

Fear the EAR: Discovering and Mitigating Execution After Redirect Vulnerabilities

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ABSTRACT

The complexity of modern web applications makes it difficult for developers to fully understand the security implications of their code. Attackers exploit the resulting security vulnerabilities to gain unauthorized access to the web application environment. Previous research into web application vulnerabilities has mostly focused on input validation flaws, such as cross-site scripting and SQL injection, while logic flaws have received comparably less attention.

In this paper, we present a comprehensive study of a relatively unknown logic flaw in web applications, which we call Execution After Redirect, or EAR. A web application developer can introduce an EAR by calling a redirect method under the assumption that execution will halt. A vulnerability occurs when server-side execution continues after the developer's intended halting point, which can lead to broken/insufficient access controls and information leakage. We start with an analysis of how susceptible applications written in nine web frameworks are to EAR vulnerabilities. We then discuss the results from the EAR challenge contained within the 2010 International Capture the Flag Competition. Finally, we present an open-source, white-box, static analysis tool to detect EARs in Ruby on Rails web applications. This tool found 3,944 EAR instances in 18,127 open-source applications. Finally, we describe an approach to prevent EARs in web frameworks.

Categories and Subject Descriptors

D.2.5 [Testing and Debugging]

General Terms

Security

Keywords

static analysis, web applications, execution after redirect

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1. INTRODUCTION

An increasing number of services are being offered online. For example, banking, shopping, socializing, reading the news, and enjoying entertainment are all available on the web. The increasing amount of sensitive data stored by web applications has attracted the attention of cyber-criminals, who break into systems to steal valuable information such as passwords, credit card numbers, social security numbers, and bank account credentials.

Attackers use a variety of vulnerabilities to exploit web applications. In 2008, Albert Gonzalez was accused and later convicted of stealing 40 million credit and debit cards from major corporate retailers, by writing SQL injection attacks [20, 30]. Another common vulnerability, cross-site scripting (XSS), is the second highest-ranked entry on the OWASP top ten security risks for web applications, behind injection attacks like SQL injection [29]. Thus, SQL injection and XSS have received a large amount of attention by the security community. Other popular web application vulnerabilities include cross site request forgery (XSRF) [5], HTTP parameter pollution (HPP) [3, 12], HTTP response splitting [27], and clickjacking [2, 21].

In this paper, we present an in-depth study of a little-known real-world web application logic flaw; one we are calling Execution After Redirect (EAR). An EAR occurs because of a developer's misunderstanding of how the web application framework operates. In the normal workflow of a web application, a user sends a request to the web application. The web application receives this request, performs some server-side processing, and returns an HTTP response. Part of the HTTP response can be a notification that the client (a web browser) should look elsewhere for the requested resource. In this case, the web application sets the HTTP response code to 301, 302, 303, or 307, and adds a `Location` header [32]. These response codes instruct the browser to look for the resource originally requested at a new URL specified by the web application in the HTTP `Location` header [31]. This process is known as redirection¹; the web application redirects the user to another resource.

Intuitively, one assumes that a redirect should end execution of the server side code; the reason is that the browser immediately sends a request for the new location as soon as the redirection response is received, and it does not process the rest of the web application's output. Some web frame-

¹In this paper, we consider only HTTP server-side redirection. Other forms of redirection, executed on the client, exist such as JavaScript redirect or HTML meta refresh.

works, however, do not halt execution on a redirect. This can lead to EAR vulnerabilities.

Specifically, an EAR can be introduced when a web application developer writes code that issues an HTTP redirect under the assumption that the redirect will automatically halt execution of the web application. Depending on the framework, execution can continue after the call to the redirect function, potentially violating the security properties of the web application.

We define *halt-on-redirect* as a web framework behavior where server-side code execution halts on a redirect, thus preventing EARs. Unfortunately, some languages make halt-on-redirect difficult to implement, for instance, by not supporting a `goto`-type statement. Therefore, web frameworks differ in supporting halt-on-redirect behavior. This difference in redirect method semantics can increase the developer's confusion when developing applications in different frameworks.

In this paper, we present a comprehensive study of Execution After Redirect vulnerabilities: we provide an overview of EARs and classify EARs into different types. We also analyze nine web application frameworks' susceptibility to EARs, specifying their redirect semantics, as well as detailing what exactly makes them vulnerable to EARs. Moreover, we develop a novel static analysis algorithm to detect EARs, which we implemented in an open-source tool to analyze Ruby on Rails web applications. Finally, we discovered hundreds of vulnerabilities in open-source Ruby on Rails web applications, with a very low false positive rate.

In summary, this paper provides the following contributions:

- We categorize EARs and provide an analysis of nine frameworks' susceptibility to various types of EARs.
- We discuss the results from the EAR challenge contained within our 2010 International Capture the Flag Competition.
- We present an algorithm to statically detect EARs in Ruby on Rails applications.
- We run our white-box tool on 18,127 open-source Ruby on Rails applications, which found 3,944 EARs.

2. OVERVIEW OF EARs

An Execution After Redirect vulnerability is a logic flaw in web applications that results from a developer's misunderstanding of the semantics of redirection. Very often this misunderstanding is caused by the web framework used by the developer². In particular, developers typically assume that the web application will halt after calling a function of the web framework that performs a redirect. Certain web frameworks, however, do not halt execution on a redirect, and instead, execute all the code that follows the redirect operation. The web browser perpetuates this misunderstanding, as it obediently performs the redirect, thus falsely indicating that the code is correct. As a result, when the

² This misunderstanding was confirmed by a developer who responded to us when we notified him of an EAR in his code, who said, "I wasn't aware at all of this problem because I thought ruby on rails will always end any execution after a redirect." This example shows that developers do not always understand how their web framework handles redirects.

```
1 class TopicsController <
2   ApplicationController
3   def update
4     @topic = Topic.find(params[:id])
5     if not current_user.is_admin?
6       redirect_to("/")
7     end
8     @topic.update_attributes(params[:topic])
9     flash[:notice] = "Topic updated!"
10  end
end
```

Listing 1: Example of an Execution After Redirect vulnerability in Ruby on Rails.

developer tests the web application using the browser, the observed behavior seems in line with the intentions of the developer, and, consequently, the application is assumed to be correct.

