Architecture as an Independent Variable

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ABSTRACT

The idea that we can separate application content from architectural form, or *style,* is a mainstay of modern software engineering. Architectural styles have themselves been a subject of intensive study. The problem is that we do not yet have an adequate account of the mappings that combine choices of application description independent of style, and of architectural style independent of application, to produce style-specific, application-specific architectural descriptions. An account of such mappings would deepen our understanding of architecture and provide a foundation for technologies for manipulating *architecture as an independent variable.* We contribute a validated early model of this kind.

Categories and Subject Descriptors

D.2.11 [**Software Engineering**]: Software Architecture

General Terms

Design, Architectural Styles

1. INTRODUCTION

Researchers and practitioners have long known that *application content* can be considered largely separately from *architectural form.* As far back as 1972, Parnas [8] described a *key word in context (KWIC)* system and consequences of choosing to design it in one of two forms: functional decomposition (FD), or information hiding (IH). As recently as 2009, in their textbook on architecture, Taylor, et al. [11] described a lunar landing control system and showed how programs implementing it could be written in many styles.

In many related works (e.g. [9, 2, 10, 11, 3]) we find the same basic assumption: a choice of *architecture-independent application description*, p, can be combined with choices of *application-independent architectural styles*, $s_1, \ldots, s_n$, to produce application- and style-specific *architectural descriptions* $i_{(p,s_1)}, \ldots, i_{(p,s_n)}$. The relative costs and benefits of the results are then compared in selected dimensions, e.g., design flexibility, coordination overhead, performance, reusability, etc. Research in this area has provided insights and technology enabling designers to reason about properties of designs in isolation from application details, and to select appropriate design forms for many systems. It has led to styles of great importance, including design patterns [2], the REST style [1], and so forth.

The problem that we address in this paper is that, while we already have a theory of architectural styles, and of specifications as application descriptions abstracted from architecture, and while we understand that we should seek to separate applications and architectural style, we do not have an adequate theory or technologies for truly making this separation, or for combining formal application and style descriptions to yield system-specific architectures. We have not yet reached a point where mechanically we can treat architecture as an independent variable.

This paper makes four basic contributions in this area. First, we formulate this problem and make the case it is worth addressing. Second, we present a vocabulary and graphical notation that support reasonably precise discussion of issues in this space. Third, we show that our ideas can be realized in a concrete, computationally effective form. We have developed an approach for combining formal application descriptions with architectural style descriptions to synthesize architectural descriptions. Fourth, we present an assessment of the viability of our approach by using it to replicate earlier architectural studies from the literature. We show our formally and automatically derived architectural descriptions to be consistent with results derived previously, informally and manually.

The rest of this paper is organized as follows. Section 2 presents our approach in theory. Section 3 shows that the theory can be automated. Section 4 hypothesizes that our automated approach produces results that are consistent with previously informal results, and presents experimental data in support of this claim. Section 5 shows that comparing our work with related efforts has the potential to improve both. Section 6 concludes.

2. THEORY

This paper makes explicit and elaborates the notion that an *architectural map* is what combines an application description, p, with a style description, s, to produce an architectural description $i_{(p,s)}$, for application p in style s.

$$i : ArchDesc = archMap(p : AppDesc, s : ArchStyle)$$

University of Virginia, Technical Report # CS-2009-11.

This map is the principal object of our study. Putting it at the center begins to balance attention to architectural styles, with attention to how style choices combine with application descriptions to yield architectures. Knowledge of this mapping is crucial to expertise in software design. Given an application description in some style, the experienced designer knows both what architectural style to pick, and how to map an application description of the given kind to an architectural description in the chosen style.

Clearly *map* is a complicated object. In some sense it embodies all our knowledge about how to realize different kinds of systems in different architectural styles. We need a way to study it in pieces.

One contribution of this work is an approach to doing this: We decompose *map* by treating it as a function polymorphic in both application style and architectural style. We then investigate *map* for specific pairs of styles. We thus make explicit a notion of *application style.* Application descriptions come in many forms, e.g., *composition of functions,* or *state machine.* Different architectural maps are, in practice, used to deal with these different styles of application description. We break up *map* into a large set of such style-pair-specific maps.

We make our idea more precise as a *dispatching* relation, *disp.* Given an application style, t, and an architectural style, s, we view *disp* as indexing, or *dispatching* to, a t-s-specific map, $disp(t, s) = map_{(t,s)}$, that in turn takes an application description, p_t in style t, and an architectural style description, s, and that yields an architectural description, $i_{(p_t,s)}$, in style s, that *refines* p_t. Decomposing *map* into style-specific pieces enables us to build up a theory and automated style-specific tools in an incremental fashion.

Our theory and language for discourse in this area includes the following basic constructs: a set, *ArchStyle* of *architectural styles;* a set of *ArchDesc*, of architectural descriptions; a binary relation, *conforms,* on the cross product, that encodes the conformance (or not) of an architectural description, i, to an architectural style, s; a set *AppStyl* of *application styles*, a set, *AppDesc*, of application descriptions; an analogous binary relation, *conforms* encoding the conformance or not of a given application description, p, to a given application style, t; and a relation, *refines,* encoding the notion that an application-specific architectural description, i, refines, or implements, the application description, p. Finally, we have *map*, which takes as inputs an application description, p_t in style t, and an architectural style, s, and that, via the sub-map, $m_{(s,t)}$, produces an architectural description, $i_{(p_t,s)}$, such that $refines(i, p)$ and $conforms(i, s)$. The following equation and Figure 1 illustrate these ideas.

$$map(p_t, s) = disp(t, s)(p_t) = map_{(t,s)}(p_t) = i_{(p_t,s)}$$

With these terms in hand, we can now say more precisely what we mean by the phrase, *architecture as an independent variable.* For a given application description, p_t, in style t, we should be able to select among architectural maps compatible with t for different architectural styles, $s_1, \ldots, s_n$. If each map is implemented by an automated tool, then we can quickly produce architectures in different styles for the given application by just applying the different maps.

