Secure and Modular Access Control with Aspects

Rodolfo Toledo Éric Tanter*
PLEIAD Laboratory
Computer Science Department (DCC)
University of Chile – Santiago, Chile
http://www.pleiad.cl

ABSTRACT

Can access control be fully modularized as an aspect? Most proposals for aspect-oriented access control are limited to factoring out access control checks, still relying on a non-modular and ad hoc infrastructure for permission checking. Recently, we proposed an approach for modular access control, called ModAC. ModAC successfully modularizes both the use of and the support for access control by means of restriction aspects and scoping strategies. However, ModAC is only informally described and therefore does not provide any formal guarantee with respect to its effectiveness. In addition, like in many other proposals for aspect-oriented access control, the presence of untrusted aspects is not at all considered, thereby jeopardizing the practical applicability of such approaches. This paper demonstrates that it is possible to fully modularize aspect control, even in the presence of untrusted aspects. It does so by describing a self-protecting aspect that secures ModAC. We validate this result by describing a core calculus for AspectScript, an aspect-oriented extension of JavaScript, and using this calculus to prove effectiveness and non-interference properties of ModAC. Beyond being an important validation for AOP itself, fully modularizing access control with aspects allows access control to be added to other aspect languages, without requiring ad hoc support.

Categories and Subject Descriptors

D.3.3 [**Programming Languages**]: Language Constructs and Features; D.3.1 [**Formal Definitions and Theory**]: Semantics

General Terms

Languages, Design

Keywords

Access control, aspect-oriented programming, restriction aspects, scoping strategies.

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1. INTRODUCTION

Access control [24] is a cornerstone of every security architecture: it is the component in charge of ensuring that sensitive resources are accessed only by the entities authorized to do so. In modern runtime environments such as the JVM [16] and the CLR [4], access control architectures rely on a fine-grained specification based on permissions. Permissions represent the ability to access and use a particular resource (*e.g.* a file) in a certain manner (*e.g.* read-only or read-write). Fine-grained access control in these architectures allows one to assign different sets of permissions to different entities. Furthermore, stack inspection [15] is used to dynamically examine if a sensitive operation can be performed or not. This is known as *basic permission checking*.

The Java access control architecture also includes two other mechanisms: *privileged execution* and *first-class permission contexts*. Privileged execution allows a trusted entity to take responsibility for a certain action. This makes it possible for untrusted entities to access sensitive resources—such as the screen—in a controlled manner. First-class permission contexts allow the programmer to capture the set of permissions at a certain point and restore it later on, for instance to incrementally perform a long task—such as classloading—in different threads safely.

While these three mechanisms together provide a very powerful access control system, they also introduce modularity issues. Indeed, using basic permission checking is a crosscutting concern: in order to trigger stack inspection, explicit calls to the access control architecture are necessary. As a consequence, code related to permission checking ends up scattered at each and every place where sensitive resources are accessed, tangled with other concerns. In addition to the crosscutting nature of the *use* of access control, the *implementation* of access control is itself non-modular in the sense that it does not only lie in standard libraries, but depends on native support from the runtime environment. For instance, the Java VM provides specific support for reifying the stack and permission contexts. This native support in the VM is specific to (and can only be used for) access control enforcement. This tends to suggest that access control needs to be supported as a primitive in the language, and that therefore, access control is not something that can be plugged into an existing language without having to modify its semantics.

Considering the fact that security has long been considered a typical aspect, this work addresses the following research question:

Can access control be fully *modularized as an aspect?*

Here, we are concerned not only with modularizing basic permission checking—a somewhat easy and well-explored problem [9, 19, 21, 23, 25, 34, 35]. We want to express the *whole* access control infrastructure as an aspect, including the support for advanced features ignored in the literature, namely privileged execution and capturable permission contexts. Also, we aim at answering the question: *is it possible to leave the programming language semantics completely* oblivious *to the presence of access control?* If so, can we ensure that malicious code, including other aspects, do not interfere with the access control aspect, and how? What are the requirements on the underlying general-purpose aspect language?

Importantly, a positive answer to these questions should also contribute the formulation of a general-purpose aspect model that can be used to add access control to languages that do not include any (or very limited) support for it, like JavaScript. Indeed, in previous work [31], we have explored how it is possible to aspectize stack-based access control with support for privileged execution and capturable permission contexts. The approach, called ModAC (for Modular Access Control) consists of expressing access control using *restriction aspects* scoped with an appropriate *scoping strategy* [26]. Restriction aspects modularize the use of access control whereas scoping strategies replace the need for a native VM mechanism specific to access control, making it possible to modularly provide basic permission checking, privileged execution, and capturable permission contexts.

The ModAC approach was instantiated in AspectScript, an aspect-oriented extension of JavaScript that supports scoping strategies [30]. The resulting implementation (hereafter called ModAC/AS) was used to provide an extensible access control library for JavaScript, called ZAC [33]. However, previous work on ModAC answers part of the above research question. First, the formulation of ModAC is informal; its actual effectiveness in controlling accesses to sensitive resources has not been proven. Second, it leaves open the possibility for untrusted aspects to interfere with access control aspects, thereby ruining its effectiveness.

Contribution. This work extends previous work on ModAC [31] with three contributions:

- We show that it is possible to fully modularize access control as an aspect, even in the presence of untrusted aspects, thanks to a *self-protecting* restriction aspect that impedes untrusted aspects to interfere with critical access control components (Sect. 3).
- We develop λ_{AS}, a core calculus for AspectScript based on λ_{JS} [17] for modeling JavaScript, and a variation of the semantics of LAScheme [28] for aspect weaving (Sect. 4).
- We state and prove the effectiveness and non-interference properties of an instantiation of ModAC in λ_{AS}, ModAC/λ_{AS}. The formulation of these results is detailed in Sect. 5; the proofs are available online [32]. We discuss the extension of the results to ModAC/AS and other aspect languages in Sect. 6.

Section 2 briefly introduces access control, and aspect-oriented approaches to it, in particular ModAC. Section 7 describes related work and Section 8 concludes.

Implementation. This work is implemented in the ZAC library for AspectScript. Also, the executable semantics of λ_{AS} are implemented in PLT Redex [13]. Both artifacts are available online [32].

2. BACKGROUND & MOTIVATION

We briefly introduce stack-based access control, illustrating its main features (Section 2.1). We then describe aspect-oriented approaches to access control, including ModAC (Section 2.2). Section 2.3 classifies various threats to modular access control.

2.1 Access control by example

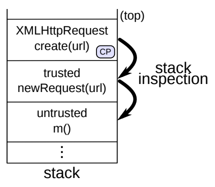
In this section we describe the three access control features based on stack inspection: basic permission checking, privileged execution, and permission contexts. We illustrate each one with real-world examples from the JavaScript realm.

Basic permission checking.

When a sensitive resource is about to be accessed, a call to the access control infrastructure triggers a stack inspection algorithm [15], which *checks* whether all the entities in the current stack of execution (starting from the top of the stack) possess the necessary permission to access the resource. If not, an exception is thrown. Stack inspection is triggered by calling SecurityManager.checkPermission in Java, passing the required permission; in C#, this is done by invoking Demand() on a permission object. In both systems, the entities to which permissions are assigned to are classes. In the following examples, permissions are assigned to individual objects, since JavaScript is prototype based.

This basic behavior prevents the confused deputy problem [18] from happening: an untrusted entity cannot lead a trusted one to access a sensitive resource on its behalf by simply invoking a method, because the stack inspection algorithm will eventually notice the presence of the untrusted entity on the stack. This is exemplified in the following piece of code, in which accessing a sensitive resource—the network—is forbidden:

```
var trusted = {
  newRequest: function(url){
    return new XMLHttpRequest(url);
  } };
var untrusted = {
  m: function(){
    var req = trusted.newRequest("...");
  } };
untrusted.m();
```

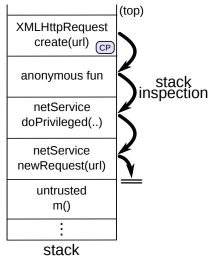


When m is executed, the untrusted object invokes newRequest on trusted to create a new XMLHttpRequest object. Assuming that the stack inspection algorithm is triggered as in Java with a call to checkPermission (signaled by the CP gray square in the figure above), the instantiation is prevented by throwing an exception. This is so because the stack inspection algorithm eventually checks the permissions of untrusted and discovers that it does not hold the necessary permission to access the network.

Privileged execution.