Note that an EAR is not a code injection vulnerability; an attacker cannot execute arbitrary code, only code already present after the redirect. An EAR is also different from XSS and SQL injection vulnerabilities; it is not an input validation flaw, but rather a mismatch between the developer's intentions and the actual implementation.

As an example, consider the EAR vulnerability in the Ruby on Rails code shown in Listing 1. The code appears to redirect the current user to "/" if she is not an administrator (Line 5), and, if she is an administrator, `@topic` will be updated with the parameters sent by the user in the `params` variable (Line 7). The code does not execute in this way, because Ruby on Rails does not support halt-on-redirect behavior. Thus, *any* user, not only the administrator, can update the topic, violating the intended authorization and compromising the security of the web application.

The simple way to fix Listing 1 is to add a `return` after the `redirect_to` call on Line 5. This will cause the `update` method to terminate after the redirect, thus, no additional code will be executed. Adding a return after all redirects is a good best practice, however, it is insufficient to prevent all EARs. Listing 2 depicts an example of an EAR that cannot be prevented by adding a return after a redirect. Here, the `redirect_to` on Line 4 is followed by a `return`, so there is no EAR in the `ensure_admin` method. However, `ensure_admin` is called by `delete` on Line 10, which calls `redirect_to` on Line 4. The `return` call on Line 5 will return the control flow back into the `delete` method, and execution will continue on Line 11. Thus, the `@user` object will still be deleted on Line 12, regardless of whether the `current_user` is an administrator or not, introducing an EAR. Unfortunately in some frameworks, the developer cannot simply use `exit` instead of return to halt execution after a redirect because the web application is expected to handle multiple requests. Therefore, calling `exit` would kill the web application and prevent further requests.

2.1 EAR History

Execution After Redirect vulnerabilities are not a new occurrence; we found 17 Common Vulnerabilities and Exposures (CVE) EAR vulnerabilities dating back to 2007. These CVE entries were difficult to find because EARs do not have a separate vulnerability type; the EAR CVE vul-

```

1 class UsersController <
2   ApplicationController
3   def ensure_admin
4     if not current_user.is_admin?
5       redirect_to("/")
6     end
7   end
8
9   def delete
10    ensure_admin()
11    @user = User.find(params[:id])
12    @user.delete()
13    flash[:notice] = "User Deleted"
14  end
15 end

```

Listing 2: Example of a complex Execution After Redirect vulnerability in Ruby on Rails.

nerabilities we found³ were spread across different Common Weakness Enumeration Specification (CWE) types: “Input Validation,” “Authentication Issues,” “Design Error,” “Credentials Management,” “Code Injection,” and “Permissions, Privileges, and Access Control.” These vulnerabilities types vary greatly, and this indicates that EARs are not well understood by the security community.

2.2 EARs as Logic Flaws

While logic flaws are typically thought of as being unique to a specific web application, we believe EARs are logic flaws, even though they are systemic to many web applications. Because an EAR is the result of the developer’s misunderstanding of the web application framework, there is an error in her logic. The intuition is that the redirect is an indication of the developer’s intent for ending server-side processing. A redirect can be thought of as a `goto` - the developer, in essence, wishes to tell the user to look somewhere else. However, it does not act as a `goto`, because the server-side control flow of the application is not terminated, even though that is how it appears from the perspective of the client.

There are almost no valid reasons to have code executed after a redirect method. The few exceptions are: performing cleanup actions, such as closing open files, and starting long-running processes, such as encoding a video file. In the former case, the cleanup code can be executed before a redirect, and in the latter case, long-running processes can be started asynchronously, alleviating the need to have code executed after a redirect.

Because there is no reason to execute code after a redirect, we can infer that the presence of code executed after a redirect is a logic flaw.

2.3 Types of EARs

Execution After Redirect logic flaws can be of two types: benign or vulnerable. A benign EAR is one in which no security properties of the application are violated, even though

³The interested reader is directed to the following EARs: CVE-2009-2168, CVE-2009-1936, CVE-2008-6966, CVE-2008-6965, CVE-2008-0350, CVE-2007-6652, CVE-2007-6550, CVE-2007-6414, CVE-2007-5578, CVE-2007-4932, CVE-2007-4240, CVE-2007-2988, CVE-2007-2776, CVE-2007-2775, CVE-2007-2713, CVE-2007-2372, and CVE-2007-2003.

```

1 $current_user = get_current_user();
2 if (!$current_user->is_admin())
3 {
4   header("Location: /");
5 }
6 echo "Sensitive Information";

```

Listing 3: Example of an information leakage Execution After Redirect vulnerability in PHP. If the `current_user` is not an administrator, the PHP `header` function will be called, redirecting the user to “/”. However, the sensitive information will still be returned in the output, thus leaking the information. The fix is to call the `exit` function after the `header` call.

additional, unintended, code is executed after a redirect. For example, the code executed after the redirect could set a local variable to a static string, and the local variable is not used or stored. Although no security properties are violated, a benign EAR may indicate that a developer misunderstood the redirect semantics of the web framework, posing the risk that code will, in the future, be added after the redirect, elevating the EAR from benign to vulnerable.

A vulnerable EAR occurs when the code executed after the redirect violates the security properties of the web application. More specifically, in a vulnerable EAR the code executed after the redirect allows unauthorized modification to the state of the web application (typically the database), and/or causes leakage (reads and returns to the browser) of data to an unauthorized user. In the former case (e.g., see Listing 1), the integrity of the web application is compromised, while in the latter case, the confidentiality of the web application is violated (e.g., see Listing 3). Thus, every vulnerable EAR is an instance of broken/insufficient access controls, because the redirect call is an indication that the user who made the request is not allowed to access the requested resource.