Figure 2 illustrates for a simple case: an application p_{cf}, written in a *composition of functions* (cf) style, is mapped to architectural descriptions, $i_{(p_{cf},oo)}$ and $i_{(p_{cf},pf)}$, in two

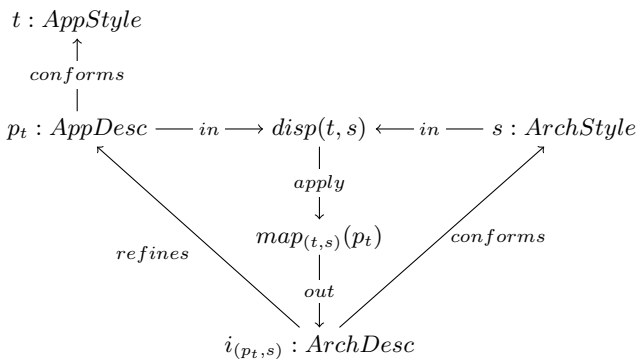


Figure 1: Key relations in a commutative diagram.

styles: *object-oriented* (oo) and *pipe-and-filter* (pf). Having architecture as an independent variables means that we can freely choose architectural styles, and even change our decisions as conditions evolve. In the next section we present early prototype technology that suggests that this idea is in fact viable.

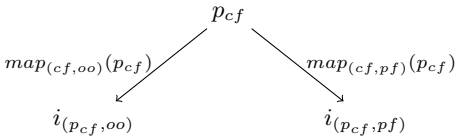


Figure 2: Architecture as an independent variable.

3. PROTOTYPE

In this section we show that our ideas can be reduced to practice. We can implement tools that support architecture as an independent variable. There are many possible approaches to implementing tools that compute architectural maps. Here we describe one approach, in which we use Jackson's Alloy specification language [5] to represent application descriptions, architectural style descriptions, architecture maps, and computed architectural descriptions.

We chose Alloy for this study for two reasons. First, its ability to compute solutions that satisfy complex sets of constraints is useful as an automation mechanism. Second, and more importantly, it allows us to use published architectural style specifications written in Alloy as inputs [6, 12]. Reusing published models is not only convenient, but is an important part of our approach to validating our ideas: It shows them to be consistent with contemporary formal accounts of architectural style.

We view the technology that we describe here as an early demonstration prototype only. We do not believe Alloy will ultimately prove to be the best, or at least the only, technology for reducing our ideas to useful tools. The novel concept in this work encompasses any technology that takes separate application and architectural style descriptions, broadly construed, and that automatically computes, or otherwise manipulates, corresponding architectural descriptions of systems with the required refinement and conformance properties.

3.1 Application Description

We illustrate our approach with a simple example, drawing on a widely known but previously informal case study from the literature: the mapping of a description of Parnas's KWIC application to an architectural description in the *pipe-and-filter* style [8, 10]. In terms of *application style*, we describe KWIC as a *composition of functions*, a structure implicit in Parnas's original paper [8]: "The KWIC [Key Word in Context] index system accepts an ordered set of lines, ... Any line may be circularly shifted by repeatedly removing the first word and appending it at the end of the line. The KWIC index system outputs a listing of all circular shifts of all lines in alphabetical order."

$$KWIC(text) = (output \circ sort \circ shift \circ input)(text).$$

For purposes of demonstrating the feasibility of reducing our approach to practice, we represent this composition of functions as a sequence of function objects in Alloy. To be specific, we specify this sequence in Alloy, and run the Alloy Analyzer to produce it as a solution. Figure 3, illustrates the result produced by Alloy: the *application description* consumed by our implementation of the architecture map. We elide the simple Alloy specification of this sequence of functions from this paper.

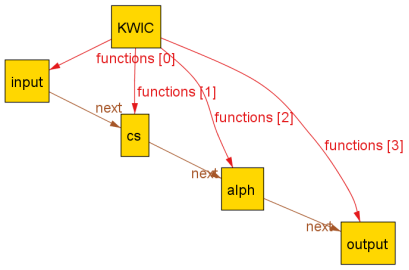


Figure 3: Alloy representation of *application description* for KWIC in *composition-of-functions* style.

We have not yet attached semantic specifications to the constituent functions, or to the $KWIC$ function as a whole; but we hypothesize that it is feasible to do so and that such specifications could be carried through our maps into the resulting architectural descriptions, to provide semantic guidance to programmers. We identify this idea as an opportunity for future research and development.

3.2 Architectural Map

In this subsection we continue our explanation of how our ideas can be reduced to practice by exhibiting an Alloy implementation of architectural map, $map_{(cf,pf)}$ taking Alloy-encoded application descriptions in the *composition-of-functions* (cf) style, and producing architecture descriptions in the *pipe-and-filter* (pf) style.

A pipe-and-filter architecture describes a system as a collection of components, *filters,* and connectors, *pipes.* A filter consumes data from an upstream pipe connected to an input port, transforms it in some way, and passes the results to a downstream pipe connected to an output port. Filters operate concurrently. Pipes connect filters to other filters.

We exploit existing Alloy formalization of such styles. Figure 4 outlines the pipe-and-filter style description, which in turn extends Wong's component-and-connector meta-model of architectural style in Alloy [12]. The style description defines eight signatures: Input, Output, Source, Sink, DataSource, DataSink, Filter and Pipe. In details elided from this paper, Filter is specified as having Input and Output ports. Pipe, a kind of Connector, has two roles: source is the input role of a pipe; sink is the output role. DataSource, DataSink model data sources and sinks, respectively, in pipe-and filter descriptions.

```
abstract sig Input extends Port {}
abstract sig Output extends Port {}
abstract sig Source extends Role {}{...}
abstract sig Sink extends Role {}{...}
abstract sig DataSource extends Component{}{...}
abstract sig DataSink extends Component{}{...}
abstract sig Filter extends Component{}{...}
abstract sig Pipe extends Connector{}{...}
```

Figure 4: Pipe-and-filter style (elided) in Alloy.

An architectural style description of this kind specifies the *co-domain* of an architecture map. To represent a map, itself, such as $map_{(cf,pf)}$, we extend the style description with mapping predicates. These predicates take application descriptions as parameters (such as the KWIC structure illustated above), and define relationships required to hold between them and computed architectural descriptions. Given an application description, and a map, Alloy computes corresponding architectural descriptions. Alloy guarantees that all computed descriptions *conform* to the given architectural style. Our predicates are responsible for ensuring that computed architectural descriptions *refine* given application descriptions. Our ideas are thereby reduced to practice. While noting that architectural styles include semantic constraints, here we only consider structural refinements. In practice it will be important to represent and refine semantics as well. We do plan to develop this observation in future work.