In some scenarios, it is necessary for an entity to access a sensitive resource on behalf of another—possibly untrusted—entity. For this, the JVM supports *privileged execution*. For instance, suppose that we want to provide a netService object that allows any client to access the network, provided that the target site pertains to a list of known sites. In this case, the creation of an XMLHttpRequest object should be allowed even when there are untrusted objects participating in the current call stack.

```
var netService = {
  newRequest: function(url){
    if(shouldAllow(url)){
      return this.doPrivileged(function(){
        return new XMLHttpRequest(url);
      });
    }
    return null;
  } };
var untrusted = {
  m: function(){
    var req = netService.newRequest("...");
  } };
untrusted.m();
```


(top)
XMLHttpRequest create(url)
CP
anonymous fun
netService doPrivileged(..)
netService newRequest(url)
untrusted m()
stack inspection
stack

A self call to doPrivileged initiates a privileged action[1]. Consequently, stack inspection only considers the permissions of objects on the stack corresponding to the dynamic extent of the privileged action, *including* the initiator of the action; *i.e.* the stack inspection algorithm stops at the frame of the initiator of the call to doPrivileged.

Permission contexts.

When accessing a sensitive resource, it can be necessary for an entity to use the permissions present at another point in the execution of the application. The JVM provides built-in means to capture a *permission context* and restore it later on.

For instance, this can be used in JavaScript to capture the permission context at the time a network connection is initiated, and reinstall it when the response from the server is received (asynchronously). This way, the response processing is performed with the same permissions as the call, similarly to a synchronous communication.

2.2 Access control with aspects

Due to its inherently crosscutting nature, access control has been a repeated target for applying aspects. We briefly explain these approaches in the following, and then dive into a recent proposal for fully modularizing access control.

Permission aspects.

The most obvious source of crosscutting due to access control is the necessity of explicitly triggering stack inspection upon access to sensitive resources. Many approaches based on aspects have been proposed in order to factor out these calls into advices [9, 19, 21, 23, 25, 34, 35]. In all these approaches, aspects follow the same pattern: their pointcuts match accesses to sensitive resources, and their advice triggers access control. For example, the following aspect, declared in AspectScript [30], guards the accesses to the network:

```
var netPermission = {
  pointcut: function(jp){ return jp.kind == NEW &&
                                 jp.fun === XMLHttpRequest; },
  advice: function(jp){
    checkPermission(new Permission(NETWORK)); //triggers stack inspection
    return jp.proceed();
  } };
```

This aspect[2] successfully modularizes the triggering of basic permission checking for network accesses. Aspects following this pattern are classified as *permissions aspects* due to their use of the permissions infrastructure and the stack inspection algorithm [31].

Restriction aspects.

While permission aspects modularize calls to check if the necessary permissions are available, they do not fully modularize access control, because they rely on native support from the runtime environment in order to perform stack inspection. Recently, we described an approach for fully modular access control, ModAC [31], based on restriction aspects and scoping strategies.

In contrast to permission aspects, *restriction aspects* do not rely on any permission infrastructure or stack inspection algorithm. Instead, the *scoping mechanism* of the aspect language is used to ensure proper resource protection. A restriction aspect works by adhering to a different, dual pattern: the pointcut selects accesses to a sensitive resource (just like a permission aspect), but the advice immediately aborts the access by not proceeding with the primitive operation; scoping strategies are used to ensure that the aspect only *sees* forbidden accesses. Consider the following restriction aspect:

```
var netRestriction = {
  pointcut : function(jp){ return jp.kind == NEW &&
                                  jp.fun === XMLHttpRequest; },
  advice: function(jp){ throw "Cannot access the net."; }
};
```

This aspect forbids the access to the network. Its pointcut identifies instantiations of XMLHttpRequest objects, and the advice throws an exception with an informative message. Another possibility is not to throw an exception but to silently abort the sensitive resource access. For instance:

```
var alertRestriction = {
  pointcut : function(jp){ return jp.kind == EXEC && jp.fun === alert; },
  advice : function(jp){ /* do nothing */ }
};
```

This restriction aspect simply skips the execution of the alert method, in order to avoid popups.

A scoping strategy for access control.

Restriction aspects are limited to see only illegal resource accesses by means of scope control. However, scope control based on control flow only, as provided by AspectJ, is insufficient to directly support features like privileged execution and permission contexts [31]. For this reason, ModAC relies on a more expressive scoping control mechanism, *scoping strategies* [26, 27, 29].

A scoping strategy permits fine-grained control over the scope of a deployed aspect. A scoping strategy itself is specified by two *propagation functions*: a *call stack* propagation function c specifies how an aspect propagates along with method calls, and a *delayed evaluation* function d specifies whether or not an aspect is "captured" in objects when they are created.[3] Intuitively, the former allows controlling dynamic scoping of aspects, stopping propagation when a certain condition is met. The latter allows an aspect to follow an object: the aspect sees all join points occurring *lexically* within all methods of the object (and may potentially propagate further in method calls done by the object depending on the call stack propagation function). Propagation functions are predicates over join points: the call stack propagation function matches *call* join points for which the aspect should propagate, while the delayed evaluation propagation function matches *object creation* join points.

Scoping strategies in AspectScript are provided as an (optional) first argument to the aspect deployment constructs: deploy(s,asp,fun), which deploys aspect asp on the body of fun; and deployOn(s,asp,obj), which deploys asp on the object obj. In both cases, s is a scoping strategy, and asp can be a single aspect or an array of aspects.

The scoping strategy for access control that supports basic permission checking, privileged execution, and permission contexts is:

```
var acs = [ //access control strategy
  function(jp){ return !(jp.fun === doPrivileged && jp.target === jp.context);},
  function(jp){ return jp.target instanceof ACContext; }
];
```

The call stack propagation function expresses both basic permission checking and privileged execution. Essentially, it specifies that a restriction aspect always propagates on the call stack, except on privileged calls. A privileged call is a *self call* to doPrivileged. This way, a restriction aspect propagating through the stack stops

[1]In Java, a privileged action is started by calling the static method AccessController.doPrivileged.

[2]Aspects are standard objects in AspectScript. They have one pointcut and one advice, defined by the pointcut and advice attributes respectively. Both pointcuts and advices receive a join point as parameter. All advices are around advices.

[3]Scoping strategies also include a third component, called *activation function*. Activation is not used in this work, so we omit it.

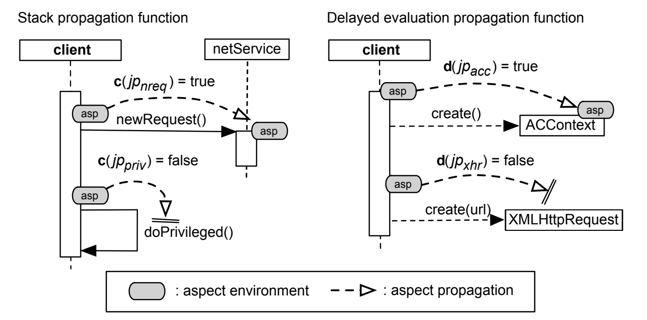


Figure 1: Propagation of aspects with the access control strategy.

its propagation upon a privileged call, and hence does not see resource accesses that occur in the control flow of that call. Considering self calls for privileged execution permits to maintain the aspects of the object initiating the action.

The delayed evaluation propagation function expresses the capture of permission contexts. It ensures that restriction aspects propagate to instances whose prototype is ACContext; therefore, creating such an object is a means to take a snapshot of the restriction aspects present at that point in time. Later on, it is enough to include these objects in the stack to restore the permission context. This is done by an overloaded version of doPrivileged that accepts an ACContext as extra parameter—more details can be found in [31].

Figure 1 depicts the propagation of an aspect asp deployed with the access control strategy. If asp is currently deployed (*i.e.* it is in the current aspect environment), it propagates on calls to newRequest (jp_{nreq}) but not on self-calls to doPrivileged (jp_{priv}). Therefore asp sees join points occurring during the execution of newRequest. Similarly, asp gets captured in new ACContext objects (jp_{acc}), and not in new XMLHttpRequest objects (jp_{xhr}). Hence, asp sees the subsequent activity of these ACContext objects.

ModAC fully modularizes aspect control, by relying only on the aspect language. As a matter of fact, scoping strategies replace the need for an ad-hoc, VM-supported mechanism specific to access control, as is the case of access control in the JVM and the CLR. For sure, the aspect language must support scoping strategies; however, scoping strategies are a general-purpose construct, with a range of applications beyond access control [26, 27, 29].

Bootstrapping access control.

Since access control is fully modularized, it is just one more aspect. In order for it to be effective in a given system, it has to be activated. In a language with dynamic aspect deployment, the only way is to do so explicitly in the program (*e.g.* around the main method, around the loading of a script, etc.). In a language with static deployment, access control must still be equivalently activated (*e.g.* command line or configuration file).

In the case of ModAC/AS, the activation of access control is performed by wrapping the main program in a deployment of the ACDeployer aspect (Figure 2). ACDeployer ensures that the relevant parts of the activity of all objects are under control of restriction aspects. It does so by deploying these restriction aspects on newly-created objects with the access control scoping strategy acs defined previously. Crucially, the deployment of restriction aspects must be done exactly in between the creation of an object and the beginning of its initialization. This way, when the object initiates computation, the necessary restriction aspects are already deployed on it.