EAR vulnerabilities can be silent. In a silent EAR, the execution of code does not produce any output. This lack of information makes silent EARs difficult to detect via a black-box approach, while information leakage EARs are easier to detect with black-box tools. Listings 1 and 2 are examples of silent EARs, and Listing 3 is an example of an information leakage EAR.

2.4 Framework Analysis

Web application frameworks vary on supporting halt-on-redirect behavior. Therefore, different frameworks provide protection against different kinds of EAR vulnerabilities. The differing semantics of redirects increases the confusion of developers. A developer we contacted said, “I didn’t realize that [Ruby on Rails] `redirect_to` was like PHP’s `header` redirect and continued to run code.” Thus, an understanding of the web framework’s redirect semantics is essential to produce correct, EAR-free, code.

We analyzed nine of the most popular web frameworks to see how they differ with respect to their built-in redirect functions. The nine frameworks were chosen based on their StackOverflow activity, and include one framework for each of the Ruby, Groovy, and Python languages, three frameworks for the PHP language, one framework that can be applied to both C# and Visual Basic, and two frameworks

for the Java language [7]. While the frameworks selected for analysis are not exhaustive, we believe they are diverse and popular enough to be representative of real-world usage.

To analyze the frameworks, we created nearly identical copies of a simple web service in each of the nine web frameworks. This web service provided access to four pages within the web application. The first was the root page, “/”, which simply linked to the other three pages. The second was the redirect page, “/redirect”, which was used to test proper redirect behavior. The third was the EAR page, “/ear”, which called the framework’s redirect function, appended a message to a log file regarding the request, and finally attempted to return a rendered response to the browser. The last page was the log page, “/log”, which simply displayed the contents of the log file.

Using this design for the web application allowed us to check for integrity violations, represented by the appended log message, and confidentiality violations, represented by output sent after the HTTP redirect response when requesting the EAR page. We approached the implementation of this web application in each framework as many developers new to that framework would. That is, whenever possible, we followed the recommended tutorials and coding practices required to build a web application in the framework.

A brief background on the model-view-controller (MVC) software architecture is necessary to follow our analysis, as each framework analyzed fits the MVC pattern. The MVC architecture supports the separation of the persistent storage (model), the user interface (view), and the control flow (controller) [33]. More precisely, the models interact with the database, the views specify the output to return to the client, and the controllers are the glue that puts everything together. The controller must handle HTTP requests, fetch or update models, and finally return a view as an HTTP response. When following the MVC paradigm, a controller is responsible for issuing a redirect call.

The following sections describe our analysis of each framework’s susceptibility to EAR vulnerabilities based on their redirect functions’ use and documentation. We developed the test application in the latest stable version of each framework available at the time. The version numbers are listed adjacent to the framework name in the section headers.

2.4.1 *Ruby on Rails 3.0.5*

Ruby on Rails, commonly referred to as Rails, is a popular web application framework. Unfortunately, Rails is susceptible to EAR vulnerabilities. Rails provides the `redirect_to` function, which prepares the controller for sending the HTTP redirect. However, the redirect is not actually sent at this point, and code continues to execute following the call to `redirect_to`. In Rails, there is no mechanism to ensure that code halts following a redirect, thus if `exit` is called, a developer must return from the controller’s entry function without executing additional code.

As previously mentioned in Section 2, the Ruby `exit` command cannot be used to halt the execution of a controller after a redirect. This is for two reasons: the first is that `redirect_to` does not immediately send output when it is called, thus if `exit` is called, the user will never see the redirect. The second reason is that Rails web applications are long-running processes that handle multiple incoming requests, unlike PHP, which typically spawns a new instance for each request. Therefore, calling `exit` to halt execution

is not feasible, as it will terminate the Rails application, preventing it from handling further requests.

On a positive note, information leakage EARs are impossible in Rails web applications because a controller can either perform a redirect, or `render` a response (view) to the user. Any call to `render` after a redirect will result in Rails throwing a `DoubleRenderError`. This exception is thrown in all possible combinations: render after a redirect, render after a render, redirect after a render, and redirect after a redirect.

2.4.2 *Grails 1.3.7*

Grails is a framework written in Groovy, which was modeled after the Ruby on Rails framework. Thus, Grails behaves in a manner nearly identical to Rails with respect to redirects. Specifically, code will continue to execute following a call to the redirect function, and, therefore, the developer must take precautions to avoid creating an EAR vulnerability. Unfortunately, as of this writing, nowhere in the Grails documentation on redirects does it mention that code will continue to execute following a redirect [34].

Unlike Ruby on Rails, the behavior of Grails is somewhat less predictable when it comes to the order of view rendering and/or calls to redirect. To explain, we will say that to “render” means to output a view, and to “redirect” means to call the redirect function. As previously mentioned in Section 2.4.1, in Rails, only one render or one redirect may be called in a controller; a `DoubleRenderError` is thrown in the case of multiple calls. In Grails, however, the only redirect exception, `CannotRedirectException`, occurs when a redirect is called following another redirect. In cases where multiple calls to render are made, the final render is the only one that is sent to the browser. More importantly, in cases where both redirect and render are called, regardless of their order, the redirect is actually sent to the browser and the render call is simply ignored. Due to this behavior of Grails, it is not vulnerable to an information leakage EAR. However, like Rails, it is still vulnerable to silent EARs that violate the integrity of the application.

2.4.3 *Django 1.2.5*

Django is a Python web application framework that differs in its handling of redirects compared to the other frameworks (save for ASP.NET MVC). Rather than calling functions to render or perform the redirect, Django requires the developer to return an `HttpResponse` object from each controller. Django’s documentation makes it clear that calling Django’s `redirect` function merely returns a subclass of the `HttpResponse` object. Thus, there is no reason for the developer to expect the code to halt when calling `redirect`. The actual HTTP redirect is sent to the browser only if this object is also returned from the controller’s entry point, thereby removing the possibility of further code execution [15]. Because the controller’s entry point can only return a single `HttpResponse` object, the developer can rely completely on her browser for testing purposes. This behavior makes Django impervious to all EARs.