Figure 5 presents *handleFunctions*, the parameterized predicate that represents $map_{(cf,pf)}$. It accepts application descriptions in the composition-of-functions style and produces pipe-and-filter architecture description. It specifies that for each function in the composition of functions there is a component in the architectural description that handles it. The Output port of filter is connected to the Source role of a downstream pipe, the Sink role of which is attached to the Input port of subsequent filter. DataSource and DataSink are specified as we described previously. The *handleFunctions* predicate additionally uses *scope-PnF* parameterized predicate to ensure the correct Alloy scope for the System.

3.3 Architecture Description

We use the Alloy Analyzer to compute architecture descriptions, represented as satisfying solutions to the constraints of a map given an application description. Figure 6 illustrates the computed result for our KWIC example. The diagram is accurate for the result that Alloy computed, but we have edited it to omit some details for readability (ports of filters, and roles of pipes, for example). In this diagram, *DataSource*, a specific type of Filter, handles the *input* function. Its output port is connected to *Pipe0*. *Filter1* handles the *CS* function. Its input and output ports are connected to *Pipe0* and *Pipe1*, respectively. Similarly, the other filters handle *alph* and *output* functions.

```
pred handleFunctions[cons:seq Function]{
  all f:Function | one x: Component |
  x.handle = f
  one DSource:DataSource, DSink:DataSink|
  DSource.handle = cons.first
  && DSink.handle = cons.last
  one s:System | all f:Filter|
  one apipe:Pipe| one nFilter:Component|
  one r1:Source| one r2:Sink  |
  one p1:Output| one p2:Input|
   {(f.handle.next!=none) &&
    (f.handle.~next!=none)} =>{
      nFilter.handle = f.handle.next
      && r1 in apipe.roles && r2 in apipe.roles
      && p1 in f.ports && p2 in nFilter.ports
      && r1->p1 in s.attachments
      && r2->p2 in s.attachments
   }
  scope_PnF[1, #cons]
}
```

Figure 5: $map_{(cf,pf)}$ represented in Alloy.

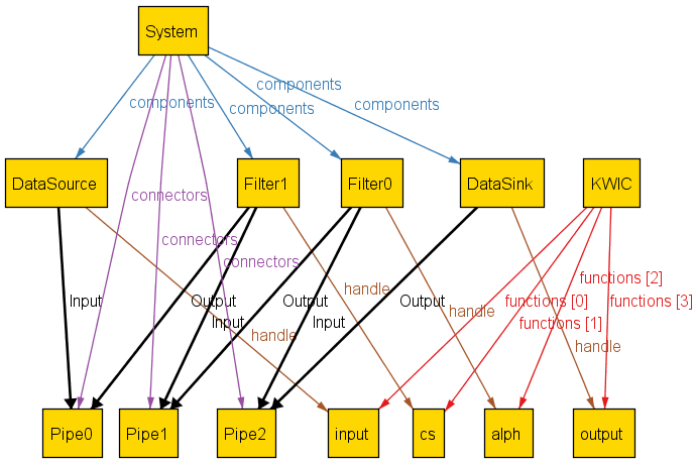


Figure 6: The map of composition-of-functions of KWIC into the PF style

We chose the example that we have presented this section for two reasons. First, it helps us explain, without undue complexity, how we have reduced our ideas to practice. We presented a software tool for taking *any* application described as a composition of functions to a corresponding pipe-and-filter architecture. Second, it illustrates our approach to experimental testing of our overall hypothesis: **Our theory supports a formal, automated approach to deriving architectural descriptions from application descriptions and architectural style descriptions. It provides for a *computationally effective* separation of application and architecture concerns.** We test this idea by exhibiting maps for a range of architectural and application styles and asking whether the results are consistent with the informally and manually produced results in the literature. The data of this section appear to support the hypothesis.

	Comp. Fun.	State-Driven
Pipe-And-Filter	KWIC, LL	
Object-Oriented	KWIC, LL	KWIC
Implicit Invocation	KWIC, LL	

Figure 7: Experiments performed to date.

4. EVALUATION

In this section, we report and interpret data from early experimental testing of our approach and hypothesis. Figure 7 summarizes our results. We have developed two application description styles, *composition-of-functions (CF)* and *state-driven behavior (SD)*, and three architectural styles, *pipe-and-filter (PF), object-oriented (OO),* and *implicit invocation (II)*. The pipe-and-filter and implicit invocation style definitions are in the published literature. Not finding an such an object-oriented style definition, we crafted a one based on Wong's meta-model.

Each non-empty cell corresponds to an architecture map that we have implemented for the application and architecture styles given on the axes. The entries in the table indicate the case studies from the literature to which we have applied our maps, to test the consistency of our results with the informal, manually derived results in the literature. We have applied our work to two case studies: KWIC, long used in studying architectural styles and their properties; and the Lunar Lander (LL) case study of Taylor et al. Overall we have thus performed seven experiments to date. We described the $(CF, PF, KWIC)$ in the preceding section. We elide discussion of (CF, PF, LL) because it does not add anything new. For reasons of space, we also elide $(CF, II, KWIC)$. The following four subsections thus report on the execution and results of four experiments: $(CF, OO, KWIC)$, $(SD, OO, KWIC)$, (CF, II, LL), and (CF, OO, LL). In each case we cite the study that we are recapitulating in a formal, automated fashion.

4.1 Experiment: CF, OO, KWIC

This experiment attempted to reproduce previous informal studies by Parnas [8] and later studies by Shaw and Garlan [10]. We map a CF description of KWIC to an architectural description in the OO style. We have already presented our simple CF description of KWIC. The rest of this subsection defines our OO architectural style, discusses our architectural map, $map_{(cf,oo)}$, and presents and analyzes results of applying it to our KWIC application described in the CF style.

One of the most common architecture styles is object-oriented. Figure 8 presents part of our Alloy model of a constrained OO style. The specification defines three Alloy signatures: Interface, Implementation, and Object. An Object has an interface, an implementation, and a set of other interfaces on which the object depends. Elided predicates state that no object may depend upon the implementation of any other Object (in our constrained formalization of this style). The implementation of one Object may depend on the Interfaces of other Objects, except that (as we define the style here) no object may depend on its own interface.