The ACDeployer aspect deploys restriction aspects on objects when they are created. First, its pointcut matches all object creations (line

```
1  var ACDeployer = {
2    acs: ..., //access control strategy
3    pointcut: function(jp){ return jp.kind == NEW; }, // creation of objects
4    advice: function(jp){
5      var obj = jp.proceed();
6      var restrictions = getRestrictionsFor(obj);
7      deployOn(acs, restrictions, obj); //per−object deployment
8      return obj;
9    } };
10 deployOn([false,true],ACDeployer, function(){ /∗ main program ∗/ });
```

Figure 2: Deployer aspect for deploying restriction aspects.

3). Then, the advice (lines 4-8) deploys the corresponding restriction aspects on the newly-created object (line 5), using deployOn (line 7) and specifying the access control scoping strategy (line 2). Finally, the object is returned (line 8). The set of restriction aspects that corresponds to a particular object is determined by the getRestrictionsFor method (line 6). This method abstracts the process of determining the needed restrictions. A possible implementation is to mimic the access control architecture of the JVM by returning the restriction aspects that correspond to the permissions declared in a policy file. Another implementation is to return restrictions based on dynamic conditions, such as the kind of user currently interacting with the application, as in role-based access control [14]. Line 10 deploys ACDeployer such that it propagates in all created objects (delayed evaluation is set to true); this ensures that it sees all object creations.

2.3 Threats to modular access control

ModAC seems to be a proof by existence that access control *can* be fully modularized using aspects, provided the aspect language supports a sufficiently expressive scoping mechanism. However, our previous work does not provide any formal guarantee in this respect. Most importantly, it does not consider threats posed by the presence of other, possibly untrusted, aspects.

We consider a simple attack model where the attacker can define an aspect whose purpose is to defeat access control. The attacker cannot alter the specifications of what entities are considered trusted or untrusted. These policies, the aspect weaver, and ModAC components themselves are part of the trusted computing base.

Inhibition.

Following the same attack model, De Borger *et al.* showed how easy it is to interfere with access control by means of aspects [8]. For instance, this AspectJ aspect completely inhibits access control in Java programs:

```
public aspect MaliciousAspect{
  void around(): execution(void SecurityManager+.check∗(..)){ }
}
```

As opposed to the JVM and the CLR, ModAC does not exhibit the previous vulnerability, simply because there are no explicit calls to a stack inspection algorithm. However, there are other alternatives for untrusted aspects to inhibit access control, to which ModAC is vulnerable: *i.e.* to prevent access control components—restriction aspects, the access control strategy, and the ACDeployer aspect—from actually controlling accesses.

We introduce the distinction between implicit and explicit inhibition. *Implicit inhibition* is based on using the aspect weaving mechanism to inhibit access control, such as in the above AspectJ example. *Explicit inhibition* consists of using other means provided by the base language (*e.g.* side effects) to prevent the different components of the access control system to fulfill their role.

Explicit inhibition.

There are many kinds of explicit inhibition, depending on the considered programming language. In a purely functional language, it is impossible to alter a function or mutate existing bindings and data structures. But in a stateful world, risks exist if the state of the access control components can be aliased and mutated. Such risks are exacerbated in languages like JavaScript, where it is possible to dynamically remove object members.

Fortunately, explicit inhibition requires the malicious entity to perform explicit actions, which can be observed and prevented by dedicated restriction aspects. For instance, the following restriction forbids any action on netRestriction (*e.g.* modification of its properties, invocation of its methods):

```
var metaNetRestriction = {
  pointcut: function(jp){ return jp.target === netRestriction; },
  advice: function(jp){ throw "Cannot manipulate the netRestriction aspect"; }
};
```

For any kind of explicit inhibition, a dedicated restriction must be defined. This shows how ModAC elegantly protects itself from explicit inhibition.

Implicit inhibition.

Because explicit inhibition can be prevented by means of restriction aspects, this paper focuses on implicit inhibition. Indeed, implicit inhibition is peculiar because it is directly enabled by the use of an aspect-oriented language; also, implicit inhibition can be achieved in any aspect language, regardless of whether or not the language allows arbitrary effects.

In the case of ModAC, there are three kinds of implicit inhibition: pointcut inhibition, advice inhibition, and scoping strategy inhibition. Pointcut inhibition consists in preventing the pointcut of an access control component from matching at relevant join points. For instance, the following malicious aspect inhibits the pointcut pc of a restriction aspect:

```
var maliciousAspect = {
   pointcut: function(jp){ return jp.kind == PCEXEC && jp.fun === pc; },
   advice : function(jp){ return false; }
};
```

The other kinds of inhibition follow a similar pattern: making a pointcut return false as above, making an advice do nothing by matching its execution but never proceeding, or impeding propagation of restriction aspects by making their propagation functions return always false, etc.

3. R̊: ONE ASPECT TO RULE THEM ALL

In this section we present R̊ (pronounced "ring"), a self-protecting restriction aspect that prevents untrusted aspects from inhibiting access control in ModAC. We first introduce some terminology to discriminate different kinds of aspects (Section 3.1). We then describe and justify our design goals for secure modular access control (Section 3.2), and a general approach to control untrusted aspects (Section 3.3). We finally present R̊ and explain how it prevents inhibition of both access control and itself (Section 3.4).

3.1 Aspect classification

First, we refer to all aspects that are part of ModAC—restriction aspects and the ACDeployer aspect—as *access control aspects*. We then make the distinction between *trusted aspects*, which should be given unrestricted freedom; and *untrusted aspects*, which are potentially trying to inhibit acces control. Classifying aspects as trusted or untrusted depends on the access control policy of a given application. For example, a possible policy consists in considering all aspects defined in local code as trusted, whereas aspects defined in remote code are deemed untrusted. We do not commit to any specific means to express this classification.

In addition, we introduce a set of *protected aspects*. By definition, this set contains all aspects whose inhibition must be prevented. In order to secure ModAC, this set must include all access control aspects (but is not restricted to those aspects).

3.2 Securing ModAC: design goals

Our design goals for secure and modular access control are as follows:

G1 *The base language must be completely oblivious to access control.*

G2 *Untrusted aspects must not inhibit protected aspects, but are otherwise free to advise any join points.*

G3 *Trusted aspects should be able to advise any join point.*

The first goal (G1) is the *raison d'être* of ModAC. Beyond being an important validation for AOP itself, fully modularizing access control with aspects allows access control to be added to other aspect languages, without requiring ad hoc support for it. The other two design goals are concerned with securing ModAC without overly restricting the programming model.

Design goal (G2) states that the non-inhibition property must be achieved without simply ruling out untrusted aspects. Untrusted aspects must be able to do whatever their access policies specify; the only strong requirement is that they do not inhibit protected aspects.

Design goal (G3) states that trusted aspects should be able to see any join point. This goal discards a restrictive approach that prohibits any kind of weaving (trusted or not) in certain core classes—thereby strongly coupling access control and weaving.

For instance, the Aspect-Oriented Permission System (AOPS) [8] ensures non-inhibition by disallowing any kind of weaving at join points lexically located in access control aspects and other sensitive components such as permission classes and the PermissionManager class. Doing so impedes even trusted aspects to advise these classes. In addition, it means that the weaver (and hence the aspect language semantics) is specifically tailored to take access control into account, something that we discard as of design goal (G1). Therefore, AOPS violates two of our design goals, (G1) and (G3).

3.3 Preventive inhibition

In order to reconcile goals (G2) and (G3)—*i.e.* preventing the inhibition of protected aspects by untrusted aspects, while allowing trusted aspects to see any join point—we introduce a simple technique: *preventive inhibition*. Preventive inhibition consists in inhibiting untrusted aspects *before* they get a chance to inhibit protected aspects.

To achieve preventive inhibition, it is sufficient to ensure that untrusted aspects do not apply at join points occurring in the control flow of protected aspects. For restriction aspects, this means that untrusted aspects cannot interfere with the identification of resource accesses nor with the process of aborting these accesses. For the ACDeployer aspect, this means that untrusted aspects cannot interfere with the identification of object creations nor with the calculation and deployment of restriction aspects.

