must match join points that indicate a change in a `FigureElement`'s abstract state. Under this XPI, `DisplayUpdate` uses the provided convenient PCD (and promises not to inject changes into a `FigureElement`). Also, `Line`'s implementer will implement `Line.moveBy()` so that the PCD captures its join point.

Adding color to figure elements. The second change is behavioral, adding `Color` as a `Line` attribute with getter and setter methods, with the requirement that all observers of a `FigureElement` update when a `Line`'s color changes.

In the non-XPI approach, one of two undesirable scenarios is necessary to ensure that the display updates properly. In one scenario, the `Color` implementer must be aware of the `DisplayUpdating` aspect and its PCD implementation to determine how to name the `Color` setter method so that the PCD will match it. In the other scenario, the aspect implementer must change the `DisplayUpdating` PCD to match whatever choice the `Color` implementer makes. As the number of aspects increases, these scenarios become increasingly problematic.

In the XPI case, the `Color` implementer need only be aware of the figure element state change XPI and its constraint that only a method whose name is `moveBy` or starts with `set` can change a state. The XPI's presence thus guides the implementer in choosing names for methods and in making other decisions that can influence PCD matching. In this case, the implementer must name the method something such as `setColor`, rather than `changeColor`;

The advantage of using an aspect is that code changes can be localized to the aspect, even if their effects aren't.

```
public aspect PointLineRelation {
  private Line Point.parent;

  public boolean Point.partOfLine() {
    return parent != null;
  }

  public Line Point.getParent() {
    return parent;
  }

  /*
   When a Line's Point is possibly set, reestablish
   the parent of the Line's Points.
  */
  private pointcut changePoint(Line l):
    target(l)
    && XFigureElementChange.joinpoint(FigureElement);

  before(Line l): changePoint(l) {
    l.getP1().parent = null;
    l.getP2().parent = null;
  }

  after(Line l): changePoint(l) {
      l.getP1().parent = l;
      l.getP2().parent = l;
  }
}
```

Figure 4. The `PointLineRelation` aspect records the `Line` to which a `Point` belongs.

merely doing so exposes color changes as abstract state changes through the XPI. To our knowledge, no prior work clearly guides programmers to design code for ease of advising.

Extending the new design

XPIs can facilitate adding a classic nonfunctional aspect, property enforcement. Adding a property and its implementation to a system is an important issue. To explore it in the context of XPIs, we add a feature that maintains a geometric invariant in the figure editor: `Line`s must not be degenerate. That is, the two points that define a line can't have identical coordinates. Enforcing this invariant requires that no `Line` is degenerate when it's first created and that no change to a `Point` in a `Line` makes it degenerate. This is an instance of the more general problem of maintaining invariants for compound structures under changes to their respective parts.

Invariant enforcement essentially changes a `Point`'s originally specified behavior by conditioning a `Point` mutator's effects on that `Point`'s participation in a `Line`. Such a change could require broad changes in the software's implementation. The advantage of using an aspect is that it does localize the code needed to effect the behavioral change in the `Point` class. However, it doesn't necessarily obviate the need for changes elsewhere in the code to accommodate that change in behavior. With this observation in mind, we argue that the use of XPIs, while not a panacea, can improve a designer's ability to express and use abstractions that both manage these complex effects and reflect key abstractions in the conceptual design.

We assume that the designer will use an aspect module to implement the invariant enforcement. An appropriate XPI to write the aspect against doesn't already exist. So, we need to determine the domain abstraction for decoupling the aspect's development from the normal case's development and then write that XPI. One abstraction we need is that of a *change to a `Point` that is part of a `Line`*. Given this, the aspect can then implement the policy *prevent changes to `Points` in `Lines` that would create any degeneracies*.

The precise invariant we seek for the given design is that a `Line` can't have two end `Points` at the same coordinates. Modifying a `Line` by calling method `Line.setP1(Point)` or `Line.setP2(Point)` can violate this invariant. So can directly modifying the coordinates of a `Point` that belongs to a `Line`, without direct reference to the `Line`. However, a key concept absent from the original system is the relation between `Points` and `Lines`. For instance, no field in `Point` stores a containing `Line`. A subtlety is that some `Points` are part of a `Line` and some aren't. (And in a real system, a point might be a part of many lines.)