2.4.4 *ASP.NET MVC 3.0*

ASP.NET MVC is a web application framework developed by Microsoft that adds a Model-View-Controller paradigm on top of traditional ASP.NET, which includes the languages C# and Visual Basic [1]. ASP.NET MVC is similar to Django, in that all controllers must return an `ActionRe-`

sult object. In order to perform redirection, either a `RedirectResult` or `RedirectToRouteResult` object must be returned, which are both subclasses of `ActionResult`. Like Django, this behavior makes ASP.NET MVC impervious to all EARs.

2.4.5 Zend Framework 2.3

By default, the PHP based Zend Framework is not susceptible to EAR vulnerabilities because its redirect methods immediately result in the termination of server-side code. This default behavior is consistent in the two methods used to perform a redirect in the Zend Framework. The simplest method is by using the `_redirect` method of the controller, however, the recommended method is to use the `Redirector` helper object [36].

While the default behavior is not vulnerable to EARs, the Zend Framework supports disabling halt-on-redirect for both methods. The `_redirect` method will not halt when the keyword argument `exit=False` is provided as part of the call. Disabling halt-on-redirect when using the `Redirector` helper requires calling `SetExit(False)` on the `Redirector` helper object prior to making the redirect call. The latter method is particularly interesting because any code executed during the request has the ability to modify the behavior of redirects called using the `Redirector` helper. Fortunately, even when using the `Redirector` helper, the developer has the option of using a set of functions suffixed with “AndExit” that always halt-on-redirect.

When halt-on-redirect is disabled in Zend, it becomes vulnerable to integrity violation EARs. However, the default view rendering behavior no longer occurs. Thus, even when modifying the default behavior, information leakage EARs will never occur in the Zend Framework.

2.4.6 CakePHP 1.3.7

Similar to the Zend Framework, the CakePHP framework is also not susceptible to EAR vulnerabilities out of the box. By default, CakePHP’s single redirect method immediately results in the termination of the PHP script. In a manner similar to the Zend Framework, this default behavior can be modified by setting the third argument of `redirect` to `False`, which in turn also disables the default mechanism for view rendering [11]. Thus CakePHP is vulnerable to EARs in exactly the same way as the Zend Framework.

2.4.7 CodeIgniter 2.0.0

Unlike the Zend Framework and CakePHP, CodeIgniter is a very lightweight PHP framework, and thus, it does not offer much out of the box. Nevertheless, the framework still provides a `url` helper class that contains a redirect method [16]. CodeIgniter’s redirect method always exits after setting the redirect header; a behavior that cannot be changed. Therefore CodeIgniter is impervious to EARs when developers use only the provided redirect function. Unfortunately, the `url` helper class must be included manually. As a result, there is the risk that developers will not use the provided redirect function and instead introduce EARs by neglecting to call `exit` following a call to `header("Location:<path>")`.

2.4.8 J2EE 1.4

Java 2 Platform, Enterprise Edition (J2EE) defines a servlet paradigm for the development of web applications and

web application frameworks in Java. Thus, to perform a redirect in J2EE, or a J2EE-based framework, the developer calls `HttpServletResponse.sendRedirect`. This redirect function will clear out everything previously in the output buffer, set the `Location` header to the redirect location, set the response code to 302, and finally flushes the output buffer to the browser. However, `sendRedirect` does not halt execution of the servlet. Thus, only silent EARs are present in J2EE web applications, or any framework that is based on J2EE servlets.

2.4.9 Struts 2.2.3

Apache Struts is an MVC framework that is built on top of the servlet model provided by J2EE. Thus, Struts inherits all the potential vulnerabilities of the J2EE framework, specifically that silent EARs are possible but information leakage EARs are not possible. This is because to perform a redirect, the `HttpServletResponse.sendRedirect` method of J2EE must be called.

2.5 EAR Security Challenge

Each year since 2003, we have organized and hosted a security competition called the International Capture the Flag (iCTF). The competition pits dozens of teams from various universities across the world against each other in a test of their security prowess. While each iCTF has a primary objective, the competitions typically involve secondary security challenges tangential to the primary objective [14].

For the 2010 edition of the iCTF, we constructed a security challenge to observe the familiarity of the teams to Execution After Redirect vulnerabilities. The challenge involved a vulnerable EAR that violated both the confidentiality and the integrity of the web application. The confidentiality was violated when the web application’s administrator view was leaked to unauthorized users following a redirect; the unauthorized users were “correctly” redirected to an error page. The information contained in the leaked view provided enough information to allow for an integrity violation had the database not purposefully been in a read-only state. More importantly, the initial data leak provided the means to leak further information, thus allowing teams to successfully solve the challenge [6].

The crux of the EAR challenge relied on the automatic redirecting of web browsers and other web clients, such as `wget` and `curl`. To our surprise, many of the teams relied only on the output produced by their web browser, and, therefore, failed to notice the leaked information. It is important to note that the teams in this competition are primarily made up of graduate and undergraduate level students from various universities; many would not be considered security professionals. Nevertheless, we assumed that the meticulous eye of a novice-to-intermediate level hacker attempting to break into a web service would be more likely to detect information leakage when compared to a web developer testing their application for “correct” page flow.