3.4 The R̊ restriction

How can preventive inhibition be achieved while maintaining (G1), *i.e.* without requiring modifications to the aspect language

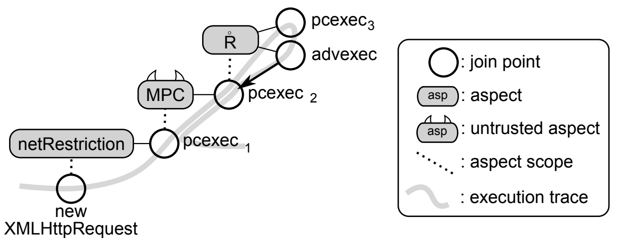


Figure 3: Pointcut inhibition prevented by R̊.

semantics? We describe a simple solution that is essentially just a programming pattern of ModAC. The approach relies on using a specific restriction aspect, called R̊. R̊ is in charge of preventive inhibition for all protected aspects, including itself, thereby fulfilling goals (G2) and (G3). Because R̊ is a restriction like any other, goal (G1) is fulfilled as well: there is no need to change the language semantics to support it.

Inhibition with R̊ .

R̊ is deployed on untrusted objects at creation time, just like other restriction aspects. Its definition is:

```
var R̊  = {
   pointcut: function(jp){
      return jp.kind == PCEXEC &&
            cflow(function(jp){ return protectedAspects.contains(jp.target); });
   },
   advice: function(jp){ return false; }
};
```

R̊ inhibits every pointcut execution it sees, provided that the execution is in the control flow of a join point whose target is in the protected aspects set. In consequence, all aspects in the protected aspects set cannot be inhibited by untrusted aspects, simply because untrusted aspects do not even get a chance to see the join points they would potentially advise. Note that R̊ is the first-class equivalent of the pointcut conjunction discussed in the previous section. Making it a restriction aspect like any other is the key to enforce this inhibition check without affecting the language semantics.

Illustration.

Figure 3 illustrates how R̊ avoids pointcut inhibition by an untrusted aspect MPC on the netRestriction aspect presented before. When a new XMLHttpRequest instance is created, a join point is generated. The netRestriction aspect sees this creation, and therefore, its pointcut is evaluated. This generates a pointcut execution join point (pcexec$_1$), which is observed by MPC. Consequently, the MPC pointcut is evaluated, which generates another pointcut execution join point (pcexec$_2$). Since MPC is untrusted, R̊ was deployed on it. Hence, the pointcut of R̊ sees pcexec$_2$, and matches it (it is a pointcut execution join point and a protected aspect, netRestriction, is in the control flow). In consequence, R̊ inhibits the pointcut of MPC. Advice and scoping strategies inhibitions are prevented in a similar way.

Self-protection.

Crucially, R̊ can protect *itself* from inhibition by untrusted aspects, following the exact same principle. To do so, R̊ is added to the set of protected aspects. Self-protection of R̊ can be observed in the same Figure 3, by replacing the reference to netRestriction on the figure with R̊. An untrusted aspect can try to inhibit R̊ as many times as it wants in the same flow of execution. If the interaction is infinite, the program does not terminate[4]. If the interaction is finite, R̊ eventually rules the untrusted aspect. Self-protection of R̊ elegantly secures ModAC by not introducing any additional mechanism; R̊ is just a restriction aspect protecting access control aspects, including itself, and other protected aspects, from inhibition by untrusted aspects.

Bootstrapping.

R̊ uses the protectedAspects set to identify the aspects it must protect from implicit inhibition. Naturally, untrusted entities must not be allowed to interfere with this data structure. Inhibiting access control by interfering with the protectedAspects set can either be done implicitly via weaving, or through explicit manipulation. Implicit inhibition is already prevented by R̊ itself (because the protectedAspects is manipulated only by entities pertaining to the set itself, like R̊). Explicit inhibition is avoided by using a dedicated restriction aspect:

```
var paRestriction = {
  pointcut: function(jp){ //any action on protectedAspects
               return jp.target === protectedAspects; },
  advice: function(jp){ throw "Cannot manipulate the protected aspects set"; }
};
```

This restriction follows the same pattern as the metaNetRestriction presented before; it forbids *any* action over protectedAspects. This restriction must be deployed on all untrusted entities at creation time. Note that this restriction is just another restriction, and therefore (G1) is still fulfilled.

4. A CALCULUS FOR ASPECTSCRIPT

The previous section has informally explained how ModAC can be made secure thanks to the R̊ restriction aspect. ZAC, a JavaScript library based on ModAC [33], has been extended to include R̊. However, ModAC itself has never been proven to be effective, even in the absence of untrusted aspects; and it remains to be proven that R̊ is effectively securing ModAC.

In order to do so, we focus on AspectScript and establish a formal basis for it: the λ_{AS} calculus. Section 5 then states formally that ModAC/λ_{AS}, the implementation of ModAC in the λ_{AS} calculus, is correct and secure. Proofs and executable semantics are provided online [32]. Note that Section 5 is also accessible to readers who prefer not to dive into the formal semantics, as it includes a precise description of the argumentation line.

λ_{AS} is a core calculus for AspectScript, and as such has to be faithful to JavaScript. We use the λ_{JS} calculus [17] as a starting point. The aspect-oriented part of AspectScript is based on the calculus of LAScheme [28], which models first-class aspects with dynamic deployment and execution levels in a higher-order procedural language. ModAC however also requires (a form of) scoping strategies, which are not part of the existing LAScheme formalization. As a result, even though we simplify the treatment of execution levels in the calculus, λ_{AS} is more complex. But this complexity is directly drawn from the required characteristics of the language (JavaScript-based, first-class aspects with dynamic deployment, execution levels, and scoping strategies).

We now first give a brief overview of λ_{JS}, and then describe its extension to support aspect weaving with dynamic aspect deployment and scoping strategies.

[4]Any untrusted piece of code is (a priori) given the power of the base language (which is Turing-complete) and can therefore always provoke non-termination. Different mechanisms (including restriction aspects!) can be used to avoid this misbehavior (*e.g.* timeout, limit on the number of produced join points), but this is out of the scope of this work [33].

$$
\begin{array}{rcrl}
\mathit{Value} & v & ::= & c \mid \textbf{fun}(x\cdots)\{e\} \mid o \mid l \\
\mathit{Bool} & b & ::= & \textbf{true} \mid \textbf{false} \\
\mathit{Const} & c & ::= & n \mid str \mid b \mid \textbf{undefined} \mid \textbf{null} \\
\mathit{Object} & o & ::= & \{str : v\cdots\} \\
\mathit{Expr} & e & ::= & x \mid v \mid \textbf{let}\,(x = e)\; e \mid e(e\cdots) \mid e[e] \mid \\
 & & & e[e] = e \mid e = e \mid \textbf{ref}\, e \mid \textbf{deref}\, e \\
\mathit{Store} & \mu & ::= & \epsilon \mid \mu + (l \mapsto o)
\end{array}
$$

$n \in \mathscr{N}$, the set of numbers; $str \in \mathscr{S}$, the set of strings; $x \in \mathscr{X}$, the set of variable names; $l \in \mathscr{L}$, the set of locations.

Figure 4: Syntax of the λ_{JS} language (excerpt; slightly modified).

4.1 Core JavaScript: λ_{JS}

Guha *et al.* designed λ_{JS} as a core subset of JavaScript to which JavaScript programs are desugared. The interest of λ_{JS} is its compactness. We briefly describe the syntax of λ_{JS}, the desugaring process, and a few reduction rules.

Syntax.

Figure 4 shows part of the syntax of λ_{JS}. The language has primitive values such as numbers, strings, booleans, and two special values **null** and **undefined**, in addition to functions (**fun**) and objects o. Objects are a series of attribute-value pairs enclosed in curly braces. Expressions include identifiers, values, a **let** construct, function application, property access, and property write. In order to support first-class mutable references, values are augmented with store locations. Objects in the store are explicitly referenced and dereferenced using **ref** and **deref**, respectively. λ_{JS} also includes typical control operators and primitive n-ary operators; we omit these for brevity.

Desugaring.

Several JavaScript constructs are specified via translation (called "desugaring") to λ_{JS} [17]. For example, the desugaring of function creation is:

desugar⟦ function(x· · ·){e} ⟧ = **ref** {
    "code": **fun**(this, fthis, x· · ·) { desugar⟦ e ⟧ },
    "prototype": **ref** {"__proto__": (**deref** Object)["prototype"]}}

A function is desugared into an object (using the {...} notation) with two attributes: code and prototype. The code attribute is the actual function (note that function is a JavaScript term, and **fun** is a λ_{JS} term). Also, this is an ordinary identifier: it is the first formal parameter of a desugared function. In JavaScript, a method is a function, which is a value, and can be shared between objects; this refers to the currently-executing object. For the sake of properly dealing with aspect environments in λ_{AS}, we slightly extend λ_{JS} and pass a second parameter to every desugared function; the parameter, named fthis, is bound to the function object thus created by the desugaring process. Note that desugaring reveals some of JavaScript peculiarities: the prototype attribute of a function object is an object whose prototype is the prototype attribute of Object.