We next define a parameterized predicate for mapping any composition of functions to an OO architecture. It takes a sequence of functions (representing a composition of functions), and constrains the architectural descriptions to have

```
abstract sig Interface{}
abstract sig Implementation{}
abstract sig Object extends Component{
  interface: one Interface,
  implementation: one Implementation,
  depends: set Interface,
  }{
    !(interface in depends)
  }

...
```

Figure 8: OO style described in Alloy.

```
pred handleFunctions(cons: seq Function){
  scope_OO[1, #cons]
  all o:Object| (o.handle.~next!=none)
  =>o.depends = o.handle.~next.~handle.interface
  else o.depends = none
}
```

Figure 9: Part of our CF-OO map predicate.

the intended structure. The sequence of functions is mapped to a corresponding set of objects, each responsible for implementing the function to which it corresponds, and where each object depends only on the interface of the object responsible for the preceding function.

Figure 10 depicts the results of mapping the $KWIC_{cf}$ application description to an OO architecture description. This diagram was computed automatically by Alloy but edited to remove inessential details. The results are consistent with Shaw and Garlan [10]. The resulting architectural descriptions consists of four objects. Each one handles a function of KWIC. *Object3* handles the input function. *Object2* handles the circular shift (CF) function and depends on the (input) Interface of *Object3*. *Object0* implements the output function. This object depends on the Interface of *Object1* , which handles the alphabetization (alph) function.

Clearly a designer would have to invent additional details to produce a more satisfactory architectural description. For example, our tool did not compute object interfaces, but rather only constrained how objects interact through them. Richer application descriptions, including semantics, would create opportunities for richer architecture maps. This issue is important to our future work.

4.2 Experiment: SD, OO, KWIC

This experiment addresses the work of Garlan, Kaiser & Notkin [4], who explored, among other things, how changing the KWIC application from batch-sequential to interactive might demand corresponding changes in architectural style. We note that change can be seen as involving, at a more abstract level, a change in the style of *application* description, and that this change is what really drives the need for a new *architectural* style.

We employ *state-driven behavior* as a style for interactive application description. The rest of this subsection introduces this style of description, an architectural map from this application style to the OO architectural style, and the results of applying this map to a description of an interactive version of KWIC.

Our interactive-KWIC system accepts a line of input at a time and outputs an alphabetized list of the current collection of lines. We modeled interactive-KWIC as a state-driven system, where each state represents one of the behavioral modes of the system (inputting, sorting, etc), and where transitions represent sequencing among modes. To do this in Alloy we use its polymorphic linear ordering module. This helps us to organize the states in a linear fashion, which is all we need in this case. Figure 11 presents our description of an interactive version of KWIC in the state-driven style. (We wrote an Alloy specification, which the Alloy Analyzer solved to produce this structure.)

The initial state of the interactive-KWIC is Wait, in which the system waits to receive a command. There are transitions from the Wait state to the Add, Delete, Print and Exit states (and back) driven by interactive commands. The line buffer is updated in the Add and Delete states. As the line buffer is altered, the circular shifter is invoked to create the shifts accordingly. It uses the shared shift lines buffer to hold the shifted lines. The Alphabetizer state has also access to the shift lines buffer. It is triggered by the completion of the shifter activities to sort lines in the buffer. The Alphabetized lines buffer is used to hold the alphabetized shifts. Finally, the Print state displays the latest buffer.

Figure 12 depicts the computed interactive-KWIC architecture description, in object-oriented style, that we computed. For clarity of presentation, we again omit details. The *System* here consists of a collection components. There is an object to handle each of the shared data objects, namely *LineBuffer*, *ShiftedLines* and *AlphLines* as well as the *InteractiveKWIC*.

Our mapping function uses the State pattern [2]. This pattern is useful when an object can be in one of several states, with different behaviors in each state. The pattern implements states as classes that are instantiated as an object enters each state. Operations invoked on the object are delegated to those instances, which have their own methods for the operations. In the same way, as can be seen from the diagram, each state is assigned to an object to be handled.

Every Object has an Interface and Implementation (elided from the Figure). Each of the state Object depends on the Interface of the Object handling the associated shared data object. As a case in point, *Object4* handles the *Alphabetizer* state, having an access to *ShiftedLines* and *AlphLines*. *Object4* thus depends on the Interfaces of *Object10* and *Object9*, which handle the two shared data objects, respectively.

4.3 Experiment: CF, II, Lunar Lander

in Chapter 4 of their text[11], Taylor, Medvidovic, and Dashofy illustrate the structuring of a lunar lander application in a range of architectural styles. We describe the Lunar Lander system formally (albeit abstractly) based on their informal description. The application is decomposed into the three basic functions: *Get User Data*, *Spacecraft* and *Display*. We have represented this application in a composition-of-functions style. From this simple model we have produced an architecture description for the pipe-and-filter style consistent with the textbook. Here we discuss only its mapping to architectural descriptions in the object-oriented and implicit invocation styles.

In some cases it is helpful to model one architectural style as inheriting rules from another. An implicit invocation object (IIObject) is thus an Object that provides both a col-