Of the 72 teams in the competition, 69 contacted the web server at least once. 44 of these 69 teams advanced past the first step, which required them to submit a file as per the web application’s specifications. 34 of the 44 teams advanced past the second step, which required them to brute force a two-digit password. It was at this point that the EAR vulnerability was exposed to the teams, resulting in both a redirect to the unauthorized error page and the leak-

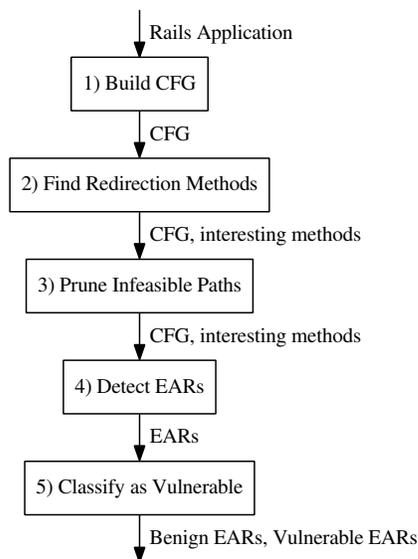


Figure 1: The logical flow of the white-box tool.

age of the administrator page as part of the HTTP redirect response. Of the 34 teams who made it this far, only 12 successfully discovered and exploited the vulnerability. The fact that only 12 out of 34 teams were successfully able to discover the information leaked to their browser in a hacking competition indicated that more research and exposure was necessary for EAR vulnerabilities.

3. EAR DETECTION

In this section, we discuss the design and implementation of our system to detect EAR vulnerabilities. This system uses static source code analysis to identify cases in which code might be executed after the call to a redirect function. We also introduce a heuristic to distinguish benign EARs from vulnerable EARs.

Our tool targets the Ruby language, specifically the Ruby on Rails web framework. We chose this framework for two reasons. First, Ruby on Rails is a very popular web framework, thus, there is a large number of open-source Ruby on Rails web applications available for inspection (e.g., on GitHub [19]). Second, due to the characteristics discussed in Section 2.4.1, all EARs present in Rails are silent. Thus, it is necessary to use a white-box tool to detect EARs in Ruby on Rails web applications. Again, it is important to note that redirects originate within the controllers⁴, thus, our white-box tool operates specifically on controllers.

3.1 Detection Algorithm

The goal of our EAR detector is to find a path in the controller’s Control Flow Graph (CFG) that contains both a call to a redirect method and code following that redirect method. An overview of our algorithm is given in Figure 1. The algorithm operates in five steps: (i) generate the CFG

⁴Redirects can also occur in Rails’ routing, before the request gets to the controller. However, EARs cannot occur in this context, because control flow never reaches a controller. Thus, we are not concerned with these redirects.

of the controller; (ii) find redirection methods; (iii) prune infeasible paths in the CFG to reduce false positives; (iv) detect EARs by finding a path in the CFG where code is executed after a redirect method is called; (v) use a heuristic to differentiate between benign and vulnerable EARs.

Step 1: Building the Control Flow Graph

We built our system on top of the Ruby parser presented by Furr et al. [18]. This parser first compiles Ruby into a subset of the Ruby language called Ruby Intermediate Language, or RIL. The purpose of RIL is to simplify Ruby code into an easier-to-analyze format. The simplification is performed by removing ambiguities in expressions, reducing Ruby’s four different branches to one canonical representation, making method calls explicit, and adding explicit returns. At the end of the transformation, every statement in RIL is either a statement with one side effect or a branch. The parser generates the CFG of RIL.

Due to Ruby’s dynamic nature, this CFG might be incomplete. In particular, strings containing Ruby code can be evaluated at run-time using the `eval` function, object methods can be dynamically called at run-time using the `send` function, and methods can be added to objects at run-time. We do not address EAR vulnerabilities associated with these language features. However, we have found that these features are rarely used in practice (see Section 3.2).

Step 2: Finding Redirection

To detect EARs, we must first find all program paths (from any program entry to any program exit point) in the CFG that call the Ruby on Rails method `redirect_to`. The reason is that we need to check these paths for the presence of code execution between the redirect call and the program exit point. Note that intra-procedural analysis is not enough to find all EARs. Consider the code in Listing 2. Simply looking in `ensure_admin` for code execution *after* the call to `redirect_to` and *before* the end of this method is not sufficient. Thus, we need to perform inter-procedural analysis to find all possible ways in which code execution can continue after a `redirect_to` call until the end of the program.

Our inter-procedural analysis proceeds as follows: we start by finding all methods that directly call `redirect_to`. These methods are added to a set called *interesting methods*. Then, for each method in the *interesting methods* set, we add to this set all methods that call it. This process is iterated until a fixpoint is reached, and no new interesting methods are found.

At this point, every element (method) in *interesting methods* can eventually lead to a `redirect_to` call. Whenever a call to an interesting method returns, its execution will continue after the call site in the caller. Thus, all paths from invocations of `redirect_to` until the end of the program are captured by the paths from all invocations (call sites) of interesting methods to the end of the methods that contain these calls. Now, to detect an EAR, we can simply look for code that is executed on a path from the call site of an interesting method until the end of the method that contains this call.

Step 3: Prune Infeasible Paths

Looking for all paths from the `redirect_to` method to the program exit point might lead to false positives due to infeasible paths. Consider the example in Listing 4. There

```

1 class UsersController <
2   ApplicationController
3   def ensure_logged_in
4     if not current_user
5       redirect_to("/") and return false
6     end
7     @logged_in_users += 1
8     return true
9   end
10  def delete_all
11    if not ensure_logged_in()
12      return
13    User.delete(:all)
14  end
15 end

```

Listing 4: Example of potential false positive.

are no EARs in this code. The `redirect_to` on Line 4 will always return `true`, thus, `return false` (also on Line 4) will execute as well. Because of this, `ensure_logged_in` will always return `false` after performing a redirect. As a result, the call to `ensure_logged_in` on Line 11 will always return `false`, and the `return` on Line 12 will always occur.

The CFG for the code in Listing 4 is shown in Figure 2. With no additional processing, we would incorrectly report the path from `redirect_to` on Line 4 to the statement in Line 6. Moreover, we would also report an EAR because of the path from the redirect to the `User.delete` on Line 13. The first path is denoted as (1) in Figure 2, the second path as (2).

To prune infeasible paths in the CFG, we explore all paths that follow an interesting method. If *all* paths following an interesting method call return the same Boolean value, we propagate this Boolean constant to all the call sites of this method. Then, we recursively continue constant value propagation at all the call sites, pruning infeasible paths everywhere after the interesting method is called. We iteratively continue this process throughout the CFG; whenever we find a constant return value, we propagate this return value to all call sites.