So, the first part of our solution creates a representation of a new `Point-Line` relation. We use an aspect to introduce a `parent` field into `Point` to record the `Line` to which a `Point` belongs, if any (see figure 4). The aspect uses the `XFigureElementChange` XPI, updating the `parent` field as appropriate when a `Line` is created or one of its `Points` is replaced. Although this aspect updates the parents of `Points`, it doesn't violate the `XFigureElementChange` requires clause because the parent is part of the hidden state of `FigureElements`. In keeping with this XPI, this solution introduces no `setParent` method, calls to which would inappropriately result in updating the `Display`.

Figure 5 presents the XPI and resulting design. The `XPointInLineChange` XPI exposes three events on a `Line`'s endpoints: change in *x* coordinate, change in *y* coordinate, and change in both coordinates.

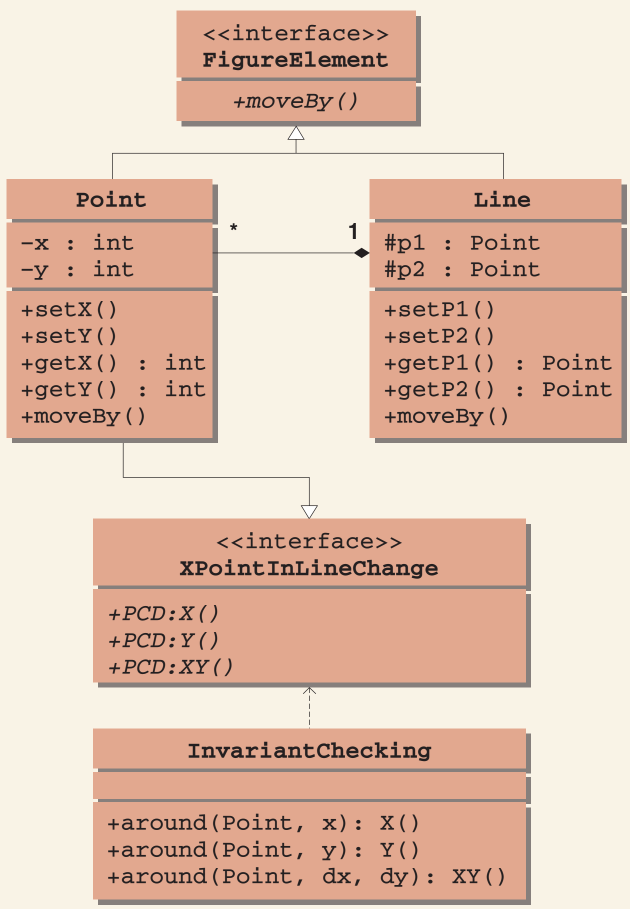
Having written this XPI, we can now straightforwardly write an aspect for invariant enforcement (not shown). Using `around` advice, the aspect advises changes in `Points` that are in `Lines` and lets them occur only if they preserve the invariant. The XPI abstracts changes to `Points` in `Lines`. The aspect separately abstracts the invariant and enforcement policy. Such separation is at the heart of our interface-oriented approach to AO design for improved modularity and abstraction. It permits reuse of the XPI for implementing other aspects and decouples those aspects from possible changes to the ways that `Points` and `Lines` may be modified.

The XPI approach decouples aspect code from the unstable details of advised code without compromising the expressiveness of existing AO languages or requiring new ones. By extending well-understood notions of module interfaces to crosscutting interfaces, this approach provides a principled alternative to the concept of oblivious design.[3] In our discussions with best-practice AO programmers, we've found that some of them indeed design and develop in stylized ways that are consistent with the XPI approach. It thus has the potential to ground, regularize, and disseminate best software engineering practices using the new mechanisms that AO programming languages provide.