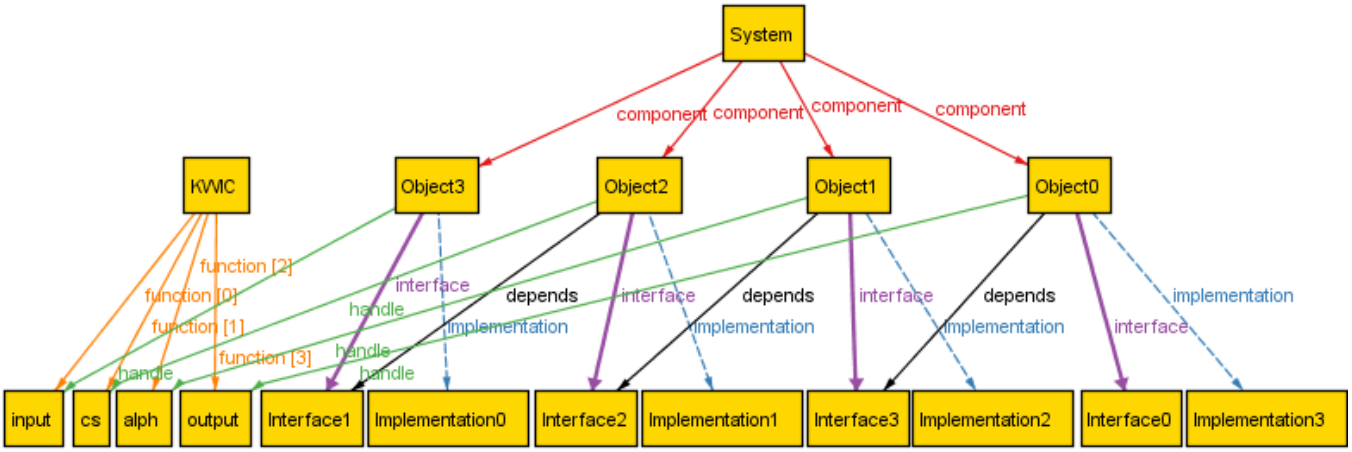


Figure 10: The map of the composition of functions of KWIC into the OO style

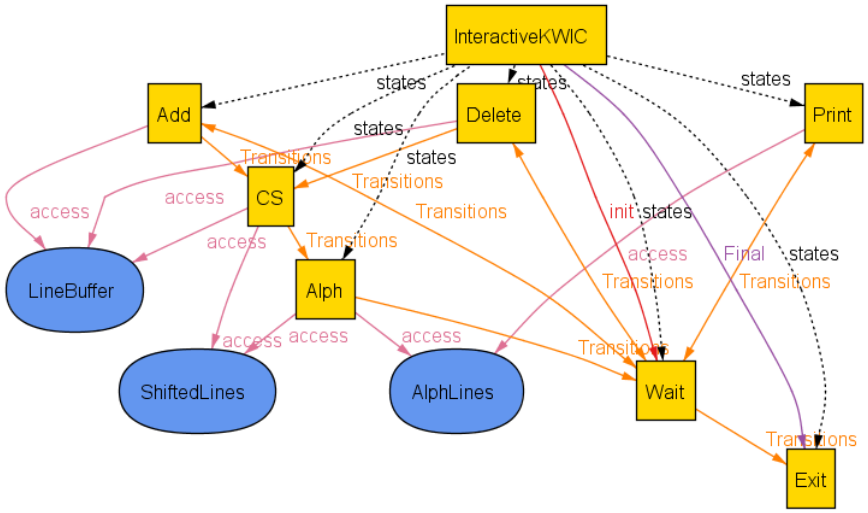


Figure 11: Interactive-KWIC described in state-driven style.

```
abstract sig Publish extends Role {}
abstract sig Subscribe extends Role {}
abstract sig PublishEvent extends Port {}{...}
abstract sig SubscribeEvent extends Port {}{...}
abstract sig IIObject extends Object{}{...}
abstract sig EventBus extends Connector {}{...}
```

Figure 13: part of II style described in Alloy

lection of interfaces (as with Object) and a set of events. Procedures may also be called in the usual way. So, an IIObject extends the definition of an Object. It can, in addition, register some of its procedures with events of the system; so those procedures will be invoked when the events are announced. Figure 13 (eliding details) makes these ideas precise in six signatures: Publish, Subscribe, PublishEvent, SubscribeEvent, IIObject and EventBus. IIObject has PublishEvent and SubscribeEvent as its ports. EventBus is a special kind of Connector and has two roles, i.e. Publish and Subscribe.

Figure 14 presents predicates that define our architectural map. The *handleIIFunctions* parameterized predicate ensures a correct architectural structure. It takes a sequence (representing a composition) of functions. It uses three other predicates: scope-OO, handleIIObjects and handleEvents. The former predicate sets the Alloy scope of the System. handleIIObjects specifies the ports of each IIObject based on its role as a Publisher and/or Subscriber. The handleEvents predicate states that for each publisher IIObject, its PublishEvent port is attached to the publish role of an EventBus. The subscribeEvent port of a relevant subscriber, on the other hand, is attached to the subscribe role of that EventBus.

According to the informal description of the lunar lander, the Spacecraft component maintains the state of the spacecraft (its altitude, fuel level, velocity, and throttle setting). After calculating the altitude, fuel level and velocity, it emits those values to the event bus. Receipt of events providing the spacecraft's altitude, fuel and velocity cause the Display component to update based on those values. The GetData component obtains new burn data settings from the user;