Figure 2 shows the results of performing our pruning process on the CFG of Listing 4. Initially, all paths after the `redirect_to` in `ensure_logged_in` do not return the same Boolean, so we cannot conclude anything about the return value of `ensure_logged_in`. However, `redirect_to` always returns `true`. Therefore, we perform constant value propagation on the return value of `redirect_to`, which is used in a branch. As a consequence, we can prune all of the paths that result from the `false` branch. The edges of this path are labeled with (1) in Figure 2. Now, all paths from `redirect_to` return `false`, which means that `ensure_logged_in` will always return `false` after a redirect. We now perform constant value propagation at all the call sites of `ensure_logged_in`, removing all the paths labeled with (2). At this point, there is nothing more to be pruned, so we stop. It can be seen that there is no path from `redirect_to` to state-changing code (defined in the next step) along the solid lines.

Step 4: Detecting EARs

Once the CFG of the controller has been simplified and interesting method information has been extracted, we perform EAR detection. This is a fairly simple process; we traverse

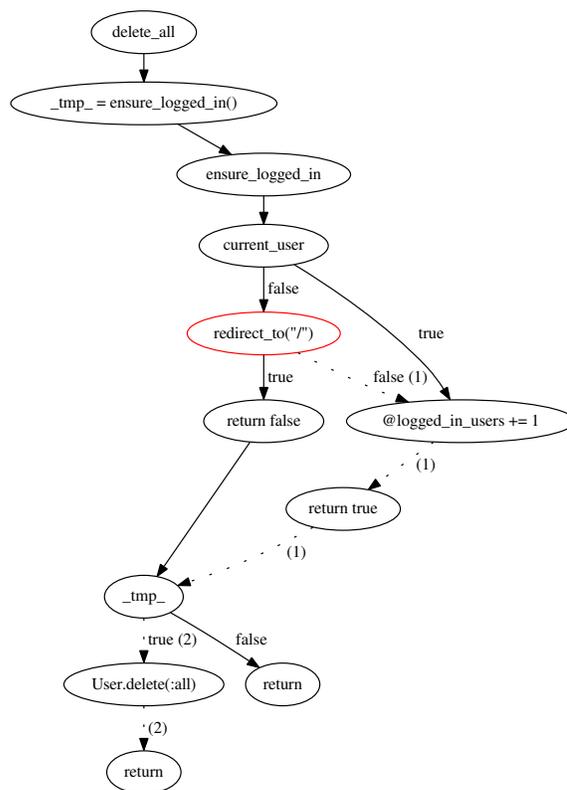


Figure 2: Control Flow Graph for the code shown in Listing 4. The dotted lines are paths removed from the CFG by Step 3 of the EAR detection algorithm.

the CFG of every method to see if potentially problematic code can be executed after a call to an interesting method. We conservatively define such code as any statement that could possibly modify the program state, excluding statements that alter the control flow. This excludes `return` and branches, but includes assignment and method calls. As a special case, we also disregard all operations that set the `flash` or `session` array variable. These arrays are used in the former case to set a message to be displayed on the destination page, and in the latter case to store some information in the user's session. These calls are disregarded because they do not affect the state of the web application and are frequently called after redirection. We report as a potential EAR each method that executes potentially problematic code between the invocation of an interesting method and its return statements.

Step 5: Distinguishing Between Benign and Vulnerable EARs

We also introduce a heuristic to identify vulnerable EARs. This heuristic looks for paths from an interesting method to a function that modifies the database. If one is found, the EAR is marked as vulnerable. We used the Rails documentation to determine the 16 functions that modify the database. Of course, this list can be easily extended. This process is not sound, because we perform no type analysis, and look only at the method names being called. Moreover, we do not analyze the models, only looking for this specific list. Despite these limitations, our results (Section 4.1) show

Type of EAR reported	Number reported
Benign	3,089
Vulnerable	855
Total	3,944
<hr/>	
Total Projects	18,127
Any EAR	1,173
Only Benign	830
At least one vulnerable EAR	343

Table 1: Results of running the white-box detector against Ruby on Rails applications, 6.5% of which contained an EAR flaw. 2.9% of the projects had an EAR classified as vulnerable.

that this heuristic is still a good indicator of potentially vulnerable EARs that deserve the developer’s attention.

3.2 Limitations

The white-box EAR detector is limited to analyzing Ruby on Rails applications, although the detection algorithm can be extended to any programming language and web framework. Detection is neither sound nor complete. False negatives can occur when a Rails application uses Ruby’s dynamic features such as `eval` or `send` to execute a redirect. While such dynamic features are used extensively in the Ruby on Rails framework itself, they are rarely used by web applications written in Rails. Of the 3,457,512 method calls in controllers that we tested our tool on, there were 428 (0.012%) `eval` method calls and 2,426 (0.07%) `send` method calls, which shows how infrequently these are used in Rails web applications.

The white-box tool can report two types of false positives: false EARs, that is, the tool reports an EAR although no code can be executed after a redirect, or false vulnerable EARs, where the tool mistakes a benign EAR as vulnerable.

False EARs can occur for several reasons. One reason is that the path from the redirect function to the code execution that we found is infeasible. A typical example is when the redirect call and the code execution occur in opposite branches. The branch conditions for these are mutually exclusive, so there can never be a path from the redirect call to the code execution. Examples of this type of false positive are discussed in Section 4.1, and these could be mitigated by introducing better path sensitivity.

False vulnerable EARs are a problem caused by the heuristic that we use. The biggest issue is that we simply look for method calls that have the same name as method calls that update/change the database. However, we do not perform any type analysis to determine the *object* that the method is called on. Thus, methods such as `delete` on a hash table will trigger a false vulnerable EAR, since `delete` is also a method of the database object. Improved heuristics could be developed, for instance, that include the type of the object the method is being invoked on.