The semantics of λ_{JS} is defined as a small-step reduction relation $\hookrightarrow$. A program configuration $\langle \mu, e\rangle$ consists of a store and an expression. The reduction relation is standard. Evaluation contexts [36] are used to specify a call-by-value, left-to-right evaluation semantics. E.g., the reduction rule for object creation is:

$$\langle \mu, E[\textbf{ref}\,\{str : v\cdots\}]\rangle \hookrightarrow \langle \mu', E[l]\rangle \qquad \textsc{New}$$
$$\text{where } l \notin dom(\mu) \text{ and } \mu' = \mu + (l \mapsto \{str : v\cdots\})$$

ref simply allocates a new location in the store and returns it.

$$
\begin{array}{rcl}
J & ::= & \epsilon \mid j + J \\
j & ::= & \lceil k, l_o, l_f, p \rceil \\
k & ::= & \texttt{new} \mid \texttt{call} \mid \texttt{exec} \mid \texttt{pc-exec} \mid \texttt{adv-exec}
\end{array}
$$

$p \in \mathscr{T}$, the set of thunks$J \in \mathscr{J}$, the set of join point stacks

$$
\begin{array}{rcrl}
\mathit{Expr} & e & ::= & \ldots \mid \texttt{jp}\,(j, \alpha) \mid \texttt{in-jp}\,(e) \mid \\
 & & & \texttt{c/asp}\, k\, e\, e \cdots \\
\mathit{EvalCtx} & E & ::= & \ldots \mid \texttt{in-jp}\,(E) \mid \\
 & & & \texttt{c/asp}\, k\, v \cdots\; E\, e \cdots \\
 & v & ::= & \ldots \mid \boxed{J}
\end{array}
$$

Figure 5: Join points

k	new	call / exec / pc-exec / adv-exec
l_o	object prototype	target object
l_f	**null**	target function
p	primitive operation	

Figure 6: Join point abstraction attributes per kind.

The function application rule is the standard β_v reduction:

$$\langle \mu, E[\textbf{fun}(x\cdots)\{e\}(v\cdots)]\rangle \hookrightarrow \langle \mu, E[e[v\cdots/x\cdots]]\rangle \quad \textsc{Call}$$

4.2 AspectScript Semantics

We now describe the syntax and operational semantics of λ_{AS}, a core calculus for AspectScript based on λ_{JS}. Its operational semantics is defined via the reduction relation $\hookrightarrow$: $\mathscr{M} \times \mathscr{A} \times \mathscr{J} \times \mathscr{E} \rightarrow \mathscr{M} \times \mathscr{A} \times \mathscr{J} \times \mathscr{E}$.

We extend the λ_{JS} configuration with two additional elements: a λ_{AS} program configuration $\langle \mu, \alpha, J, e\rangle$ consists of a store $\mu \in \mathscr{M}$, an aspect environment $\alpha \in \mathscr{A}$, a join point stack $J \in \mathscr{J}$, and an expression $e \in \mathscr{E}$. The *stack aspect environment* α is used to maintain the aspects propagated through the stack by means of the call stack propagation function.[5]

In the following we describe the semantics of join points, aspects and their deployment, as well as the weaving semantics. The formalism is based on the semantics of LAScheme [28], an aspect-oriented Scheme-like language with execution levels, itself based on a combination of Clifton and Leavens's work [6] (modeling of the join point stack) and Dutchyn *et al.* [10] (weaving semantics). By convention, when we introduce new user-visible syntax (*e.g.* the aspect deployment expression), we use **bold** font. Internal terms are written in `typewriter` font.

4.2.1 Join Points

The join point stack J is a list of *join point abstractions* j, which are tuples $\lceil k, l_o, l_f, p\rceil$ (Figure 5). We introduce five kinds of join points: `new` for object creation, `call` for function application and method invocation, and `exec`, `pc-exec`, `adv-exec` for function, pointcut, and advice execution, respectively. Figure 6 describes the different values for the components of join point abstractions, depending on their kind. For instance, p is always the primitive operation (used to perform the original computation); l_o denotes the prototype of the object being created in a `new` join point, and the target object for `call` and the three execution join points.

In order to keep track of the join point stack in the semantics we introduce two internal expression forms. `jp` (j, α) introduces

[5]We also maintain the currently-executing object/function in the program configuration, omitted here for simplicity. The online Redex model includes the full configuration.

$$\begin{array}{rclll} \textit{Expr} & e & ::= & \ldots \mid \textbf{deployOn}[e,e](e,e) \\ \textit{EvalCtx} & E & ::= & \ldots \mid \textbf{deployOn}[E,e](e,e) \mid \\ &&& \textbf{deployOn}[b,E](e,e) \mid \\ &&& \textbf{deployOn}[b,b](E,e) \mid \\ &&& \textbf{deployOn}[b,b](v,E) \end{array}$$

$$\begin{array}{rclll} \textit{AspectEnv} & \alpha & ::= & \alpha + (b_c, b_d, l) \mid \epsilon \\ \textit{Store} & \mu & ::= & \epsilon \mid \mu + (l \mapsto o^{\alpha}) \\ & \texttt{asps}(l) & = & \alpha, \text{ where } \mu(l) = o^{\alpha} \end{array}$$

$$\langle \mu, \alpha, J, E[\textbf{deployOn}[b_c, b_d](l_{asp}, l_{obj})]\rangle \qquad \textsc{DeployOn}$$
$$\hookrightarrow \langle \mu', \alpha, J, E[l_{obj}]\rangle$$
$$\text{where} \quad \mu(l_{obj}) = o^{\alpha'} \text{ and } \mu' = \mu(l_{obj} \mapsto o^{\alpha' + (b_c, b_d, l_{asp})})$$

Figure 7: Aspects and deployment.

a join point j whose underlying computation via proceed will be executed with aspect environment α. `in-jp` (e) keeps track of the fact that execution of e is proceeding under a dynamic join point. We extend the definition of evaluation contexts accordingly (Figure 5). The expression `c/asp` (which stands for "call/aspect") is used later to treat pointcut and advice execution join points similarly. It is a function application annotated with the kind of join point k that needs to be created; this expression form is generated by the weaver, discussed later on.

A join point abstraction captures the minimum context information necessary for ModAC to work (target object and function), as well as to trigger its corresponding computation when necessary (the p function). We write $\boxed{J}$ to denote the reification of the join point stack J as a λ_{AS} value. A number of introspection primitives are provided; for instance, **kind** ($\boxed{J}$) is the λ_{AS} equivalent of jp.kind in AspectScript. Similarly, **tobj** (resp. **tfun**) can be used to retrieve the (location of the) target object (resp. function).

4.2.2 *Aspects and Deployment*

For the sake of conciseness and simplicity, we make the three following simplifications to λ_{JS} in this paper: *i)* scoping strategies have constant boolean components (instead of join point predicates); *ii)* only per-object deployment (**deployOn**) is described; *iii)* we do not account for context exposure (*i.e.* pointcuts simply return **true** if they match, instead of an environment). These simplifications do not affect the validity of our results: constant propagation functions are enough to state and prove the desired properties of ModAC, **deployOn** is strictly more expressive than **deploy** [29], and context exposure is an orthogonal feature for this work.

As described on Figure 7, an aspect environment α is a list of tuples (b_c, b_d, l) where l denotes the reference to the aspect, and the two boolean values corresponds to the `c` and `d` components of the scoping strategy specified at deployment time. An aspect can be any object whose pointcut attribute is a function that takes a join point stack as input and produces either **true** or **false**. To compensate for the absence of context exposure from pointcuts, an advice function also receives as first argument the current join point stack. An advice proceeds using the **proceed** ($\boxed{J}$) primitive.