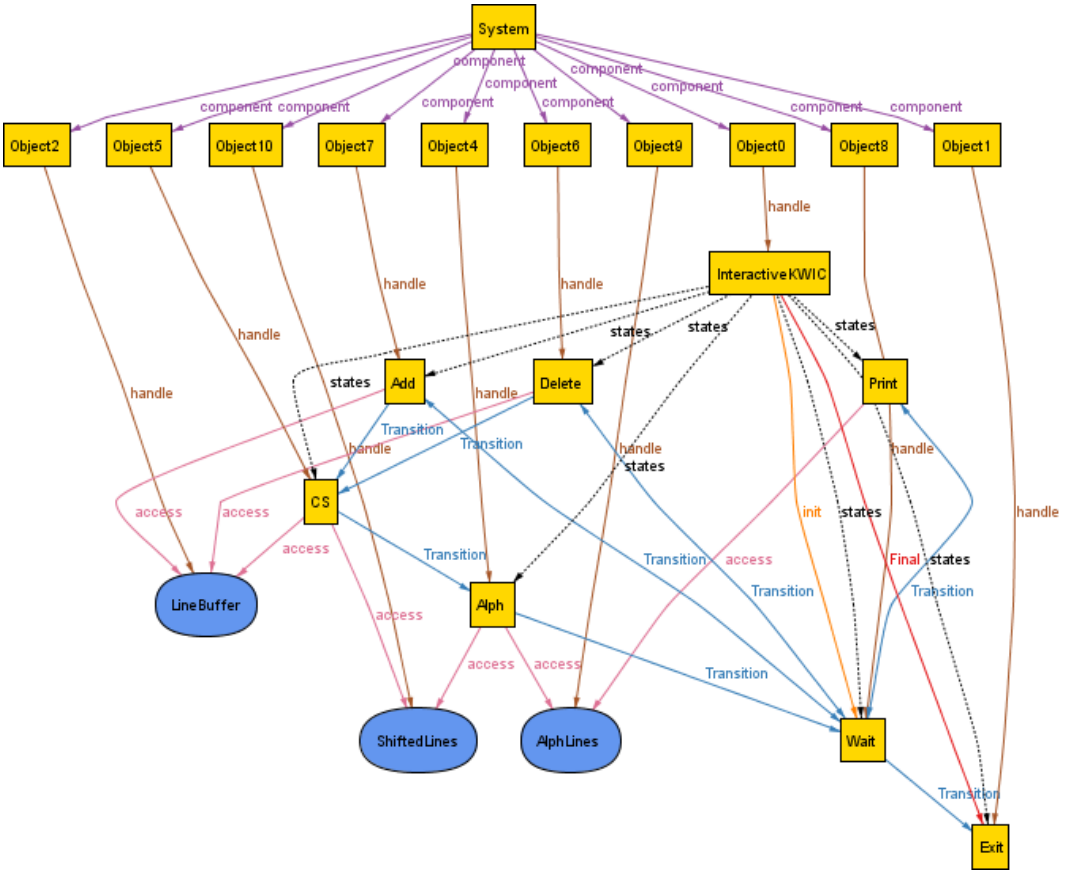


Figure 12: The map of state-driven KWIC into the OO style

when this happens the component emits a notification of this new value onto the event bus. Upon receipt of this notification the Spacecraft component updates its internal model of the spacecraft and emits the updated state back to the bus.

Figure 15 presents the architectural description of the *System*, generated by Alloy. To simplify the diagram, we omit some details, such as interface and implementation of objects as well as the roles of *EventBus* elements. The architectural description has three *IIObjects*. The *LunarLander* element, inferred from the input specification, represents the function set of the Lunar Lander System. *GetData*, *Spacecraft* and *Display* constitute *LunarLander*. Each *IIObject* handles a function. As a case in point, *IIObject2* handles *GetData* and publishes a notification of new value through *PublishEvent0* that should be connected to *EventBus0*. On the other hand, *IIObject1*, handles *Spacecraft* , subscribes to input events through *SubscribeEvent0*, and will be implicitly invoked. This allows it to update the state of the spacecraft. This in turn causes *Display* to be invoked implicitly so that it refreshes its display based on new data.

4.4 Experiment: CF, OO, Lunar Lander

Mapping our composition-of-function description of the Lunar Lander to the OO architectural style yields the architectural description depicted in Figure 16. As an aside, we note that Taylor et al., indicate that the application description of the lunar lander that the use in discussing the OO architectural style is not exactly the same as the one illustrated in the OO style section of the book.

According to Figure 16, generated again by Alloy, the *System* comprises three components. *LunarLander* along with the system's functions, namely *GetData*, *Spacecraft* and *Display*, can be seen at the right side of the diagram. Each *Object* has its *Interface* and *Implementation*. Their connections are mentioned by labeled arcs. *Object2* handles *GetData* function. *Object1*, on the other hand, depends on the Interface of *Object2* and handles the *Spacecraft* function. The last function of Lunar Lander is *Display* which is handled by *Object0* depending on the Interface of *Object1*.

4.5 Discussion

Our experiments show that architectural maps can be implemented in a computationally effective manner. We have used this technology to recapitulate studies of architectural style and choice from the research literature. The results of our formal and automated computations are consistent with the informally and manually produced results documented in the literature. By simply swapping between implementations of architectural maps, we are able to produce difference architectural descriptions for a given system from a high-level application description. Although we have not yet attempted experiments beyond those replicating studies from the literature, we are encouraged. Our early work appears to support the idea that being able to treat architecture as an independent variable is a plausible aspiration.

```
pred handleIIObjects(){
  all o:IIObject|
    {(o.handle.next!=none) &&
     (o.handle.~next!=none)} =>
    { one SubscribeEvent & o.ports
      one PublishEvent & o.ports}
    else  {(o.handle.next=none) } =>
    {  one SubscribeEvent & o.ports
       no PublishEvent & o.ports}
    else  {(o.handle.~next=none) } =>
    {  no SubscribeEvent & o.ports
       one PublishEvent & o.ports}
}

pred handleEvents(){
  all o:IIObject|
  {(o.handle.next!=none) &&
    (o.handle.~next!=none)} =>
    { some s:System| one e:EventBus |
   one sRole:Subscribe| one pRole:Publish|
   one sPort:SubscribeEvent| one pPort:PublishEvent|
   sRole in e.roles && pRole in e.roles
   && pRole-> pPort in s.attachments
   && sRole-> sPort in s.attachments
   && sPort in o.handle.next.~handle.ports
   && pPort in o.ports
}}

pred handleIIFunctions(cons: seq Function){
  scope_OO[1,#cons]
  handleIIObjects[]
  handleEvents[]
}
```

Figure 14: Selected Alloy predicates for the II style.

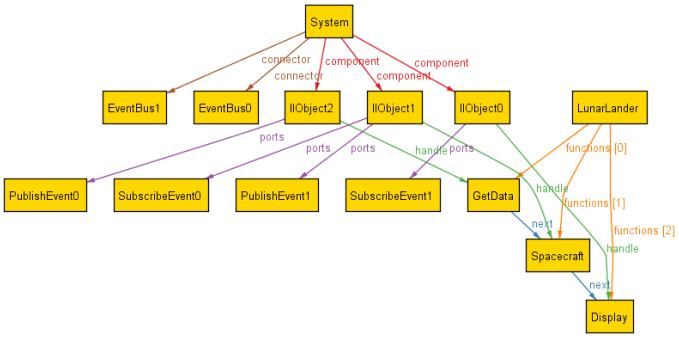


Figure 15: The Lunar Lander in the II style.

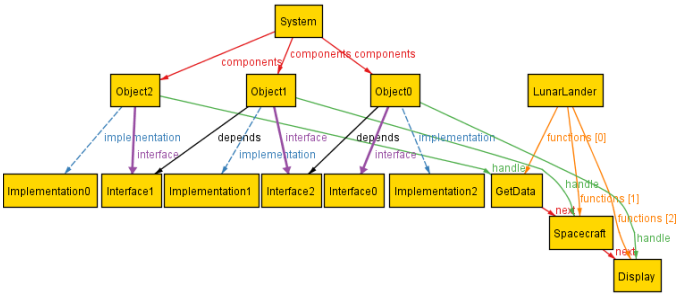


Figure 16: Lunar Lander in the OO style.

5. RELATED WORK

The work we present here is related to many other research efforts. In this paper, we discuss two especially close connections: to *model-driven architectures* [7] for program synthesis from abstract models, and to recent work of Garlan et al. [3] on the evolution of programs in terms of architectural style.