Despite these limitations, our experiments demonstrate that the tool works very well in practice. In addition, Ruby on Rails controllers are typically very small, as most application logic is present in the models. Thus, our tool works very well on these types of controllers. We provide⁵ our tool to the community at large, so that others may use it to detect EARs in their code.

⁵https://github.com/adamdoupe/find_ear_rails

Classification after manual analysis	Number
True Vulnerable EARs	485
Benign EARs	325
No EARs (False Positives)	45

Table 2: Results of manually inspecting the 855 vulnerable EARs reported by our white-box tool. 40.1% were benign, and 5.3% were not EARs.

4. RESULTS

We used our EAR detection tool to find real-world EARs in open-source Ruby on Rails web applications. First, we downloaded 59,255 open-source projects from GitHub [19] that were designated as Ruby projects and that were not a fork of another project. We identified 18,127 of the downloaded Ruby projects that had an `app/controllers` folder, indicating a Ruby on Rails application.

Table 1 summarizes the results. In total, we found 3,944 EAR instances in 1,173 projects. 855 of these EARs, present in 343 projects, were classified as vulnerable by our system. This means that 6.5% of Rails applications we tested contained at least one EAR, and 29.3% of the applications containing EARs had an EAR classified as vulnerable.

Of the 1,173 projects that contained at least one EAR, we notified those project owners that had emails listed in their GitHub profile, for a total of 624. Of these project owners, 107 responded to our email. Half of the respondents, 49, confirmed the EARs we reported. 26 other respondents told us that the GitHub project was no longer being maintained or was a demo/toy. Three respondents pointed out false positives, which we confirmed, while 6 of the project owners said that there were not going to fix the EAR because there was no security compromise. The rest of the responses thanked us for the report but did not offer a confirmation of the reported EAR.

4.1 Detection Effectiveness

To determine the effectiveness of our tool, we manually inspected all 855 vulnerable EARs. The results are shown in Table 2. We manually verified that 485, or 59.9%, were true positives. Many of these were caused by ad-hoc authorization checks, where the developer simply introduced a redirect when the check failed. Some examples of security violations were allowing non-administrators access to administrator functionality, allowing modifications to items not belonging to the current user, and being able to sign up for a conference even though it was full.

Listing 5 shows an interesting example adapted from a real EAR where the redirect is followed by `and return` (Line 3), however, due to Ruby’s semantics, this code contains an EAR. In Ruby, a `return` with no arguments returns `false`⁶, thus, `redirect_to_login` will always return `false` (because of the “no argument” `return` call on Line 3). The result is that the `return` on Line 8 will never be executed, because `redirect_to_login` will always return `false`, and the short-circuit logic of `and` will cause Line 10 to be executed. This example shows that our tool discovers non-obvious EARs.

For vulnerable EARs, we consider two different types of false positives: false *vulnerable* EARs, which are benign

⁶Technically `nil`, but `nil` and `false` are equivalent for Boolean comparisons.

```

1 class BanksController <
2   ApplicationController
3   def redirect_to_login
4     redirect_to("/login") and return
5   end
6
7   def create
8     if not current_user.is_admin?
9       redirect_to_login() and return
10    end
11    @bank = Bank.create(params[:bank])
12  end
end

```

Listing 5: True positive Execution After Redirect vulnerability in Ruby on Rails.

EARs mistakenly reported as vulnerable, and false EARs (false positives).

As shown in Table 2, the white-box tool generated 45 false EARs, for a false positive rate of 5.3%. These false positives came from two main categories. About half of the false positives were due to impossible paths from the redirect methods to some code. An example of this is when a redirect method was called at the end of a branch that checked that the request was an HTTP GET, while the code executed after a redirect was in a branch that checked that the request was an HTTP POST. These two conditions are mutually exclusive, thus, this path is impossible. The other half of false positives were due to local variables that had the same name as a redirect method. The parsing library, RIL, mistakenly identified the local variable access as a method call to a redirect method. We are currently looking into fixing this issue in RIL, which will almost halve our false positive rate.

While our false EAR rate was only 5.5%, our vulnerable EAR detection heuristic had a higher false detection rate of 40.1%. The biggest culprit for false vulnerable EARs (72.9% of the instances) was due to no feasible path from the redirect to the method that changed the state of the database. For instance, the redirect method occurred in a branch that was taken only when a certain object was `nil`⁷. Later, the database method was called on this object. Thus, when the redirect happens, the object will be `nil`. Because of the presence of an EAR flaw, execution will continue and reach the database access method. However, since the object is `nil`, the database will not be affected. Because our heuristics cannot detect the fact that, after the redirect, the database function will always be called with a `nil` object, we report a vulnerability. The other common false vulnerable EAR were instances where the redirect method was called before code was executed, however, it was clear that the developer was fully aware of the redirect semantics and intended for the code to be executed.

We also checked that the false EAR rate did not differ significantly among the benign EARs by manually inspecting 200 random EARs reported as benign. We saw 13 false EARs in the manual inspection, for a false positive rate of 6.5%. Thus, the total false positive rate among the instances we manually inspected is 5.5%. We also did not see any vulnerable EARs among the benign EARs, thus, we did not see any false negative vulnerable EARs in our experiments.

⁷`nil` is Ruby’s `null`

From our results, we can conclude that we detect EARs well. However, it is more difficult to distinguish between benign and vulnerable EARs. Classification could be improved by using a better heuristic to detect intended redirects. However, even though certain EARs might not be vulnerable at the moment, they are still programming errors that should be fixed. This is confirmed by the responses that we received from developers who were grateful for error reports even though they are not exploitable at the moment. Also, our tool reports one true vulnerability for every benign EAR mistakenly classified as vulnerable. This is well in line with the precision of previous static analysis tools [24,25,28].

4.2 Performance

To evaluate the performance of our tool, we measured the running time against the 18,127 Ruby on Rails applications. We ran our experiments on an Intel Core i7 with 12 gigabytes of RAM. Our algorithm scales linearly with the size of the CFG and is fast; no project took longer than 2.5 seconds even with the largest CFG size of 40,217 statements.