An aspect is deployed with **deployOn**. Because **deployOn** embeds an aspect within an object, the stack aspect environment of the program configuration is not enough; each object needs to have its own aspect environment as well. To do so, we annotate an object

$$\langle \mu, \alpha, J, E[\textbf{ref}\ \{str : v \cdots\}]\rangle \qquad \textsc{New}$$
$$\hookrightarrow \langle \mu, \alpha, J, E[\texttt{jp}(\lceil \texttt{new}, \textit{proto}, \textbf{null}, p\rceil, \alpha)]\rangle$$
where
$$\textit{proto} = v_i \text{ if } str_i = \texttt{"\_\_proto\_\_"}$$
$$\alpha' = (\texttt{asps}(\texttt{cobj}()) \oplus \texttt{asps}(\texttt{cfun}()) \oplus \alpha)|_d$$
$$p = \textbf{fun}()\{\ \texttt{new/prim}\ \{str : v \cdots\}^{\alpha'}\ \}$$

$$\langle \mu, \alpha, J, E[\textbf{fun}(x \cdots)\{e\}(l_0\ l_1\ v \cdots)]\rangle \qquad \textsc{Call}$$
$$\hookrightarrow \langle \mu, \alpha, J, E[\texttt{jp}(\lceil \texttt{call}, l_0, l_1, p_c\rceil, \alpha')]\rangle$$
where
$$\alpha' = (\texttt{asps}(\texttt{cobj}()) \oplus \texttt{asps}(\texttt{cfun}()) \oplus \alpha)|_c$$
$$p_e = \textbf{fun}()\{\ \texttt{app/prim}\ \textbf{fun}(x \cdots)\{e\}\ l_0\ l_1\ v \cdots\ \}$$
$$p_c = \textbf{fun}()\{\ \texttt{app/prim}\ \textbf{fun}()\{\texttt{jp}(\lceil \texttt{exec}, l_0, l_1, p_e\rceil, \alpha')\}\}$$

$$\langle \mu, \alpha, J, E[\texttt{c/asp}\ k\ \textbf{fun}(x \cdots)\{e\}\ l_0\ l_1\ v \cdots]\rangle \qquad \textsc{C/Asp}$$
$$\hookrightarrow \langle \mu, \alpha, J, E[\texttt{jp}(\lceil k, l_0, l_1, p\rceil, \alpha)]\rangle$$
$$\text{where} \quad p = \textbf{fun}()\{\ \texttt{app/prim}\ \textbf{fun}(x \cdots)\{e\}\ l_0\ l_1\ v \cdots\ \}$$

Figure 8: Join point creation.

o with its aspect environment α as o^{α}. By construction, an object is annotated with its aspect environment as soon as it is allocated in the store (with **ref**). We therefore extend the definition of the store, and introduce an internal function `asps` in order to access the aspects of an object in the store.

The DeployOn rule shows the semantics of per-object deployment: the aspect (at location) l_{asp} is added at the end of the aspect environment of the object (at location) l_{obj}, along with the specified scoping strategy components.

4.2.3 *Join Point Creation & Disposal*

We change the New rule of λ_{JS} to account for the creation of `new` join points (Figure 8). The join point abstraction components are filled according to Figure 6. The primitive operation p is a thunk that returns a fresh reference to the newly-created object. Actual object creation is done using `new/prim`, an internal expression that performs creation without generating any join point. Note that the object value passed to `new/prim` is annotated with its initial aspect environment, α'. This environment is calculated as the order-preserving union ($\oplus$) of three aspect environments: the ones deployed on the currently-executing object and function (obtained with `cobj` () and `cfun` (), respectively); and the stack aspect environment. Only aspects that propagate in newly-created objects are included in α'. The notation $\alpha|_d$ refers to the aspects in α whose `d` component is true.

To account for the creation of `call` and `exec` join points, we change the λ_{JS} evaluation rule for function application/method invocation as well. The new Call rule generates a `call` join point whose components are filled according to Figure 6. The primitive operation p_c is a thunk that generates an `exec` join point when applied. The primitive operation of this `exec` join point, p_e, performs the actual function execution by means of `app/prim`, another internal expression that does not generate join points. Note that the `jp` expressions associated to both join points specify that the stack aspect environment must change to α' when p_c or p_e are applied in order to reflect the propagation of aspects through the stack. This aspect environment is determined by taking the order-preserving union of three aspects environments: the ones deployed on the currently-executing object and function; and the stack aspect environment; and filtering the resulting environment along the `c`

$$\langle \mu, \alpha, j + J, E[\texttt{in-jp}\ (v)] \rangle \hookrightarrow \langle \mu, \alpha, J, E[v] \rangle \qquad \textsc{OutJp}$$
$$\langle \mu, \alpha, j + J, E[\texttt{in-jp}\ (\textbf{err}\ v)] \rangle \hookrightarrow \langle \mu, \alpha, J, E[\textbf{err}\ v] \rangle \quad \textsc{OutJp-Err}$$

Figure 9: Join point disposal.

$$\begin{array}{ll}
\langle \mu, \alpha, J, E[\texttt{jp}(\lceil k, l_o, l_f, p \rceil, \alpha_p] \rangle & \textsc{Weave} \\
\hookrightarrow \langle \mu, \alpha, J', E[\texttt{in-jp}(\texttt{swap}(\texttt{app/prim}\, W[\![\alpha']\!]_{\alpha_p, J'}, \epsilon))] \rangle & \\
\text{where} & \\
\quad J' = \lceil k, l_o, l_f, p \rceil + J & \\
\quad \alpha_s = \epsilon \text{ if } k \in \{\texttt{pc-exec}, \texttt{adv-exec}\}, \alpha \text{ otherwise} & \\
\quad \alpha' = \texttt{asps}(\texttt{cobj}()) \oplus \texttt{asps}(\texttt{cfun}()) \oplus \alpha_s &
\end{array}$$

$$W[\![\epsilon]\!]_{\alpha, \lceil k, l_o, l_f, p \rceil + J} = \textbf{fun}()\{\texttt{swap}(\texttt{app/prim}\, p, \alpha)\}$$

```
$W[\![\alpha_w + (b_c, b_d, l_{asp})]\!]_{\alpha, \lceil k, l_o, l_f, p \rceil + J} =$
  app/prim
   $\textbf{fun}(next)\{$
     $\textbf{let}(pc = (\textbf{deref}\, l_{asp})[\text{"}pc\text{"}])$
     $\textbf{if}(\texttt{c/asp pc-exec}\ (\textbf{deref}\, pc)[\text{"}code\text{"}]\ l_{asp}\ pc\ \boxed{j_p + J})\{$
      $\textbf{let}(adv = (\textbf{deref}\, l_{asp})[\text{"}adv\text{"}])$
      $\textbf{fun}()\{$
        $\texttt{c/asp adv-exec}\ (\textbf{deref}\, adv)[\text{"}code\text{"}]\ l_{asp}\ adv\ \boxed{j_a + J}\ \}$
     $\}\textbf{else}\{\ next\ \}$
  $\}$
  $W[\![\alpha_w]\!]_{\alpha, \lceil k, l_o, l_f, p \rceil + J, p}$
```

$$\begin{array}{ll}
\text{where} & j_a = \lceil k, l_o, l_f, \textbf{fun}()\{\texttt{app/prim}\, next\} \rceil \\
& j_p = \lceil k, l_o, l_f, \textbf{fun}()\{\textbf{err}\ \text{"pc cannot proceed"}\} \rceil
\end{array}$$

Figure 10: Aspect weaving.

component (written $\alpha|_c$), which determines the aspects that should propagate on the call stack.

Rule C/ASP accounts for the creation of `pc-exec` and `adv-exec` join points. This rule matches a function application/method invocation, but receives a first argument (k) that specifies which join point must be generated. Because invocations of pointcuts and advices are implicit, C/ASP does not generate `call` join points. Join point attributes are filled according to Figure 6; the primitive operation p performs the pointcut/advice execution by means of `app/prim`, just like in the case of `exec` join points.

Once the computation underlying a join point is reduced to a value, the OUTJP rule gets rid of the join point and the `in-jp` expression (Figure 9). OUTJP-ERR does the same in the case of an error.

4.2.4 *Weaving*

We now turn to the semantics of aspect weaving, specified by the WEAVE rule (Figure 10). A `jp` expression reduces to an `in-jp` expression (to signal the fact that the upcoming computation is associated to a join point), and the join point is pushed onto the stack (we discuss the use of `swap` and α_s later below). The list of aspects in scope α' is calculated as the order-preserving union of the aspect environments of the object and function in context, and the aspects propagated through the stack.

The weaving process is based on evaluating the function returned by the W metafunction. W recurs on α' and returns a composed procedure whose structure reflects the way advice is going to be dispatched. The base case, $W[\![\epsilon]\!]$, corresponds to the execution of the primitive operation. Otherwise, for each aspect (b_c, b_d, l_{asp}) in the environment, W first applies its pointcut to the current join point stack (which generates a `pc-exec` join point using the `c/asp` construct). If the pointcut matches, then W returns a function that applies the advice of l_{adv} (and generates an `adv-exec` join point). All this process is parameterized by the function to proceed with, $next$. In order to allow an advice to call **proceed** to trigger either the base computation or the next advice in the chain, rule WEAVE creates an auxiliary join point j_a whose p component is a thunk that applies $next$. To be complete, an auxiliary join point j_p is also created and passed to the pointcut; its p component triggers an error if **proceed** is called. Finally, If an aspect does not apply, then W simply returns $next$.

$$\begin{array}{llll}
\mathit{Expr} & e & ::= & \ldots \mid \texttt{app/prim}\, e\, e \cdots \mid \texttt{new/prim}\, e \\
\mathit{EvalCtx} & E & ::= & \ldots \mid \texttt{app/prim}\, v \cdots\ E\, e \cdots \\
& & & \mid \texttt{new/prim}\, E
\end{array}$$

$$\begin{array}{ll}
\langle \mu, \alpha, J, E[\texttt{app/prim}\, \textbf{fun}(x \cdots)\{e\}\ v \cdots] \rangle & \textsc{AppPrim} \\
\hookrightarrow \langle \mu, \alpha, J, E[e[v \cdots / x \cdots]] \rangle & \\
\langle \mu, \alpha', J, E[\texttt{new/prim}\, o^\alpha] \rangle \hookrightarrow \langle \mu', \alpha', J, E[l] \rangle & \textsc{NewPrim} \\
\text{where} \quad l \notin \mathit{dom}(\mu) \text{ and } \mu' = \mu + (l \mapsto o^\alpha) &
\end{array}$$

Figure 11: Primitive function application and object allocation.