5.1 Model-Driven Architecture

The term model-driven architecture (MDA), refers to the architecture of a kind of programming system that support mapping of high-level, platform-independent application descriptions to executable code specialized to run on specific, often distributed and highly constrained, hardware-software platforms. The MDA architecture is rooted in a mapping that takes a *platform-independent model*, p, and a *platform definition model*, s, to a *platform-specific model*, i. That is, $i : PSM = map(p : PIM, s : PDM)$.

The analogy with our approach is clear in this equation. Compare it with our mapping equation: $i : ArchDesc = map(p : AppDesc, s : ArchStyle)$. We can understand both the key similarities and the key differences between our work and MDA by comparing and contrasting these relations.

The key similarity is of course that both approaches map high-level descriptions of applications, by way of choices of some *target domain* (platforms in MDA work, and architectural descriptions in our work) to detailed descriptions *in the given target space*. In particular, both methods take high-level, target-independent application descriptions as inputs: PDM-independent models in the MDA context, and architectural style-independent application descriptions in our work.

The key differences between MDA work and our own are also clear. First, our target domain is one of architectural descriptions, whereas the target domain for MDA work is that of executable program representations (PSMs). PSM's are often Java or C++ programs, for example. Second, MDA mappings are parameterized by descriptions of computing platforms as targets for code generation, placing MDA work broadly in the tradition of *retargetable compilers* for high-level languages. Our maps, by contrast, are parameterized by formal architectural style descriptions. In a sense, abusing terminology, what we propose could be seen an an MDA for generating, from high-level application descriptions, not programs for given platforms but architectural descriptions of programs in given architectural styles.

In this context we identify two areas for future work. First, we plan to explore the hypothesis that research in PIM languages can inform our own work on formal application descriptions. Perhaps we can literally share some kinds of application models.

Second, it seems clear that the MDA's can perhaps be described overall in terms of our diagram in Figure 1, including, in particular, notions of PIM *styles*, analogous to application styles. Furthermore, we might explore the analogy between PSM's and *architectural* style descriptions.

The incongruity in the analogy is that PSM's describe platform *instances* while architectural styles, in a manner of speaking, seem to define *types* of architecture descriptions. Perhaps both MDA and our own work can be helped by completing the picture on both sides. First, we can see an

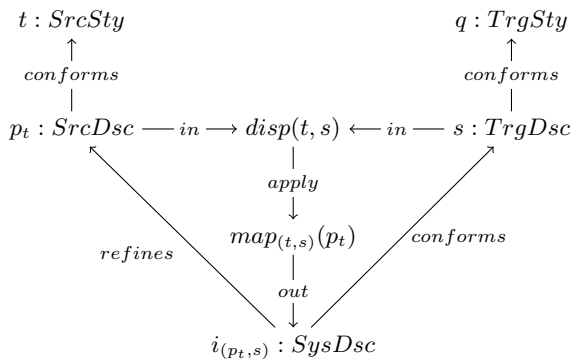


Figure 17: Diagram of common structure.

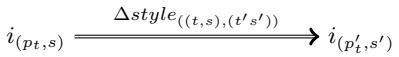
architectural style description, such as OO, an an instance of a broader class, *architectural style,* that explicitly captures, at a meta-level, what we mean by the term *style.* Such a meta-model is in fact present even in this work, as Wong's Alloy architectural style meta-model, which introduces terms such as component and connector. In either case, what we're doing is introducing a higher-level abstraction and a new conformance relation.

Similarly, on the MDA side, we have a clear notion of platform instance, but lack a notion of *platform style,* which we now make explicit. We thus treat each PSM as having some style. The symmetrization of our diagram in Figure 17 is graphically nice; it suggests that we can increase reuse by characterizing the polymorphic nature of our *maps* in terms of high level styles on both sides; and it now clearly exhibits the style-pair-based polymorphism that provides the basis for the modular implementation and incremental development of specialized *map* functions.

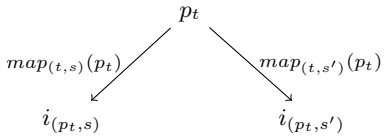
5.2 Incremental Evolution of Architecture Style

The second piece of related work that we discuss is the recent work of Garlan et al. on the evolution of programs with respect to architectural style. The premise of this work is that it is sometimes necessary to change a program written in one architectural style into a related program in another style. Garlan et al. note that such changes are often hard to make because they involve substantial disruption to the existing code base. The approach that they propose is one involving incremental steps between programs, each step being effected by the application of a well defined incremental *architectural operator.*

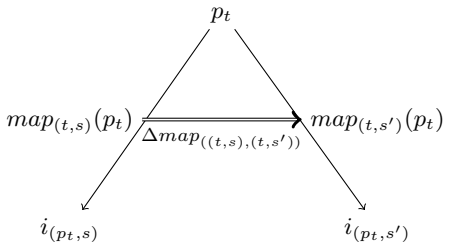
We can use the style notation that we have developed in this paper both to characterize the work of Garlan et al., and also to compare and contrast it with our work. Thus, Garlan et al. start with an architectural description $i_{(p_t,s)}$ and decompose its transformation into a new system, $i_{(p'_t,s')}$. We will refer to $i_{(p_t,s)}$ as the original system and to $i_{(p'_t,s')}$ as the final system. Garlan et al. do not explicitly recognize *application* descriptions or styles (t and t'), but they do of course recognize architectural styles (s and s') as first-class abstractions. In terms of our notation (in which application styles are explicit in t and t') Garlan et al. focus on the nature of, and on a theory to support automated implementation of, transitions of the following kind, where a double arrow indicates an evolutionary transition:



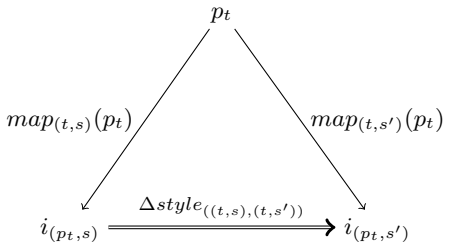
The key ideas that remains implicit in Garlan et al., and which are the central focus of our work, are (1) we are dealing with are one or more architecture-independent application descriptions (p_t and $p'_{t'}$), (2) architectural descriptions ($i_{(p_t,s)}$ and $i_{(p'_t,s')}$) are obtained from such application descriptions by way of architectural maps, and (3) we can and should make the architectural maps explicit: $map_{(t,s)}(p_t)$ and $map_{(t',s')}(p'_t)$. Beyond just evolutionary transitions between pairs of architecture descriptions, involving changes in architectural style, we focus on architectural style as an independent variable in design. The following tree depicts a choice between architectural styles implicit in kinds of evolutionary transitions that Garlan et al. discuss.