5. PREVENTION

The old adage “an ounce of prevention is worth a pound of cure” is true in software. Boehm showed that the later in an application’s life-cycle bugs are caught, the more expensive they are to fix [8]. Thus, preventing certain types of bugs from even being introduced is attractive from both an economic standpoint, and a security perspective. Our recommendation to web frameworks, therefore, is to make Execution After Redirect vulnerabilities impossible to occur, by having every invocation of the redirect method halt execution, which we call halt-on-redirect behavior.

As we have shown in Section 2.4, some frameworks have already either adopted the approach of making EARs impossible, or their approach to generating HTTP responses makes EARs highly unlikely. For existing frameworks that wish to decrease the chance of EARs being introduced, such draconian measures may not be acceptable because they break backward-compatibility. Our suggestion in these cases is to make an application-wide setting to enable halt-on-redirect behavior, along with an argument to the redirect function to halt execution after the redirect. Of course, we suggest making halt-on-redirect the default behavior, however each framework will have to properly balance security and backward-compatibility.

To improve the security of Ruby on Rails, we are in discussions with the Rails development team about our proposed change. The difficulty with implementing halt-on-redirect behavior in Rails is that there are no `gotos`, and Rails applications run in a single-threaded context. This limits the two obvious forms of implementing halt-on-redirect: we cannot use a `goto` or language equivalent statement to jump from the end of the `redirect_to` method to the code after the controller is called. Moreover, we also cannot, at the end of the `redirect_to` method, send the HTTP response and cause the current thread to stop execution. PHP frameworks can use the `exit` function to implement halt-on-redirect behavior, because each request spawns a new PHP process.

Our proposed solution is to throw a new type of exception, `RedirectOccuredException`, at the end of the `redirect_to` body. In the Ruby on Rails framework core, where the controller is called, there is a catch block for this exception. While this will prevent almost all EARs, there is a possi-

bility for code to be executed in an `ensure` block, Ruby’s equivalent of a “finally” block. Code in this block will be executed regardless of a redirect. However, we believe this is semantically in line with the way the language should work: ensure blocks will always be executed, no matter what happens, and this is clear to the programmer via the language’s semantics.

6. RELATED WORK

Specific instances of Execution After Redirect vulnerabilities have been previously identified. Hofstetter wrote a blog post alerting people to not forget to exit after a redirect when using the PHP framework CakePHP [22]. This discussion resulted in a bug being filed with the CakePHP team [9]. This bug was resolved by updating the CakePHP documentation to indicate the redirect method did not end execution [10].

Felmetsger et al. presented a white-box static analysis tool for J2EE servlets to automatically detect logic flaws in web applications. The tool, Waler, found Execution After Redirect vulnerabilities in a web application called Global Internship Management System (GIMS) [17]. However, neither Felmetsger nor Hofstetter identified EARs as a systemic flaw among web applications.

Wang et al. manually discovered logic flaws in the interaction of Cashier-as-a-Service (CaaS) APIs and the web applications that use them [35]. This is interesting because there is a three-way interaction between the users, the CaaS, and the web application. In our work, we consider one specific type of logic flaw across many applications.

Our white-box EAR detection tool uses the Ruby Intermediate Language (RIL) developed by Furr et al. [18]. RIL was used by An et al. to introduce static typing to Ruby on Rails [23]. They use the resulting system, DRails, on eleven Rails applications to statically discover type errors. DRails parses Rails applications by compiling them to equivalent Ruby code, making implicit Rails conventions explicit. This differs from our tool, which operates directly on the Rails application’s control flow graph. Moreover, we are looking at a specific logic flaw, while DRails is looking for type errors.

Chaudhuri and Foster built a symbolic analysis engine on top of DRails, called Rubyx [13]. They are able to analyze the security properties of Rails applications using symbolic execution. Rubyx detected XSS, XSRF, session manipulation, and unauthorized access in the seven applications tested. Due to the symbolic execution and verifying of path conditions, false positives are reduced. However, Rubyx requires the developer to manually specify an analysis script that defines invariants on used objects, as well as the security requirements of the applications. Our tool, on the other hand, operates on raw, unmodified Rails applications, and does not require any developer input. This is due to the different focus; we are focusing on one specific type of flaw, while Rubyx is broader and can verify different types of security violations.

Our work is also related to numerous white-box tools that have previously been published. Huang et al. were one of the first to propose a static analysis tool for a server-side scripting language, specifically PHP. They implemented taint propagation to detect XSS, SQL injection, and general injection [24]. Livshits and Lam proposed a static analysis technique for Java web applications that used points-to analysis for improved precision [28]. Their tool detected 29 in-

stances of SQL injection, XSS, HTTP response splitting, and command injection in nine open-source applications. Jovanovic et al. developed Pixy, an open-source static analysis tool to discover XSS attacks by performing flow-sensitive, inter-procedural, and context-sensitive data flow analysis on PHP web applications [26]. They later improved Pixy, adding precise alias analysis, to discover hundreds of XSS vulnerabilities in three PHP applications, half of which were false positives [25]. Balzarotti et al. used static and dynamic analysis to develop MiMoSa, a tool that performs inter-module data flow analysis to discover attacks that leverage several modules, such as stored XSS. They found 27 data flow violations in five PHP web applications [4].

All of these static analysis tools differ from our white box tool because we are not looking for unsanitized input vulnerabilities, but rather for unexpected execution that a developer did not intend. We also performed our analysis on a large corpus of real-world applications, and found a correspondingly large number of true vulnerable EARs.

7. CONCLUSIONS

We have described a new type of vulnerability, Execution After Redirect, and developed a novel static analysis tool to effectively find EARs. We showed that EARs are difficult to differentiate between benign and vulnerable. This difficulty is due to vulnerable EARs violating the specific logic of the web application. Better understanding of the application’s logic should help differentiate vulnerable and benign EARs and it will be the focus of future work.

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