Primitive forms.

The semantics of λ_{AS} use internal primitive forms `app/prim` and `new/prim`, described in Figure 11. `app/prim` is an application that does not trigger a join point: rule APPPRIM simply performs the classical β_v reduction. `app/prim` is used to perform the actual application of a function, as well as to hide "administrative" application, *i.e.* the initial application of the composed aspect chain, and its recursive applications. Similarly, `new/prim` allocates an object in the store and reduces to the corresponding location without producing a join point.[6]

Execution levels.

The weaving semantics explained previously is insufficient, because any aspect language must take precautions with infinite regression. Indeed, if we omitted the use of `swap` and α_s in Figure 10, a λ_{AS} program would never terminate. Tanter addressed this issue with execution levels [28], which ensure that pointcut and advice computation by default always happen at a higher level than base computation, avoiding infinite loops such as those due to pointcuts matching against themselves. Recall that in λ_{AS}, pointcuts and advices are standard functions. With execution levels, pointcuts and advices are always evaluated at the level above the expression that generates a join point. When the last advice in the chain proceeds, execution shifts back to the original level in order to run the base computation.[7]

[6]These primitive forms are necessary for the semantics to allow actual computation to happen. The fact that they are *internal* means that it is not necessary to protect them from untrusted aspects: they cannot be used by any user code, and cannot be advised since they do not produce join points. Recall that in a higher-order aspect language, the use of execution levels is key to supporting these primitive forms as internal only [28].

[7]Full-fledged execution levels include the possibility to explicitly shift execution up and down if needed, as well as to define level-capturing functions [28]. We do not include these advanced facilities in this work.

$$\begin{array}{rrcl} \textit{Expr} & e & ::= & \ldots \mid \texttt{swap}(e,\alpha) \mid \texttt{in-swap}(e,\alpha) \\ \textit{EvalCtx} & E & ::= & \ldots \mid \texttt{in-swap}(E,\alpha) \end{array}$$

$$\begin{array}{lr} \langle \mu, \alpha, J, E[\texttt{swap}(e,\alpha')] \rangle & \textsc{In-Swap} \\ \hookrightarrow \langle \mu, \alpha', J, E[\texttt{in-swap}(e,\alpha)] \rangle & \\ \langle \mu, \alpha', J, E[\texttt{in-swap}(v,\alpha)] \rangle & \textsc{Out-Swap} \\ \hookrightarrow \langle \mu, \alpha, J, E[v] \rangle & \\ \langle \mu, \alpha', J, E[\texttt{in-swap}((\mathbf{err}\ v),\alpha)] \rangle & \textsc{Out-Swap-Err} \\ \hookrightarrow \langle \mu, \alpha, J, E[\mathbf{err}\ v] \rangle & \end{array}$$

Figure 12: Swapping aspect environments.

We introduce a simple modeling of execution levels, that does not require having to explicitly track the current execution level in the program configuration. Instead, we use the call stack with internal expressions so as to *swap* aspect environments and restore them when appropriate (Figure 12). Swapping per se is a very simple process: given an expression e and an aspect environment α', `swap` installs the aspect environment, and evaluates the expression (In-Swap). `in-swap` is used to restore the swapped aspect environment α when the expression is fully reduced (Out-Swap). Additionally, α_s is used to remove aspects in the stack aspect environment from scope when weaving `pc-exec` and `adv-exec` join points. This prevents the aspects deployed on the currently executing object/function from seeing their own activity. Note that this approach does support multiple levels of execution.

Weaving (Figure 10) uses `swap` exactly where the original levels semantics [28] uses **up** and **down** shifting. The whole weaving process is wrapped by a `swap`, so that the current aspect environment is swapped with an empty environment ϵ that represents the upper level environment . This environment is used to evaluate pointcuts and advices. Of course, the fact that the stack aspect environment starts empty does not prevent aspects that have been deployed in objects and functions from taking effect. If the last advice proceeds (the base case of W), aspect environments are swapped again, in order to restore the original environment to evaluate the base computation. The environment in which weaving is carried out is restored once the base computation has completed. Finally, when the whole weaving is complete, the original aspect environment is restored.

5. PROPERTIES OF MODULAR ACCESS CONTROL

In this section we state two theorems corresponding to the following properties of ModAC:

Basic effectiveness. ModAC is effective in absence of untrusted aspects. This means that restriction aspects are actually deployed on untrusted objects, see illegal resource accesses, and effectively prevent them.

Non-inhibition. ModAC with R̊ is effective even in presence of untrusted aspects. This means that R̊ effectively prevents untrusted aspects from inhibiting protected aspects.

More precisely, we show the results for ModAC/λ_{AS}. The extension of these results to ModAC/AS (and other aspect languages) in Section 6. This section sketches the formal argument by describing the main intermediate steps. Each step includes an informal explanation, and a formal statement. The actual proofs, which rely on the operational semantics above, are provided online [32].

First, we describe the properties that define basic effectiveness.

Definition 1 (Basic effectiveness). *An implementation of ModAC is said to comply with basic effectiveness if the following properties are fulfilled:*

- Restrictions deployment. *Restrictions are deployed on all the corresponding objects before these objects can be used.*
- Restrictions scope. *A restriction aspect sees all the computation produced by the objects it is deployed on.*
- Restrictions effectiveness. *A restriction aspect always prevents the resource accesses it identifies.*

Theorem 1 (ModAC/λ_{AS} basic effectiveness). *ModAC/λ_{AS} complies with basic effectiveness.*

This theorem is a direct consequence of Lemmas 1, 2, and 3, exposed below, which address each property of basic effectiveness separately.

Lemma 1 states that any aspect (referenced by l_{depl}), in particular ACDeployer, deployed with scoping strategy (**false**,**true**) propagates to every new object in the store, and does so *in the first position* in the aspect environment of these objects. This ensures that l_{depl} sees all object creations in the application and gets a reference to these objects before any other entity. The only prerequisite is that l_{depl} is already deployed in the first position on all objects at a given point. This can be straightforwardly achieved in the bootstrapping process by exhaustively deploying ACDeployer on every object.[8]

Lemma 1 (Restrictions deployment). *Let C = $\langle \mu, \cdot, \cdot, \cdot \rangle$ be a program configuration where $\forall\ (l \mapsto o^{\alpha}) \in \mu$, $\alpha = (\textbf{false}, \textbf{true}, l_{depl}) + \alpha'$, for some α', and $l_{depl} \in dom(\mu)$. If $C \hookrightarrow \langle \mu', \cdot, \cdot, \cdot \rangle$, then $\forall\ (l \mapsto o^{\alpha}) \in \mu'$, $\alpha = (\textbf{false}, \textbf{true}, l_{depl}) + \alpha''$, for some α''.*

Lemma 2 states that all aspects in the stack aspect environment deployed with **c = true**, propagate through the stack if the same level of execution is considered; *i.e.* the stack inspection algorithm is correctly implemented by means of scoping strategies.

Lemma 2 (Restrictions scope). *Let C = $\langle \cdot, \alpha, \cdot, \cdot \rangle$ be a program configuration and $\alpha_s = \alpha|_c$. If $C \hookrightarrow^* \langle \cdot, \alpha', \cdot, \cdot \rangle$, and the sequence of reductions starts and ends at the same execution level, then $\alpha_s \subseteq \alpha'$.*

Lemma 3 states that if a restriction aspect R matches a join point j and does not proceed, then the primitive operation associated to j is not evaluated. Consequently a restriction aspect fulfills its role no matter in which position it is woven at the illegal resource access join point.

Lemma 3 (Restrictions effectiveness). *Let C = $\langle \mu, \cdot, J, E[e] \rangle$ be a program configuration where $J = \lceil \cdot, \cdot, \cdot, p \rceil + J'$, for some J', $e = \texttt{app/prim}\ W[\![\alpha]\!]_{\cdot,J}$, $(\cdot, \cdot, l_R) \in \alpha$, and l_R is a valid aspect reference in μ to a restriction aspect that matches J and does not proceed for J. If $C \hookrightarrow^* \langle \cdot, \cdot, J, E[v] \rangle$, for some v, then p is not applied in these reductions.*

Finally, we present the non-inhibition theorem. This theorem states that if the evaluation of a pointcut whose aspect has R̊ deployed on it reduces to a value, this value is either **false** or ($\mathbf{err}\ \cdot$). This holds whenever the join point stack contains a join point whose target is in the set of protected aspects PA. Notice that the theorem implicitly permits the existence of other untrusted aspects trying to inhibit R̊ itself.