Of course a fundamental motivation for our work is an identical concern with the difficulty of selecting and changing decisions about architectural style. We are thus fully "on board" with the notion that one will sometimes wish to change the architectural style of a system. Success in making architectural style an independent variable would, in practice, ease such transitions by allowing for the automated regeneration of a system from a given application description: as a kind of architectural retargeting. Adding a double arrow to our diagram illustrates this idea:



The potential synthesis of our work with work in the style of Garlan et al. is now clear. We need only re-draw the diagram to show Garlan's (incremental) re-architecting operator, applied to one architectural description, as equivalent in effect to changing our architectural map.



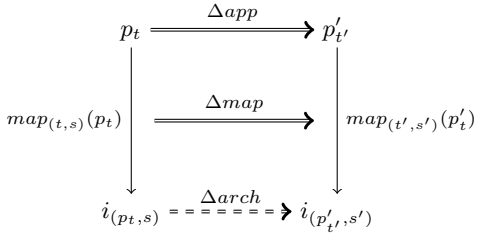
The difference between these diagrams is not trivial. The diagram of our idea suggests that, at least with the application style fixed, one can simply substitute one choice of architectural map for another. This is what it would mean to treat architecture as an independent variable. The Garlan et al. diagram, by contrast, suggests that one must operate on the actual architectural descriptions themselves to

achieve the same effect. Of course the latter is indeed what we do today, and so having a theory to describe it is very helpful, while the previous diagram represents an aspiration for a fundamentally better approach.

As a last note in this section, we observe that the preceding diagram does not capture the exact evolutionary scenario of Garlan et al. They assumed that some change *in the application,* p_t, and perhaps in its description style, t, drove the need for a change in architectural style. What the diagram above depicts is a fundamental change in architectural style independent of any change in either the meaning of the application, p, or in the application style, t, in which that meaning is described.

The notation that we have described makes these separate dimensions of evolution explicit, and thus provides what appears to be a useful and interesting new category-theoretic-like, graphical language for describing a wide variety of software change scenarios, involving changes in important independent dimensions: application style, architectural style, application content, and, indeed, mapping strategies.

Here then is a diagram capturing the scenario of Garlan et al. expressed in our terms and related to our concept. A change in the application, p, and perhaps (we assume) even in the application style, t, is driving the need to re-architect the system, taking it from $i_{(p_t,s)}$ to $i_{(p'_t,s')}$. The change *also* includes a transition from architectural style s to s'. Garlan decomposes the bottom path into intermediate system states. Without depicting this decomposition, we use a dashed double arrow to represent the idea that, with the kind of automation we envision and have demonstrated in a prototype form, the amount of manual work at this level might be substantially reduced or even eliminated.



6. CONCLUSION

In summary, the principal contributions of this work are in four areas. First, we identified the treatment of architecture as an independent variable as a key problem area and goal for software engineering. Second, we presented a conceptual architecture to make this idea precise, including a category-theory-like graphical notation showing how the key concepts relate to each other. Third, we demonstrated the feasibility of automated computation of architectural descriptions with an executable prototype developed in Alloy, exploiting previously peer-reviewed, formal definitions of architectural styles as inputs. Fourth, we presented data that appear to support our hypotheses, and the proposition that these ideas are perhaps worth pursuing further.

We identify three key goals for future work. The first is to further develop what at present are clearly rudimentary application description styles. Extending such descriptions to include richer semantics, and then refining these semantics through mappings down to architectural descriptions appears to be quite important. Second, we are considering exploring the extension of our work to include subsequent mappings from architectural descriptions to code. Ultimately we want not only to map high-level descriptions to code, but for these maps to be invertible, so that we can abstract high-level descriptions from code, prior to remapping back to code with a new architecture. Finally, at an appropriate point, we intend to undertake experimental tests of the viability of these ideas for realistic system design, implementation, and architectural evolution.

7. ACKNOWLEDGMENTS

We thank Professor David Garlan of Carnegie Mellon University for helpful discussion of this work, especially on the relationship between the ideas in this paper and his recent work on how systems evolve from one style to another. This work was supported by a grant from the National Science Foundation.

8. REFERENCES

[1] R. T. Fielding and R. N. Taylor. Principled design of the modern web architecture. In *Proceedings of the 22nd international conference on Software engineering*, pages 407—416, Limerick, Ireland, 2000.

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

[3] D. Garlan, J. M. Barnes, radley Schmerl, and O. Celiku. Evolution styles: Foundations and tool support for software architecture evolution. In *Joint 8th Working International Conference on Software Architecture and 3rd European Conference on Software Architecture*, Cambridge, UK, Sept. 2009.

[4] D. Garlan, G. Kaiser, and D. Notkin. Using tool abstraction to compose systems. *Computer*, 25(6):30—38, June 1992.

[5] D. Jackson. Alloy: a lightweight object modelling notation. *ACM Transactions on Software Engineering and Methodology (TOSEM)*, 11(2):256—290, 2002.

[6] J. S. Kim and D. Garlan. Analyzing architectural styles with alloy. In *In Workshop on the Role of Software Architecture for Testing and Analysis 2006 (ROSATEA 2006)*, Portland, ME, USA, July 2006.

[7] OMG. UniïňĄed modeling language. http://www.omg.org/mda/.

[8] D. L. Parnas. On the criteria to be used in decomposing systems into modules. *Communications of the ACM*, 15:1053—1058, 1972.

[9] D. E. Perry and A. L. Wolf. Foundations for the study of software architecture. *ACM SIGSOFT Software Engineering Notes*, 17(4):40—52, 1992.

[10] M. Shaw and D. Garlan. *Software Architecture: Perspectives on an Emerging Discipline*. Prentice Hall, 1996.

[11] R. N. Taylor, N. Medvidovic, and E. Dashofy. *Software Architecture: Foundations, Theory, and Practice*. Wiley, 2009.

[12] S. Wong, J. Sun, I. Warren, and J. Sun. A scalable approach to multi-style architectural modeling and verification. In *Proceedings of the 13th IEEE International Conference on on Engineering of Complex Computer Systems*, pages 25—34. IEEE Computer Society, 2008.