Our experience to date with XPIs is limited to two systems, HyperCast[3] and the figure editor. We expect that integrated-development-environment support could aid programmers by showing the scope of an XPI's applicability. Being nonhierarchical, XPIs can overlap in scope.

```
/*
 The X() PCD exposes changes to the x coordinate of
 any point that belongs to a line (similarly for
 Y() and XY().
*/
public aspect XPointInLineChange {
  public pointcut X(Point p, int x):
    call(void Point+.setX(int))
    && target(p) && args(x) && if(p.partOfLine());

  public pointcut Y(Point p, int y):
    call(void Point+.setY(int))
    && target(p) && args(y) && if(p.partOfLine());

  public pointcut XY(Point p, int dx, int dy):
    call(void Point+.moveBy(int,int))
    && target(p) && args(dx, dy) && if(p.partOfLine());
}
```

(a)



(b)

Figure 5. Using an XPI to add an invariant property: (a) The `XPointInLineChange` XPI and (b) the resulting design.

Also, we haven't yet investigated the promise of XPIs for AO languages with different mechanisms than AspectJ's. An appealing aspect of our approach, however, is that it's neutral with respect to a language's join-point model. It forces specified behaviors to be revealed through interfaces implemented in terms of whatever join-point model a language supports.

Acknowledgments

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References

1. G. Kiczales et al., "An Overview of AspectJ," *Proc. 15th European Conf. Object-Oriented Programming* (ECOOP 01), LNCS 2072, Springer, 2001, pp. 327–353.
2. W. Teitelman, *PILOT: A Step toward Man-Computer Symbiosis*, PhD thesis, tech. report AITR-221, Massachusetts Inst. of Technology, 1966.
3. K.J. Sullivan et al., "Information Hiding Interfaces for Aspect-Oriented Design," *Proc. 10th European Software Eng. Conf. Held Jointly with 13th ACM SIGSOFT Int'l Symp. Foundations of Software Eng.* (ESEC/FSE 2005), ACM Press, 2005, pp. 166–175.
4. J. Liebeherr and T.K. Beam, "HyperCast: A Protocol for Maintaining Multicast Group Members in a Logical Hypercube Topology," *Proc. 1st Int'l Workshop Networked Group Communication* (NGC 99), LNCS 1736, Springer, 1999, pp. 72–89.
5. R.E. Filman and D.P. Friedman, "Aspect-Oriented Programming Is Quantification and Obliviousness," *Aspect-Oriented Software Development*, Addison-Wesley, 2005, pp. 21–35.
6. R. Laddad, *AspectJ in Action: Practical Aspect-Oriented Programming*, Manning Publications, 2003.
7. C.Y. Baldwin and K.B. Clark, *Design Rules: The Power of Modularity*, MIT Press, 2000.
8. D.L. Parnas, "On the Criteria to Be Used in Decomposing Systems into Modules," *Comm. ACM*, vol. 15, no. 12, 1972, pp. 1053–1058.
9. B. Meyer, "Applying 'Design by Contract,'" *Computer*, vol. 25, no. 10, 1992, pp. 40–51.
10. G. Kiczales and M. Mezini, "Aspect-Oriented Programming and Modular Reasoning," *Proc. 27th Int'l Conf. Software Eng.* (ICSE 05), ACM Press, 2005, pp. 49–58.
11. J. Aldrich, "Open Modules: Modular Reasoning about Advice," *Proc. 2005 European Conf. Object-Oriented Programming* (ECOOP 05), LNCS 3586, Springer, 2005, pp. 144–168.

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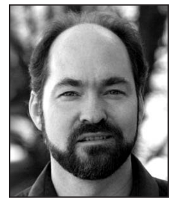

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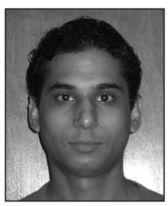

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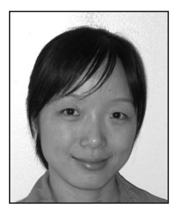

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