[8]Whenever an element of an entity (program configuration, join point, tuple, etc.) is not required, we use $\cdot$ as a wildcard.

THEOREM 2 (NON-INHIBITION). *If l_{asp} is a valid aspect reference in μ, $\mathring{R} \in \mathtt{asps}(l_{asp})$, and $\lceil \cdot, s, \cdot, \cdot \rceil \in J$; where $s \in PA$, then:*
*If $\langle \mu, \alpha, J, E[\mathbf{jp}(\lceil \mathtt{pc\text{-}exec}, l_{asp}, \cdot, \cdot \rceil, \cdot)] \rangle \hookrightarrow^* \langle \cdot, \alpha, J, E[v] \rangle$, then $v =$ **false** or $v = ($**err** $\cdot)$.*

6. DISCUSSION

We discuss how to extend our results from λ_{AS} to full-fledged AspectScript, and the requirements for a general-purpose aspect language to securely support ModAC.

From λ_{AS} to AspectScript .

Due to desugaring, results obtained in λ_{JS} do not immediately apply to JavaScript [17]. This is because desugaring introduces new behavior that was not present in the original code. When going from λ_{AS} to AspectScript, the theorems remain valid because they are based on the aspect-oriented features of the language, which have no relation to the desugaring process. However, access control aspects can be led to behave incorrectly if they use "exploitable" features that introduce holes upon desugaring. For example, consider a slight modification of the pointcut of the netRestriction aspect in order to allow communication with safe.cl:

```
function(jp){ return /* same as before */ && !(jp.args[0] == "safe.cl"); }
```

The equality operator == forces both operands to be of the same type [11]. For this reason, jp.args[0] is transformed to a string by an invocation of toString. The problem is that this extra method call opens the opportunity for bypassing access control:

```
var req = netService.newRequest(
        { t: 0, toString: function(){return ["safe.cl", "evil.com"][this.t++]}});
```

The toString method of the argument to newRequest returns "safe.cl" the first time it is invoked (in the pointcut of netRestriction) and "evil.com" the second time (in the body of newRequest).

In order to avoid such holes, the first possibility is to simply avoid using exploitable features in the definition of restriction aspects. For instance, it is safe to use reference equality === because it does not perform any kind of type conversion [11] (notice that all restriction aspects defined in this work follow this guideline). A less drastic solution is to permit the use of exploitable features, but to carefully examine access control aspects in order to check if their *particular usage* of the feature is safe. For example, the equality operator == is safe if both operands are of the same runtime type! As detailed by Guha *et al.*, this checking can be automated by a specialized type system [17].

Finally, AspectScript uses a scoping strategy acs, which supports privileged execution and capturable permission contexts; acs is expressed with propagation functions, c and d. We made a simplification in λ_{AS} by supporting only constant boolean propagation values. As we said in Section 4.2.2, this simplification does not affect our results. In fact, supporting propagation functions only requires that $\mathring{R}$ prevents inhibition of these functions; this is achieved by extending the pointcut of $\mathring{R}$:

```
function(jp){return ... || cflow(function(jp){return acs.contains(jp.fun);});}
```

This way, $\mathring{R}$ also inhibits untrusted aspects in the control flow of acs components. Theorem 2 and its proof must be reformulated accordingly, but this is direct.

Aspect languages for secure ModAC .

This paper focuses on AspectScript to be as close as possible to our practical implementation, ZAC [33]. Still, both ModAC and the approach for securing it using $\mathring{R}$ are independent of AspectScript. They can be realized in any aspect language, provided it meets certain key conditions. First of all, the language must support scoping strategies, or an equivalently expressive scoping mechanism. Per-object aspects are only necessary if one wants to provide per-object access control. Execution levels are necessary to avoid infinite loops whenever pointcut and/or advice execution join points are exposed to weaving; in order to control implicit inhibition, $\mathring{R}$ relies on matching pointcut execution join points.

A crucial point in ModAC that is directly informed by the formal framework and explicitly used in Lemma 1 is related to aspect precedence: ACDeployer must always be the aspect with least precedence in the aspect environment to be woven at a `new` join point. This allows ACDeployer to deploy restriction aspects on objects before they get a chance to execute any piece of code. The semantics of λ_{AS} ensures this premise because per-object aspects are "engrained" within the object following the semantics of dynamically-deployed aspects in AspectScheme [10]. In AspectScheme this is a design decision; here it is not—it is a *requirement*. If an aspect language uses a different approach to ordering aspects, or permits to undeploy aspects, then it must provide a mechanism to guarantee the above invariant related to the presence and position of ACDeployer. For example, in AspectJ [20], aspects cannot be undeployed, but manual ordering is provided. Therefore, some mechanism must be added, as in AOPS [8]. On a related note, it is necessary that ACDeployer can deploy the restrictions on a newly-created object before any code is run on behalf of this object. In λ_{AS}, this is obtained thanks to the desugaring, which creates an empty object and then calls an initializer. In AspectJ, this can be achieved thanks to the pre-initialization join points. If an aspect language does not exhibit this specific event of an object life time, then it is not possible to guarantee that restrictions see all the computation of untrusted objects.

7. RELATED WORK

The relation between aspects and security has a long history. We now discuss a number of related approaches. To the best of our knowledge, AOPS is the only approach that supports untrusted aspects while preventing inhibitions of access control aspects.

Modularization of access control.

There are several proposals that modularize (part of) access control into aspects, particularly in Java [9, 19, 21, 23, 25, 34, 35]. However, these solutions implicitly assume that no other entities can affect the behavior access control aspects. This implies that access control is vulnerable to inhibition. Work on *inlined reference monitors* [12] is also related. These monitors are used to maintain access control state in the application, executing security actions whenever certain events occur. Monitors are inlined in the application code at appropriate places. Here again, it is assumed that no further code transformations can change the semantics of the security policies.

Limiting the effects of advice.

A number of static reasoning approaches deal with ensuring that advice cannot have unwanted effect on the base program (*e.g.* Harmless Advice [7], EffectiveAdvice [22], Translucid Contracts [3]). These proposals focus on control flow and side effects, and can therefore express the fact some aspects cannot skip proceed. However, inhibition of access control as dealt with in this work requires more fine-grained control, since it limits untrusted aspects only on well-defined join points, leaving them otherwise unrestricted.

Treatment of permission contexts.

Caromel and Vayssière addressed the issue of correctly handling permission contexts in the presence of metaobjects [5]. The issue is to ensure that the permission context at the base level does not affect that of the metalevel, and vice-versa. The proposed solution relies on capturing the permission context when jumping to the metalevel, and restoring it when going back to the base level. Because permission contexts are part of aspect environments in ModAC, we generalize this approach to deal with aspect environments (using `swap` and `in-swap`); also, our execution-level based approach properly deals with proceed.

Preventing access control inhibition.

The aspect-oriented permission system (AOPS) [8] is the most related approach; it uses history-based access control (HBAC) [1], in which the decision of allowing access to a sensitive resource is taken based on *all* the entities that have participated in the execution trace. This characteristic makes HBAC a good alternative for discovering interferences produced by untrusted aspects. As discussed in Section 3.2, AOPS sacrifices two of our design goals: the aspect language semantics is customized to prevent weaving of crucial elements of the access control architecture (G1), thereby impeding even trusted aspects to apply at these points (G3). This being said, history-based access control is more expressive than stack-based access control. Extending or adapting our approach to HBAC is a potentially fruitful perspective.

8. CONCLUSION

Access control has been a recurrent target for aspect-oriented programming, mainly because of the obvious crosscutting nature of basic permission checking. However, security is a delicate concern, and therefore a correct aspectization cannot ignore potentially malicious aspects.

We have shown that access control, including privileged execution and first-class permission contexts, can be fully modularized as an aspect: the aspect language is oblivious to access control, untrusted aspects cannot inhibit access control, and trusted aspects are able to see any join point. The approach relies on defining $\mathring{R}$, a self-protecting restriction aspect in ModAC. $\mathring{R}$ is in charge of ensuring *non-inhibition* of access control. We define λ_{AS}, a core calculus for AspectScript, and use it for stating and proving the properties of ModAC. Crucially, the language must provide some guarantee with respect to aspect precedence.

The ZAC library for access control in JavaScript, implemented in AspectScript and based on ModAC and $\mathring{R}$, is the first practical realization of the proposed approach. Optimizing this implementation, and porting the approach to different languages are valuable perspectives for further validating the benefits of modular and secure access control with aspects.

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